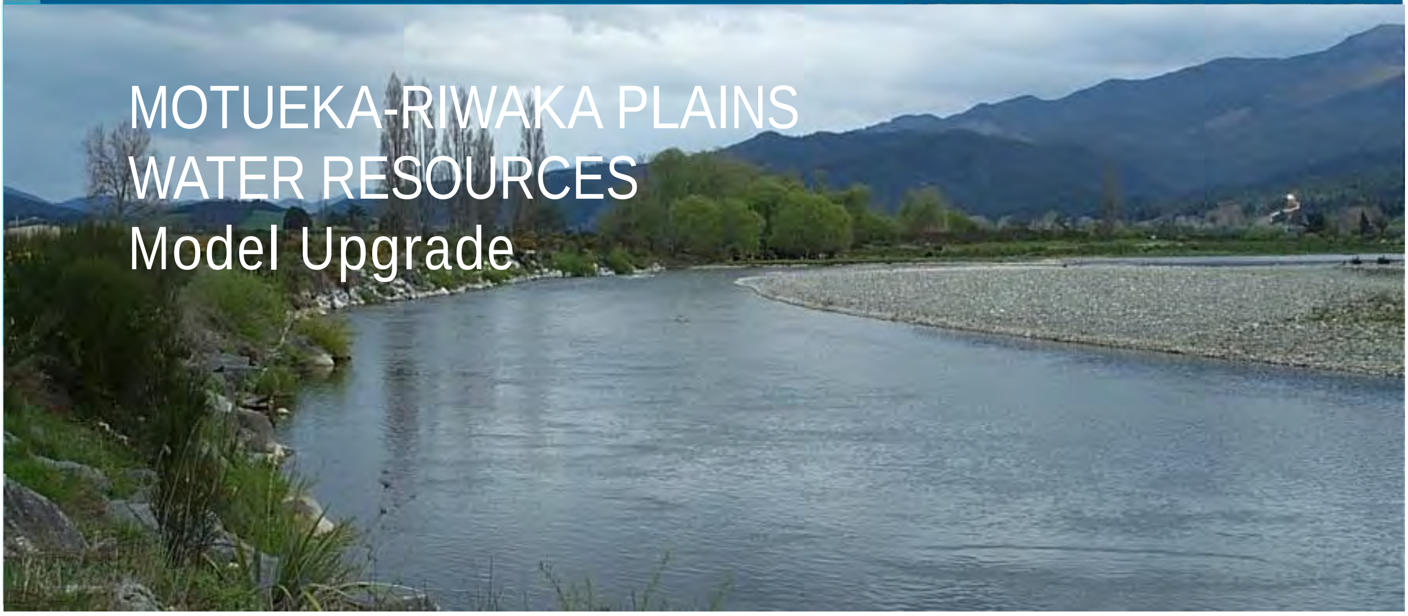
AQUALINC

Groundwater REPORT



MOTUEKA-RIWAKA PLAINS WATER RESOURCES

Model Upgrade

PREPARED FOR
Tasman District Council

C17050

26/04/2018

PREPARED BY
Julian Weir
Joseph Thomas

Quality Control

Client	Tasman District Council
Document Title	Motueka-Riwaka Plains Water Resources: Model Upgrade
Document Number	1
Authors	Julian Weir, Joseph Thomas
Reviewed By	Helen Rutter
Approved By	Helen Rutter
Date Issued	26/04/2018
Project Number	C17050
Document Status	Final
File Name	Mot-Riw GW Model_Stage5_Version1.docx

For more information regarding this document please contact

Julian Weir
Senior Engineer
Aqualinc Research Limited
(03) 964 6521
j.weir@aqualinc.co.nz

The preferred citation for this document is:

Weir, J & Thomas, J (2017). Motueka-Riwaka Plains Water Resources: Model Upgrade. Tasman District Council. Aqualinc Research Limited.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

The Motueka-Riwaka Plains is situated in the Tasman District, north west of Nelson. Gravels deposited into Tasman Bay from the Motueka and Riwaka rivers have formed the Motueka-Riwaka coastal plains (Joseph Thomas, TDC, pers. comm.). Covering an area of approximately 40 km^2, these plains support intensive horticulture and the towns of Motueka and Riwaka.

Underlying the coastal plains is the Motueka-Riwaka aquifer system. This system is the main source of water for irrigation, industrial, community and domestic supplies on the plains. Water is also exported for potable supply to the nearby Kaiteriteri community. It is proposed to supplement Motueka's reticulated supply and to also supply smaller communities along the coast to the south from a proposed Motueka Community Water Supply.

Model Purpose and History

The Motueka-Riwaka groundwater flow model has been developed to assist management of the aquifer system by Tasman District Council (TDC). An initial model (Stage 1), developed by Robb (1999)[1], was used by Robb & Weir (2002)[2] to determine a sustainable level of groundwater abstraction from the Central Plains zone of the Plains. Two subsequent model updates (Stage 2 and Stage 3) were completed by Aqualinc (2007)[3] and Aqualinc (2008)[4]. The Aqualinc (2008) work concluded that an additional 24,500 m^3/day, over and above the allocation limit in the Central Plains zone set by Robb & Weir (2002), could be abstracted without breaching groundwater level and groundwater flux criteria at the coast (to prevent saltwater intrusion).

Based on the recommendations of Aqualinc (2008), TDC installed additional groundwater level monitoring wells within the plains from which additional groundwater level data was collected. This new data, along with additional data collated from existing monitoring bores, was incorporated into the current (Stage 4) version of the model. The Stage 4 model run period was extended from earlier models to cover the period 1 June 1990 through to 31 May 2012. This extended period enabled the incorporation of groundwater level data collated from older, disestablished monitoring bores and from older stream flow monitoring sites. It also permitted the use of a greater length of data collated from other bores. This widened the calibration scope in both space and time and enabled a more thorough representation of the groundwater system.

---

[1] Robb, C (1999): Groundwater Model of Motueka/Riwaka Plains Aquifer System. Report No. 2325/1, prepared for Tasman District Council. Lincoln Environmental, a division of Lincoln Ventures Ltd.

[2] Robb, C and Weir, J (2002): Regional-Scale Effects of Water Export from the Central Plains Zone, Motueka Plains Aquifer. Report No. 4553/1, prepared for Tasman District Council. Lincoln Environmental, a division of Lincoln Ventures Ltd.

[3] Aqualinc (2007): Motueka-Riwaka Plains Groundwater Resource Investigation: Model Update Report. Report No. L07021/3, prepared for Tasman District Council's Engineering Department. Aqualinc Research Ltd.

[4] Aqualinc (2008): Motueka-Riwaka Plains Groundwater Resource Investigation: Model Enhancement and Allocation Assessment. Report No. L07021/9, prepared for Tasman District Council's Environment & Planning Department. Aqualinc Research Ltd.

Latest Model Development

Key model updates since the Aqualinc (2008) model include:

- Switching to a newer version of MODFLOW (MODFLOW-2005);
- Adjusting the active domain (including the off-shore boundary) in three-dimensions based on topographical maps, geological maps and bore logs;
- Refining the model grid size to 100 x 100 m (which is finer than the earlier 450 x 450 m versions of the model);
- Assigning land surface elevations based on LiDAR information provided by TDC (flown on 6th May 2008; vertical accuracy less than 0.01 m);
- Revising the aquifer layering based on all available bore log data and utilising pilot-points to represent key aquifer hydraulic properties;
- Extending the run period to 1 June 1990 through to 31 May 2012 (8,035 days) with daily time steps;
- Utilising rainfall data measured by TDC at Tui Close;
- Updating daily time steps of land surface recharge and groundwater pumping with time-varying land use, stepped in three stages: 1 June 1990-31 May 2004, 1 June 2004-31 May 2010, and 1 June 2010-31 May 2012;
- Simulating key rivers and streams using Stream Flow Routing (SFR2) package with measured variable-shaped cross-sections;
- Expanding the coastal drainage network; and
- Initiate development of groundwater nitrate-nitrogen transport modelling.

The modified and updated model was recalibrated to measured groundwater levels and lowland drain flows, and verified using an independent set of measured groundwater levels. Calibration was carried out over the period 1 January 2001 to 31 May 2012. The normalised root mean square error (RMSE) and the mean error (ME) for this calibration period were 2.6% and 0.13 m, respectively. Verification was carried out over the period 1 June 1990 to 31 December 2000. The normalised RMSE and the ME for this verification period were 2.7% and 0.15 m, respectively. Based on these values, the model has been suitably calibrated with calibration statistics within industry standards (Donnell, *et al.,* 2004[5], MDBC, 2001[6], Barnett *et al.,* 2012[7]).

---

[5] Donnell, B.P. and the ERDC-CHL Groundwater Team (2004): *DDJC-Sharpe Defense Distribution Depot: FEMWATER 3D transport model of TCE plume migration with natural attenuation.* US Army Corps of Engineers report. March 2004.

[6] MDBC (2001): *Groundwater flow modelling guideline.* Murray-Darling Basin Commission. URL: www.mdbc.gov.au/nrm/water_management/groundwater/groundwater_guides

[7] Barnet, B; Townley, LR; Post, V; Evans, RE; Hunt, RJ; Peeters, L; Richardson, S; Werner, AD; Knapton, A; Boronkay, A. (2012): *Australian Groundwater Modelling Guidelines.* Waterlines Report. Published by the Australian National Water Commission, Canberra. June 2012.

Management Scenarios and Results

The calibrated model has been used to run various management scenarios. Initially, a ‘No Abstraction’ scenario was run. This scenario simulates the groundwater system assuming no groundwater abstraction and with corresponding dryland land surface recharge everywhere. Motueka River flows at Woodmans Bend have been naturalised by increasing the measured flows by an amount equivalent to actual water use in the upper Motueka catchment.

A ‘Baseline’ scenario was then developed based on the calibrated model but assuming the existing (status quo) level of irrigation development occurs for the entire model simulation period (1990-2012), with corresponding land surface recharge. Full irrigation on the plains is assumed (i.e. existing unirrigated areas are irrigated, modelled as pasture). Motueka River flows at Woodman’s Bend have been adjusted to account for the maximum permissible irrigated area of 3,200 ha in the Upper Motueka River catchment (also modelled as irrigated pasture). All industrial and community takes are assumed to pump at their maximum consented rates continuously.

Additional scenarios were then run, grouped into the following two broad categories:

A. Scenarios with water restrictions in the Hau Plains for drought years exceeding a 1 in 10 year event (this is required by TDC); and

B. Scenarios without water restrictions in the Hau Plains.

Within each of these two broad categories, the following management scenarios have been considered:

1. An additional 20,000 m^3/day abstraction from TDC’s Parker Street well field, located adjacent to the Motueka River, to supply a future urban supply;
2. A further 5,000 m^3/day (total 25,000 m^3/day) from the proposed well field; and
3. A further 5,000 m^3/day (total 30,000 m^3/day) from the proposed well field.

Additional scenarios have been developed to consider:

- The effects of Motueka River bed degradation of 0.3 m at Woodman’s Bend.
- Aquifer flow response from a predicted sea level rise of 1 m.
- The aquifer response under four different climate change predictions.

Effects on the Overall Water Balance

Considering the entire aquifer system as a whole, an increase in groundwater abstraction is balanced by an increase in net recharge from the rivers, a reduction in drain flows, a reduction in storage (i.e. groundwater level lowering) and a reduction in off-shore flow. Where the additional abstraction results in additional land surface recharge (e.g. under increased levels of irrigation), then the additional recharge also contributes to the water rebalance.

Effects on Groundwater Levels

There is no visible long-term cumulative decline in groundwater levels from year to year as a result of groundwater abstraction. By and large, groundwater levels return to the No Abstraction state most years during the wetter winter periods when irrigation abstractions cease. The groundwater system recovers quickly from the hydraulic effects of pumping.

Ignoring localised effects of pumping, overall (regional) groundwater levels drop 0.5-1.2 m over much of the plains as a result of the level of the current level of development compared to the No Abstraction state. Groundwater levels are affected less towards the coast and the main rivers due to the regulating effects of these boundaries.

When continuous abstraction from TDC's proposed Parker Street well field occurs, groundwater levels decline in some wells, particularly those located in close proximity to the well field. This is due to the sustained nature of the well field abstraction which does not stop during winter, in the way that irrigation takes do. Should the well field cease abstraction, then groundwater levels would recover to their less developed state.

When 20,000 m^3/day of groundwater is abstracted from the proposed Parker Street well field, groundwater levels lower by an additional 0-0.4 m over the aquifer system. Closer to the well field (within approximately 600 m), groundwater level lowering of 0.4-0.8 m is predicted. When 25,000 m^3/day is abstracted, the groundwater level lowering increases to 0-0.6 m over the aquifer system, and 0.6-1 m nearer the well field location. When 30,000 m^3/day is taken, the groundwater level lowering increases to 0-0.8 m, and 0.8-1.2 m nearer the well field location.

Hau Plains restrictions reduce groundwater level lowering by approximately 0.1 m in the Fernwood coastal monitoring bore. These restrictions during dry periods have a positive effect on reducing the risk of saltwater intrusion.

Motueka River bed degradation affects groundwater levels primarily in the upper reaches of the river where the greatest bed reduction is simulated. In this area, a groundwater level lowering of 0.2-0.3 m is predicted from a bed reduction of 0.3 m. The effects propagate from the river's upper reaches and diminish over a distance of approximately 2-3 km from either side of the river, with only a small effect (< 0.1 m) beyond this.

A sea level rise of 1 m results in a rise in groundwater levels over much of the plains, but the rise becomes more prominent with proximity to the coast, and reduces with distance inland. A rise of 0.2 m or more is predicted to extend up to 3 km inland from the coast. Wells located close to rivers are predicted to experience very little effect from sea level rise due to the regulating effect of the river. Sea level rise is expected to increase the area of land that may experience groundwater flooding during extreme wet periods.

Overall the additional effects on groundwater levels from climate change alone (no sea level rise) is very small compared to natural variation of groundwater levels. Sea level rise dominates the climate change scenario where this is additionally included.

Effects on Motueka River Flows

Generally, groundwater abstraction results in an increase in recharge from the Motueka River to groundwater. This occurs because groundwater abstraction lowers groundwater levels, which in turn increases the hydraulic gradient between the river and adjacent groundwater. An increase in recharge from rivers to groundwater results in a direct reduction in river flows.

Typically, the river loses more flow, and a greater percentage of flow, to groundwater during dry periods, compared to average periods. The reason for this is twofold: firstly, the river flows are lower, hence any loss is proportionally greater; and secondly groundwater abstraction (and therefore induced river loss) is greater during dry periods compared to the long-term average.

The modelling work predicts that historical abstraction has resulted in an increase in average Motueka River losses of approximately 2%, and up to 19% during dry periods, between Woodmans Bend and the coast. During the dry periods, losses are predicted to increase a further 3-6% under the Baseline scenario.

Restrictions in the Hau Plains have very little benefit (1% at most) on Motueka River recharge to groundwater. Lowering the Motueka River bed 0.3 m reduces the losses by 1-2% compared to the Baseline scenario. This is because the lower river elevations reduce the hydraulic gradients between the river and adjacent groundwater. A sea level rise of 1 m is predicted to reduce Motueka River losses by 8-15% over the plains. This is because the resulting raised groundwater levels reduce the hydraulic gradients between the river and adjacent groundwater.

Climate change alone is predicted to have only a very small effect on catchment river flows.

Effects on Drain Flows

Increased groundwater abstraction results in reduced drain flows. The greatest percent changes occur during dry periods when drain flows are naturally lower due to low groundwater levels. During dry periods, the predicted percentage changes in flows are large for some scenarios. Thorp Drain is predicted to be more affected by groundwater abstraction compared with other drains due to its location relative to regional groundwater flow directions and areas of greatest groundwater use.

Hau Plains restrictions are predicted to benefit Thorp Drain by 5-8% during dry periods. Of the drains modelled, Thorp Drain is the only drain located in close vicinity to the Hau Plains management zone. Consequently, the other drains show no benefit from Hau Plains restrictions.

The small changes in regional groundwater levels predicted near the drains as a result of Motueka River bed degradation results in a reduction in average drain flows by 0-3%, and 4-16% during dry periods. A sea level rise of 1 m is predicted to substantially increase all drain flows. However, raised sea level is likely to result in additional sea water seeping, diffusing and/or back-flowing into these drains. Currently, water flowing in the drains is brackish nearer the costal ends of the drains; sea level rise is likely to increase the salt content in these lower reaches.

Climate change alone is predicted to have only a very small effect on drain flows.

Assessing the Sustainable Abstraction

TDC's principle concern for managing the Motueka-Riwaka groundwater system relates to saltwater intrusion. Consequently, the following decision criteria have been used to decide a limit of sustainable abstraction:

- The average groundwater level at Fernwood for the first 90 days of 2001 and 2006 is not to drop below 0.40 m amsl;
- The average seaward flux for the first 90 days of 2001 and 2006 is not to drop below 0.52 m^3/s; and
- There is to be no occurrence of landward flux.

These three decision variables are consistent with previous studies (such as Aqualinc, 2007[8] and Aqualinc, 2008[9]).

Under historical patterns of climate (and subsequent river flows and land surface drainage) and sea level, groundwater abstraction of over 30,000 m^3/day is predicted to be sustainable from the Parker Street well field without breaching any decision criteria. This is greater than recommended in earlier studies, primarily due to the improved accuracy of the model and the more realistic representation of industrial and community supplies. However, a lesser rate may be needed if management of coastal drain flows is important to TDC.

Sea level rise is predicted to result in coastal backflow of sea water into the aquifer. If this occurs, mitigation against saltwater intrusion may be needed, which may require a lesser abstraction than the 30,000+ m^3/day discussed above. No assessment of the likely occurrence of sea level rise has been made in this investigation.

Ongoing Monitoring

To improve the understanding of the groundwater system, and how it responds to increased abstraction, it is recommended that the existing monitoring network be continued. In addition, it is recommended that a piezometric survey of the plains be completed at a resolution finer than the spacing of the existing monitoring bores. This will provide information on the patterns of groundwater levels between and beyond the existing monitoring bores. Further gaugings of coastal springs (including winter-

---

[8] Aqualinc (2007d): *Motueka-Riwaka Plains Groundwater Resource Investigation: Technical Assessment of Environmental Effects for Proposed Community Water Supply.* Report No. L07021/4, prepared for Tasman District Council's Engineering Department. Aqualinc Research Ltd.

[9] Aqualinc (2008): *Motueka-Riwaka Plains Groundwater Resource Investigation: Model Enhancement and Allocation Assessment.* Report No. L07021/9, prepared for Tasman District Council's Environment & Planning Department. Aqualinc Research Ltd.

period flows) and losses in the Motueka and Riwaka rivers would provide valuable data against which to further calibrate the model.

Future Model Enhancement

If further abstraction is to be considered, it is recommended that the results from the additional monitoring discussed above be incorporated into the groundwater model, and the model updated accordingly. This updated model should then be used to consider the effects of the additional abstraction.

If TDC are concerned about saltwater intrusion risk due to future sea level rise, and want to investigate suitable mitigation measures, then density-dependent flow should be incorporated into the model.

Site-specific calculations of land surface nitrate loadings should be completed to improve the numerical transport modelling.

1 INTRODUCTION

The aquifer system underlying the Motueka-Riwaka Plains is a primary source of water for irrigation, industrial, community, domestic and stockwater supplies. Both the Motueka township and the nearby Riwaka settlement provide reticulated community water supplies from the aquifer system. Many other houses outside of the reticulated supply areas have individual shallow domestic wells for potable water supply. Water is also exported from the aquifer system to the north of the Motueka River for potable supply to the nearby Kaiteriteri community. Future supply is also proposed from the Motueka Community Water Supply. This scheme will take groundwater from the south side of the Mouteka River to supplement and expand the existing Motueka reticulated supply, and also to supply smaller communities along the coast to the south.

The Motueka-Riwaka Plains groundwater flow model has been developed as a tool to assist management of the aquifer system by Tasman District Council (TDC). An initial model of the aquifer system was developed in 1999. Since then, the model has been updated and improved, and has been used to assist setting sustainable levels of water allocation on the plains. Results from model management scenarios have been used to assist setting allocation limits in TDC's Tasman Resource Management Plan (TRMP).

With new data collected, TDC commissioned Aqualinc Research Ltd (Aqualinc) to further update the model and to run new management scenarios in order to improve allocation strategies. This report documents the history of model development, the latest state of the model, and the results from the most recent scenarios.

1.1 Project Tasks and Objectives

The tasks and objectives of this stage of model development are to:

- Discretise the model with a grid size of 100 x 100 m (this is finer than earlier 450 x 450 m versions of the model);
- Revise the hydrogeological representation with new bore log data and land surface LiDAR data (as flown by TDC on 6th May 2008; less than 0.01 m vertical accuracy), and utilise pilot-points to represent key aquifer hydrological properties (where appropriate);
- Update the model with new groundwater level and spring flow information, extending the coastal drainage network where needed;
- Use measured data to incorporate variable-shaped river cross sections into MODFLOW's Stream Flow Routing (SFR2) package;
- Extend the model run period to 1 June 1990 through to 31 May 2012 (continuous) allowing for time-varying land use;

- Recalibrate and verify the model;
- Run management scenarios to identify the cumulative effects on the aquifer system from additional groundwater takes in the Central Plains zone;
- Determine the sustainable level of abstraction from the Central Plains zone in and surrounding a proposed abstraction area; and
- Develop transient nitrate-nitrogen transport modelling capability.

2 BACKGROUND OF THE MOTUEKA-RIWAKA GROUNDWATER INVESTIGATION

The Motueka-Riwaka Plains is situated in the Tasman District, north west of Nelson (Figure 2-1). As discussed in Robb (1999), gravels deposited into Tasman Bay from the Motueka and Riwaka rivers have formed the Motueka-Riwaka coastal plains. The rich agricultural soils on the plains support intensive horticulture and the towns of Motueka and Riwaka.

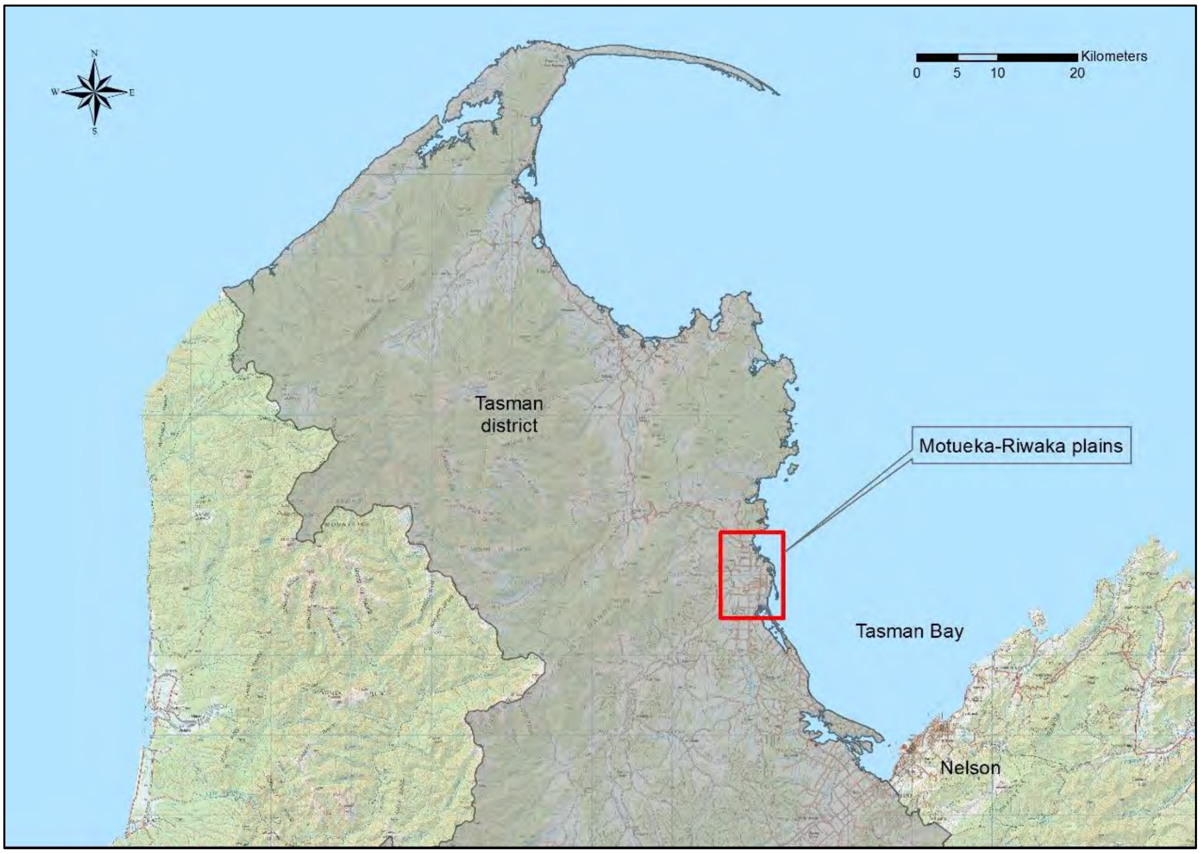


Figure 2-1: Location of the Motueka-Riwaka Plains

A summary of the hydrogeology of the Motueka-Riwaka Plains is provided below along with overviews of key management objectives and earlier investigations.

2.1 Hydrogeological Overview

The Motueka-Riwaka Plains cover approximately 40 km^2. A map showing an aerial photograph of the plains overlain with the model grid is provided in Figure 2-2. Figure 2-3 presents the model grid underlain by a 1:50,000 scale topographic map.

Figure 2-2: Aerial photograph with grid

Figure 2-3: Topographic map with grid

The Motueka-Riwaka aquifer system is bounded in the west, north and base by faulted granite rock and in the south by older, low permeability Moutere gravels. The lithology and thickness of the aquifer layers are variable. A schematic cross section of the aquifer system is provided in Figure 2-4 (reproduced from Robb, 1999, originally generated by Joseph Thomas, TDC).

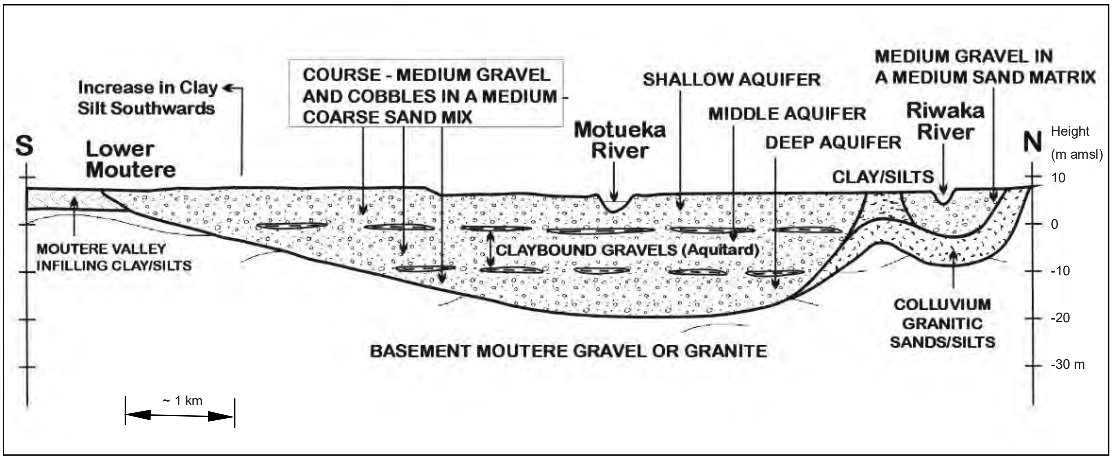


Figure 2-4: Schematic north-south cross section of the aquifer system (reproduced from Robb, 1999, originally generated by Joseph Thomas, TDC)

Thicknesses of the alluvial gravels in the central area of the plains are approximately 20-30 m and reduce to about 6 m towards the fringes. To the south, the gravels are mixed with material flushed out of the Moutere valley and have a high content of fine sands, silts and clays. More centrally, the gravels are freer, consisting of well-rounded clasts predominately of granite, sandstone, siltstone and basic igneous rock (Robb, 1999). Towards the Riwaka River, the gravels are reworked by the river and are mixed with colluvial granite deposits (Robb, 1999).

The aquifer system is highly interconnected with the Motueka and Riwaka rivers and previous investigations indicate that a large proportion of aquifer recharge is sourced from these rivers (Robb, 1999; Aqualinc, 2007c). Additional water is supplied by rainfall and irrigation recharge across the plains. Groundwater exits the aquifer system by subsurface flow into Tasman Bay, into springs near the coast, into rivers, or via groundwater pumping.

2.2 Aquifer System Management

Surface water and groundwater resources of the Motueka-Riwaka Plains are managed by TDC in an integrated manner. Key water management objectives include:

- Protecting against saltwater intrusion around the coastal margins;
- Maintaining flows in coastal springs;
- Ensuring adequate flow regimes for the Motueka and Riwaka rivers; and
- Providing a reliable water supply for existing and future groundwater users.

For water management purposes, TDC has divided the Motueka-Riwaka Plains into seven management zones, as depicted in Figure 2-5.

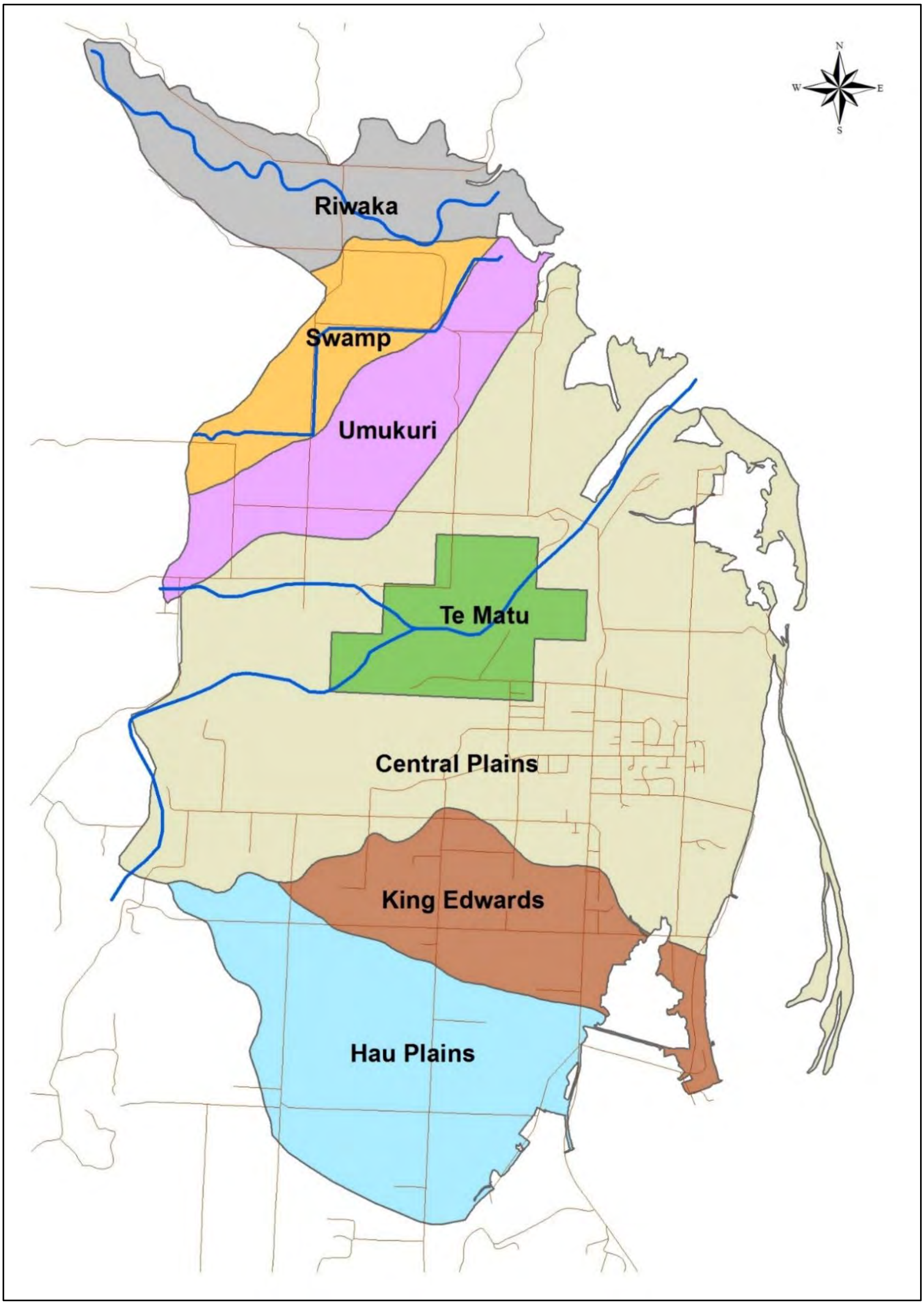


Figure 2-5: TDC water management zones

2.3 Stage 1: Original Model

The original Motueka-Riwaka model was developed in 1999 by Robb (1999) in partnership with TDC. It was developed as a MODFLOW 1988 model (McDonald & Harbaugh, 1988) within the graphical user interface Visual MODFLOW 2.7.

The aquifer system was represented as a three-layer system comprising an unconfined aquifer overlaying two semi-confined (leaky) aquifers overlaying relatively impermeable Moutere Gravels and a granite basement (Figure 2-4). A uniform grid of 450 m × 450 m cells was used.

Each of the three layers represented by the model was separated into various material zones representing different hydraulic conductivities. All three layers were isotropic in the horizontal directions. Vertical conductivities were calibrated at 1/20 of the horizontal values, which was sufficiently high to result in predicted water levels in all three layers being the same. The model incorporated zones of varying storativity in a similar way to the conductivity zones. However, model calibration proved to be insensitive to storativity.

No-flow boundaries were defined to the south, north and west, and along the model base. All three layers were assumed to extend beyond the coastline, discharging to the sea. Layer thickness decreased with distance offshore. The coastal boundary was represented by a constant head boundary (head equal to zero metres at mean sea level) with high conductance (i.e. no resistance for water flow to the sea).

Daily stress periods were applied for one year at a time (January to December). Water sources included rainfall recharge, irrigation recharge and river inflows (Motueka and Riwaka rivers). Rainfall and irrigation recharge was dependent on soil moisture conditions which, in turn, was dependent on climatic conditions, soil type and crop type. Recharge was calculated using a Conceptual Soil Moisture Model (CSMM) and was based on one combination of crop type, soil type and rainfall per cell.

River flows were based on flow data supplied by TDC from their flow recorders at Woodstock on the Motueka River, and Littles and Moss Bush on the Riwaka River. The two rivers were represented using MODFLOW's stream package (STR).

The model was calibrated as a transient model only. Calibration was based on groundwater level data from 1994-95 which was an average to wet year. Model predictions were then verified against groundwater level data from 1989-90, which was a dry year (considered a 1-in-10-year drought).

Calibration and verification were based on groundwater levels in six observation wells. These processes were complicated by the fact that the observation wells were not located at the centre of the model cells, yet Visual MODFLOW 2.7 only calculated groundwater levels at the cell centres. To overcome this, the predicted groundwater levels at the observation wells were calculated by interpolation with groundwater levels in surrounding cells.

Once the model was calibrated, it was used to predict groundwater levels in a 1-in-20-year drought by using climate and river flow data from 1972-73.

2.3.1 Conclusions from the Stage 1 Model

The original Stage 1 model was used in 2002 to inform the Tasman Regional Water Study on additional sustainable abstraction above the allocated rates from the Central Plains zone (Robb & Weir, 2002). This work formed part of the broader regional study which assessed future water demand and water availability in numerous catchments throughout the Tasman region. The work concluded that there was potential for abstracting up to 500 l/s (43,200 m^3/day) more water from the Central Plains zone, depending on the location of the take and the management regime selected.

2.4 Stage 2: Model Update

In 2007, TDC's Engineering Department further investigated the potential for more abstraction from the Central Plains zone for a public water supply to the Motueka, Mapua and coastal areas of Tasman. As part of this investigation, TDC's Engineering Department engaged Aqualinc to update the original groundwater model to include new data, improve calibration of the model, and include their proposed well field site. This phase of the development involved four distinct stages of work:

(i) Aquifer testing (shallow and deep layers) of a proposed well field site (Aqualinc, 2007a).

(ii) Using the results from the aquifer tests to design a well field and to assess the potential local effects from the proposed take (Aqualinc, 2007b).

(iii) Updating the existing groundwater model (Robb, 1999) to include new data, better calibrate the model, and include the proposed well field site (Aqualinc, 2007c).

(iv) Preparing a technical assessment of environmental effects on the groundwater system from the proposed take (Aqualinc, 2007d).

The Stage 2 model was upgraded to MODFLOW 2000 (Harbaugh et al., 2000) and was developed using the graphical user interface Visual MODFLOW 3.0. It was constructed to simulate two-year periods for the years 1989-90, 1994-95 and 2000-01 with groundwater pumping updated accordingly. In addition, the Stage 2 model was re-engineered to bring it into line with standards of good modelling practice current at the time (Hill, 1998; MfE, 2002). This involved the following changes:

- Zones of hydraulic conductivity and storage coefficients were altered to better represent the natural geologic environment found in the area. Three zones parallel to the river were used (Aqualinc, 2007c);

- The coastal boundary condition was changed to a general head to better reflect how the layers interact with the sea;

- River parameters within the STR package were updated with new information; and

- Parameter optimisation using PEST (Dougherty, 2010) was used to assist with calibration of the model.

2.4.1 Conclusions from the Stage 2 Model Update

The Stage 2 work concluded that an additional abstraction of 20,000 m^3/day from the Central Plains zone was sustainable, over and above the allocation limits at the time. However, further work was required to determine if further abstraction, greater than 20,000 m^3/day, was also sustainable. Aqualinc recommended that further long-term monitoring of groundwater levels be undertaken to better calibrate the groundwater model in the coastal areas north of Motueka township. This would then allow a more accurate prediction of the effects on saltwater intrusion in this area, and hence the effects from additional groundwater abstraction could be better predicted.

2.5 Stage 3: Model Update

Following on from the Stage 2 work, TDC installed new monitoring wells in the coastal areas and collected additional groundwater level data. Additional data also become available from TDC's Engineering Department as part of their resource consent application for a community water supply.

The Stage 3 model was completed for TDC's Environment and Planning Department to assist in setting new allocation limits for the Motueka-Riwaka Plains. This model incorporated the additional monitoring data, which was used to recalibrate the model and reassess the effects of additional abstraction. In addition, TDC provided measured cross sections of the Motueka and Riwaka rivers which were incorporated into the model to improve the representation of these features.

The Stage 3 model was developed as a MODFLOW 2000 model using the Groundwater Vistas (Version 5) graphical user interface. Other areas of focus during the Stage 3 update of the Motueka-Riwaka groundwater model included:

- Constructing a single model that ran continuously from 1 January 1995 through to 1 July 2007 (4,565 days) with daily time steps. This provided information on the potential long-term cumulative effects from abstraction over several years, and other long-term natural phenomenon that may affect regional groundwater levels.

- Changing the model grid numbering system to align with the same numbering system used by MODFLOW 2000 (Harbaugh *et al.,* 2000).

- Altering discretisation of model hydraulic conductivity and storage. New monitoring data increased the freedom to introduce more parameter zones to enhance the accuracy of the model;

- Rivers and streams were represented using the Stream Flow Routing Package (SFR1) (Prudic *et al.,* 2004). The Motueka and Riwaka rivers were modelled using variable-shaped cross sections based on measured data.

The Brooklyn and Little Sydney streams were modelled with rectangular bed geometry.

2.5.1 Conclusions from the Stage 3 Model Update

Various management scenarios were run with the revised model. Results from the analyses concluded that water restrictions in the Hau Plains zone for droughts exceeding 1-in-10 year events (as required by the TRMP) is an effective means to reduce the risk of saltwater intrusion while permitting additional groundwater abstraction in the Central Plains zone. Therefore, the sustainable level of additional abstraction was determined based upon the scenarios that considered water restrictions in the Hau Plains. The recommended sustainable additional abstraction from the Central Plains zone, above that currently permitted under the TRMP, was 24,500 m^3/d.

To be conservative in managing the Motueka-Riwaka Plains groundwater system, it was recommended that the additional volume of 24,500 m^3/d be only made available from the area within a sub zone of the Central Plains zone identified in Figure 2-5 as the Te Matu zone. The revised allocation limits for the TRMP, which are the current limits, are summarised in Table 2-1 (Joseph Thomas, TDC, pers. comm., reproduced from Figure 31.1E of the TRMP).

Table 2-1: Current TRMP allocation limits for each management zone (reproduced from Figure 31.1E of the TRMP)

Allocation zone		**Allocation limit (l/s)**
Central Plains (excluding the Te Matu zone)		795
Te Matu		344
Kind Edwards		135
Umukuri	Groundwater	133
	Brooklyn River	62
Swamp	Groundwater	73
	Little Sydney River	31
Hau Plains		228 subject to conditions (1)
Riwaka	Groundwater	30
	Surface water	170
(1) Condition 31.1.2.3(d)(i) of the TRMP		

2.6 Stage 4: Model Update

Subsequent to the Stage 3 development, TDC installed additional groundwater level monitoring wells across the plains from which additional groundwater level data was collected. This new data, along with additional data collated from the existing monitoring bores, was incorporated into the Stage 4 version of the model. In addition, the model run period was extended. This enabled the incorporation of groundwater level data collated from older disestablished monitoring wells, and from older stream flow monitoring sites. It also permitted the use of a greater length of data collated from other wells. This widened the calibration scope in both space and time, and enhanced the model's ability to accurately replicate the groundwater system.

Stage 4 of the model was based on MODFLOW 2005 (Harbaugh, 2005) and was constructed using the graphical user interface Geological Modelling System (GMS, 2014). MODFLOW 2005 provided faster run times and improved numerical stability compared with previous versions.

The Stage 4 update focussed on:

- Refining the model domain;
- Including new geological data from bore logs;
- Incorporating new monitoring data (both from existing bores and newly installed bores);
- Extending the model run period;
- Utilising measured rainfall at Tui Close;
- Improving the river representation; and
- Expanding the coastal drainage network.

The refined and calibrated model was used to assess ten different management scenarios. The scenarios range from various abstraction and water use management options to effect of potential degradation of the Motueka River bed, and potential effects of sea level rise. These ten scenarios are:

1. No Abstraction
2. Baseline (status quo)
3. Baseline + abreaction of addition 20,000 m^3/day from a well field (the well field) located adjacent to the Motueka River
4. Baseline + abreaction of addition 25,000 m^3/day from a well field
5. Baseline + abreaction of addition 30,000 m^3/day from a well field

6. Baseline + abreaction of addition 20,000 m^3/day from the well field, with 35% restrictions for takes in the Hau Plains for droughts exceeding 1 in 10 year events (Hau restrictions)
7. Baseline + abreaction of addition 25,000 m^3/day from the well field, with Hau restrictions
8. Baseline + abreaction of addition 30,000 m^3/day from the well field, with Hau restrictions
9. Motueka River Bed Degradation
10. Sea level rise.

2.6.1 Conclusions from the Stage 4 Model Update

Based on the results from scenario assessment, it was recommended that groundwater abstraction of over 30,000 m^3/day is sustainable from the well field under the historical patterns of climate (and subsequent river flows and land surface drainage). This volume is greater than that recommended by Aqualinc (2008), primarily due to the improved accuracy of the model and the more realistic representation of industrial and community supplies. However, the report suggested that a lesser volume should be abstracted from the well field if management of coastal drain flows is important to TDC.

The sea level rise scenario predicted that coastal backflow of sea water into the aquifer would occur. If this occurs, mitigation against saltwater intrusion may be needed, which may require a lesser abstraction than the 30,000 m^3/day.

2.7 Stage 5: Model Update

Stage 5 of the modelling work commenced in 2012. The primary focus of the Stage 5 modelling was two-fold:

(i) Further assess the effect of climate change on water resources and water use in the Motueka-Riwaka Plains; and

(ii) Further develop transient nitrate-nitrogen transport modelling capability.

2.7.1 Climate Change Scenarios

Two additional scenarios were developed to be run through the Motueka-Riwaka Plains groundwater flow model, to encompass a range of climate change predictions. Two sets of time series of rainfall and potential evapotranspiration (PET) were developed to simulate two extreme climate change scenarios, using information from NIWA (2015). These were:

(i) Climate Change Scenario 1: projected lowest rainfall + projected highest PET; and

(ii) Climate Change Scenario 2: projected highest rainfall + projected lowest PET.

These climate data time series were used to generate new time series of crop irrigation demand, actual evapotranspiration and land surface recharge (LSR) using Aqualinc's soil-water balance model IRRICALC.

Projected time series of river flows were also generated to reflect the impact of climate change for the Motueka and Riwaka rivers, and Little Sydney and Brooklyn streams. Historical river flows were adjusted based on rainfall and actual evapotranspiration (AET) values taken from the IRRICALC outputs for each climate change scenario assuming representative dryland soils for each river catchment. Climate change scenario 1 resulted in decreased river flows while climate change scenario 2 resulted in increased river flows.

These altered river flows, irrigation demand and land surface recharge time series were applied to the existing calibrated Motueka-Riwaka Plains groundwater flow model in order to assess the change in water dynamics. Each of these scenarios was run with, and without, sea level rise, as modelled under the Stage 4 work.

2.7.2 Transport Modelling

The transport modelling work focussed on collating and reviewing literature relating to nitrate-nitrogen losses and transport in the Motueka-Riwaka Plains groundwater system, which were then mapped and assessed for spatial patterns. Transient modelled nitrate-nitrogen losses for six land uses and four soil groups in the Waimea Plains (Fenemor *et al.,* 2016) were matched to Motueka land uses and soil groups. These modelled nitrate losses were then used to map projected nitrate leaching losses and nitrate concentrations in LSR waters across the Motueka-Riwaka Plains. An attempt was then made to calibrate the modelled time series of nitrate-nitrogen concentrations in groundwater to measured values (where available) with mixed success.

3 OVERVIEW OF THE MODEL

An overview of the Motueka-Riwaka groundwater flow model is presented in this section. The current version of the model has been developed using MODFLOW 2005 (Harbaugh, 2005) within the graphical user interface GMS (2014). The following documents the status of the current model.

3.1 Model Extent and Grid Size

The overall extent of the model was defined based on topographical and geological information. Topographical maps provided the extent for key hydrological surface features, whilst geological maps, combined with lithological logs, provided information on subsurface features. A topographic map of the Motueka-Riwaka area is provided in Figure 2-3. Section 3.2 summarises the geological information considered in developing the model.

A uniform grid zone of 100 m x 100 m was specified. This provided a balance between model precision and simulation run times. Each hydrological layer (aquifer or aquitard) was divided into two numerical layers.

3.2 Land Surface Elevations

High-resolution LiDAR data was provided by TDC. This enabled accurate definition of the land surface. The LiDAR data provided by TDC included spot measurements at 0.01 m vertical resolution and contours at 0.5 m elevation intervals. Model surface elevations were assigned based on the LiDAR elevation closest to the centre of each model cell.

In addition to defining the model surface, the LiDAR data was used to verify surveyed river cross-section elevations and land surface elevations at well heads, and also to fill in this data where gaps existed.

3.3 Geological Representation

Figure 3-1 presents a geological map of the Nelson region by Rattenbury *et al*. (1998), focussing on the Motueka-Riwaka area. The model grid is also shown on this map.

The eastern (inland) and northern boundaries of the model were defined at the surface by the foothills locations. The deeper water-bearing layers thin and pinch-out as the basement rock rises up towards these boundaries. To the south, the boundary is defined by the low porosity clay/silt Moutere valley infilling (Figure 2-4), largely defined by the Q2a deposits in Figure 3-1. The permeable gravels overlying these low porosity clay/silts thin and pinch out towards this boundary.

The eastern coastal boundary is less certain. The off shore extent for all layers has been aligned with the general extent of the low-tide mud flats (shown in Figure 2-3) and Motueka River delta, in combination with the geological formations labelled Q1b and Q1d (various coastal deposits) in Figure 3-1. For aquifer 1, all cells beyond the coast have been assigned specific heads equal to mean sea level, to accommodate the upwelling and seepage of groundwater discharging from deeper layers into the ocean. So in effect, the boundary for layer 1 is the coast. Deeper layers are only permitted to discharge vertically through the overlying layers into layer 1 to represent the spatial seepage of water into the ocean. Further discussion on how the eastern boundary is modelled is provided in Section 3.10.6.

The low permeability zone nearer the Riwaka River (Figure 2-4) is simulated by low hydraulic conductivity in the upper layer this area.

Scanned bore cards for 256 wells with lithological information were supplied by TDC. The locations of wells with lithological records are shown in Figure 3-2.

Much of the model domain is underlain by well-sorted, permeable gravels, depicted in Figure 3-1 by the deposits labelled Q1a and in Figure 2-4 by the description of ‘course-medium gravel and cobbles in a medium coarse sand mix’.

Considering Figure 2-4, the permeable gravels are separated vertically by low-permeability clay-bound gravels. The lithological data derived from bore logs suggest that the ‘Middle Aquifer’ depicted in Figure 2-4 acts as a reduced permeability aquitard[10], effectively dividing the gravels into two clearly defined water-bearing layers, the shallow and deeper aquifers. Therefore, the lithological data was grouped into three hydrogeological layers for subsequent processing; an upper aquifer, an intermediate aquitard and a lower aquifer. The three hydrological layers were relatively well defined in most logs where wells were sufficiently deep to penetrate through all layers. In some of the deeper wells, the total depth to basement rock (or to low permeability material) was also reported.

This simplified hydrogeological information was then imported to GMS for visualisation and generation of three-dimensional solids. An overall block diagram of the model is shown in Figure 3-3 and a fence diagram is presented in Figure 3-4. Figure 3-5 presents examples of three model cross sections showing the different hydrological layers. The locations of the cross section are shown in Figure 3-2, as is the approximate window of bore logs that are presented at each cross section for comparison. Thicknesses of the three hydrological layers are presented in Figure 3-6, Figure 3-7 and Figure 3-8.

---

[10] The aquitard is typically water bearing, but it is not as permeable as the upper and lower layers.

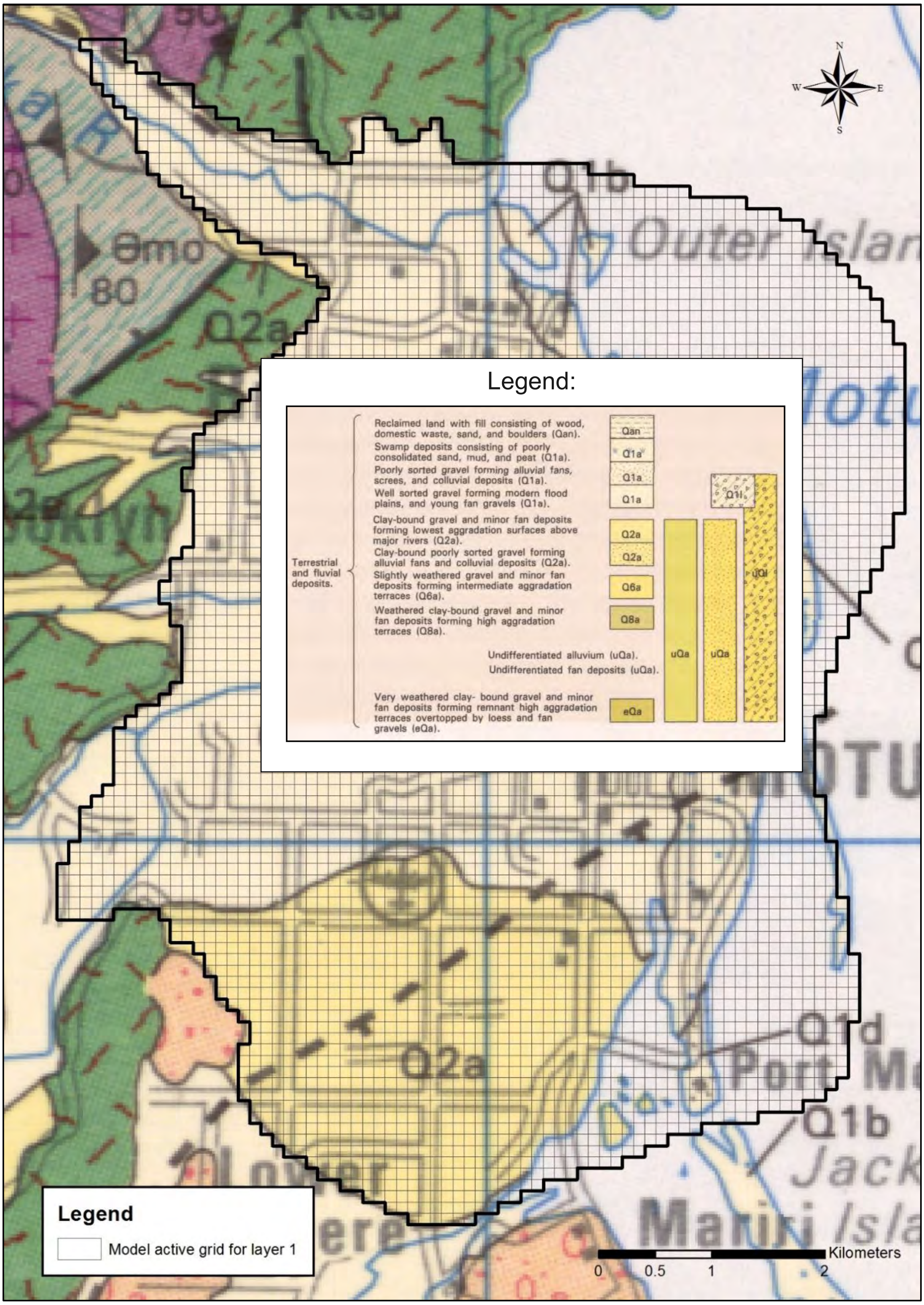


Figure 3-1: Geological map

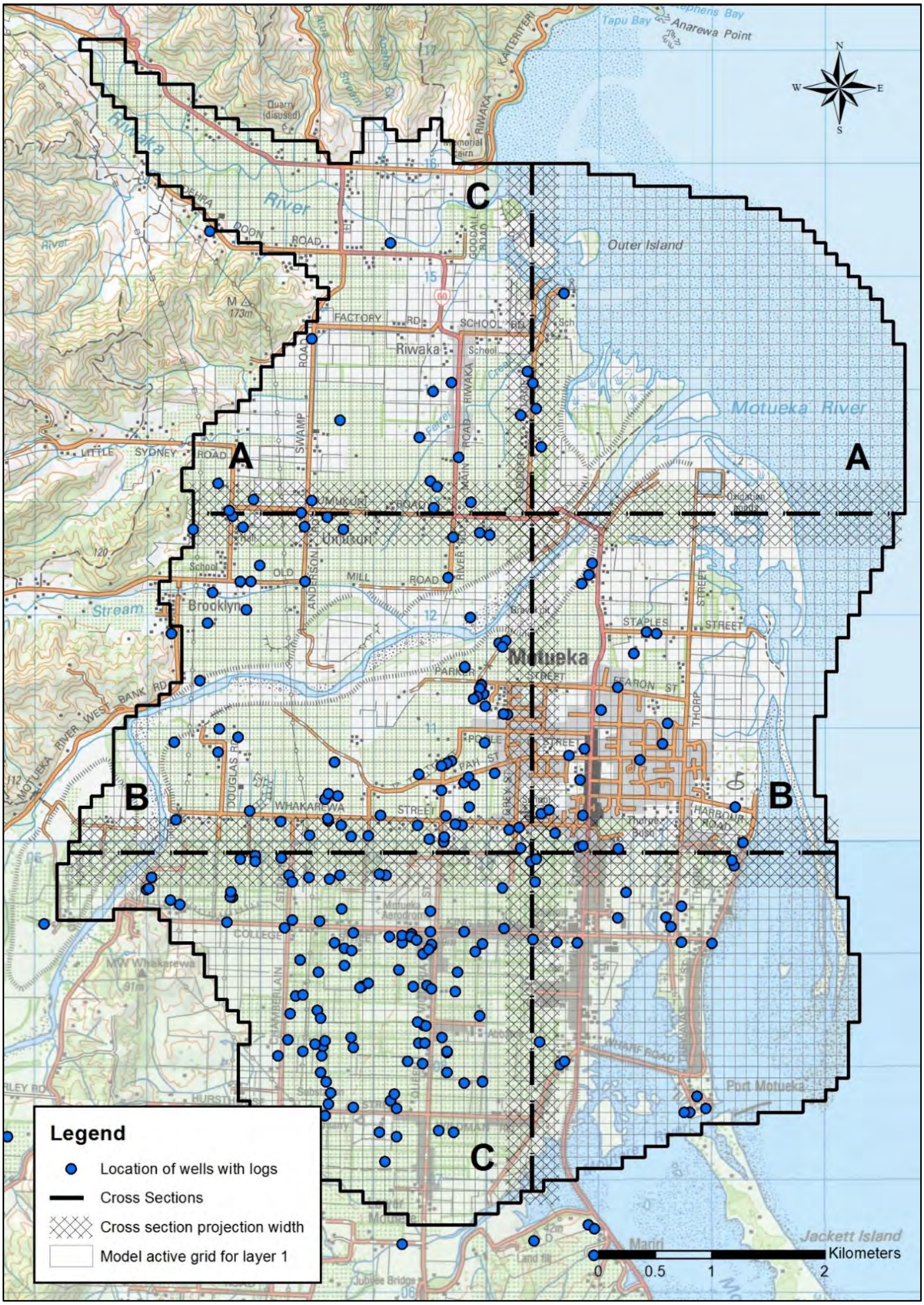


Figure 3-2: Locations of cross-sections and wells with lithological logs

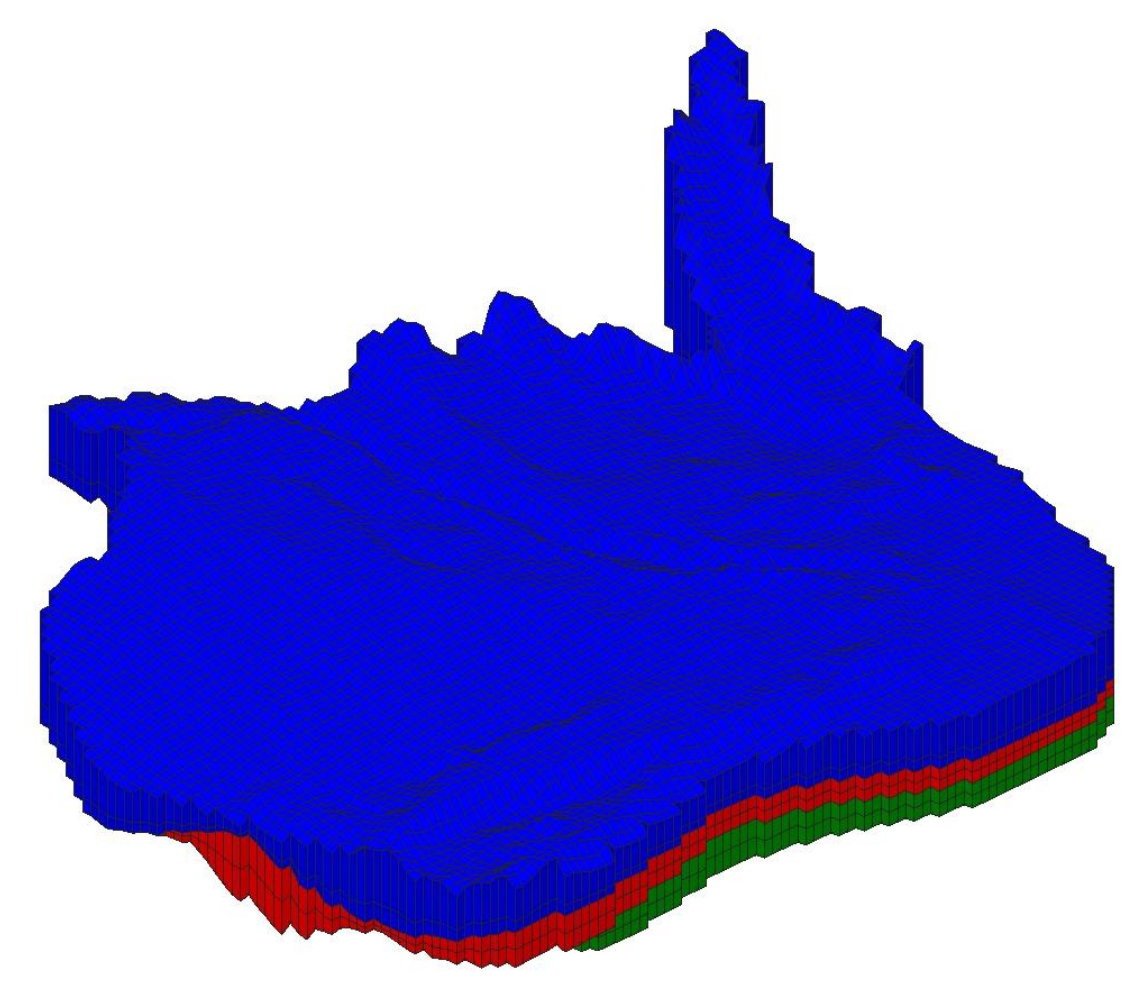


Figure 3-3: Model block diagram (horizontal:vertical scale = 1:75)

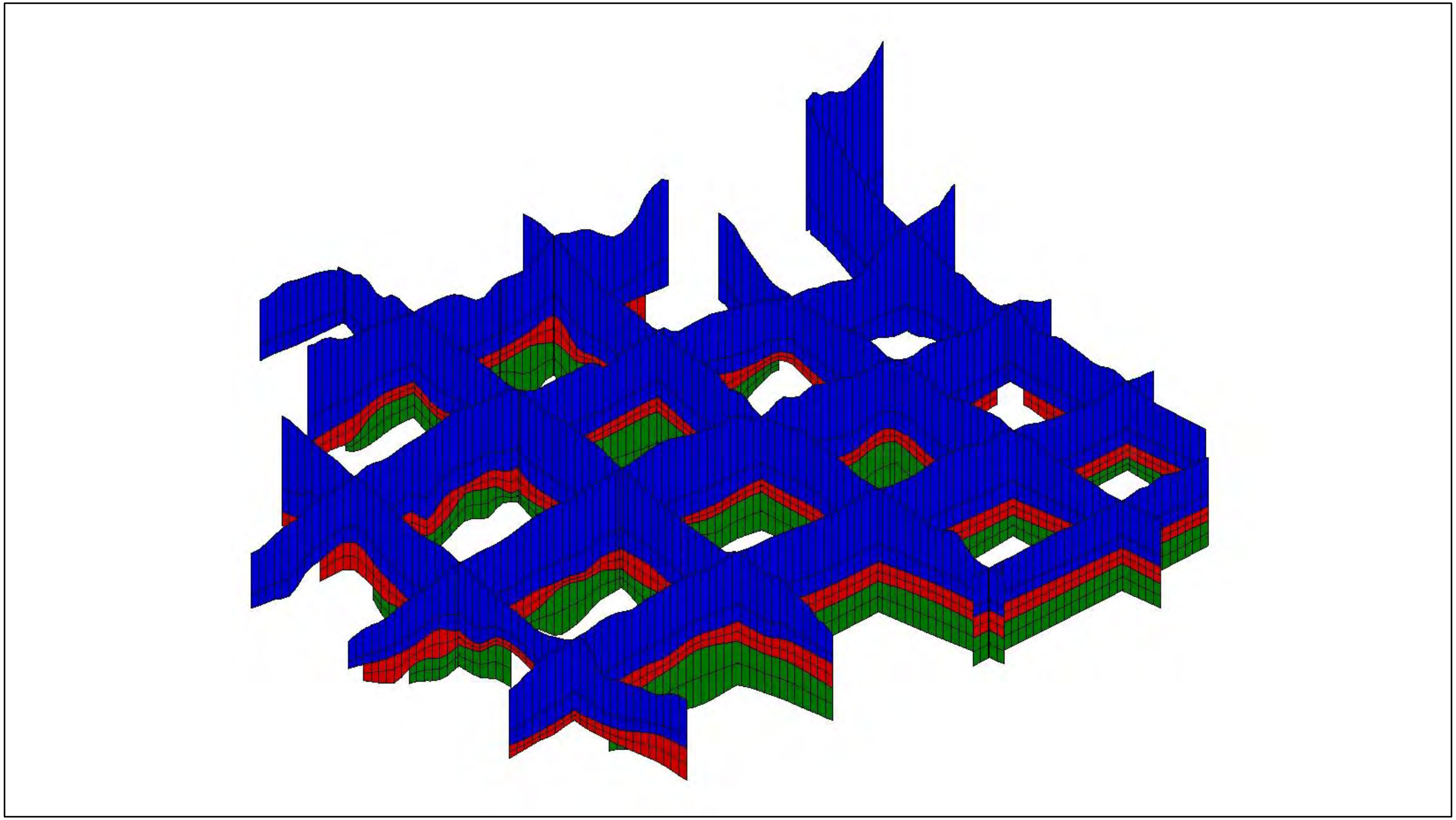


Figure 3-4: Model fence diagram (horizontal:vertical scale = 1:75)

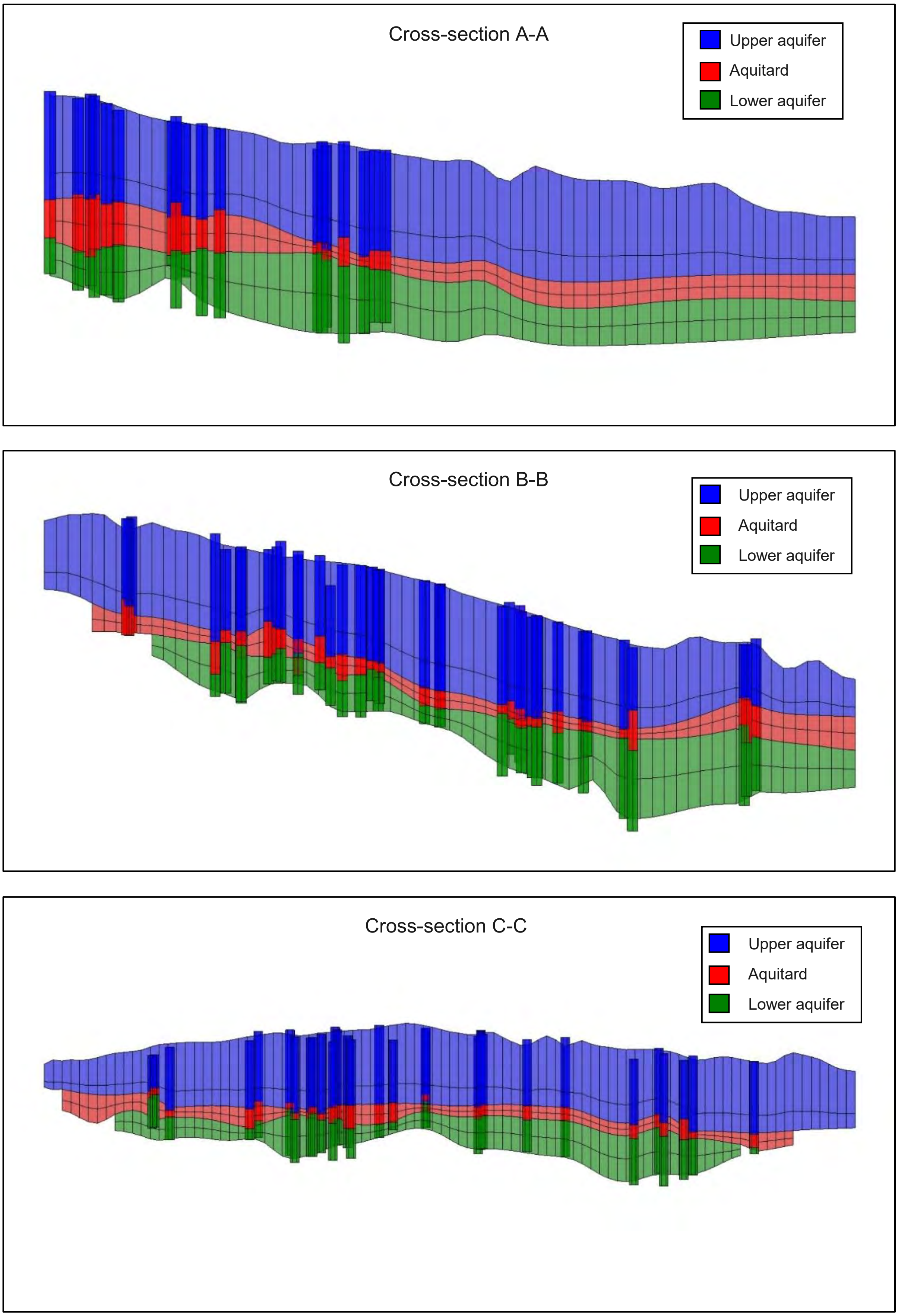


Figure 3-5: Model example cross-sections (horizontal:vertical scale = 1:75) (cross-section locations are shown in Figure 3-2)

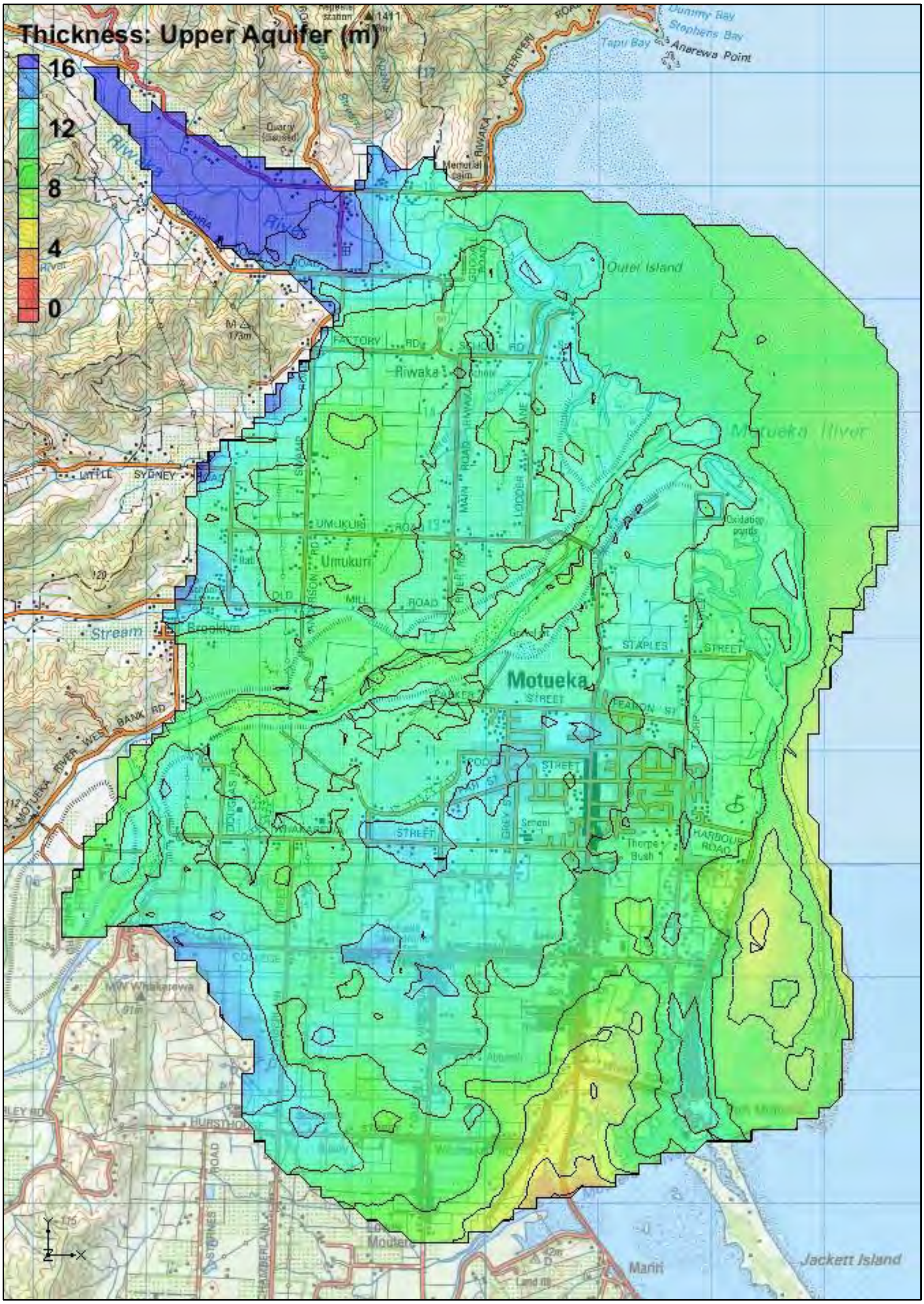


Figure 3-6: Thickness of the upper aquifer

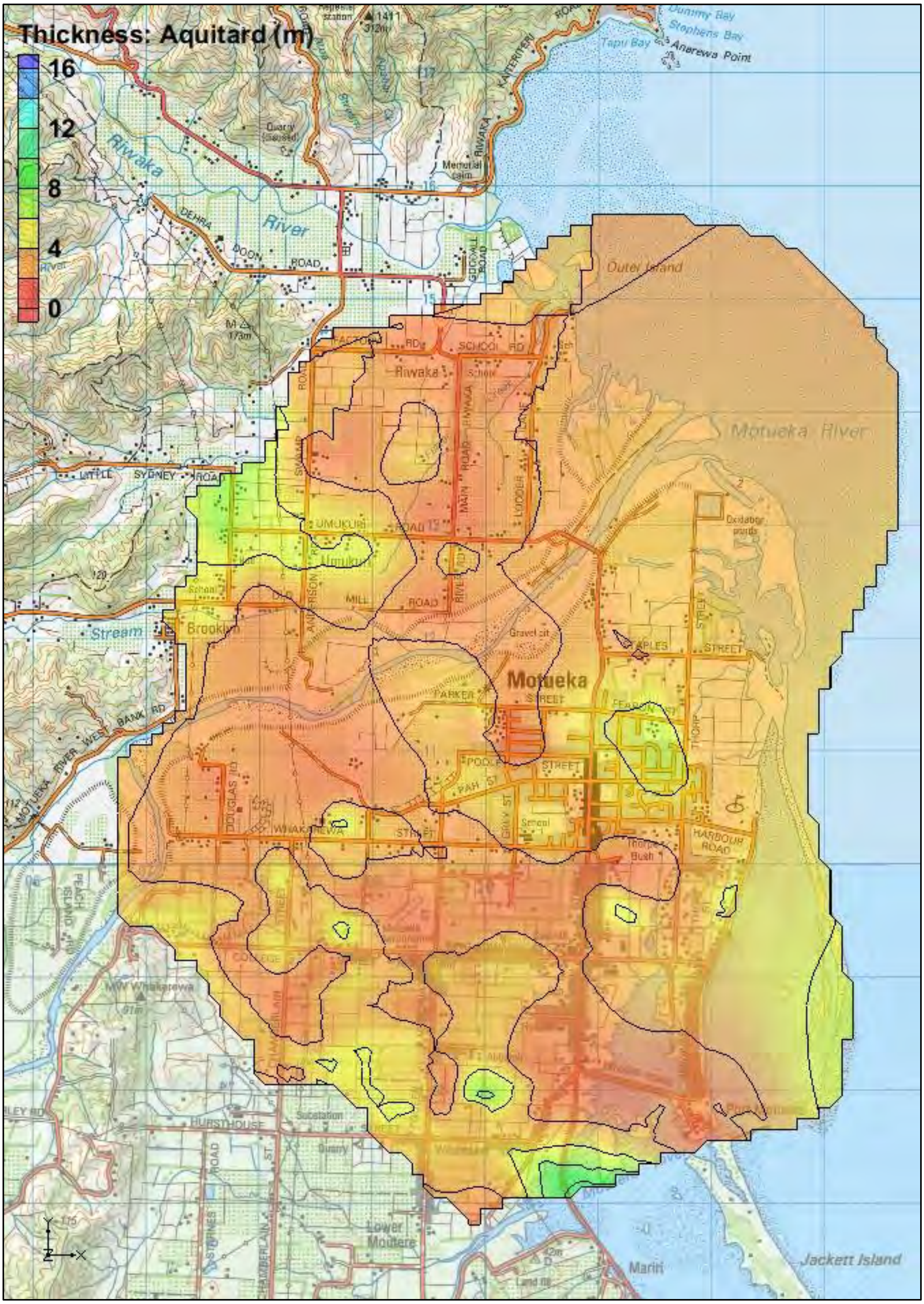


Figure 3-7: Thickness of the aquitard

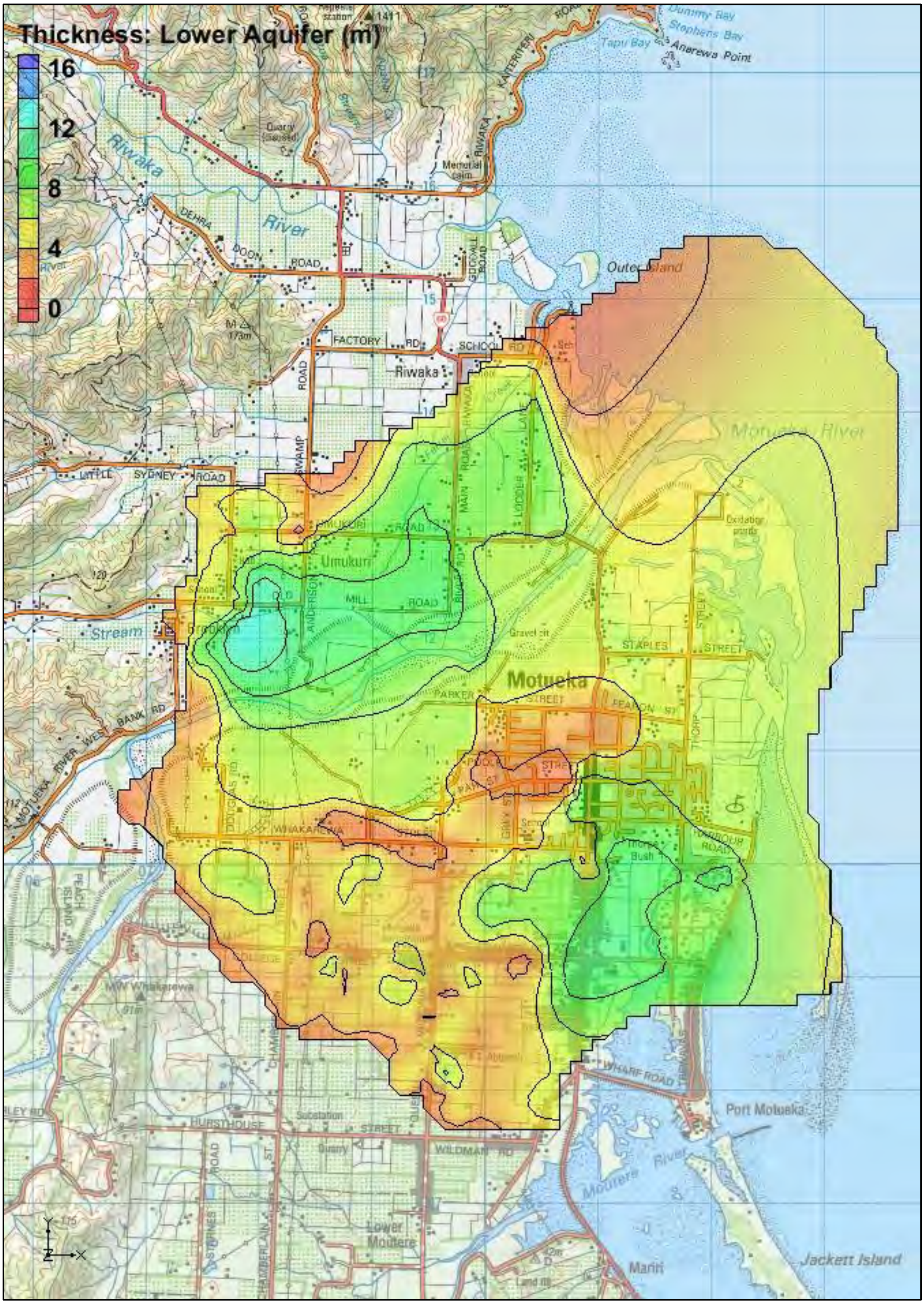


Figure 3-8: Thickness of the lower aquifer

3.4 Model Grid

As discussed in Section 3.2, the Motueka-Riwaka groundwater model has been constructed with three hydrological layers (aquifer or aquitard). Figure 3-6 through Figure 3-8 demonstrate how each hydrological layer has variable thickness. The horizontal extent of each hydrological layer is also variable, defined by the subsurface geology. The horizontal extent of each layer is presented in Figure 3-9.

Each hydrological layer is also divided into two numerical layers to aid numerical stability. The intermediate aquitard and the lower aquifer are evenly divided into two numerical layers. For the upper aquifer, the top numerical layer is also divided into two numerical layers, but the upper numerical layer is thicker than the underlying numerical layer. This was specified primarily to maintain adequate depth, within which surface water features could interact with groundwater without causing numerical instabilities associated with cells drying and rewetting.

Overall the model has 27,246 active cells of uniform size 100 m x 100 m. Average cell thickness is approximately 3 m with cell thicknesses ranging between approximately 0.4 m and 22 m.

3.5 Simulation Time and Stress Periods

The Motueka-Riwaka groundwater model has been developed to run from 1 June 1990 through to 31 May 2012 with daily stress periods. This is a total simulation time of 8,035 days (22 years).

This extended period (compared with previous models) enables the incorporation of groundwater level data collated from older, disestablished monitoring bores and from older stream flow monitoring sites. It also permits the use of a greater length of data collated from other bores. This widened the calibration scope in both space and time and enabled a more robust representation of the groundwater system.

The 22-year continuous simulation period enables the inclusion of potential long-term cumulative effects from abstraction over several years, and other long-term natural phenomena that may affect regional groundwater levels.

The very first stress period (day 1) is simulated as steady state to provided stable initial conditions for the ongoing transient simulation.

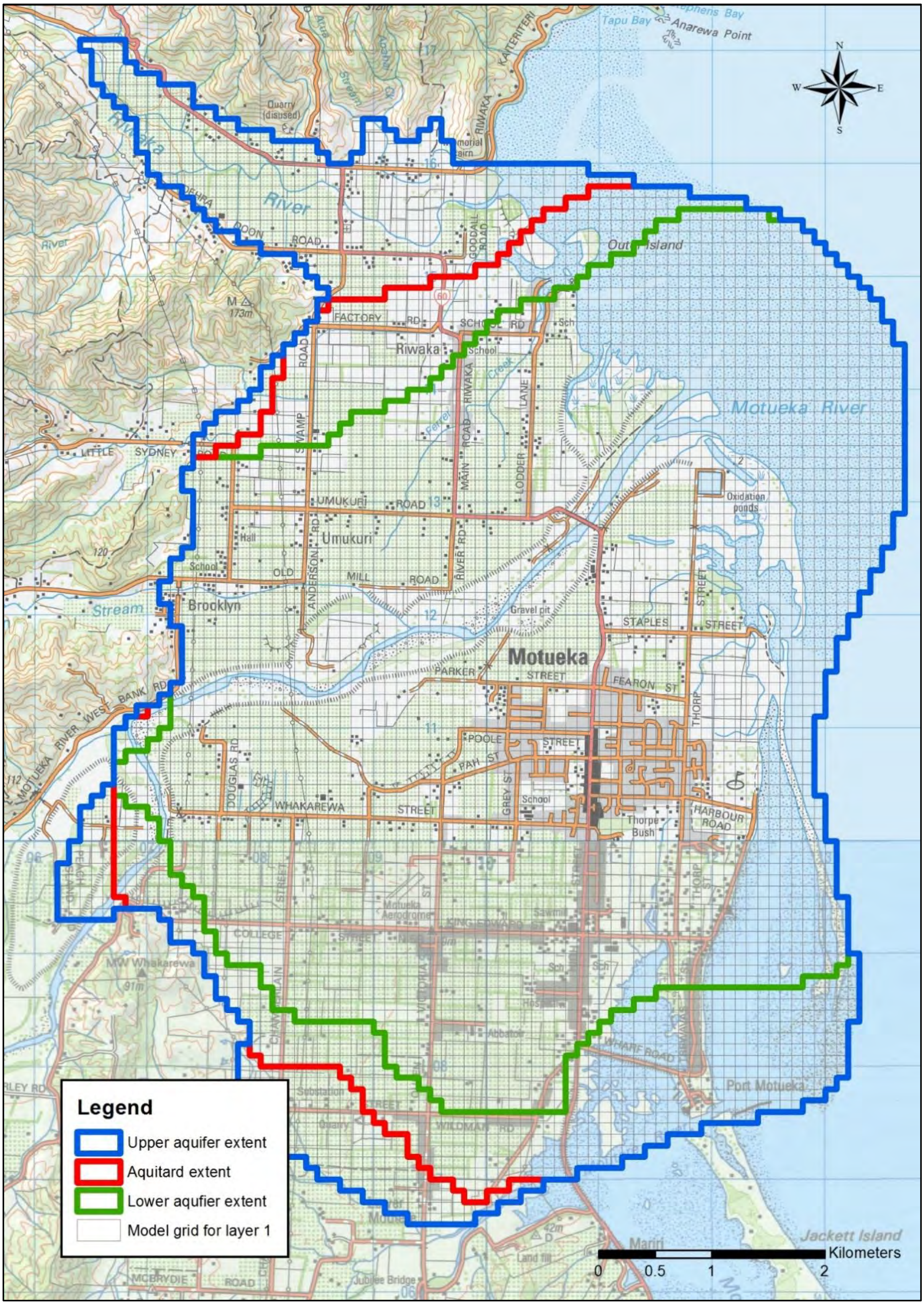


Figure 3-9: Model extent

3.6 Land Use

Measured groundwater levels and surface water flows are dependent, among other factors, on land use and how water has been used historically. Consequently, to allow calibration to be as accurate as possible, time-varying land use has been assigned.

Time-varying land use was derived from historical records and discussions with TDC staff (Joseph Thomas, *pers. comm.*) for three different time periods: 1998/99, 2004/05 and 2010/11. The overall model run period spans 1 June 1990 through to 31 May 2012. Land use over the 1998/99 season was assigned to the period from June 1990 up to 31 May 2004. Following this, land use over the 2004/05 season was assigned through to 31 May 2010. Then land use during the 2010/11 season was assigned through to the end of simulation period. Modelled land use change is stepped at the appropriate simulation date.

Figure 3-10, Figure 3-11 and Figure 3-12 show the spatial distribution of land use for the three periods, respectively. The grid used for assigning land use, shown in these figures, is the MODFLOW grid used in earlier versions of the model. Each grid cell is 450 m x 450 m which equates to an area of approximately 20 ha. This is a typical farm-unit size for the Motueka-Riwaka plains and was sufficient for assigning land use characteristics. A finer grid was not justified given the limited historical land use information available.

The land uses shown in Figure 3-10 through to Figure 3-12 are the predominant land uses at each location. Though not shown in these figures, other less predominant land uses are also included in the model.

Table 3-1 summarises the modelled irrigated areas for each land use type for each of the three land use periods. All remaining areas are either unirrigated (assumed pasture) or are residential. Land surface drainage and groundwater pumping (discussed later) were calculated accounting for these time-varying land uses. Based on Table 3-1, the main changes to irrigation on the Motueka-Riwaka Plains have arisen from increased areas of irrigated apples.

Table 3-1: Land use summary

Land Use	Area (ha)		
	1998/99	2004/05	2011/12
Apples	857	1,137	1,261
Currants	0	0	3
Grapes	25	61	56
Hops	78	100	51
Kiwifruit	547	549	534
Maize	18	14	0
Vegetables	35	10	10
Irrigated pasture	126	104	62
Total	**1,686**	**1,975**	**1,977**

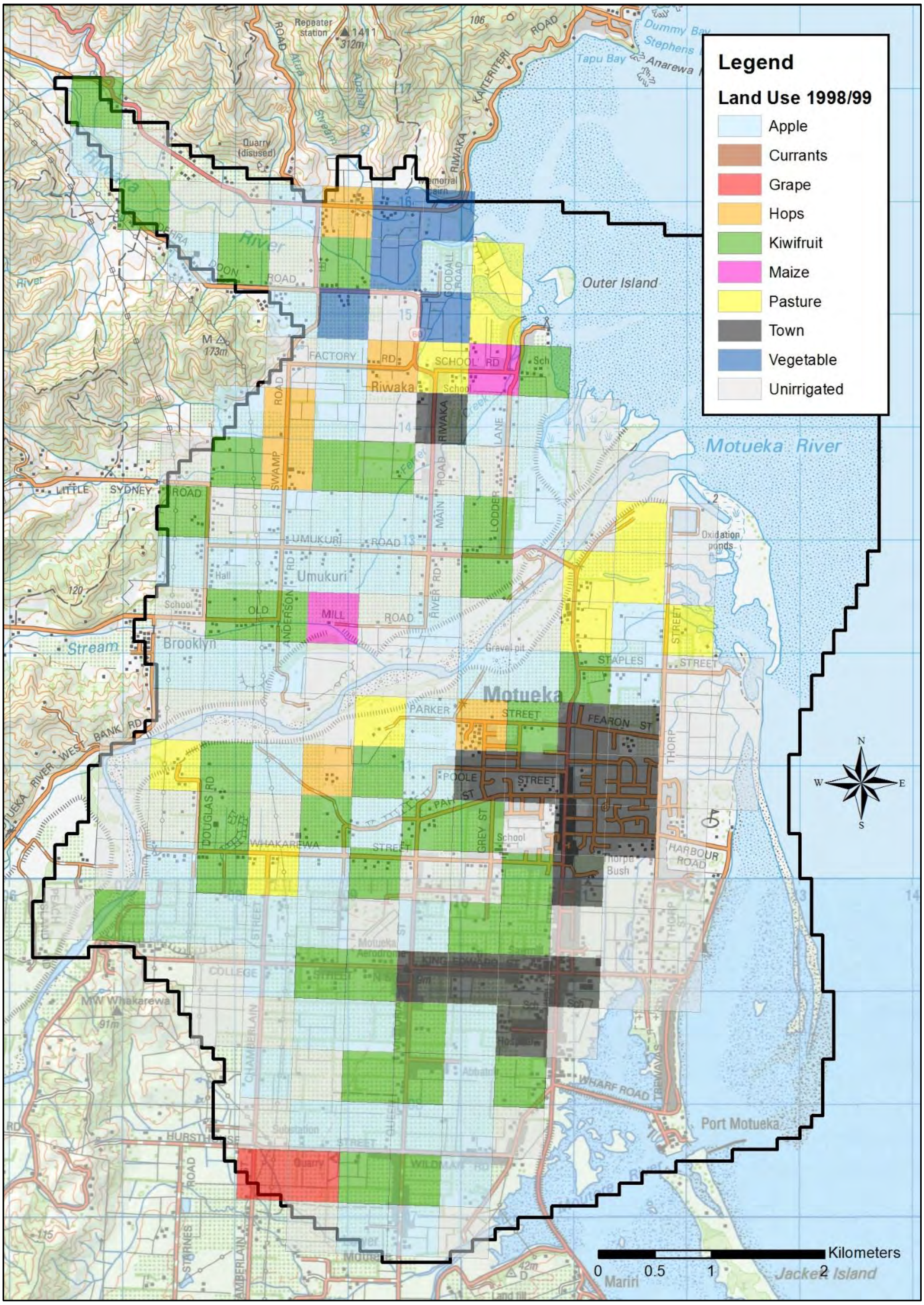


Figure 3-10: Predominant land use during the 1998/99 season

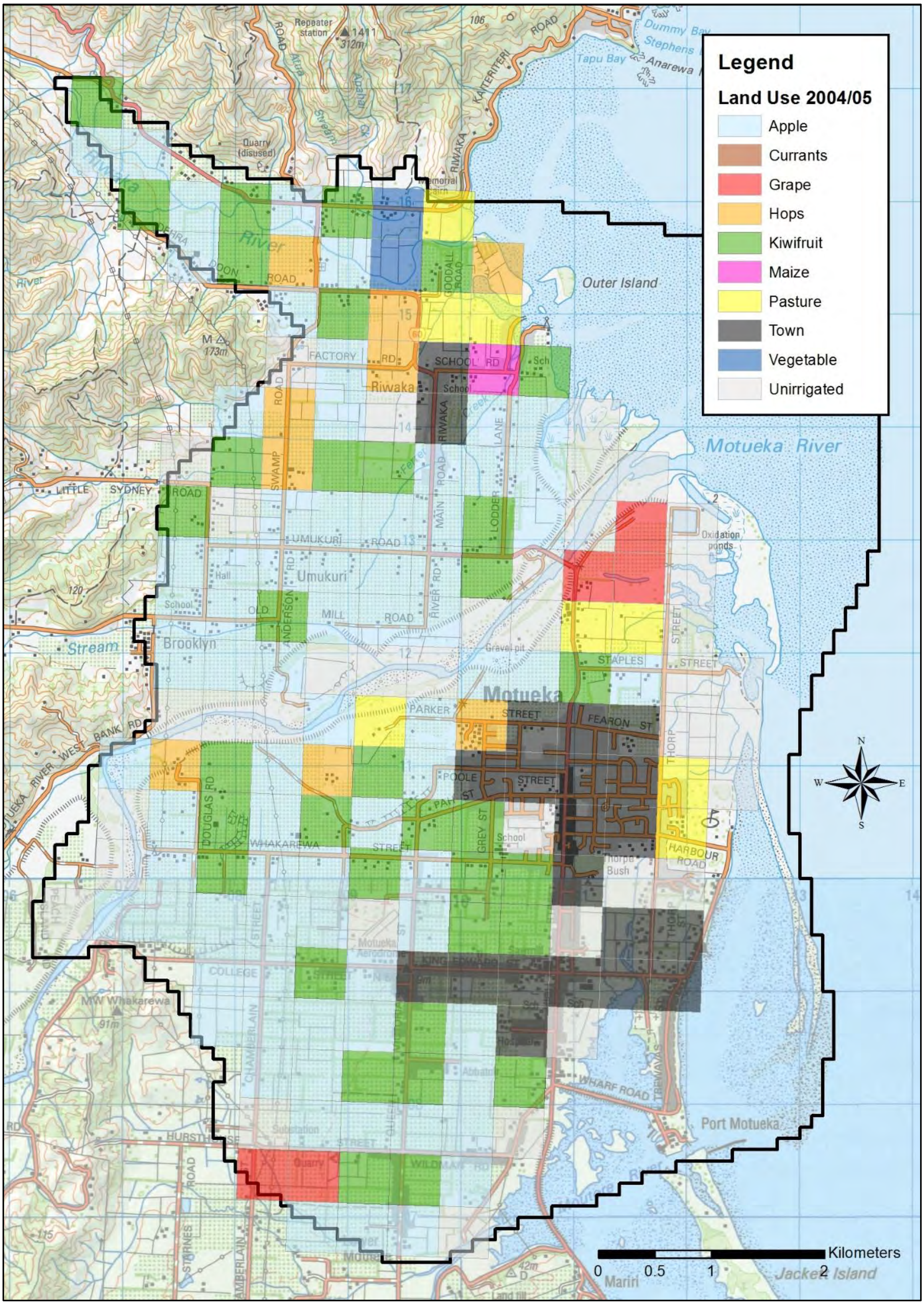


Figure 3-11: Predominant land use during the 2004/05 season

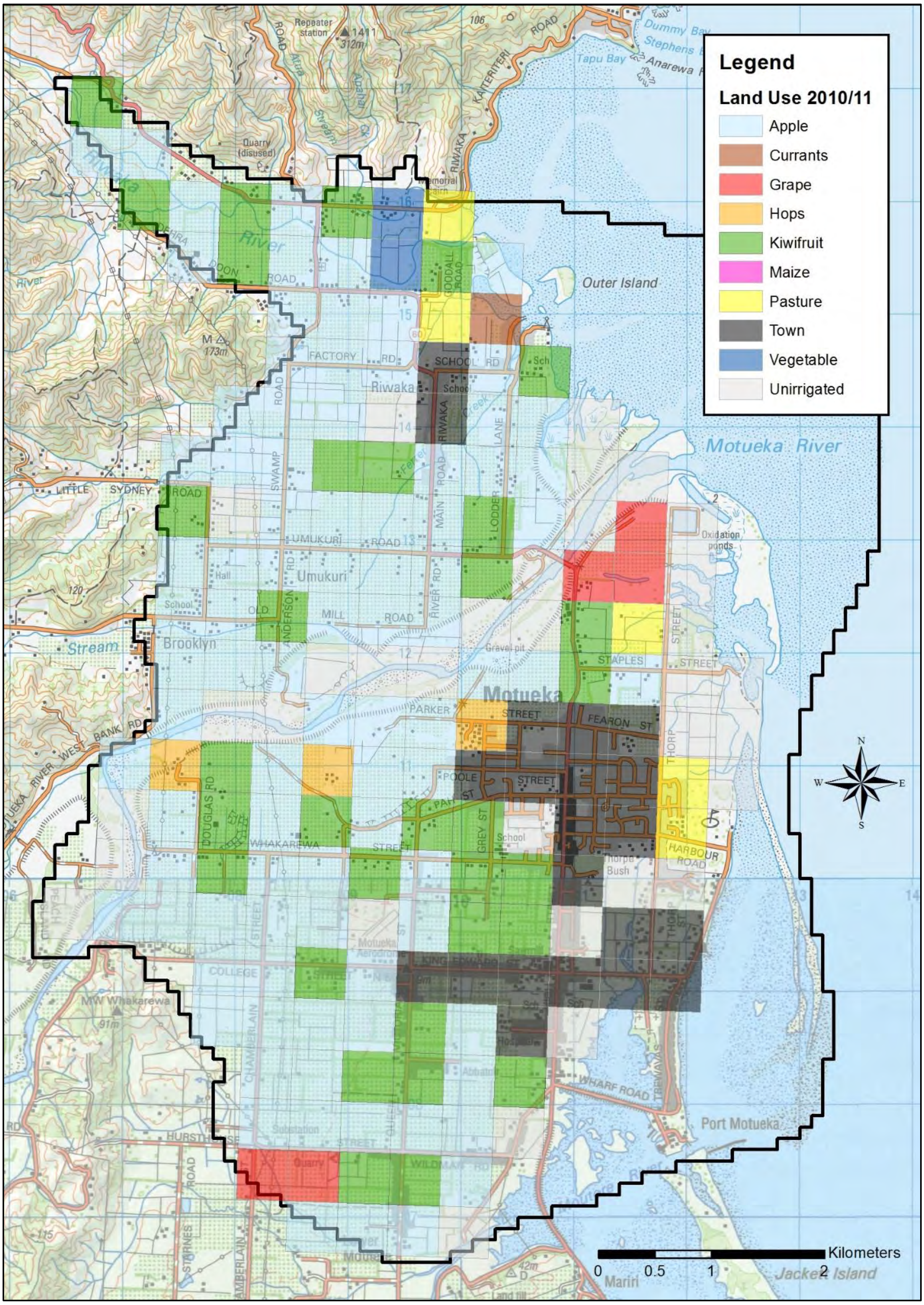


Figure 3-12: Predominant land use during the 2011/12 season

3.7 Climate

Rainfall and potential evapotranspiration (PET) data for the model run period (1 June 1990 through to 31 May 2012) were retrieved from NIWA's Riwaka climate station. Data missing in this Riwaka record was filled with data correlated from NIWA's Nelson Airport climate station and with NIWA's Virtual Climate Station (VCS) data. Additional rainfall data since mid-1998 was retrieved from TDC's rainfall station located at Tui Close. This record was gap-filled and extended back to the beginning of the simulation period by correlating with the Riwaka rainfall site.

The method of spatially distributing rainfall over the plains has been based on the same method used in previous models, initially described by Robb (1999). Robb (1999) compared monthly 30-year averages for the Riwaka station with the now-closed Motueka and Lower Moutere stations. This resulted in two zones of rainfall over the plains. Robb (1999) assigned the measured rainfall data from the Riwaka station to the area under the hills to the north of the plains. All other areas were assigned an alternative zone to which Robb (1999) assigned 80% of the Riwaka station rainfall. Rather than assigning 80% of the Riwaka rainfall, this area has now been assigned the actual rainfall time series measure at Tui Close. The two rainfall zones are shown in Figure 3-13 as are the locations of the Tui Close and Riwaka rainfall stations.

A single PET time series was used for the entire model domain. PET is not highly variable spatially, so no further discretisation of this data was warranted.

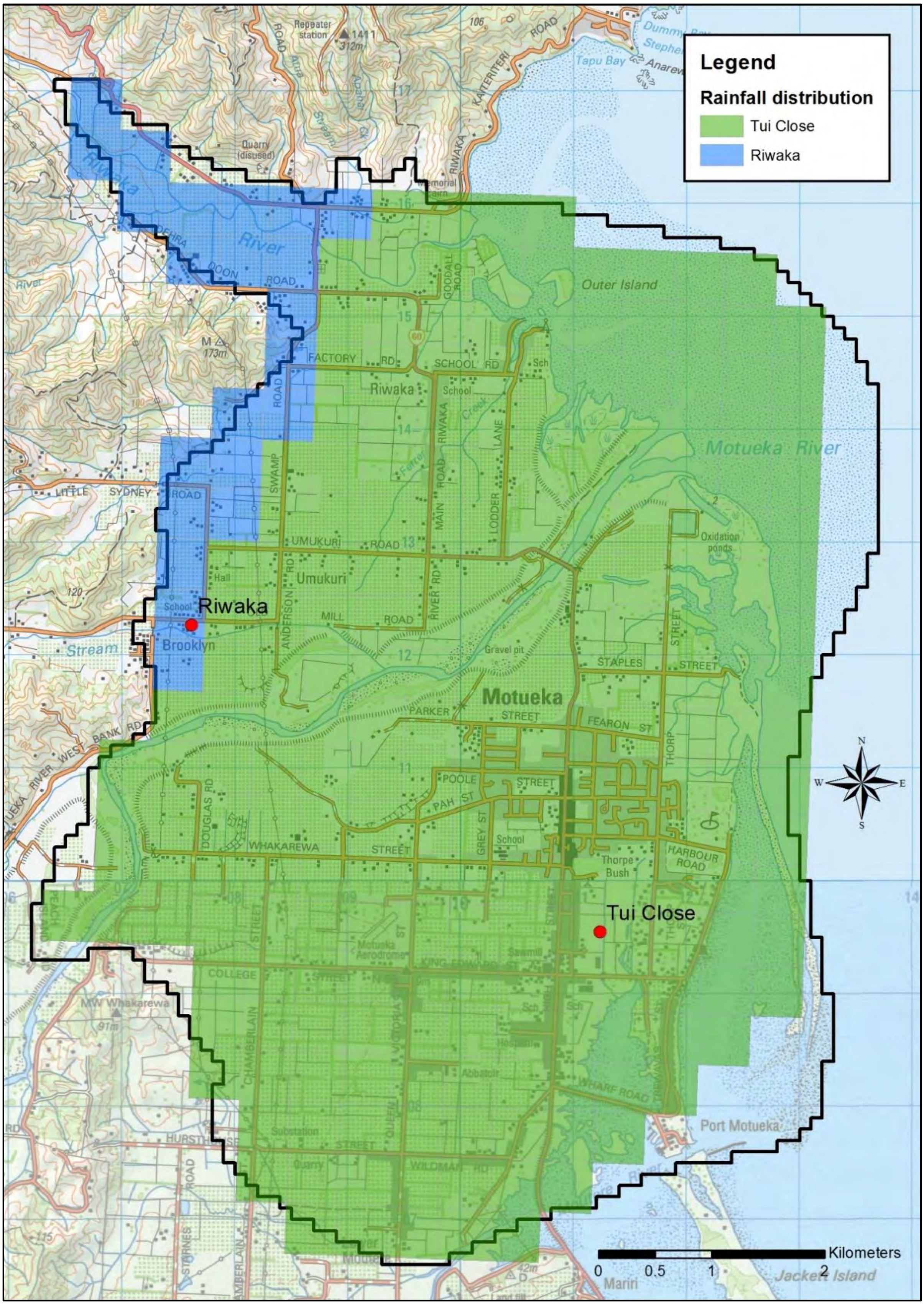


Figure 3-13: Rainfall stations and distribution

3.8 Soils

Figure 3-14 presents the various soil types that have been considered, as reported by Robb (1999). One primary soil type is assigned to each grid cell. Table 3-2 (reproduced from Robb, 1999) summarises the hydraulic characteristics of each soil type.

Table 3-2: Soil hydraulic characteristics

Soil name	Soil depth (mm)	Water holding capacity per metre of soil (mm/m)	Available water (mm)(1)
Hau	550	70	38
Riwaka	550	230	127
Sherry	600	150	90
Tahunanui	350	43	15

(1) Available water = soil depth x soil WHC. The available water will be reduced if the crop rooting depth is less than the soil depth.

(This table is reproduced from Robb, 1999)

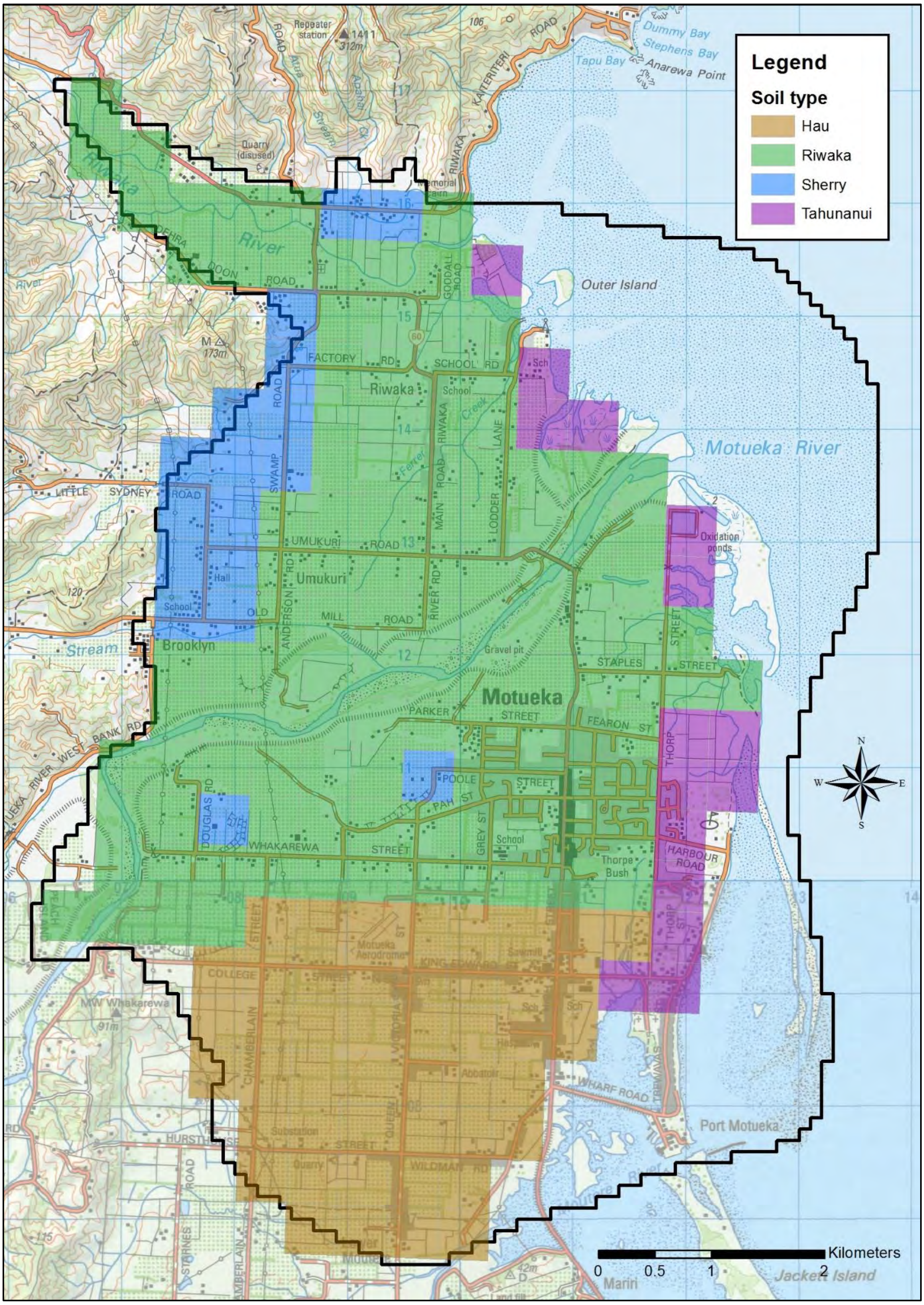


Figure 3-14: Soils types

3.9 Irrigation Methods

Irrigation is the primary use of water on the Motueka-Riwaka Plains. Irrigation water demand varies from day to day, and changes depending on climate (rainfall and evapotranspiration), soil type, crop type and irrigation methods.

Modelled irrigation regimes have largely been based on similar methods detailed by Robb (1999). Irrigation regimes for each crop type were established by Robb (1999) based on knowledge of irrigation practices and systems. These have been further adjusted to account for modern irrigation techniques and understandings.

Appendix A summarises the irrigation scheduling assumptions for the various land use types, along with an overview of Aqualinc's soil-moisture balance model, IRRICALC, which has been used to calculate irrigation use and resulting land surface drainage. This is further discussed in Section 3.10.3 and Section 3.10.5.

3.10 Boundary Conditions

The boundary conditions of the updated model are as follows:

- Streams: used for representing the main rivers and streams;
- Drains: used to represent spring-fed drains and seep areas;
- Land surface drainage: used to represent groundwater recharge from the land surface;
- Wells: used for domestic, community, agricultural and industrial abstraction;
- General head: used to represent the head-dependent boundary condition at the coastal boundary; and
- No-flow: used to represent the boundaries where groundwater inflows or outflows to and from the model are insignificant.

These boundaries are discussed below.

3.10.1 Streams

The main rivers and streams in the model are represented using MODFLOW's Stream Flow Routing (SFR2) package (Niswonger & Prudic, 2009). This routes water from upstream, interacting with groundwater (gaining and losing) as the river passes over the plains. Figure 3-15 provides an overview of the river system as simulated in the SFR2 package. Stream cells are located solely in the uppermost layer.

The exchange of water between surface water and groundwater is documented in Niswonger & Prudic, (2009) and its predecessor publication Prudic *et al.* (2004). In simple terms, the transfer of water is a combination of the bed conductivity (CBED) and the gradient between the river free surface and adjacent groundwater levels.

Equation 1 defines CBED as a function of the length of the channel (L), the wetted perimeter of the channel (w), the bed thickness (t) and the hydraulic conductivity of the bed (KBED).

$$C_{BED} = \frac{K_{BED}\ w\ L}{t} \qquad (1)$$

Channel geometry was defined by variable shaped cross-sections (each with eight points) which were specified as model inputs (based on surveyed data). The SFR2 package then uses this information with Mannings equation to derive wetted perimeter and river stage. Mannings roughness coefficients for all streams have been set at a constant value of 0.029 for the main channels and 0.035 for the river banks. These values were derived from Streeter & Wylie (1981) for bed materials of 'gravel' and 'earth with stones or weeds', respectively.

Reach length (L) was determined by the length of the river passing through each model cell. Actual bed thicknesses (t) for all reaches are generally unknown and so have been set at a nominal constant value of 0.5 m. Variations in this parameter were accommodated by the stream bed hydraulic conductivity term (KBED) which is determined through model calibration.

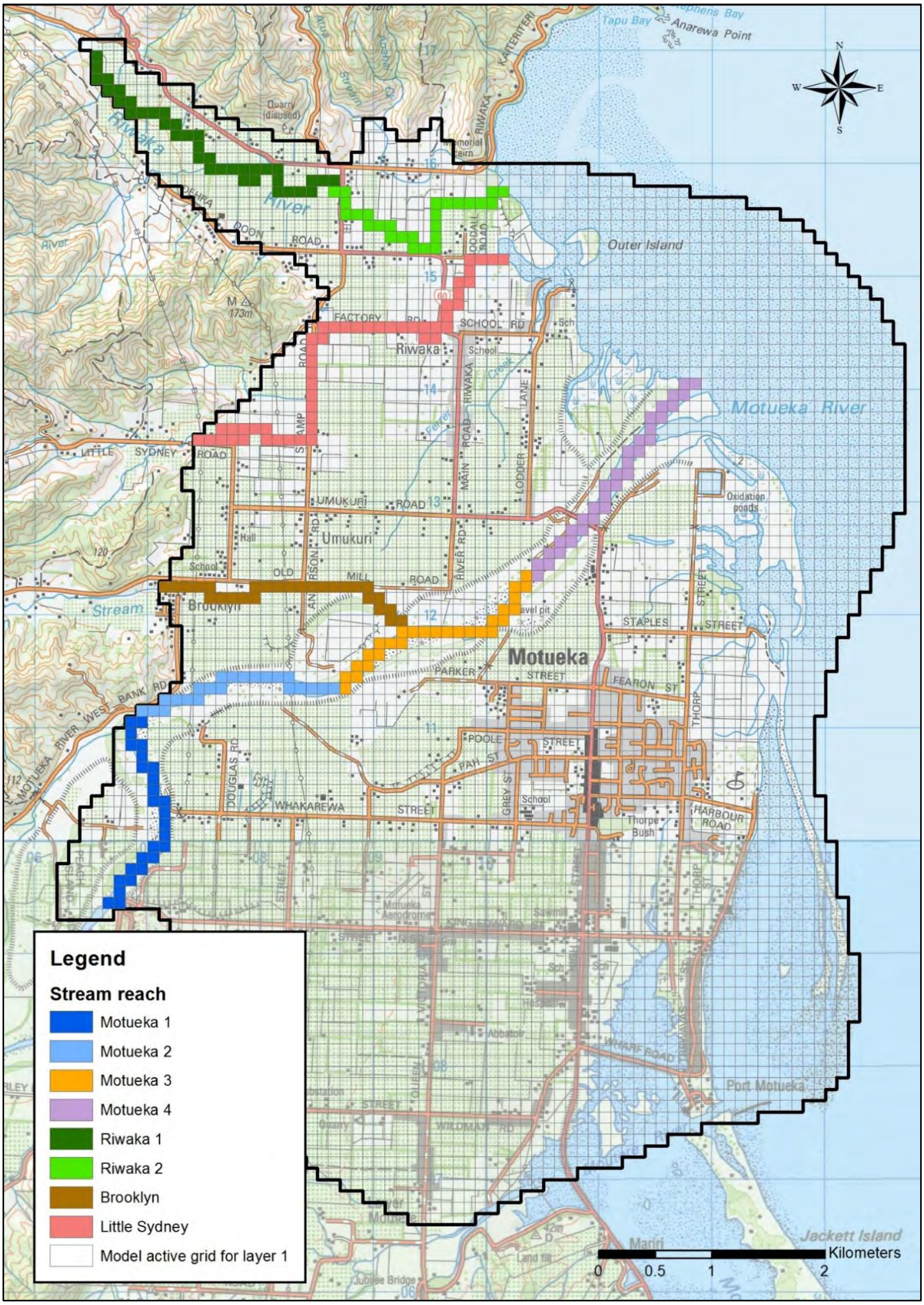


Figure 3-15: Cells assigned to simulate rivers and streams using the stream flow routing (SFR2) package

3.10.2 Drains

The spring-fed drains have been represented using the MODFLOW drain (DRN) package. Three key spring-fed drain networks have been modelled. These are Thorp Drain, Staples Drain and Frys Drain. The locations of these drains are shown in Figure 3-16. Drain cells are located solely in the uppermost layer.

Drains have been used to simulate spring-fed drains. Drain cells act to remove water from the aquifer at a rate proportional to the difference between the groundwater level elevation underlying the drain and a specified drain invert elevation (Harbaugh, 2005). A specified bed conductance factor also contributes to determining the rate of water removal. If groundwater levels are below the invert of the drain then no flow is removed (the drains are dry). Drain invert levels and conductances were generally unknown. Consequently, these parameters were adjusted during the calibration process.

3.10.3 Land Surface Recharge

Aqualinc's in-house crop-soil water balance model (IRRICALC) has been used to generate time series of land surface drainage. The crop-soil water balance model simulates the variable use of water in agriculture with differing crops, agricultural soil types, climate and irrigation strategies. The basis of the model is a daily soil moisture balance with an irrigation scheduling component. An overview of the model is provided in Appendix A.

Data inputs to the IRRICALC model were:

(i) Land use (see Section 3.6);

(ii) Potential evapotranspiration (PET) (see Section 3.7);

(iii) Rainfall (see Section 3.7);

(iv) Soil plant available water (see Section 3.8); and

(v) Irrigation methods (see Section 3.9).

Daily time series of land surface recharge were generated for each of the land use grid cells shown in Figure 3-10 through to Figure 3-12. The long-term average annual land surface recharge as calculated by IRRICALC for each of the land use grid cells is presented in Figure 3-17. It was assumed that land surface recharge under residential areas was equivalent to 50% of unirrigated pasture.

Average annual land surface recharge for the whole model is approximately 680 mm/year and varies between 250 and 950 mm/year.

3.10.4 Vadose Zone Travel

Due to the shallow depth to groundwater on the Motueka-Riwaka plains, unsaturated vadose zone travel time will be relatively short and therefore has been ignored. It has been assumed that any land surface recharge will enter the upper aquifer instantly after leaving the root zone.

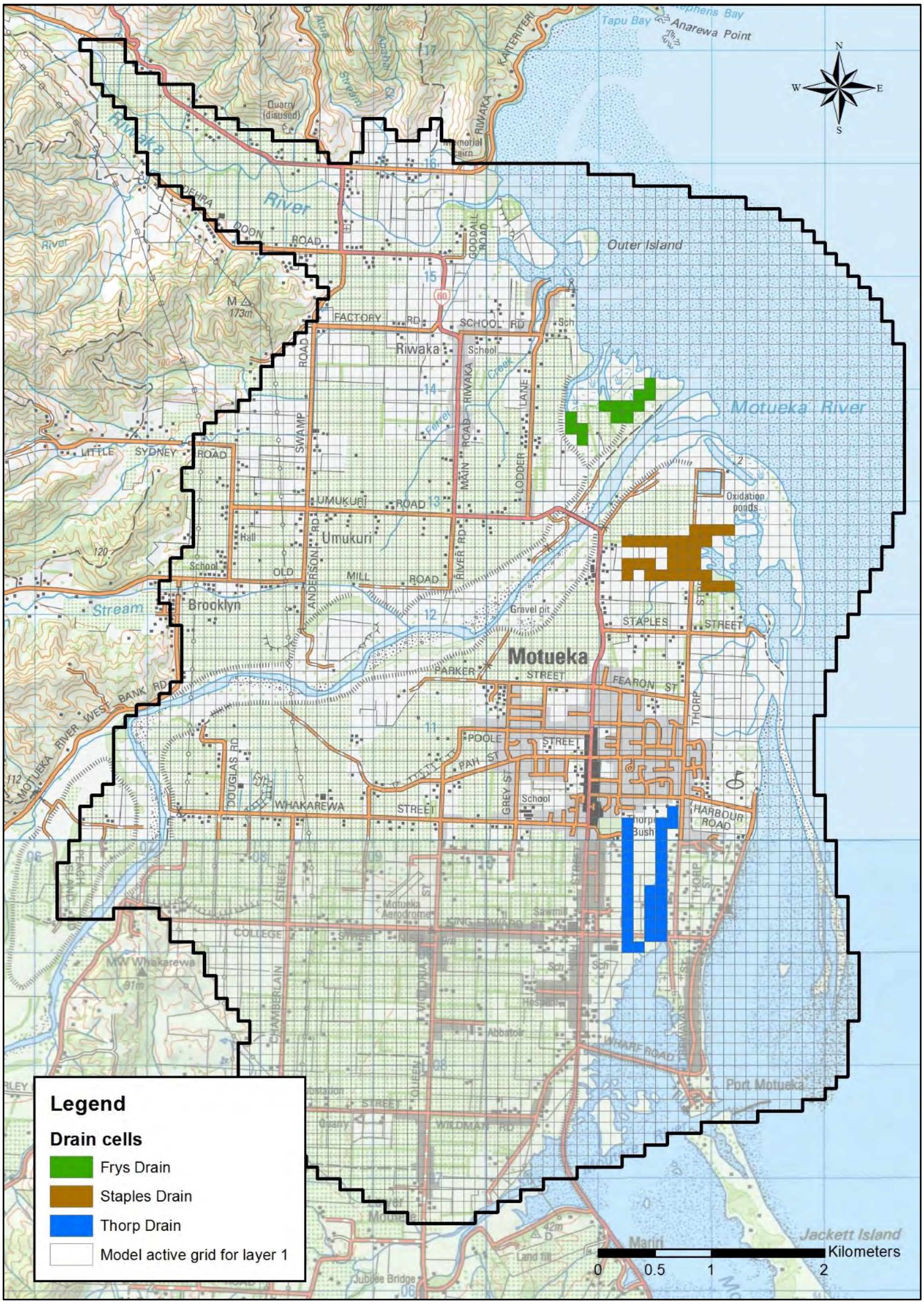


Figure 3-16: Cells assigned to simulate spring-fed drains using the drain (DRN) package

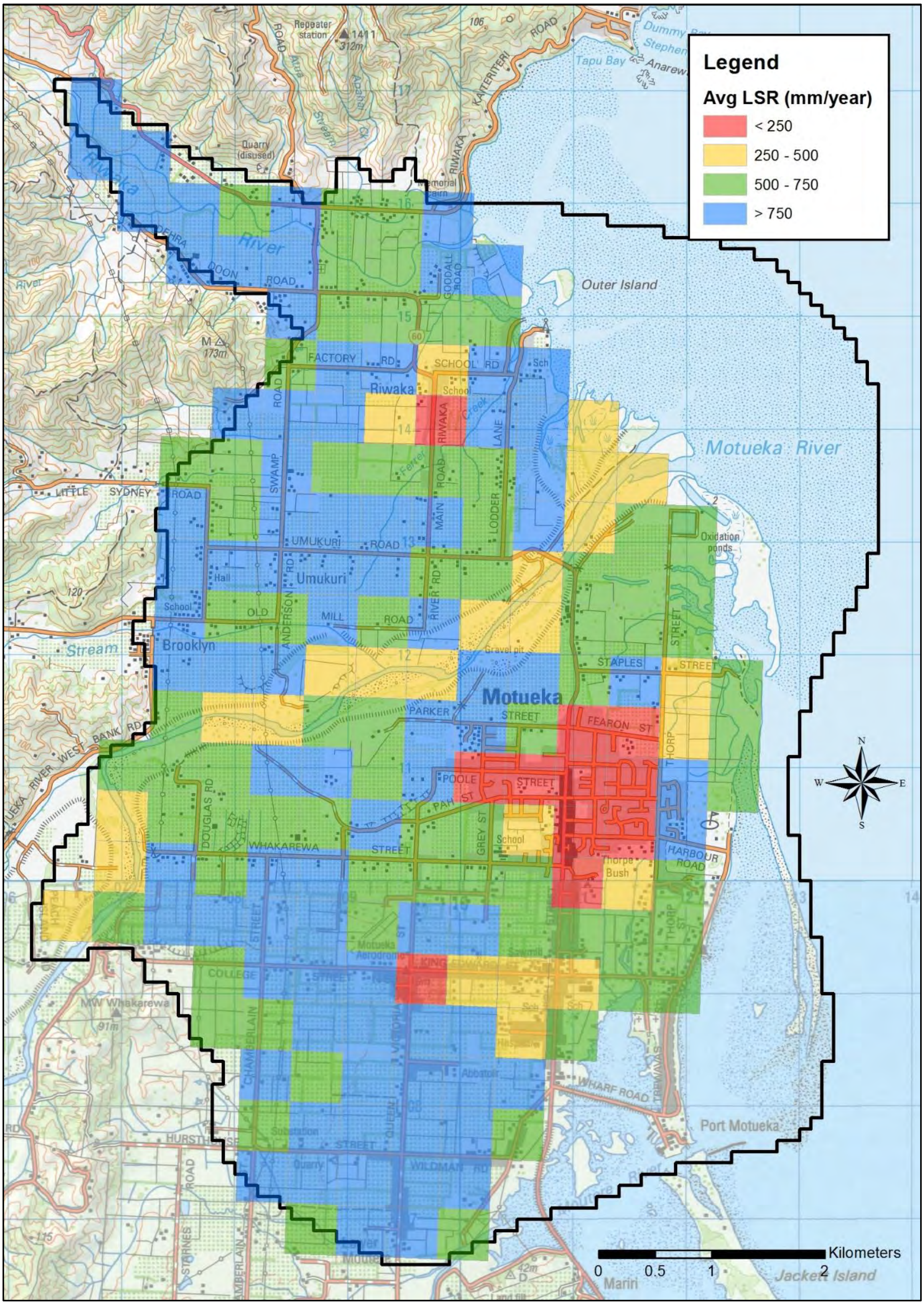


Figure 3-17: Long-term average land surface recharge

3.10.5 Wells

The model incorporates four different types of groundwater abstraction wells; domestic, community, industrial and irrigation. The locations of the wells are provided in Appendix B. The methods used to calculate abstraction rates for each of these well types are discussed below.

Domestic Wells

Domestic wells refer to those installed on individual properties to supply household domestic water needs. Domestic pump rates have been estimated from a combination of census data, TDC flow records and estimates of average use per household. This method was derived by Robb (1999) and has been used to extend the domestic pumping time series to cover the full modelled period.

Robb (1999) reportedthat the average use per household is approximately 350 l/day (based on TDC community supply records). This equates to approximately 135 l/day per person, given an average household occupancy of 2.6 people per house.

Meter records for TDC's community supplied schemes indicate that demand varies over the year. Based on pumping records, Robb (1999) derived monthly multipliers to estimate the variation in demand either side of the long-term average take. These multipliers are reproduced in Table 3-3.

Table 3-3: Monthly multiplier for estimating domestic takes

Month	Multiplier
January	1.4
February	1.2
March	1.1
April	1.1
May	1.0
June	1.0
July	0.8
August	0.7
September	0.8
October	0.9
November	1.0
December	1.0
Multipliers derived by Robb (1999)	

Recent census data (for 2006, as provided by TDC) enabled the calculation of the number of households in each land use grid cell for each of the three land use periods. Then, assuming the long-term average household use of 351 l/day and the monthly multipliers above, monthly-varying time series of domestic takes for each grid cell were calculated. This pattern was repeated year after year for the full simulation period based on recent census population data. In total, 170 domestic wells were modelled, where one well represents all domestic takes within any one land use grid cell.

Population has not changed markedly over the model simulation period and consequently, domestic water use has also not changed significantly, compared to other water uses. Therefore, variations from year to year have not been modelled; only monthly variations as described above.

All domestic takes were assumed to abstract from the upper aquifer. Water abstracted for domestic use was not included in estimates of land surface recharge. It was assumed to be used or discharged into reticulation systems.

Community Wells

Community wells refer to those that are used to supply community reticulated water schemes. There are eight community supply wells located on the Motueka-Riwaka plains. These are:

(i) Kaiteriteri: WWD 3142 (abstracting since 6/5/99);

(ii) Ferons Bush: WWD 3394 (abstracting since before the beginning of the model period at 1/6/90);

(iii) Lower Moutere Water Scheme (LMWS) - four wells:

- 1a: WWD 2136 (abstracting since 28/10/03)
- 1b: WWD 2135 (abstracting since 28/10/03)
- 2a: WWD 2153 (abstracting since 25/10/05)
- 2b: WWD 2154 (abstracting since 25/10/05)

(iv) A fifth well, WWD 23401, was added to LMWS' second well field in January 2008, near wells WWD 2153 and WWD 2154. Because of its close proximity to the other two wells, the modelled take from bore WWD 23401 has been combined with the take from bore WWD 2153 and WWD 2154.

(v) Naumai: WWD 3411 (abstracting since before the beginning of the model period at 1/6/90 through to 31/12/99; decommissioned thereafter); and

(vi) Rec Centre: WWD 2544 (abstracting since 1/1/94). There is also a second backup well (WWD 23807) located very close (~17 m) to this well, but due to the near vicinity of the two wells, the total take has been simulated by the one well. The backup well does not alter the overall rate of take.

Apart from the Naumai well, all daily take volumes have been modelled based on actual weekly meter readings. There were no records for the Naumai well, so the take from this bore was set at the consented rate of 150 m^3/day.

The depths of abstraction for all community wells were based on the screen depth. For some wells, the screen interval spanned all modelled aquifers. In these cases, the rate of water abstracted from each layer was apportioned based on the proportion of screen spanning the respective layer. Similar to the domestic takes, it was assumed that community takes do not contribute to land surface recharge.

Industrial Wells

Industrial wells are those used to supply groundwater for industrial purposes. There are 14 industrial wells on the plains. These are:

(i) Plant & Food (formerly Hort Research): WWD 3197

(ii) Motueka Gravels: WWD 3443 (this plant ceased operation on 26 October 2012, which is beyond the end of the model simulation run period)

(iii) Inglis vegetable wash: WWD 3410

(iv) Te Awhina Marae: WWD 2026

(v) Motueka New World (formerly TDC supplemental supply): WWD 3181

(vi) Motueka Rest Home (formerly Woodlands Rest Home): WWD 2536

(vii) Wakatu Cold Store (formerly Poley Cold Store): WWD 3215

(viii) Concrete and Metals Batching Plant: WWD 2030

(ix) Motueka Cold Store Well 1: WWD 3263

(x) Motueka Cold Store Well 2: WWD 3409

(xi) CH Industries Gravel Wash Plant (formerly Abattoir): WWD 3232 and WWD 3233 (combined) (abstracting since before the beginning of the model period at 1/6/90)

(xii) Motueka Apple Storage Ltd Cold Store: WWD 2086

(xiii) Talleys: WWD 3359 (abstracting since before the beginning of the model period at 1/6/90)

Where available, the modelled pumped rate has been set equal to historical measured use. Where this was not available, the abstraction rate was set equal to the consented daily rate. All industrial takes were modelled as operating for the full model period.

The depths of abstraction for all industrial wells were based on the screen depth. For some wells, the screen interval spanned all modelled aquifers. In these cases, the rate of water abstracted from each layer was apportioned based on the proportion of screen spanning the respective layer. Like the domestic and community takes, it was assumed that industrial takes do not contribute to land surface recharge.

Irrigation Takes

Irrigation is the primary water use on the Motueka-Riwaka plains. Aqualinc's in-house crop-soil water balance model (IRRICALC) has been used to generate daily time series of irrigation demand. The soil-water balance model is briefly described in Section 3.10.3 and a more comprehensive overview is provided in Appendix A. Irrigation demand has been calculated considering land use, climate, soil and irrigation methods. A summary of key irrigation parameters for each crop type is provided in Appendix A.

Figure 3-18 presents a comparison between modelled and measured seasonal irrigation use for the Central Plains, King Edwards and Hau groundwater management zones (see Figure 2-5 for the locations of these zones). These seasonal irrigation use summaries have been collated only for measured takes. There are additional irrigation takes (both in these zones and in other management zones) that cannot be included in the comparison because records are not provided. Although there are some 'unders and overs', the comparison shows that the overall modelled seasonal irrigation use is consistent with measured.

Figure 3-19 provides an equivalent comparison of cumulative irrigation use for the same three management zones. These demonstrate the patterns of take over each season. Again, measured and modelled are consistent.

Land surface recharge under irrigated land includes the effects of irrigation. Therefore, irrigated land surface recharge is greater than under dryland conditions.

In total, 125 irrigation takes were modelled. Similar to the domestic takes, there are places where there are multiple irrigation wells located in the same land use grid cell. In these cases, a single well has been modelled at the cell centre which represents all irrigation wells in that cell.

The depths of abstraction for all irrigation wells was based on the screen depth. For some wells, the screen interval spanned all modelled aquifers. In these cases, the rate of water abstracted from each layer was apportioned based on the proportion of screen spanning the respective layer.

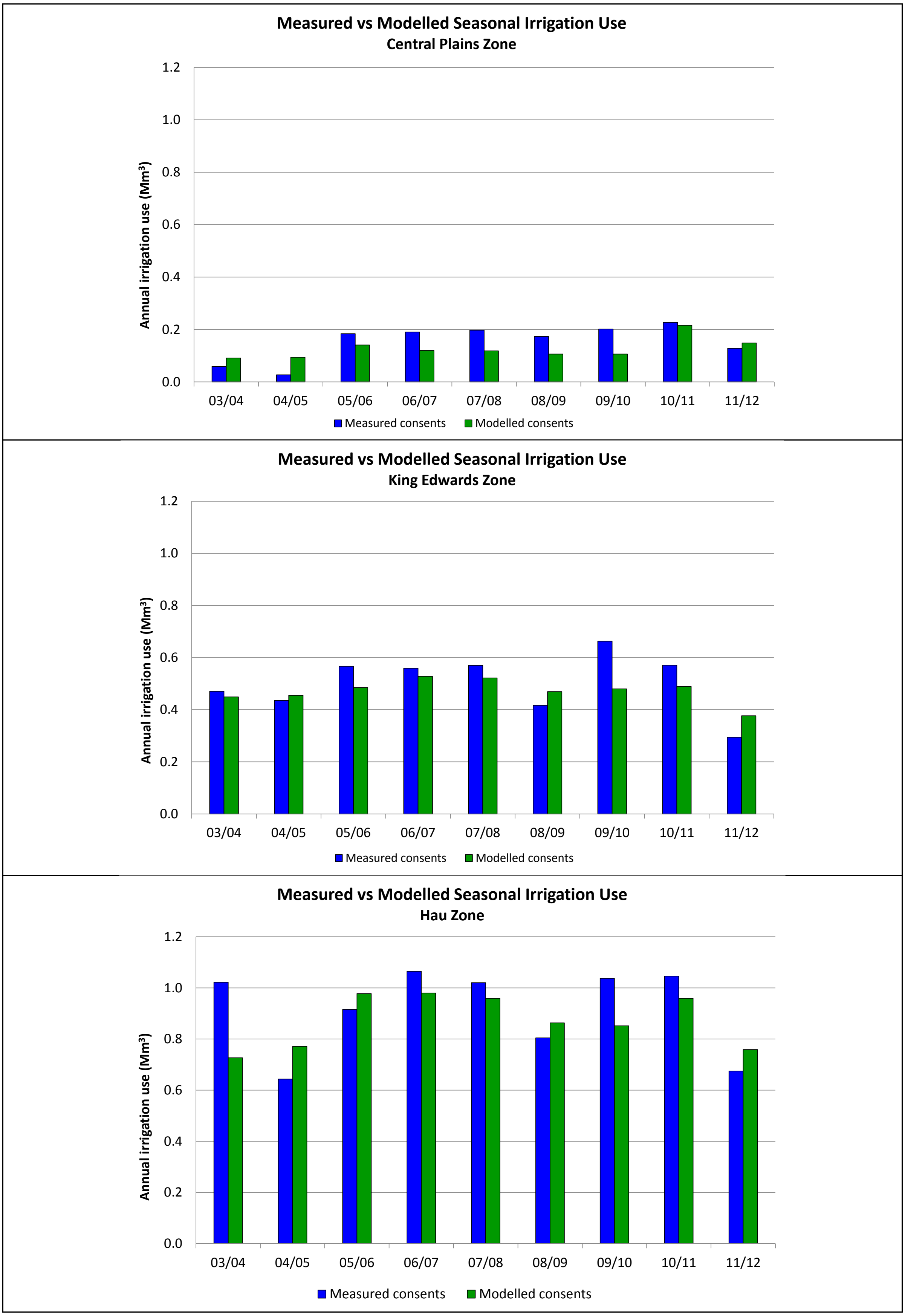


Figure 3-18: Measured versus modelled total seasonal irrigation use

('measured consents' sums only those takes that are measured and reported to TDC; there are additional takes in the three zones above that are not measured and/or not reported)

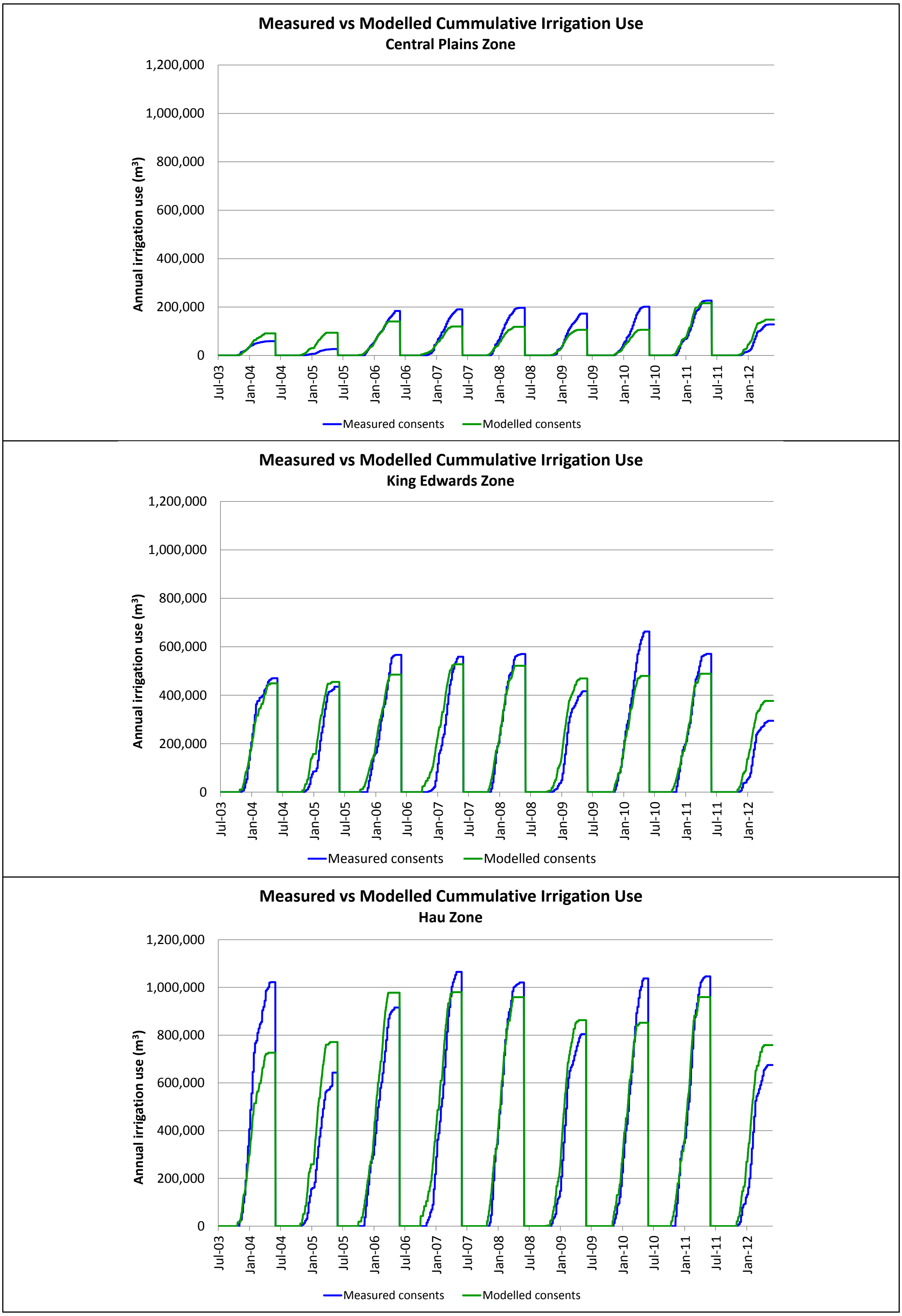


Figure 3-19: Measured versus modelled seasonal cumulative irrigation use

('measured consents' sums only those takes that are measured and reported to TDC; there are additional takes in the three zones above that are not measured and/or not reported)

3.10.6 General Head Boundary

General head boundaries (GHB) are specified at the coast, along inlets and offshore to represent how the groundwater system discharges to the sea. The GHB has been defined only for the upper layer. The deeper layers (layers 2 and 3) continue under the marine sediments and are restricted to discharge vertically into layer 1 via diffuse seepage. Figure 3-20 (modified from Aqualinc, 2007c) shows the conceptual model for the GHB.

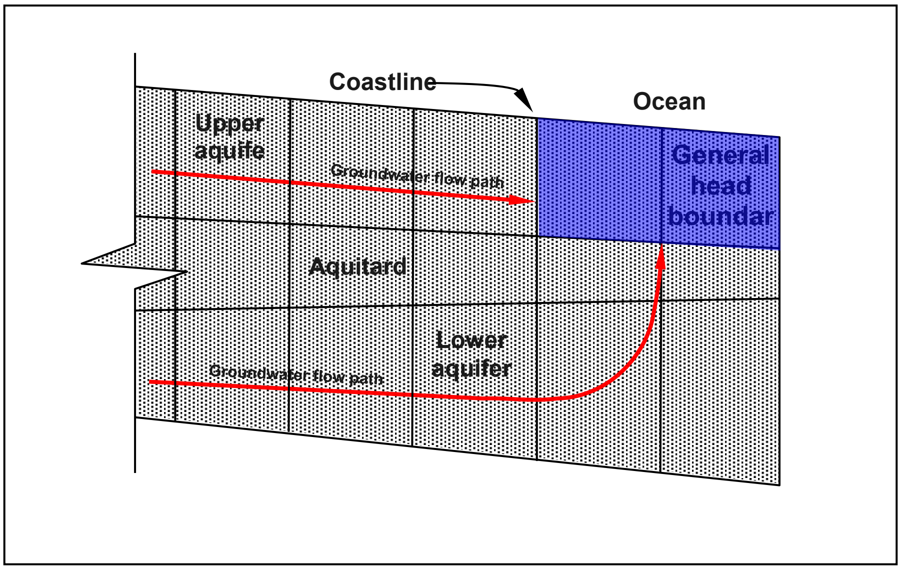


Figure 3-20: Conceptual model of the general head boundary condition

The GHB requires the specification of a boundary water level elevation and a conductance term. The boundary water level elevation has been set at a constant value of mean sea level. The conductance of the GHB has been adjusted through calibration. Figure 3-21 presents the location of the GHB in layer 1 and the various conductance zones assigned.

If the adjacent (or underlying) groundwater level is higher than the specified boundary water level, then water flows into the GHB. This simulates the normal flow of water off shore. Conversely, if groundwater levels are lower than the specified boundary water level, then water flows out of the GHB into the groundwater system. This simulates the back-flow of sea water into the aquifer (saltwater intrusion). The rate of flow into or out of the GHB is determined by the hydraulic gradient (between groundwater levels and the specified boundary water level) and the GHB conductance term.

3.10.7 No-Flow Boundary

No-flow boundaries are inactive cells in MODFLOW. They are used to represent boundaries where there is no (or very little) groundwater flow in or out of the model. All cells beyond the active extent shown in Figure 3-21 (and other similar figures) are inactive, as is the lower surface of layer 3.

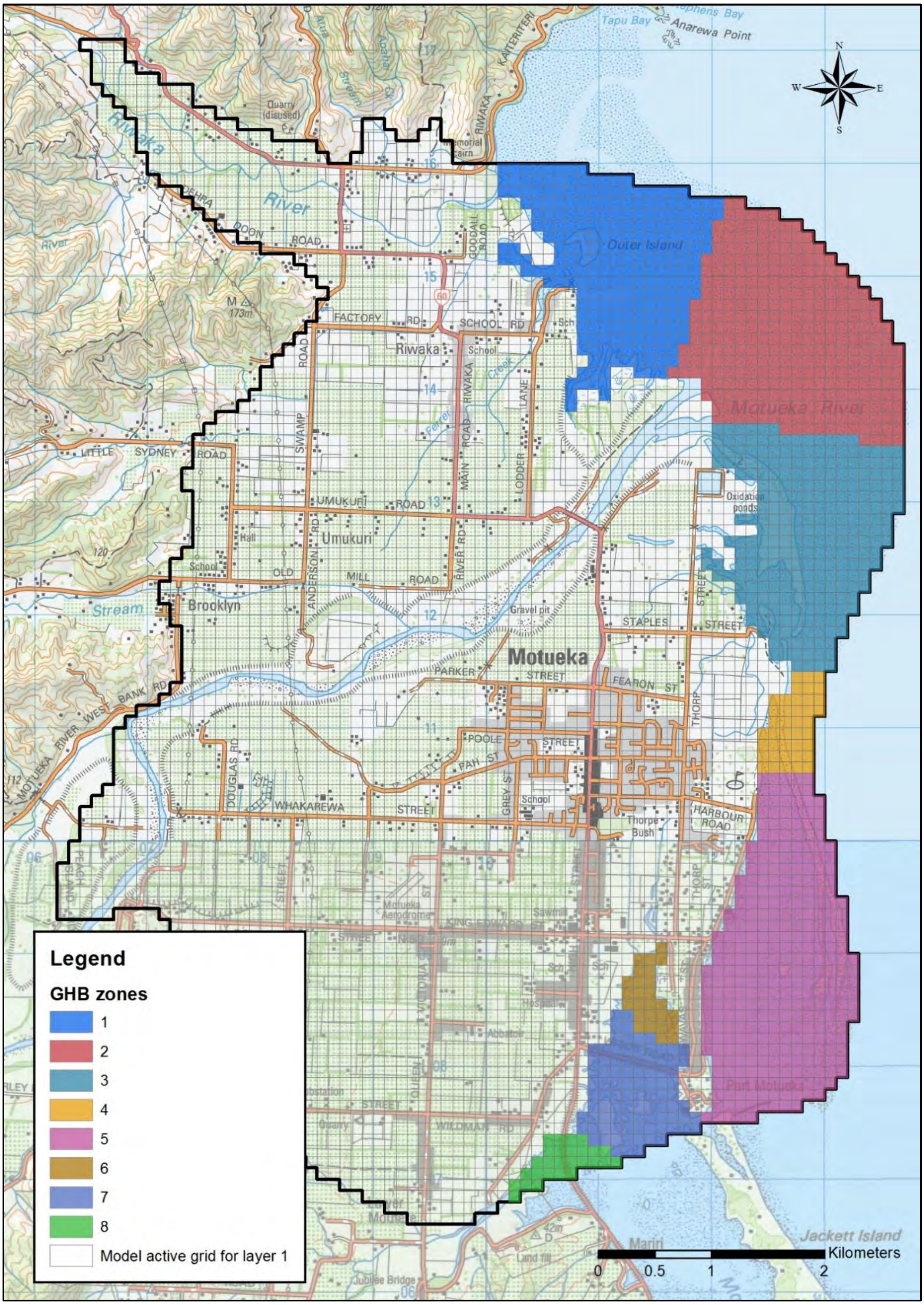


Figure 3-21: General head boundary cells

3.11 Calibration Data

Several datasets were used to calibrate the Motueka-Riwaka Plains groundwater model. The key data set used was groundwater levels, but spring and drain flow data was also considered, as were flow losses from the Motueka River. In addition, results from aquifer tests were used to constrain aquifer parameters in the vicinity of the tests. Each of these datasets are described below.

3.11.1 Groundwater Levels

Based on the recommendations of Aqualinc (2008), TDC have recently installed additional groundwater level monitoring wells from which additional groundwater level data was collected. This new data, along with additional data collated from the existing monitoring wells, was incorporated into the updated version of the model. Compared to earlier models, the additional data provided freedom to introduce more complex parameter distributions and widened the calibration scope in both space and time. This enhanced the model’s ability to accurately replicate the groundwater system.

In total there are 18 monitoring wells on the Motueka-Riwaka plains that have been used for calibration. Figure 3-22 maps the locations of these monitoring wells. Table 3-4 overviews the calibration data collected from the monitoring well.

Table 3-4: Monitoring well data summaries

Well name	Well number	Screen interval (m bgl)	Date of first measurement used [1]	Date of last measurement used [2]	Percent of days with data
Andersons	WWD 23547	4.0 – 19.0	18/02/09	31/05/12	100%
Fernwood	WWD 2614	5.9 – 6.9	30/12/03	31/05/12	100%
Greenwood	WWD 23548	4.0 – 19.0	24/12/09	31/05/12	100%
Horrells	WWD 2609	17.0 – 24.8	01/06/90	31/05/12	100%
Inglis	WWD 3141	9.5 – 12.5	25/02/09	31/05/12	100%
Lodders	WWD 2629	14.0 – 20.0	16/08/06	31/05/12	100%
Marchwood	WWD 2700	11.0 – 16.0	25/02/09	31/05/12	100%
Motueka River Bed	WWD 2164	14.4 – 18.4	17/10/03	23/05/12	100%
Nursery North	WWD 2179	14.4 – 20.4	18/09/06	31/05/12	97%
Nursery South	WWD 2180	14.0 – 17.5	07/09/06	31/05/12	100%
OWR	WWD 2003	10.4 – 24.0	17/01/90	31/03/04	5%
Riwaka Hall	WWD 2607	19.0 – 36.8	01/06/90	31/05/12	100%
Rossiters	WWD 2601	12.0-13.0 20.4 – 21.9	01/06/90	31/05/12	100%
Thorp	WWD 23479	~5.0 – 8.0	04/09/09	11/09/11	88%
Smiths	WWD 2033	6.1 – 9.5	16/11/90	23/04/98	100%
Staples	WWD 2628	14.5 – 20.0	16/08/06	31/05/12	100%
Tui Close	WWD 2166	15.0 – 20.0	16/08/04	31/05/12	100%
Wratts	WWD 2603	12.4 – 13.4	01/06/90	31/05/12	100%

(1) The model simulation period commences on 1/6/90. Even though some wells have monitoring data prior to this period, only data from this date onwards has been used for model calibration.

(2) Monitoring for most wells is ongoing. However, since the model run period stops at 31/5/12, the data used for model calibration has also stopped at this date.

Figure 3-22: Location of monitoring wells

3.11.2 Spring and Drain Flows

Three key drainage networks have been modelled, Thorpe Drain, Staples Drain and Frys Drain. These are shown in Figure 3-16 and the approach to representing them is discussed in Section 3.10.2.

Flow data collated from the drains is sparse and consists of one-off spot measurements, typically during periods of low rainfall (during summer months). Flows measured during these dry periods represent the baseflow groundwater component of the drain at the time. In addition to the one-off spot measurements, a flow recorder was temporarily installed near the Thorp Drain outlet over the period May 1990 through to August 1994. Table 3-5 summarises the data available for the three drain networks.

Table 3-5: Drain flow data summaries

Drain name	Spot measurements of recorder	Date of first measurement used	Date of last measurement used	Percent of days with data
Thorpe Drain	Recorder	16/05/90	04/08/94	99.5%
	Spot	16/01/12	16/01/12	(only 1 measurement)
Staples Drain	No measurements - see discussion below			
Frys Drain	Spot	16/01/12	16/01/12	(only 1 measurement)

There are no flow measurements for Staples Drain. Visual inspections by TDC staff over the 2012-2013 summer indicated that the average baseflow from this drain is typically in the order of 50-200 l/s (Joseph Thomas, TDC, pers. comm.). Therefore, model calibration has attempted to simulate Staples Drain flows in this range.

The flows measured by the Thorpe Drain recorder include quick-flow run-off (e.g. stormwater) from the land surface as well as the slower baseflow contribution from groundwater. However, the groundwater model simulates only the groundwater baseflow component of the measured flow. Therefore a simple baseflow separation was applied to the measured flow by taking the minimum flow over a 14-day moving window. This was then compared to modelled groundwater contribution to this drain.

3.11.3 Motueka River Losses

Simultaneous gaugings of river flows in the Motueka River have provided estimates of river flow losses to groundwater. Motueka River flows at Woodmans Bend (location shown in Figure 2-2 and Figure 2-3) have been compared with flows at the State Highway bridge to calculate the net loss of river flow to groundwater on the day of measurement. The results that fall within the model simulation period are listed in Table 3-6. These all occur within the verification period.

Table 3-6: Motueka River losses

Date	River flow at Woodmans Bend (m^3/s)	River flow at State Highway Bridge (m^3/s)	Flow loss to groundwater (m^3/s)
25/03/91	15.33	13.77	1.56
18/06/91	15.92	15.01	0.91
13/02/92	17.33	17.43	-0.10
17/02/93	16.18	15.47	0.71
13/04/94	12.57	12.31	0.26
24/01/97	24.80	21.37	3.43
15/02/99	9.86	9.39	0.47
25/02/99	8.73	8.21	0.52
		Average	**0.97**

3.11.4 Aquifer Tests

Due to its inherently local representation, aquifer test data has not been used to calibrate the model. It has, however, been used to constrain aquifer parameters in the locations of test data. At other locations, aquifer parameters have been allowed to vary to achieve calibration.

Three key data sets that relate to groundwater modelling are derived from aquifer tests. These are:

(i) *Hydraulic conductivity (k):* Hydraulic conductivity is a measure of how readily water passes through the aquifer material under a unit hydraulic gradient. Aquifer tests calculate aquifer transmissivity, which is the product of hydraulic conductivity and aquifer saturated thickness. To derive suitable hydraulic conductivity values for the numerical model, aquifer transmissivity was divided by the modelled aquifer thickness at the location of the test to calculate a conductivity value at that location representative of the model's numerical thickness. By using the modelled aquifer thickness, discrepancies in model thicknesses between measured and modelled are accommodated while maintaining the equivalent transmissivity derived from testing.

(ii) *Specific storage (Ss):* Specific storage is a measure of how readily water is released from storage under a unit drop in water level. Aquifer tests report aquifer storage. Specific storage is calculated by dividing the storage by the aquifer saturated thickness. For the same reason as described above for hydraulic conductivity, the model’s numerical thickness has been used to convert aquifer tests storage to specific storage at the locations of the tests.

(iii) *Aquitard vertical hydraulic conductivity (k’):* For constant discharge tests conducted in the lower aquifer, a measure of the vertical hydraulic conductivity of the overlying aquitard can be derived. This is a measure of how leaky the overlying layer is, and therefore how connected the upper and lower aquifers are.

Figure 3-23, Figure 3-24 and Figure 3-25 present the locations and magnitudes of hydraulic conductivity, specific storage and aquitard leakage (respectively) derived from aquifer test and as applied to the model.

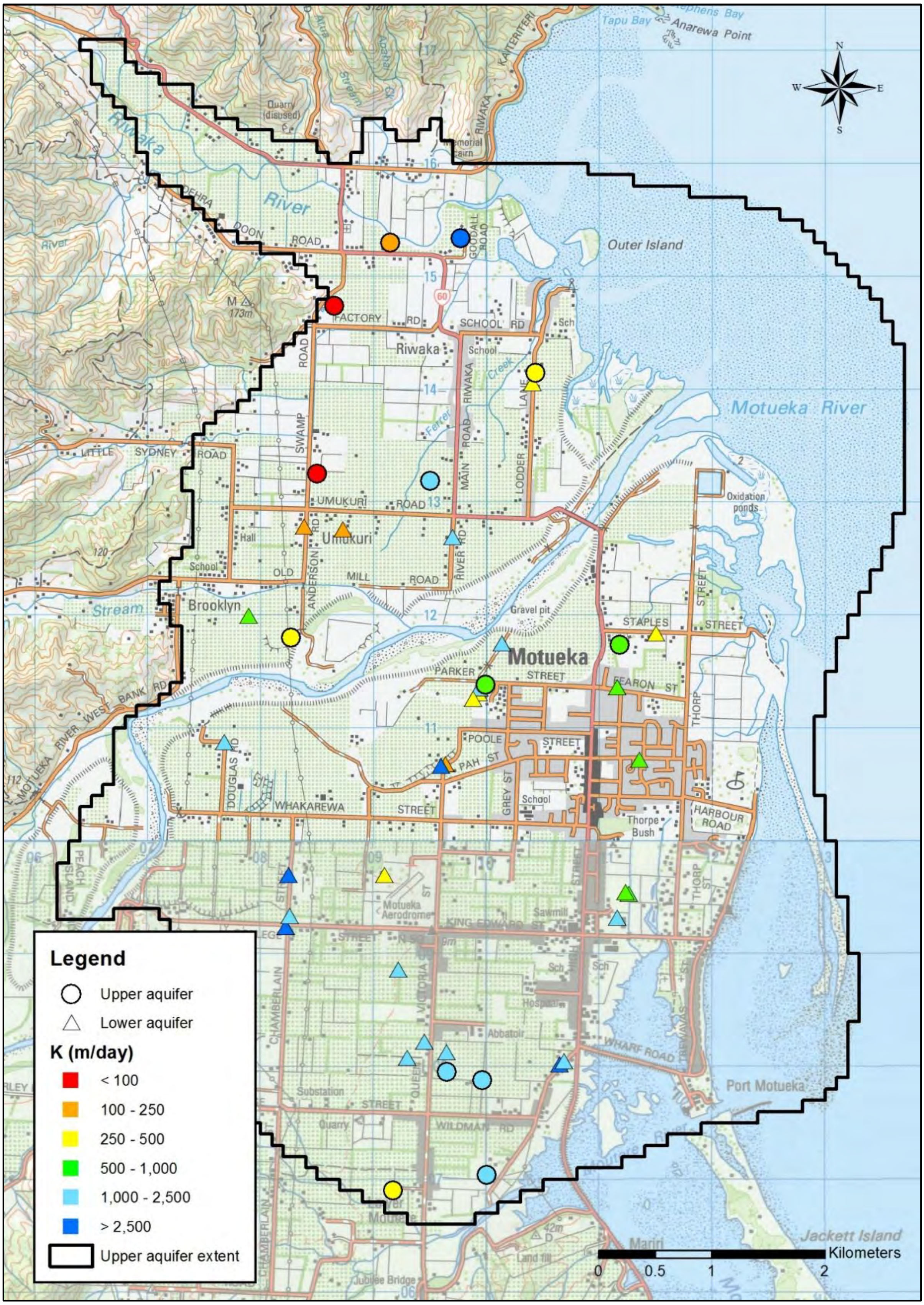


Figure 3-23: Aquifer test hydraulic conductivity

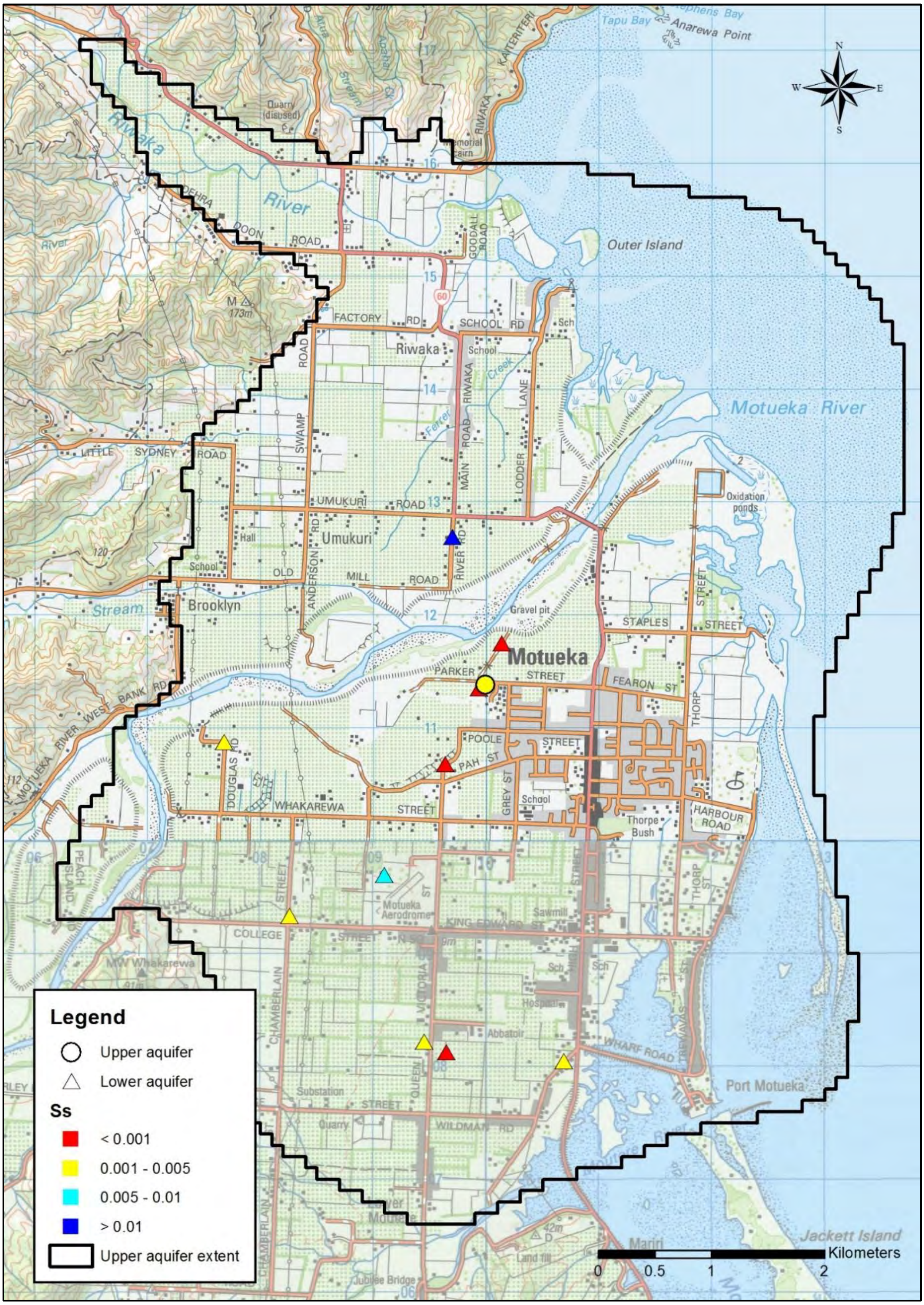


Figure 3-24: Aquifer test specific storage

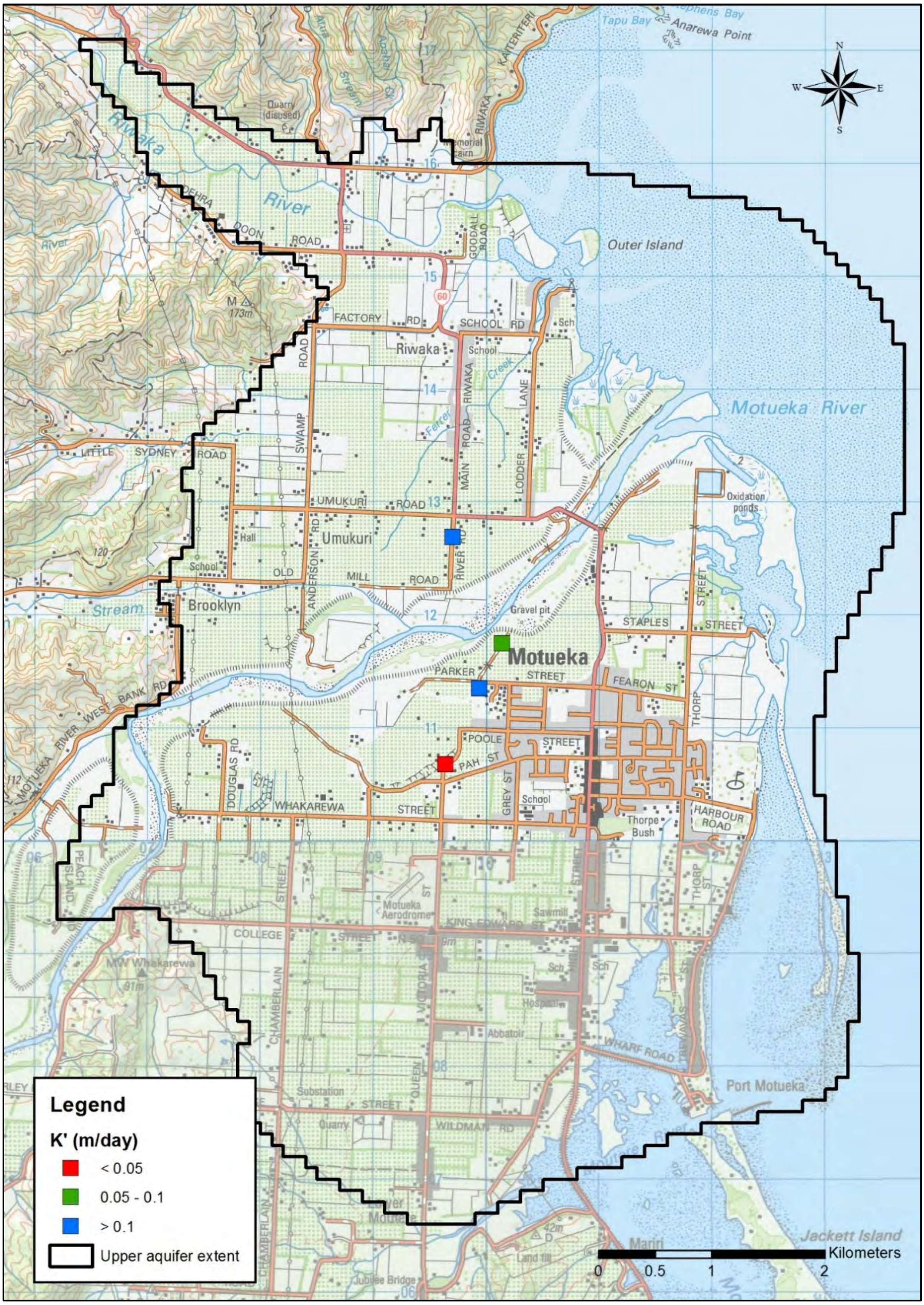


Figure 3-25: Aquifer test leakage

4 MODEL CALIBRATION AND VERIFICATION

Model calibration consists of adjusting model parameters (within realistic limits) until the simulated outputs agree with measured data as best as practical. The calibrated model is then verified using measured data that has not been used during the calibration process. Verification is an independent test of the calibrated model's ability to predict model outputs for time or space not covered by the calibration data.

The updated groundwater model has been constructed to simulate groundwater levels from 1 June 1990 through to 31 May 2012. Since approximately 2006 onwards, TDC have progressively installed new observation wells. Therefore, many new observations are available for the latter part of the simulation period but are not available for the earlier part. Because of this, the model has been calibrated for the latter half of the model period, between 1 January 2001 and 31 May 2012. The calibrated model has then been verified for the earlier period from 1 June 1990 to 31 December 2000.

Within this report, plots of simulated groundwater levels and river flows include both the verification and calibration periods. However, statistics presented on each of these periods have been separated.

4.1 Model Calibration

The updated model has been calibrated to the measured data presented in Section 3.11. Calibration was conducted within GMS using a combination of PEST (Parameter Estimation software by Doherty, 2010) and manual trial and error. A combination of pilot points and parameter zones were used, as summarised in Table 4-1.

Table 4-1: Method of parameter assignments

Parameter	Method
Upper aquifer K_h	Pilot points
Aquitard K_h	Pilot points
Lower aquifer K_h	Pilot points
Upper aquifer K_v	Single value (for this layer)
Aquitard K_v	Pilot points
Lower aquifer K_v	Single value (for this layer)
Upper aquifer S_s	Pilot points
Aquitard S_s	Pilot points
Lower aquifer S_s	Pilot points
S_y	Single value (for all layers)
River bed conductivity	8 zones (Figure 3-15)
Drain conductance	3 zones (Figure 3-16)
GHB conductance	8 zones (Figure 3-21)

Definitions:

Kh = horizontal hydraulic conductivity

Kv = vertical hydraulic conductivity

Ss = specific storage

Sy = specific yield

The values for pilot points at the location of aquifer tests (Section 3.11.4) have been fixed as the test value. A few pilot points located near boundaries have been fixed and adjusted manually. Other pilot points have been allowed to vary.

Model calibration commenced with initial model parameter values set to aquifer test results (where available) or estimated values. PEST was run, and discrepancies between simulated and measured calibration groundwater levels and drain flows were assessed. If the simulated values did not adequately match measured, then pilot points were modified, and PEST run again. This was repeated until a suitable match between measured and simulated groundwater levels was achieved. In some instances, parameter values were adjusted manually to speed up the calibration process.

Once suitable calibration to groundwater levels and drain flows was achieved, modelled Motueka River losses were compare to measured, parameters were further adjusted accordingly, and PEST re-run. This process was iteratively carried out until an acceptable match was obtained. The calibration process is outlined in Figure 4-1.

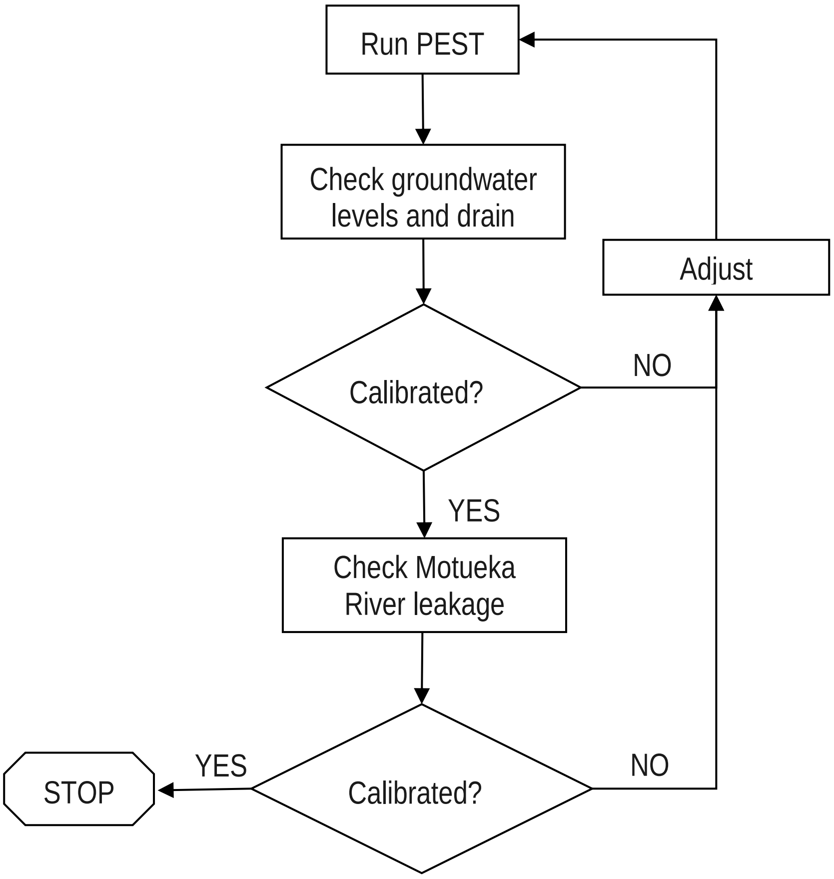


Figure 4-1: Calibration process flow chart

4.1.1 The Objective Functions

An objective function is a mathematical formula that numerically expresses the goal that is to be achieved during calibration. For the purpose of this model, two objective functions have been used, as follows:

i) The mean error (ME), which assists in showing the presence of bias (systematic error); and

ii) The root mean square error (RMSE), which is a classical measure of model error (a small RMSE may indicate a good calibration) (MfE, 2002).

Both the ME and the RMSE are usually reported as a percentage of the range within which the measured values vary (this is also referred to as the 'normalised' error). The two key objective functions are presented mathematically below.

Mean error (ME):

$$\mathrm{ME} = \frac{1}{n}\sum_{i=1}^{n}\left(H_i - h_i\right) \tag{2}$$

Root mean square error (RMSE):

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(H_i - h_i\right)^2} \tag{3}$$

Where: n = Number of points being considered
H_i = Measured head at location *i*
h_i = Simulated head at location *i*

The difference between measured and modelled head ($H_i - h^i$) at any location and time is called the ‘residual’. One of the key goals of model calibration is to minimise the objective functions (i.e. minimise the residuals).

Table 4-2 presents the groundwater level objective function values for the calibrated model along with additional statistics that have been generated and a brief description of these statistics.

Table 4-2: Groundwater level objective function values and other statistics for the calibration period

Calibration period statistics (1 January 2001 – 31 May 2012)		
Objective function or statistic	**Value**	**Definition**
Maximum absolute residual	1.3 m	Maximum difference between modelled and measured
Minimum absolute residual	0.0 m	Minimum difference between modelled and measured
Mean error (ME)	0.14 m	Average difference between modelled and measured
Normalised ME	1.5%	ME normalised by the range in measured values
Root mean square error (RMSE)	0.26 m	Classical, unbiased measure of error
Normalised RMSE	2.6%	RMSE normalised by the range in measured values
R^2 (square of the correlation coefficient)	0.992	Correlation between measured and modelled values

The United States Army Corps of Engineers use a rule of thumb for an acceptable normalised RMSE of 10% when considering groundwater flow calibration or verification (Donnell *et al.,* 2004). The 2001 Australian Groundwater Flow Modelling Guidelines indicate that the normalised RMSE should be less than 5% (MDBC, 2001), though the revised 2012 guidelines (Barnett *et al*., 2012) suggest that alternative (larger) values may be acceptable depending on the model scope. As the normalised RMSE is 2.6% for the calibrated model (Table 4-2), the model is suitably calibrated.

4.1.2 Modelled Versus Measured Groundwater Levels

Figure 4-2 presents a plot of simulated versus measured groundwater levels for the 18 observation wells used for calibrating the groundwater model. In total, 40,742 groundwater level measurements over the period 1 January 2001 through to 31 May 2012 were used to calibrate the 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 real world system.

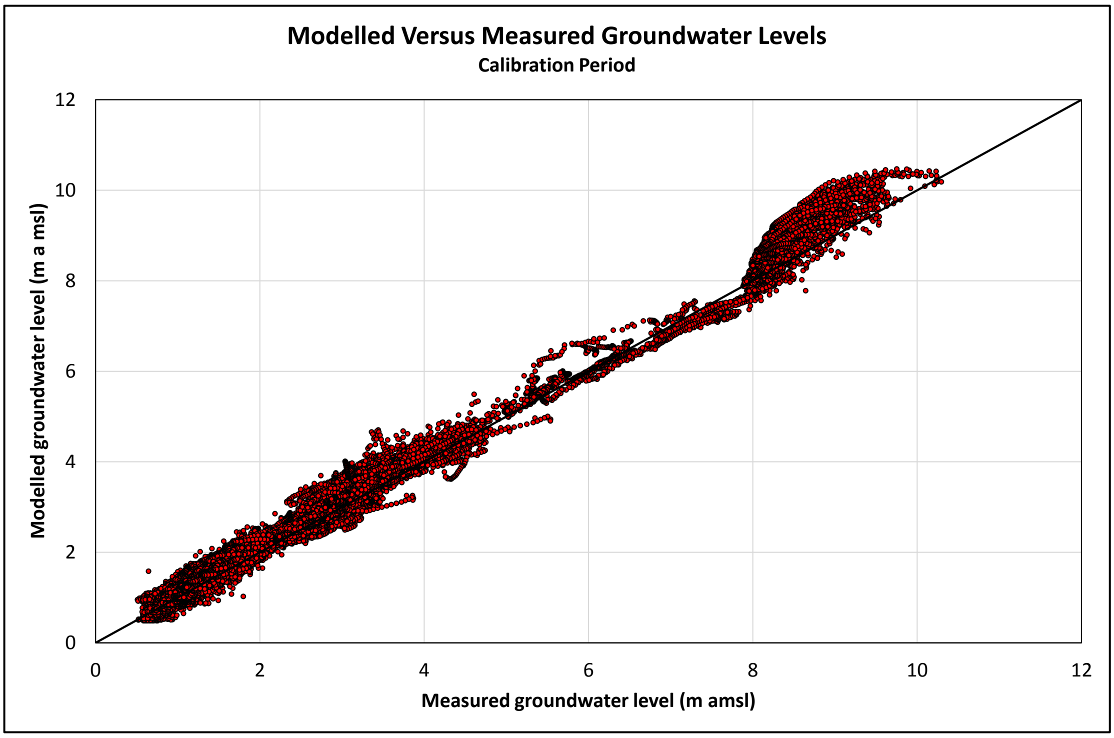


Figure 4-2: Modelled versus measured groundwater levels for the calibration period

Figure 4-3 presents a histogram of the residuals along with theoretical curves showing normally distributed residuals. Figure 4-4 compares residuals to measured groundwater levels, along with the mean error. The distribution of residuals is generally both above and below the target levels (i.e. positive and negative residuals) and is relatively close to a normal distribution. However, the plots indicate a small positive bias, indicating that the model predictions are (on average) slightly higher than the observed values (shown by the positive mean error).

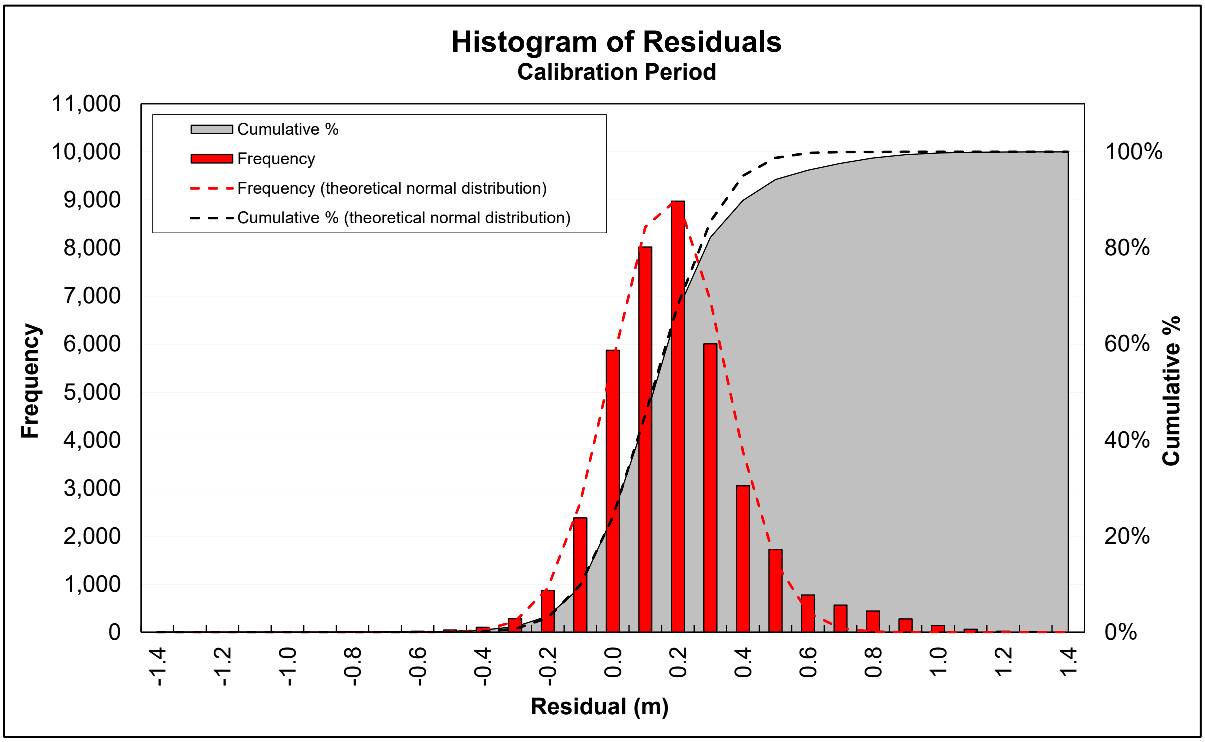


Figure 4-3: Histogram of residuals for the calibration period

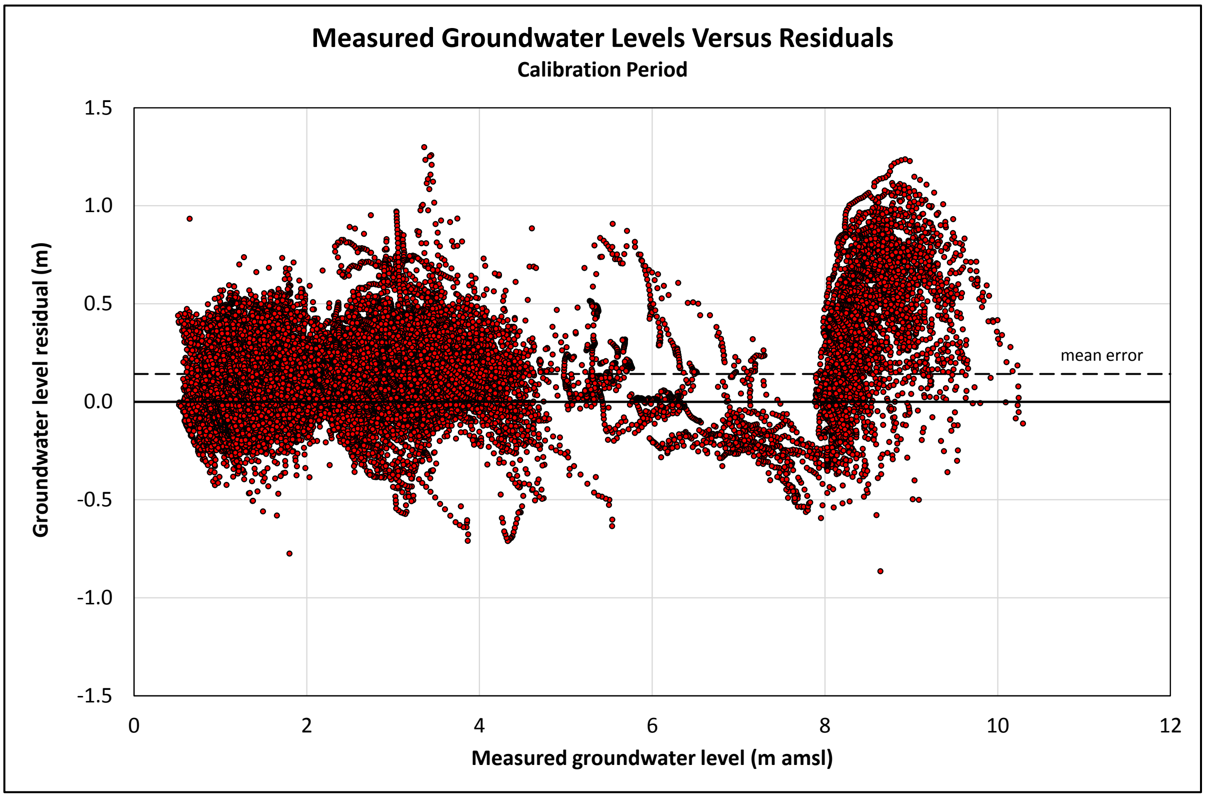


Figure 4-4: Measured groundwater levels verses residuals for the calibrated period

4.1.3 Motueka River Losses

All measured Motueka River losses (listed in Table 3-6) fall within the model verification period; therefore no comparison can be made for the calibration period.

4.1.4 Model Parameters

Model calibration resulted in various parameter values. The values for all zoned parameters are presented in Table 4-3. Figure 4-5 through to Figure 4-11 present maps of all parameters derived by pilot points, these being horizontal conductivities and specific storages for the three hydrological layers, and vertical conductivities for the aquitard.

Table 4-3: Zoned parameter values

Parameter		Calibrated value	Unit
Upper aquifer K_h/K_v		8.0	-
Lower aquifer K_h/K_v		8.8	-
S_y		0.11	-
River bed conductance (see Figure 3-15)	Motueka 1	8.0	m/day
	Motueka 2	0.14	
	Motueka 3	1.5	
	Motueka 4	0.02	
	Riwaka 1	4.9	
	Riwaka 2	1.2	
	Brooklyn	1.1	
	Little Sydney	0.1	
Drain conductance (see Figure 3-16)	Frys	42.0	m^2/day
	Staples	12.0	
	Thorp	25.0	
GHB conductance (see Figure 3-21)	1	4.3	m^2/day
	2	0.92	
	3	0.07	
	4	5.3	
	5	0.004	
	6	0.002	
	7	2.0	
	8	0.18	
Definitions:	K_v = vertical hydraulic conductivity		S_y = specific yield

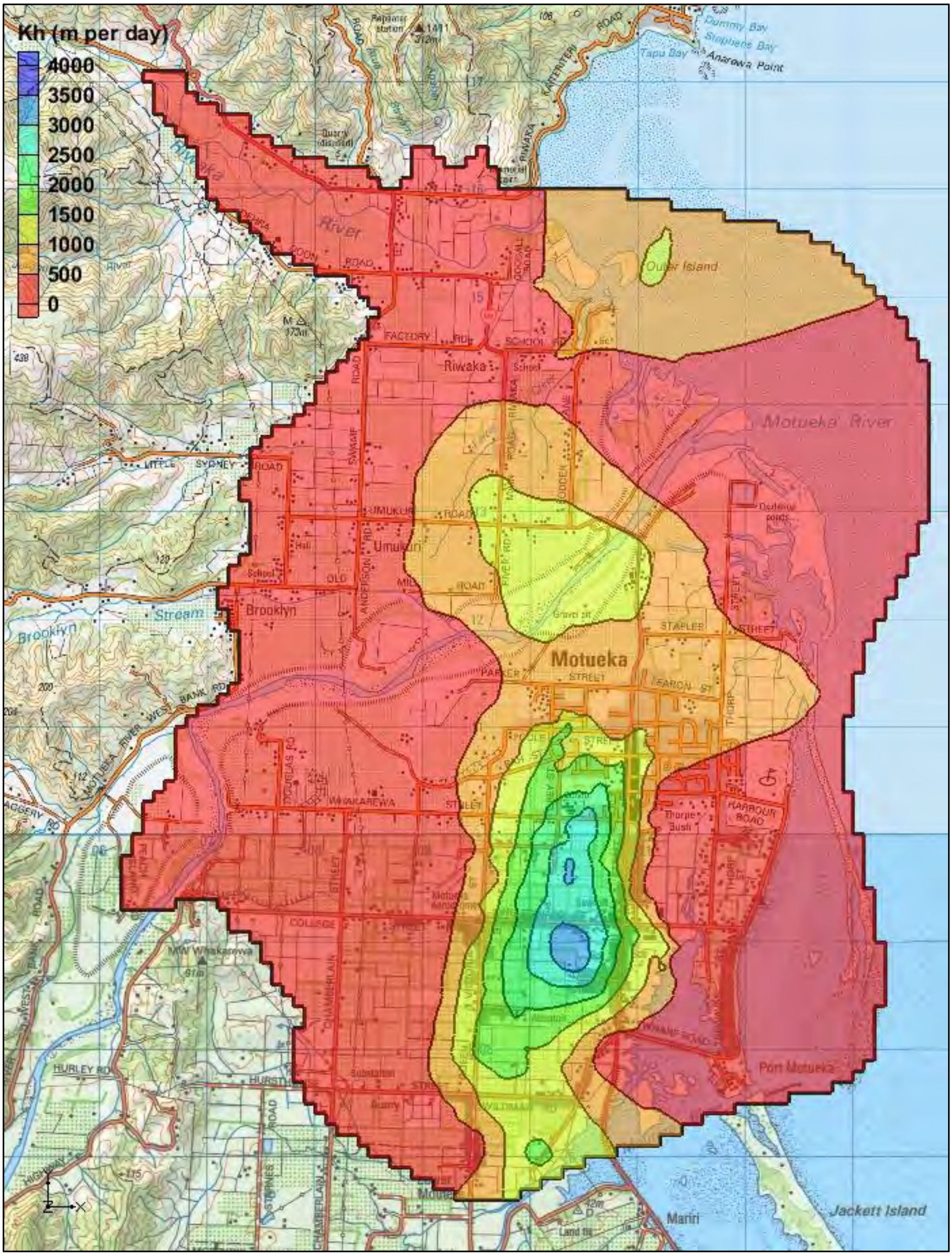


Figure 4-5: Calibrated horizontal hydraulic conductivity for the upper aquifer

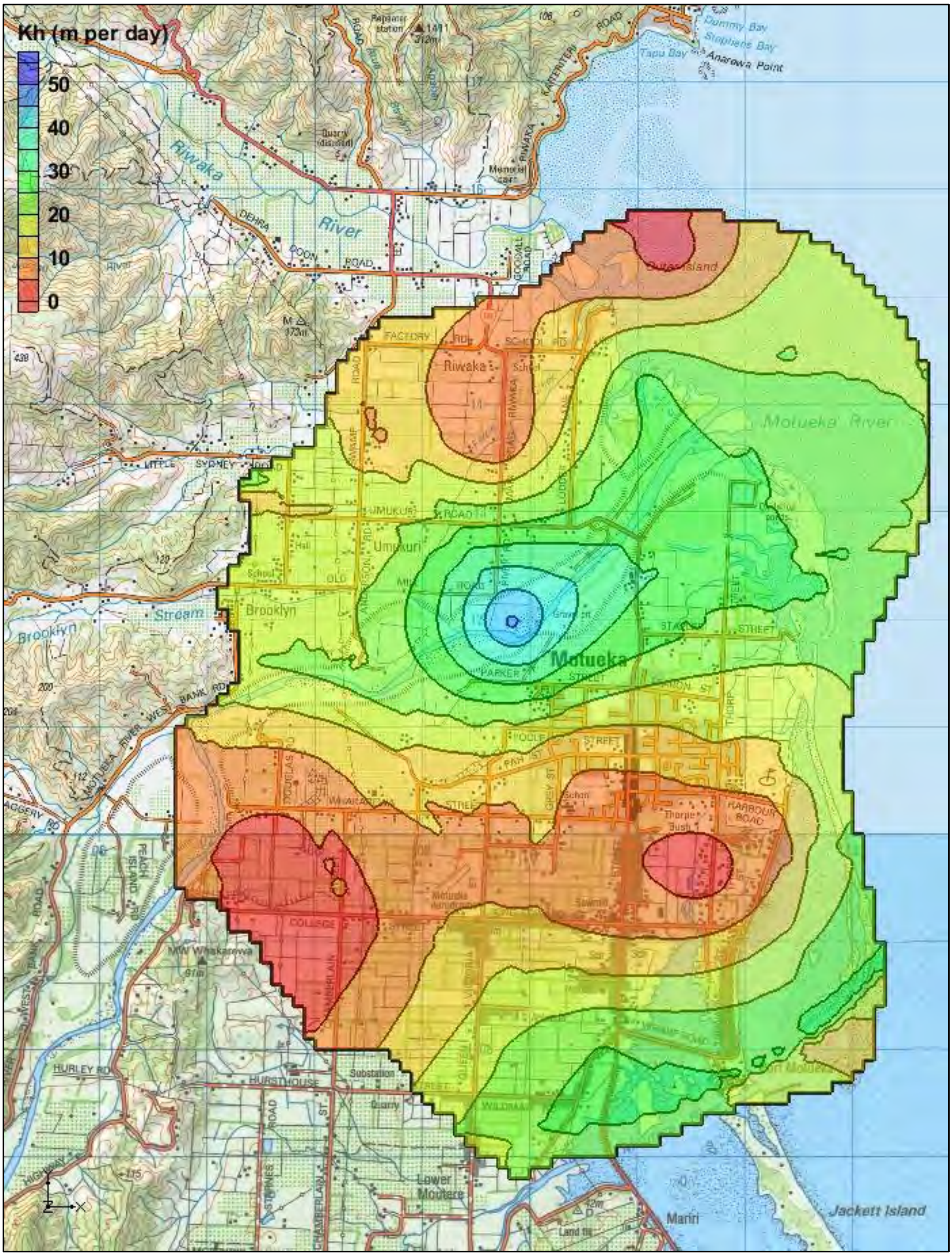


Figure 4-6: Calibrated horizontal hydraulic conductivity for the aquitard

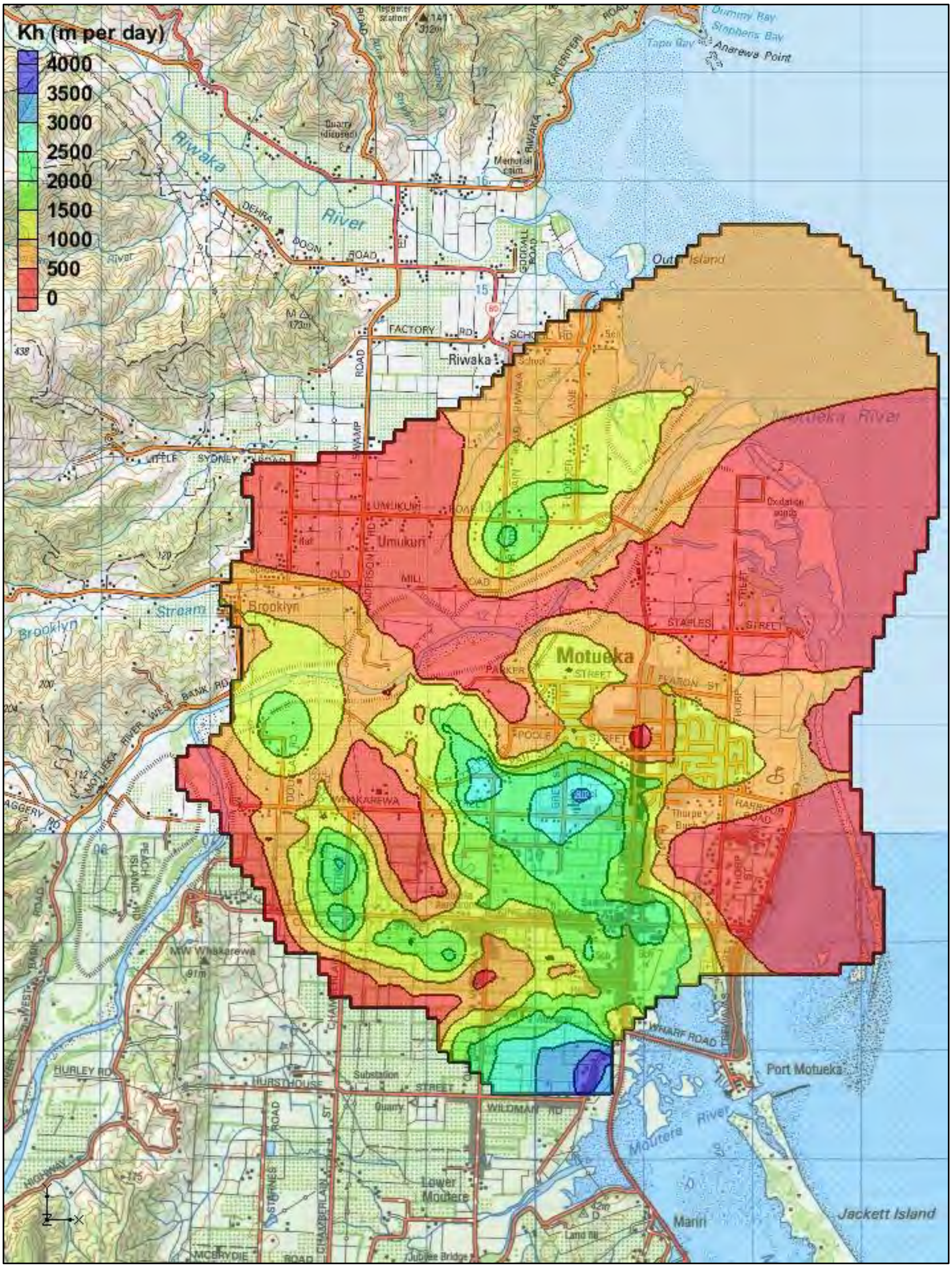


Figure 4-7: Calibrated horizontal hydraulic conductivity for the lower aquifer

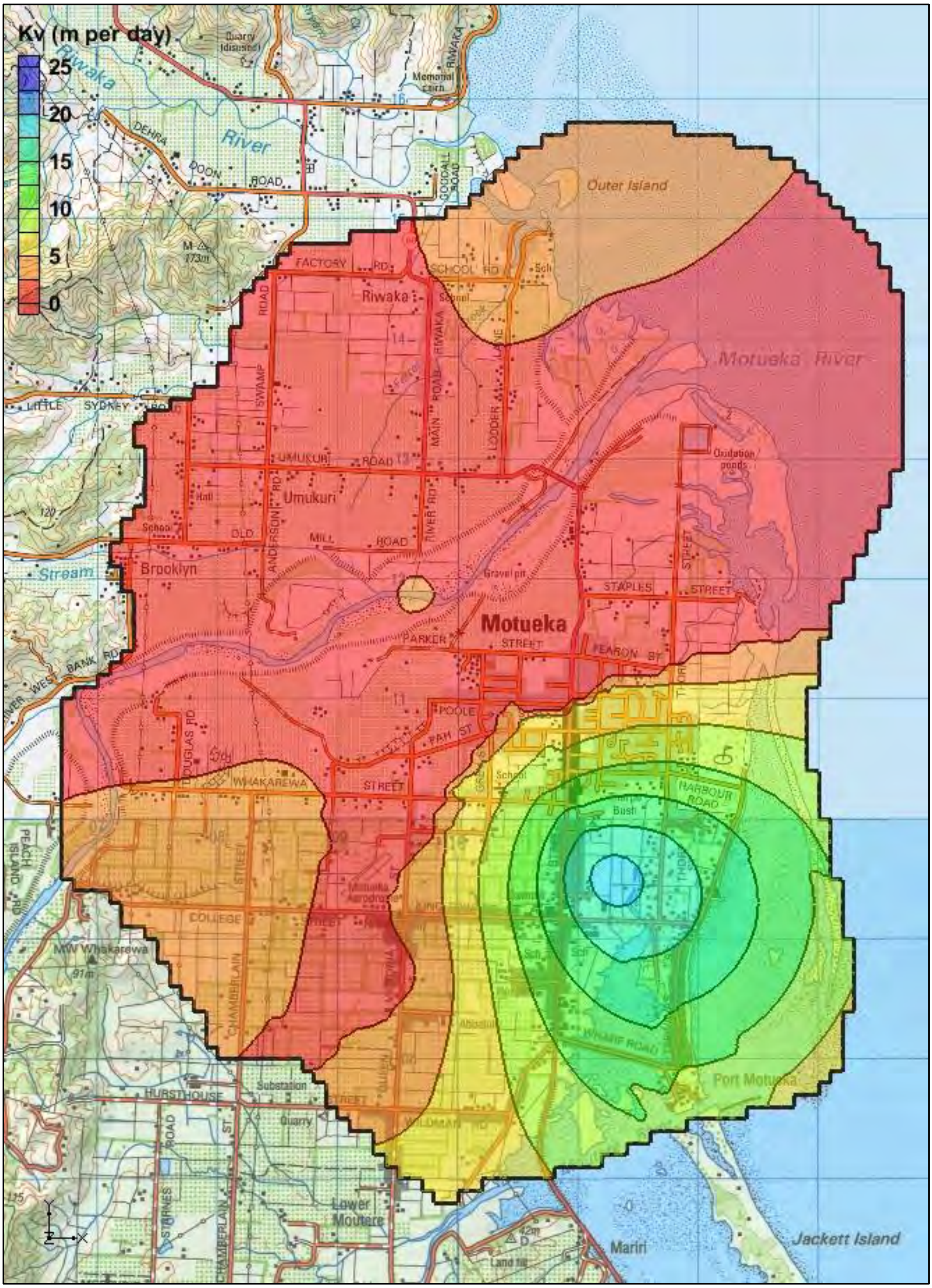


Figure 4-8: Calibrated vertical hydraulic conductivity for the aquitard

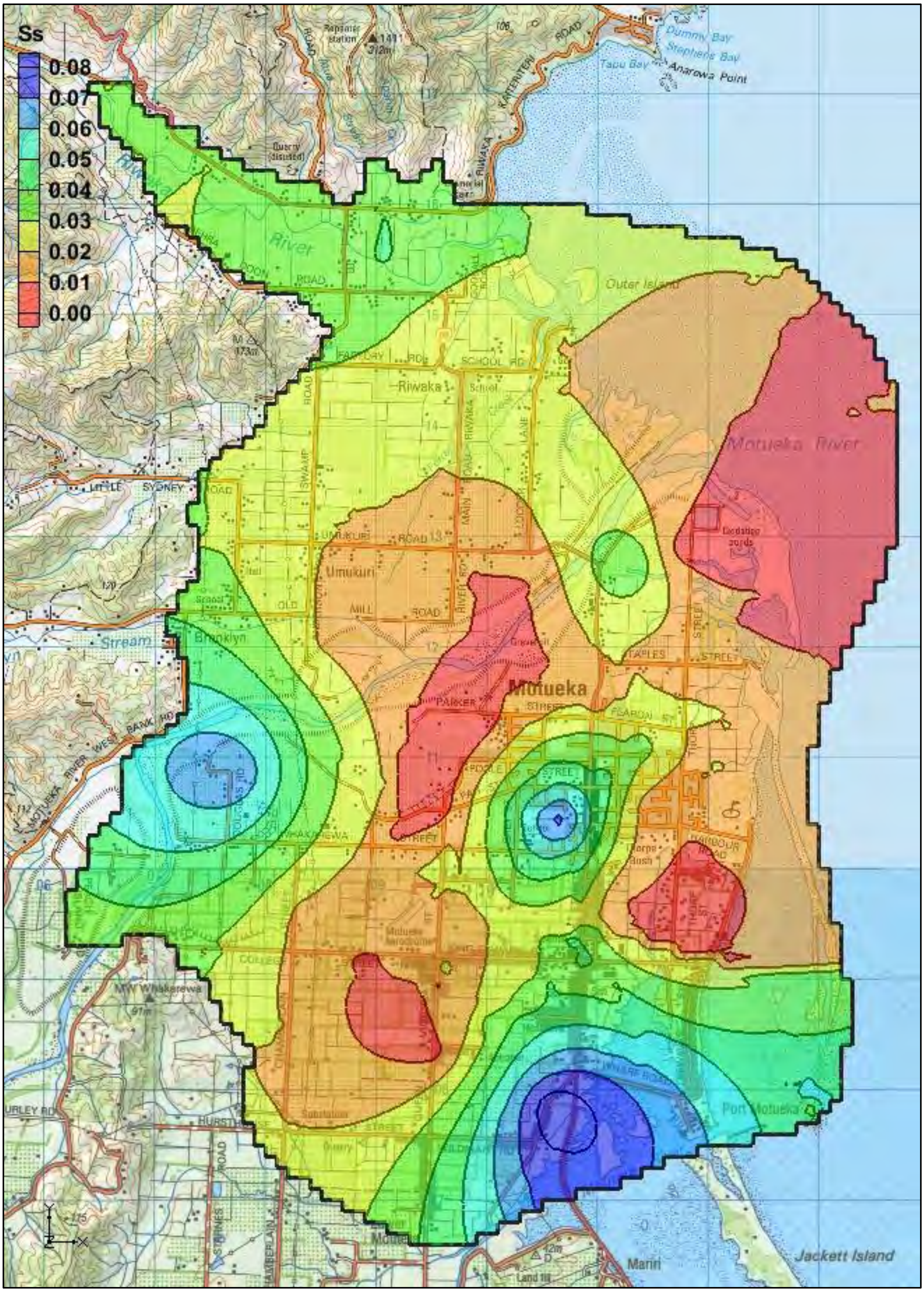


Figure 4-9: Calibrated specific storage for the upper aquifer

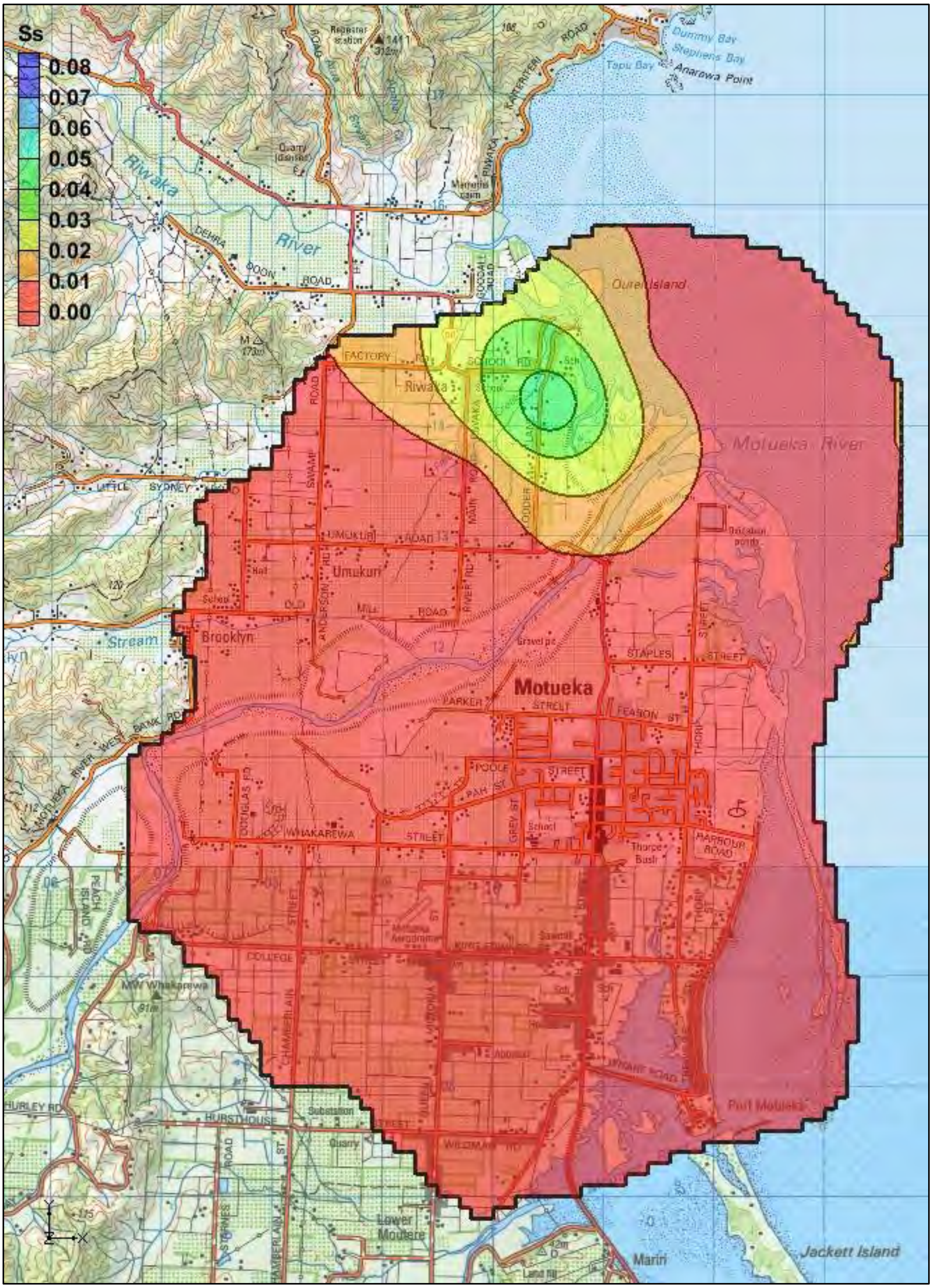


Figure 4-10: Calibrated specific storage for the aquitard

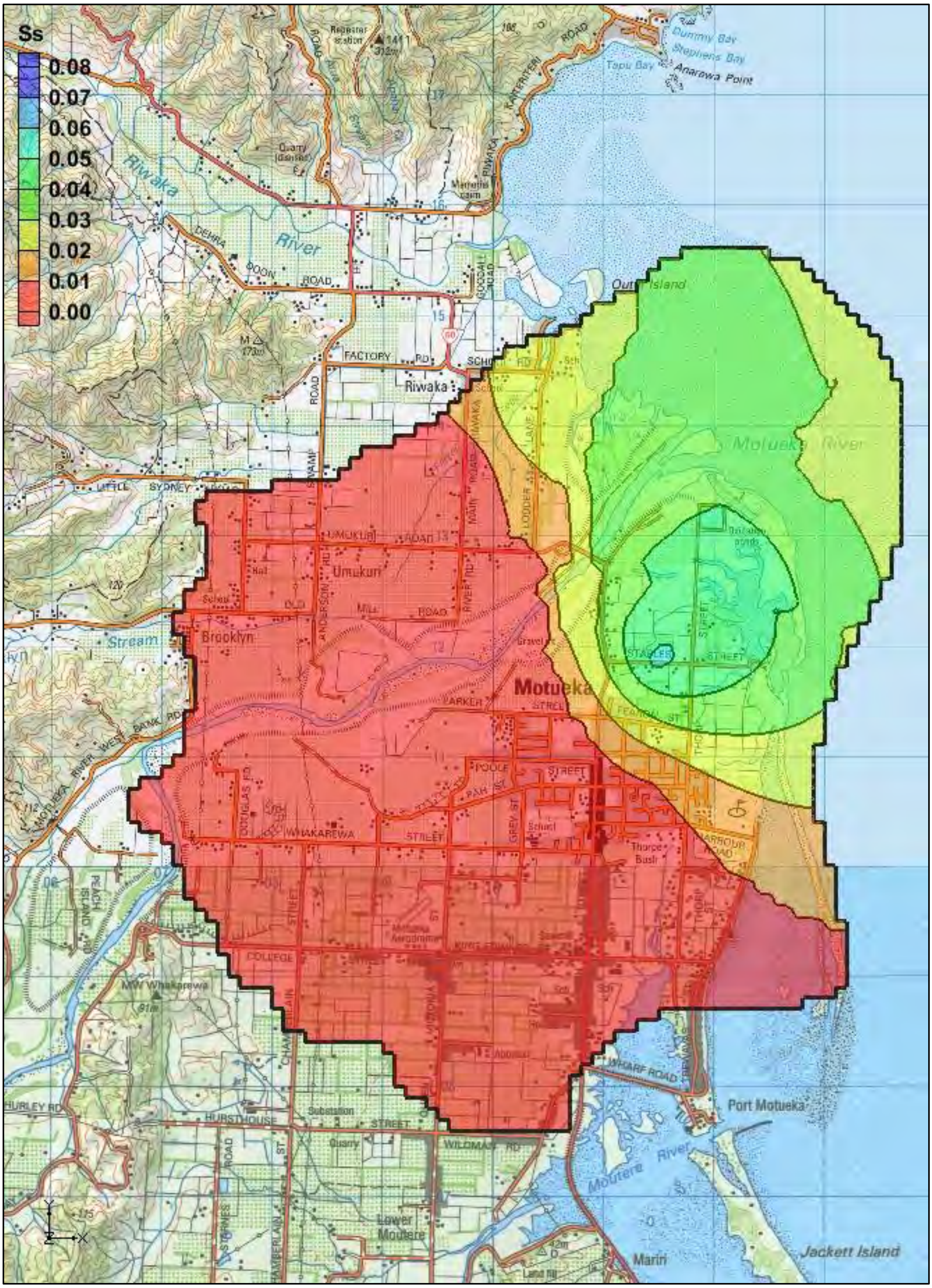


Figure 4-11: Calibrated specific storage for the lower aquifer

4.1.5 Sensitivity Analysis

A sensitivity analysis of a model determines which parameters are most important for model calibration and therefore for determining aquifer behaviour. This in turn provides focus for additional field investigations and monitoring. The sensitivity analyses have been generated by PEST.

PEST uses the following objective function (Φ) to consider the sensitivity of various model parameters:

$$\Phi = \sum_{i=1}^{n} \left[w \left(H_i - h_i \right) \right]^2 \tag{4}$$

Where: H_i = measured value (e.g. groundwater levels)

h_i = calculated value

w = observation weight

n = the total number of observations

The objective function is a measure of how well the calculated values compare to measured. In brief, PEST determines how the objective function varies relative to changes in model parameters. If the objective function changes significantly with small changes in a particular parameter, then model predictions are considered to be sensitive to that parameter. Similarly, if the objective function does not change significantly with large changes in a particular parameter, then model predictions are considered to be relatively insensitive to that parameter.

Figure 4-12 provides a summary of the sensitivities of the zoned parameters listed in Table 4-3. Sensitivity maps for all pilot points are provided in Appendix C.

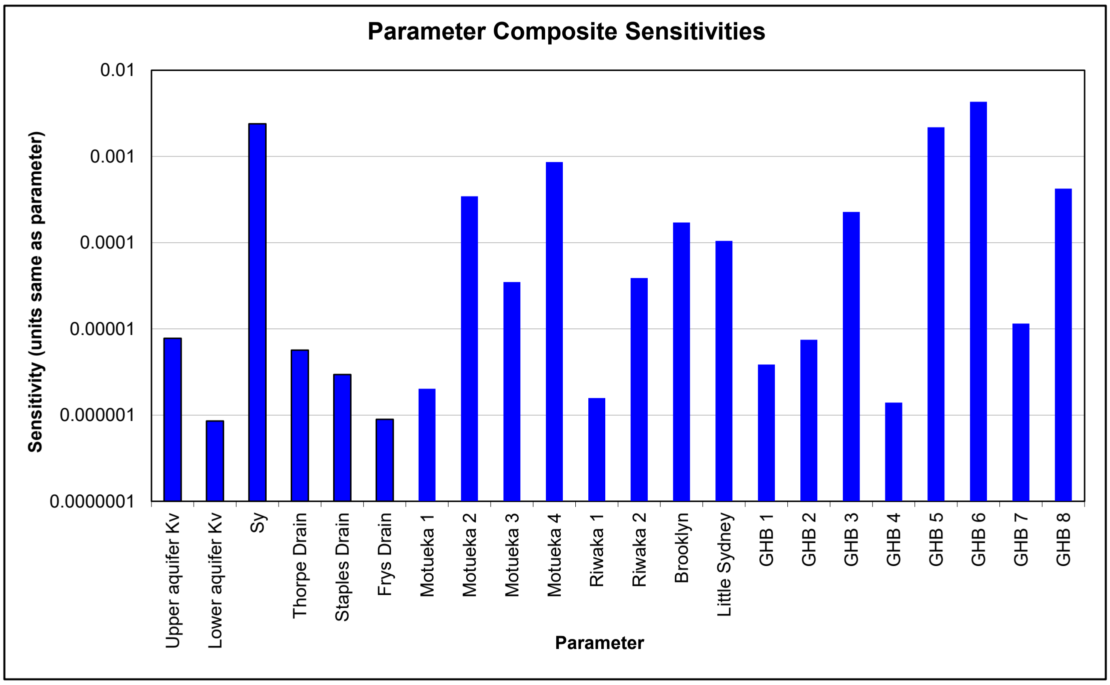


Figure 4-12: Zoned parameter sensitivities for the calibrated model

Considering the zoned parameters, model calibration is most sensitive to Sy and GHB 5 and 6. These GHB zones are both located to the south of the model and work as a key relief mechanism for groundwater discharging in that area, which is dominated by recharge from the Motueka River. Hence, model calibration is also relatively sensitive to Motueka River reach 2.

Overall model calibration is relatively insensitive to the bed conductances of Thorpe, Staples and Frys drains. This is because the drains flow residuals contribute only a small proportion to the overall model objective function. However, at a local scale, calibration of the drain flows is sensitive to the bed conductance terms in individual drains (not shown).

Considering the pilot points presented in Appendix C, model calibration is more sensitive to pilot points representing horizontal hydraulic conductivity and specific storage that are located inland compared to those that are located closer to the coast. This is because the inland values dominate the passage of water from the rivers out onto the plains.

Overall, model calibration is also relatively sensitive to the vertical hydraulic conductivity of the aquitard. This is because these values control the leakage from aquifer 1 to aquifer 2. In addition, model calibration is highly sensitive to specific storages of all layers. These parameters determine the transient response of the aquifer system to time-varying stresses (recharge and pumping).

In the calibration process, PEST evaluates all the possible combinations of parameters in order to construct the smallest objective function. Therefore, the final parameters produced by PEST represent the most accurate parameter, irrespective of their sensitivity to the model objective function.

4.1.6 Parameter Correlations

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 greater the likelihood that the model is uniquely defined. 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 205 parameters considered for the Motueka-Riwaka Plains model. This results in a correlation matrix of 42,025 values, which is too large to reproduce herein. However, 34 of these correlations are considered high (they have correlation coefficients of 0.5 or greater, either directly or inversely correlated) and most would be consider only slightly high. This suggests there is only a very small degree of non-uniqueness present. This is confirmed by the manual trial-and-error calibration process where only a narrow set of parameters would result in the simultaneous reproduction of all measured values.

4.1.7 Parameter Confidence Intervals

Figure 4-13 presents 95% confidence intervals for the zoned parameters as determined by PEST. The wider the range between upper and lower confidence limits, the less certain the parameter value is.

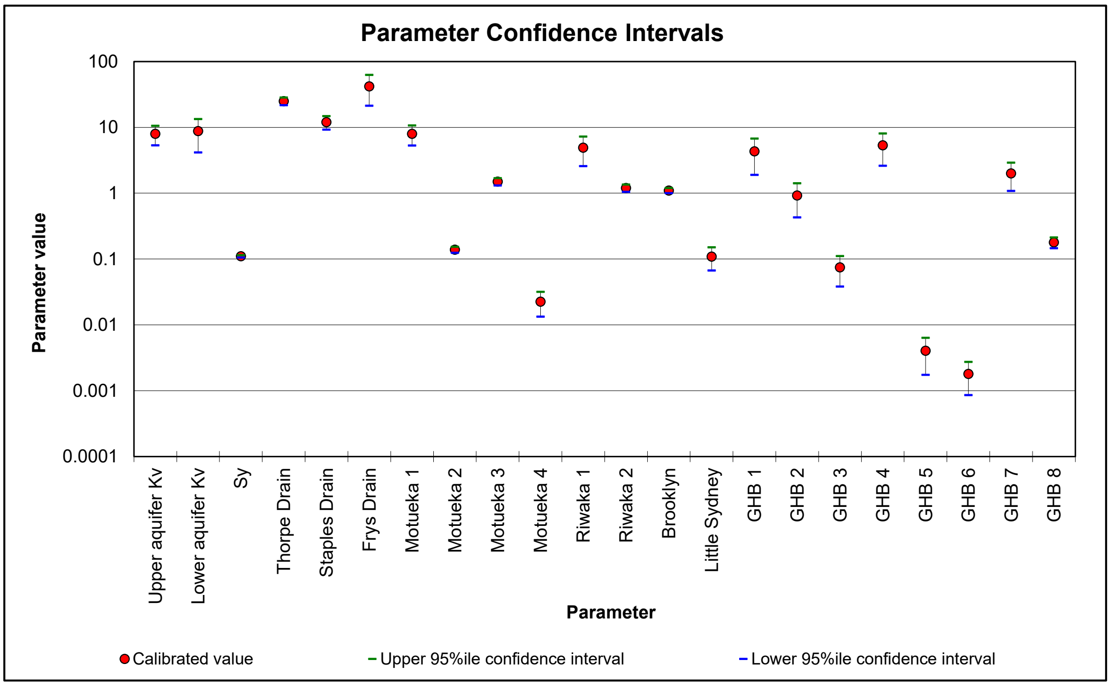


Figure 4-13: Parameter confidence intervals

All parameters have a relatively narrow range of acceptable values, which implies that they have been well defined (i.e. suitable parameter values have been chosen to give the best possible model prediction within the 95% confidence intervals). Most pilot points also have similar narrow ranges of confidence intervals (not shown herein).

This is consistent with the low sensitivities and weak correlations reported for most parameters. It is also consistent with the manual trial-and-error calibration process where it was found that a small change to a parameter value resulted in a relatively large change to model predictions.

4.2 Model Verification

Data used for model verification may be measured at a different simulation time from the period used for calibration (verification in time), at a different location in the model domain (verification in space), or a combination of both. Model verification in time has been conducted for the period 1 June 1990 to 31 December 2000. Verification in space adds in the Smith monitoring bore, this being the only bore that does not have groundwater level measurements after 31 December 2000.

Plots of simulated versus measured groundwater levels and residuals for the verification period are presented in Figure 4-14, Figure 4-15 and Figure 4-16. Model statistics for the verification period are listed in Table 4-4. These statistics are similar to the calibration period statistics (Table 4-2) and like the calibration period, they are less than accepted industry standards (Section 4.1.1). Therefore, it is reasonable to conclude that the model has been sufficiently calibrated and verified, and that it is suitable to be used as a tool to manage the Motueka-Riwaka Plains aquifer system.

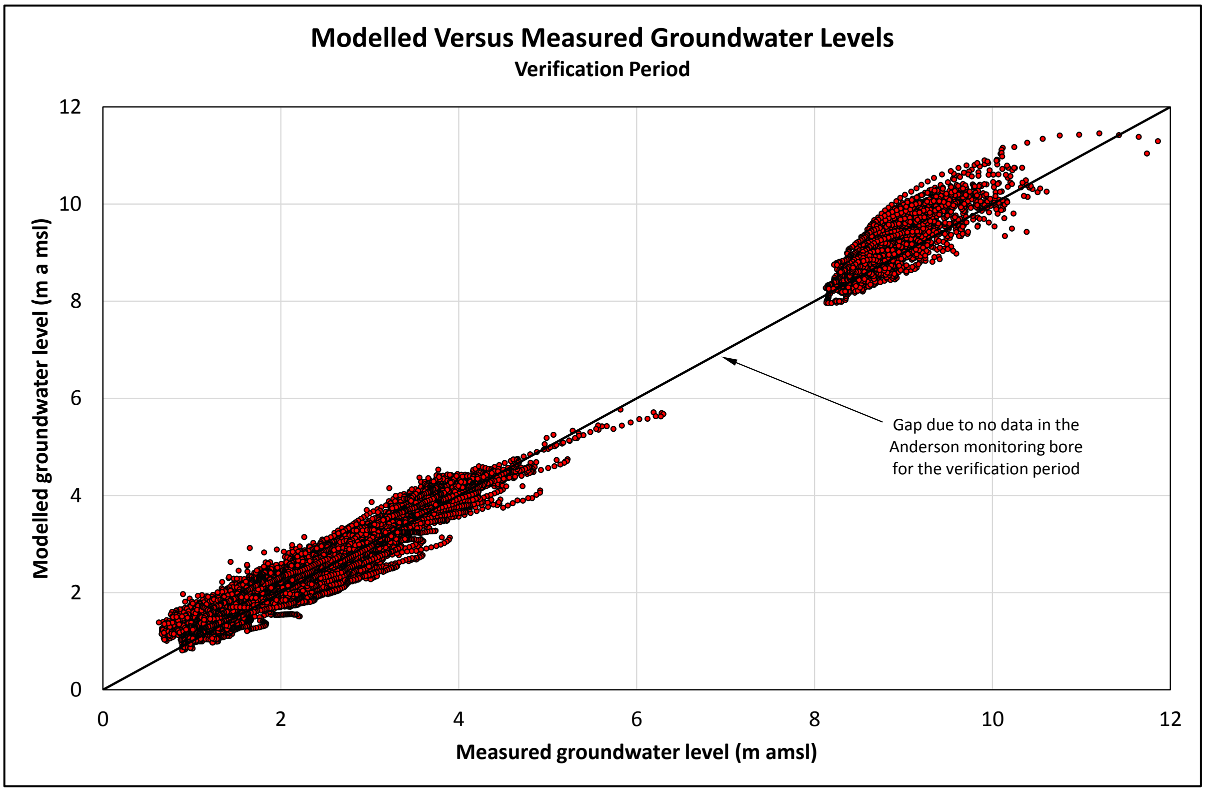


Figure 4-14: Modelled versus measured groundwater levels for the verification period

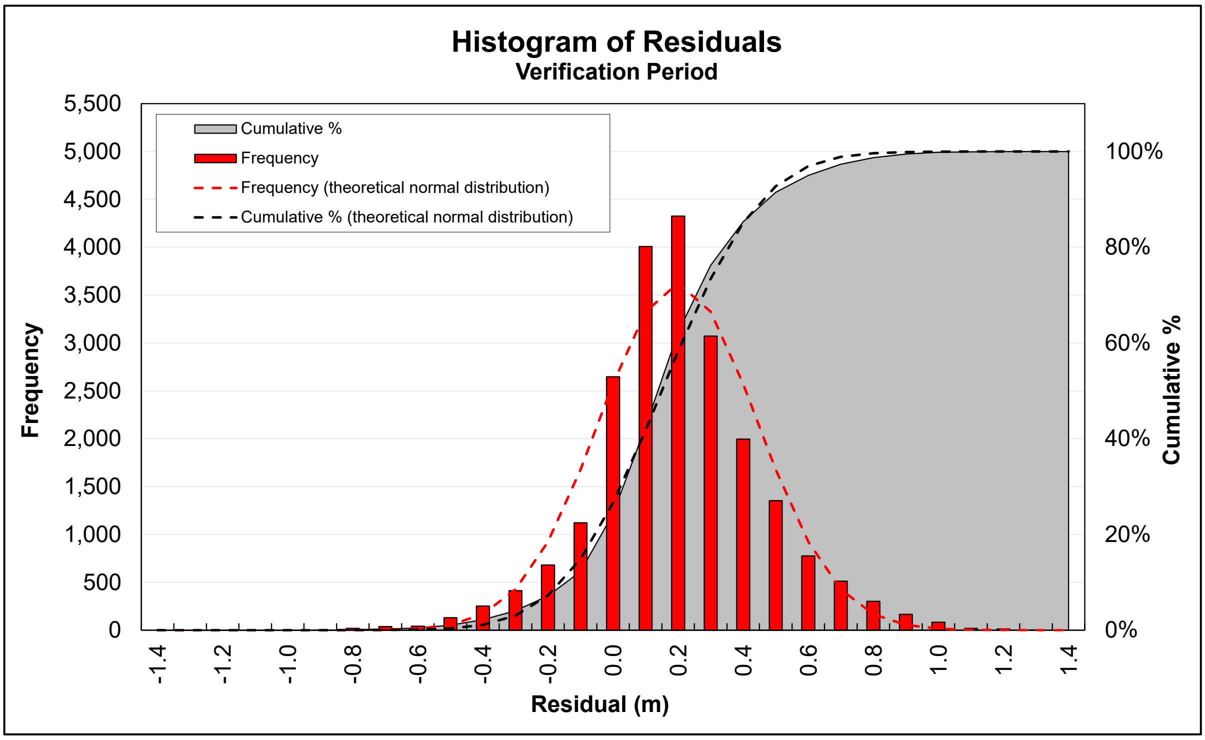


Figure 4-15: Histogram of residuals for the verification period

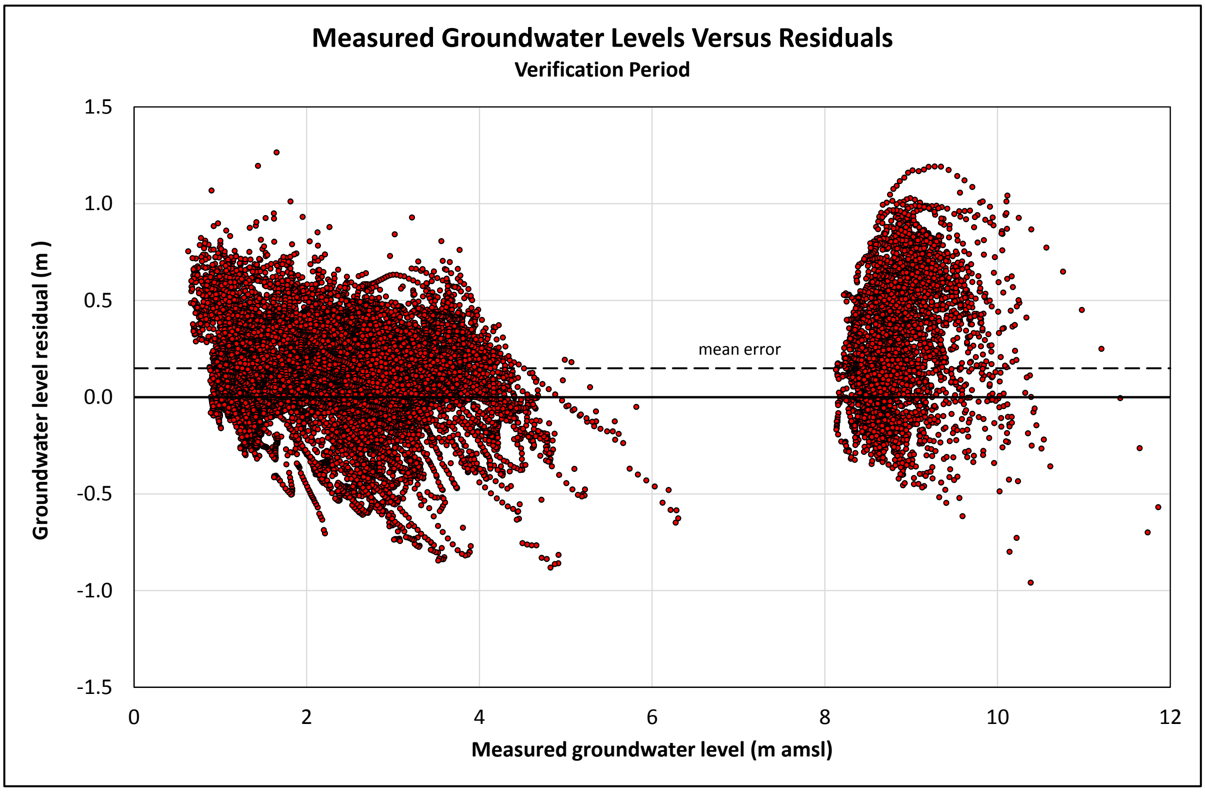


Figure 4-16: Measured groundwater levels verses residuals for the verification period

Table 4-4: Groundwater level objective function values and other statistics for the verification period

Objective function or statistic	Value
Maximum absolute residual	1.3 m
Minimum absolute residual	0.0 m
Mean error (ME)	0.15 m
Normalised ME	1.3%
Root mean square error (RMSE)	0.30 m
Normalised RMSE	2.6%
R^2 (square of the correlation coefficient)	0.992

4.2.1 Motueka River Losses

Measured losses from the Motueka River are listed in Table 3-6 and average 0.97 m^3/s. The average modelled losses from the Motueka River for the same dates is 0.72 m^3/s.

4.3 Entire Model Simulation Period

The normalised ME and RMSE for the entire model simulation period (1 June 1990 to 31 May 2012) are 1.3% and 2.3% respectively. This indicates suitable calibration according to acceptable industry standards (Section 4.1.1). Hydrographs of measured and simulated groundwater levels in the 18 observation wells, flows in the three drains and losses from the Motueka River are presented in Appendix D for the full simulation period.

The monitoring of the Old Wharf Road well ceased in March 2006 and it was replaced by another well at Tui Close located approximately 20 m from the Old Wharf Road well. Based on the groundwater level hydrographs in Appendix D, the calibrated model has replicated groundwater levels in the Tui Close well reasonably accurately, but is less accurate for the Old Wharf Road well.

Measured groundwater levels in the Old Wharf Road well are typically lower than in the Tui Close well, even though these two wells are located spatially very close. Although these measurements occur at different times, this behaviour is unusual compared to other hydrographs in the model area. This may indicate the presence of local heterogeneity at a scale that cannot be represented with the regional scale model. The differences may also be due to errors in the measuring point datum for the Old Wharf Road well. However, this well has been removed and so the measuring point elevation cannot be verified.

4.3.1 Groundwater Level Contours

The summer of 2001 was an extremely dry period due to low rainfall and associated river flows. TDC rated this summer as a 1-in-24 year drought. Groundwater levels reached record lows (or near record lows) in the longer-term monitoring wells around 24 March 2001. This date has been used to represent a period of extreme low groundwater levels.

As a consequence of concerns relating to low ground water levels and associated saltwater intrusion risk, TDC established the Fernwood monitoring well in 2003 in an area that had historical occurrences of saltwater intrusion. Reliable groundwater level data is available from this bore since January 2004. The lowest recorded groundwater level in the Fernwood well was 0.52 m amsl on 24 January 2006 which was also during a period of low rainfall and river flows. This period has therefore been used to represent a time of historical low groundwater levels with a known risk of saltwater intrusion.

TDC manage the groundwater system based on how it responds during the extreme dry periods. Future management scenarios (discussed later) are based on these dry periods. Therefore, modelled contours of groundwater levels are presented in Figure 4-17 and Figure 4-18 for 24 March 2001 and 24 January 2006, respectively. Indicative flow directions are also shown on these figures.

Local-scale variations in contours are evident in some areas of the model, particularly in the north-west and south-west inland fringes of the model (Figure 4-17 and Figure 4-18). These variations are an artefact of the model predictions and methods of contouring, and they may not be a real representation of actual groundwater level variations at these locations. There is insufficient resolution of groundwater level observations in these areas to validate this phenomenon.

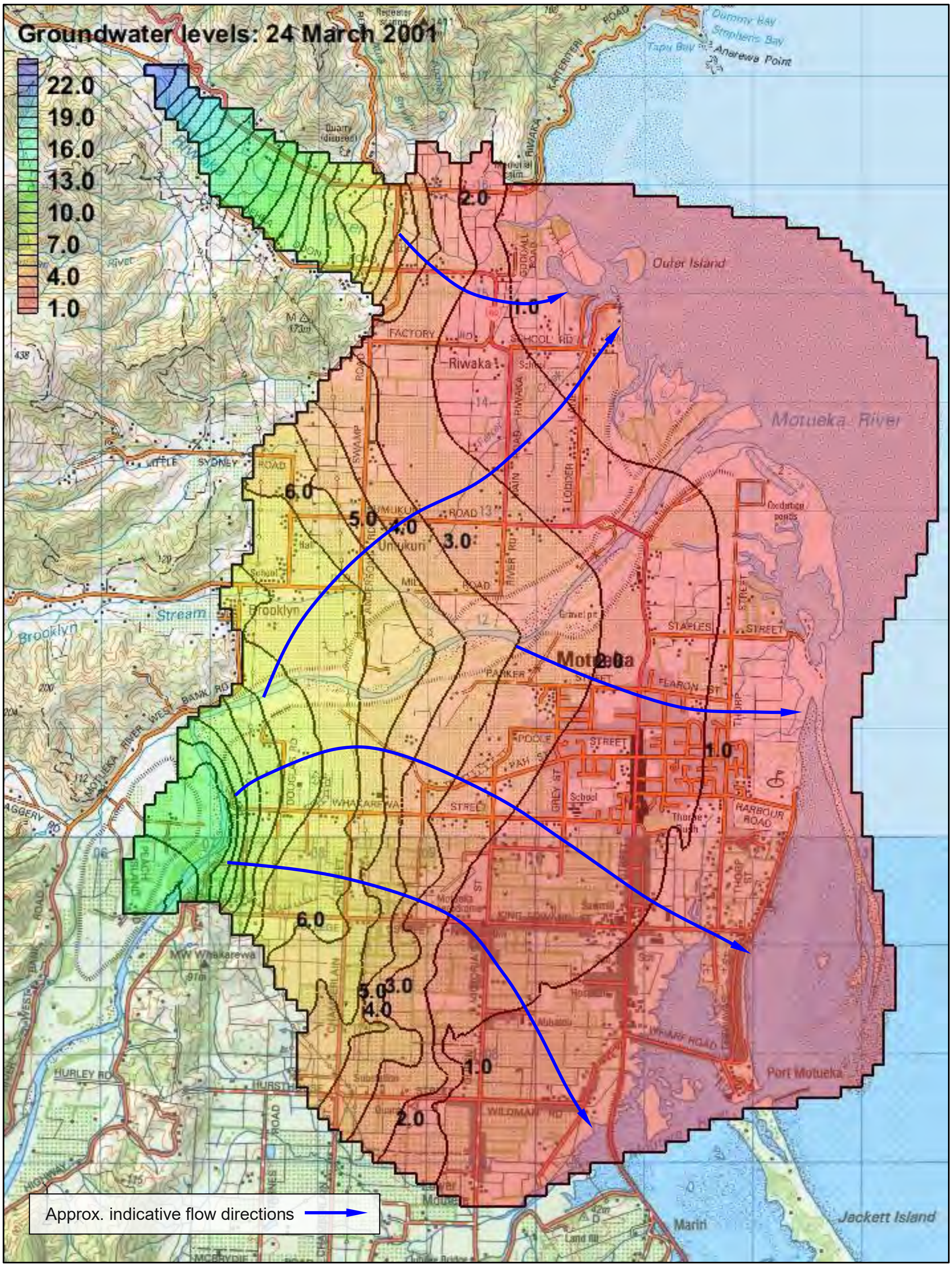


Figure 4-17: Modelled groundwater level contours and indicative flow directions for 24 March 2001

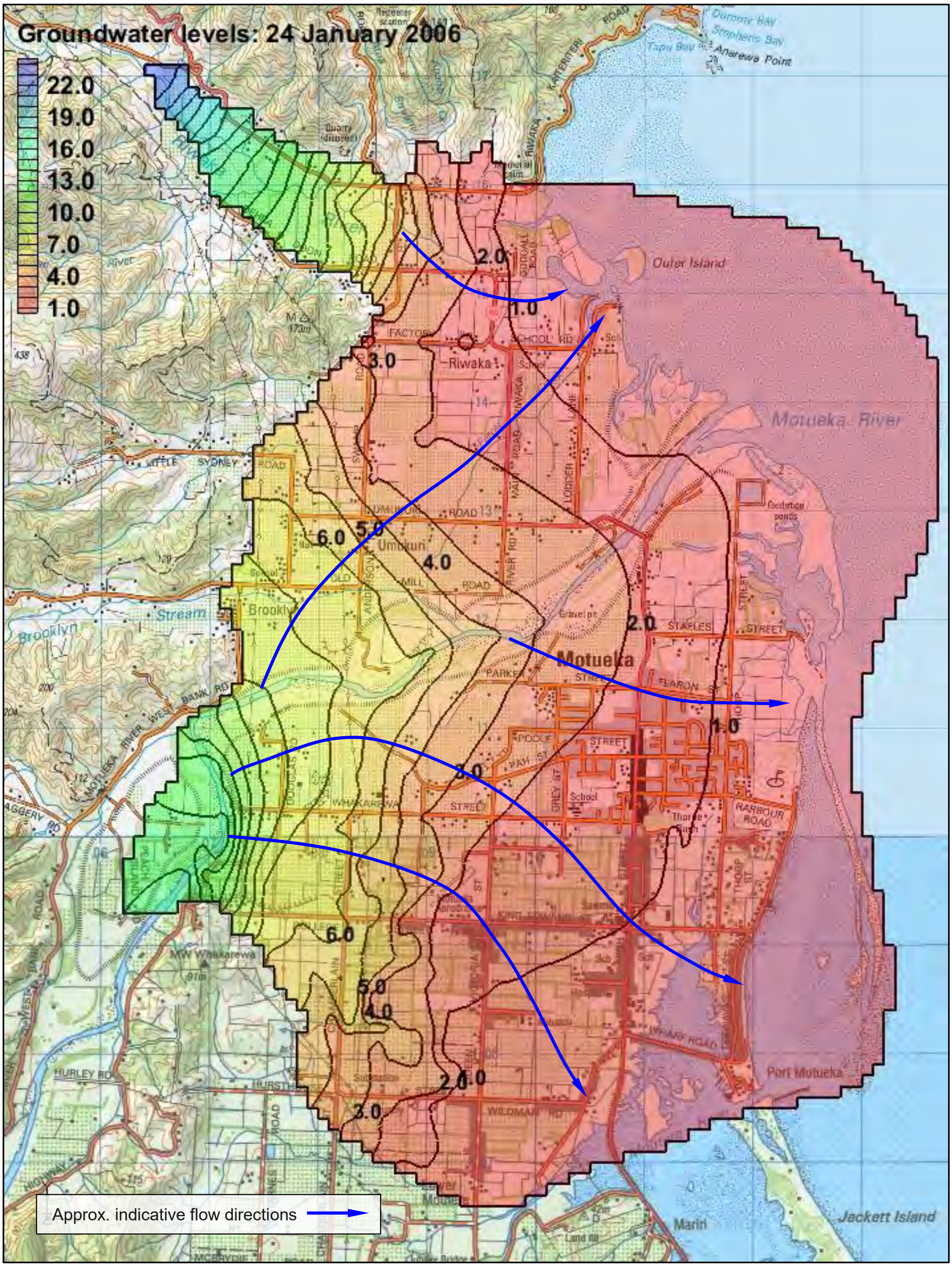


Figure 4-18: Modelled groundwater level contours and indicative flow directions for 24 January 2006

4.3.2 Model Mass Balance

The overall groundwater flow budget for the calibrated model is summarised in Table 4-5. This presents an average budget for the full simulation period. The overall mass balance error is very small, indicating that MODFLOW has accounted for flows without noticeable numerical error.

Table 4-5: Model groundwater flow budget

Overall groundwater flow budget (l/s)	
Inflows	
Land surface recharge	823
Rivers (SFR2)	3,351
Coastal boundary (GHB)	0
Storage	1,164
Total IN	5,338
Outflows	
Wells	225
Drains	462
Rivers (SFR2)	2,294
Coastal boundary (GHB)	1,192
Storage	1,167
Total OUT	5,340
Summary	
In-Out	-2
% discrepancy	-0.037

The overall model error presented in Table 4-5 is the average for the full model simulation. However, errors are different for each time step, varying throughout the simulation. Figure 4-19 plots model error for each time step, which vary between -0.47% and +0.49% over the full simulation period.

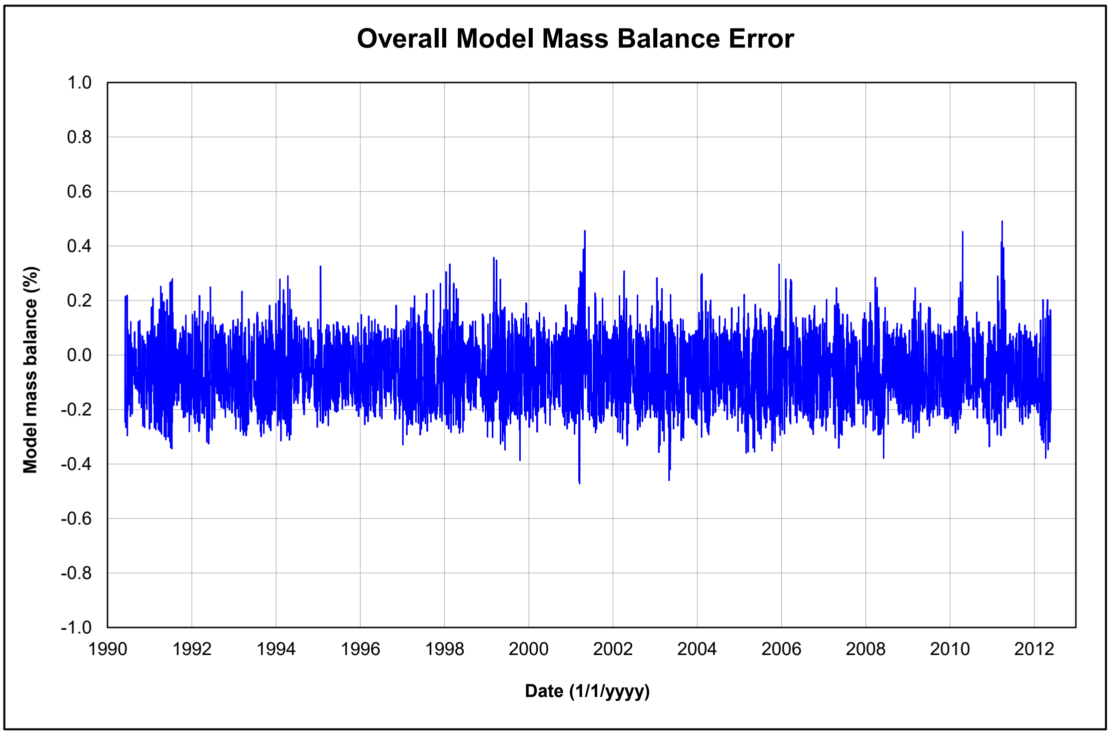


Figure 4-19: Time series of overall model mass balance error

4.3.3 Total Modelled Groundwater Abstraction

Figure 4-20 summarises total modelled groundwater abstraction per hydrological year (1 June through to 31 May). While there are seasonal variations due to wetter and drier years, there is a general increase in groundwater abstraction over the simulation period.

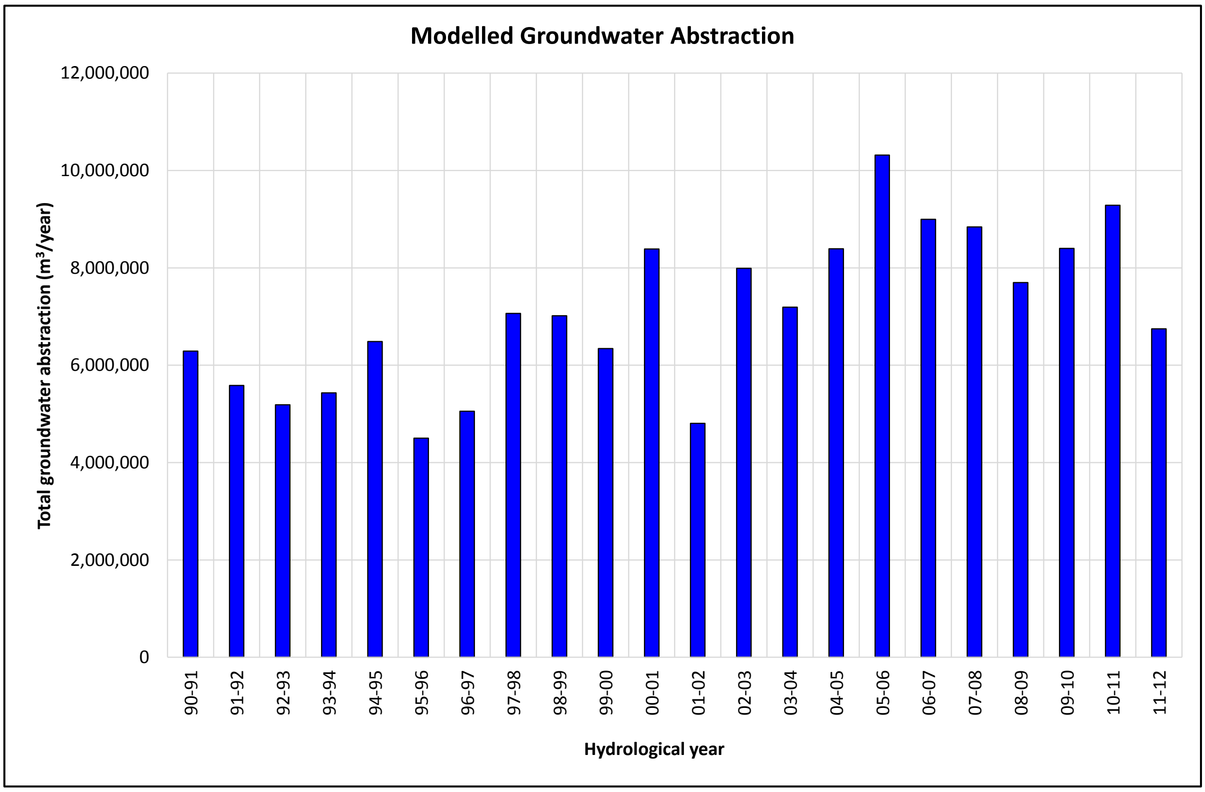


Figure 4-20: Total modelled groundwater abstraction per hydrological year

4.3.4 Management Zone Water Exchanges

TDC has divided the Motueka-Riwaka Plains into seven zones for water management purposes (Figure 2-5). The MODFLOW zone budget tool facilitates the analysis of water exchange into and out of these zones and can be used to assess the water management options for different zones. The assignment of the management zones to the model is shown in Figure 4-21.

Water exchanges for the calibrated model for each management zone, averaged over the entire simulation period (1 June 1990-31 May 2012), are presented in Figure 4-22. The values for ‘abstraction’ and ‘drainage’ represent actual rates as calculated by Aqualinc’s soil-water balance model (see sections 3.10.3 and 3.10.5). The abstraction rates are neither the consented rates for each management zone, nor are they allocation limits. Examples of water exchange summaries have also been prepared for the first 90-days (1 January through to 31 March) of both 2001 and 2006 (i.e. the extreme dry years). These summaries are presented in Figure 4-23 and Figure 4-24 respectively. Changes in storage are not presented in these figures. Therefore, the summaries do not present the complete flow budget.

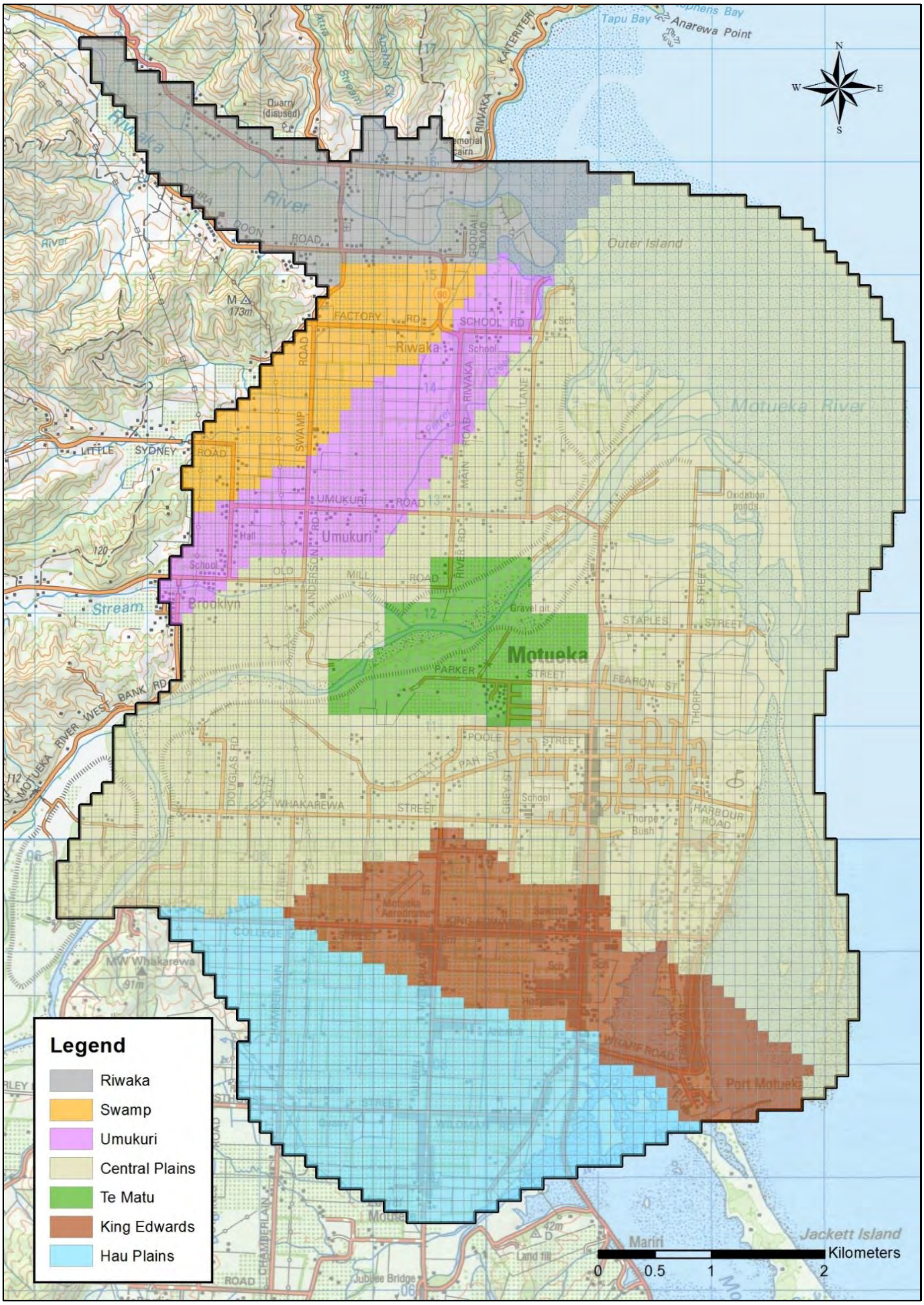
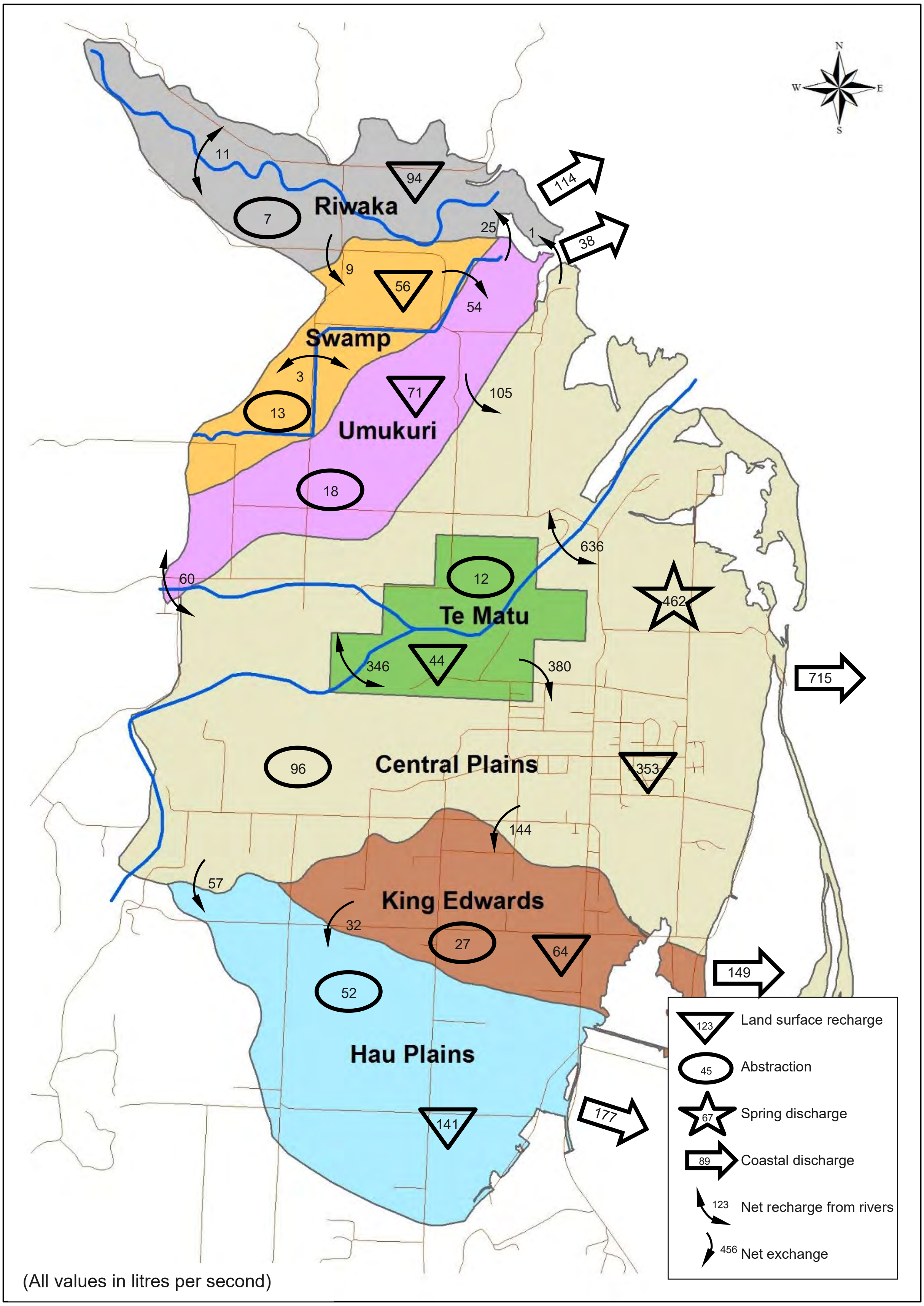
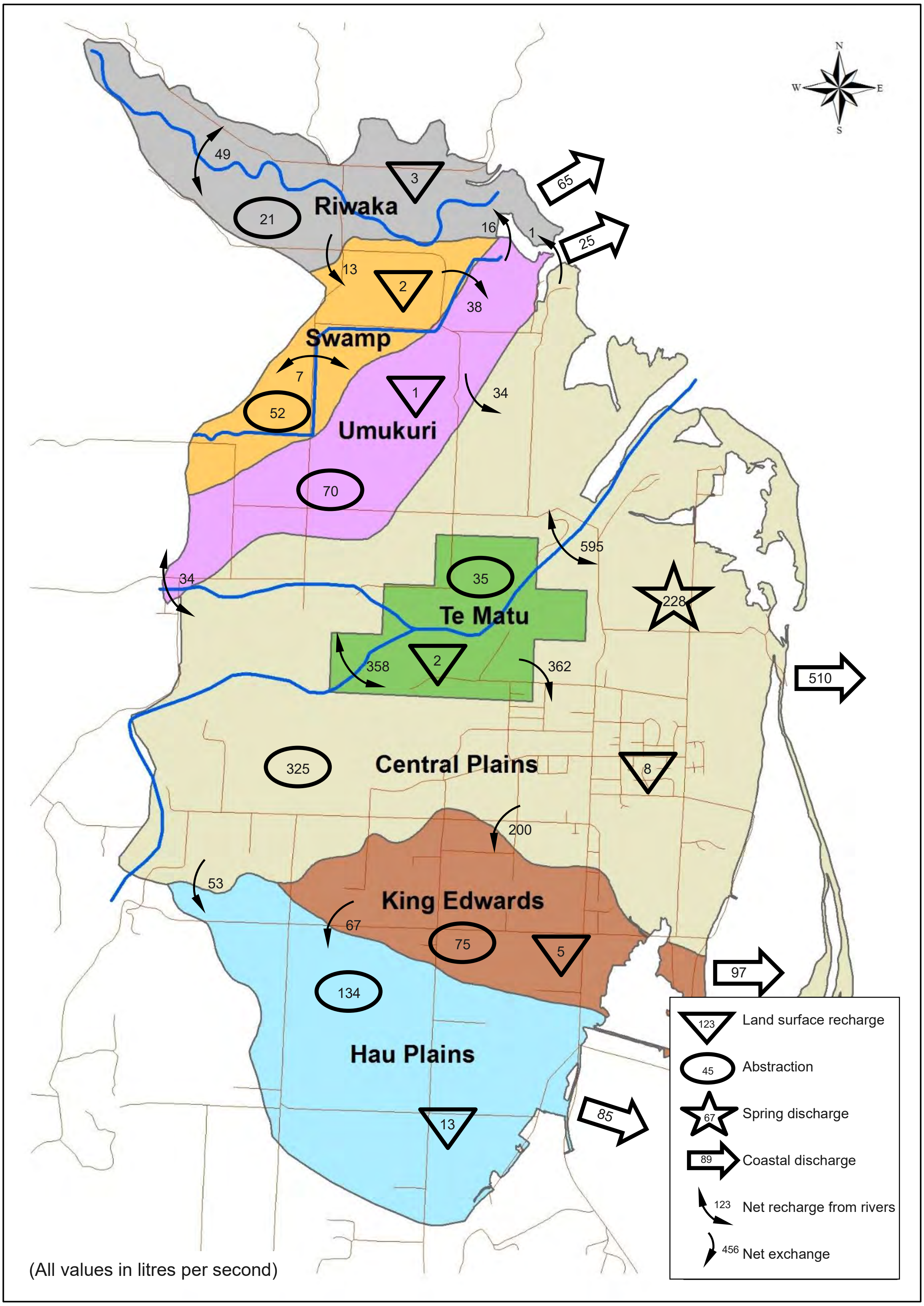


Figure 4-21: Model budget zones



(All values in litres per second)

Figure 4-22: Average groundwater flows for the entire simulation period



(All values in litres per second)

Figure 4-23: Average groundwater flows for first 90-days of 2001

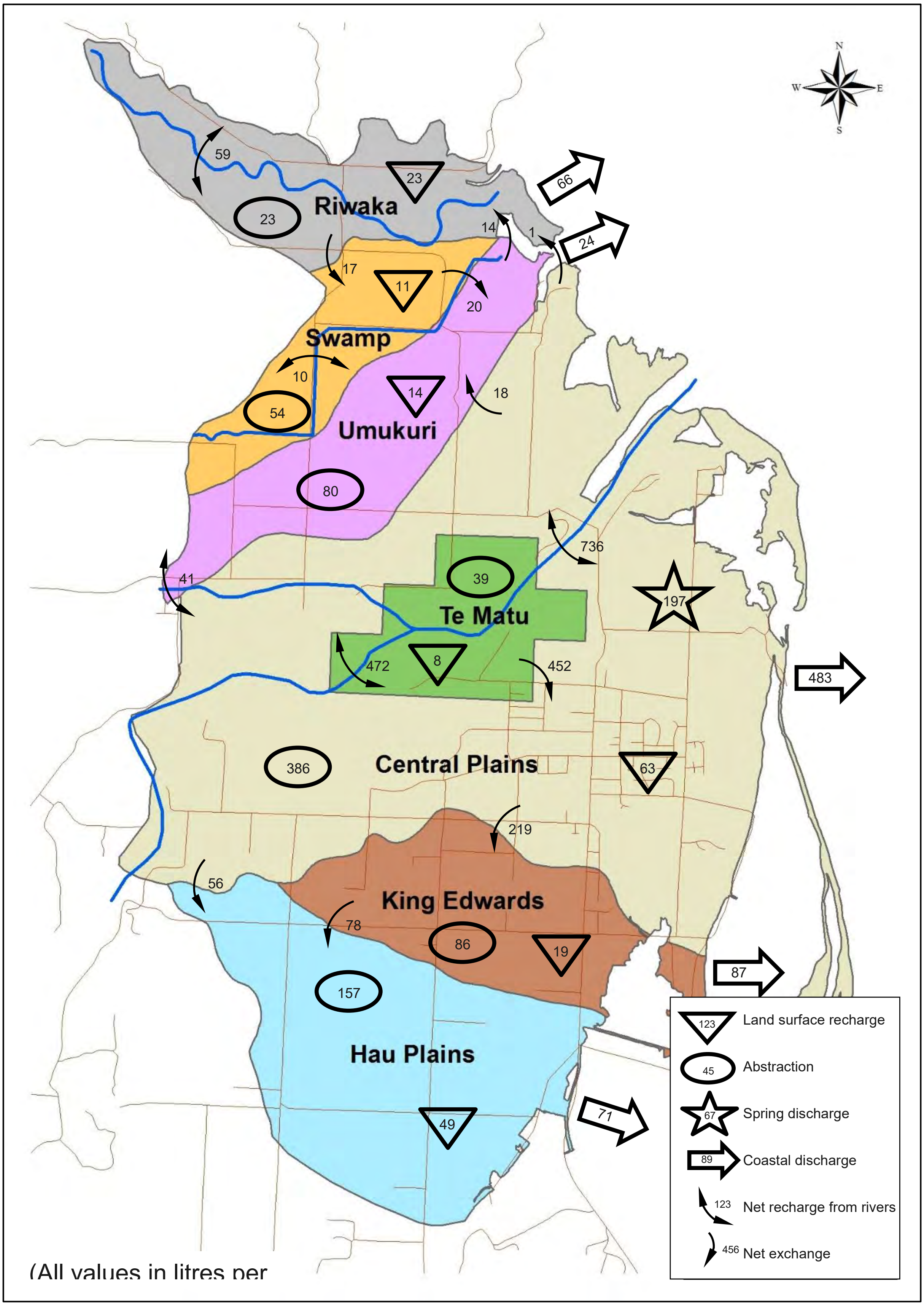


Figure 4-24: Average groundwater flows for first 90-days of 2006

5 TIME SERIES ANALYSES USING EIGEN MODELLING

Prior to development of the original Robb (1999) model, an independent time-series analysis was undertaken to provide a check on the relative contributions of land surface recharge versus river recharge. In particular, the work considered the effect on groundwater level dynamics from the two sources using an eigen model approach.

Dr Vince Bidwell (formerly of Lincoln Environmental, now retired) completed the time series analyses documented in Appendix V of Robb (1999), and he is the developer of the eigen model method that was applied.

Since this work was completed, additional monitoring bores have been installed and further data collected in both the new bores and the existing bores. TDC therefore requested that a similar analysis of the full data sets be undertaken to determine if the aquifer response at the new well locations, and the extended datasets of the existing wells, remained consistent with the earlier findings of Robb (1999). This has been completed and is documented in Appendix E. Dr Bidwell was engaged as an adviser and peer reviewer of this new eigen modelling work. A brief summary of Appendix E is provided below.

5.1 Brief Summary of Eigen Modelling Work

The eigen method analysis completed assumed that river recharge provides a steady recharge component. Therefore, the dynamic response in groundwater levels was assumed to be solely due to land surface recharge. With these assumptions, very good matches to measured data were obtained. This is consistent with the effects of river recharge attenuating rapidly with distance from the river.

Because of the assumption of a steady river component, wells located closer to rivers had poorer calibration than those located further away. In addition, bores located very close to the coast are affected by tidal variations, which are not represented in the eigen models. Consequently, the quality of the calibration in these bores is reduced.

Overall, the bulk transmissivity, bulk storativity and river recharge components derived by the eigen modelling work are consistent with equivalent values from the calibrated MODFLOW groundwater model. Vadose zone residence times are very short, which suggests that the entire system responds rapidly, with little attenuation in the vadose zone.

The overall conclusion from the eigen modelling work is that river recharge is the major water source to the plains. In addition, given that groundwater levels can be adequately calibrated by assuming a steady river recharge component, then land surface recharge is the dominant source of variation in groundwater levels. These conclusions were also reached by Robb (1999).

6 TREND ANALYSES

Tasman District Council requested a brief trend analysis be undertaken on groundwater levels and climate data for the Motueka-Riwaka plains area. This was completed by Dr Tim Kerr (Water Scientist, Aqualinc), the report for which is provided in Appendix F. The following summarises this work.

6.1 Brief Summary of Trend Analysis Work

Groundwater level data (supplied by TDC) for 19 monitoring bores was considered. Data from one site was discarded as the length of record was too short to detect a trend. Of the remaining sites, the following attributes were assessed for trends:

- Monthly average groundwater levels;
- Annual minimums;
- Annual maximums;
- Change in groundwater levels over the non-irrigation season, and;
- Change in levels groundwater over the irrigation season.

Of the sites assessed, six showed a statistically significant trend. Four of these sites have decreasing trends in the range 9-20 mm/year, typically located in the Central Plains area. The remaining two sites are located at the coast and show a trend of increasing groundwater levels in the range 16-17 mm/year. Figure 6-1 presents the interpolated trends over the model domain.

The reducing trend for the Central Plains area is consistent with observed degradation of the Motueka River bed. Furthermore, the annual maximum groundwater levels of three central sites were found to have a lowering trend, but not as much as the annual minimums. This discrepancy has been attributed to increased groundwater pumping over time, likely due to increased community supply takes, increased irrigated areas, increased crop water demand over the summer months (as a result of increased evapotranspiration), and changes in crops types grown. The increase in groundwater pumping over time is briefly discussed in Section 4.3.3.

The reasons for the increasing groundwater levels at the coast are not so clear. The trend is greater than historical sea level rise (~1.6 mm/year), and may be attributed to a reduction in groundwater abstraction in the area, and/or it may be an artefact of the shorter length of measured data.

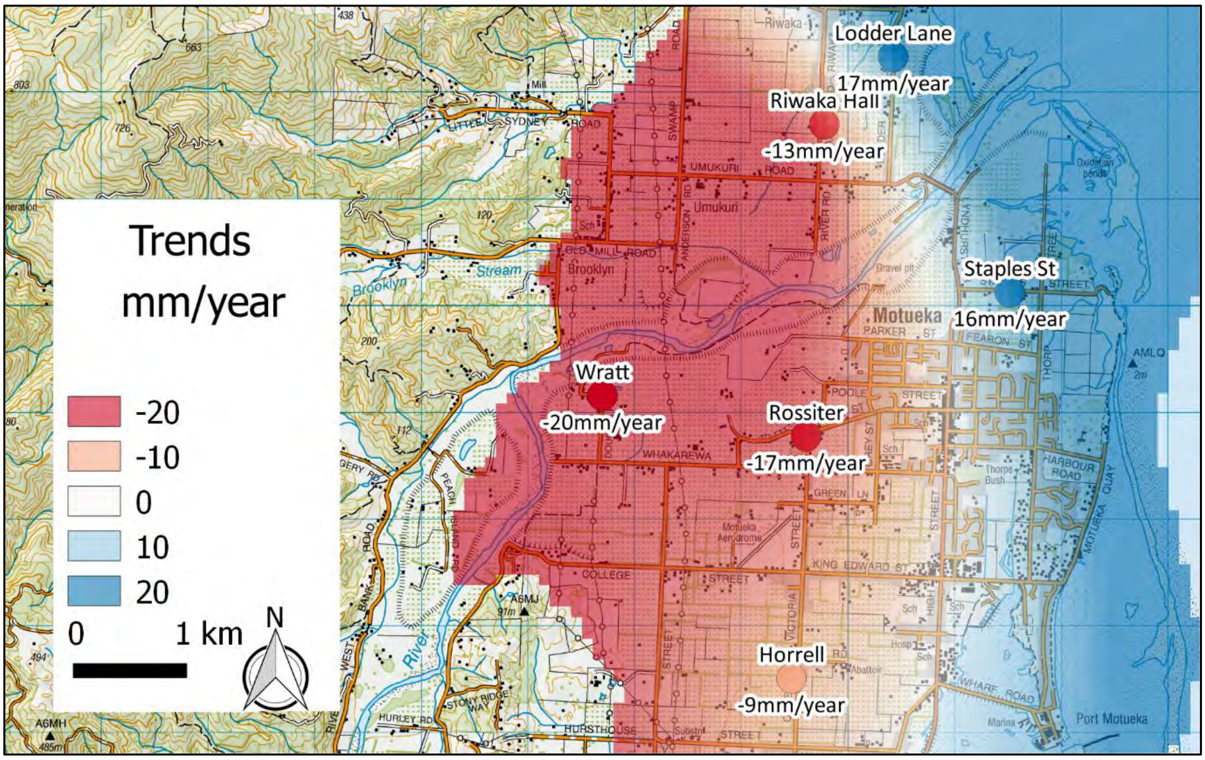


Figure 6-1: Estimated long-term trend in groundwater levels.

The trend analyses provide a robust means of determining whether trends are detectable in the measured data. Where trends are not found to be statistically significant, it does not mean that no trend exists, merely that the variability of data prevents a trend to be detected. As the observation record grows, the ability to determine trends becomes increasingly robust. The quality of measurements and commitment to ongoing observations places Tasman District Council in a strong position for continued quality assessment of groundwater trends.

7 MODEL SCENARIOS

The updated and calibrated Motueka-Riwaka Plains groundwater model has been used to assess different management scenarios. These scenarios consider the effects on the groundwater system from different abstraction and water use management options over the plains, from potential degradation of the Motueka River bed, and from potential effects of sea level rise.

7.1 Introduction

An initial model scenario was run that considers no groundwater pumping. This scenario represents a quasi-natural state of the groundwater system, unaffected by groundwater abstraction and subsequent use. This scenario does not represent the true 'natural' state of the system for two reasons. Firstly, it assumes existing land cover remains (e.g. pasture, crops, residential, etc.). Secondly, it assumes the existing altered state of waterways remains (stop banks, channel alignments, drains, etc.). Instead, it represents the dynamic state of the groundwater system should all groundwater abstraction (and subsequent use) cease, both on the plains and in the Upper Motueka catchment.

A second model scenario was then run that considers the current state of groundwater development. This scenario was based on the calibrated model but assumes that the existing (status quo) level of groundwater development, land use, and corresponding land surface recharge, occurs for the entire model simulation period. This scenario represents a baseline of existing use alongside which future changes can be compared.

Various other scenarios have been run to assess the effects of additional abstraction from TDC's Parker Street well field and the effectiveness of different management regimes to reduce the effects on the groundwater system.

Managing abstractions without causing saltwater intrusion is the principal concern for TDC. TDC's monitoring data indicates that saltwater intrusion has occurred only in specific areas of the Hau Plains, once in the early 1990's and more recently during the 2014/15 summer. The occurrence of saltwater intrusion during the 1990s was principally due to localised intensive pumping combined with the failure of stormwater non-return values during high tides (allowing sea water to naturally flow inland along drains). During the 2014/15 summer, localised saltwater intrusion was recorded in the Fernwood monitoring bore. This was due to a combination of naturally low groundwater levels, unusually high tides, open drains transmitting saltwater inland, and local commercial abstraction beyond consented volumes (Joseph Thomas, *pers. comm.*).

Wide-spread saltwater intrusion has not occurred and local mitigation has reversed and avoided recurrence of localised events. In addition, a few key irrigators in the coastal area have moved further inland and many of the long-term irrigators have joined the Lower Moutere irrigation scheme. Furthermore, the TRMP does not permit the installation of new bores in the coastal margin of the Hau Plains Zone (Joseph Thomas, *pers. comm.*).

To further reduce the risk of saltwater intrusion in the coastal margin of the Hau Plains Zone, TDC impose 35% water restrictions for droughts exceeding 1 in 10 year events. Earlier studies (Robb, 1999; Robb & Weir, 2002; Aqualinc, 2007c and Aqualinc, 2008) tested the effectiveness of this method and showed that these water restrictions decreased the risk of coastal saltwater intrusion. As discussed in Aqualinc (2008), the Hau Plains zone is the most sensitive area to saltwater intrusion, primarily due to the local hydrogeology (the water-bearing gravels thin towards the southern margins of the plains), distance from the main recharge source (the Motueka River) and overall water abstractions in the area.

In earlier studies, the primary trigger for considering saltwater intrusion in the Hau Plains had been groundwater levels in the Fernwood coastal monitoring bore. These earlier studies also tested the influence of domestic pumping in the Hau Plains. Aqualinc (2008) reported that removing the domestic pumping in the Hau Plains for droughts exceeding 1 in 10 year events had no noticeable effect on flows across the coastal boundary or groundwater levels at the coast. This is because domestic abstraction in this area is small compared to irrigation pumping. Given this, no restrictions to domestic pumping will be considered in the scenarios considered herein.

The calibrated model has been used to assess different management scenarios, grouped into the following two broad categories:

a. Scenarios without water restrictions; and

b. Scenarios with water restrictions in the Hau Plains and the Coastal Exclusion zone for drought years exceeding a 1 in 10 year event.

Within each of these two broad categories, the following management scenarios have been considered:

1. An additional 20,000 m^3/day abstraction from TDC's Parker Street well field, located adjacent to the Motueka River, to supply a future Urban Supply;

2. A further 5,000 m^3/day (25,000 m^3/day total) from the proposed well field; and

3. A further 5,000 m^3/day (30,000 m^3/day total) from the proposed well field.

In addition, a further four scenarios have been developed. One scenario considers the effects of Motueka River bed degradation. Another assesses the aquifer flow response from predicted sea level rise. The final two assess the effects of two extremes of projected climate change on rainfall, potential evapotranspiration and river flows.

Further description of these scenarios is presented in the following sections, and results are later compared.

7.2 Scenario Details

Various model scenarios have been constructed using the calibrated model. These are discussed in the following sections. All scenarios have been run for the full simulation period of 1 June 1990 through to 31 May 2012.

7.2.1 Scenario 1: No Abstraction

The *No Abstraction* scenario represents a quasi-natural state of the groundwater system, unaffected by groundwater abstraction and subsequent use. This scenario does not represent the true 'natural' state of the system for two reasons. Firstly, it assumes existing land cover remains (e.g. pasture, crops, residential, etc.). Secondly, it assumes the existing altered state of waterways remains (stop banks, channel alignments, drains, etc.). Instead, it represents the dynamic state of the groundwater system should all groundwater abstraction (and subsequent use) cease, both on the plains and in the Upper Motueka catchment.

The No Abstraction scenario has been founded on the calibrated model with the following modifications:

- All groundwater pumping has been switched off;
- Land use has been set to existing land use (2011/12) with corresponding dryland land surface recharge;
- Motueka River flows at Woodman's Bend have been naturalised. Measured flows have been naturalised by adding on to the measured flows an estimate of net irrigation water use in the upper catchment. The net irrigation use has been calculated using Aqualinc's soil-water balance model (see Sections 3.10.3 and 3.10.5) for an irrigated area based on existing allocated rates (currently 1,258 l/s, Joseph Thomas, TDC, pers. comm.) and an allocation depth of 30 mm per week. This equates to an existing irrigated area of 2,536 ha. Conservatively, pasture has been assumed with a rooting depth of 550 mm and a soil water holding capacity of 80 mm (which is an approximate area-weighted average). Rainfall and PET data have been taken from NIWA's virtual climate station closest to Woodstock. Net irrigation water use was determined by reducing the pumping rate by the difference between irrigated and dryland land surface recharge (this accounts for the additional land surface recharge return water derived under irrigated land). The resulting time series was smoothed using a 7-day running average to account for travel times and soil storage in the upper catchment.

7.2.2 Scenario 2: Baseline

The *Baseline* scenario represents the existing (status quo) level of groundwater development and is chosen as a baseline against which other scenarios have been compared. This scenario was based on the calibrated model but assumes that the existing (status quo) level of groundwater development, land use, and corresponding land surface recharge, occurs for the entire model simulation period.

In developing the Baseline scenario, the following modifications to the calibrated model have been made:

- Land use has been set to existing land use (2011/12) with corresponding irrigated areas and land surface recharge for the entire model simulation period;

- All industrial and community takes are assumed to cycle through the measured rates abstracted during the period 1 June 2009 through to 31 May 2010, every year, continuously. Based on records of use, peak takes during this period were at (or close to) a maximum for the last five years of record and were therefore expected to represent a realistic prediction of maximum future take allowing for seasonal variation. This assumption results in less water abstracted via these takes compared to how they were represented in Aqualinc (2008) and previous studies. In addition, the following modifications have been made to community and industrial takes:

    - The Naumai community supply well (WWD 3411) is no longer used and has therefore been removed from the baseline scenario.

    - The Motueka Gravels plant (WWD 3443) ceased operation on 26 October 2012, which is beyond the end of the model simulation run period. Therefore, this take has also been removed from the baseline scenario.

- Motueka River flows at Woodman's Bend have been adjusted to account for full irrigation in the Upper Motueka River catchment using the same method as described for the No Abstraction scenario (Section 7.2.1). The measured flows have been adjusted based on a maximum irrigable area in the Upper Motueka catchment of 3,200 ha (Joseph Thomas, TDC, *pers. comm.*). Again, to be conservative, pasture is assumed.

- Full irrigation on the plains is assumed (to allow for future development), with corresponding land surface recharge. Based on existing irrigated areas, there is potential for a further 140 ha (approximately) of irrigation on land that is currently unirrigated; these are spread over the 14 cells shown in Figure 7-1 (10 ha each), as follows:

    - In the Central Plains zone: C3-R8, C4-R9, C4-R10, C6-R12, C7-R12, C15-R12, C8-R13, C15-13, C12-R14

    - In the Te Matu zone: C9-R13, C10-R13, C11-R14

    - In the Umukuri zone: C6-R16, C9-R18

These assumed areas of future new irrigation were chosen based on the following features:

- Existing unirrigated land;

    - Likely residential expansion;
    - Avoiding the Motueka airfield; and
    - Avoiding any additional coastal irrigation (including near the Motueka River downstream of the state highway bridge) to minimise the potential for increasing the risk of saltwater intrusion.
- All domestic takes are unchanged from the calibration scenario which is based on recent census population data applied over the full simulation period.

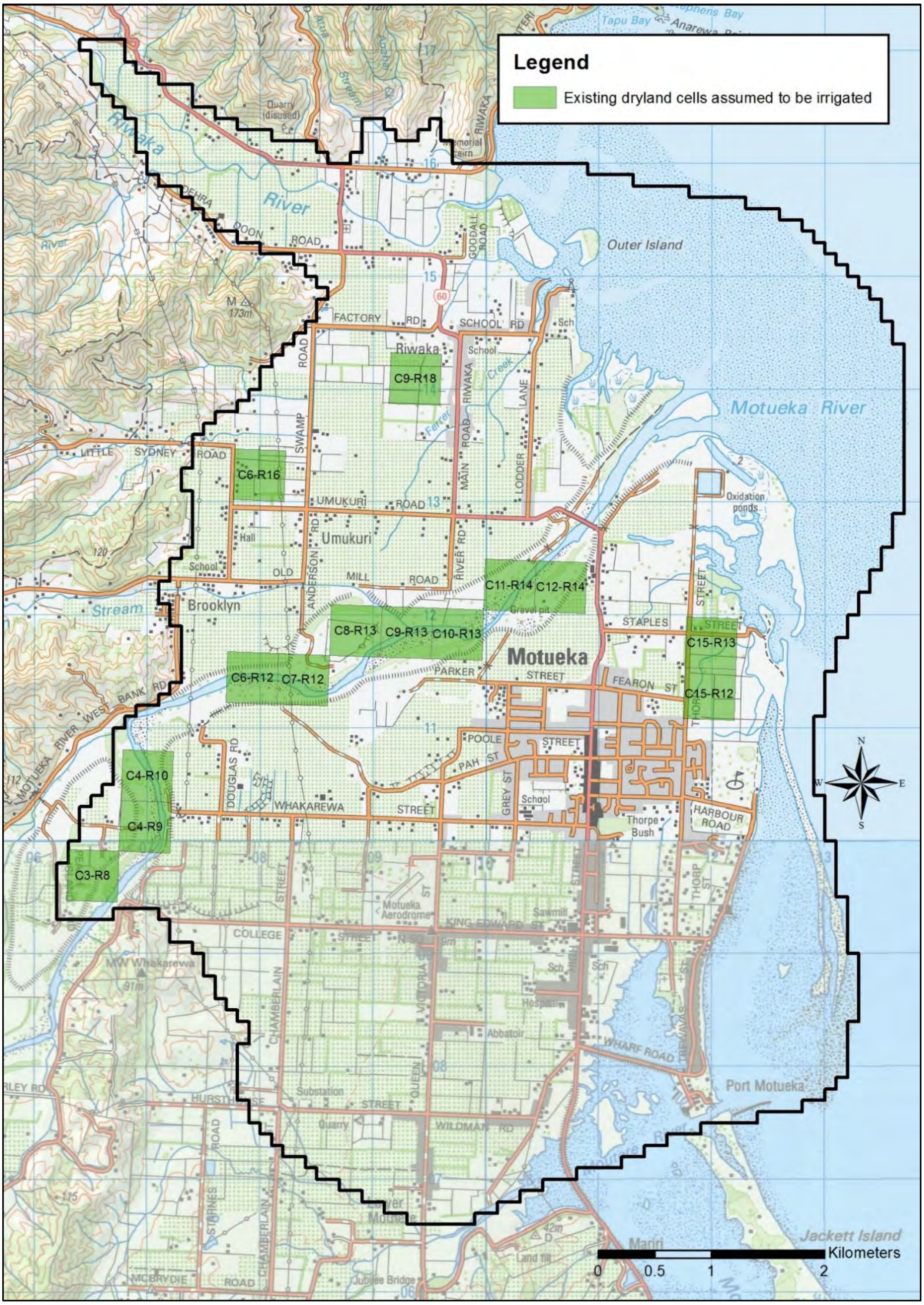


Figure 7-1: Assumed areas of future new irrigation

7.2.3 Scenario 3: 20,000 m^3/day

This scenario is based on Scenario 2 'Baseline' with the addition of a future Urban Supply taken from a proposed well field located adjacent to the Motueka River (within the Te Matu zone shown in Figure 2-5). This is intended to supply potable water to Motueka, Mapua and the Coastal Tasman area. The urban supply is currently consented for 16,000 m^3/day. However, TDC have provided for 20,000 m^3/day in the TRMP. Consequently, the scenario has been run at this higher rate.

It is proposed to supply the 20,000 m^3/day take from up to 8 bores located at TDC's Parker Street well field, as shown in Figure 7-2. The well field configuration was determined through a well field design documented in Aqualinc (2007b), but is not yet operational. The proposed abstraction from each of the eight bores is shown in Table 7-1 (reproduced from Aqualinc, 2007b).

Table 7-1: Urban supply take for Scenario 3

Bore	Modelled abstraction rate	
	(l/s) (daily average)	(m^3/day)
WWD 2179	38	3,277
WWD 2182	20	1,723
Proposed 1	38	3,277
Proposed 2	38	3,277
Proposed 3	20	1,723
Proposed 4	20	1,723
Proposed 5	20	1,723
Proposed 6	38	3,277
Total	**232**	**20,000**

As discussed in Aqualinc (2008), the location of TDC's Parker Street well field is considered the most suitable for additional abstraction within the plains. Abstraction closer to the coast will increase the risk of saltwater intrusion occurring in this area. Abstraction west of the well field (i.e. further inland nearer, Woodman's Bend) will intercept groundwater flowing from the upper segments of the Motueka River towards the Hau Plains (Figure 4-17 and Figure 4-18), which will increase the risk of saltwater intrusion in this area. The proposed abstraction from the well field provides an optimum balance between these two effects.

Figure 7-2: TDC's Parker Street well field proposed bore locations

It has been assumed that any new wells installed will fully penetrate the aquifer system (i.e. all wells are installed into the deepest known layer). As discussed in Aqualinc (2008), this will maximise the available resource for the new wells while minimising the interference effects on existing neighbouring shallow wells[11].

This scenario makes no allowance for the replacement of private domestic groundwater takes in the Motueka area by supply from the community scheme. Consequently, the scenario may over predict the total groundwater abstraction.

7.2.4 Scenario 4: 25,000 m^3/day

This scenario is founded on Scenario 3 (20,000 m^3/day) but with an additional 5,000 m^3/day abstraction (total of 25,000 m^3/day). The additional flow will be pro-rated over the bores relative to the rates presented in Table 7-1. The resulting abstraction rates are listed in Table 7-2.

Table 7-2: Urban supply take for Scenario 4

Bore	**Modelled abstraction rate (m^3/day)**
WWD 2179	4,096
WWD 2182	2,154
Proposed 1	4,096
Proposed 2	4,096
Proposed 3	2,154
Proposed 4	2,154
Proposed 5	2,154
Proposed 6	4,096
Total	**25,000**

7.2.5 Scenario 5: 30,000 m^3/day

This scenario is based on Scenario 3 (20,000 m^3/day) but with an additional 10,000 m^3/day abstraction (total of 30,000 m^3/day). The additional flow will be pro-rated over the bores relative to the rates presented in Table 7-1. The resulting abstraction rates are listed in Table 7-3.

---

[11] The model is a regional-scale model and is therefore not suitable for predicting local interference effects. This has been completed at a local scale using local hydrogeological parameters, as documented in Aqualinc (2007d).

Table 7-3: Urban supply take for Scenario 5

Bore	Modelled abstraction rate (m^3/day)
WWD 2179	4,915
WWD 2182	2,585
Proposed 1	4,915
Proposed 2	4,915
Proposed 3	2,585
Proposed 4	2,585
Proposed 5	2,585
Proposed 6	4,915
Total	**30,000**

7.2.6 Scenarios 6-8: With Hau Restrictions

TDC requires a 35% restriction for all takes in the Hau Plains (Figure 2-5) for droughts exceeding 1 in 10 year events. Earlier studies (Robb, 1999; Robb & Weir, 2002; Aqualinc, 20087c) demonstrated that these water restrictions are an effective method of decreasing the likelihood of saltwater intrusion in these areas. Consequently, scenarios 6-8 have been constructed to test the same requirements with the updated groundwater model.

Under scenarios 6-8, 35% restrictions have been applied to all irrigation and industrial takes located in the Hau Plains for the first 90 days of 2001 and 2006. These periods are classified by TDC as being equal to, or exceeding, a 1 in 10 year drought.

No restrictions have been applied to domestic or community takes in the Hau Plains.

7.2.7 Scenario 9: Motueka River Bed Degradation

This scenario considered the effects on the aquifer system due to natural degradation of the Motueka River bed. TDC's historical river surveys have indicated that the Motueka River bed has lowered approximately 0.3 m since regular and thorough surveys began in 1978 (Joseph Thomas, TDC, *pers. comm.*). Therefore, this scenario is based on Scenario 2 'Baseline' but with the Motueka River bed inverts lowered by 0.3 m at Woodman's Bend and pro-rated to zero towards the sea (i.e. no bed invert change at the sea). River cross-sectional shapes remain unchanged.

7.2.8 Scenario 10: Sea Level Rise

This scenario takes Scenario 2 'Baseline' and imposes a predicted sea level rise due to climate change. MfE (2014) recommends planning for a future 'base value' sea level rise of 0.5 m, relative to the 1980-1999 average, by 2090. In addition, MfE (2014) recommends that consideration be given to the potential effects from a range of possible higher sea level rise values, and suggests that a sea level rise of at least 0.8 m be considered.

Further to this, Bell (2014) suggests that, through adopting a 100-year planning timeframe, sea level rives of up to 1.0 m should be accommodated. Consequently, a permanent sea level rise of 1.0 m has been applied to the model's coastal boundary.

Short-period allowances for storm surges have been ignored due to the daily-average stress periods employed and the long-term focus of the study.

7.2.9 Scenarios 11 and 12: Climate Change Scenario 1

These scenarios take into account lowest projected rainfall and highest projected PET for 2090 (95-year trends) based on data that NIWA has downscaled for the Tasman District from an ensemble of different global climate models (NIWA, 2015). This represents a predicted future scenario of greatest climate change (B. Mullen, NIWA, *pers. comm.*). It is referred to as Representative Concentration Pathway 8.5 (RCP 8.5).

NIWA reports 5th and 95th percentile seasonal climate change values, averaged from 41 global climate models for RCP 8.5. Several options were considered to describe the extremes of projected climate change in the Tasman District. These options are described in Appendix G along with the detailed methodology for calculating the projected time series for rainfall, PET and river flows to input into the model.

For rainfall, Climate Change Scenario 1 uses the 5th percentile for each season reported by NIWA for RCP 8.5 at the Appleby grid point. These are shown in Table 7-4 and represent what is considered to be probable extremes. Time series of projected 2090 rainfall were calculated by directly applying these percentage changes for each season to daily rainfall from the Riwaka and Tui Close climate stations.

Table 7-4: Projected change in rainfall for 2090 used in Climate Change Scenario 1 (RCP 8.5)

Season	Summer	Autumn	Winter	Spring
Change in rainfall	-1%	-5%	-8%	-17%

Changes in PET for Climate Change Scenario 1 were estimated based on projected changes in temperature, where a temperature increase of 0.8°C results in a PET increase of 3% (Aqualinc, 2016). The description of this method is set out in Appendix G. The reported 95th percentile projected seasonal temperature increases for the Tasman District from NIWA (2015) were used to estimate projected PET increases for 2090. The temperature and resulting PET increases are shown in Table 7-5. New time series of PET were generated by applying the projected increases for each season to daily historical time series from the Riwaka and Tui Close climate stations.

Table 7-5: Projected increase in temperature and PET for 2090 for Climate Change Scenario 1 (RCP 8.5)

Season	Summer	Autumn	Winter	Spring
Temperature change (°C)	5.4	4.7	4.1	3.5
PET change	18.3%	15.9%	13.8%	11.7%

IRRICALC was run using the new rainfall and PET time series to produce daily irrigation, actual evapotranspiration (AET) and drainage for all previously modelled crops and soil type combinations.

Time series of river flows were also developed for Climate Change Scenario 1 for the Motueka and Riwaka rivers, and Little Sydney and Brooklyn streams. Projected river flows were calculated from projected rainfall and AET. AET was calculated assuming dryland pasture and representative soil PAW values for each river catchment. A more detailed description of the development of these time series is provided in Appendix G.

Climate Change Scenario 1 was run with and without sea level rise (Section 7.2.8). Scenario 11 represents Climate Change 1 alone, and Scenario 12 represents both Climate Change 1 and sea level rise combined. All other aspects of the scenarios remain the same as the Baseline scenario.

7.2.10 Scenarios 13 and 14: Climate Change Scenario 2

These scenarios takes into account highest projected rainfall and lowest projected PET for 2090 (95-year trends), based on data that NIWA has downscaled for the Tasman District as described for Climate Change Scenario 1 (NIWA, 2015). This represents a predicted future scenario of least climate change (B. Mullen, NIWA, pers. comm.). It is referred to as Representative Concentration Pathway 2.6 (RCP 2.6). NIWA (2015) report that 23 global climate models were used to predict ensemble averages for the RCP 2.6 scenario.

For rainfall, Climate Change Scenario 2 uses the 95th percentile for each season reported by NIWA for RCP 2.6 at the Appleby grid point, as listed in Table 7-6.

Table 7-6: Projected change in rainfall for 2090 used in Climate Change Scenario 2 (RCP 2.6)

Season	Summer	Autumn	Winter	Spring
Change in rainfall	+8%	+13%	+11%	+7%

For PET, the 5th percentile changes in seasonal temperature were used to estimate projected percent PET increases for 2090 (Table 7-7).

Table 7-7: Projected increase temperature and PET for 2090 for Climate Change Scenario 2

Season	Summer	Autumn	Winter	Spring
Temperature change (°C)	0.2	0.1	0.3	0.1
PET change	0.7%	0.3%	1.0%	0.3%

Projected river flows were also calculated for Climate Change Scenario 2 using projected rainfall and AET, as described for Climate Change Scenario 1 and in Appendix G. Climate Change Scenario 2 was run with and without sea level rise (Section 7.2.8). Scenario 13 represents Climate Change 2 alone and Scenario 14 represents both Climate Change 2 and sea level rise combined.

8 SCENARIO RESULTS AND ASSESSMENT OF MAXIMUM SUSTAINABLE ABSTRACTION RATE

Summaries of key simulation results are provided below along with an assessment of the sustainable level of additional abstraction from TDC's Parker Street well field (over and above current and potential water needs).

8.1 Overall Scenario Results

Key results from each management scenario and the calibrated scenario are summarised below. Results are presented for overall groundwater flow budgets, groundwater levels, Mouteka River leakage and spring discharge.

8.1.1 Overall Groundwater Flow Budgets

The overall average groundwater flow budgets for each scenario are presented in Table 8-1 and Table 8-2. The flow budget for the calibration scenario is also shown in both tables for completeness (reproduced from Table 4-5).

The overall mass discrepancies in Table 8-1 and Table 8-2 are all very low (less than 0.1%) which indicates that MODFLOW has accounted for flows without noticeable numerical error. Mass balance errors for any individual time step (not shown) are smaller than ±0.7%.

Considering the entire aquifer system as a whole, an increase in groundwater abstraction is balanced by an increase in net recharge from the rivers, a reduction in drain flows, a reduction in storage (i.e. groundwater level lowering) and a reduction in off-shore flow. Where the additional abstraction results in additional land surface recharge (e.g. under increased levels of irrigation), then the additional recharge also contributes to the water rebalance. Overall, the reductions in storage are small compared to other components of the groundwater rebalance, which is reflected in the relatively small changes in groundwater levels between scenarios.

Table 8-1: Model average groundwater flow budgets for scenarios 1-8

Overall groundwater flow budgets (l/s)									
Scenario	**Calibration**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**	**Scenario 7**	**Scenario 8**
		No Abstraction	**Baseline**	**+ 20,000 m^3/day**	**+ 25,000 m^3/day**	**+ 30,000 m^3/day**	**+ 20,000 m^3/day (restricted)**	**+ 25,000 m^3/day (restricted)**	**+ 30,000 m^3/day (restricted)**
Inflows									
Land surface recharge	823	650	866	866	866	866	866	866	866
Rivers (SFR2)	3,351	3,356	3,343	3,431	3,455	3,479	3,429	3,454	3,479
Coastal boundary (GHB)	0	0	0	0	0	0	0	0	0
Storage	1,164	989	1,200	1,205	1,206	1,207	1,204	1,205	1,206
Total IN	**5,338**	**4,995**	**5,409**	**5,502**	**5,527**	**5,552**	**5,499**	**5,525**	**5,551**
Outflows									
Wells	225	-	263	495	553	610	493	551	609
Drains	462	482	460	420	410	400	420	411	401
Rivers (SFR2)	2,294	2,302	2,297	2,238	2,225	2,212	2,237	2,225	2,212
Coastal boundary (GHB)	1,192	1,223	1,188	1,144	1,133	1,122	1,144	1,134	1,123
Storage	1,167	990	1,203	1,208	1,209	1,210	1,206	1,208	1,209
Total OUT	**5,340**	**4,997**	**5,411**	**5,505**	**5,530**	**5,554**	**5,500**	**5,529**	**5,554**
Summary									
In-Out	-2	-2	-2	-3	-3	-2	-1	-4	-3
% discrepancy	-0.037	-0.040	-0.037	-0.055	-0.054	-0.036	-0.018	-0.072	-0.054

Table 8-2: Model average groundwater flow budgets for scenario 9-14

Overall groundwater flow budgets (l/s)							
Scenario	Calibration	Scenario 9	Scenario 10	Scenario 11	Scenario 12	Scenario 13	Scenario 14
		Motueka River degradation	Sea level rise	Climate change 1	Climate change 1 + sea level rise	Climate change 2	Climate change 2 + sea level rise
Inflows							
Land surface recharge	823	866	866	704	704	957	957
Rivers (SFR2)	3,351	3,378	3,187	3,223	3,068	3,521	3,364
Coastal boundary (GHB)	0	0	34	0	36	0	32
Storage	1,164	1,206	1,191	1,071	1,062	1,276	1,267
Total IN	**5,338**	**5,450**	**5,278**	**4,997**	**4,870**	**5,754**	**5,620**
Outflows							
Wells	225	263	263	235	235	235	235
Drains	462	453	774	429	743	496	810
Rivers (SFR2)	2,294	2,349	2,370	2,127	2,198	2,492	2,565
Coastal boundary (GHB)	1,192	1,179	680	1,136	632	1,253	740
Storage	1,167	1,209	1,194	1,074	1,064	1,279	1,270
Total OUT	**5,340**	**5,453**	**5,281**	**5,001**	**4,872**	**5,755**	**5,620**
Summary							
In-Out	-2	-3	-3	-4	-2	-1	0
% discrepancy	-0.037	-0.055	-0.057	-0.080	-0.040	-0.017	0

8.1.2 Groundwater Levels

Changes in groundwater abstraction, and subsequent land use, affects groundwater levels, both temporally and spatially. These are discussed below.

Temporal Effects

Appendix H presents hydrographs of groundwater levels comparing the Calibration scenario and scenarios 1-5. Generally, as abstraction increases, low groundwater levels during the summer periods reduce further (i.e. there is an increase in the 'saw-tooth' effect). In wells located near to rivers, the low groundwater levels do not lower noticeably with increased abstraction due to the regulating effect of the river.

Comparing the No Abstraction, Calibration and Baseline scenarios, there is no visible long-term cumulative decline in groundwater levels from year to year. By and large, groundwater levels return to the No Abstraction state most years during the wetter winter periods when irrigation abstractions cease. In some cases, groundwater levels return a little higher than the No Abstraction scenario due to a net transfer of water from deep to shallow layers via irrigation and increased land surface recharge. The groundwater system recovers quickly from the hydraulic effects of pumping.

Under scenarios 3-5, which include the effects of continuous abstraction from the Parker Street well field, groundwater levels in some wells are constantly reduced, particularly in wells located in close proximity to the well field (such as the two nursery wells and, to a lesser extent, Rossiters and Greenwood). This is due to the sustained nature of the well field abstraction which does not turn off during winter in the same way that irrigation takes do. Should the well field cease abstracting, then groundwater levels would recover to their less developed state.

Similar groundwater level hydrographs are not provided for comparing scenarios 6-8 as these are identical to scenarios 3-5, apart for the first 90 days of 2001 and 2006. Instead, Figure 8-1 presents low-groundwater-level hydrographs for the Fernwood coastal monitoring bore (which is used by TDC to manage regional saltwater intrusion) over the 2001-2006 period when restrictions were imposed. Comparisons are shown for scenario pairs 3 and 6, 4 and 7, and 5 and 8.

For each scenario pair, the positive effects on groundwater levels are predicted by the deviations indicated during the two time periods circled on Figure 8-1. Overall, Hau Plains restrictions reduce groundwater level lowering by approximately 0.1 m in the Fernwood coastal monitoring bore. These restrictions during dry periods have a positive effect on reducing the risk of saltwater intrusion.

Appendix I presents hydrographs of groundwater levels comparing the Baseline scenario with scenarios 9 and 10. Motueka River bed degradation (Scenario 9) has only a very small effect on groundwater levels, primarily in wells located close to the river. Due to the simulated permanent nature of the degradation, the lowering in wells that are noticeably affected is continuous over the full simulation period. Scenarios 11-14 provide very little change over and above Scenario 10, so no additional hydrographs are provided for these scenarios.

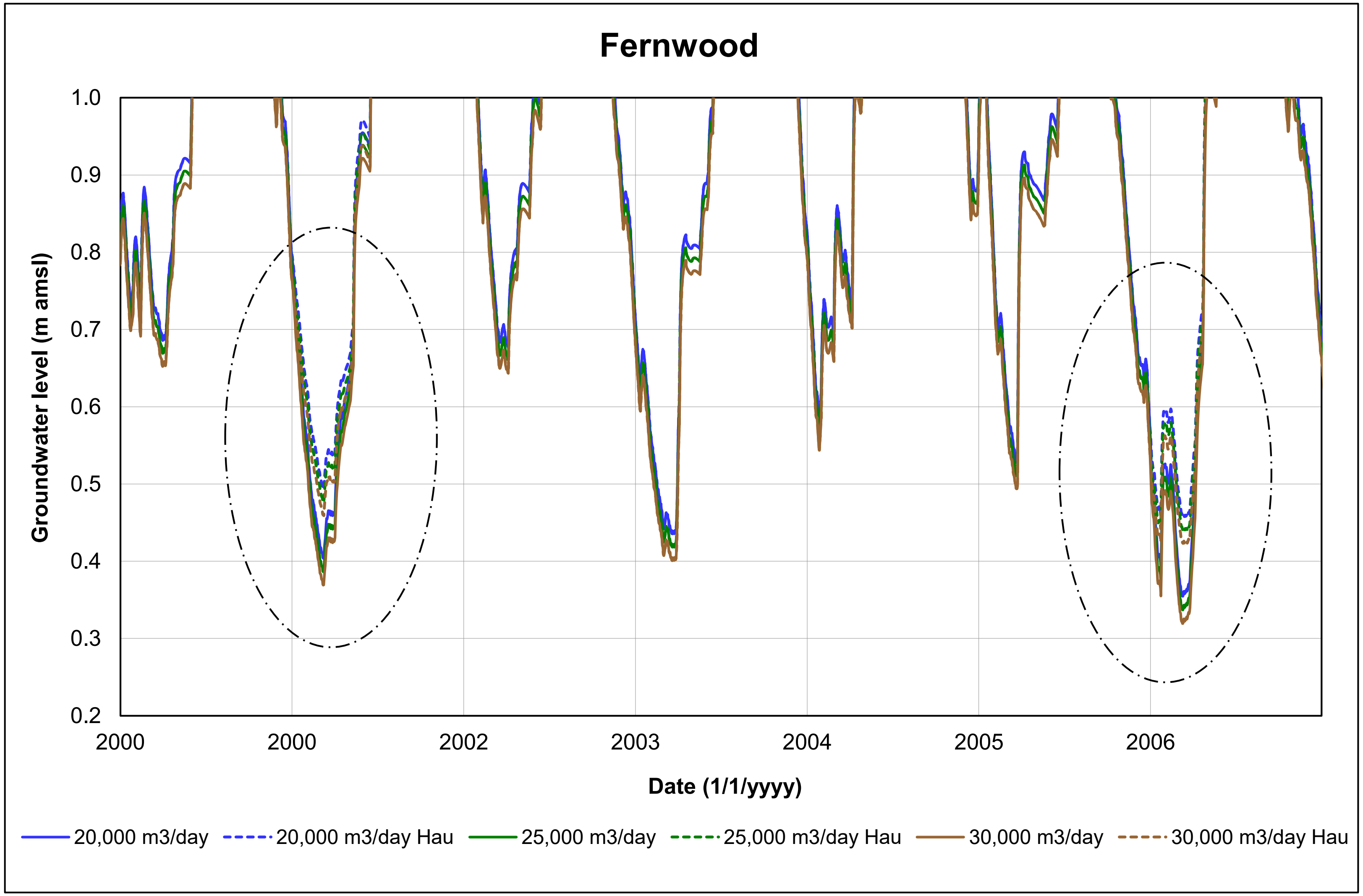


Figure 8-1: Low-groundwater-level hydrographs for the Fernwood monitoring bore comparing scenario pairs with and without Hau Plains restrictions

A sea level rise of 1 m (Scenario 10) results in a rise in groundwater levels over much of the plains, but the rise is more prominent with proximity to the coast, and reduces with distance inland. Wells located close to rivers are predicted to experience very little effect from sea level rise due to the regulating effect of the river. Again, due to the simulated permanent nature of the sea level rise, the subsequent rise in groundwater levels is continuous over the full simulation period.

Spatial Effects

Appendix J contains maps of simulated differences in groundwater levels between various scenarios as at 24 March 2001. Appendix K contains equivalent comparisons for 24 January 2006. These two dates were chosen to represent the groundwater system in a state of stress when groundwater levels were low as a consequence of low recharge (both land surface recharge and river recharge) and high groundwater abstraction.

Ignoring localised effects of pumping, overall (regional) groundwater levels drop 0.5-1.2 m over much of the plains as a result of the level of development under Scenario 2 (Baseline) compared to the No Abstraction scenario. Groundwater levels are affected less towards the coast and the main rivers due to the regulating effects of these boundaries.

When 20,000 m^3/day of groundwater is abstracted from the Parker Street well field (Scenario 3), groundwater levels lower by an additional 0-0.4 m over the aquifer system compared to the Baseline scenario. Closer to the well field (within approximately 600 m), groundwater level lowering of up to 0.4-0.8 m is predicted. When 25,000 m^3/day is abstracted (Scenario 4), the groundwater level lowering increases to 0-0.6 m, and 0.6-1 m nearer the well field location. When 30,000 m^3/day is taken (Scenario 5), the groundwater level lowering increases to 0-0.8 m, and 0.8-1.2 m nearer the well field location.

Under scenarios 3-5, the predicted regional lowering at 24 March 2001 is slightly larger than the predicted lowering on 24 January 2006, but the difference is very small (~0.02 m). Restrictions in the Hau Plains (scenarios 6-8) makes no obvious difference to the regional groundwater level lowering as result of abstractions from the Parker Street well field.

Motueka River bed degradation (Scenario 9) affects groundwater levels primarily in the upper reaches of the river where the greatest bed lowering is simulated. In this area, a groundwater level lowering of 0.2-0.3 m is predicted from a bed lowering of 0.3 m. The effects propagate from the river's upper reaches and diminish over a distance of approximately 2-3 km from either side of the river, with only a small effect (< 0.1 m) beyond this. Groundwater level changes due to Motueka River bed degradation are relatively consistent between the two dates presented (24 March 2001 and 24 January 2006).

A sea level rise of 1 m (Scenario 10) results in a rise in groundwater levels at the coast of approximately 0.8 m. The full 1 m rise in groundwater levels is predicted to occur in the groundwater system off-shore under the general head boundaries (Figure 3-21). The Motueka and Riwaka rivers partially regulate the groundwater level rise. Elsewhere, a rise of 0.2 m or more is predicted to extend up to 3 km inland from the coast. These predictions are relatively consistent between the two dates presented (24 March 2001 and 24 January 2006).

Of concern with sea level rise is the potential for groundwater flooding whereby groundwater levels reach the surface causing ponding, and affecting land use. To assess this risk, a date of 13 August 1990 has been considered, which is when highest groundwater levels were measured (over the period of record). Figure 8-2 presents the area of the plains where shallow groundwater levels were predicted to reach the land surface under the Calibrated model during an extreme wet period (as represented by 13 August 1990). An equivalent map for the sea level rise scenario (Scenario 10) is shown in Figure 8-3.

This assessment shows that:

- Some areas of the coastal plains would have experienced historical groundwater flooding;
- If sea level was to rise 1 m, then during very wet periods the area of groundwater flooding is predicted to move 200-800 m inland from where historical flooding occurred. The greatest horizontal shift is predicted around the golf course and into the south-eastern areas of Motueka township.

Due to features that are not represented in the model (such as local drainage networks; smaller scale land surface variations; etc.), these groundwater flooding predictions are very approximate.

Groundwater level differences for climate change scenarios 11 and 12 are provided in Appendix J and Appendix K. Scenario 11 shows almost no change compared to the baseline and Scenario 12 (Climate Change 1 with sea level rise) shows a very similar response to Scenario 10 (sea level rise alone). Results from scenarios 13 and 14 (climate change 2 scenarios) have not been provided as they are very similar to scenarios 11 and 12, respectively.

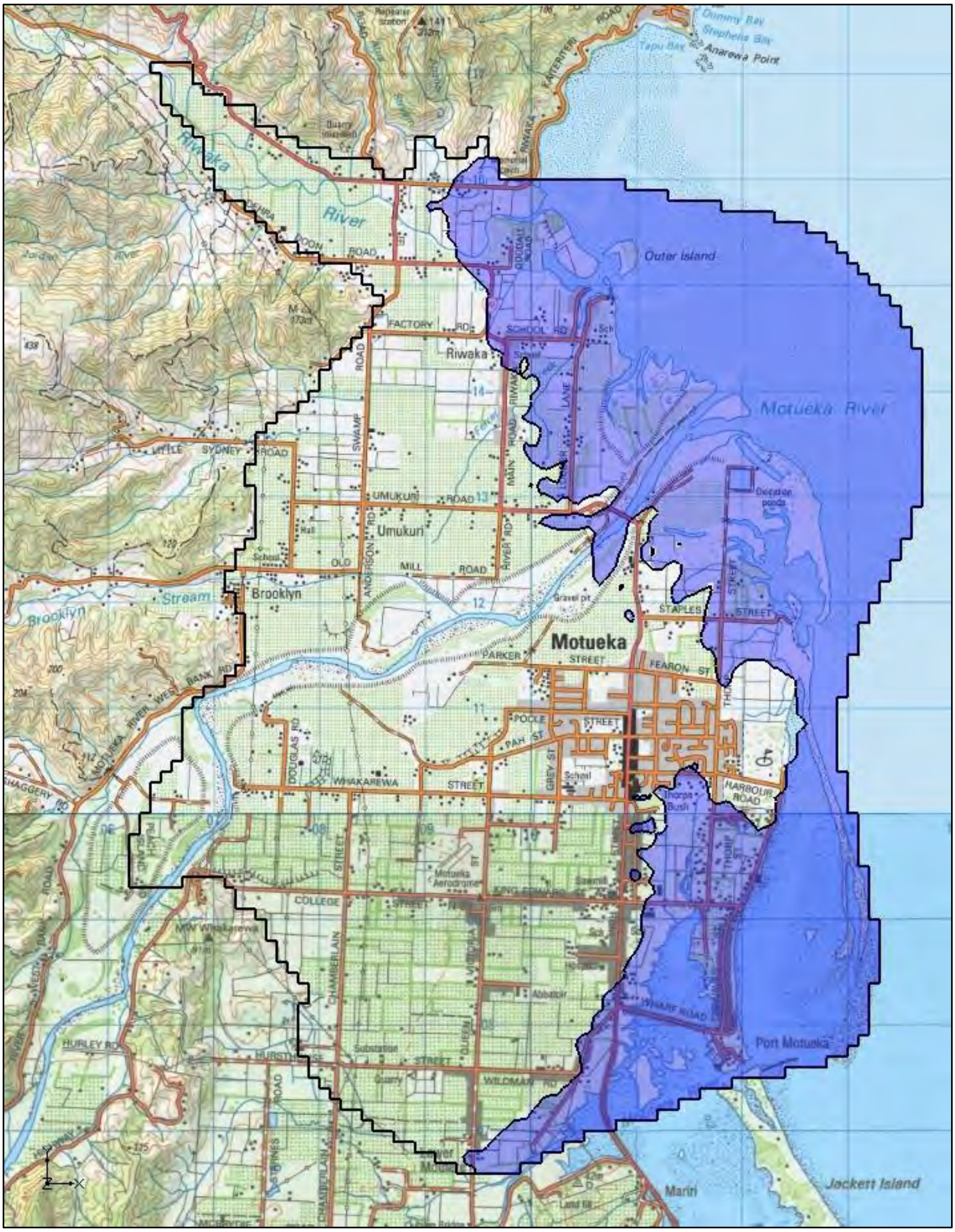


Figure 8-2: Modelled areas of groundwater flooding under the calibrated model scenario on 13 August 1990

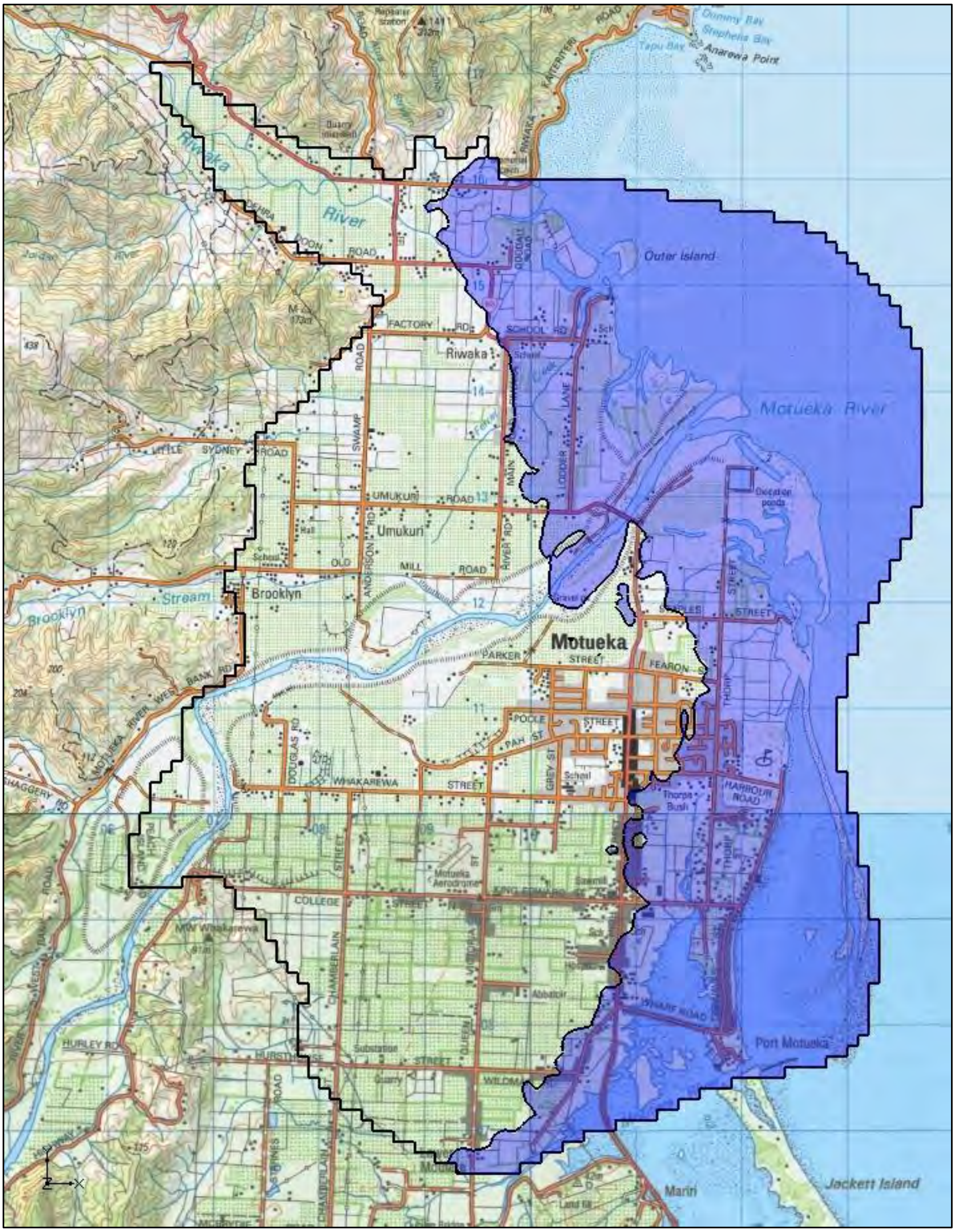


Figure 8-3: Modelled areas of groundwater flooding under the sea level rise scenario on 13 August 1990

8.1.3 Groundwater Recharge from the Motueka River

Table 8-3 lists the average modelled groundwater recharge from the Motueka River for the entire model period as well as for the first 90 days of 2001 and 2006. These recharges include the contribution from Brooklyn Stream, which is a tributary of the Motueka River. Also included in the table is the percent flow change compared to the 'Calibration' scenario.

Generally, groundwater abstraction results in an increase in recharge from the Motueka River to groundwater. This occurs because groundwater abstraction lowers groundwater levels, which in turn increases the hydraulic gradient between the river and adjacent groundwater.

Typically, the river loses a greater amount of flow, and a greater percentage of flow, to groundwater during dry periods compared to average. The reason for this is twofold: firstly, the river flows are lower, hence any loss is proportionally greater; and secondly groundwater abstraction (and therefore induced river loss) is greater during dry periods compared to the long-term average.

Comparing the No Abstraction and Calibrated scenarios, historical abstraction has resulted in an increase in average Motueka River losses of approximately 2%, and up to 19% during dry periods. During these dry periods, losses are predicted to increase a further 3-6% under the Baseline scenario (Scenario 1).

Restrictions in the Hau Plains (scenarios 6-8) have very little benefit (1% at most) on Motueka River recharge to groundwater (compared to scenarios 3-5).

Lowering the Motueka River bed (Scenario 9) reduces the losses by 1-2% compared to the Baseline scenario. This is because the lower river elevations reduce the hydraulic gradients between the river and adjacent groundwater.

Sea level rise (Scenario 10) is predicted to reduce Motueka River losses by 8-15%. This is because the resulting raised groundwater levels reduce the hydraulic gradient between the river and adjacent groundwater. Sea level change with climate change (Scenarios 12 and 14) provides similar change to sea level rise alone (Scenario 10). Climate change alone (Scenarios 11 and 13) results in a very small change in river recharge (less than 3%).

Table 8-3: Groundwater recharge from the Motueka River

Scenario	Motueka River recharge to groundwater (l/s)		
	Average over 1990-2012	Average over first 90-days in 2001	Average over first 90-days in 2006
Calibrated	1,030	980	1,240
Scenario 1 No abstraction	1,010 (-2%)	790 (-19%)	1,000 (-19%)
Scenario 2 Baseline	1,020 (-1%)	1,040 (+6%)	1,280 (+3%)
Scenario 3 +20,000 m^3/day	1,170 (+14%)	1,180 (+20%)	1,420 (+15%)
Scenario 4 +25,000 m^3/day	1,210 (+17%)	1,220 (+24%)	1,460 (+18%)
Scenario 5 +30,000 m^3/day	1,250 (+21%)	1,250 (+28%)	1,490 (+20%)
Scenario 6 +20,000 m^3/day (restricted)	1,170 (+14%)	1,180 (+20%)	1,420 (+15%)
Scenario 7 +25,000 m^3/day (restricted)	1,210 (+17%)	1,210 (+23%)	1,450 (+17%)
Scenario 8 +30,000 m^3/day (restricted)	1,250 (+21%)	1,250 (+28%)	1,490 (+20%)
Scenario 9 Motueka River degradation	1,010 (-2%)	1,020 (+4%)	1,260 (+2%)
Scenario 10 Sea level rise	870 (-15%)	900 (-8%)	1,130 (-9%)
Scenario 11 Climate change 1	1,060 (+3%)	1,000 (+2%)	1,260 (+2%)
Scenario 12 Climate change 1 + sea level rise	900 (-13%)	870 (-11%)	1,110 (-10%)
Scenario 13 Climate change 2	1,020 (-1%)	1,010 (+3%)	1,270 (+2%)
Scenario 14 Climate change 2 + sea level rise	860 (-17%)	870 (-11%)	1,120 (-10%)

Note: The values within the bracket indicate the percent difference with respect to the corresponding calibrated values. Recharge from the Brooklyn Stream is included.

8.1.4 Discharge to Spring Fed Drains

Changes in modelled groundwater discharge to (flows in) Thorpe Drain, Staples Drain and Frys Drain are summarised in Table 8-4, Table 8-5 and Table 8-6, respectively. The locations of these drains are shown in Figure 3-16. Flows are presented for the entire model period as well as for the first 90 days of 2001 and 2006. Percent changes compared to the 'Calibration' scenario are also included.

Increased groundwater abstraction results in reduced drain flows. The greater percentage changes occur during dry periods when drain flows are naturally lower due to low groundwater levels. During these dry periods, the predicted percentage changes in flows are large for some scenarios.

Comparing results from the No Abstraction and Calibrated scenarios, a large reduction in drain flows is predicted to result from existing groundwater abstraction. Thorp Drain is predicted to be affected more by groundwater abstraction compared to the other two drains due to its location relative to regional groundwater flow directions and areas of greatest groundwater use (including the Parker Street well field).

Hau Plains restrictions (scenarios 6-8) are predicted to benefit Thorp Drain by 5-8% during dry periods (compared to scenarios 3-5). Of the three drains modelled, Thorp Drain is the only drain located in near vicinity to the Hau Plains management zone. Consequently, the other two drains show no benefit from Hau Plains restrictions.

The small changes in regional groundwater levels predicted near the drains as a result of Motueka River bed degradation (Scenario 9) results in a reduction in average drain flows by 0-3%, and 4-16% during dry periods.

Sea level rise (Scenario 10) is predicted to substantially increase all drain flows. However, raised sea level is likely to result in additional sea water seeping, diffusing and/or back-flowing into these drains. Currently, water flowing in the drains is brackish; sea level rise is likely to increase the salt content in these drains.

Sea level change with climate change (Scenarios 12 and 14) provide similar changes to sea level rise alone (Scenario 10). Climate change alone (Scenarios 11 and 13) results in changes in drain flows of ±14% compared with other scenarios.

Table 8-4: Thorpe Drain flow

Scenario	**Thorp Drain flow (l/s)**		
	Average over 1990-2012	**Average over first 90-days in 2001**	**Average over first 90-days in 2006**
Calibrated	251	116	91
Scenario 1 No abstraction	268 (+7%)	192 (+66%)	179 (+97%)
Scenario 2 Baseline	249 (-1%)	105 (-9%)	84 (-8%)
Scenario 3 +20,000 m^3/day	218 (-13%)	73 (-37%)	52 (-43%)
Scenario 4 +25,000 m^3/day	210 (-16%)	64 (-45%)	44 (-52%)
Scenario 5 +30,000 m^3/day	202 (-20%)	57 (-51%)	36 (-60%)
Scenario 6 +20,000 m^3/day (restricted)	218 (-13%)	80 (-31%)	59 (-35%)
Scenario 7 +25,000 m^3/day (restricted)	211 (-16%)	72 (-38%)	51 (-44%)
Scenario 8 +30,000 m^3/day (restricted)	203 (-19%)	63 (-46%)	43 (-53%)
Scenario 9 Motueka River degradation	243 (-3%)	98 (-16%)	77 (-15%)
Scenario 10 Sea level rise	353 (+41%)	211 (+82%)	182 (+100%)
Scenario 11 Climate change 1	232 (-8%)	106 (-9%)	78 (-14%)
Scenario 12 Climate change 1 + sea level rise	335 (+33%)	212 (+83%)	186 (+104%)
Scenario 13 Climate change 2	269 (+7%)	123 (+6%)	98 (+8%)
Scenario 14 Climate change 2 + sea level rise	372 (+48%)	228 (+97%)	205 (+125%)

Note: The values within the bracket indicate the percent difference with respect to the corresponding calibrated values.

Table 8-5: Staples Drain flow

Scenario	Staples Drain flow (l/s)		
	Average over 1990-2012	Average over first 90-days in 2001	Average over first 90-days in 2006
Calibrated	87	34	31
Scenario 1 No abstraction	89 (+2%)	50 (+47%)	47 (+52%)
Scenario 2 Baseline	87 (0%)	32 (-6%)	29 (-6%)
Scenario 3 +20,000 m^3/day	80 (-8%)	26 (-24%)	23 (-26%)
Scenario 4 +25,000 m^3/day	78 (-10%)	25 (-26%)	21 (-32%)
Scenario 5 +30,000 m^3/day	77 (-11%)	23 (-32%)	20 (-35%)
Scenario 6 +20,000 m^3/day (restricted)	80 (-8%)	26 (-24%)	23 (-26%)
Scenario 7 +25,000 m^3/day (restricted)	78 (-10%)	25 (-26%)	21 (-32%)
Scenario 8 +30,000 m^3/day (restricted)	77 (-11%)	23 (-32%)	20 (-35%)
Scenario 9 Motueka River degradation	86 (-1%)	31 (-9%)	27 (-13%)
Scenario 10 Sea level rise	153 (+76%)	90 (+165%)	87 (+181%)
Scenario 11 Climate change 1	79 (-9%)	31 (-9%)	27 (-13%)
Scenario 12 Climate change 1 + sea level rise	144 (+65%)	88 (+159%)	85 (+174%)
Scenario 13 Climate change 2	95 (+9%)	37 (+9%)	35 (+13%)
Scenario 14 Climate change 2 + sea level rise	162 (+86%)	96 (+182%)	94 (+203%)
Note: The values within the bracket indicate the percent difference with respect to the corresponding calibrated values.			

Table 8-6: Frys Drain flow

Scenario	**Frys Drain flow (l/s)**		
	Average over 1990-2012	**Average over first 90-days in 2001**	**Average over first 90-days in 2006**
Calibrated	124	78	74
Scenario 1 No abstraction	125 (+1%)	92 (+18%)	90 (+22%)
Scenario 2 Baseline	124 (0%)	74 (-5%)	71 (-4%)
Scenario 3 +20,000 m^3/day	122 (-2%)	72 (-8%)	69 (-7%)
Scenario 4 +25,000 m^3/day	122 (-2%)	71 (-9%)	69 (-7%)
Scenario 5 +30,000 m^3/day	121 (-2%)	71 (-9%)	68 (-8%)
Scenario 6 +20,000 m^3/day (restricted)	122 (-2%)	72 (-8%)	69 (-7%)
Scenario 7 +25,000 m^3/day (restricted)	122 (-2%)	71 (-9%)	69 (-7%)
Scenario 8 +30,000 m^3/day (restricted)	121 (-2%)	71 (-9%)	68 (-8%)
Scenario 9 Motueka River degradation	124 (0%)	73 (-6%)	71 (-4%)
Scenario 10 Sea level rise	269 (+117%)	220 (+182%)	218 (+195%)
Scenario 11 Climate change 1	118 (-5%)	75 (-4%)	70 (-5%)
Scenario 12 Climate change 1 + sea level rise	263 (+112%)	222 (+185%)	217 (+193%)
Scenario 13 Climate change 2	131 (+6%)	82 (+5%)	77 (+4%)
Scenario 14 Climate change 2 + sea level rise	276 (+123%)	228 (+192%)	224 (+203%)

Note: The values within the bracket indicate the percent difference with respect to the corresponding calibrated values.

8.2 Sustainable Abstraction Decision Criteria

In order to compare scenarios and assess a sustainable level of additional abstraction from the Parker Street well field, it is necessary to establish one or more decision criteria. In accordance with previous investigations, the principle concern relating to groundwater abstraction is managing saltwater intrusion. Consequently, the decision criteria have been decided to assess the potential for saltwater intrusion. Decision criteria comprise a decision variable and a decision trigger. These are discussed below.

8.2.1 Decision Variables

To monitor for saltwater intrusion in the Coastal Margin of the Hau Plains, TDC established the Fernwood groundwater level monitoring well (WWD 2614). Reliable groundwater level data is available from the Fernwood well since January 2004 (Figure 8-4). The recorded lowest groundwater level in this bore was 0.52 m amsl on 24 January 2006.

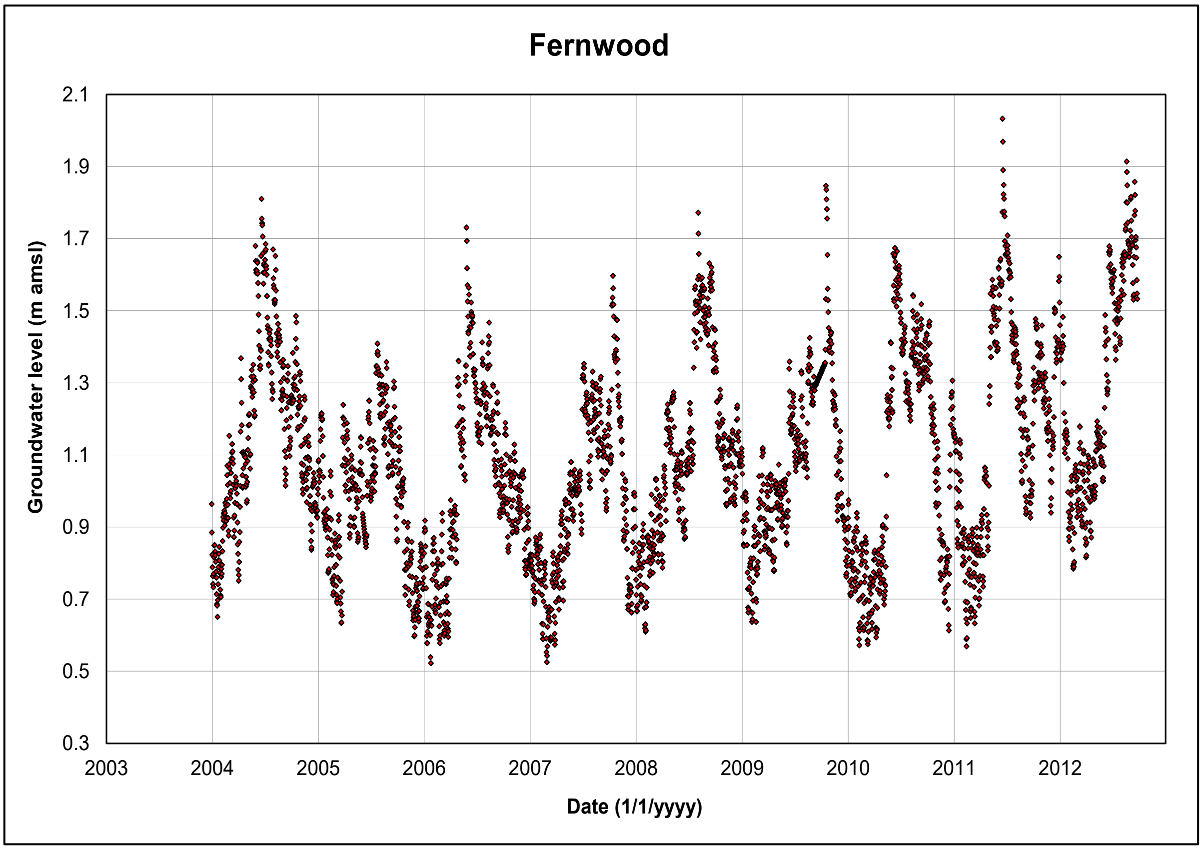


Figure 8-4: Measured groundwater levels in Fernwood monitoring well

Both groundwater level and groundwater flux are important controls of potential saltwater intrusion, and as such, both have been chosen as decision variables. While groundwater levels can be readily measured, groundwater flux can realistically only be assessed via a model.

Groundwater level provides a sub-regional indication of saltwater intrusion risk, and groundwater flux provides a larger scale picture, particularly when also considering the presence of landward flux (i.e. flow of water from the sea to inland). Based on the saltwater intrusion measured in the Fernwood monitoring bore during the 2014/15 summer, the regional model may not be fully capable of predicting local events. These need to be addressed by managing the local causes (e.g. over pumping).

Figure 8-5 presents rainfall sums at Tui Close (Figure 3-13). Both annual sums and sums for the first 90-days of each year are shown. The lowest annual rainfall occurred in 1997. The lowest first-90-day rainfall occurred in 2001.

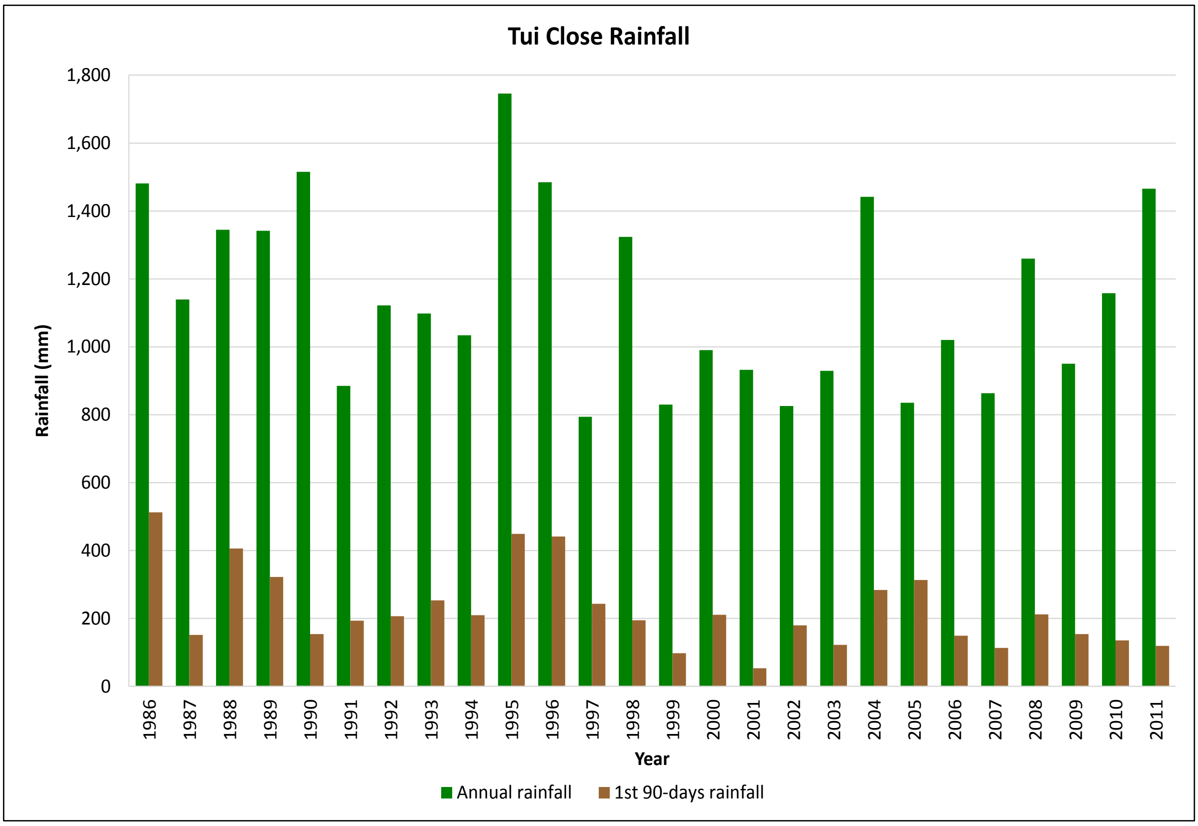


Figure 8-5: Tui Close rainfall sums

Considering both the timing of the lowest groundwater levels in the Fernwood monitoring bore and the lowest rainfall over the first 90 days of any year, two time periods have been considered for decision variables, these being the first 90 days of 2001 and 2006. Given this, and the criteria above for assessing saltwater intrusion risk, the following three decision variables have been chosen:

- The average groundwater level at Fernwood for the first 90 days of 2001 and 2006;
- The average seaward flux for the first 90 days of 2001 and 2006; and
- The occurrence of landward flux.

These three decision variables are consistent with previous studies.

8.2.2 Decision Triggers

Based on historical occurrences of saltwater intrusion in the coastal zone of the Hau Plains, TDC's guideline for managing saltwater intrusion has been based on a groundwater level of 0.5 m amsl in any coastal monitoring bore (Aqualinc, 2008). This is approximately the same as the lowest measured groundwater level in this well (0.52 m). However, salt water has never been monitored in the well (Joseph Thomas, TDC, *pers. comm.*). In addition, the lowest groundwater level occurred without any restrictions in place (Joseph Thomas, TDC, *pers. comm.*). Consequently, water restrictions in the Hau Plains would further reduce the likelihood of saltwater intrusion.

Therefore, there is capacity to lower groundwater levels in the Fernwood monitoring bores lower than the 0.5 m amsl trigger currently used by TDC. Among other criteria, the Stage 3 model (Aqualinc, 2008) considered a groundwater level trigger of 0.4 m amsl, which is 80% of TDC's current management trigger. For consistency, this same trigger will be applied to the Stage 4 model. This provides additional capacity for abstraction while still maintaining adequate groundwater level at the coast (with a margin of safety).

The model has been used to represent the coastal flux. For consistency with previous studies, the seaward flux trigger was set equal to 80% of the flux modelled under the calibration scenario. Under the calibration scenario, the average coastal flux over the first 90 days of 2001 was 0.70 m^3/s and over the first 90 days of 2001 was 0.65 m^3/s. Therefore, 80% of these values is 0.56 m^3/s and 0.52 m^3/s respectively. The lesser of the two (0.52 m^3/s) has been chosen as the trigger.

The groundwater level trigger at the Fernwood well and the seaward flux trigger have both been assessed for the first 90 days of 2001 and 2006. However, the third decision viable trigger, landward flux, has been assessed for the entire model period; there should be no occurrences of landward flux (i.e. groundwater should be flowing out to sea at all times).

8.2.3 Decision Summary

Table 8-7 summarises the decision variables and triggers that will be applied to all management scenarios to determine a sustainable level of groundwater abstraction.

Table 8-7: Decision triggers

Decision variable	Decision trigger
Average groundwater level at Fernwood for the first 90 days of 2001 and 2006	0.40 m amsl
Average seaward flux for the first 90 days of 2001 and 2006	0.52 m^3/s
Number of occurrences of landward flux	0 days

8.3 Assessment of Sustainable Abstraction

Table 8-8 presents a summary of decision criteria for each scenario. No criteria are predicted to be breached under scenarios 1-9, 11 and 13, which suggests that more than 30,000 m^3/day could be abstracted sustainably from the Parker Street well field, so long as sea level rise either does not occur or the effects of it are adequately managed.

Sea level rise (scenarios 10, 12 and 14) is predicted to result in coastal backflow of sea water into the aquifer system. If the simulated magnitude of sea level rise occurs, then saltwater intrusion may need to be managed to protect water quality in wells located nearer the coast. This can be achieved by maintaining adequate subsurface flows of fresh water at the coast. If managing saltwater intrusion due to sea level rise is of concern to TDC, then further investigation is needed to quantify the risk and necessary mitigation measures. This will require the inclusion of density-dependent modelling that can account for, and quantify, the salt-water/fresh-water interface.

Table 8-8: Scenario decision criteria exceedance

Scenario	Percent exceedance of decision variables				
	Avg. GW level in Fernwood for first 90 days (m amsl)		Avg. coastal flux (m^3/s)		Occurrence of landward flux (days)
	2001	2006	2001	2006	
Calibrated	-	-	-	-	-
Scenario 1 No abstraction	-	-	-	-	-
Scenario 2 Baseline	-	-	-	-	-
Scenario 3 +20,000 m^3/day	-	-	-	-	-
Scenario 4 +25,000 m^3/day	-	-	-	-	-
Scenario 5 +30,000 m^3/day	-	-	-	-	-
Scenario 6 +20,000 m^3/day (restricted)	-	-	-	-	-
Scenario 7 +25,000 m^3/day (restricted)	-	-	-	-	-
Scenario 8 +30,000 m^3/day (restricted)	-	-	-	-	-
Scenario 9 Motueka River degradation	-	-	-	-	-
Scenario 10 Sea level rise	-	-	59%	66%	8,035
Scenario 11 Climate change 1	-	-	-	-	-
Scenario 12 Climate change 1 + sea level rise	-	-	57%	68%	8,035
Scenario 13 Climate change 2	-	-	-	-	-
Scenario 14 Climate change 2 + sea level rise	-	-	47%	57%	8,035

9 TRANSPORT MODELLING

Following is a summary of investigations into the modelling of nitrate transport through the Motueka-Riwaka plains groundwater system.

9.1 Measured Nitrate-Nitrogen Concentrations

As part of their regular monitoring programme and to fulfil State of the Environment Monitoring (SEM) requirements, TDC measure water quality in a number of streams and wells in the district. A key contaminant that they monitor for is nitrate-nitrogen, as elevated concentrations are usually attributed to human-induced activities.

Figure 9-1 presents the measured nitrate-nitrogen concentrations for the model study area, averaged over all measurements on record. Both groundwater and surface water concentrations are presented.

The following observations have been derived from the nitrate-nitrogen measurements:

- Surface water concentrations are low compared to groundwater.
- Groundwater concentrations are typically lower nearer the main rivers (Motueka and Riwaka rivers), likely due to the dilution effect from river water.
- Conversely, groundwater concentrations are typically higher in locations further from the main rivers (e.g. the Hau Plains and Umukuri zones) where agriculture is more intensive and there is less dilution effect from the main rivers.

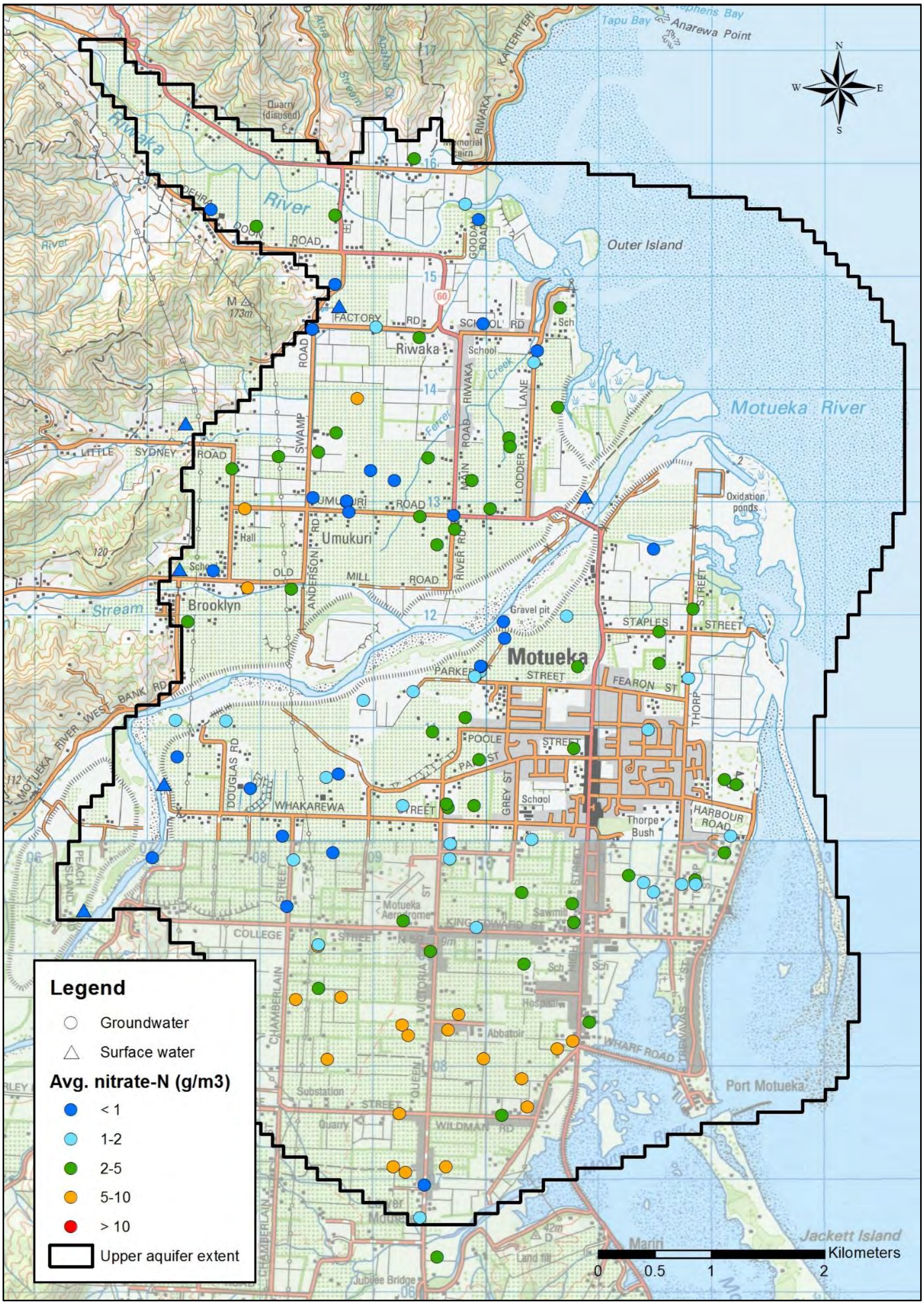


Figure 9-1: Average measured nitrate-nitrogen concentrations in both groundwater and surface water

9.2 Transient Transport Modelling

Land use nitrate leaching rates were collated from similar soils and crop combinations on the Waimea Plains, with the assistance of Andrew Fenemor (Landcare). Much of this information was derived from Fenemor *et al.* (2016), which models transient nitrate-nitrogen losses for four Waimea catchment land uses and four soil groups. Motueka soil types were matched to the closest of these four Waimea soil groups, using total plant available water (PAW) values. PAW values for the Waimea soil groups were obtained from Fenemor *et al.* (2015).

The combinations of Motueka soil types and land uses matched to the closest Waimea soil and land uses are shown in Table 9-1, as are the consequential average modelled nitrate leaching losses used in the present study. The values presented are consistent with rates reported in studies from other districts of New Zealand (for example, Aqualinc, 2014; Cameron *et. al*, 2013; Menneer *et. al,* 2004; Rutherford *et. al,* 2009), although the values presented in Table 9-1 tend towards the lower end of ranges reported.

Transient nitrate-nitrogen losses calculated by Fenemor *et al.* (2016) were supplied as monthly loss rates (in kg N/ha/month) for each soil and crop combination. Through use of this data, it was found that losses under dryland pasture were unexpectedly high from approximately 2008 onwards for all soil types. Unfortunately, discussions with Steve Green (a co-author of Fenemor *et al.*, 2016) did not resolve this problem. Therefore, modelled losses under dryland pasture from 2008 onwards were assigned the values from 1998, repeating yearly. This year was chosen as it approximately matched the scale of modelled losses post-2008 under irrigated pasture.

Nitrate leachate rates under the Motueka and Riwaka townships are unknown, though it is expected that the rates will be less than agricultural rates, particularly given the reticulated sewerage system and centralised treatment plant at the coast. Therefore, a nitrate nitrogen concentration equivalent to dryland pasture has been assumed.

Nitrate concentrations in land surface recharge were calculated for each cell in the groundwater model using the monthly loss values provided by Landcare apportioned over each month based on the calculated recharge within that month. Figure 9-2 and Figure 9-3 present the resulting average modelled mass of nitrate leaching and the calculated LSR concentrations, respectively.

The spatial distribution of LSR concentrations in Figure 9-3 is broadly consistent with the spatial variation in measured concentrations presented in Figure 9-1, particularly in the Hau Plains area.

Table 9-1: Modelled average nitrate-nitrogen leaching losses for Motueka soil and land use combinations

Motueka soil type	Closest Waimea soil group (by PAW)	Motueka land use	Modelled average NO_3-N losses (kg N/ha/y)
Hau	Ranzau	Apples, kiwifruit, hops & currants	8
		Grapes & olives	18
		Vegetables, maize and nurseries	51
		Irrigated pasture	64
		Non-irrigated pasture (incl. towns)	15
Riwaka	Waimakariri	Apples, kiwifruit, hops & currants	5
		Grapes & olives	8
		Vegetables, maize and nurseries	33
		Irrigated pasture	63
		Non-irrigated pasture (incl. towns)	10
Sherry	Dovedale & Richmond (averaged)	Apples, kiwifruit, hops & currants	6
		Grapes & olives	9
		Vegetables, maize and nurseries	24
		Irrigated pasture	42
		Non-irrigated pasture (incl. towns)	5
Tahunanui	Ranzau	Apples, kiwifruit, hops & currants	8
		Grapes & olives	18
		Vegetables, maize and nurseries	51
		Irrigated pasture	64
		Non-irrigated pasture (incl. towns)	15

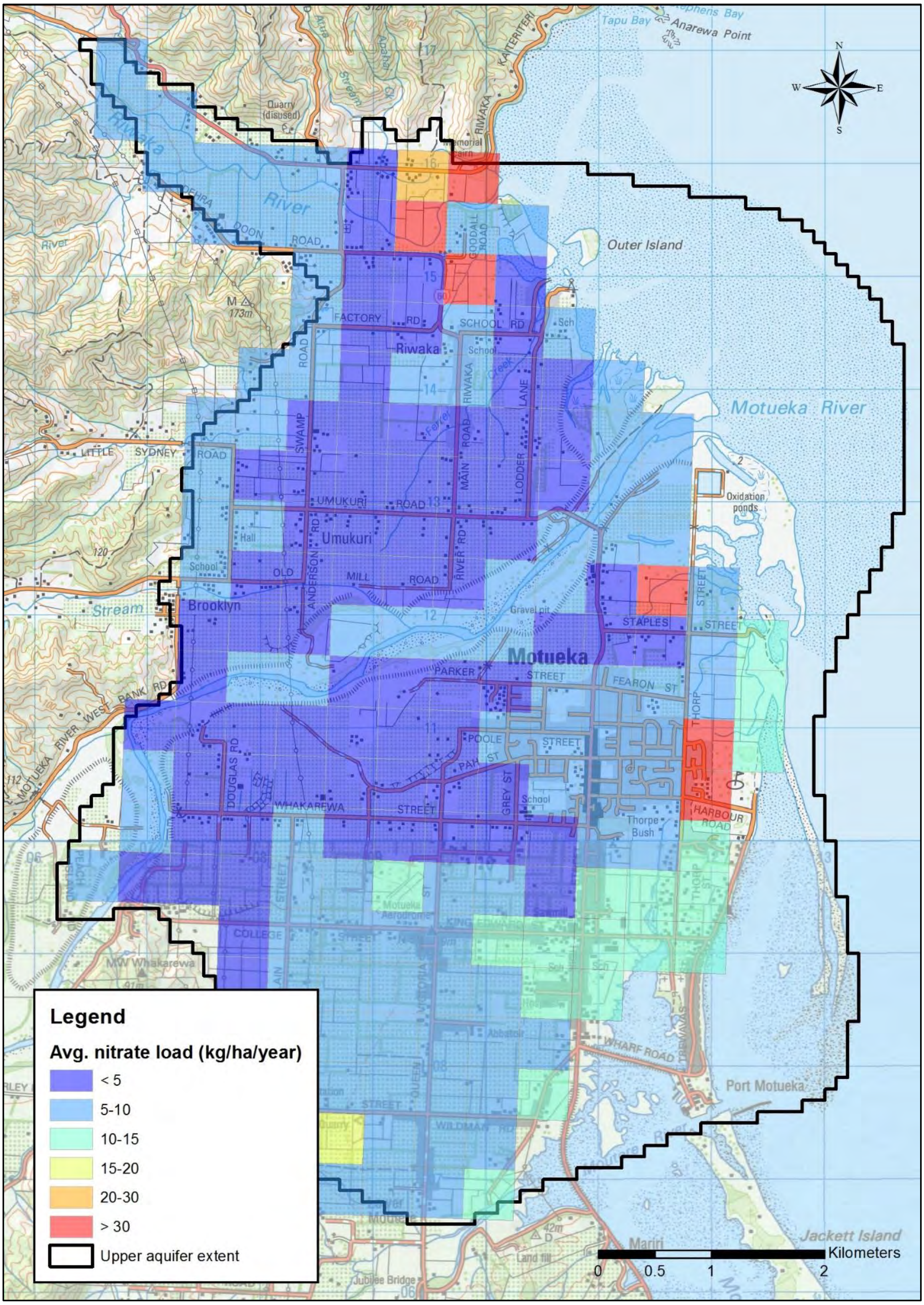


Figure 9-2: Average modelled mass of nitrate leaching losses from the Motueka-Riwaka plains for the 2011/12 predominant land use

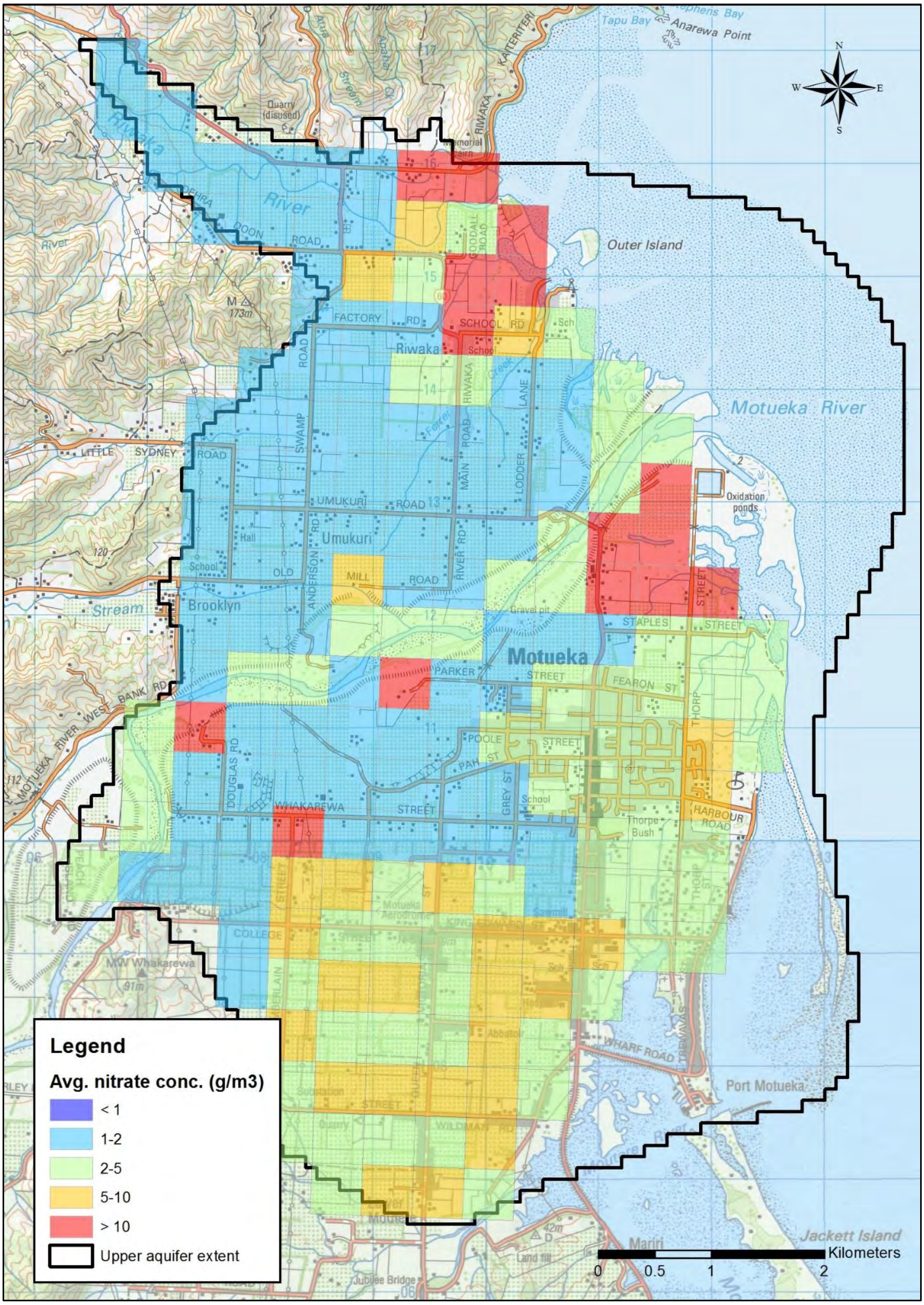


Figure 9-3: Average modelled nitrate concentrations in land surface recharge

Transient nitrate-nitrogen transport was then modelled using MT3DMS (Zheng *et al.*, 1999) for simulating groundwater transport. The transient MODFLOW flow field was used with the transient concentrations discussed above for the full model run period from 1990-2012. The resulting comparison between measured and modelled nitrate-nitrogen concentrations is show in Figure 9-4.

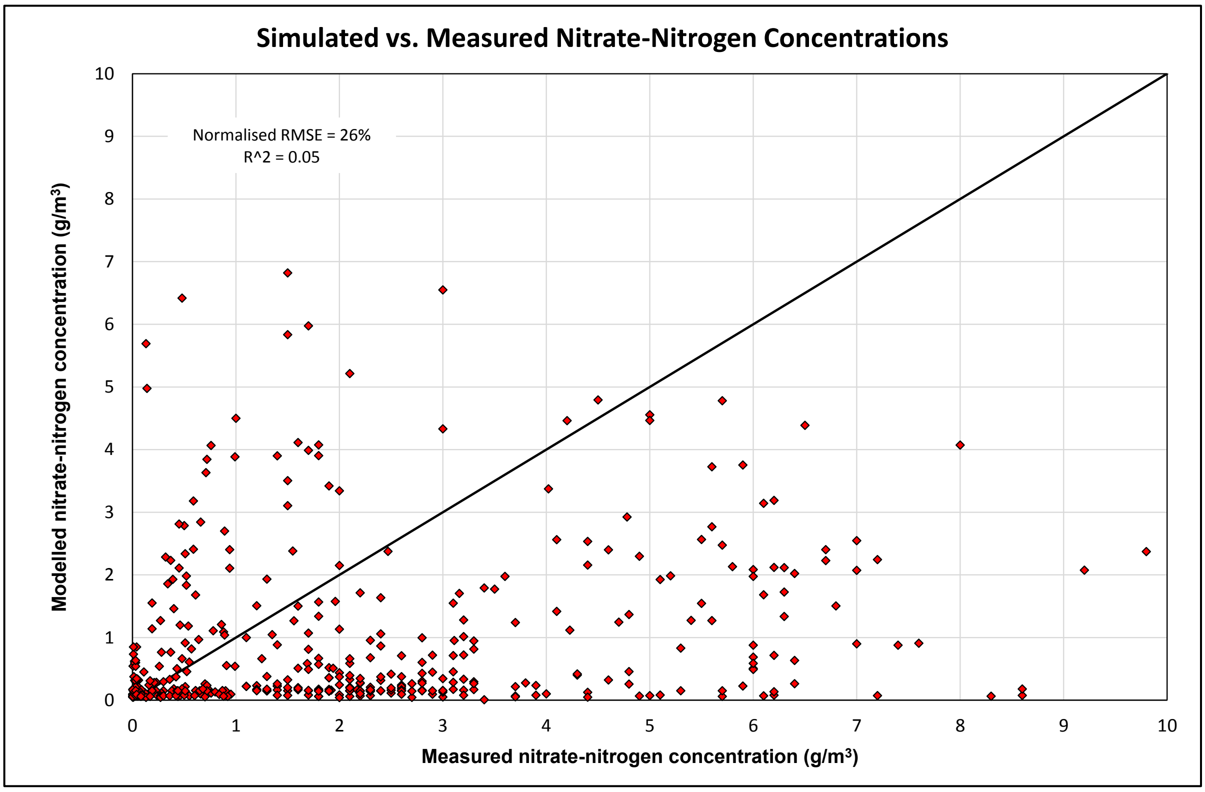
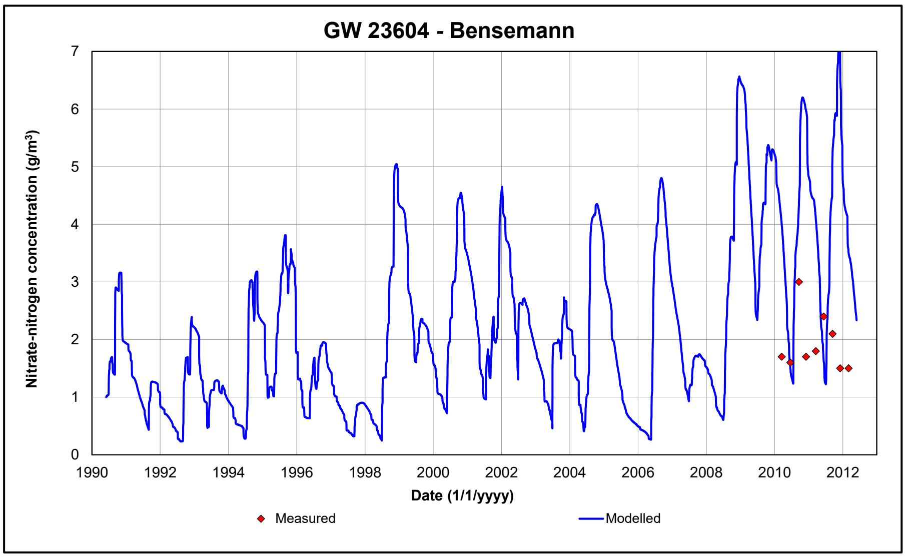
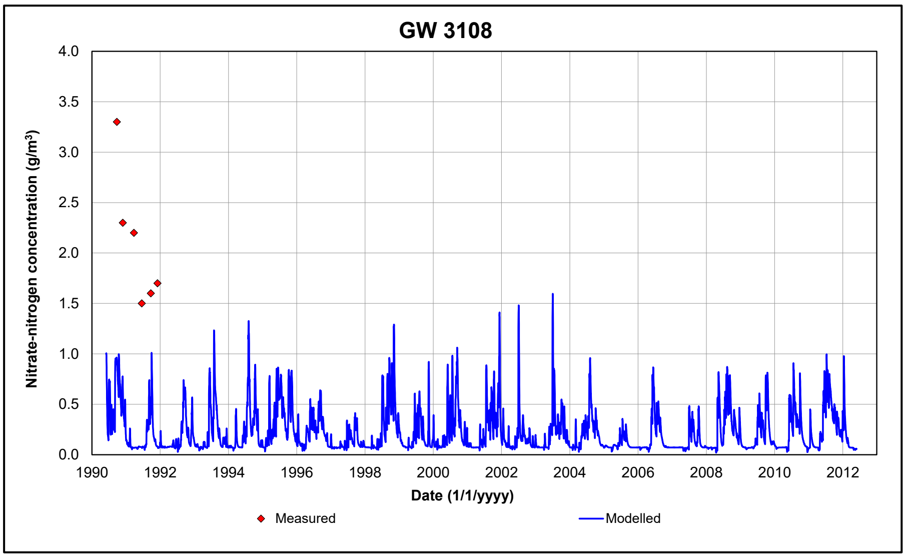


Figure 9-4: Modelled versus measured groundwater nitrate-nitrogen concentrations for the full model run period

Six monitoring bores with multiple records of nitrate-nitrogen measurements have been used to compare the transient modelled nitrate-nitrogen response with measured. The locations of these bores are shown in Figure 9-5. Time series of measured versus modelled transient concentrations are provided in Figure 9-6 and Figure 9-7.

Figure 9-5: Locations of nitrate-nitrogen monitoring bores with multiple readings





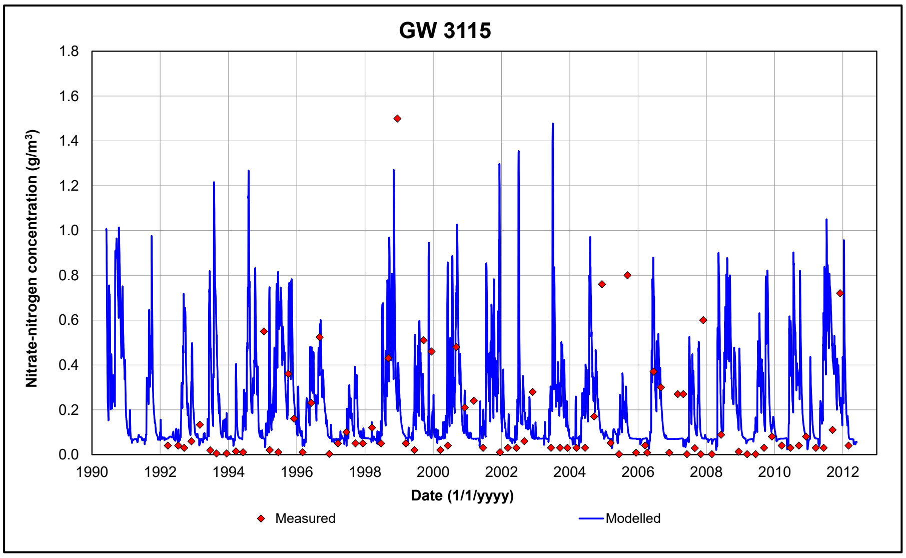
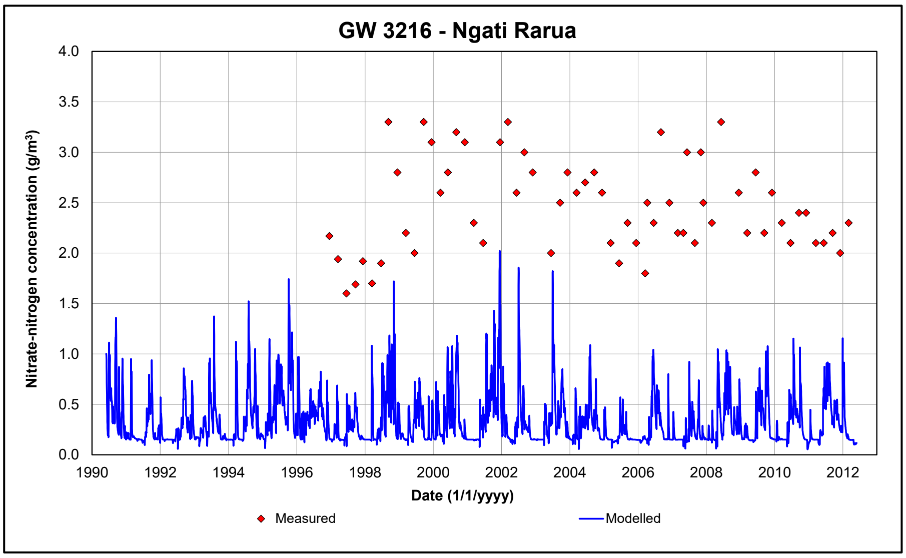
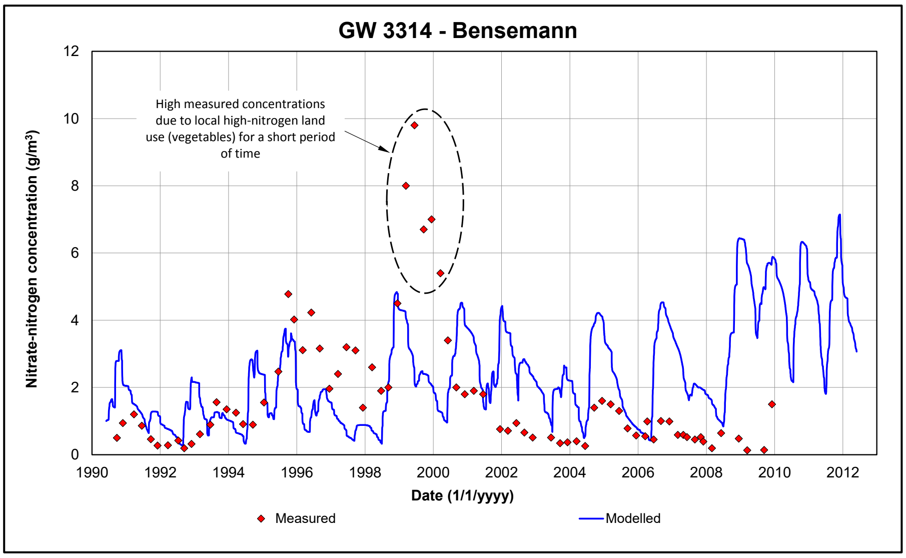


Figure 9-6: Modelled versus measured groundwater nitrate-nitrogen concentrations for selected monitoring bores with multiple records – part 1





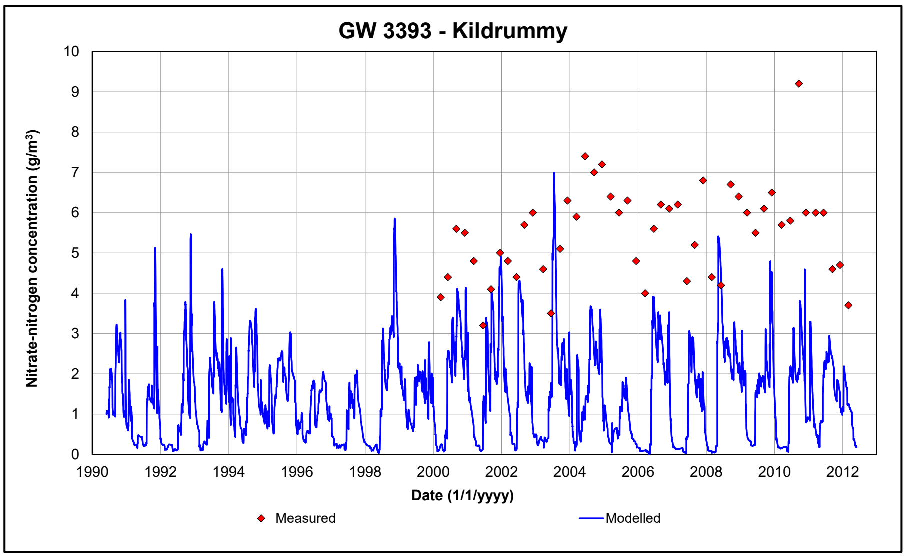


Figure 9-7: Modelled versus measured groundwater nitrate-nitrogen concentrations for selected monitoring bores with multiple records – part 2

The concentrations presented in Figure 9-4, Figure 9-6 and Figure 9-7 were achieved using the following general transport parameters:

- Longitudinal dispersivity: spatially variable (using pilot points) with values ranging between 10-20 m;
- Transverse dispersivity: equal to longitudinal;
- Vertical dispersity: 0.5 of longitudinal;
- Effective porosity: spatially variable (using pilot points) with values ranging between 0.005-0.025;
- Rivers: modelled as fixed concentration boundaries based on measured data (Figure 9-1).

Molecular diffusion was not included. Nitrate-nitrogen was modelled as a conservative tracer; therefore chemical and bio-chemical reactions were not simulated.

Based on Figure 9-4, Figure 9-6 and Figure 9-7, the transient transport model poorly replicates measured nitrate-nitrogen concentrations. This is primarily due to uncertainties and unknowns with estimating the land surface loadings. Further catchment-specific work is required to improve these estimates.

However, the dynamic response of nitrate-nitrogen concentrations is generally replicated well, such as is demonstrated in bores 3115 and 3314.

Measurements from bore 3314 show high nitrate-nitrogen concentrations over the period 1999-2001. This is indicated on Figure 9-7. According to Joseph Thomas (TDC, *pers. comm.*), this is due to a short period of vegetable growing on the land upgradient of the bore. Prior to 1999, kiwifruit were grown; post-2001, the land was converted to housing. Both of these land uses have much lower nitrate-nitrogen losses than vegetable growing. The model does not replicate this spike in concentrations as the temporal resolution of the modelled land use (Figure 3-10 to Figure 3-12) is coarser than the observed response.

Bore 3393 has consistently high nitrate nitrogen concentrations (approximately 3-9 g/m^3) compared to elsewhere on the plains. According to Joseph Thomas (TDC, *pers. comm.*), this is due to waste discharge from the nearby abattoir on Hau Road, which is not specifically included in the modelled land use.

10 CONCLUSIONS AND RECOMMENDATIONS

In the following paragraphs, a summary of the recommended sustainable level of additional abstraction is provided, as are suggestions for future resource monitoring and model enhancements.

10.1 Sustainable Additional Abstraction

Under historical patterns of climate (and subsequent river flows and land surface drainage), groundwater abstraction of over 30,000 m^3/day is predicted to be sustainable from the Parker Street well field without breaching coastal saltwater intrusion criteria. This is greater than recommend by Aqualinc (2008), primarily due to the improved accuracy of the model and the realistic representation of industrial and community supplies. However, a lesser rate may be needed if management of coastal drain flows is important to TDC.

Sea level rise is predicted to result in coastal backflow of sea water into the aquifer. If this occurs, mitigation against saltwater intrusion may be needed, which may require a lesser abstraction than the 30,000+ m^3/day discussed above. No assessment of the likely occurrence of sea level rise has been made in this investigation.

10.2 Resource Monitoring

Recommendations regarding additional monitoring of the groundwater resource and water restrictions have been determined based on the findings of this study. These are discussed in the following paragraphs.

The sustainable level of additional abstraction has been established based on the current allocated takes and allowing for potential future in-catchment needs. As the existing takes have not yet been fully utilised, the decisions have been based on modelling. It is likely that future resource use would increase as existing consents are fully utilised and additional consents are granted within specified allocation limits. This is the case for both abstractions within the Motueka-Riwaka Plains and from within the Motueka River catchment upstream of Woodman's Bend. It is important to continue collecting accurate field measurements (groundwater levels; river flows; spring flows etc.) to validate the calibrated model and expand the understanding of the groundwater system.

Managing abstractions without causing saltwater intrusion is the principal concern for TDC. Although saltwater intrusion has historically occurred (such as in the early 1990's and the 2014/15 summer), this has been attributed to localised pumping and the failure of non-return flaps in tidal-affected drains. The intrusion has not been wide spread. Mitigation of these probable causes has been undertaken and recent monitoring has indicated that the intrusion has been reversed.

To improve the understanding of the groundwater system, and how it responds to increased abstraction, it is recommended that the existing monitoring network be continued, specifically:

- Continue monitoring the existing groundwater network, including the presence of saltwater in coastal monitoring wells;
- Provide additional flow gaugings of Thorpe, Staples and Frys drains, both during summer low- and winter high-flow periods;
- Undertake additional gaugings of Motueka and Riwaka river flows to provide more calculations of river losses; and
- Continue monitoring flows, bed cross sectional shapes and elevations of the Motueka River, Riwaka River, Little Sydney Stream and Brooklyn Stream.

In addition, it is recommended that a piezometric survey of the plains be completed at a resolution finer than the spacing of the existing monitoring bores. This will provide information on the patterns of groundwater levels between and beyond the existing monitoring bores.

10.3 Future Model Enhancement

If further abstraction (over and above the maximum 30,000 m^3/day modelled) is to be considered, it is recommended that the results from the additional monitoring discussed above be incorporated into the groundwater model, and the model updated accordingly. This updated model should then be used to consider the effects of the additional abstraction.

If TDC are concerned about saltwater intrusion risk due to future sea level rise, and want to investigate suitable mitigation measures, then density-dependent flow should be incorporated into the model.

Site-specific calculations of land surface nitrate loadings should be completed to improve the accuracy of the numerical transport modelling.

REFERENCES

Aqualinc (2007a): *Motueka-Riwaka Plains Groundwater Resource Investigation: Aquifer Testing (February 2007).* Report No. L07021/1, prepared for Tasman District Council's Engineering Department. Aqualinc Research Ltd.

Aqualinc (2007b): *Motueka-Riwaka Plains Groundwater Resource Investigation: Well Field Design.* Report No. L07021/2, prepared for Tasman District Council's Engineering Department. Aqualinc Research Ltd.

Aqualinc (2007c): *Motueka-Riwaka Plains Groundwater Resource Investigation: Model Update Report.* Report No. L07021/3, prepared for Tasman District Council's Engineering Department. Aqualinc Research Ltd.

Aqualinc (2007d): *Motueka-Riwaka Plains Groundwater Resource Investigation: Technical Assessment of Environmental Effects for Proposed Community Water Supply.* Report No. L07021/4, prepared for Tasman District Council's Engineering Department. Aqualinc Research Ltd.

Aqualinc (2008): *Motueka-Riwaka Plains Groundwater Resource Investigation: Model Enhancement and Allocation Assessment.* Report No. L07021/9, prepared for Tasman District Council's Environment & Planning Department. Aqualinc Research Ltd.

Aqualinc (2014): *Groundwater Modelling of the Upper Waikato Catchment: Stage 5.* Report No. C14061/1. Prepared for Waikato Regional Council. June 2014.

ASTM (2002): D5981-96(2002) *Standard guide for calibrating a ground-water flow model application.* American Society for Testing and Materials.

Aqualinc (2016): Impact of Climate Cycles and Trends on Selwyn District Water Assets. Prepared for Selwyn District Council by Aqualinc Research Ltd, May 2015.

Barnet, B; Townley, LR; Post, V; Evans, RE; Hunt, RJ; Peeters, L; Richardson, S; Werner, AD; Knapton, A; Boronkay, A. (2012): *Australian Groundwater Modelling Guidelines.* Waterlines Report. Published by the Australian National Water Commission, Canberra. June 2012.

Bell, RG (2014): *Evidence of Robert Gordon Bell.* Environment Court appeal: C&D Gallagher and Tasman District Council. ENV 2012 WLG 000052. 29 April 2014.

Cameron, KC; Di, HJ; Moir, JL (2013*): Nitrogen losses form the soil/plant system: a review.* Annals of Applied Bilogy, **162**(2013) 145-173.

Donnell, B.P. and the ERDC-CHL Groundwater Team (2004): *DDJC-Sharpe Defense Distribution Depot: FEMWATER 3D transport model of TCE plume migration with natural attenuation.* US Army Corps of Engineers report. March 2004.

Dougherty, J (2010): *PEST – Model-independent parameter estimation, User Manual: 5th Edition.* Watermark Numerical Computing. Version 12.3 of PEST used.

Fenemor, A; Green, S; Dryden, G; Samarasinghe, O; Newsome, P; Price, R; Betts, H; Lilburne, L (2015): *Crop Production, Profit and Nutrient Losses in Relation to Irrigation Water Allocation and Reliability – Waimea Plains, Tasman District.* Prepared for Ministry for Primary Industries by Landcare Research, Nelson, New Zealand, June 2015.

Fenemor, A; Price, R; Green, S (2016): *Modelling the Source and Fate of Nitrate-Nitrogen Losses from Waimea Plains Land Uses.* Prepared for Tasman District Council (Envirolink Advice Grant: 1592-TSDC116) by Landcare Research, Nelson, New Zealand, January 2016.

GMS (2014): *Geological modelling system (version 9.2.5).* Software developed by Brigham Young University (USA). Support and distribution by Aquaveo. Build date 21 February 2014. Copyright 2014.

Harbaugh, AW; Banta, ER; Hill, MC; McDonald, MG (2000): *MODFLOW-2000, The US Geological Survey Modular Ground-Water Model – User Guide to Modularization Concepts and the Ground-Water Flow Process.* US Geological Survey Open-File Report 00-92.

Harbaugh, AW (2005): *MODFLOW-2005, The US Geological Survey Modular Ground-Water Model – The Ground-Water Flow Process.* US Geological Survey Techniques and Methods 6-A16.

Hill, MC (1998): *Methods and guidelines for effective model calibration.* US Geological Survey Water-Resources Investigations Report 98-4005.

McDonald, MG and Harbaugh, AW (1988): *Techniques of Water-Resource Investigations of the United States Geological Survey. Chapter A1. A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model.* US Geological Survey.

MDBC (2001): *Groundwater flow modelling guideline.* Murray-Darling Basin Commission.
URL: www.mdbc.gov.au/nrm/water_management/groundwater/groundwater_guides

Menneer. JC; Ledgard, SF; Gillingham, AG (2004): *Land Use Impacts on Nitrogen and Phosphorus Loss and Management Option for Intervention.* AgResearch client report. Prepared for Environment Bay of Planet. June 2004.

MfE (2002): *Groundwater model audit guidelines.* Prepared for the Ministry for the Environment by Pattle Delamore Partners Ltd under funding from the Sustainable Management Fund. October 2002.

MfE (2014): *How Climate Change Affects New Zealand. Climate change predictions for the Nelson-Tasman Region.* October 2014.
URL: http://www.mfe.govt.nz/climate-change/how-climate-change-affects-nz/how-might-climate-change-affect-my-region/nelson-and

Niswonger, RG and Prudic, DE (2009): *Documentation of the Streamflow-Routing (SFR2) Package to Include Unsaturated Flow Beneath Streams – A Modification to SFR1.* US Geological Survey Techniques and Methods 6-A13. 50 p. Revised August 2009.

NIWA (2015): *Climate Change and Variability – Tasman District.* Prepared for Tasman District Council by the National Institute of Water and Atmospheric Research (NIWA), August 2015.

Prudic, DE; Konikow, LF; Banta, ER (2004): *A New Streamflow-Routing (SFR1) Package to Simulate Stream-Aquifer Interaction With MODFLOW-2000.* US Geological Survey Open-File Report 2004-1042.

Rattenbury, MS; Cooper, RA; Johnston, MR (1998): *Geology of the Nelson Area.* Institute of Geological and Nuclear Sciences 1:250,000 geological map 9.1 sheet + text. Lower Hutt, New Zealand: Institute of Geological and Nuclear Sciences Ltd.

Robb, C (1999): *Groundwater Model of Motueka/Riwaka Plains Aquifer System.* Report No. 2325/1, prepared for Tasman District Council. Lincoln Environmental.

Robb, C and Weir, J (2002): *Regional-Scale Effects of Water Export from the Central Plains Zone, Motueka Plains Aquifer.* Report No. 4553/1, prepared for Tasman District Council. Lincoln Environmental.

Rutherford, K; Palliser, C; Wadhwa, S (2009): *Nitrogen exports for the Lake Rotorua catchment - calibration of the ROTAN model.* NIWA client report HAM2009-019. April 2009.

Streeter, VL; Wylie, EB (1981): *Fluid Mechanics.* First SI Metric Edition. McGRaw-Hill Ryerson Ltd.

Zheng, C and Wang, P (1999): *MT3DMS: A Modular Three-Dimensional Multispecies Transport Model for Simulation of Advection, Dispersion and Chemical Reactions of Contaminants in Groundwater Systems; Documentation and User's Guide.* Prepared for US Army Corps of Engineers. Engineer Research and Development Centre. Contract Report SERDP-99-1. December 1999.

Overview of the IRRICALC crop-soil water balance model

To calculate the irrigation demand and subsequent land surface drainage, Aqualinc's IRRICALC water balance model was used. The model simulates how the use of water in agriculture varies with crop, soil type, representative daily climatic conditions and irrigation strategies. The basis of the model is a daily soil moisture balance and an irrigation scheduling component. These components are described in more detail below.

The model was developed by Lincoln Environmental as part of a research project funded by the Foundation for Research, Science and Technology (FRST). It has been based on New Zealand field data and was initially tested on Canterbury irrigation schemes. Further details and this testing can be found in AEI (1991)[12]. More recently, the model has been tested by Aqualinc (2013)[13].

Soil Moisture Balance Component

The model is designed to simulate a single paddock in which a specified crop is grown. The soil is treated as a reservoir, with a capacity equal to the maximum plant available water content of the soil. Soil moisture levels are calculated on a daily basis in response to daily data on climate (rainfall and potential evapotranspiration), crop uptake and irrigation using the following equation:

$$Soil\ moisture(day_t) = Soil\ moisture(day_{t-1}) + rainfall + irrigation - actual\ evapotranspiration$$

Actual evapotranspiration (AET) describes the combined effects of evaporation from the soil and transpiration by the crop. The model considers AET to be a function of the atmospheric demand for water, crop characteristics (including stage of growth) and the soil moisture content in the root zone. The atmospheric demand for water is the daily potential evapotranspiration calculated from meteorological conditions such as radiation, wind run and temperature. Crop characteristics can vary throughout a season to reflect relative ground cover, root development and the onset of crop maturity. Soil moisture influences evapotranspiration because as the soil becomes drier, it becomes increasingly difficult for more moisture to be transpired or evaporated.

Once calculated, soil moisture levels then become an input to the irrigation scheduling component of the model. The model assumes that the maximum amount of water a soil can hold is the soil's available water capacity. Water (either from rainfall or irrigation) in excess of the soil's available water capacity is assumed to drain through the root zone and into underlying substrata as land surface recharge.

---

[12] AEI (1991): *A model for assessing the impact of Regional Water Plans on irrigated agriculture.* AEI Science Report, 1991; Agricultural Engineering Institute.

[13] Aqualinc (2013): *Field Verification of the Water Balance Model used for Development of Irrigation Guidelines for the Waikato Region*. Prepared by Aqualinc Research Ltd for Waikato Regional Council. Report No 12003/2. April 2013.

Irrigation Scheduling Component

The depth of water applied and the timing of irrigation is determined by the irrigation strategy. For a given irrigation strategy, the model predicts the timing and depth of irrigation applications based on the crop type, stage of growth, and subsequent water requirements. It also accounts for the irrigation return period.

Irrigation is triggered when the soil water content is reduced below a user-defined level (e.g. 50% of the maximum available soil water). The irrigation depth can be determined in two ways. Firstly, it can be specified by the user as a fixed amount. Secondly, it can be calculated by the model as the depth required to restore the soil water content to a user defined level (e.g. field capacity).

A user-defined irrigation efficiency factor is also set to allow for on-farm losses due to wind losses, surface runoff and non-uniform distribution of water.

The following summarises the irrigation rules applied to each crop type:

Apples:

- Trickle irrigation with a coefficient of uniformity of 90%
- Irrigation season 1 October through 31 March
- Return period of 1 day
- Application depth of 10 mm
- Maximum rooting depth = 550 mm
- Irrigation on trigger = 75% of PAW

Grapes and Currants:

- Trickle irrigation with a coefficient of uniformity of 90%
- Irrigation season 1 September through 30 April
- Return period of 1 day
- Application depth of 5 mm
- Maximum rooting depth = 900 mm
- Irrigation on trigger = 30% of PAW

Hops:

- Spray irrigation with a coefficient of uniformity of 80%
- Irrigation season 1 October through 31 March
- Return period of 10 day
- Application depth of 50 mm
- Maximum rooting depth = 550 mm
- Irrigation on trigger = 60% of PAW

Kiwifruit:

- Trickle irrigation with a coefficient of uniformity of 90%
- Irrigation season 1 October through 30 April
- Return period of 1 day
- Application depth of 10 mm
- Maximum rooting depth = 500 mm
- Irrigation on trigger = 60% of PAW

Maize:

- Spray irrigation with a coefficient of uniformity of 70%
- Irrigation season 1 October through 31 March
- Return period of 10 day
- Application depth of 50 mm
- Maximum rooting depth = 550 mm
- Irrigation on trigger = 60% of PAW

Vegetables:

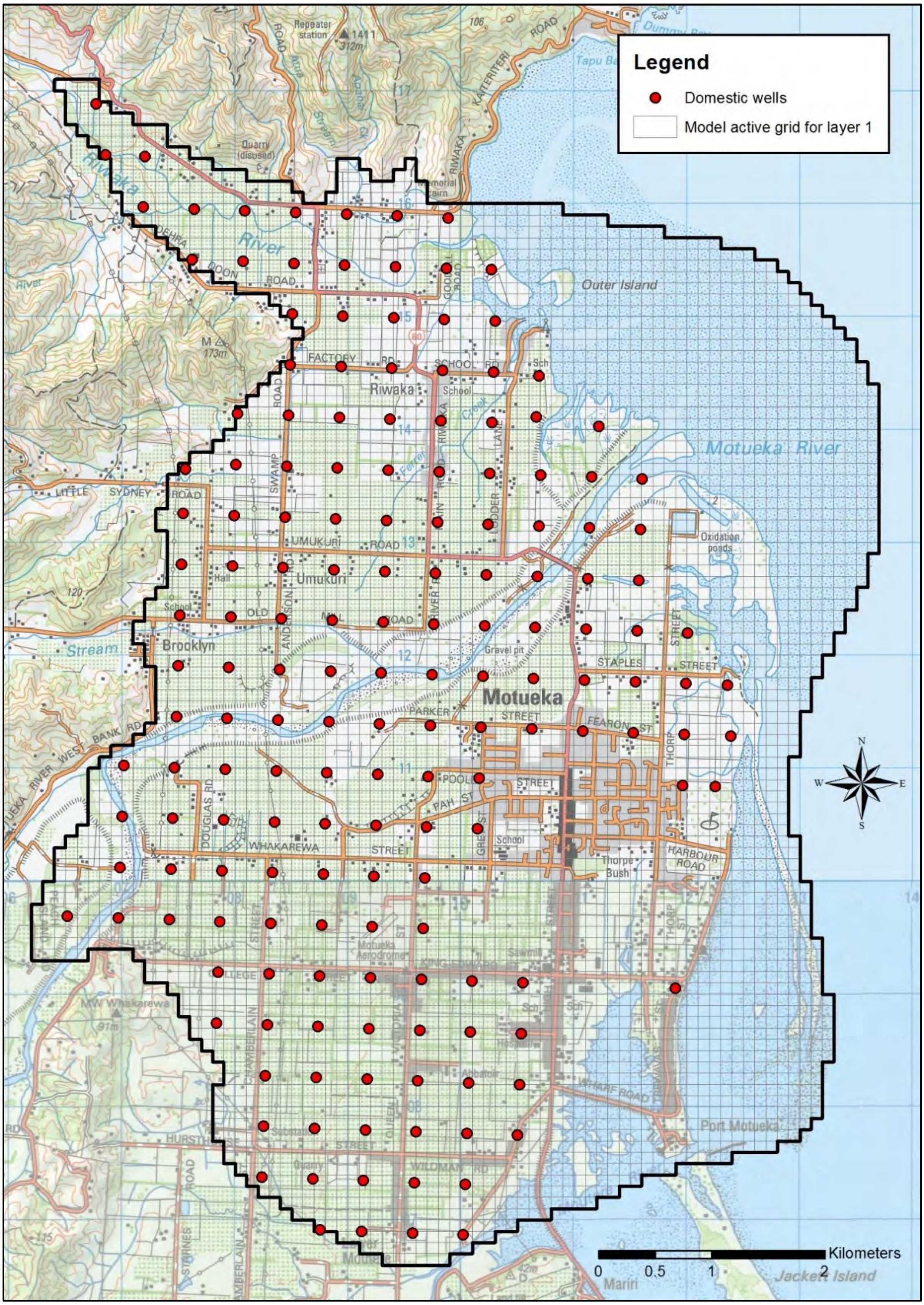
- Spray irrigation with a coefficient of uniformity of 80%
- Irrigation season 1 October through 31 March
- Return period of 3 day
- Application depth of 20 mm
- Maximum rooting depth = 550 mm
- Irrigation on trigger = 60% of PAW

Pasture:

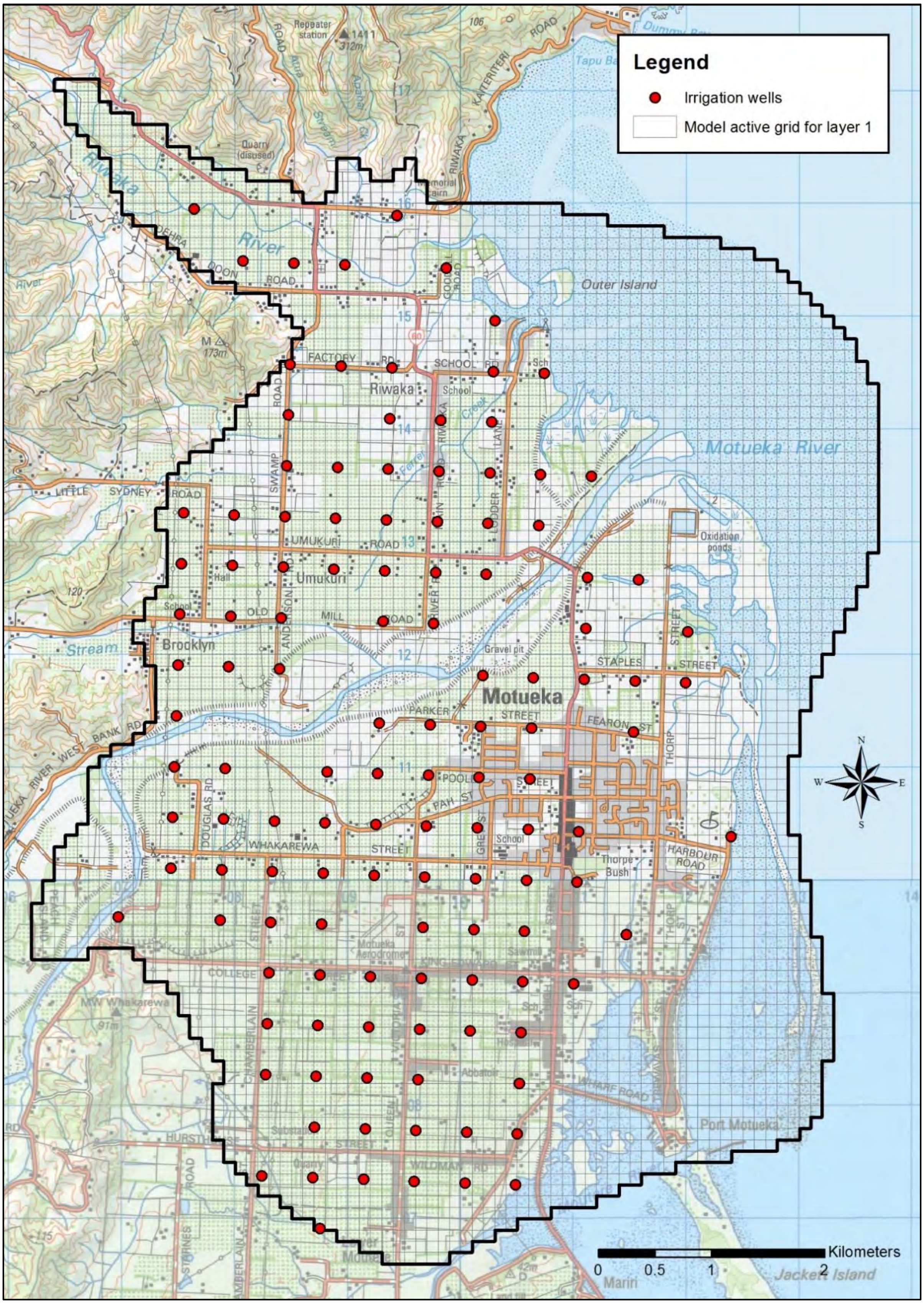
- Spray irrigation with a coefficient of uniformity of 70%
- Irrigation season 1 October through 31 March
- Return period of 10 day
- Application depth of 50 mm
- Maximum rooting depth = 550 mm
- Irrigation on trigger = 50% of PAW

Appendix B: Abstraction wells

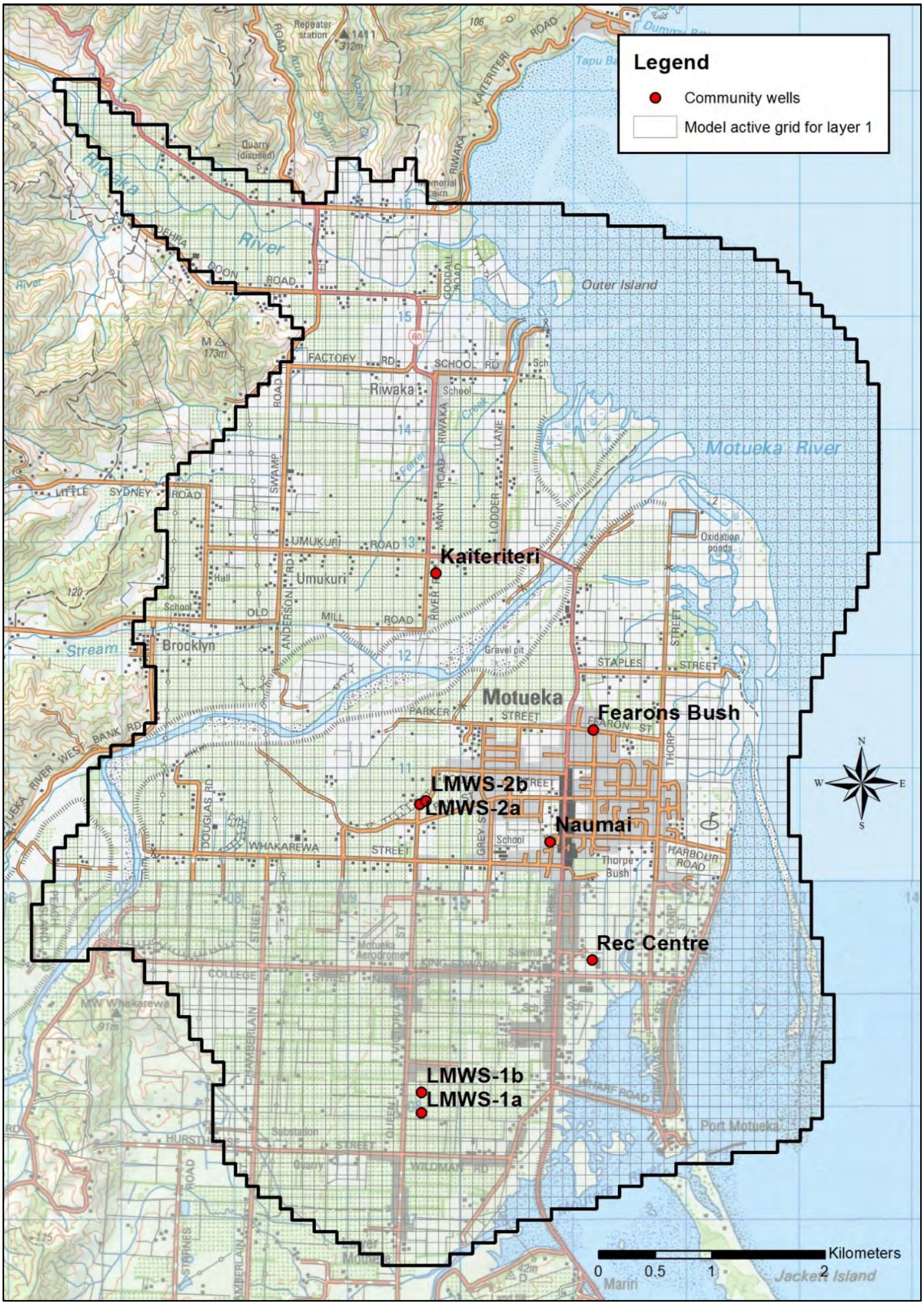
The following maps illustrate the domestic, community, industrial and irrigation wells represented in the model. The locations of industrial and community wells shown on these maps are true locations. However, for domestic and irrigation takes, there are multiple wells at close proximity in some places. Therefore, to simplify the modelling process, these wells have been amalgamated externally from MODFLOW. Abstraction has been calculated and assigned to the centre of the individual land use cells (where applicable) shown in Figure 3-10 through to Figure 3-12.



Representative location of domestic wells



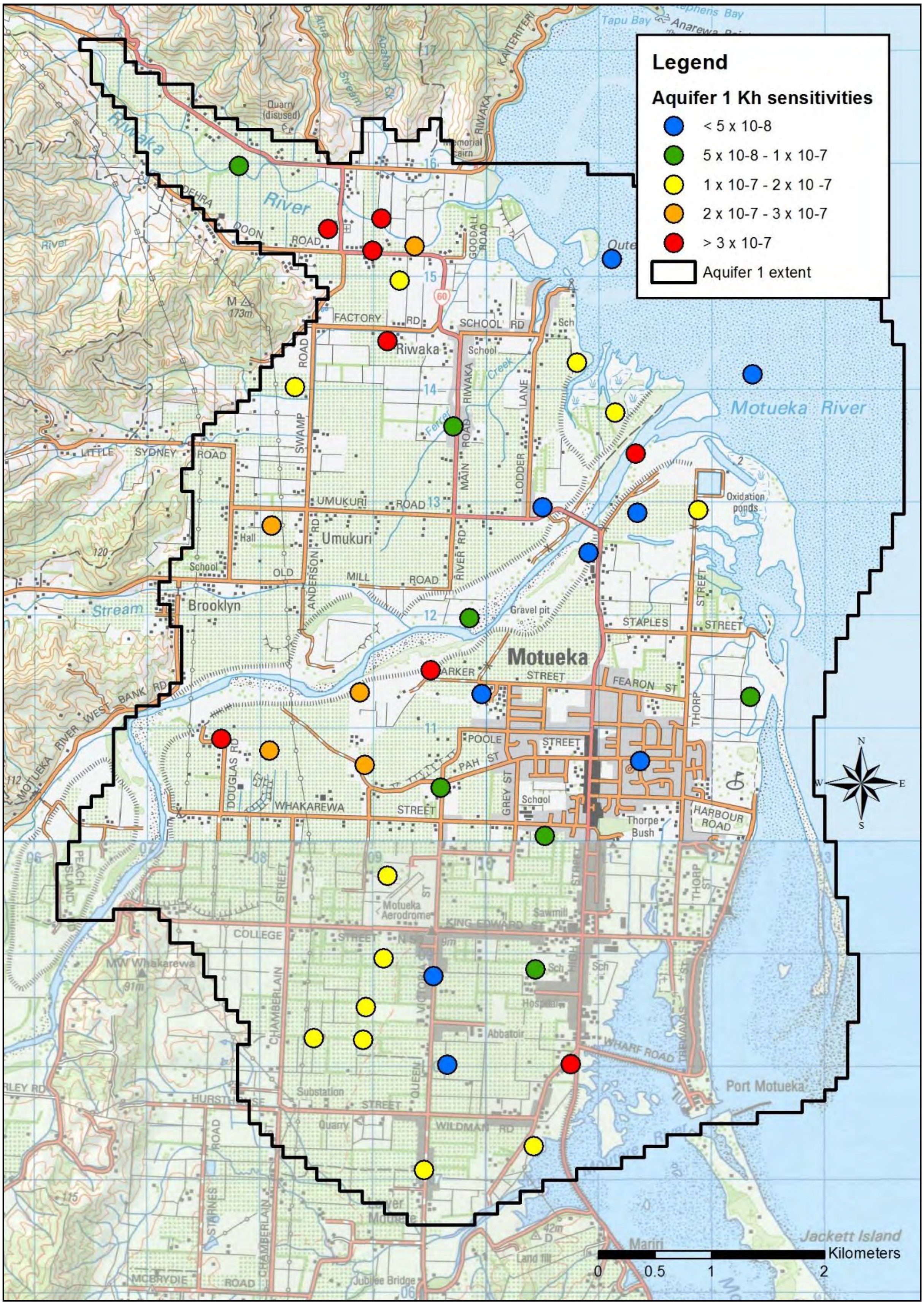
Representative location of irrigation wells

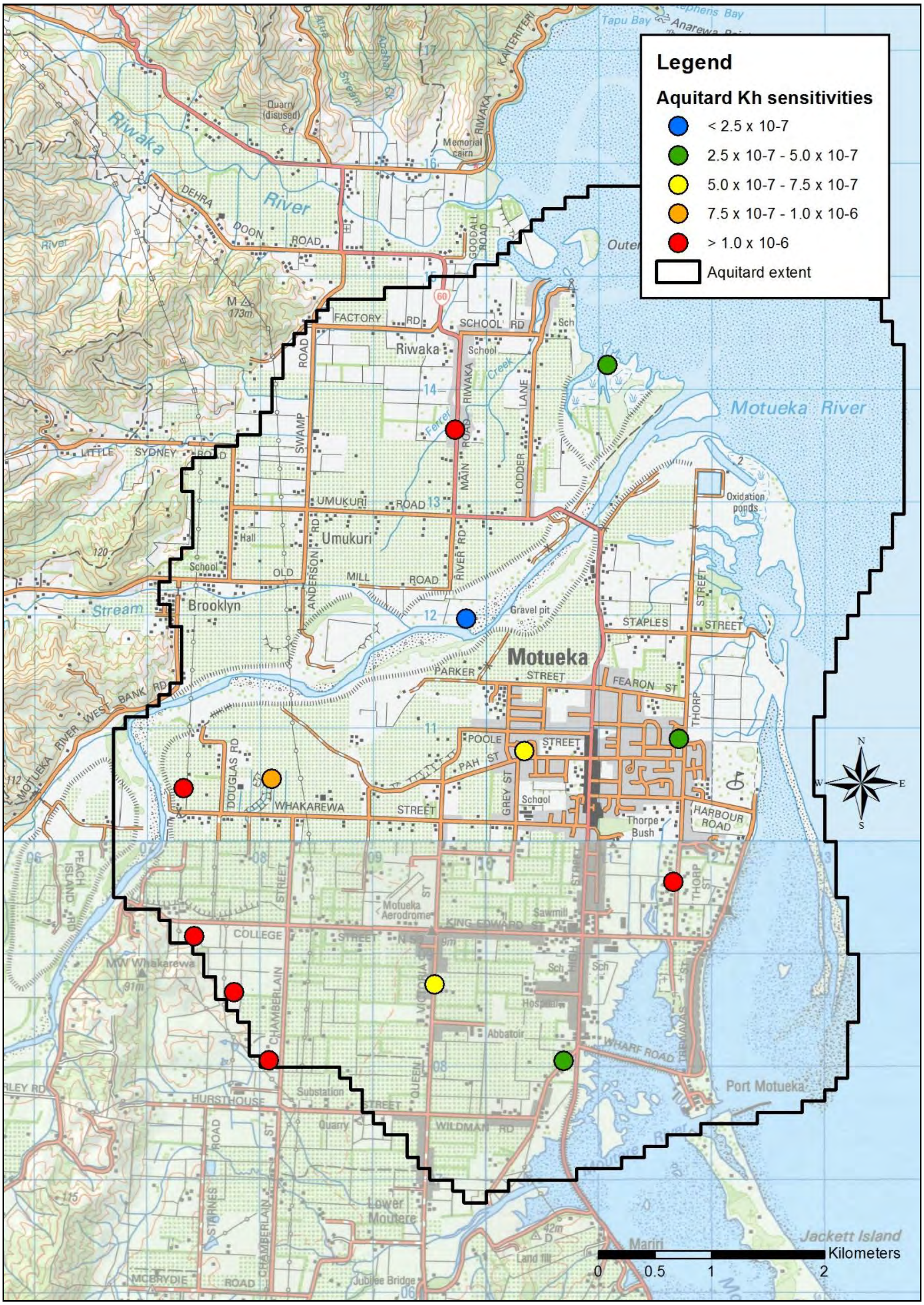


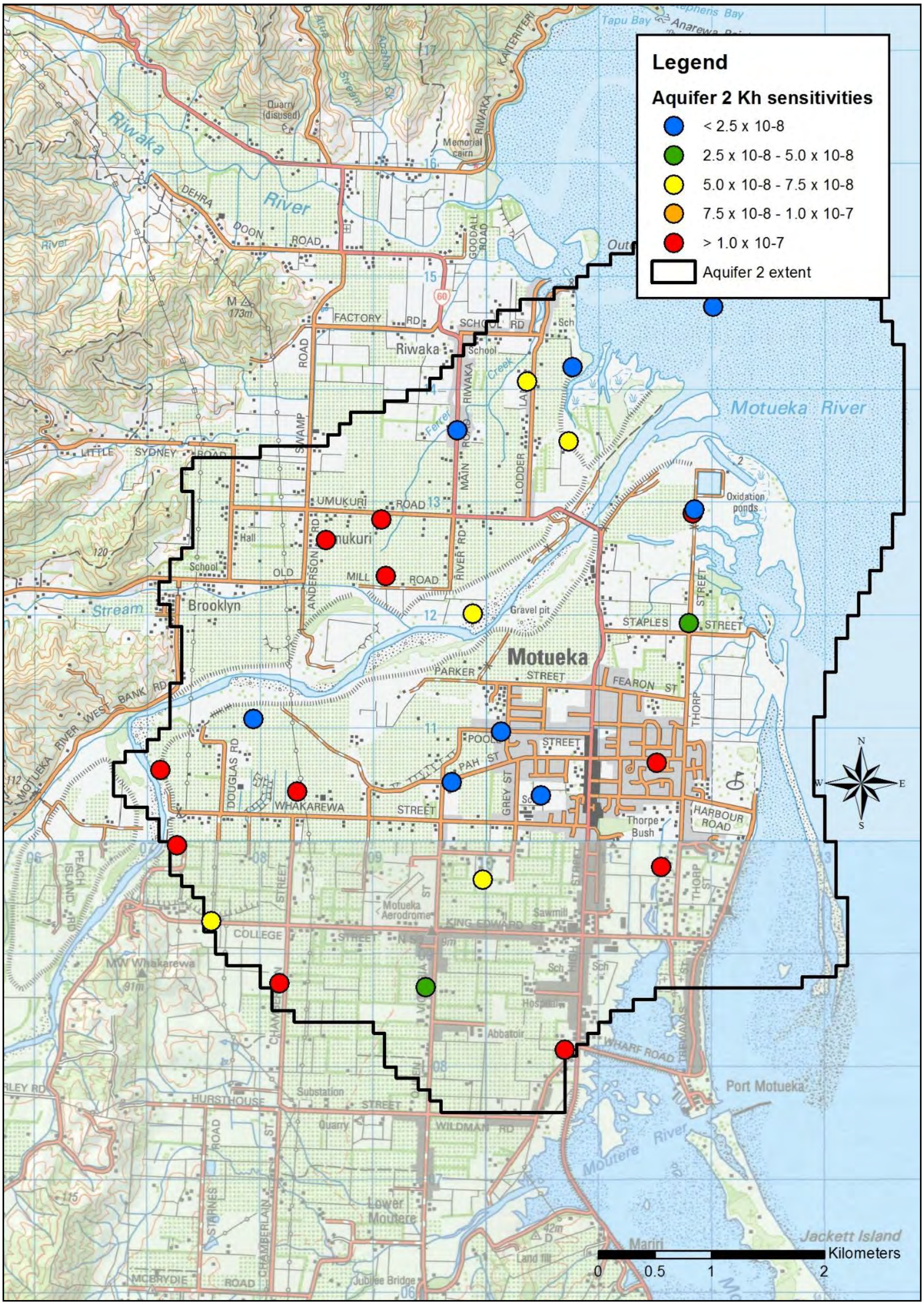
Location of community wells

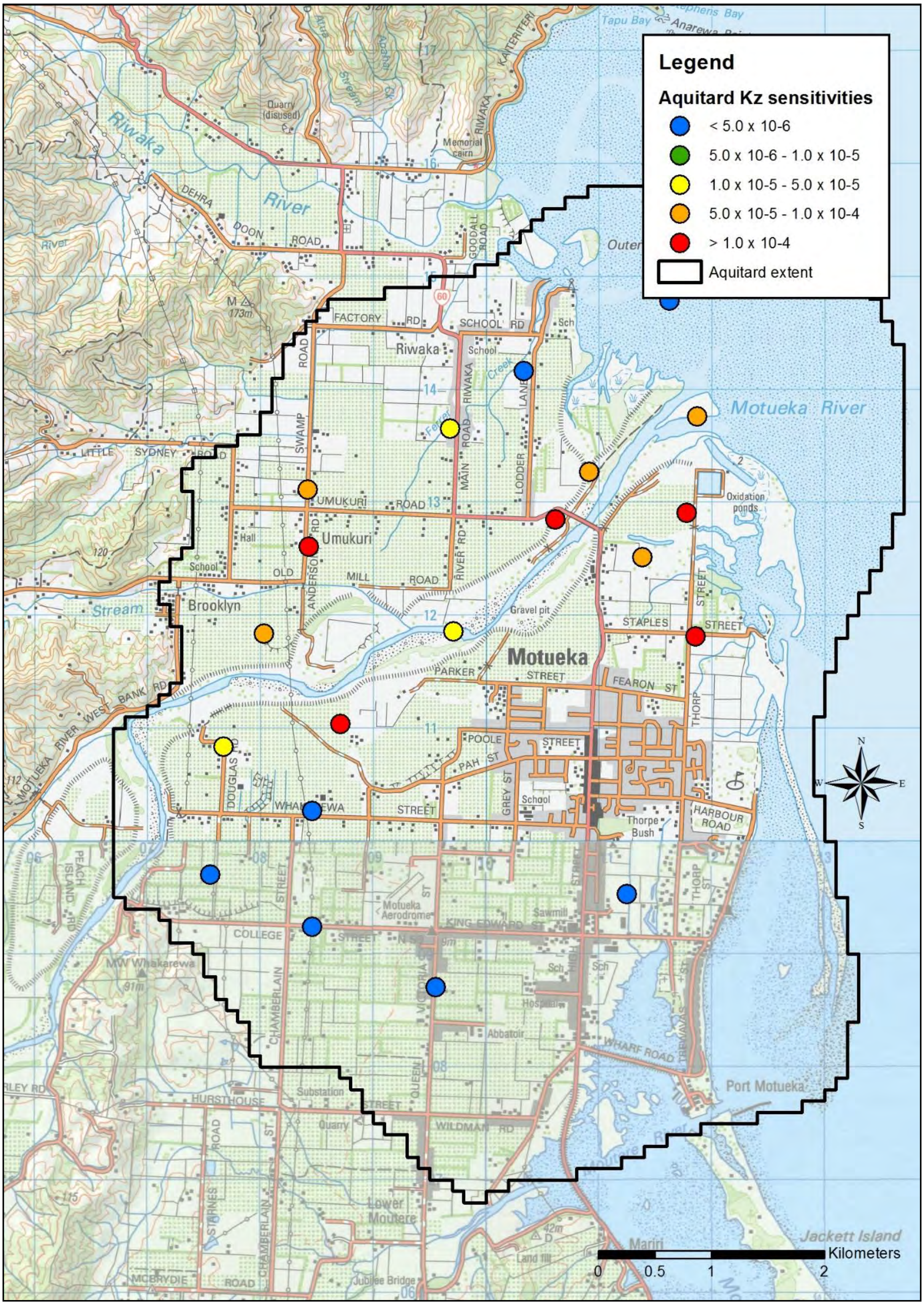
Location of industrial wells

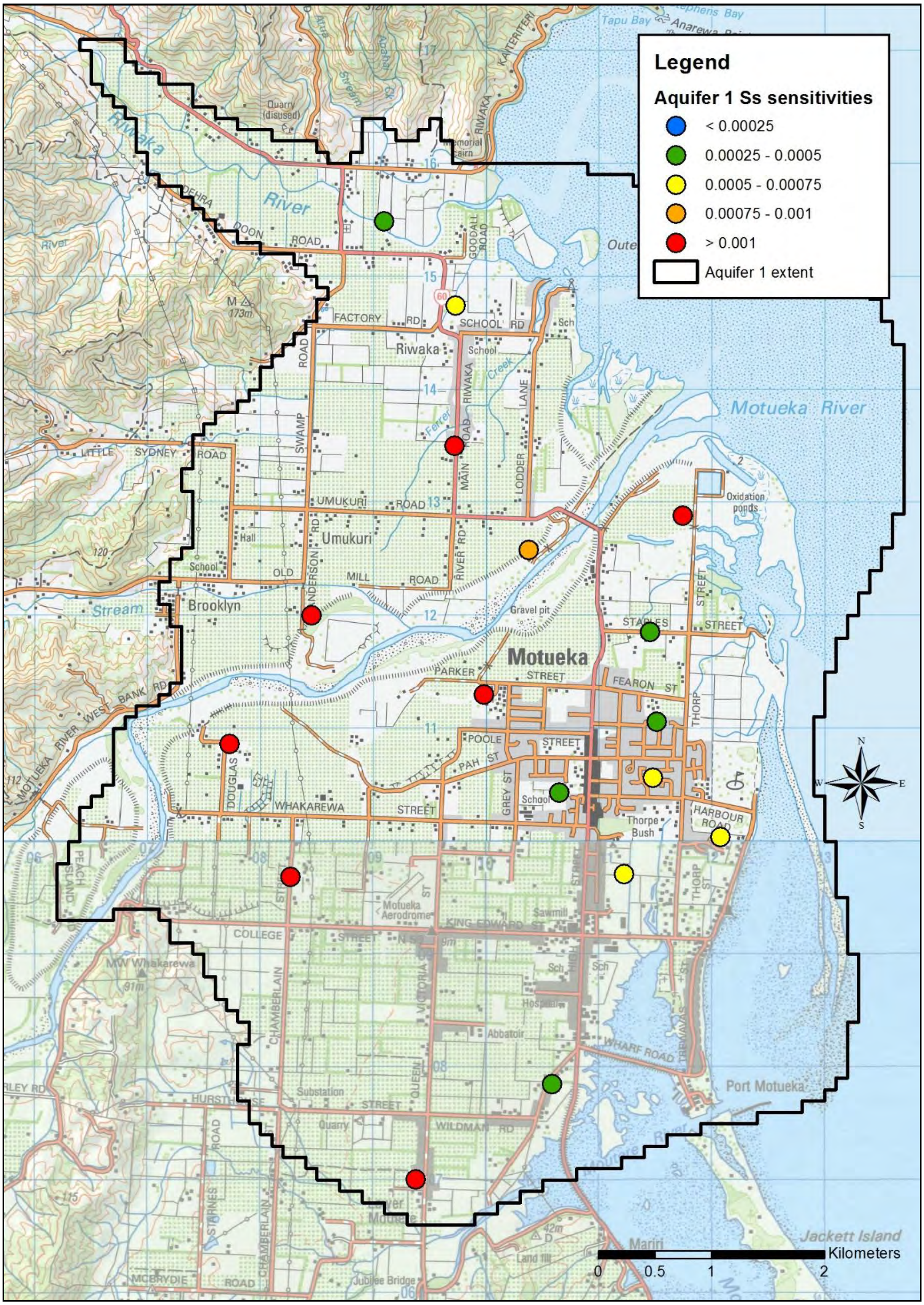
Appendix C: Pilot point sensitivities

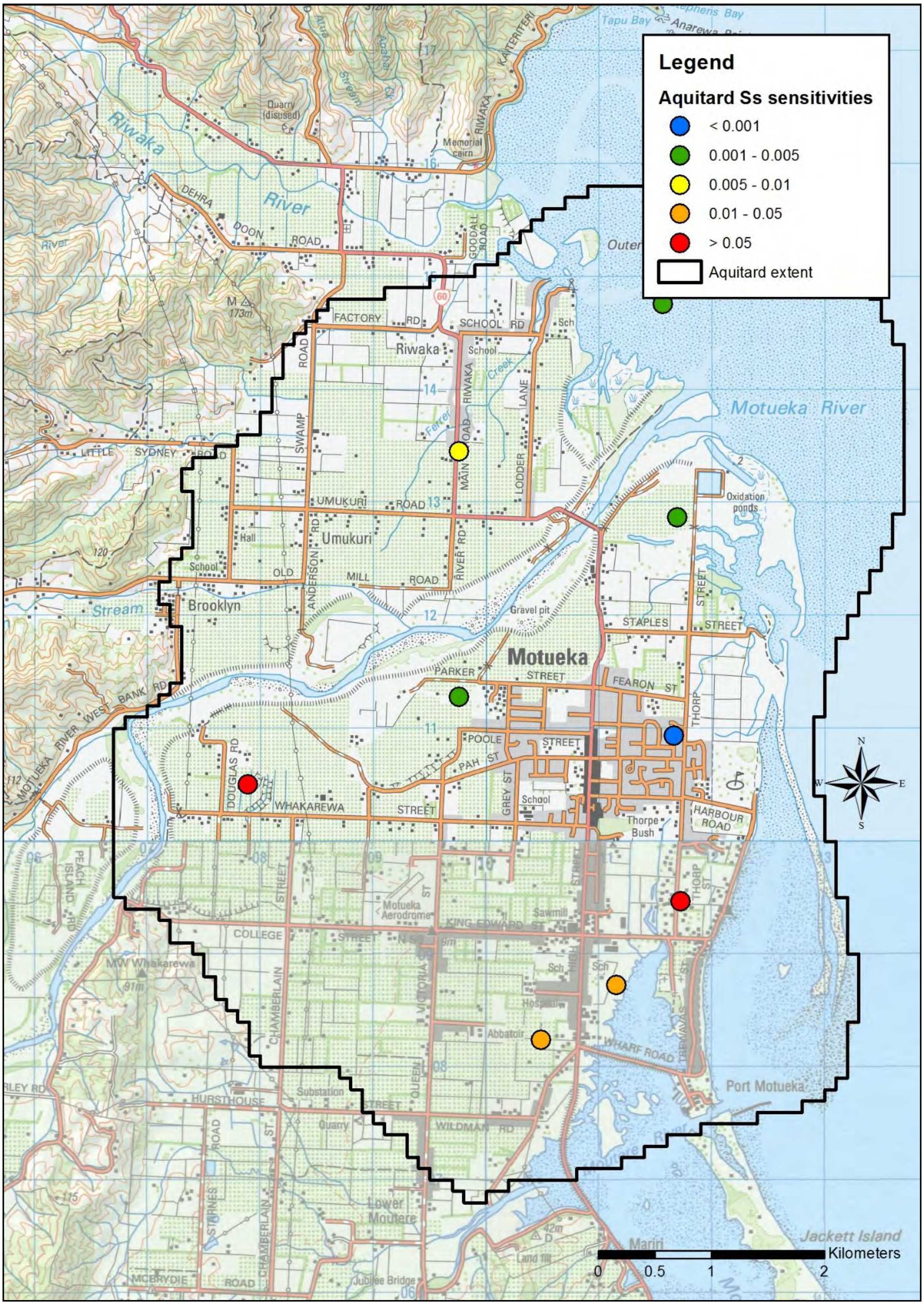

Legend
Aquifer 1 Kh sensitivities
< 5 x 10-8
5 x 10-8 - 1 x 10-7
1 x 10-7 - 2 x 10 -7
2 x 10-7 - 3 x 10-7
> 3 x 10-7
Aquifer 1 extent
Riwaka
Motueka
Motueka River
Umukuri
Brooklyn
Port Motueka
Jackett Island
0
0.5
1
2
Kilometers
N
S
E
W

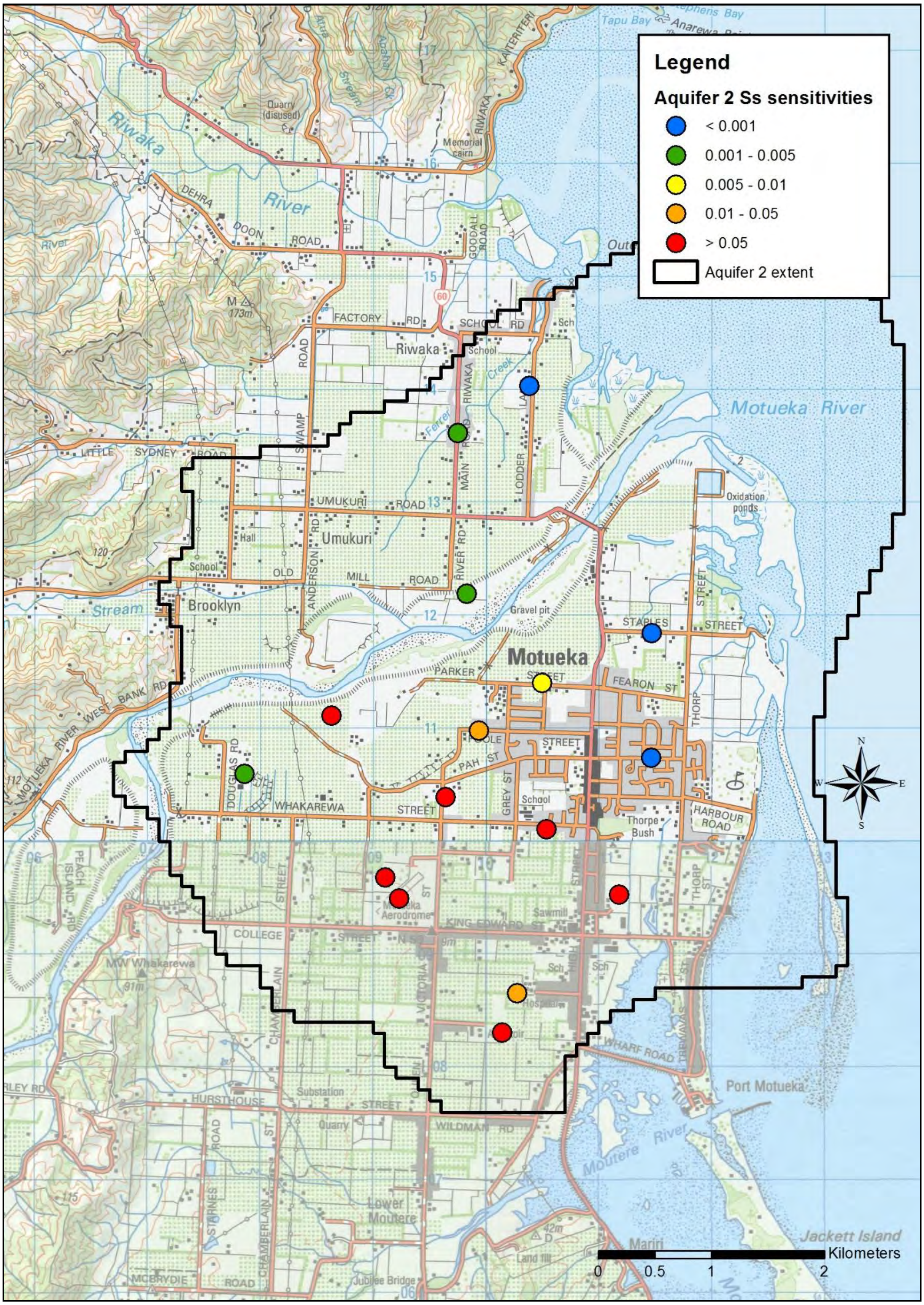

Legend
Aquitard Kh sensitivities
● < 2.5 x 10-7
● 2.5 x 10-7 - 5.0 x 10-7
● 5.0 x 10-7 - 7.5 x 10-7
● 7.5 x 10-7 - 1.0 x 10-6
● > 1.0 x 10-6
Aquitard extent
Kilometers
0
0.5
1
2
N
S
E
W
Riwaka
Umukuri
Brooklyn
Motueka
Motueka River
Riwaka River
Port Motueka
Jackett Island
Lower Moutere
Tapu Bay
Oxidation ponds
Thorpe Bush
Motueka Aerodrome


Legend
Aquifer 2 Kh sensitivities
< 2.5 x 10-8
2.5 x 10-8 - 5.0 x 10-8
5.0 x 10-8 - 7.5 x 10-8
7.5 x 10-8 - 1.0 x 10-7
> 1.0 x 10-7
Aquifer 2 extent
Riwaka
Motueka
Brooklyn
Motueka River
Riwaka River
Port Motueka
Moutere River
Jackett Island
Lower Moutere
Kilometers
0
0.5
1
2
N
E
S
W

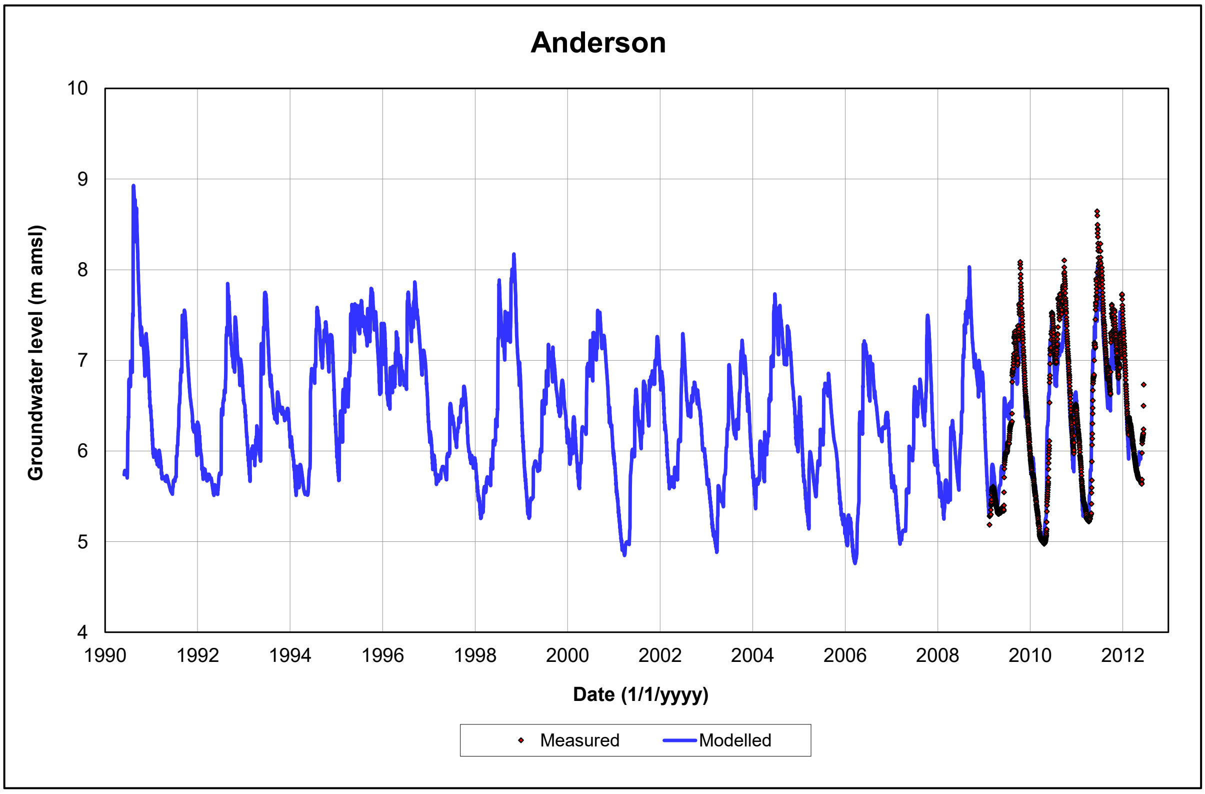

Legend
Aquitard Kz sensitivities
● < 5.0 x 10-6
● 5.0 x 10-6 - 1.0 x 10-5
● 1.0 x 10-5 - 5.0 x 10-5
● 5.0 x 10-5 - 1.0 x 10-4
● > 1.0 x 10-4
☐ Aquitard extent
Riwaka
Umukuri
Brooklyn
Motueka
Motueka River
Riwaka River
Port Motueka
Jackett Island
Tapu Bay
Outer
Oxidation ponds
Gravel pit
Motueka Aerodrome
Thorpe Bush
Lower Moutere
Mariri
0 0.5 1 2 Kilometers

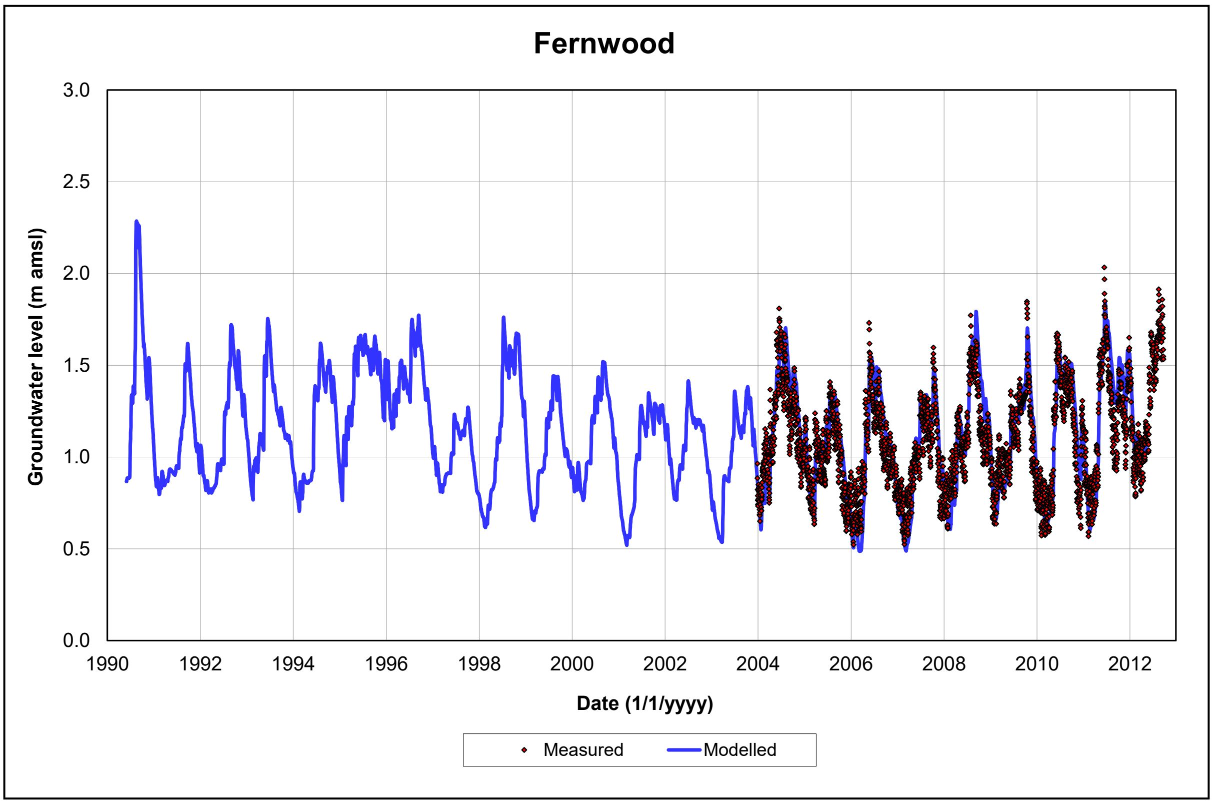

Legend
Aquifer 1 Ss sensitivities
< 0.00025
0.00025 - 0.0005
0.0005 - 0.00075
0.00075 - 0.001
> 0.001
Aquifer 1 extent
Motueka
Riwaka
Umukuri
Brooklyn
Motueka River
Port Motueka
Jackett Island
Kilometers
0
0.5
1
2

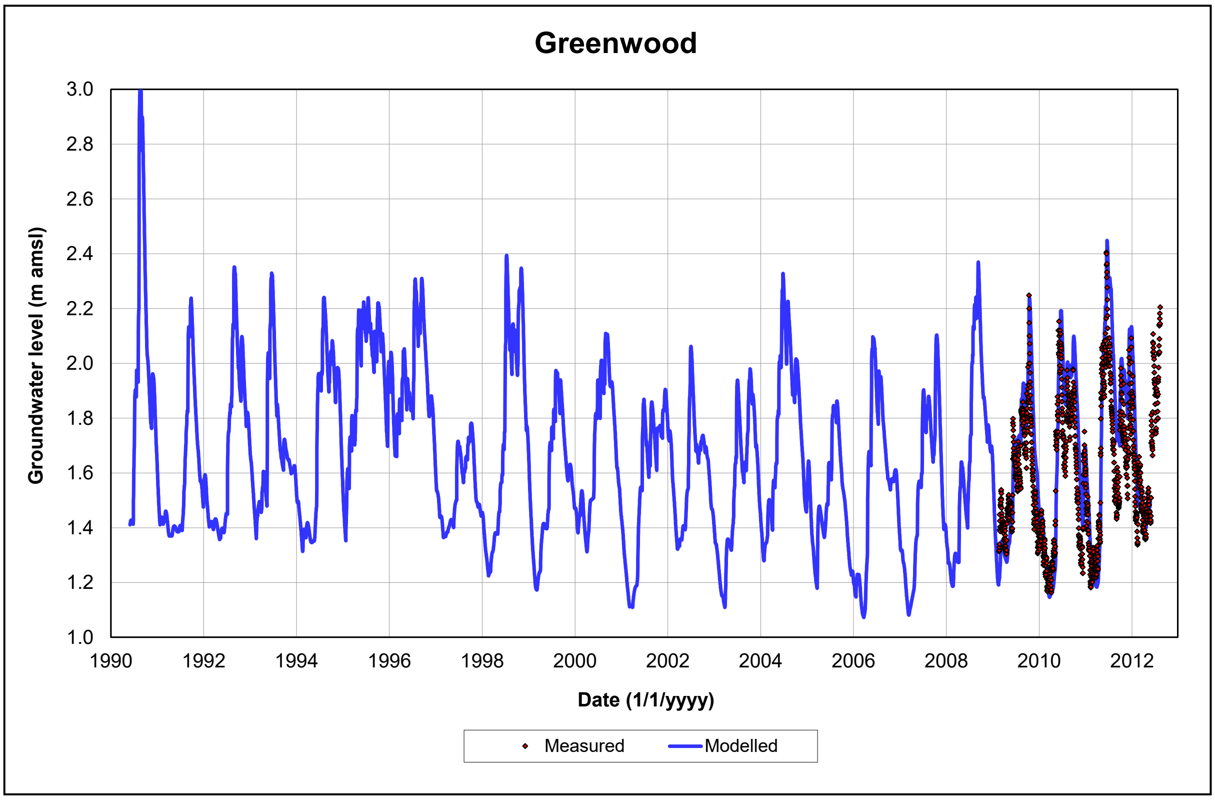

Legend
Aquitard Ss sensitivities
< 0.001
0.001 - 0.005
0.005 - 0.01
0.01 - 0.05
> 0.05
Aquitard extent
Kilometers
0
0.5
1
2
N
S
E
W
Riwaka River
Motueka River
Motueka
Riwaka
Umukuri
Brooklyn
Port Motueka
Jackett Island
Lower Moutere
Mariri
Tapu Bay
Outer
Oxidation ponds
Gravel pit
Motueka Aerodrome
Thorpe Bush
Hospital
Abbatoir
Sawmill
Substation
Quarry
Jubilee Bridge
FACTORY RD
SCHOOL RD
UMUKURI ROAD
OLD MILL ROAD
STAPLES STREET
FEARON ST
PARKER STREET
POOLE STREET
PAH ST
WHAKAREWA STREET
HARBOUR ROAD
WHARF ROAD
COLLEGE STREET
KING EDWARD ST
HURSTHOUSE STREET
WILDMAN RD
DEHRA DOON ROAD
LITTLE SYDNEY ROAD
WEST BANK RD
MOTUEKA RIVER
DOUGLAS RD
MAIN ROAD RIWAKA
RIVER RD
ANDERSON RD
SWAMP ROAD
LODDER LANE
GOODALL ROAD
THORP STREET
TREWAVAS ST
GREY ST
VICTORIA ST
QUEEN ST
CHAMBERLAIN ST
MCBRYDIE ROAD
PEACH ISLAND RD
MW Whakarewa

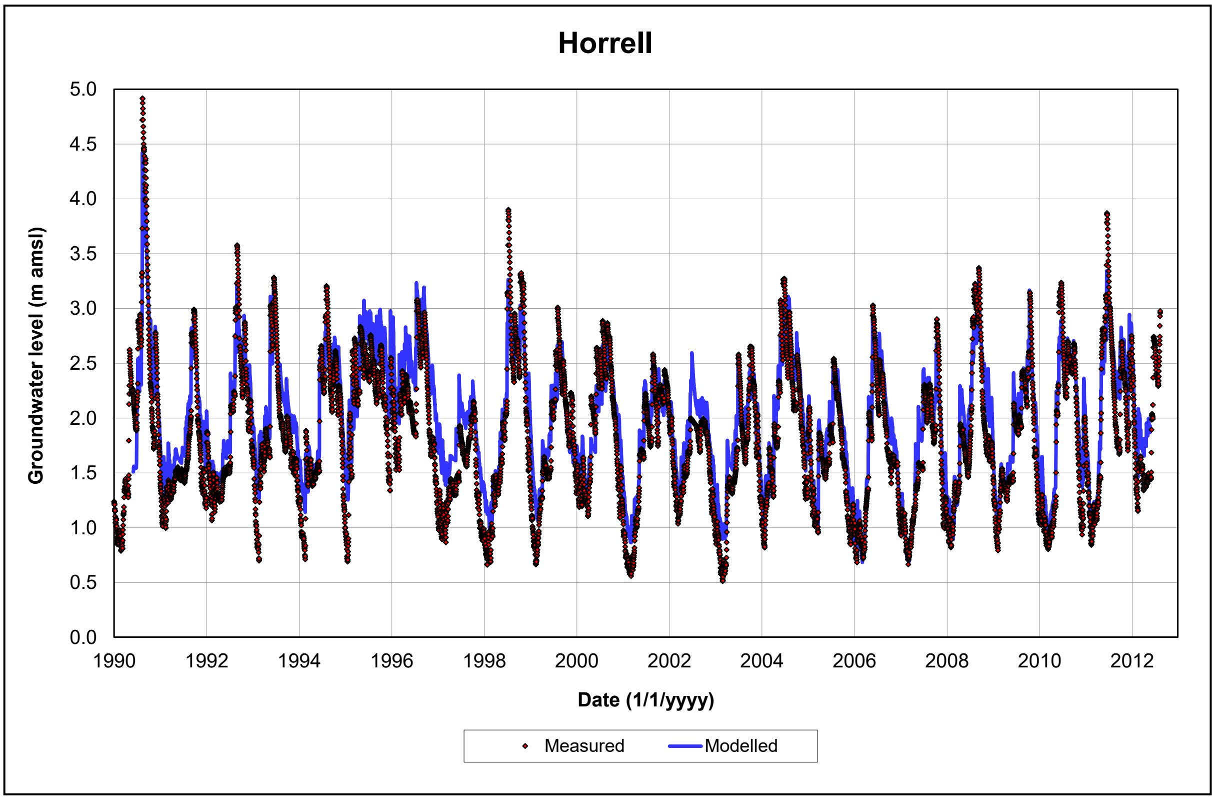

Legend
Aquifer 2 Ss sensitivities
< 0.001
0.001 - 0.005
0.005 - 0.01
0.01 - 0.05
> 0.05
Aquifer 2 extent
Riwaka
Umukuri
Brooklyn
Motueka
Motueka River
Riwaka River
Port Motueka
Moutere River
Lower Moutere
Jackett Island
Thorpe Bush
Motueka Aerodrome
Kilometers
0
0.5
1
2
N
S
E
W

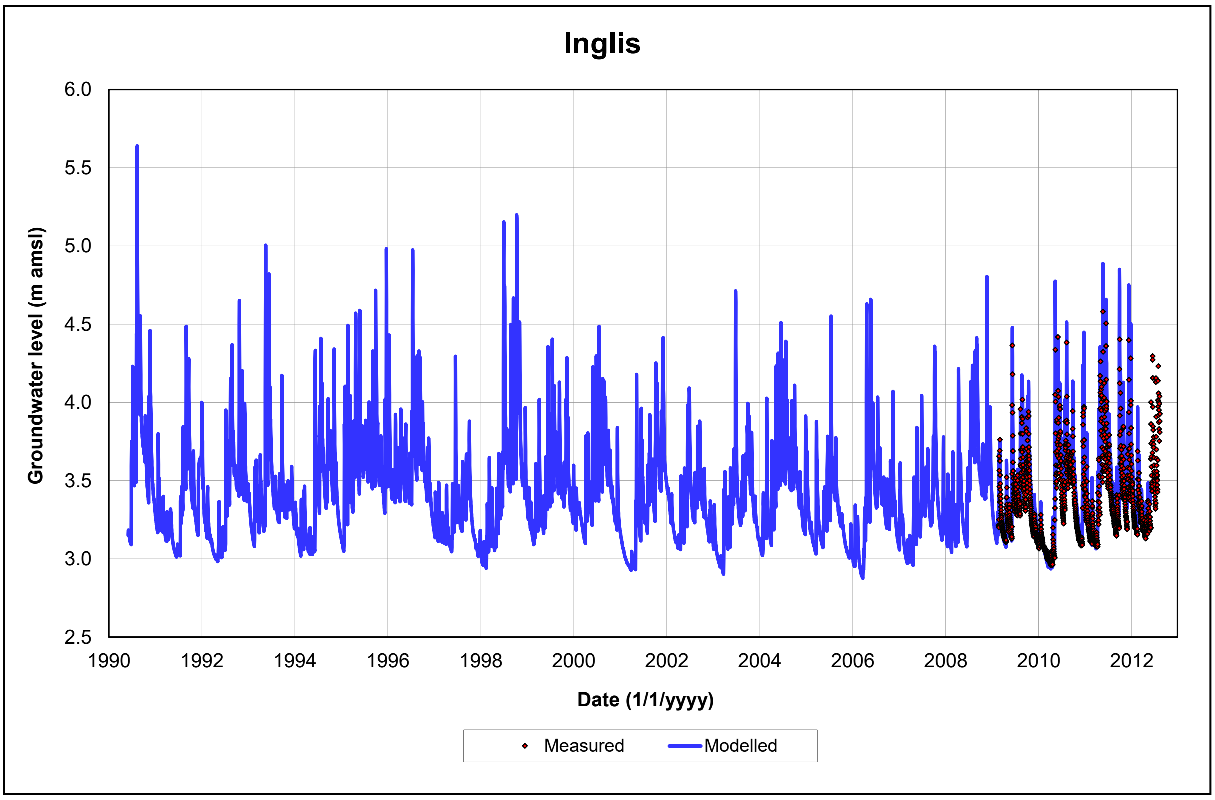
Appendix D: Hydrographs of measured and modelled groundwater levels, drain flows and river losses

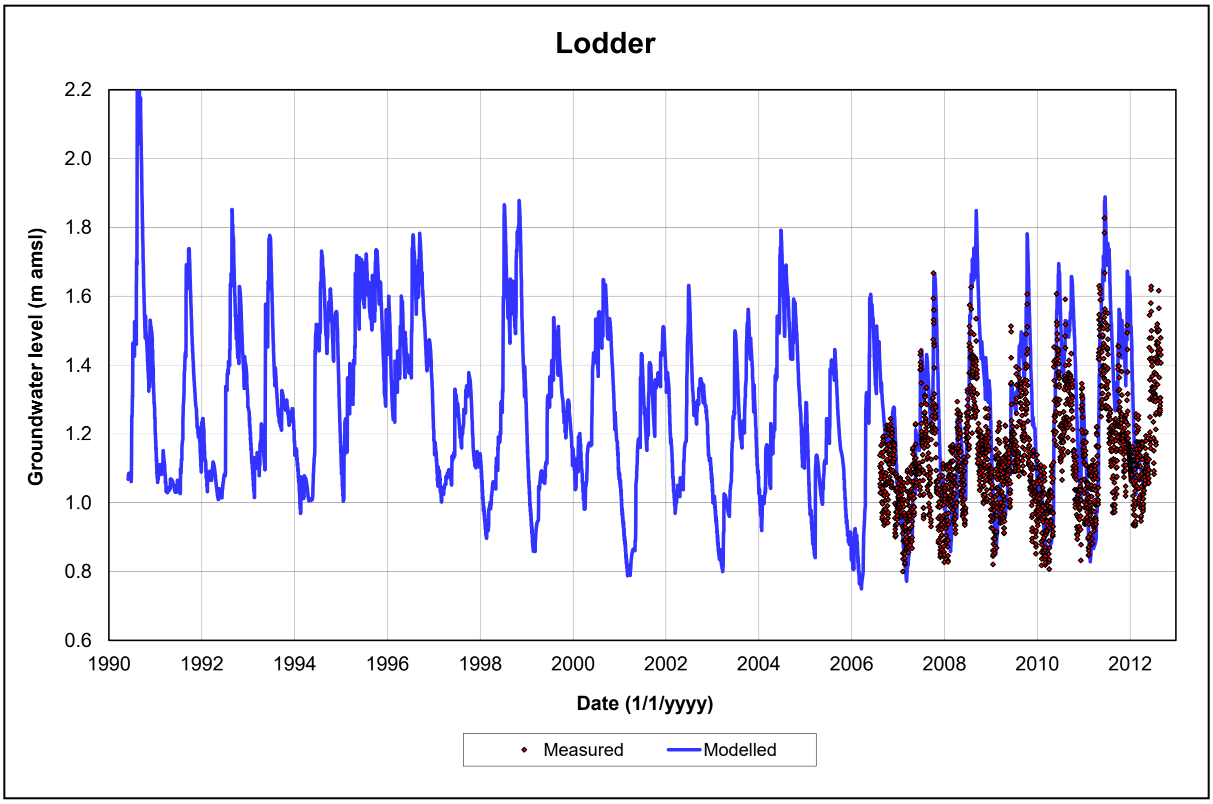


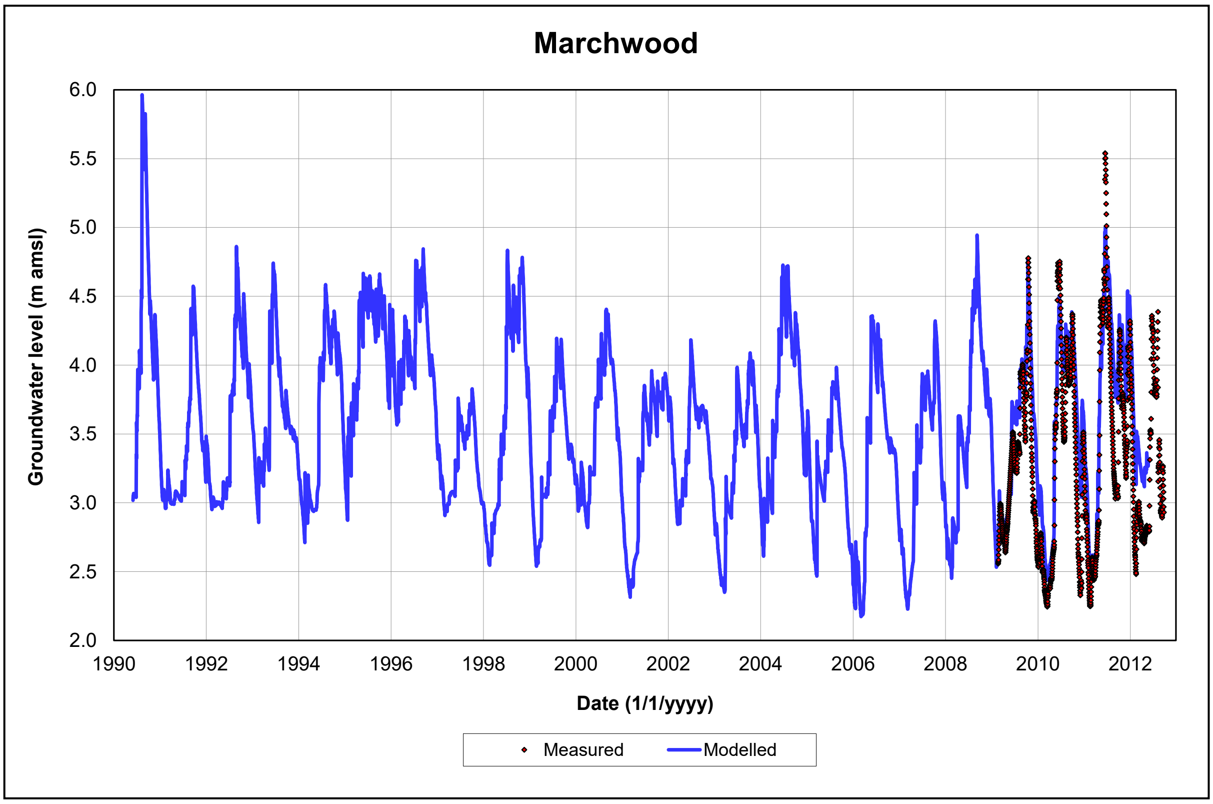


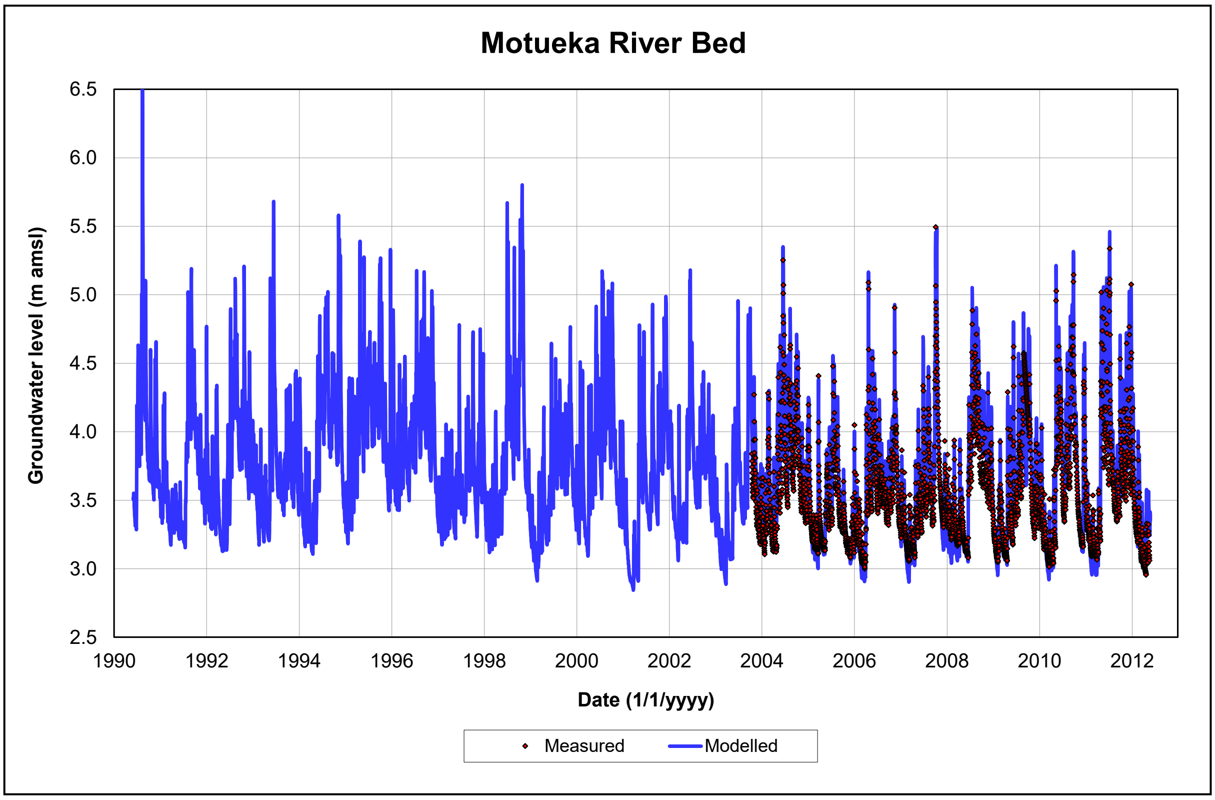

Greenwood
Groundwater level (m amsl)
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
Measured
Modelled

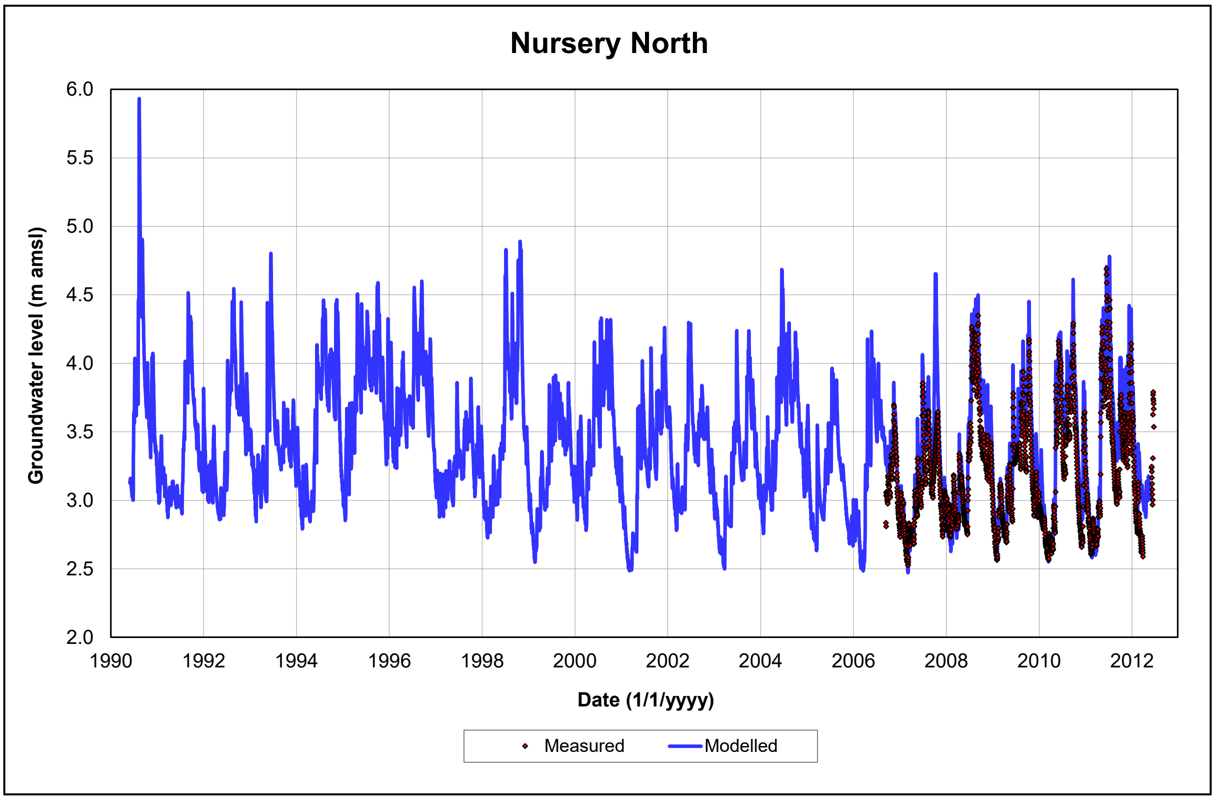

Horrell
Groundwater level (m amsl)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
Measured
Modelled

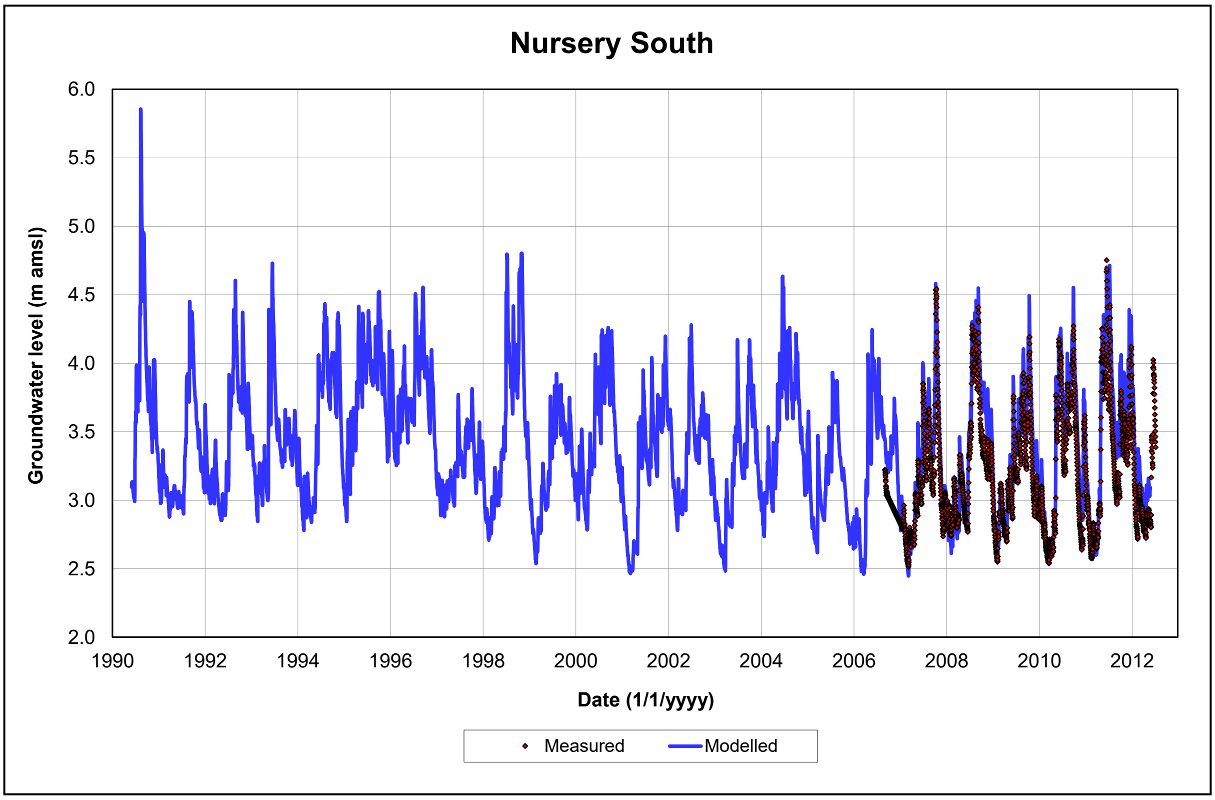

Inglis
Groundwater level (m amsl)
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
Measured
Modelled

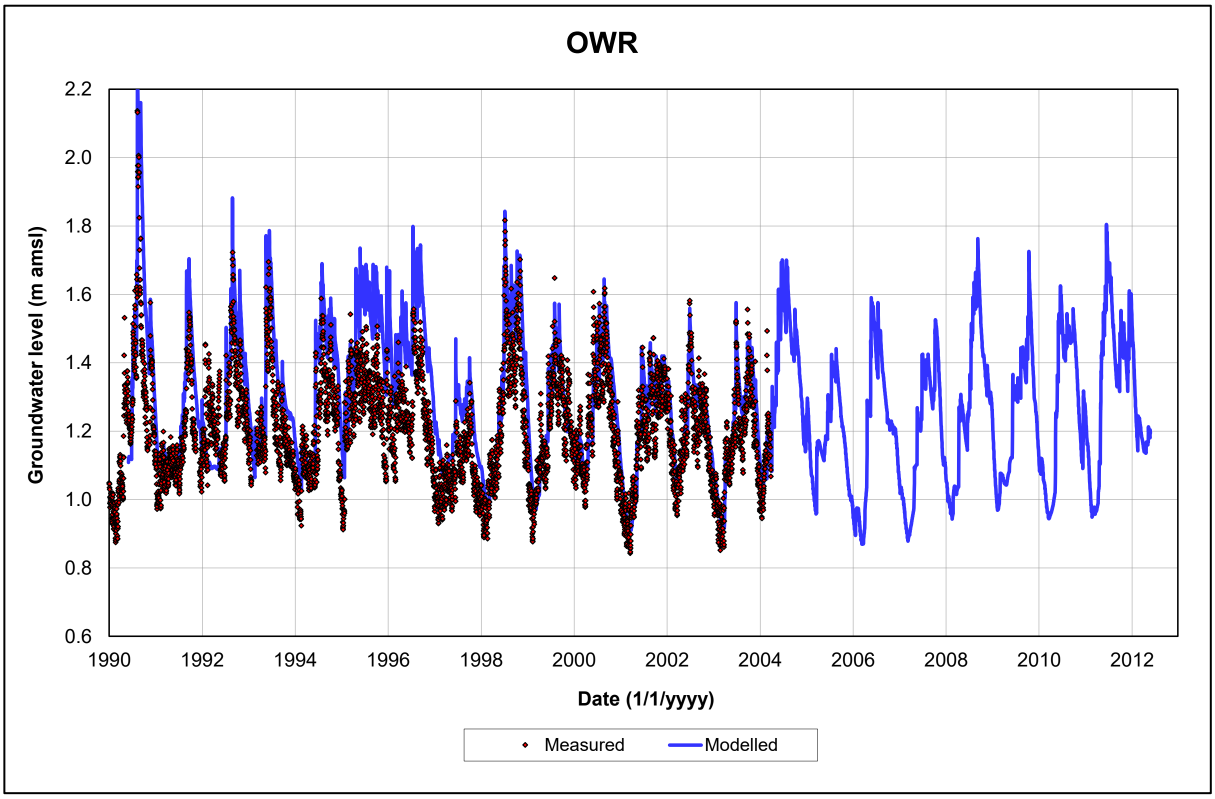

Lodder
Groundwater level (m amsl)
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
Measured
Modelled

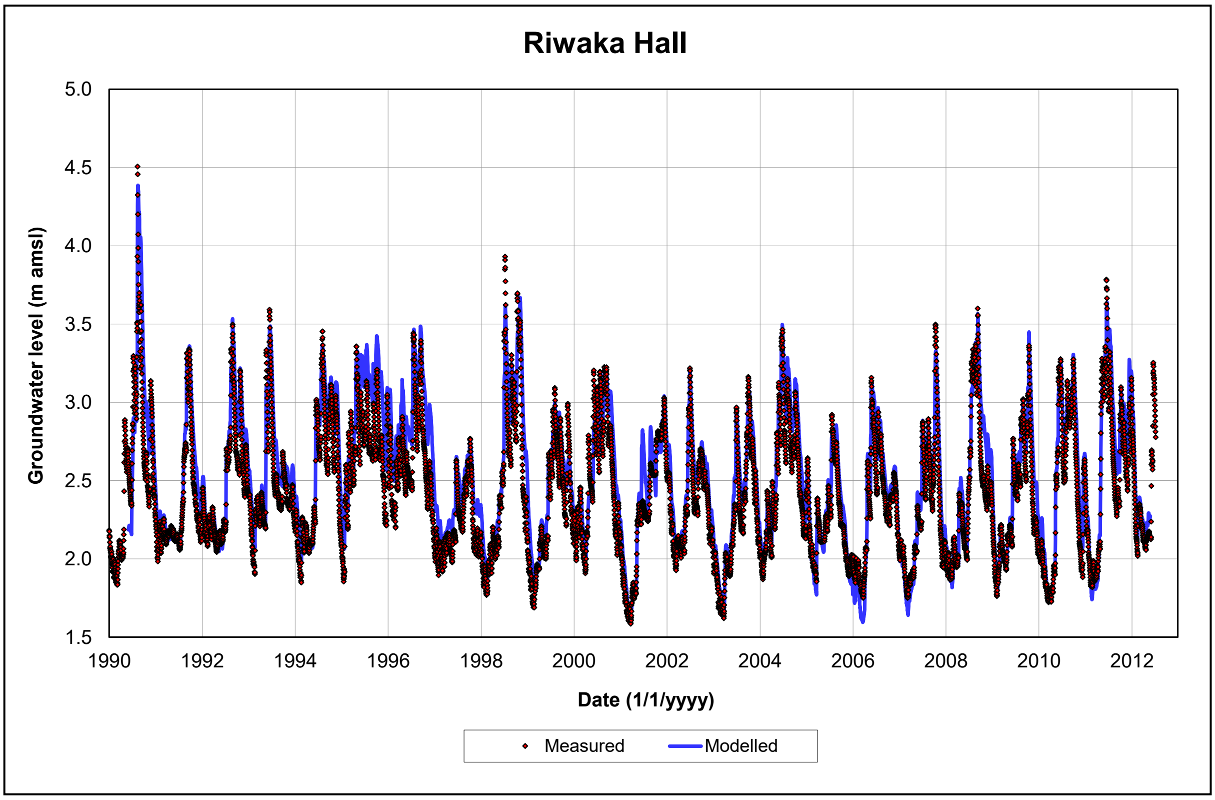

Marchwood
Groundwater level (m amsl)
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
Measured
Modelled

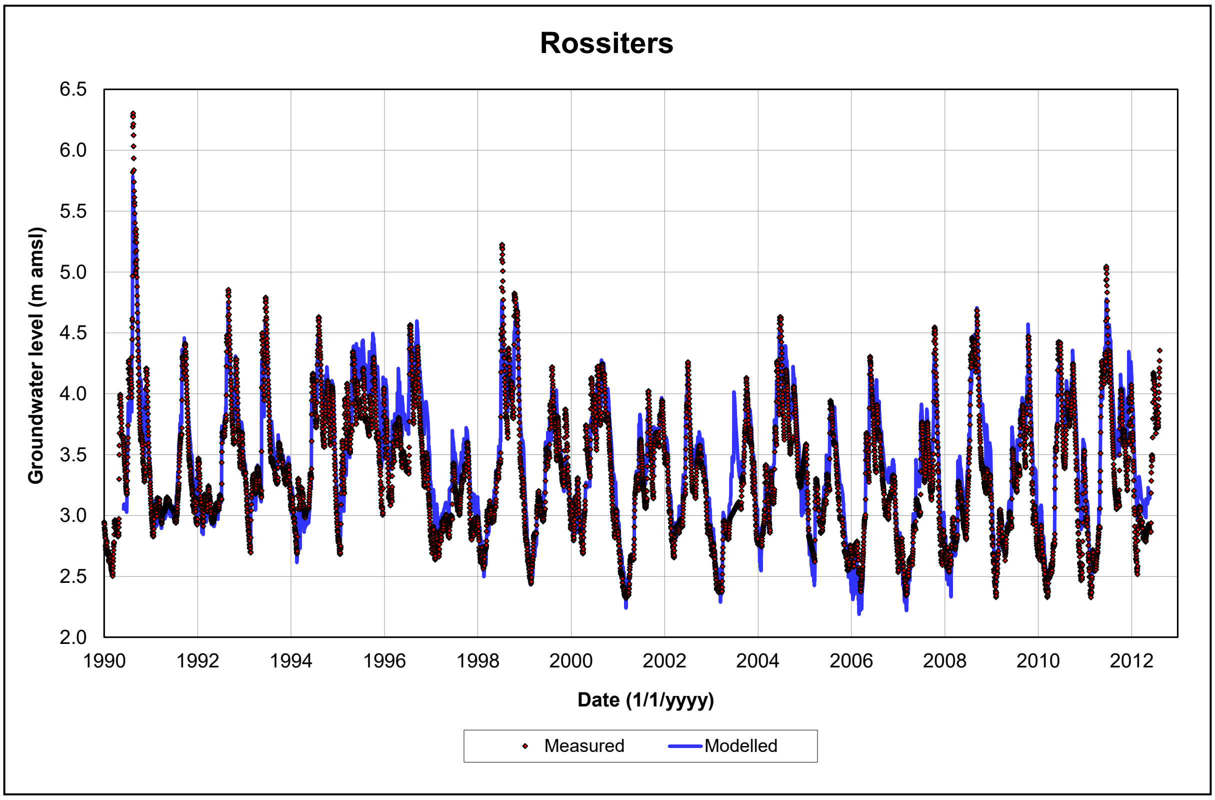

Motueka River Bed
Groundwater level (m amsl)
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
Measured
Modelled

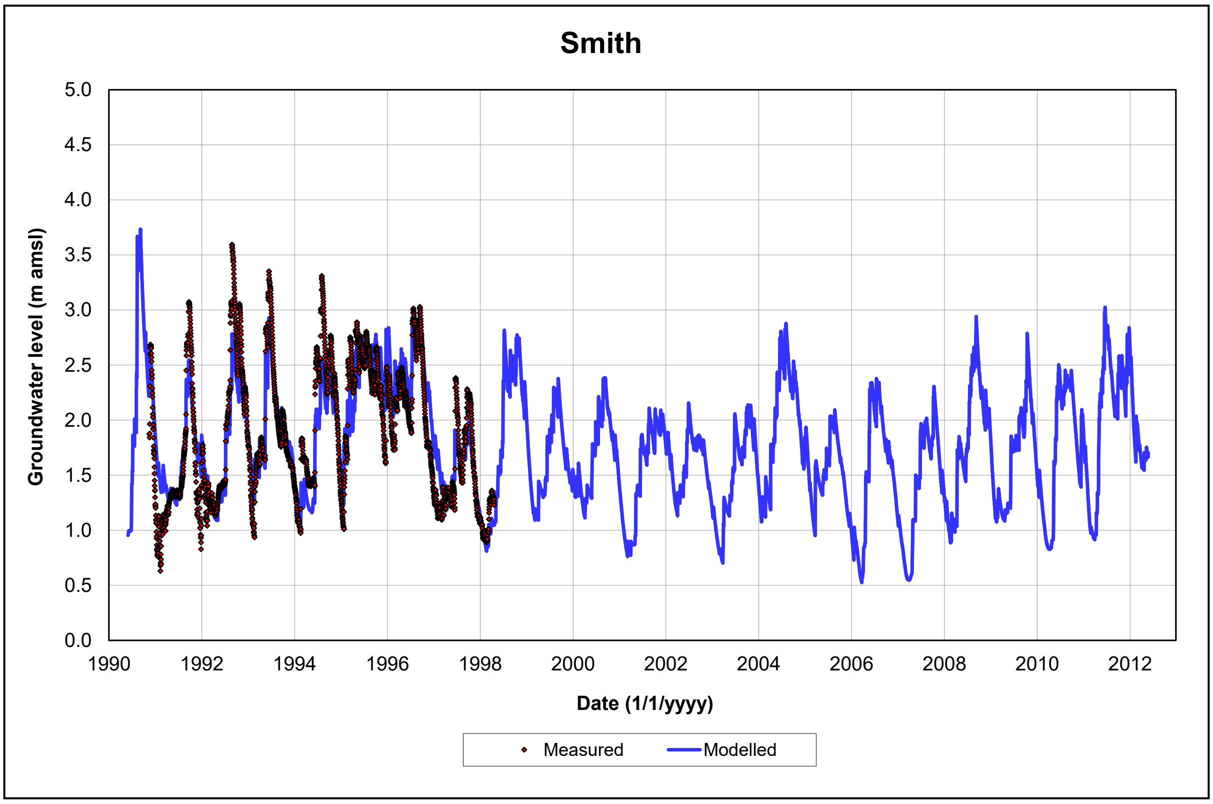

Nursery North
Groundwater level (m amsl)
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
Measured
Modelled

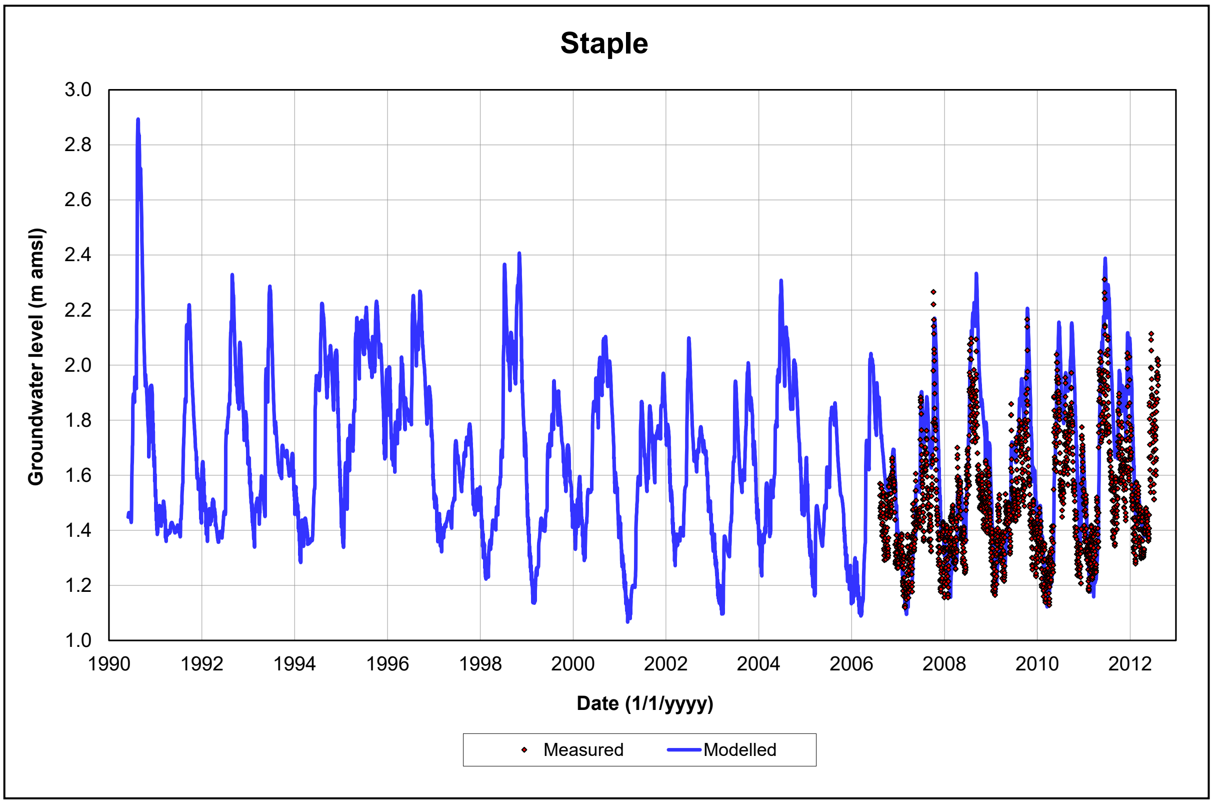

Nursery South
Groundwater level (m amsl)
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
Measured
Modelled

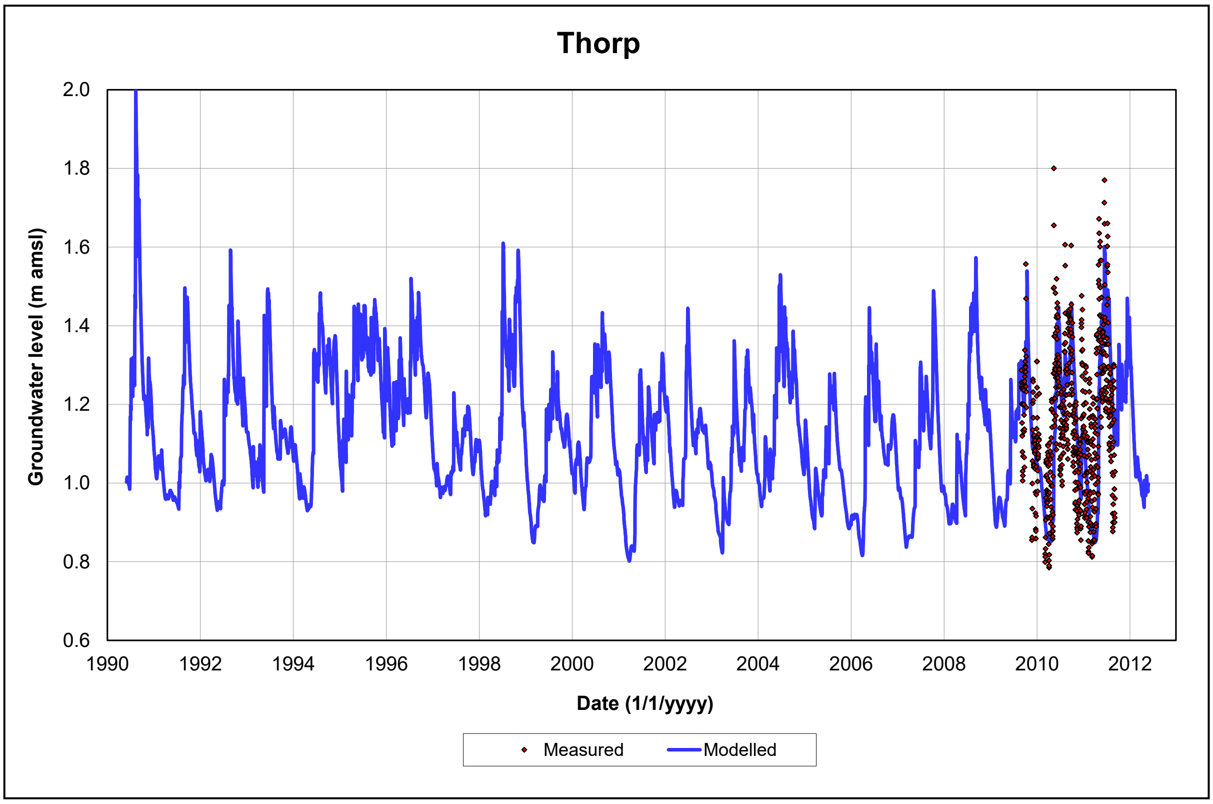

OWR
Groundwater level (m amsl)
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
Measured
Modelled

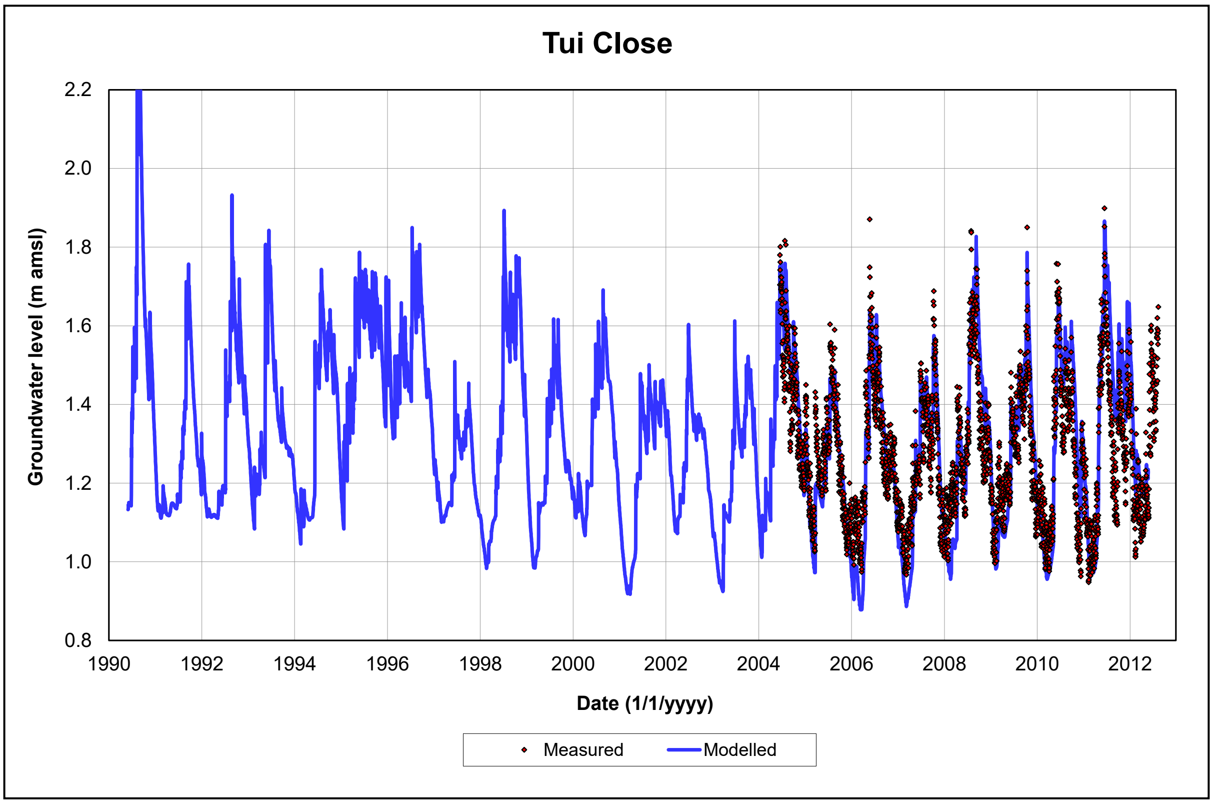

Riwaka Hall
Groundwater level (m amsl)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
Measured
Modelled

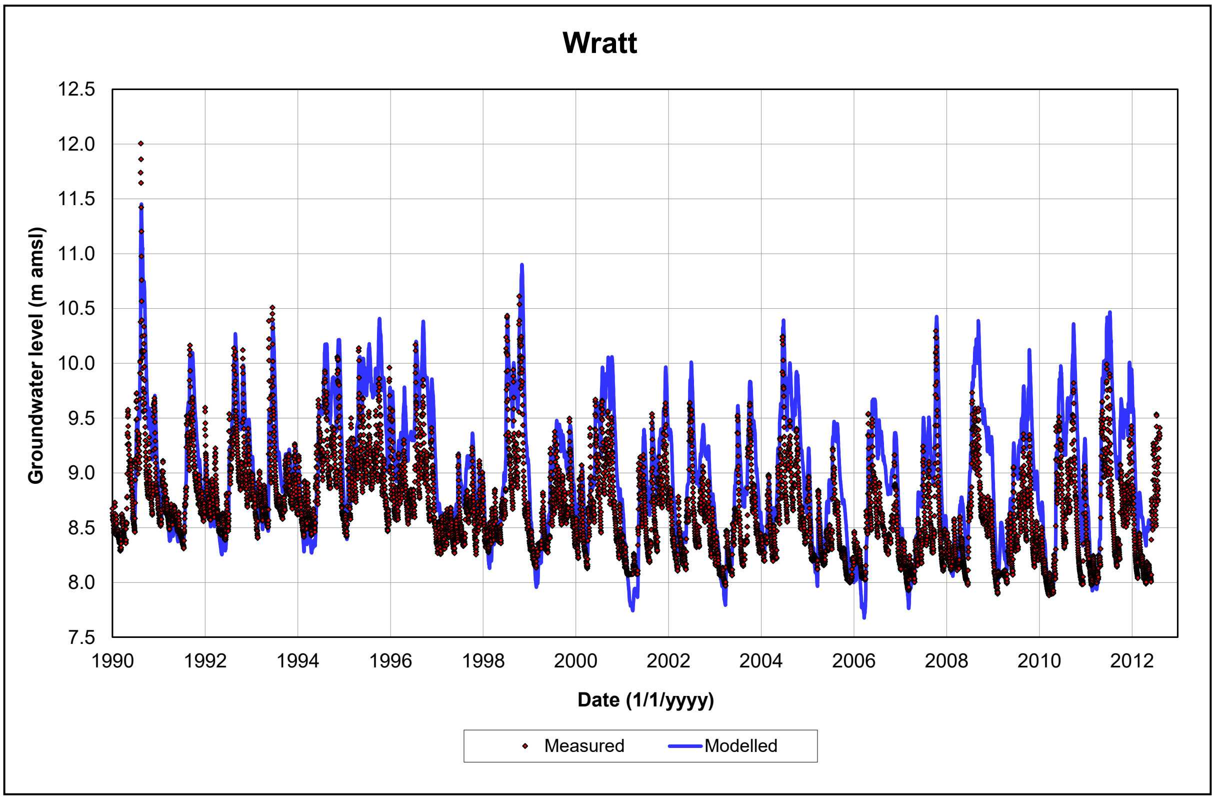

Rossiters
Groundwater level (m amsl)
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
Measured
Modelled

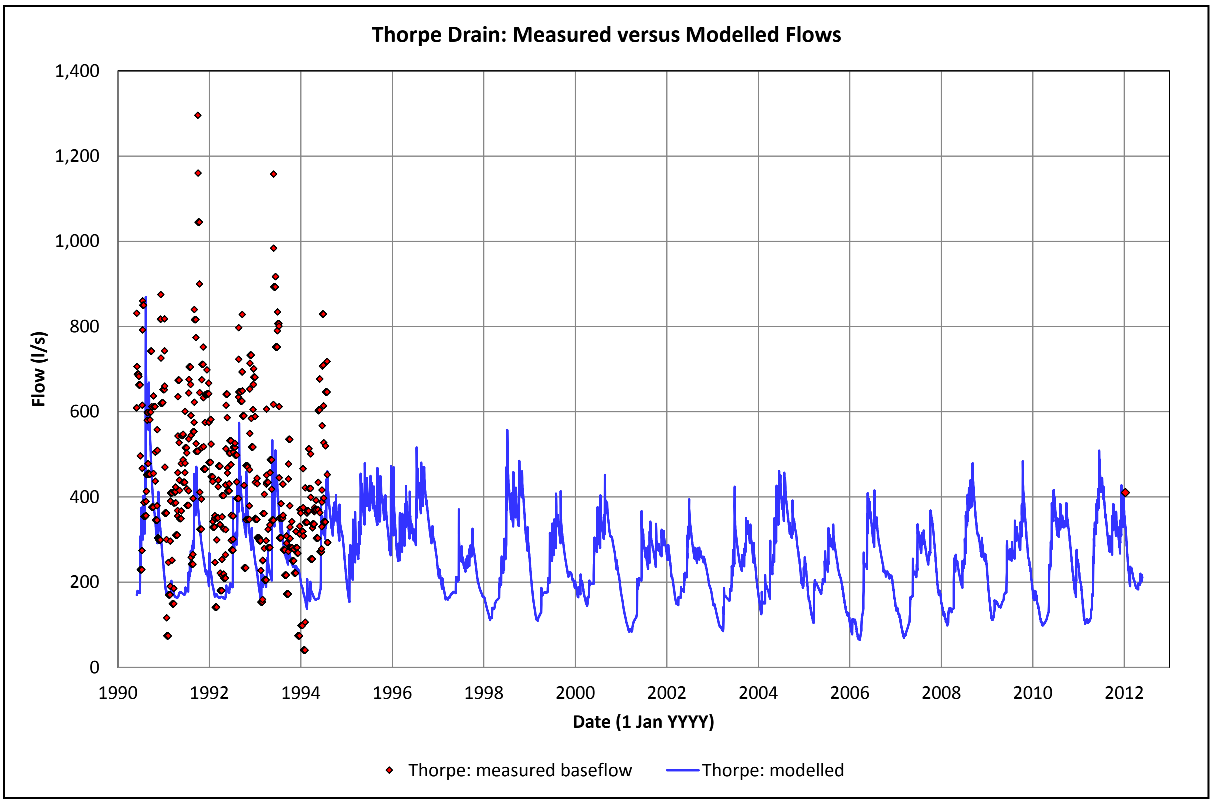

Smith
Groundwater level (m amsl)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
Measured
Modelled

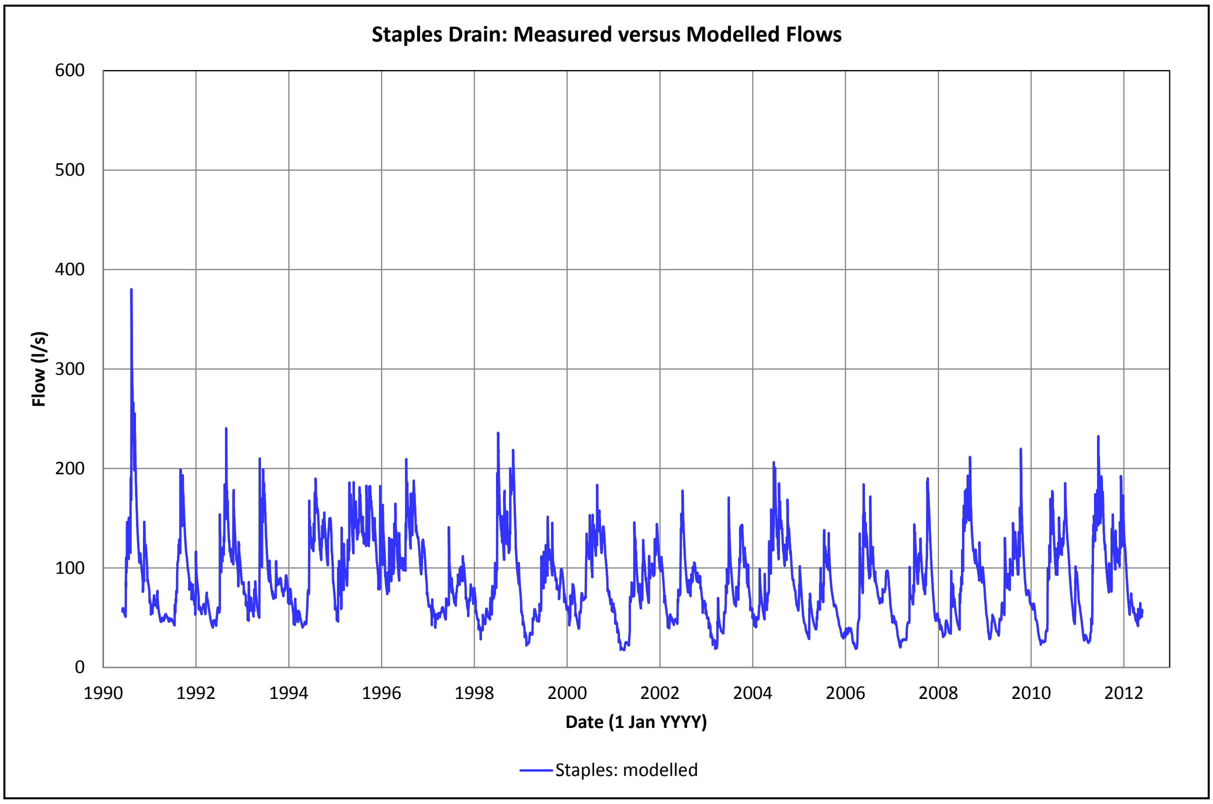

Staple
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
Groundwater level (m amsl)
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
Measured
Modelled

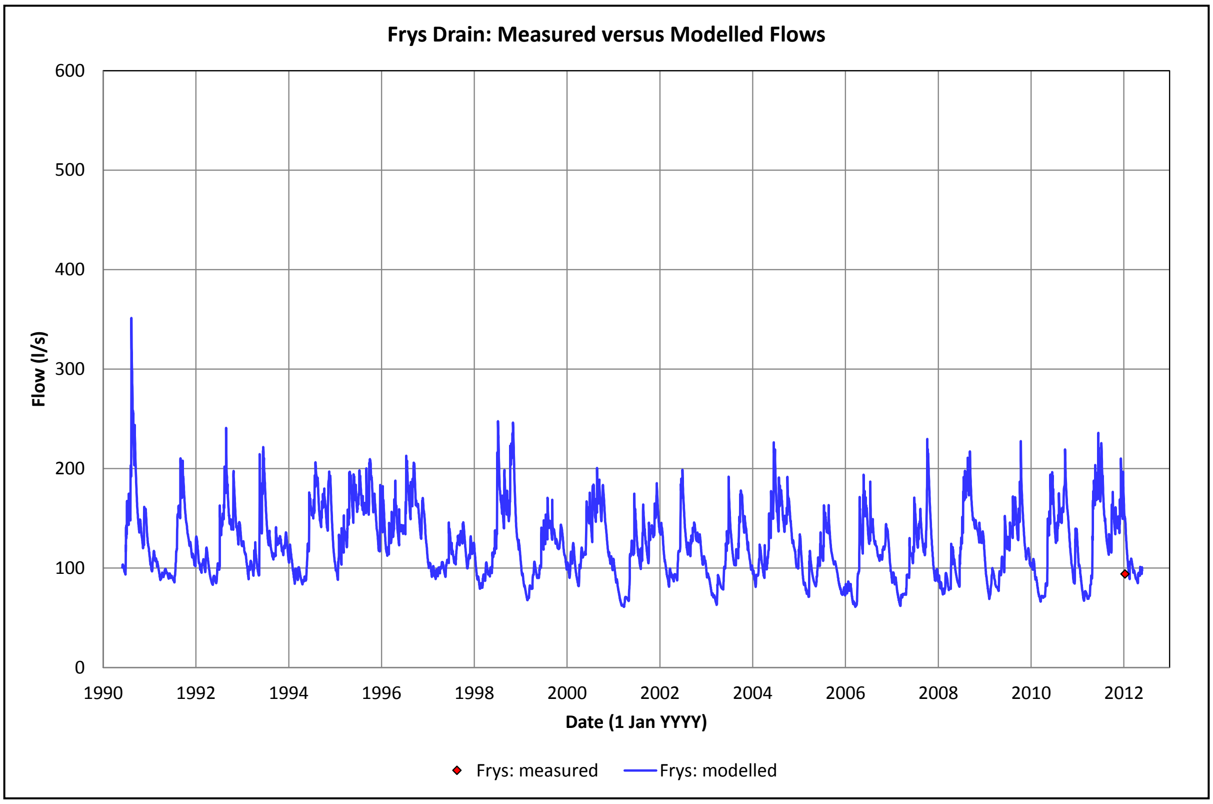

Thorp
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
Groundwater level (m amsl)
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
Measured
Modelled

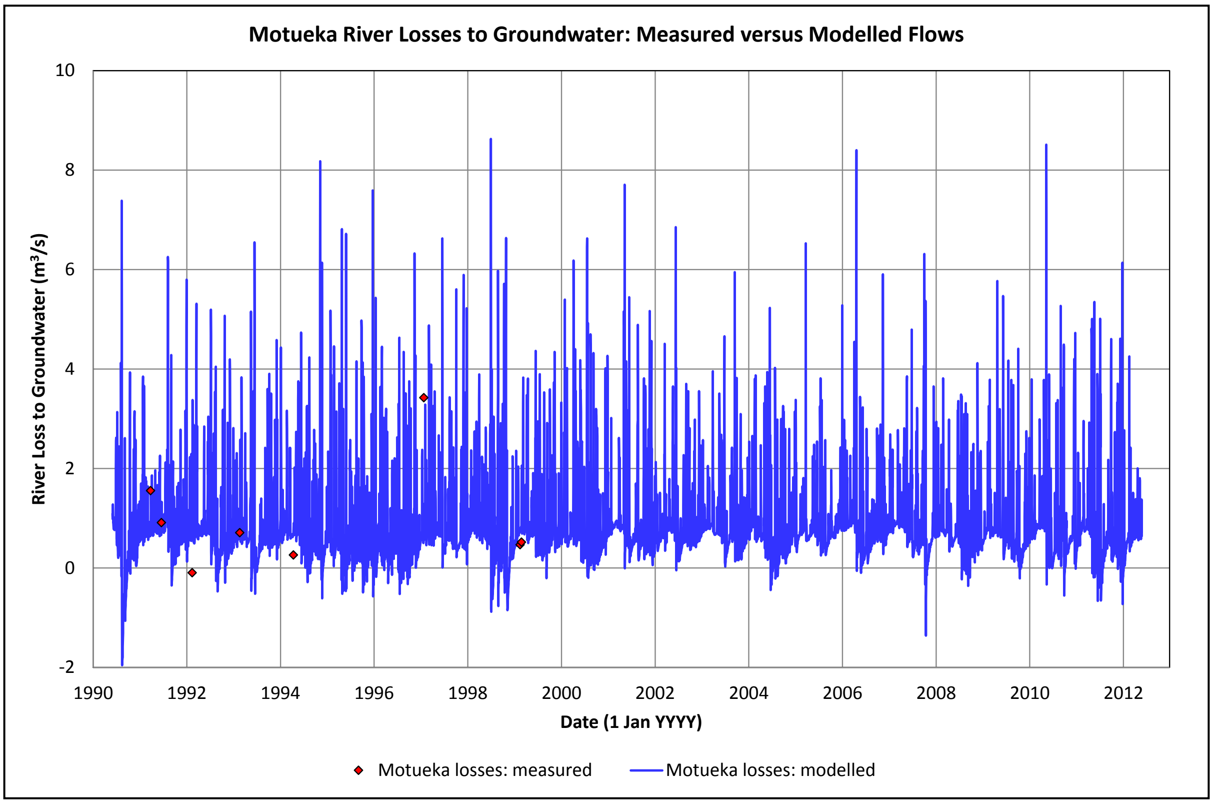

Tui Close
Groundwater level (m amsl)
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
Measured
Modelled


Wratt
Groundwater level (m amsl)
12.5
12.0
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0
7.5
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
Measured
Modelled


Thorpe Drain: Measured versus Modelled Flows
Flow (l/s)
1,400
1,200
1,000
800
600
400
200
0
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1 Jan YYYY)
Thorpe: measured baseflow
Thorpe: modelled


Staples Drain: Measured versus Modelled Flows
Flow (l/s)
600
500
400
300
200
100
0
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1 Jan YYYY)
Staples: modelled


Frys Drain: Measured versus Modelled Flows
Flow (l/s)
600
500
400
300
200
100
0
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1 Jan YYYY)
Frys: measured
Frys: modelled


Motueka River Losses to Groundwater: Measured versus Modelled Flows
River Loss to Groundwater (m³/s)
10
8
6
4
2
0
-2
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1 Jan YYYY)
Motueka losses: measured
Motueka losses: modelled

Appendix E: Time-series analyses using eigen modelling

1 BACKGROUND

Appendix V of Robb (1999)[14] presents a time-series analysis of aquifer dynamics for the Motueka-Riwaka groundwater system. This work considered the effect on groundwater level dynamics from river and rainfall recharge and quantified the variation in groundwater levels as a result of these recharge sources in three regional monitoring bores. Since this work was completed, additional monitoring bores have been installed and further data collected in both the new bores and the existing bores. Tasman District Council have commissioned Aqualinc to undertake similar analyses of the full data sets to determine if the aquifer response at the new well locations and the extended datasets of the existing wells remain consistent with the earlier findings of Robb (1999). Dr Vince Bidwell (formerly of Lincoln Environmental, now retired) completed the time series analysis work documented in Appendix V of Robb (1999), and he is the developer of the eigen model method. Dr Bidwell has been engaged as an advisor and peer reviewer of the new work documented herein.

2 PURPOSE OF THE WORK

The purpose of the time-series analysis is to ascertain the relative proportion of river recharge versus land surface recharge over the plains and the relative sensitivity of groundwater levels in regional monitoring bores to these recharge sources. This work acts as an independent regional-scale check to the numerical MODFLOW model and is to be compared to the findings described in Appendix V of Robb (1999).

3 CONCEPTUAL MODEL

The time-series analysis documented in Appendix V of Robb (1999) is a forerunner of the eigen model methods considered herein. The spreadsheet-based version of the eigen model used for the current investigation is documented in Bidwell & Burbery (2011)[15].

Eigen models employ simplifications to describe complex aquifer behaviour. The models are one-dimensional and consider a set of model parameters that characterise the aquifer system in terms of a set of conceptual groundwater reservoirs. The governing equations have been shown to be good simulators of aquifer response to recharge and they are directly related to the physics of aquifer behaviour (Bidwell *et. al.*, 1991[16]).

---

[14] Robb, C (1999): *Groundwater Model of Motueka/Riwaka Plains Aquifer System.* Prepared for Tasman District Council. Lincoln Environmental Report No. 2325/1. January 1999.

[15] Bidwell, VJ and Burbery, LF (2011): *Groundwater Data Analysis - Quantifying Aquifer Dynamics.* Lincoln Ventures Ltd. Report no. 4110/1, prepared for Envirolink Tools project 420-NRLC50.

[16] Bidwell, VJ; Callander, PF; Moore, CR (1991): *An application of time-series analysis to groundwater investigation and management in Central Canterbury, New Zealand.* New Zealand Journal of Hydrology, 30(1), pp 16-36.

Bidwell (2003)[17] and Bidwell & Burbery (2011) provide further discussion on eigen models and their use in simulating groundwater levels and discharge. These publications describe how an eigen model is a method for quantifying the dynamic behaviour of groundwater storage and groundwater discharge in response to time varying recharge. Recharge includes that from rivers, land surface (both rainfall and irrigation) and groundwater abstraction (effective as negative recharge).

For the Motueka-Riwaka plains, a novel approach has been taken in using one-dimensional eigen models to represent slices across the plains from the foothills through to the coast. The inland foothills are represented as no-flow boundaries, and the coastal discharge area is represented as a specified head boundary (set equal to mean sea level of zero). Slices have been aligned with regional flow paths. In total, six slices have been considered which pass through, or in near vicinity to, the regional monitoring bores. Figure 1 shows the location of these slices, the location of the monitoring bores and regional groundwater level contours as reported by the calibrated model for 24 January 2006.

There will always be approximations and simplifications required to simulate a three-dimensional system with a one-dimensional model. However, using multiple flow paths, each with their own models and calibrated parameters, is a step closer to the three-dimensional system than if a single slice was used to represent all locations.

Each eigen model slice comprises a very short upper zone which receives the river recharge. The remainder of the slice is divided into two zones which each receive a different time series of land surface drainage (to account for recharge variations between the foothills and the coast). So overall, there are three zones of recharge.

The modelled groundwater level response at a given monitoring bore location is a function of various parameters including the bulk aquifer transmissivity and storativity, the distance of the bore location to the model boundary and recharge sources, the storage time of the unsaturated (vadose) zones and the time series of model stresses (river recharge, land surface recharge and pumping). The time series of land surface recharge and pumping have been calculated externally to the eigen models and are directly specified as model inputs. These time series are the same as used in the numerical MODFLOW model, spatially averaged over the two recharge zones for each slice. The values for all other parameters are determined through model calibration. It was found that good model calibration could be achieved with a steady river recharge component, and so for simplicity, this assumption was applied.

---

[17] Bidwell (2003): *Groundwater Management Tools: Analytical; Procedures and Case Studies.* Ministry of Agriculture and Forestry (MAF) Technical Paper No: 2003/06. Prepared for MAF Policy by Vincent Bidwell. October 2003.

Figure 1: Eigen model slices and regional monitoring bore locations

4 RESULTS AND DISCUSSION

Eigen models were set up for each slice with recharge and pumping time series varying between slices. Calibrated parameters and calibration statistics are summarised in Table 1. The model fits to measured groundwater levels are presented in Figure 2. Definitions of the parameters in Table 1 are as follows:

x/L = Ratio of well location to total slice length between the foothills and the coastal boundary (dimensionless)

S = Bulk aquifer storativity (dimensionless)

T = Bulk aquifer transmissivity (m^2/day)

T_v = Hydraulic residence time (days) for unsaturated (vadose) flow within each recharge zone

River R = Long-term average river recharge (m^3/s/km) assuming a 50 m wetted width

River % = River recharge as a percent of total natural recharge (river recharge and land surface recharge combined) (%)

RMSE = Normalised root-mean-square error (%)

ME = Normalised mean error (%)

R^2 = Square of the correlation coefficient

Monitoring bores Tui Close and OWR (Old Wharf Road) are located within a few metres of each other. OWR has been decommissioned and removed, and has been replaced by Tui Close. Consequently, only Tui Close has been modelled as this has the most recent groundwater level record. Similarly, monitoring bores Nursery North and Nursery South are located very close to each other. Because it is the deeper of the two bores (and would therefore be more representative of larger-scale groundwater responses), only Nursery North has been modelled.

4.1 Overall Calibration

Overall, very good matches to measured data were obtained. Based on visual comparisons and also the model RMSE and ME, most bores are very well calibrated. Because of the assumption of a steady river recharge component, bores located closer to rivers (such as Wratts, Nursery North, Motueka River bed and Inglis) typically have a poorer calibration than other bores. In addition, bores located very close to the coast (such as Thorp, Tui Close and Fernwood) are affected by tidal variations which are not represented in the eigen models. Consequently, the quality of the calibration in these bores is reduced.

4.2 Well Location (x/L)

All values for x/L increase with proximity to the coast, which is physically correct.

4.3 Transmissivity (T)

Bulk aquifer transmissivities vary between 660 and 94,380 m^2/day. Given an average aquifer saturated thickness of approximately 20 m, this results in bulk aquifer horizontal hydraulic conductivities ranging between approximately 33 and 4,720 m/day. This is consistent with values from the MODFLOW regional groundwater model which ranges between 1 m/day and 3,600 m/day for the main water bearing layers (Figure 4-5 and Figure 4-7). Typically, aquifer transmissivities are largest in the central plains area (slices 4 and 5) and are lesser towards the north and the coast where aquifers thin out and tighten.

4.4 Storativity (S)

Bulk aquifer storativities vary between 0.02 and 0.26. Over an average aquifer saturated thickness of 20 m, the resulting specific storage values range between 0.001-0.01 m^{-1}. This is within the range of specific storage derived for the MODFLOW regional groundwater model, which varies between 0.0001-0.08 m^{-1} for the main water bearing layers (Figure 4-9 and Figure 4-11).

4.5 Vadose Zone Residence Time (Tv)

Vadose zone residence times are very short. The entire system is very fast responding with little attenuation in the vadose zone.

4.6 River Recharge

The Wratts monitoring bore is located very close to the Motueka River and consequently is highly dominated by river recharge. As a result this bore has a river recharge component that is much higher than the other bores. The range of river recharge values for the other bores vary between 0.11-0.86 m^3/s/km. The higher values tend to occur along slice four, which is a zone of high transmissivity and therefore has good hydraulic connection to the Motueka River. The average flow in the Motueka River is approximately 58 m^3/s, so the modelled river recharge of 0.11-0.86 m^3/s/km equates to approximately 0.2-1.5 % of the mean flow per kilometre of river length.

Measured losses from the Motueka River average approximately 0.97 m^3/s (Table 3-6) as it flows over the plains between the foothills and the State Highway bridge (this is a length of approximately 7 km). However, measurements have historically only been taken during low flows and therefore do not represent long-term average flow conditions. The MODFLOW regional groundwater model reports a long-term average river loss of approximately 0.94 m^3/s over the same river reach. This equates to a loss of 0.13 m^3/s/km, averaged over both space and time. The range of river recharge for the eigen models (0.11-0.86 m^3/s/km) is consistent with this value, although on average the eigen models have higher values.

In addition, the eigen models suggest that river recharge is approximately 42-89% of the total recharge (excluding results from the Wratts monitoring bore). The

MODFLOW regional groundwater model reports a long-term average loss from all rivers of approximately 0.93 m^3/s (derived from Table 4-5 as the net difference between river inflows and outflows). Long term average land surface recharge from the MODFLOW regional groundwater model is approximately 0.82 m^3/s (Table 4-5). Hence, the total recharge is approximately 1.8 m^3/s (combining both river and land surface recharge) and river recharge accounts for 53% of this recharge. The proportion of river recharge from the eigen models (42-89%) spans the value derived from the MODFLOW model (53%). Therefore, the two modelled results are consistent.

The eigen models can be fitted well with steady river recharge values (i.e. not time varying). This is consistent with the effects of river recharge attenuating rapidly with distance from the river.

4.7 Comparison With Robb (1999)

By comparing the eigen model results with that presented in Appendix V of Robb (1999), similar conclusions can be drawn, that is, river recharge is the major water *source* to the plains. In addition, given that groundwater levels can be adequately calibrated by assuming a steady river recharge component, then land surface recharge is the dominant source of *variation* in groundwater levels. This conclusion was also reached by Robb (1999) where it is concluded from Table 2 (of Robb, 1999) that rainfall results in the greatest variance in groundwater levels.

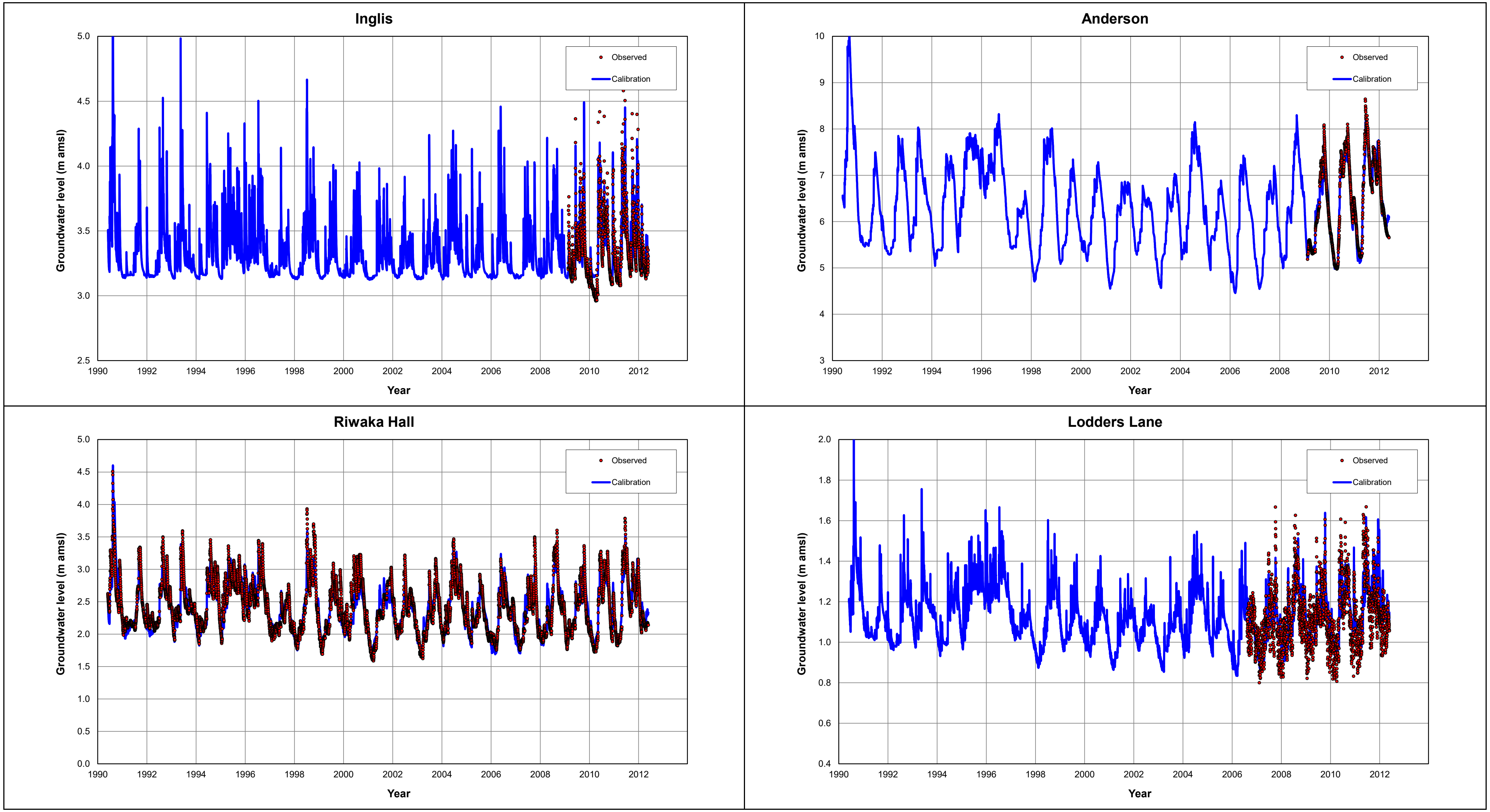
Table 1: Eigen model parameters and calibration statistics

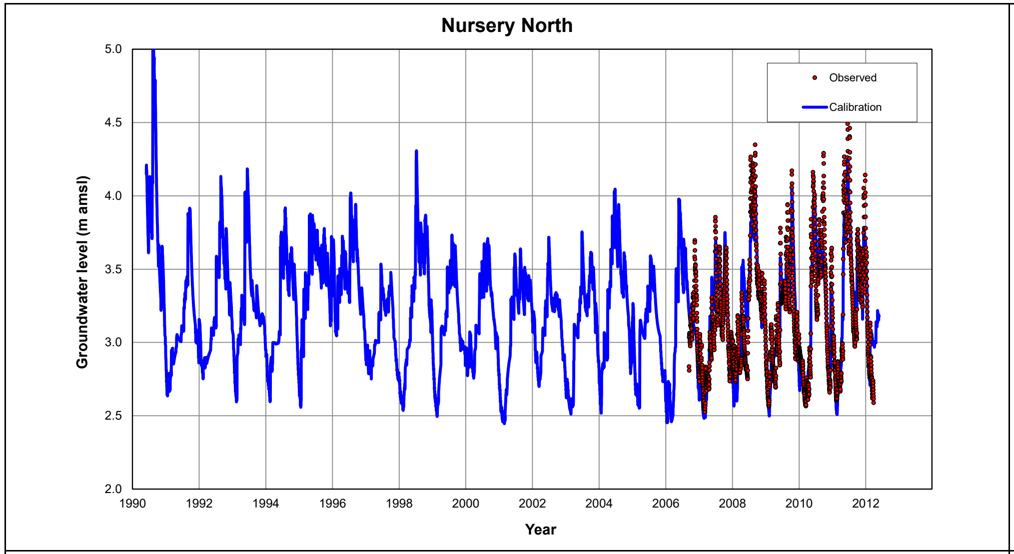
Bore name	**Slice**	**x/L**	**S**	**T (m^2/day)**	**T_v (days) (1)**			**River R $(m^3/s/km)$**	**River %**	**Normalised calibration statistics**		**R^2**
					1	**2**	**3**			**RMSE**	**ME**	
		Values reached through calibration						*Values calculated after calibration*				
Inglis	1	0.16	0.08	15,080	0	0	26	0.15	79%	6.9%	0%	0.83
Anderson	2	0.26	0.13	11,370	0	0	7	0.23	72%	5.6%	0%	0.95
Riwaka Hall	2	0.73	0.12	17,360	0	0	3	0.39	81%	5.0%	0%	0.87
Lodders Lane	2	0.98	0.07	3,170	0	0	1	0.35	79%	9.7%	0%	0.59
Nursery North	3	0.10	0.20	16,410	0	0	0	0.28	65%	8.2%	0%	0.82
Motueka River Bed	3	0.10	0.16	25,010	0	0	0	0.47	76%	10.8%	0%	0.52
Staples	3	0.83	0.12	10,520	0	0	0	0.44	75%	7.4%	0%	0.82
Thorp	3	0.97	0.06	660	0	0	1	0.11	42%	16.4%	0%	0.46
Wratts	4	0.10	0.20	94,380	0	0	0	1.79	94%	7.2%	0%	0.57
Rossiters	4	0.74	0.09	30,200	0	0	5	0.72	87%	5.0%	0%	0.86
Tui Close	4	0.88	0.24	27,440	0	0	0	0.53	84%	10.9%	0%	0.67

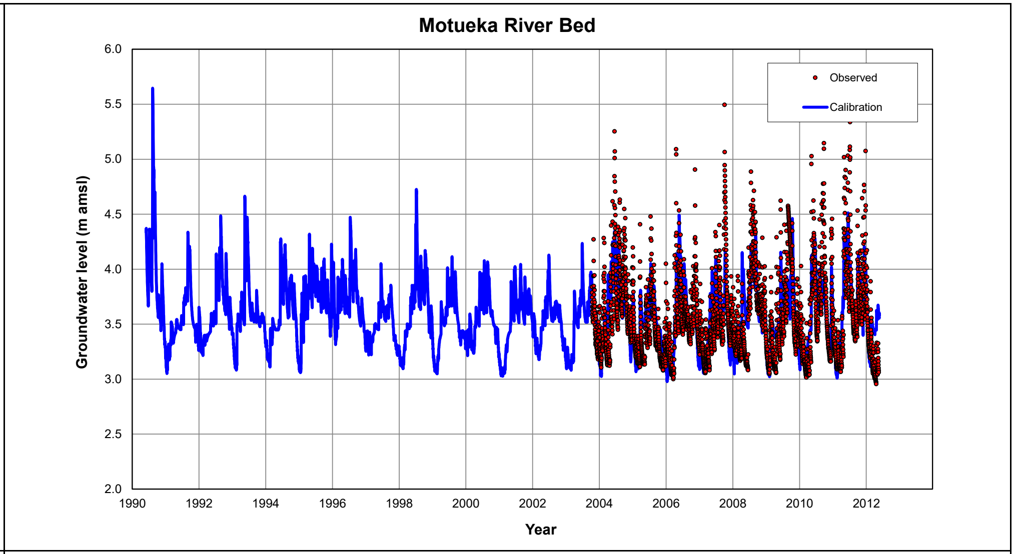
Bore name	Slice	x/L	S	T (m^2/day)	T_v (days) (1)			River R (m^3/s/km)	River %	Normalised calibration statistics		R^2
					1	2	3			RMSE	ME	
		Values reached through calibration						*Values calculated after calibration*				
Greenwood	4	0.93	0.05	19,670	0	0	0	0.86	89%	7.7%	0%	0.85
Marchwood	5	0.10	0.15	47,510	0	0	0	0.37	74%	7.0%	0%	0.89
Horrells	5	0.52	0.13	34,080	0	0	0	0.26	67%	4.7%	0%	0.90
Fernwood	5	0.62	0.26	79,980	0	0	0	0.48	79%	6.8%	0%	0.85
Smiths	6	0.50	0.02	28,010	0	33	33	0.14	53%	5.7%	0%	0.92

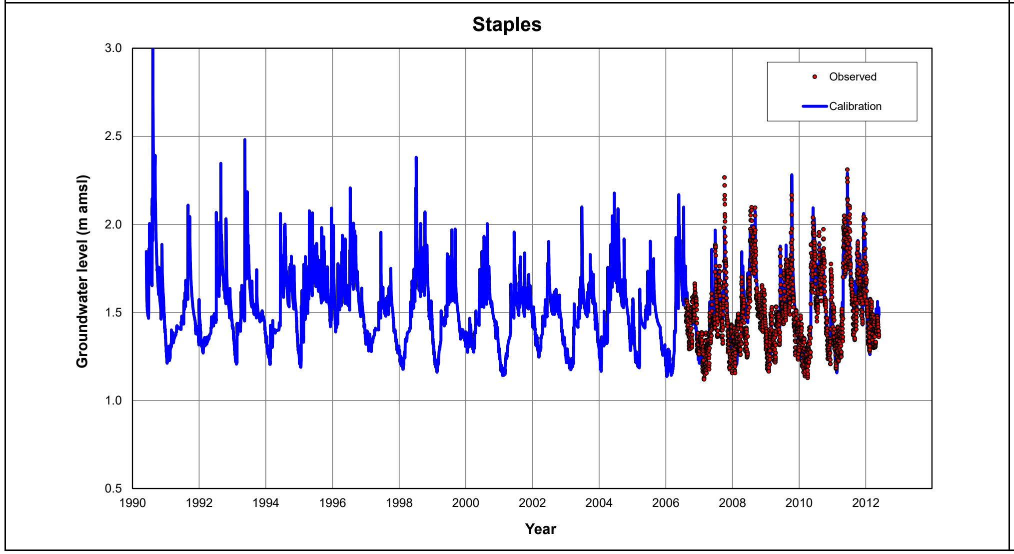
[1] River recharge is only specified in vadose zone 1; land surface recharge and pumping are only specified in vadose zones 2 and 3

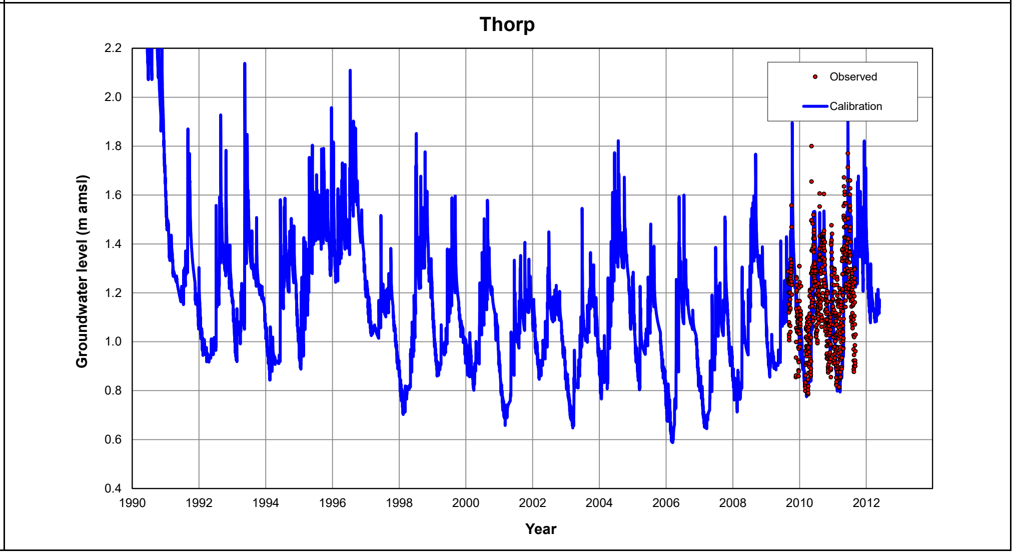
Figure 2: Calibration plots

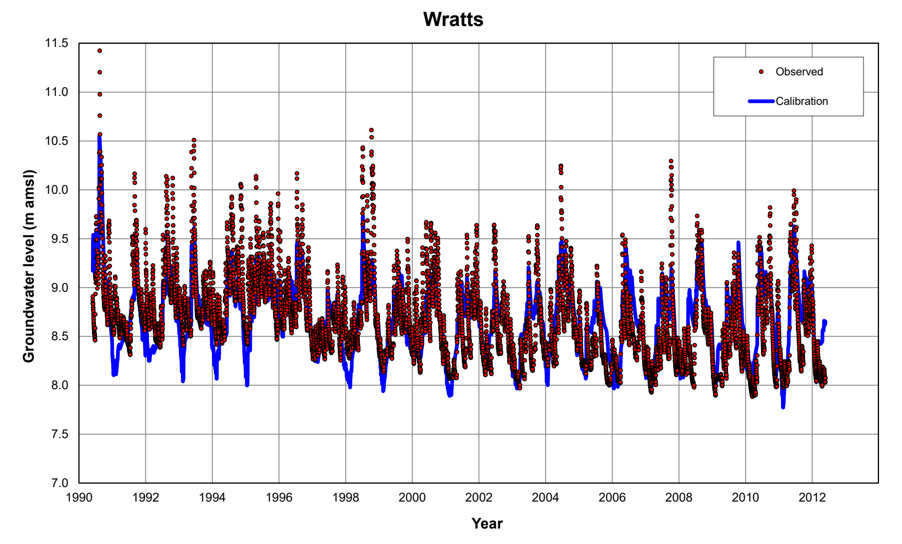


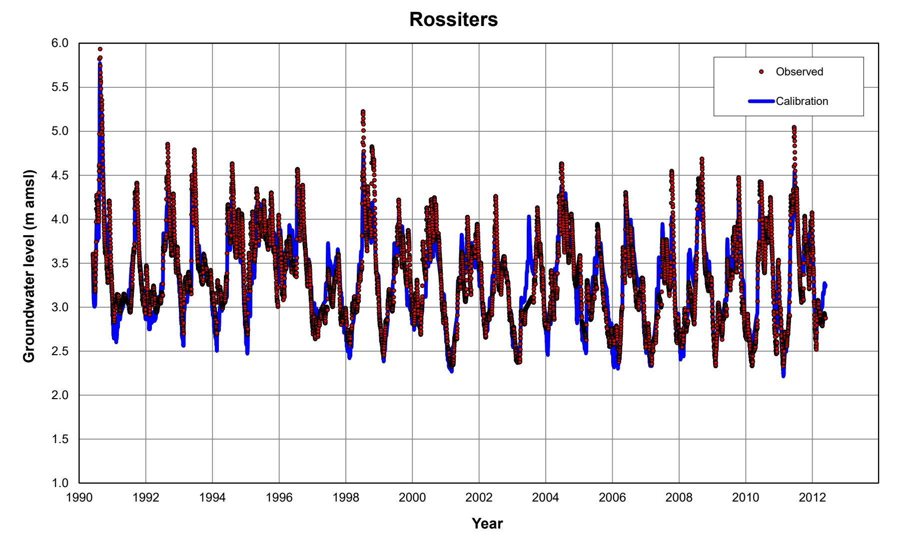

Nursery North
Groundwater level (m amsl)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Year
Observed
Calibration

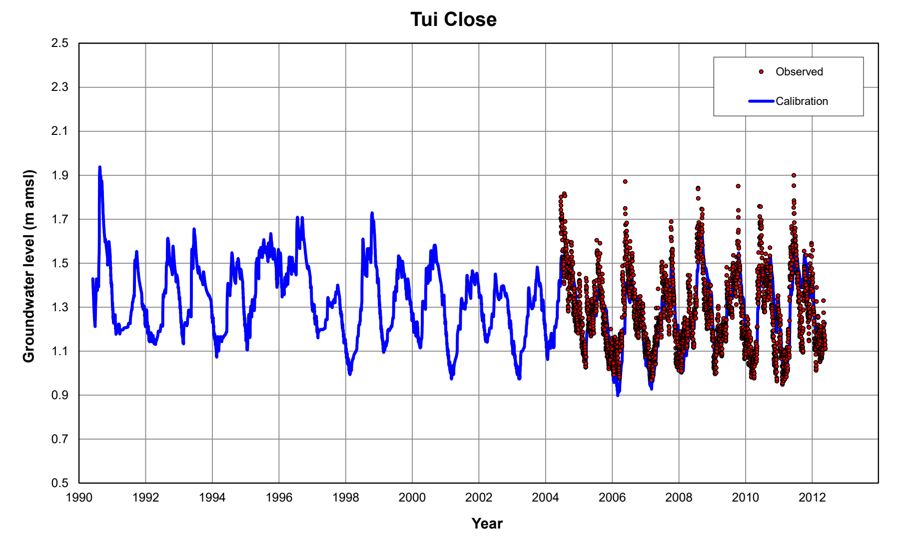

Motueka River Bed
Groundwater level (m amsl)
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Year
Observed
Calibration

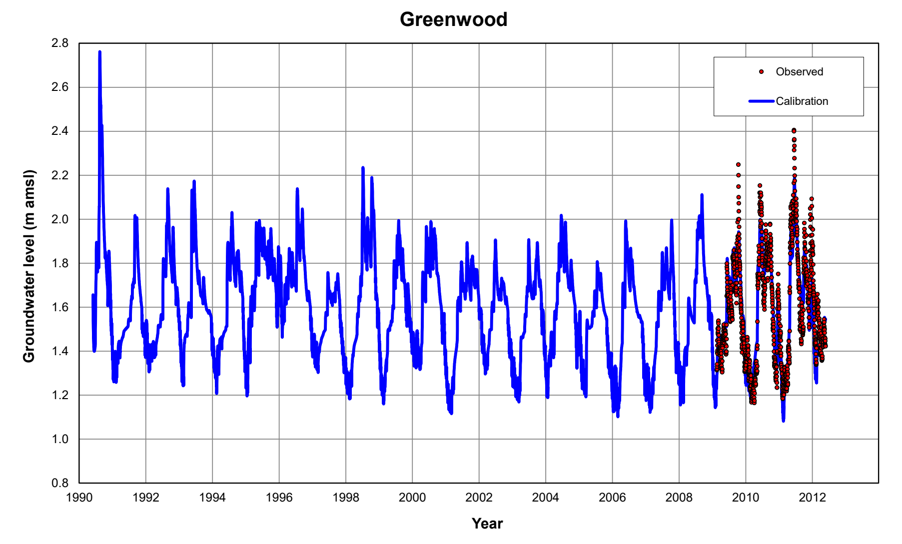

Staples
Groundwater level (m amsl)
3.0
2.5
2.0
1.5
1.0
0.5
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Year
Observed
Calibration

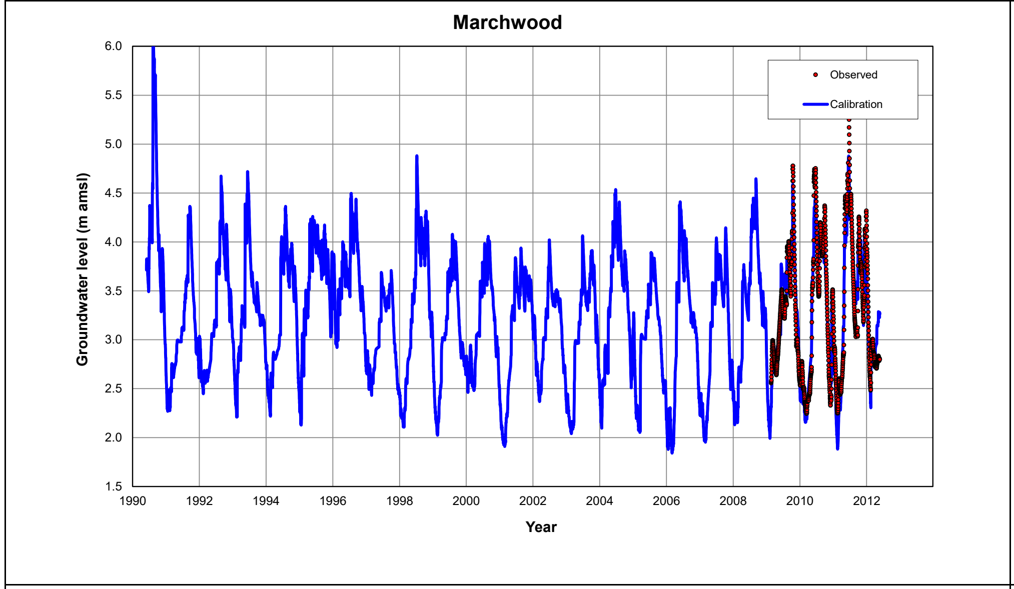

Thorp
Groundwater level (m amsl)
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Year
Observed
Calibration

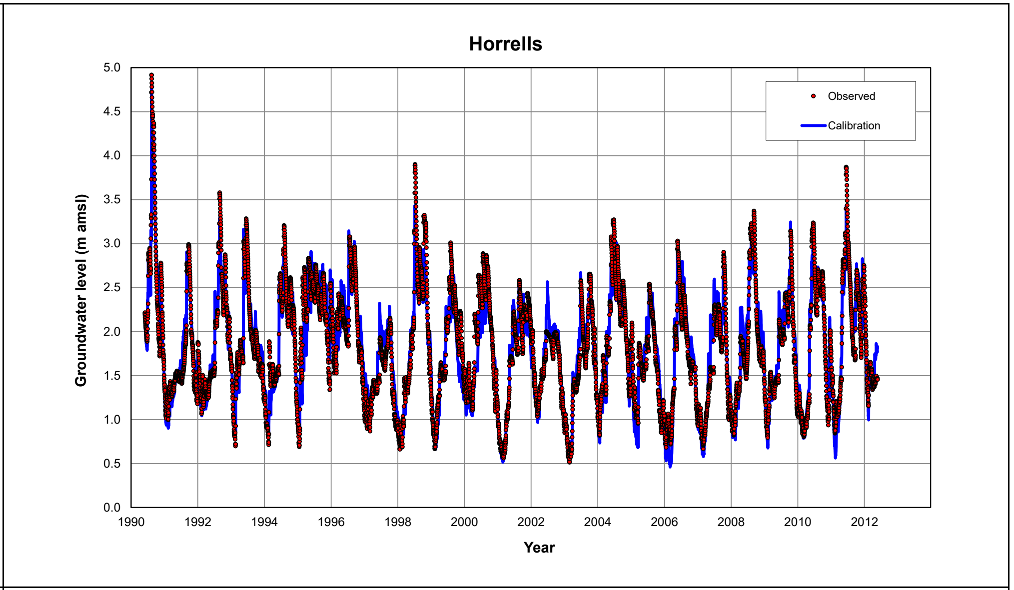

Wratts
Observed
Calibration
Groundwater level (m amsl)
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0
7.5
7.0
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Year

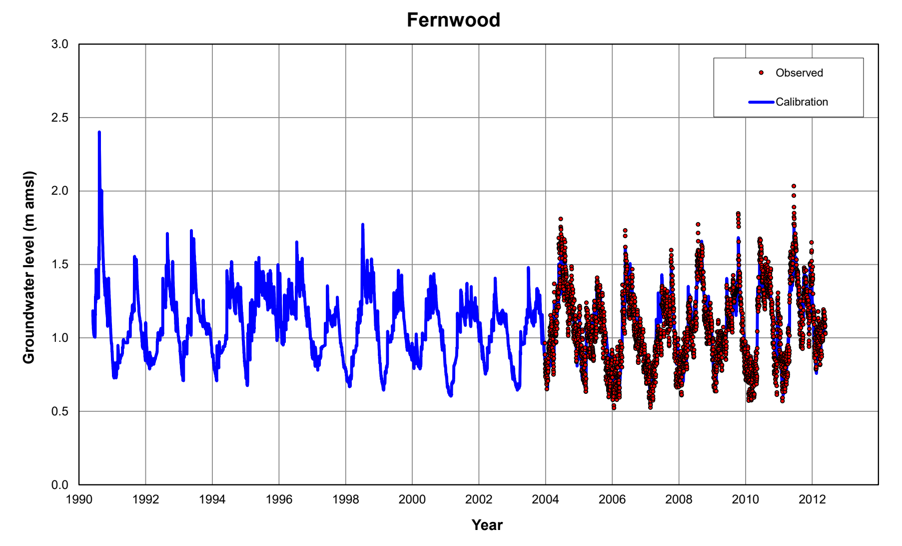

Rossiters
Observed
Calibration
Groundwater level (m amsl)
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Year

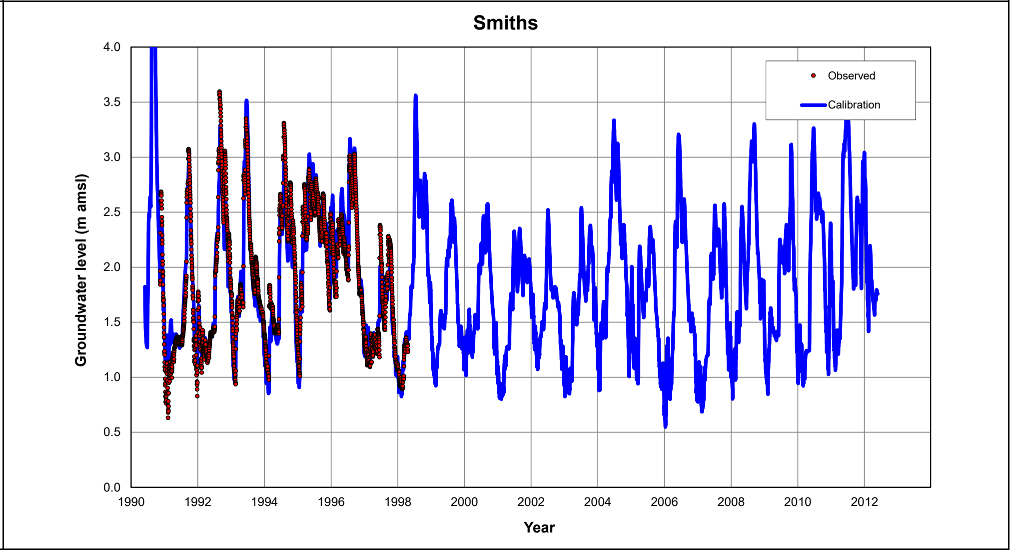

Tui Close
Observed
Calibration
Groundwater level (m amsl)
2.5
2.3
2.1
1.9
1.7
1.5
1.3
1.1
0.9
0.7
0.5
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Year


Greenwood
Observed
Calibration
Groundwater level (m amsl)
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Year


Marchwood


Horrells


Fernwood


Smiths

EXECUTIVE SUMMARY

Groundwater levels for the Motueka-Riwaka Plains have been assessed for long term trends. Long term decreasing trends are apparent in the graphs of the groundwater levels at three well sites in the central aquifer, west of Motueka. This is supported by statistical metrics that found trends of reducing groundwater levels in the order of 17 mm/year (approximately 700 mm over a 41-year record length) that are unlikely to be a result of random variability. In addition, the metrics identified two sites closer to the coast with increasing trends of 16 mm/year (approximately 170 mm over a 11-year record length), though these sites had a shorter record.

Figure 1 shows an interpolated map of the observed long term trends.

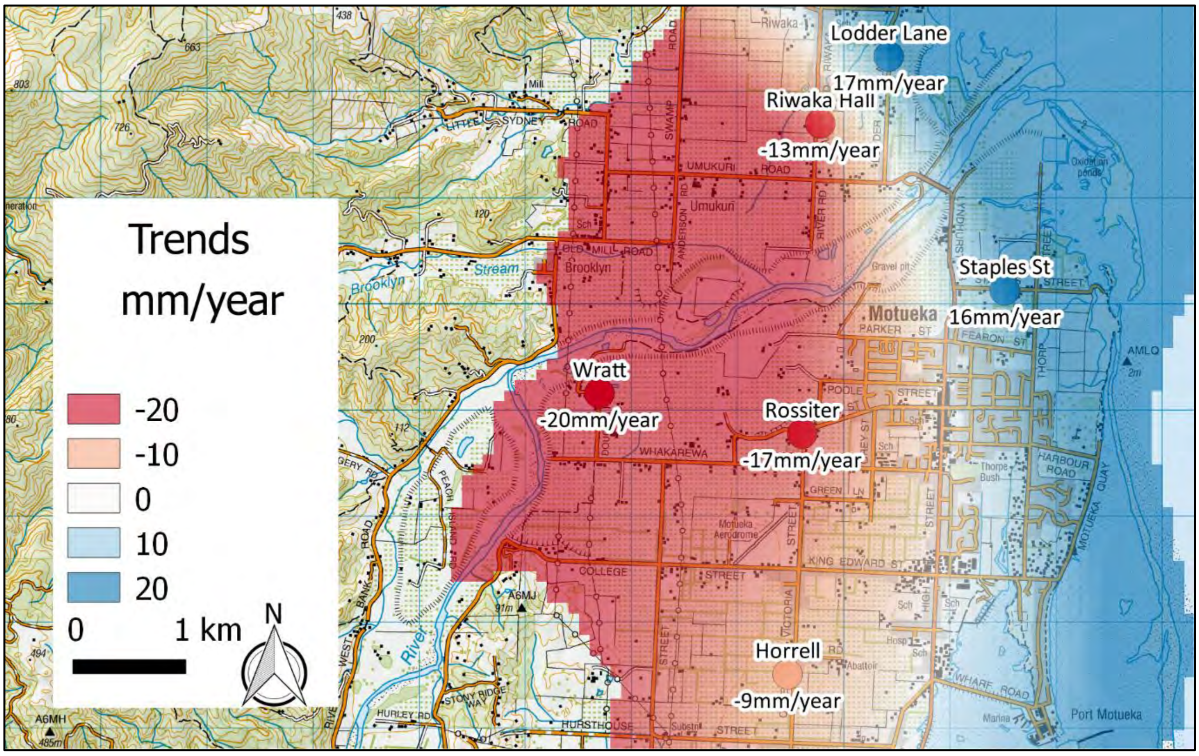


Figure 1. Estimated long-term trend in groundwater levels

The annual maximum groundwater levels of the three central sites were found to have a lowering trend, but not as much as the annual groundwater minimums. The discrepancy between the trend of the annual groundwater maximums and minimums indicates an increase in loss of water from the aquifer over summer, which may be explained by increased groundwater pumping. One of the three central sites showed an increasing trend in the summer depletion, which supports this explanation. While winter recharge is generally not water limited, the likelihood of this occurring will increase as the amount of water required to fully recharge the aquifer continues to increase.

The reducing trends for the central sites are consistent with the degrading Motueka River bed which results in a reduction in the maximum levels of the aquifer, and an equivalent reduction in minimum levels.

The reason for the increased groundwater levels at the two coastal sites is not clear. The increase is much greater than sea level rise. The increase is potentially related to reductions in pumping in the area, or may be an artefact of the short time series.

The tests used here provide a robust means of determining whether trends can be detected in the data. Where trends are not found to be statistically significant, it does not mean that no trend exists, merely that the variability of data prevents a trend to be detected.

As the observation record grows, the ability to determine trends becomes increasingly robust. The quality of measurements and commitment to ongoing observations places Tasman District Council in a strong position for continued quality assessment of groundwater trends.

1 DATA

Data has been provided by Tasman District Council for 19 different locations in the Motueka-Riwaka Plains (Figure 2).

Figure 2. Groundwater well locations

Of the 19 sites, the data from Thorp was discarded because it only had two complete years of data. This is not enough time to detect trends. The groundwater level observations from Old Wharf Rd (obtained from 1989 until 2004) were combined with the observations from Tui Close (collected from 2004 until present) as both sites are in nearly the same location. There is an apparent offset in water level datums between the Old Wharf Rd data and the Tui Close data. This has potential to affect the trend analysis. A correction was applied to the Old Wharf Rd data based on linear relationships to the data from the Horrell well, which operated during the transition period from the Old Wharf Rd well to the Tui Close well. This led to scaling of the Old Wharf Rd by 1.06, and subtracting 7 mm. Details of the derivation of this correction are provided in the Annexure 1.

The summary statistics for the sites are provided in Table 1.

Table 1. Summary statistics for the groundwater site data

Site	Start year	End year	Length (years)	Minimum (mm amsl [(1)])	Maximum (mm amsl [(1)])	Average (mm amsl [(1)])
Golf Course	2012	2017	5	858	1,830	1,240
Marchwood Park	2009	2017	8	2,070	5,612	3,302
Inglis	2009	2017	8	2,959	5,001	3,371
River.Bed	2003	2017	14	3,000	6,032	3,605
Tui Close and OWR	1989	2017	28	893	2,276	1,278
Nurs Nth	2006	2017	11	2,526	4,928	3,230
Nurs Sth	2006	2017	11	2,509	4,968	3,230
Anderson Rd	2009	2017	8	4,743	8,719	6,396
Greenwood St	2009	2017	8	1,145	2,473	1,615
Rossiter	1976	2017	41	2,125	6,303	3,434
Wratt	1976	2017	41	7,707	12,005	8,768
Riwaka Hall	1978	2017	39	1,586	4,507	2,533
Horrell	1978	2017	39	512	4,917	1,891
Fernwood	2003	2017	14	522	2,033	1,107
Staples St	2006	2017	11	646	2,398	1,532
Lodder Lane	2006	2017	11	800	1,872	1,163
Thorp	2009	2011	2	785	1,800	1,160
Smith	1990	1998	8	630	3,595	1,878

[(1)] mm amsl = millimetres above mean sea level (Nelson Vertical Datum, 1955)

The following summary variables have been extracted from the observations prior to assessment of trends:

- monthly average ground water levels
- annual minimums,
- annual maximums,
- change in levels over the non-irrigation season, and the
- change in levels over the irrigation season.

These Summary Variables were selected to provide an indication of overall trend, and to assist with attribution of cause of any detected trends.

The annual maximums and minimums were calculated from the monthly average series. The daily observations were not directly used to avoid rapid changes in groundwater levels, associated with pumping or recharge, from influencing the trend analysis.

The change in groundwater level over the non-irrigation season was calculated by subtracting the post-irrigation (February to June) minimum from the pre-irrigation (September-October) maximum (Figure 3). Positive values indicate an increase in groundwater levels. Note that the pre-irrigation season maximum is not always the annual maximum, as it is possible for the groundwater level to peak prior to September the 1st. For the purposes of assessing the effect of irrigation, the September the 1st date is considered appropriate.

The change in groundwater level over the irrigation season was calculated by subtracting the pre-irrigation (September-October) maximum of the previous year from the post-irrigation (February to June) minimum (Figure 3). Negative values indicate a decrease in groundwater level.

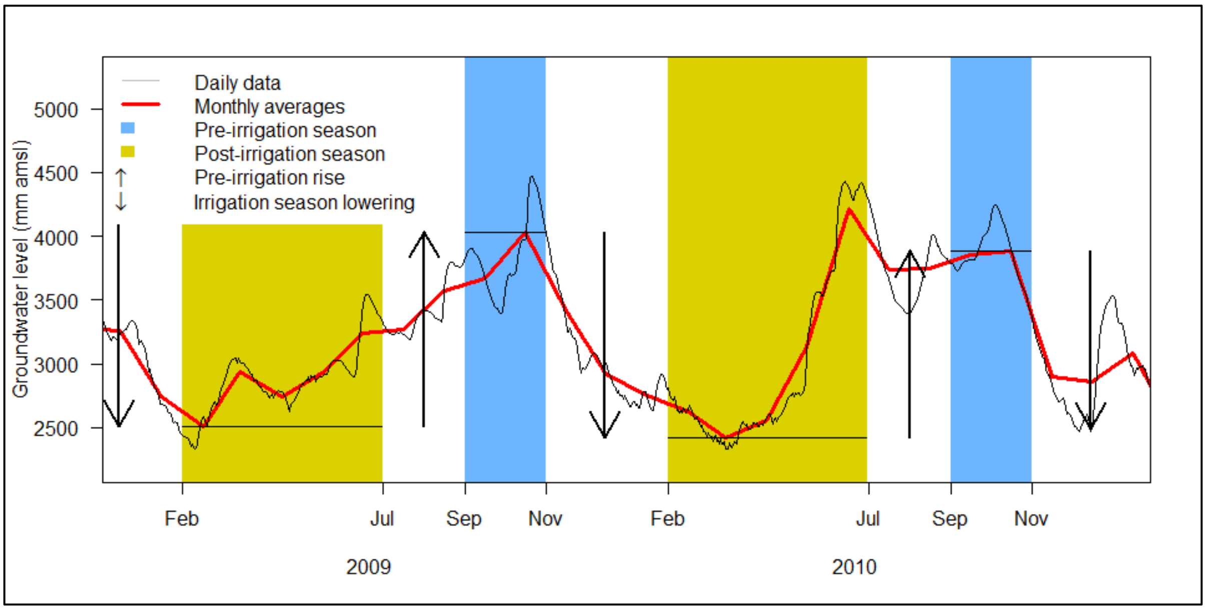


Figure 3. Example plot showing calculation of the changes in groundwater level in the non-irrigation season (up arrows) and irrigation season (down arrows) (Rossiter site)

Time series plots of all data and the summary Variables are provided in Annexure 2.

For each Summary Variable at each site, trends were assessed qualitatively through plots, and quantitatively using statistical metrics.

2 TRENDS

2.1 Qualitative Assessment

Visual qualitative assessment of the time series (see Annexure 2) for each well indicates that the longer series of Rossiter and Wratt have an almost continuous decreasing trend. The Riwaka Hall and Horrell data appear to initially have a decreasing trend then remain steady from about 2000. The other long term site of the combined Old Wharf Rd and Tui Close does not show any clear trend, but there is an indication of a shift in 2004 when the sites changed. This shift may simply be a datum difference, in which case potential exists to offset the Old Wharf Road data to match Tui Close and repeat the trend analysis. Trends are not clear on any of the other sites. The variation in levels is very similar between the long term sites, indicating that individual well properties are not obscuring the aquifer level response and that the aquifer levels vary synchronously across the region.

2.2 Statistical Assessment of Monthly Averages

The Mann-Kendal test for trend is a statistical measure of how frequently values in a time series change in the same direction. It is a measure of the strength of a trend. The measure is called Kendall’s “tau” statistic. If every value increases (or decrease) compared to the previous value, then the test returns a value of tau = 1. If the values go up the same number of times as going down then a value of tau = 0 is returned. It is also possible to determine the likelihood of the observed trend occurring just by chance. This is called the “p” value. A very low p value indicates the observed trend is unlikely to have occurred by chance. A p value of 0.1 indicates that the observed trend could occur by chance from random data one in every ten times.

The Mann-Kendal test has been applied to monthly or annual time series for computational efficiency. For monthly data, the seasonal Mann-Kendall test is used, which applies the test to all January’s data, then all February’s data, etc., then averages the results. This leads to a more robust measure of the trend than using annual values, and accounts for seasonality. Groundwater exhibits serial correlation whereby the groundwater level of one month affects the groundwater level of subsequent months, and so monthly levels are not independent. This affects the calculation of the likelihood of a trend being observed by chance (the p value) generally leading to under-estimated values. A corrected p value can be calculated which takes into account serial correlation and provides an improved measure of the likelihood of the trend occurring by chance. Series require more than 10 years of data for the corrected p value to be determined.

The results of the Seasonal Mann-Kendall test are presented in Table 2.

Table 2. Likelihood that trends occur by chance (p) for monthly average groundwater levels, strength of long term trends (tau) and slopes of trends for those sites and variables where the trend has a less than 0.05 chance of occurring by chance

	p value	corrected p value	tau	Slope (mm/year)
Golf Course	0.068	NA	-0.271	
Marchwood Park	*0*	*0.007*	*0.504*	*60.374*
Inglis	0.608	NA	-0.056	
River Bed	0.098	0.172	0.122	
Tui Close and OWR	0.302	0.478	-0.050	
Nurs Nth	0.094	0.279	0.145	
Nurs Sth	0.094	0.228	0.145	
Anderson Rd	0.418	NA	-0.086	
Greenwood St	0.096	NA	0.172	
Rossiter	*0*	*0*	*-0.367*	*-17.005*
Wratt	*0*	*0*	*-0.484*	*-19.577*
Riwaka Hall	*0*	*0*	*-0.35*	*-13.132*
Horrell	*0*	*0.007*	*-0.172*	*-8.592*
Fernwood	*0.004*	*0.083*	*0.215*	
Staples St	*0*	*0.012*	*0.341*	*15.893*
Lodder Lane	*0*	*0.002*	*0.444*	*16.785*
OWR	0.227	0.416	-0.086	
Smith	1	NA	-0.005	

Slopes of the trends are shown for those sites where the trend has a less than 0.05 likelihood of occurring by chance. Five of the series were not long enough to establish the corrected p value so the uncorrected p values are also shown. Slopes were calculated using the Kendall Slope estimator. P values are reported to three decimal places, so sites with p values of 0 have trends that are highly unlikely (less than 1 chance in 1,000) to have occurred by chance. The cut-off level of $p < 0.05$ (1 chance in 20) was arbitrarily selected as the threshold below which it is not unreasonable to expect the trend to be real.

Statistically significant decreasing trends were found for Rossiter, Wratt, Riwaka Hall and Horrell though the trend for Horrell was weak. This confirms the visual assessment. Statistically significant increasing trends are found for Staples St and Lodder Lane.

A map of the slope of the statistically significant (corrected $p < 0.05$) trends of the monthly time series is shown in Figure 4. To assist with visualising the distribution of these trends they are presented as an interpolated map in Figure 1. The interpolation was carried out in QGIS version 2.18.10[18] using a thin plate smoothing spline with a 10 km search area and a regularisation weight of 0.0001.

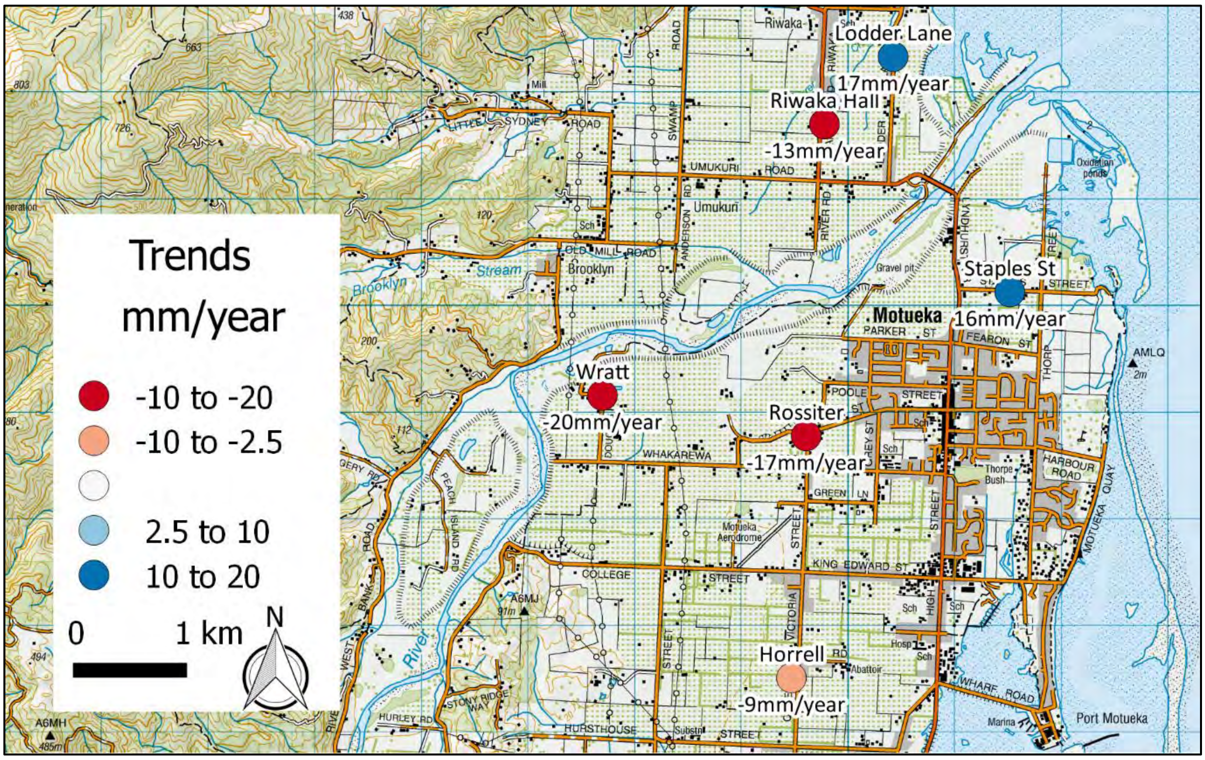


Figure 4. Map of groundwater level trends

The map indicates that the aquifer surface gradient is reducing over time. This has implications for aquifer through flow which has implications for water quality and quantity. Possible reasons for the trends and the variation in trends are presented in the Section 2.4 discussion below.

---

[18] Quantum GIS Development Team (2009). Quantum GIS Geographic Information System. Open Source Geospatial Foundation Project. http://qgis.osgeo.org

2.3 Statistical Assessment of Annual Time Series

Mann-Kendall test for trend of the annual Summary Variables and their slopes, calculated using the Thiel-Sen’s slope, are provided in Table 3. Slopes are only provided for those sites that returned a p value less than 0.05. This level of p (1 chance in 20) was arbitrarily selected as the threshold below which it is not unreasonable to expect the trend to be real.

The three sites with strong decreasing trends in the monthly series also show decreasing trends for their annual maximum and annual minimum values. For each of these sites, their annual minimum values are decreasing faster than their annual maximums. The Horrel site also shows a decreasing trend for the annual minimums, though not as large as for Rossiter, Wratt and Riwaka Hall.

Only Rossiter returned statistically significant trends of the non-irrigation season (winter) change in levels (increasing by 14 mm/year) and the irrigation season (summer) change in levels (extra loss of 13 mm/year). For Rossiter, the irrigation season decline is getting greater, but the non-irrigation season recharge is able to compensate for it. The irrigation season decline is attributed to increased pumping over time for the nearby Lower Moutere Water Scheme (in recent years, new wells have been installed near the Rossiters well to service this scheme) (Joseph Thomas, TDC, *pers. coms.*).

Table 3. Likelihood that trends occur by chance (p) for annual Summary Variables and slopes of trends for those sites and variables where the trend has a less than 0.05 chance of occurring by chance

	Annual max		Annual Min		Winter change		Summer change	
	p	Slope mm/year	p	Slope mm/year	p	Slope mm/year	p	Slope mm/year
Golf Course	0.06		0.71		0.09		0.31	
Marchwood Park	0.08		0.35		0.71		1	
Inglis	0.08		1		0.11		0.37	
River Bed	0.55		0.92		1		1	
Tui Close & OWR	0.75		0.24		0.93		0.8	
Nurs Nth	0.73		0.84		0.88		0.72	
Nurs Sth	0.37		0.73		0.44		0.15	
Anderson Rd	0.12		0.6		0.39		0.13	
Greenwood St	0.12		0.25		0.54		1	
Rossiter	0	-13	0	-22	0.02	14	0.02	-13
Wratt	0	-16	0	-20	0.34		0.3	
Riwaka Hall	0	-11	0	-13	0.21		0.16	
Horrell	0.06		0.01	-9	0.28		0.47	
Fernwood	0.77		0.06		1		0.58	
Staples St	0.73		0.11		0.21		0.15	
Lodder Lane	1		0	14	0.21		0.47	
Smith	0.18		0.6		0.13		0.76	

2.4 Discussion

Degradation of the Motueka River, changed river flows, increased groundwater pumping, changes in irrigation efficiency, increased sea levels and climate trends are all possible reasons for the change in groundwater levels.

A degraded river will lower the groundwater maximum levels, and for the same groundwater pumping, will also lead to a lowered minimum groundwater level. The Motueka river has degraded at an average rate of 23 mm/year between 1978 and 2001[19].

---

[19] Sriboonlue, S., Basher, L., 2003. Trends in bed level and gravel storage in the Motueka River 1957–2001: a progress report on results from analysis of river cross section data from the upper and lower Motueka River (Unpublished report prepared for Stakeholders of the Motueka Integrated Catchment Management Programme Landcare ICM Report No. 2002-03/04), Motueka Integrated Catchment Management (Motueka ICM) Programme Report Series. Landcare Research.

Reduced river flows will have the same effect on groundwater levels as a degraded river bed.

Increased groundwater pumping will result in decreasing minimum levels, increased over-summer loss, but only decreased maximum levels on the years when winter recharge is water limited.

Increased irrigation efficiency, without increased groundwater pumping, will increase summer depletion through the loss of the summer groundwater recharge resulting from irrigation.

Increased sea levels will lead to an increase in coastal groundwater levels. Sea level around New Zealand has historically increased at approximately 1.6 mm/year[20]. This is much lower than the increases observed at Lodder Lane and Staples St.

Climate trends affect the amount of rainfall, evapotranspiration and river flows. There are indications of increased rainfall in winter and spring, decreased rainfall in autumn and no change in summer for the Motueka region[21]. At the same time, temperature (and hence evapotranspiration) has been increasing[22]. The impact of increased winter rainfall would only be observed if the winter aquifer recharge was water limited. The impact of increased evapotranspiration would mainly be seen through increased irrigation and its associated groundwater pumping. Land use change (e.g. change in crop types away from hops) will impact groundwater use, but analysis of the magnitude of this effect has not been carried out.

If the trends observed at Rossiter are a reasonable expression of the overall aquifer, then a plausible scenario for the observed trends are that the degrading Motueka River is leading to lowering of the aquifer's maximum level, except in the coastal areas of the aquifer where the seawater interface regulates changes (as evidenced by their smaller range of groundwater levels). The difference in trend between the central and coastal sites indicates a reduction in the overall groundwater level gradient, reducing aquifer throughflow. Reduced throughflow has implications for groundwater quality and quantity management. The increasing trend in groundwater levels at the two coastal sites may be related to reduced pumping in those areas as households switch from domestic bores to reticulated supply sourced from more inland wells. When the data for all sites were re-analysed using only post 2007 data, Staples St. and Lodder Lane were the only sites that showed a statistically significant trend. Rossiter, Wratt, Riwaka and Horrell all showed no statistically significant trend for the limited 2007 – 2017 period. This confirms the increasing trend effect at Staples St and Lodder Lane over the last ten years as not being widespread, but does not clarify whether it is only a relatively recent effect.

The decreasing aquifer minimum levels may be partly a result of the lower initial state each end-of-winter, with increased groundwater pumping adding to the reduction and

---

[20] New Zealand Government, 2009. Preparing for coastal change (Report No. ME 907). Ministry for the Environment, Wellington. http://www.mfe.govt.nz/sites/default/files/preparing-for-coastal-change.pdf

[21] Caloiero, T., 2014. Analysis of rainfall trend in New Zealand. Environ Earth Sci 73, 6297–6310. doi:10.1007/s12665-014-3852-y

[22] Mullan, A.B., Stuart, S.J., Hadfield, M.G., Smith, M.J., 2010. Report on the Review of NIWA's "Seven-Station" Temperature Series (No. NIWA Information Series No. 78). NIWA, Wellington.

overcoming any increased rainfall that is occurring. As the summer minimums are decreasing faster than the winter maximums the probability of occurrence of winters when the aquifer is not fully recharged will increase. Understanding this probability is an important consideration for reliability of supply and provides potential direction for future assessments.

The lack of a statistically significant trend does not necessarily mean that no trend exists. It just means that the variability of the time series is too great to discern a trend. Only with longer time series of data does the detection of trends become increasingly possible. This supports the continuation of the high quality observations that Tasman District Council carry out.

ANNEXURE 1: DATUM SHIFT CORRECTION FOR OLD WHARF RD AND TUI CLOSE

The Old Wharf Rd was last monitored on 30th March 2004. Approximately ten weeks later on 19th June 2004, monitoring began on the new Tui Close well (64 m away). The two wells are considered to be measuring the same aquifer at effectively the same location, so combining their data provides an extended data series, useful for trend analysis. Unfortunately, plots of their data indicate an offset in the level between sites suggesting a datum misalignment.

The nearby Horrell (2.2 km away) and Rossiter (1.9 km away) wells were both operating during the transition from Old Wharf Rd to Tui Close. For both of these long term sites, linear relationships were developed to correlate with the time series from Old Wharf Rd and Tui Close. Horrel returned R^2 values of 0.87 to Tui Close, and 0.82 to Old Wharf Rd. These were slightly better than for Rossiter (0.87 and 0.80 respectively). Based on the better R^2 values, the Horrell relationships were combined and the long term site removed from the equations to provide relationships between Old Wharf Rd and Tui Close. This equation was used to adjust the Old Wharf Rd data prior to the trend analysis.

$$Horrell = m_{Tui}Tui + c_{Tui}$$

$$Horrell = m_{OWR}OWR + c_{OWR}$$

Combining these equations and solving for Tui provides:

$$Tui = \frac{m_{OWR}}{m_{Tui}}OWR + \frac{c_{OWR} - c_{Tui}}{m_{Tui}}$$

$$Tui = 1.07 * OWR - 7$$

(in units of mm amsl, Nelson Vertical Datum, 1955)

ANNEXURE 1: TIME SERIES PLOTS

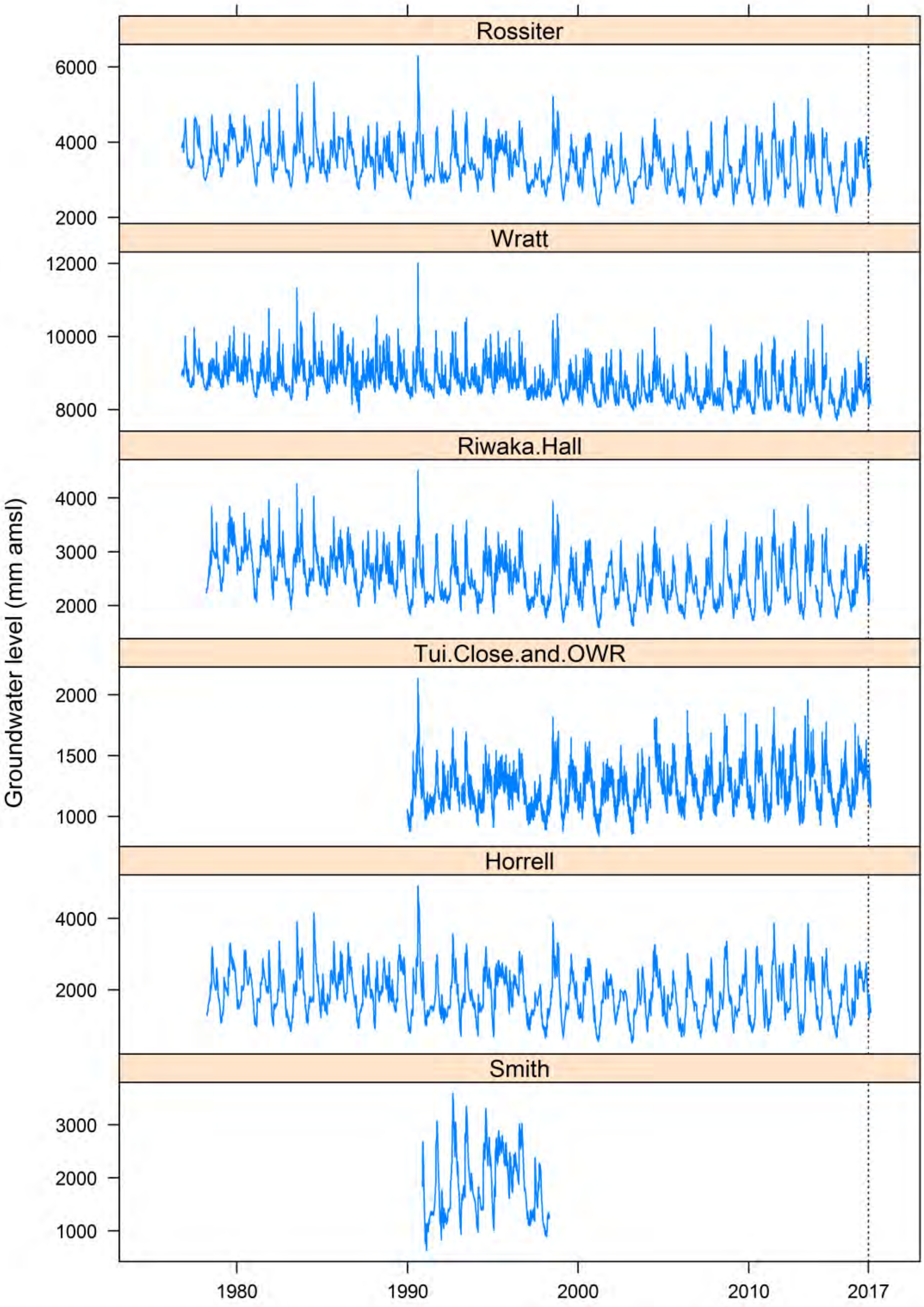


Figure 5. Time series plots of groundwater level for those wells that have data prior to 2003

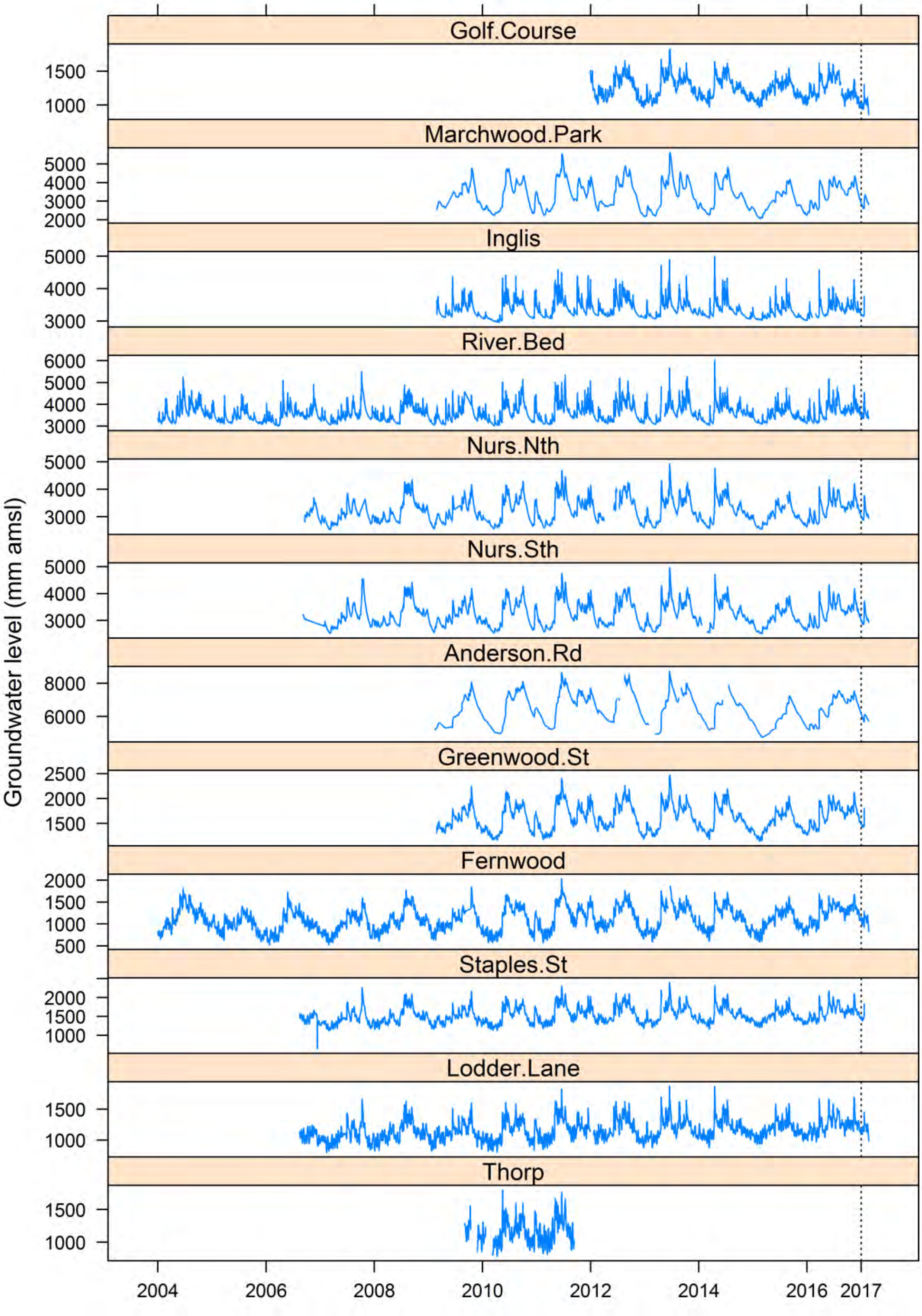


Figure 6. Time series plots of groundwater levels for those sites that only have data after 2003.

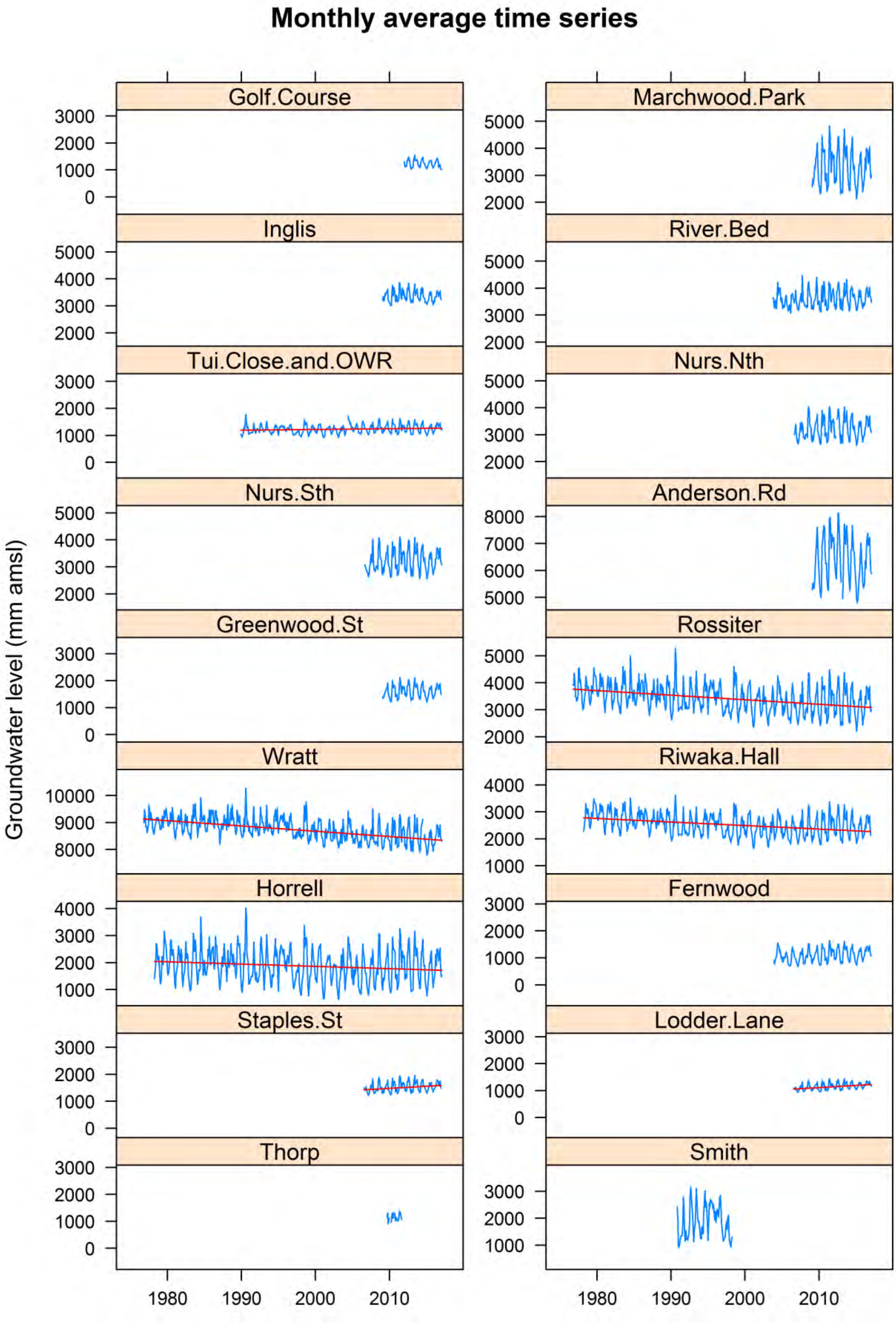


Figure 7. Time series plots of monthly averages of groundwater level. Note the scales are consistent for each site, and full records for each site are shown.

Annual maximum time series

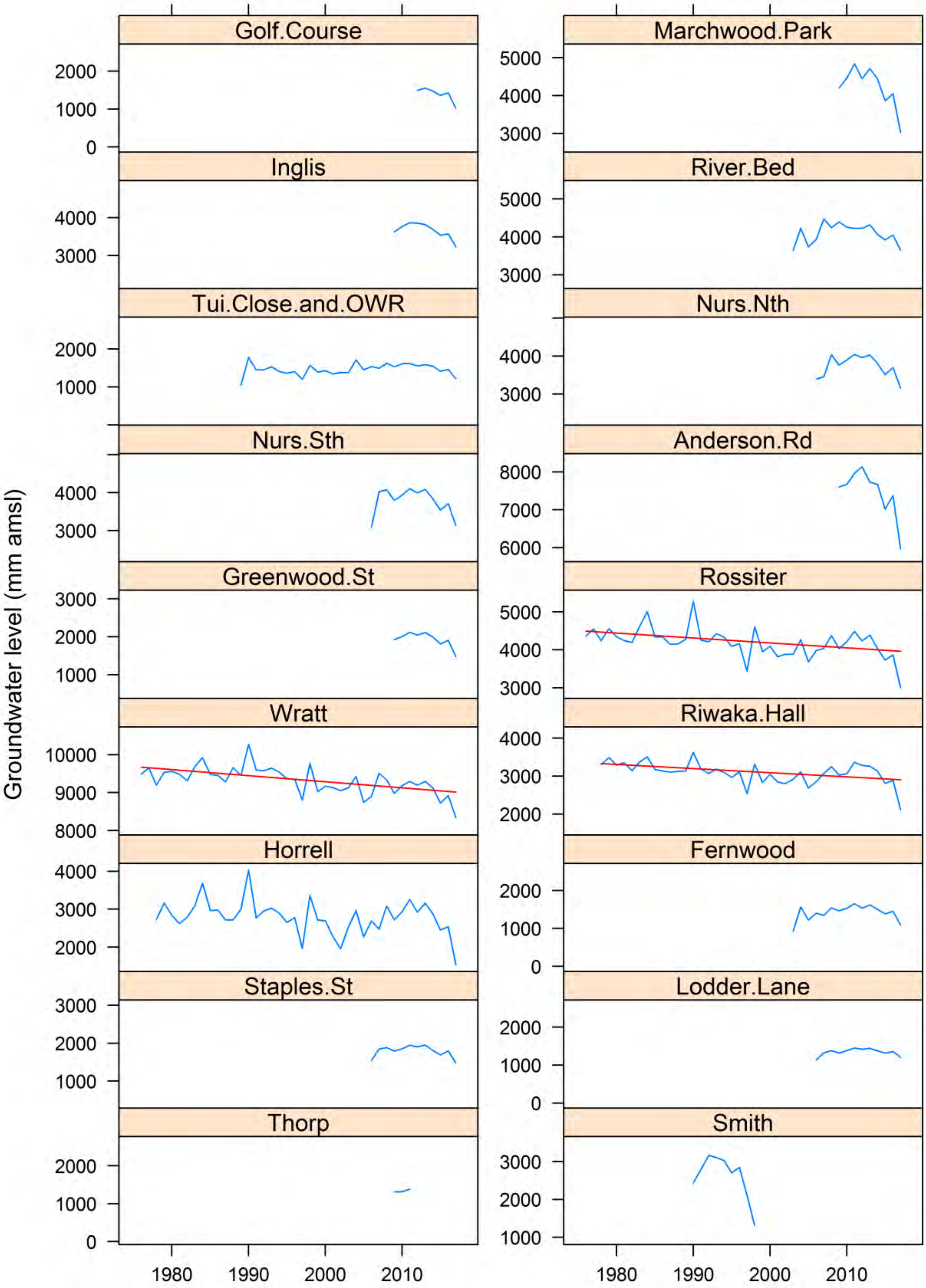


Figure 8. Time series plots of annual maximum of monthly groundwater level.

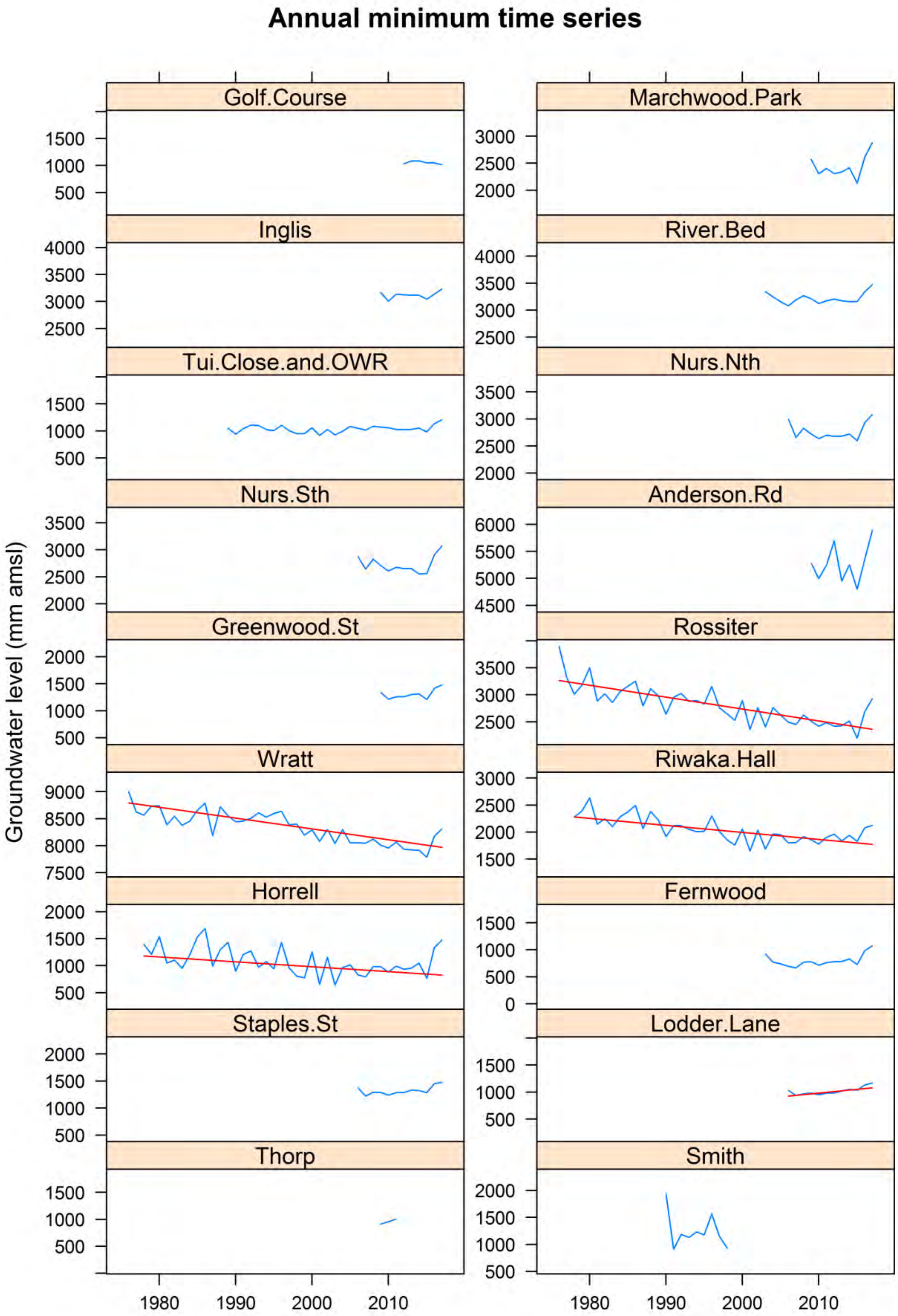


Figure 9. Time series plots of annual minimum of monthly groundwater level.

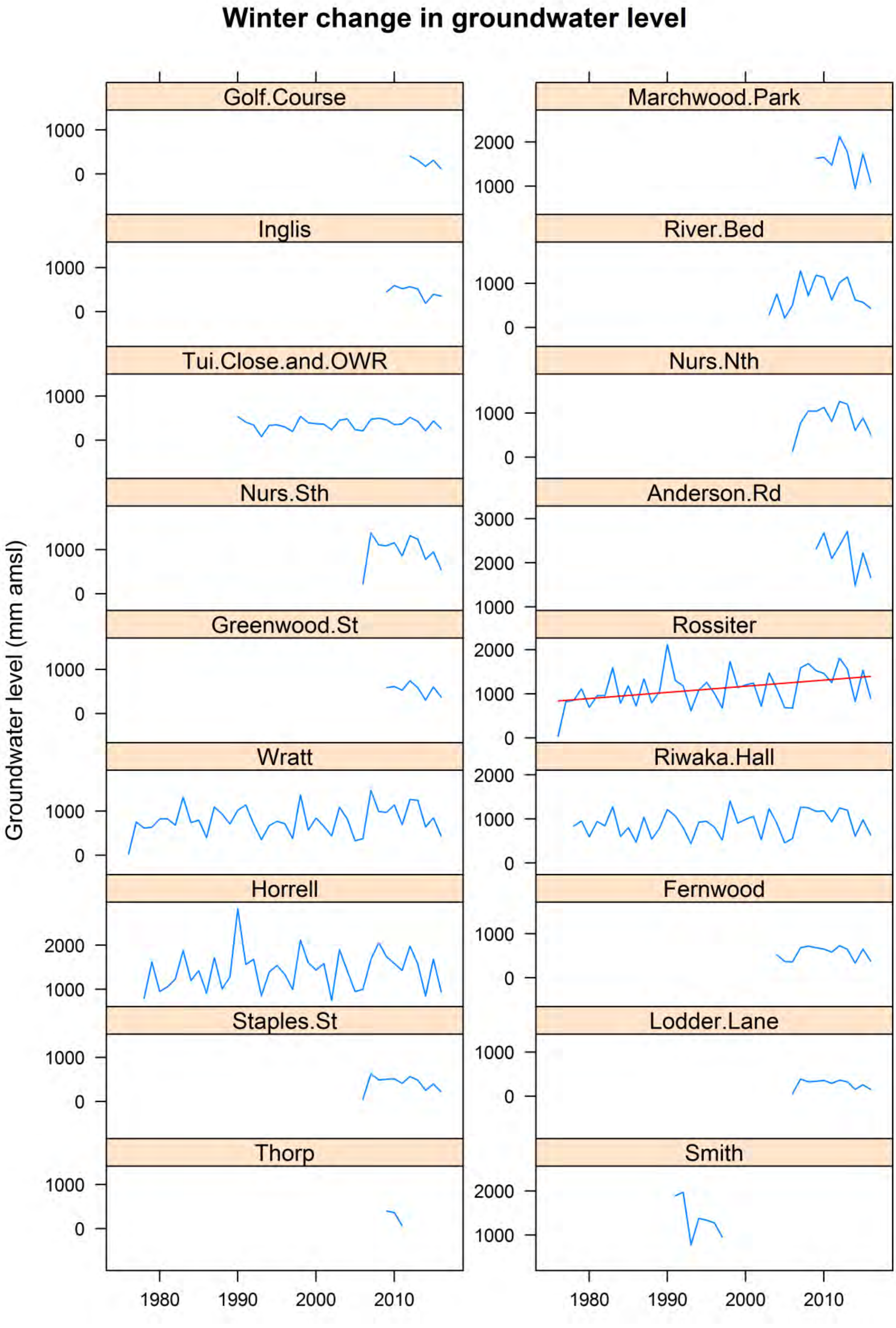


Figure 10. Time series plots of winter change of groundwater level.

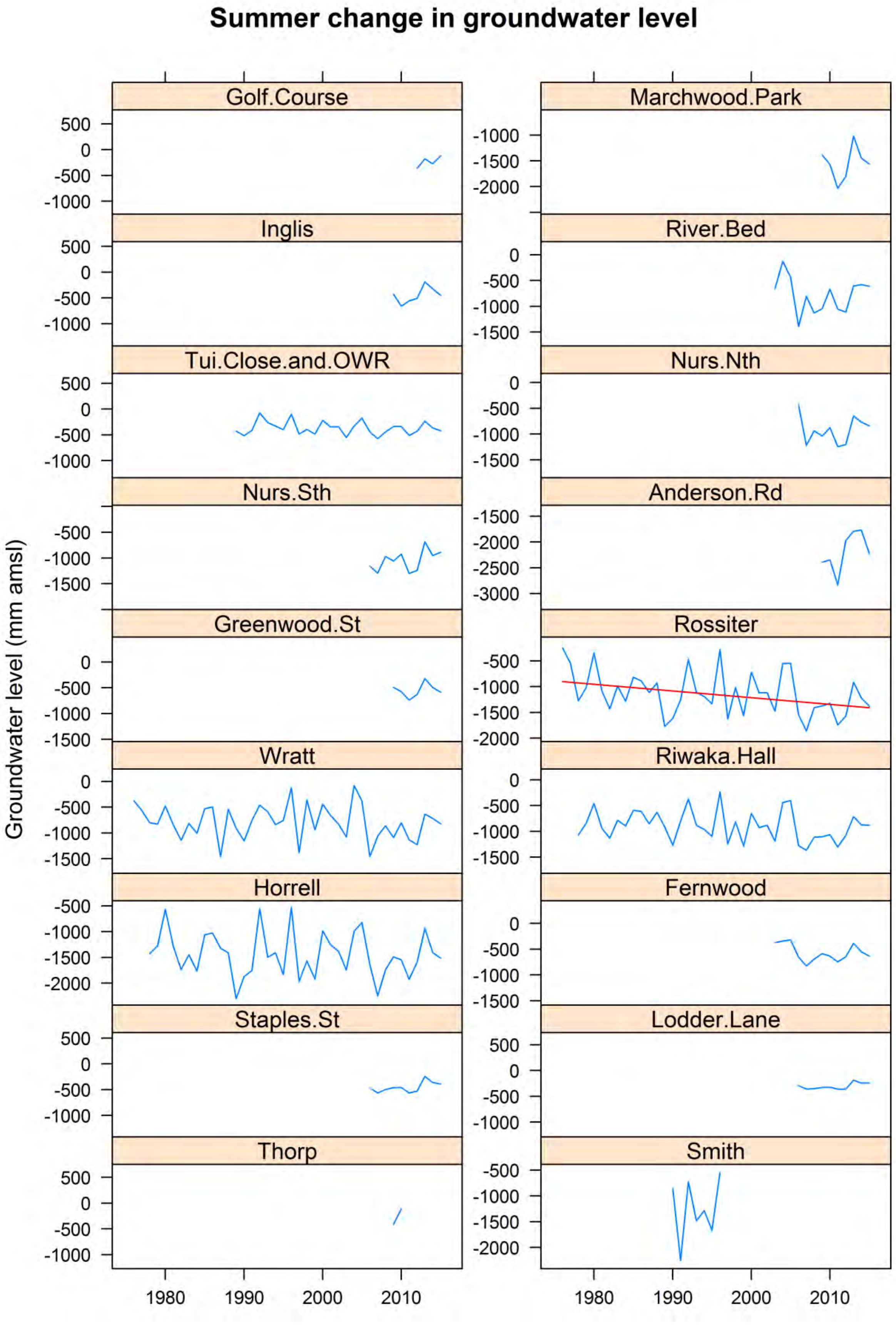


Figure 11. Time series plots of summer change of groundwater level.

Appendix G: Detailed methodology of climate change scenarios

1. CLIMATE CHANGE SCENARIOS

To identify the effect of climate change for the study area, the most relevant source for information is NIWA (2015). Four 'Representative Concentration Pathways' (RCPs) are described in the report (RCP 2.6, 4.5, 6.0 and 8.5), covering a range of future climate change scenarios. RCP 2.6 corresponds to a scenario leading to a very low level of greenhouse gas emissions and removal of greenhouse gases from the atmosphere (likely with least climate change), while RCP 8.5 leads to very high greenhouse gas concentrations (likely with greatest climate change) (Mullen, B. *NIWA, pers. comm.*).

For each RCP scenario, NIWA downscaled the data from several different global climate models (23 models for RCP 2.6, 37 for RCP 4.5, 18 for RCP 6.0, and 41 models for RCP 8.5) using regional and statistical downscaling processes, in order to create climate change scenarios for the Tasman District in 2040 and 2090. For the present work, 2090 data was used, in order to match the sea level modelling scenarios. The baseline period for the projected changes in rainfall and temperature is 1986-2005, so 2090 projected changes can be thought of as 95-year trends (NIWA, 2015). NIWA reports seasonal ensemble averages for each scenario taken over all climate models, with 5th and 95th percentiles.

2. RAINFALL

NIWA (2015) sets out projected changes in seasonal rainfall for the Appleby and Takaka grid points; data for the Appleby grid point was used in the present work as it is the most relevant for the Motueka-Riwaka Plains. A few options based on the 2090 projections were considered:

Option 1:

Use two extremes of RCPs, i.e. 2.6 and 8.5, based on the ensemble-average (i.e. the average of all models) for 2090, relative to 1986–2005 (Table 1).

Table 1: Option 1 percent rainfall increase

	Summer	Autumn	Winter	Spring
RCP 2.6	0%	+3%	+3%	+1%
RCP 8.5	+11%	+6%	+9%	-2%

Option 2:

Use two extremes of the projected average changes in each season among all RCPs, i.e. each season is considered independently (based on ensemble-average for 2090, relative to 1986–2005; Table 2).

Table 2: Option 2 percent rainfall increase

	Summer	Autumn	Winter	Spring
Max change	+11%	+6%	+9%	+1%
Min change	0%	+3%	+3%	-2%

Option 3:

Use extremes of the reported model ranges based on 5th and 95th percentiles for RCP 2.6 and 8.5. However, use the 95th percentile for RCP 2.6 and the 5th percentile for RCP 8.5, due to the fact that these RCPs represent the least and greatest climate change, respectively (Table 3). This option was used in further calculations.

Table 3: Option 3 percent rainfall increase

	Summer	Autumn	Winter	Spring
RCP 2.6	+8%	+13%	+11%	+7%
RCP 8.5	-1%	-5%	-8%	-17%

Option 4:

Use extremes of reported model ranges based on 5th and 95th percentiles in each season among all RCPs, i.e. each season is considered independently (Table 4).

Table 4: Option 4 percent rainfall increase

	Summer	Autumn	Winter	Spring
Max change	+27%	+16%	+26%	+9%
Min change	-14%	-6%	-8%	-17%

Option 3 was considered to represent reasonable and probable extremes, so was used to produce the projected time series for rainfall (Table 3). Time series of projected 2090 rainfall were calculated by applying the percentage changes for each season to daily rainfall of two historical time series. These historical time series were from the Riwaka and Tui Close climate stations, covering the period 01/06/1985–31/05/2012.

3. POTENTIAL EVAPOTRANSPIRATION

No climate change predictions for PET are available for the study area. However, Aqualinc (2016)[23] showed that change in PET can be estimated based on temperature. This study showed that if temperature increases by 0.8 °C (relative to the period 1995 to 2015), and other factors remain constant (wind speed, humidity, radiation), PET will increase by about 3% in Lincoln, Canterbury. Aqualinc (2016) also states that NIWA also undertook a similar analysis in 2011, and came to the same conclusion that a 0.8 °C increase in temperature by 2046 would result in approximately a 3% increase in mean annual PET. NIWA also assumed that wind speed, radiation and relative humidity would remain constant.

The Aqualinc (2016) method was applied to Motueka. PET was calculated using the Penman-Monteith equation, which is the recommended method for estimating PET by the UN's Food and Agriculture Organization. Minimum and maximum temperature, wind speed, relative humidity and radiation were used to calculate PET for the period from 1972 to 2015. The climate data was primarily sourced from NIWA's Motueka-Riwaka climate station (Site No. 12429 and 4162), and gaps were filled using Appleby (21937) and Nelson Aero (4241 and 4271).

The estimated average annual PET for 1972-2015 is 754 mm/year. For the same period, NIWA estimates PET of 821 mm/year; NIWA uses the Penman method to estimate PET.

Estimated percentage PET increases for a range of temperature increases were then calculated using the Aqualinc (2016) method and Motueka-Riwaka data as described above, and are given in Table 5.

---

[23] Aqualinc (2016). Impact of climate cycles and trends on Selwyn District water assets. Prepared for Selwyn District Council by Aqualinc Research Ltd, May 2015.

Table 5. Estimated percent PET increase due to temperature increase, if other factors remain constant (wind speed, humidity, radiation) in Motueka for the period of 1972–2015.

Temperature increase (^{0}C)	Percentage PET increase (%)	Temperature increase (^{0}C)	Percentage PET increase (%)
0.1	0.3	2.9	9.6
0.2	0.7	3.0	10.0
0.3	1.0	3.1	10.3
0.4	1.3	3.2	10.7
0.5	1.6	3.3	11.0
0.6	2.0	3.4	11.4
0.7	2.3	3.5	11.7
0.8	2.6	3.6	12.0
0.9	2.9	3.7	12.4
1.0	3.3	3.8	12.7
1.1	3.6	3.9	13.1
1.2	3.9	4.0	13.4
1.3	4.3	4.1	13.8
1.4	4.6	4.2	14.1
1.5	4.9	4.3	14.5
1.6	5.3	4.4	14.8
1.7	5.6	4.5	15.2
1.8	5.9	4.6	15.5
1.9	6.3	4.7	15.9
2.0	6.6	4.8	16.2
2.1	6.9	4.9	16.6
2.2	7.3	5.0	16.9
2.3	7.6	5.1	17.3
2.4	7.9	5.2	17.6
2.5	8.3	5.3	18.0
2.6	8.6	5.4	18.3
2.7	9.0	5.5	18.7
2.8	9.3		

Projected temperature changes by 2090 were selected to be consistent with the rainfall projections (Option 3 in the section above), using the extremes of NIWA's reported model ranges (here the 5th percentile for RCP 2.6 and 95th percentile for RCP 8.5; NIWA, 2015). The projected temperature increases for 2090 are shown in Table 6. Note that, unlike for rainfall for which data is available for the Appleby grid point, NIWA's predictions for seasonal mean temperature changes are the mean estimates for the entire Tasman District (NIWA, 2015).

Table 6: Option 3 projected temperature increase for 2090

ºC	Summer	Autumn	Winter	Spring
RCP 2.6	0.2	0.1	0.3	0.1
RCP 8.5	5.4	4.7	4.1	3.5

The estimated percent PET increases that match the projected temperature increases for 2090 for Option 3 (as can be seen in Table 5) are listed in Table 7.

Table 7: Option 3 projected percent PET increase for 2090

	Summer	Autumn	Winter	Spring
RCP 2.6	0.7%	0.3%	1.0%	0.3%
RCP 8.5	18.3%	15.9%	13.8%	11.7%

For completeness, the projected temperature increases for 2090 for the other options (as described in the rainfall section above) are listed in Table 8, and the related percentage PET increases are listed in Table 9.

Table 8: Projected increase in temperature for 2090

ºC	Summer	Autumn	Winter	Spring
Option 1				
RCP 2.6	0.6	0.7	0.7	0.6
RCP 8.5	3.2	3.2	3.1	2.6
Option 2				
Min change	0.6	0.7	0.7	0.6
Max change	3.2	3.2	3.1	2.6
Option 4				
Min change	0.2	0.1	0.3	0.1
Max change	5.4	4.7	4.1	3.5

Table 9: Projected increase in PET for 2090 for Options 1, 2 and 4

	Summer	Autumn	Winter	Spring
Option 1				
RCP 2.6	2.0%	2.3%	2.3%	2.0%
RCP 8.5	10.7%	10.7%	10.3%	8.6%
Option 2				
Min change	2.0%	2.3%	2.3%	2.0%
Max change	10.7%	10.7%	10.3%	8.6%
Option 4				
Min change	0.7%	0.3%	1.0%	0.3%
Max change	18.3%	15.9%	13.8%	11.7%

New time series of PET for each climate change scenario were generated by applying the projected percent PET increases for each season (Option 3, Table 7) to daily historical time series from Riwaka and Tui Close climate stations, as described for rainfall above.

4. IRRIGATION, AET AND DRAINAGE: IRRICALC MODELLING

Given the fast response of the Motueka-Riwaka Plain groundwater system and therefore its dependence on seasonal rainfall and PET, two extreme climate change scenarios were devised for IRRICALC modelling:

- Scenario 1: lowest rainfall (Table 3, RCP 8.5) + highest PET (Table 6, RCP 8.5)
- Scenario 2: highest rainfall (Table 3, RCP 2.6) + lowest PET (Table 6, RCP 2.6)

IRRICALC was run for both scenarios, to produce daily irrigation, actual evapotranspiration (AET) and drainage for all previously modelled crops and soil types and using both the Riwaka and Tui Close future projected climate data for some crop and soil combinations.

5. RIVER FLOWS

Two time series of river flow were developed for the extreme climate change scenarios modelled with IRRICALC, for each of the Motueka and Riwaka rivers and the Little Sydney and Brooklyn streams. River flow is related to rainfall minus AET. Future time series of AET were taken from the IRRICALC outputs for dryland soil with representative profile available water (PAW) values for the particular river catchment. AET derived from the Sherry soil with 90 mm PAW was used for the Motueka River, and AET derived from the Riwaka soil with 126.5 mm PAW was used for the Riwaka River, Little Sydney Stream and Brooklyn Stream.

The rainfall time series that was used for river flow calculations (historical and for both climate change scenarios) was from the Riwaka climate station. For each of the four rivers, the percentage difference averaged by season was calculated between the historical rainfall minus AET and each climate change scenario rainfall minus AET. These percentage differences were applied to the daily historical river flow time series for each river (with a different percentage for each season), to develop the future river flow time series.

Figure 1 shows the historical and projected river flow time series for the Motueka River under climate change scenario 1 (lowest rainfall and highest PET, RCP 8.5). Figure 2 shows the Motueka River flows under climate change scenario 2 (highest rainfall and lowest PET, RCP 2.6). The river flow time series for the other are shown in Figures 3-8.

Motueka River

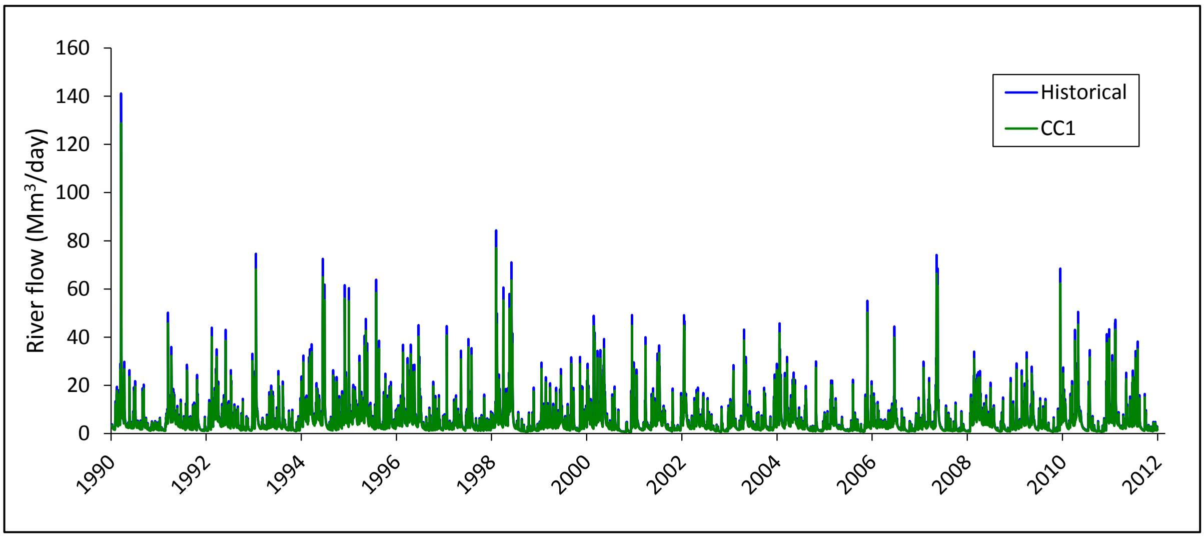


Figure 1: River flow time series of the Motueka River at Woodmans Bend for 1990–2012 (historical) and for climate change scenario 1 (lowest rainfall and highest PET; CC1)

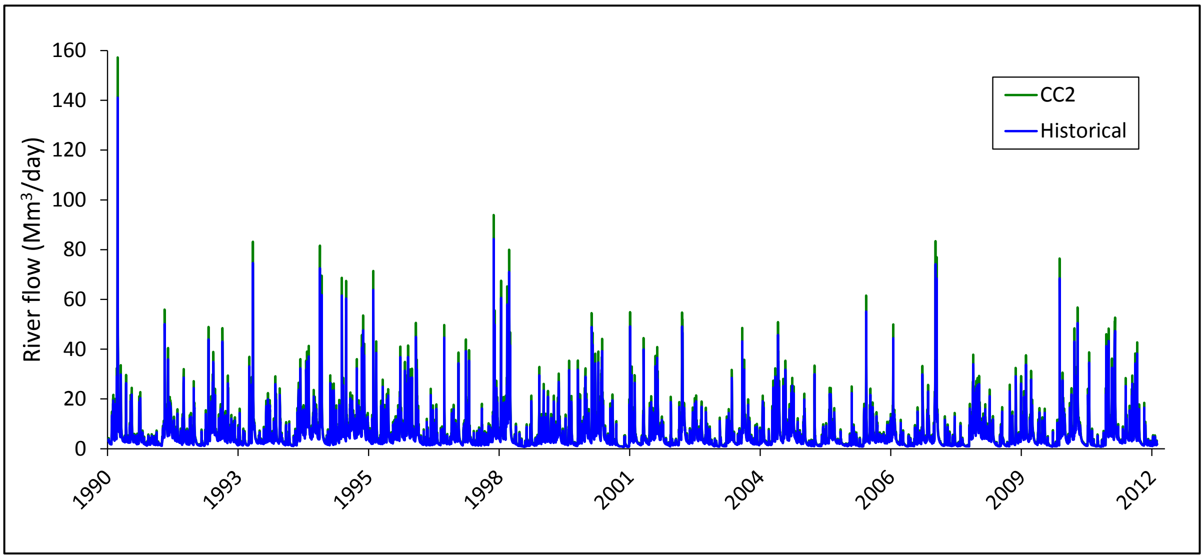


Figure 2: River flow time series of the Motueka River at Woodmans Bend for 1990–2012 (historical) and for climate change scenario 2 (highest rainfall and lowest PET; CC2)

Riwaka River

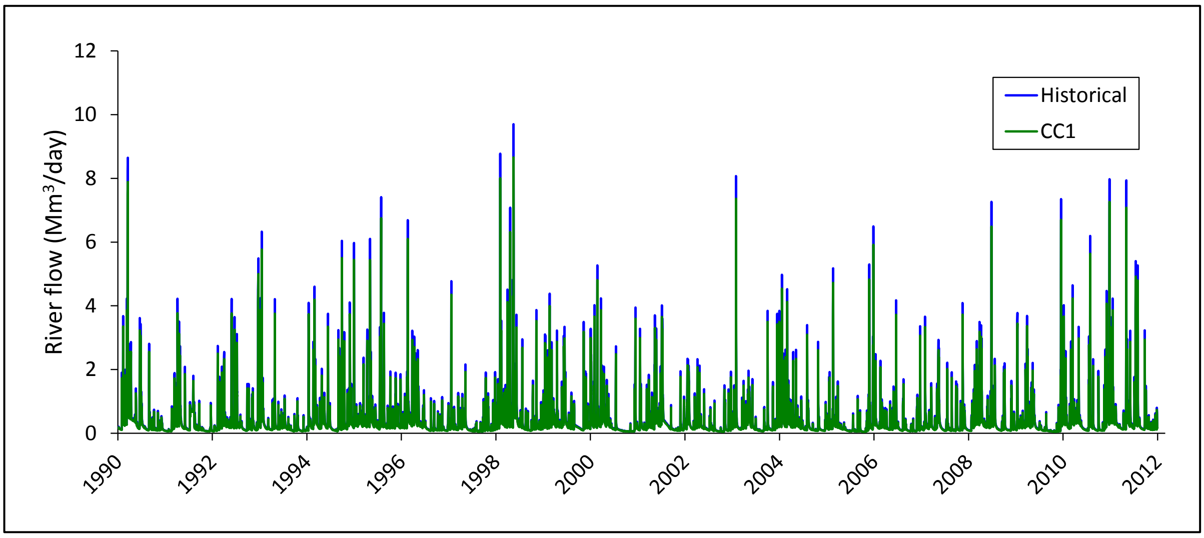


Figure 3: River flow time series of the Riwaka River at Hicksmott for 1990–2012 (historical) and for climate change scenario 1 (lowest rainfall and highest PET; CC1)

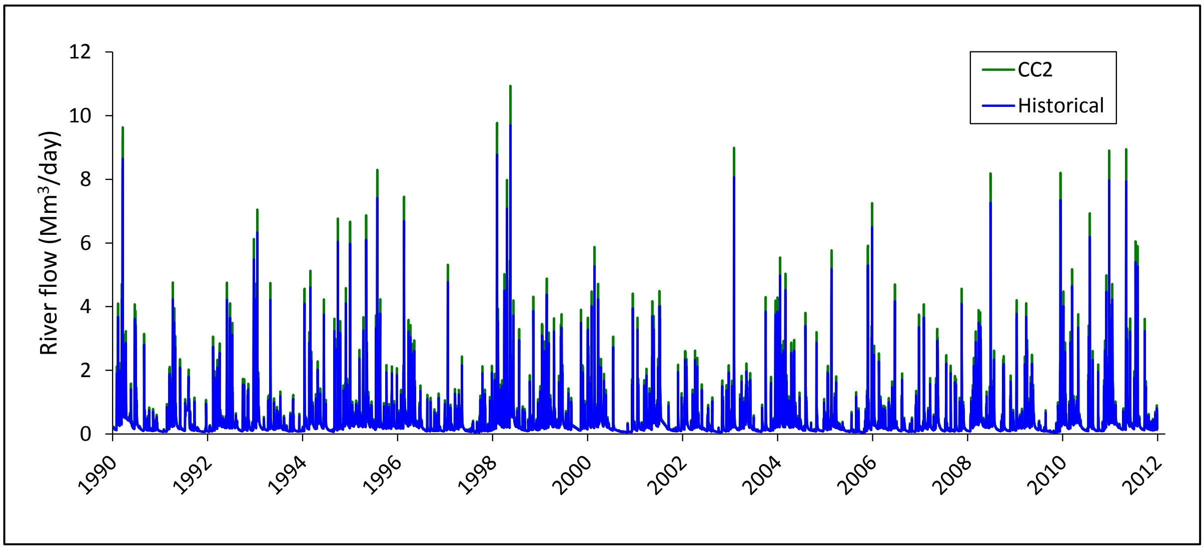


Figure 4: River flow time series of the Riwaka River at Hicksmott for 1990–2012 (historical) and for climate change scenario 2 (highest rainfall and lowest PET; CC2)

Little Sydney Stream

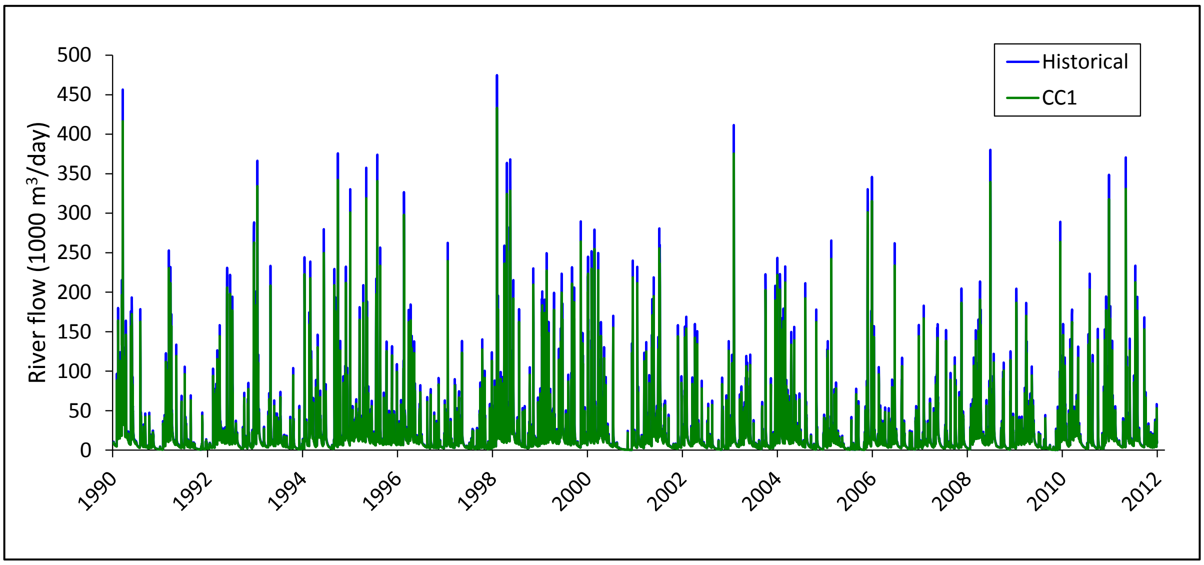


Figure 5: River flow time series of the Little Sydney Stream at Valley Bridge for 1990–2012 (historical) and for climate change scenario 1 (lowest rainfall and highest PET; CC1)

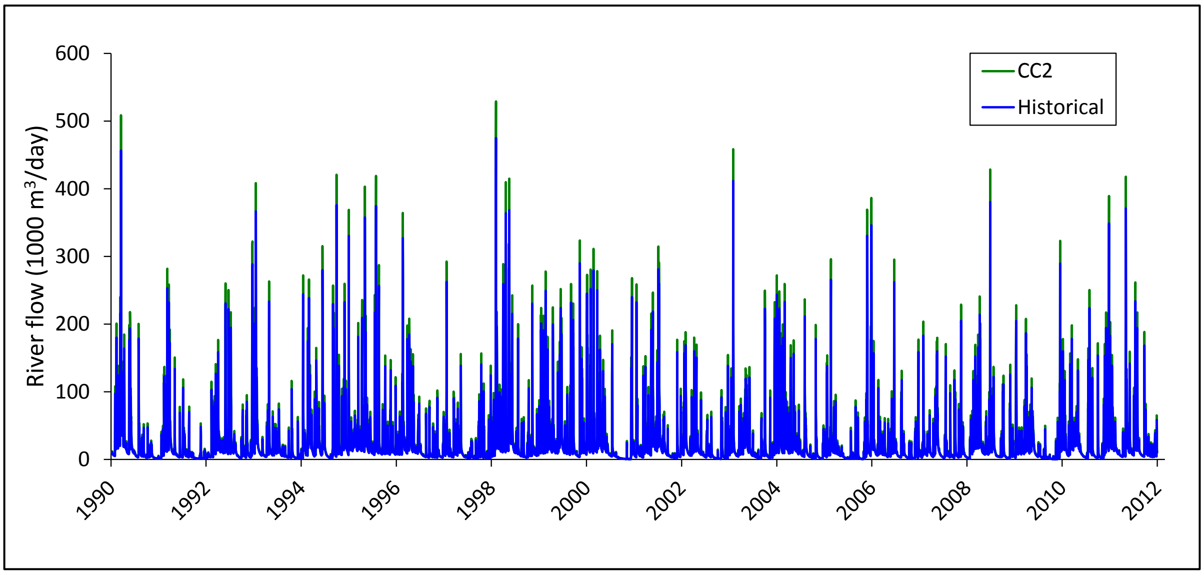


Figure 6: River flow time series of the Little Sydney Stream at Valley Bridge for 1990–2012 (historical) and for climate change scenario 2 (highest rainfall and lowest PET; CC2)

Brooklyn Stream

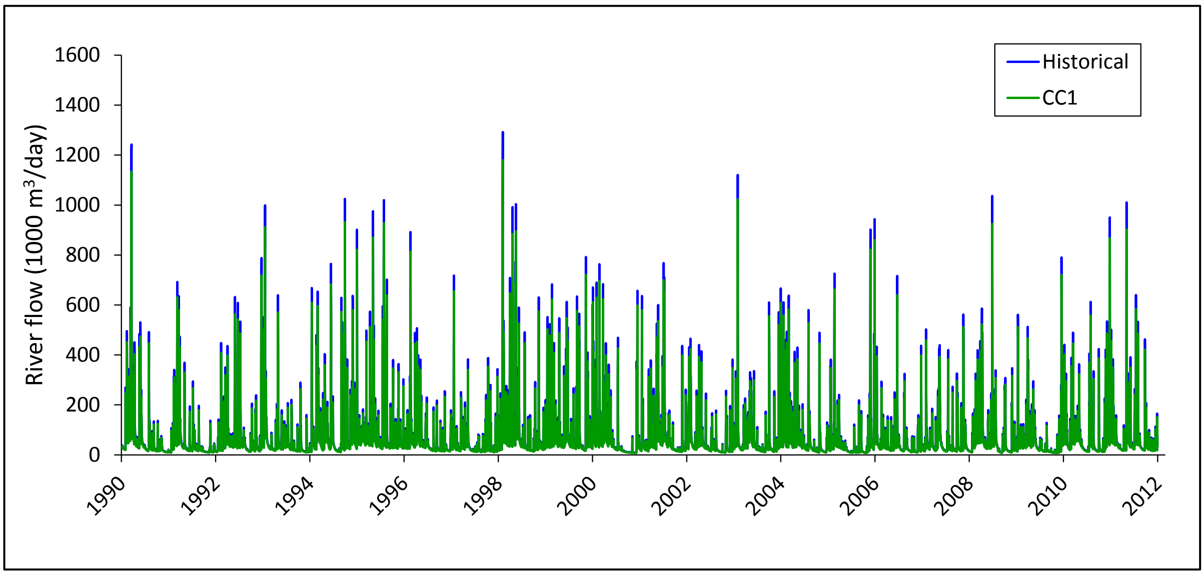


Figure 7: River flow time series of the Brooklyn Stream at West Bank Road Bridge for 1990–2012 (historical) and for climate change scenario 1 (lowest rainfall and highest PET; CC1)

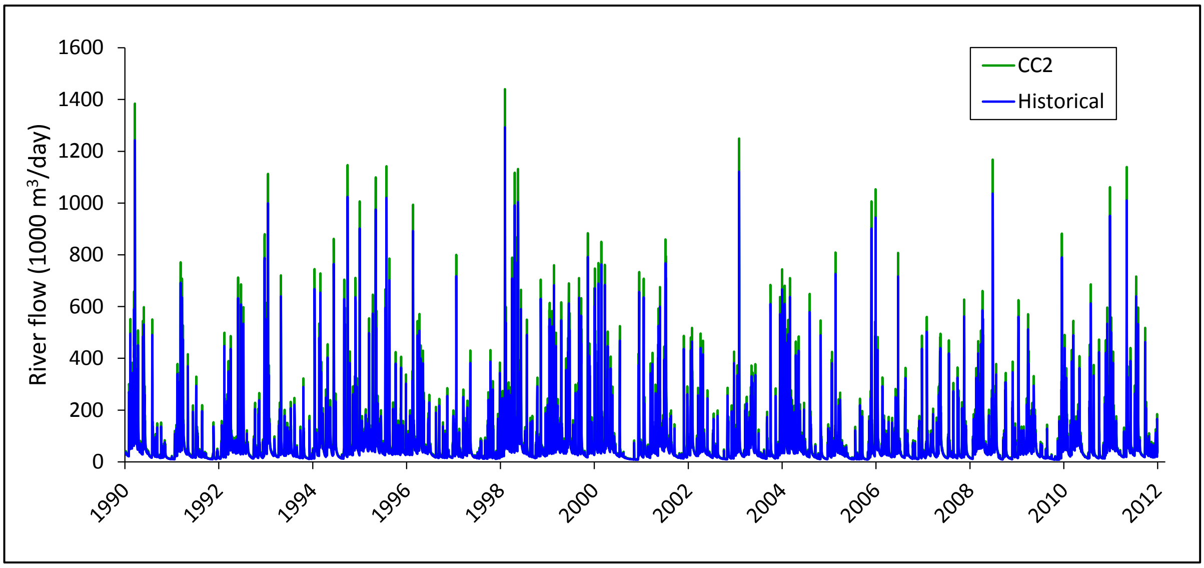
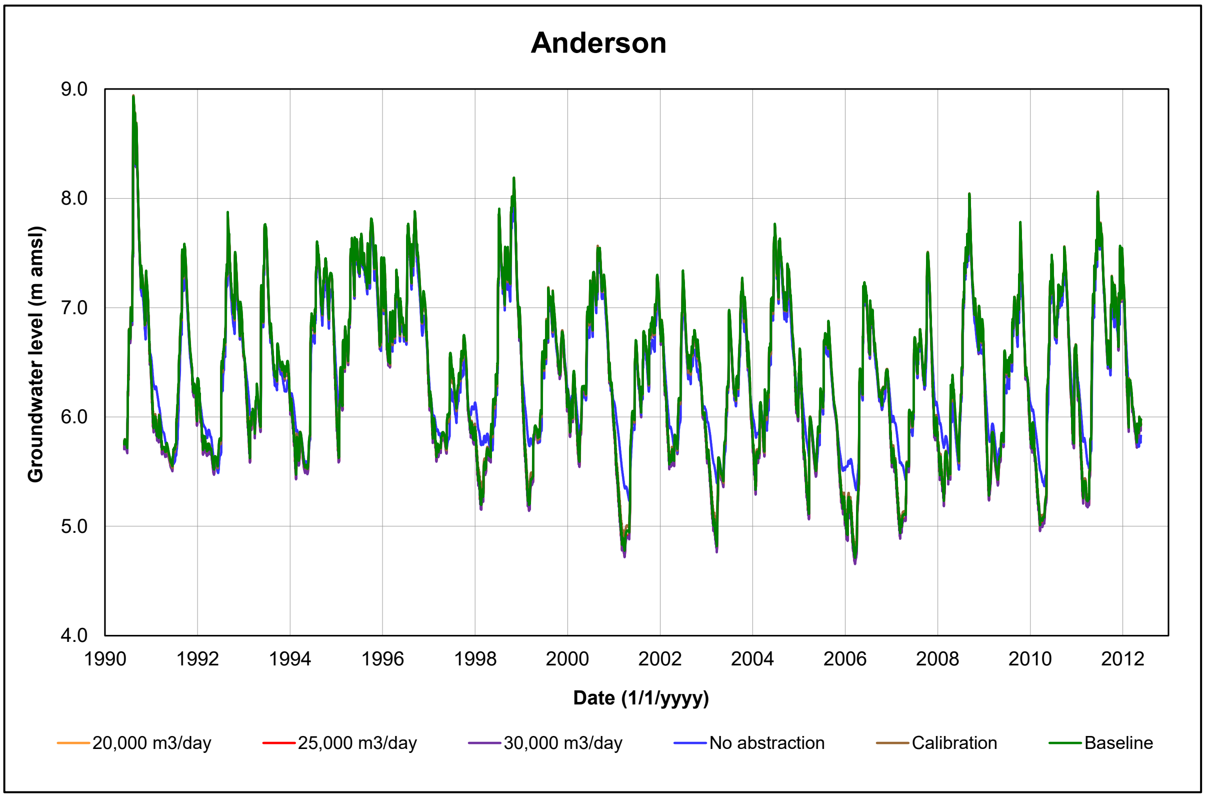
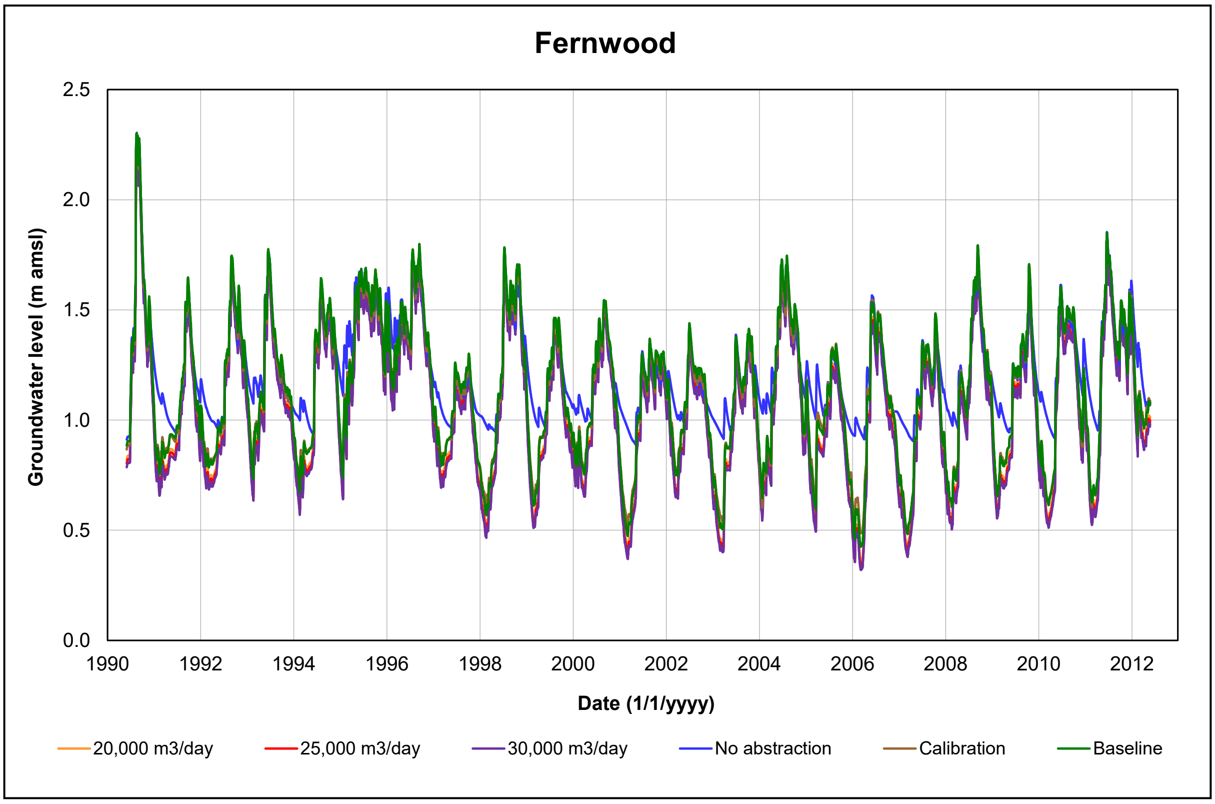
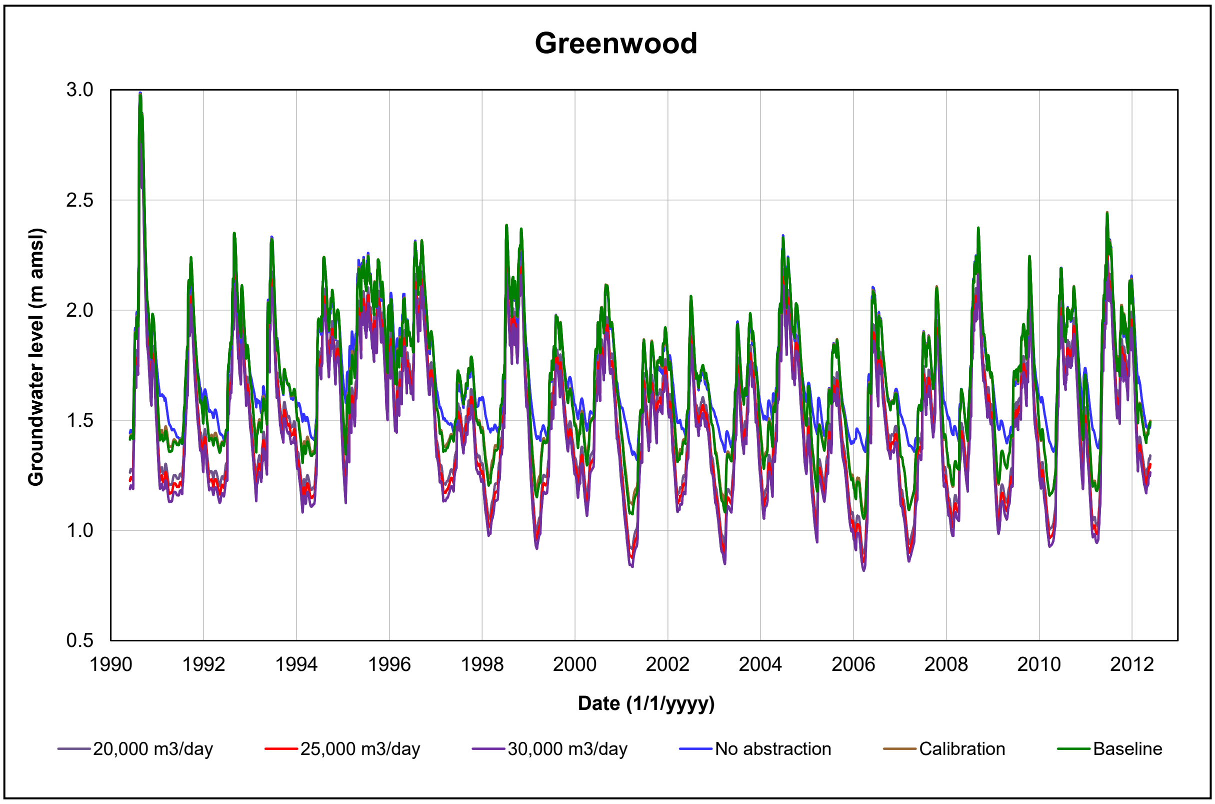


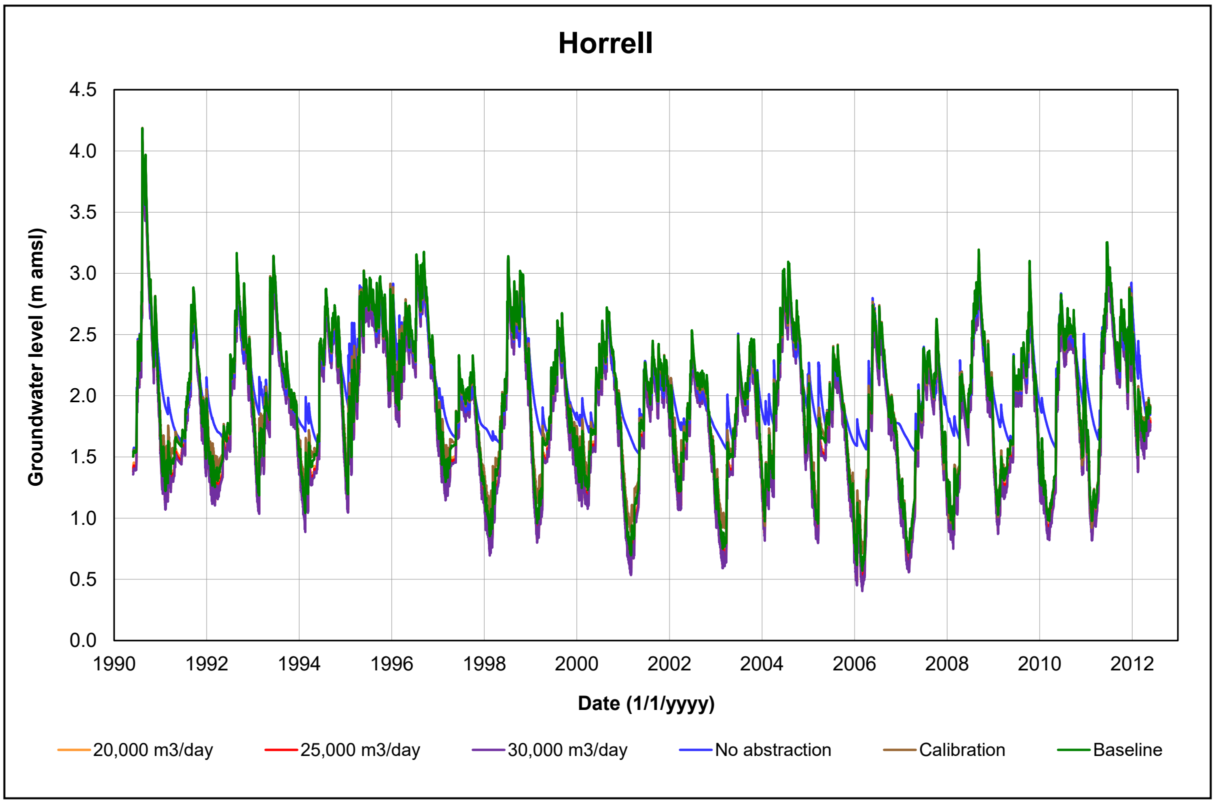
Figure 8: River flow time series of the Brooklyn Stream at West Bank Road Bridge for 1990–2012 (historical) and for climate change scenario 2 (highest rainfall and lowest PET; CC2)

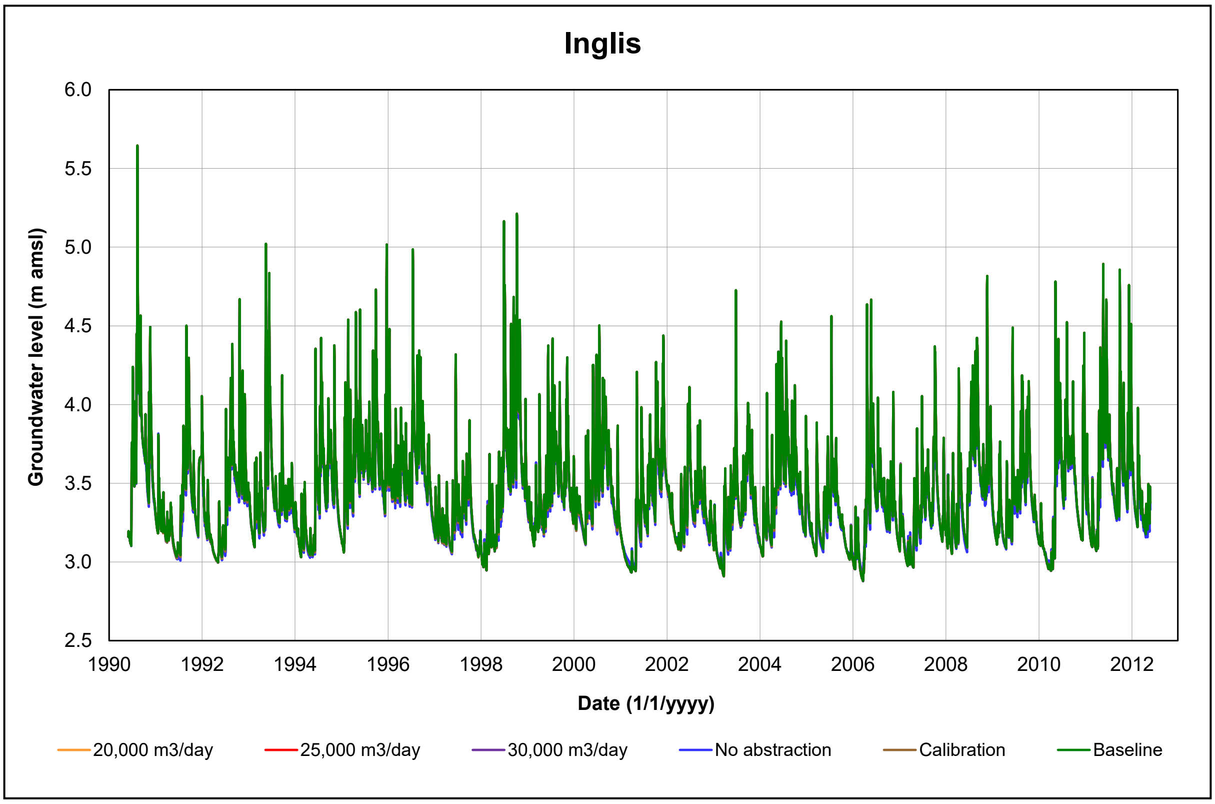
Appendix H: Hydrographs of modelled groundwater levels under scenarios 1-6

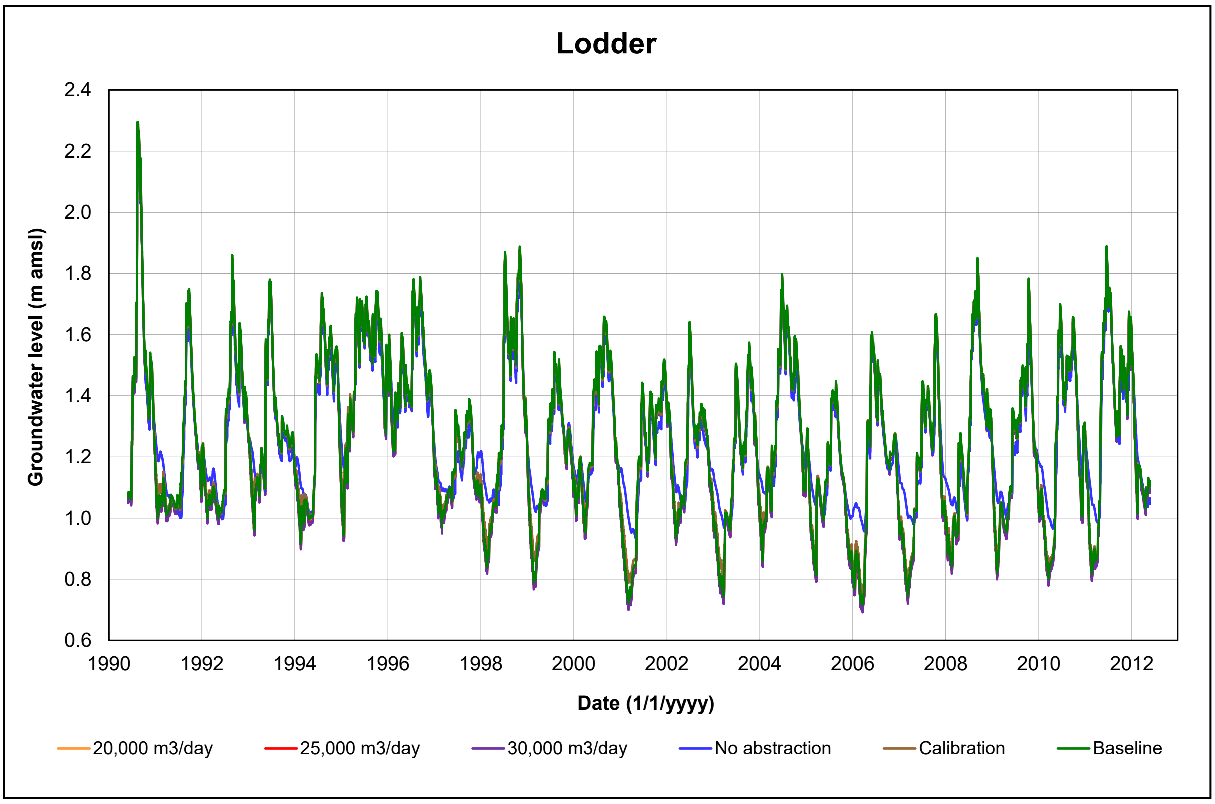


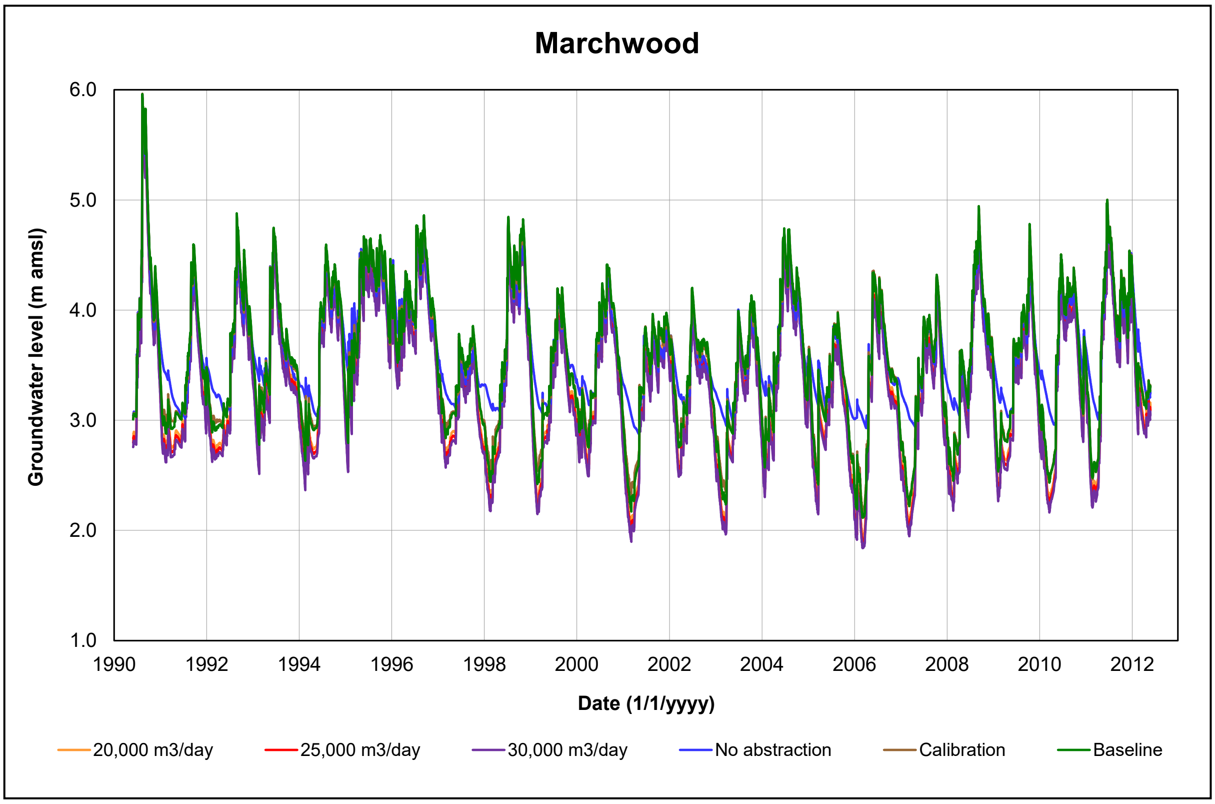


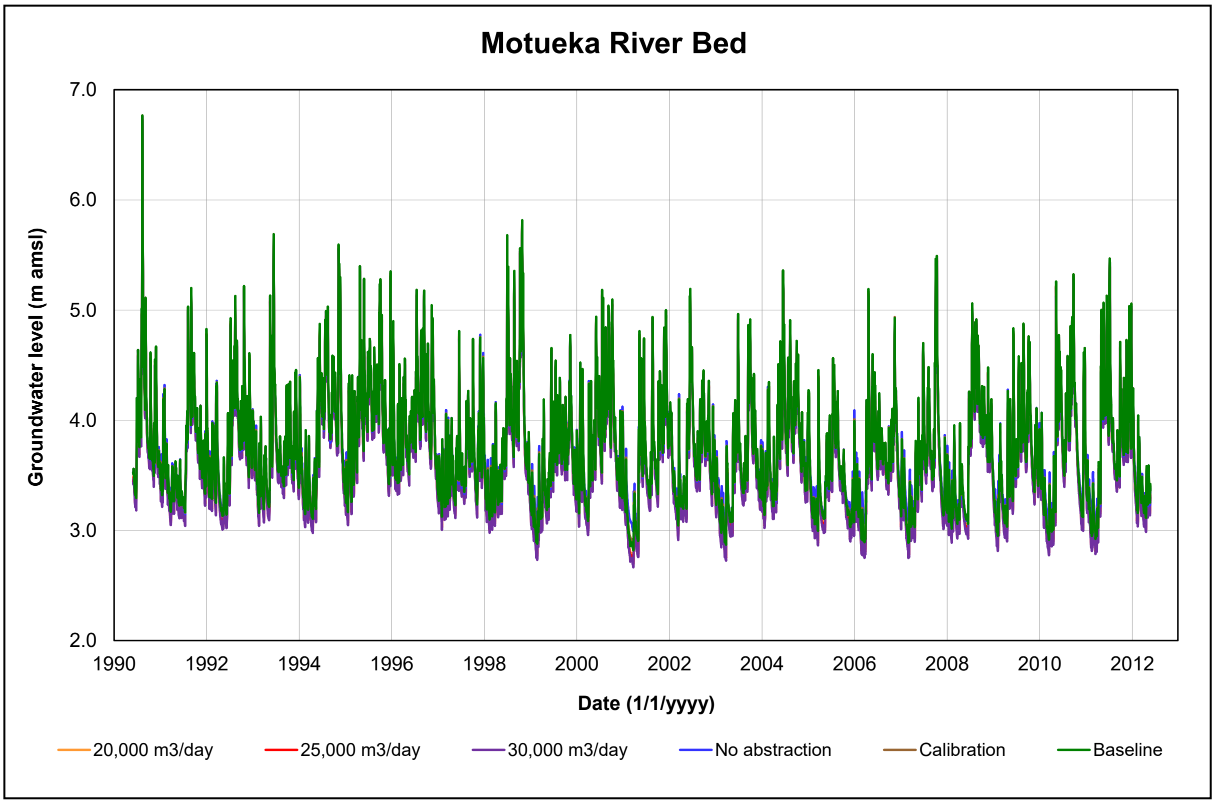

Greenwood
Groundwater level (m amsl)
3.0
2.5
2.0
1.5
1.0
0.5
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
20,000 m3/day
25,000 m3/day
30,000 m3/day
No abstraction
Calibration
Baseline

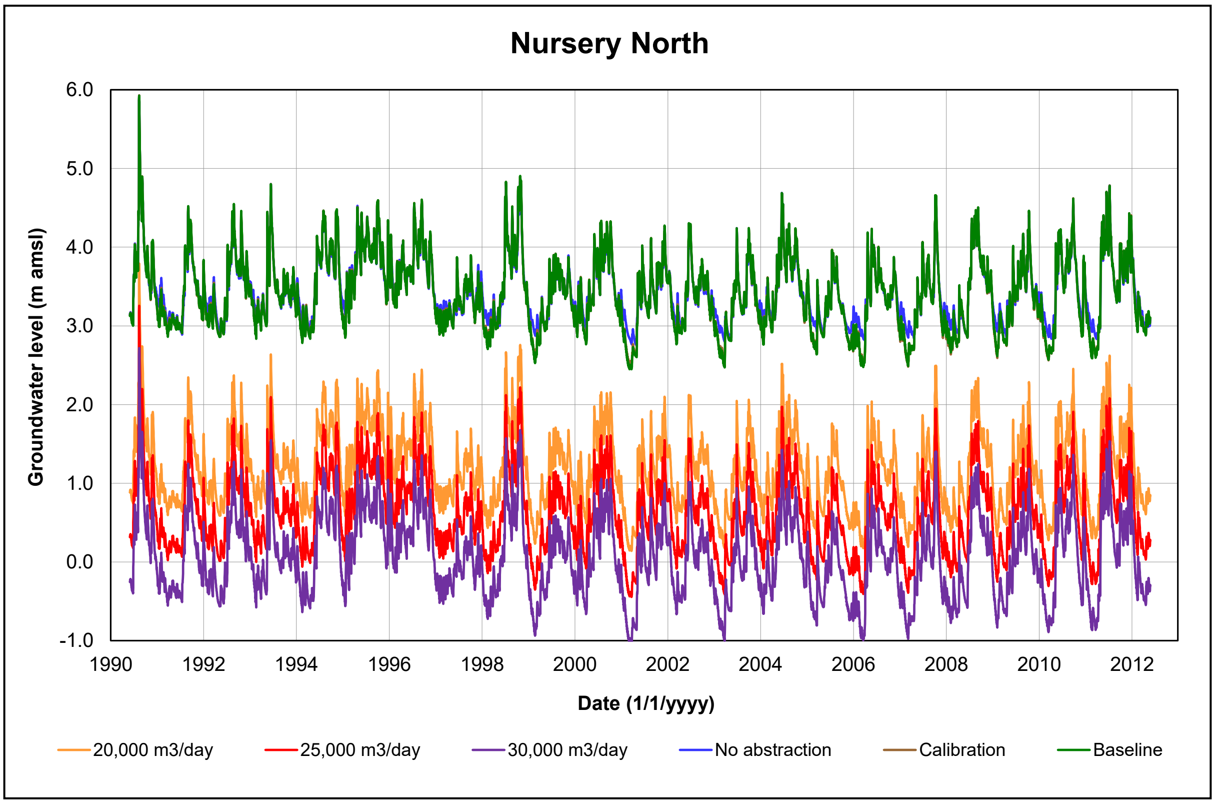

Horrell
Groundwater level (m amsl)
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
20,000 m3/day
25,000 m3/day
30,000 m3/day
No abstraction
Calibration
Baseline

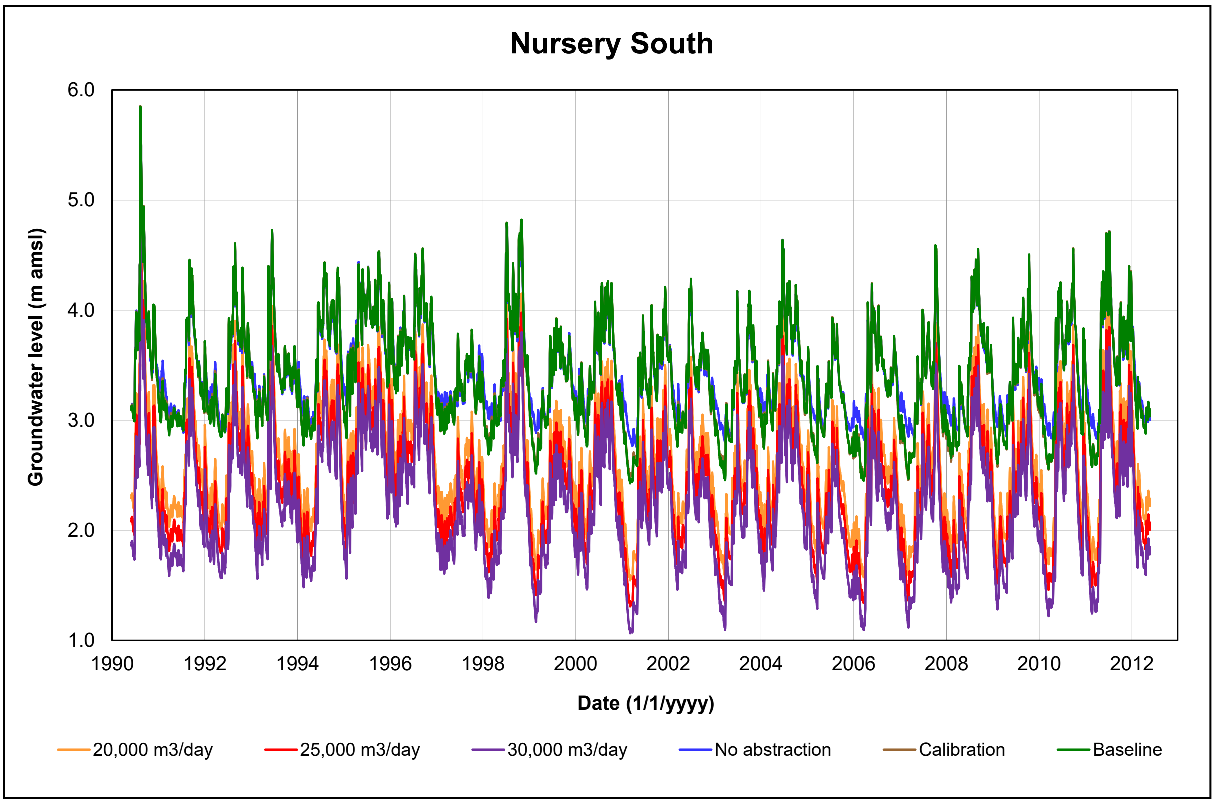

Inglis
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
Groundwater level (m amsl)
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
20,000 m3/day
25,000 m3/day
30,000 m3/day
No abstraction
Calibration
Baseline

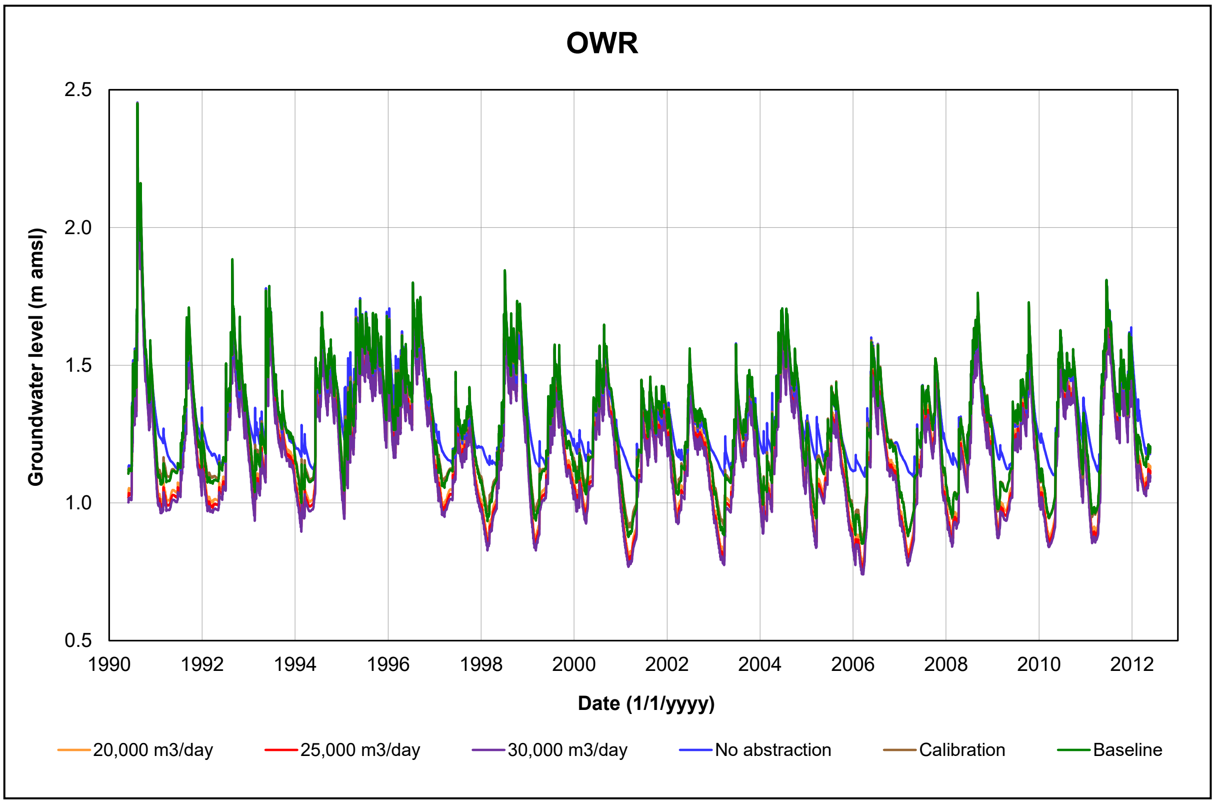

Lodder
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
Groundwater level (m amsl)
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
20,000 m3/day
25,000 m3/day
30,000 m3/day
No abstraction
Calibration
Baseline

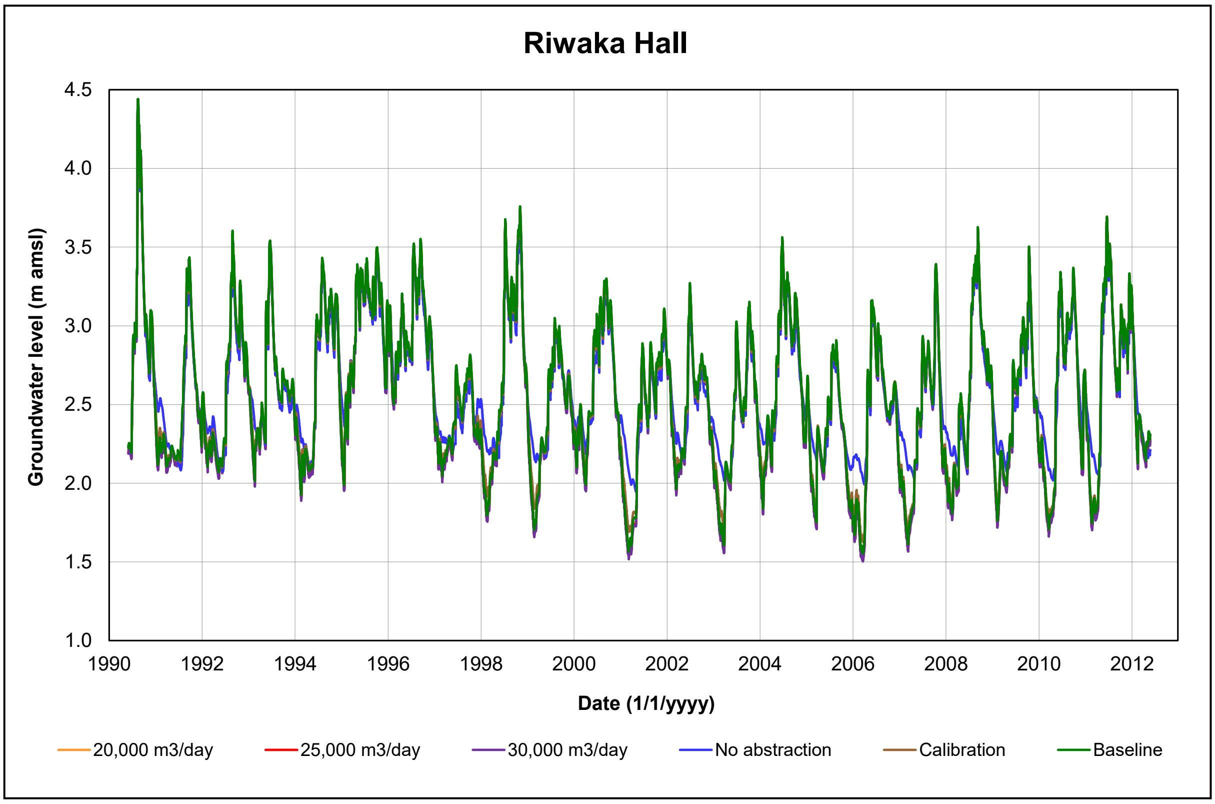

Marchwood
Groundwater level (m amsl)
6.0
5.0
4.0
3.0
2.0
1.0
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
20,000 m3/day
25,000 m3/day
30,000 m3/day
No abstraction
Calibration
Baseline

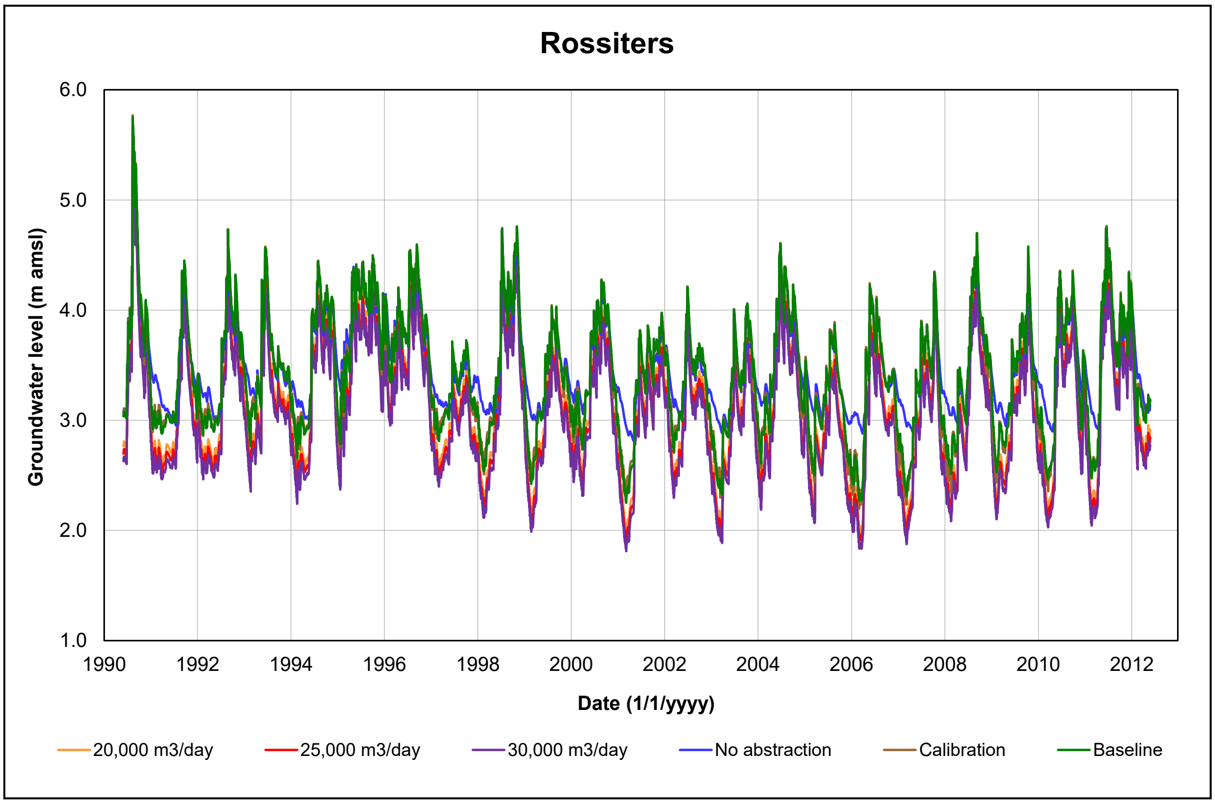

Motueka River Bed
Groundwater level (m amsl)
7.0
6.0
5.0
4.0
3.0
2.0
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
20,000 m3/day
25,000 m3/day
30,000 m3/day
No abstraction
Calibration
Baseline

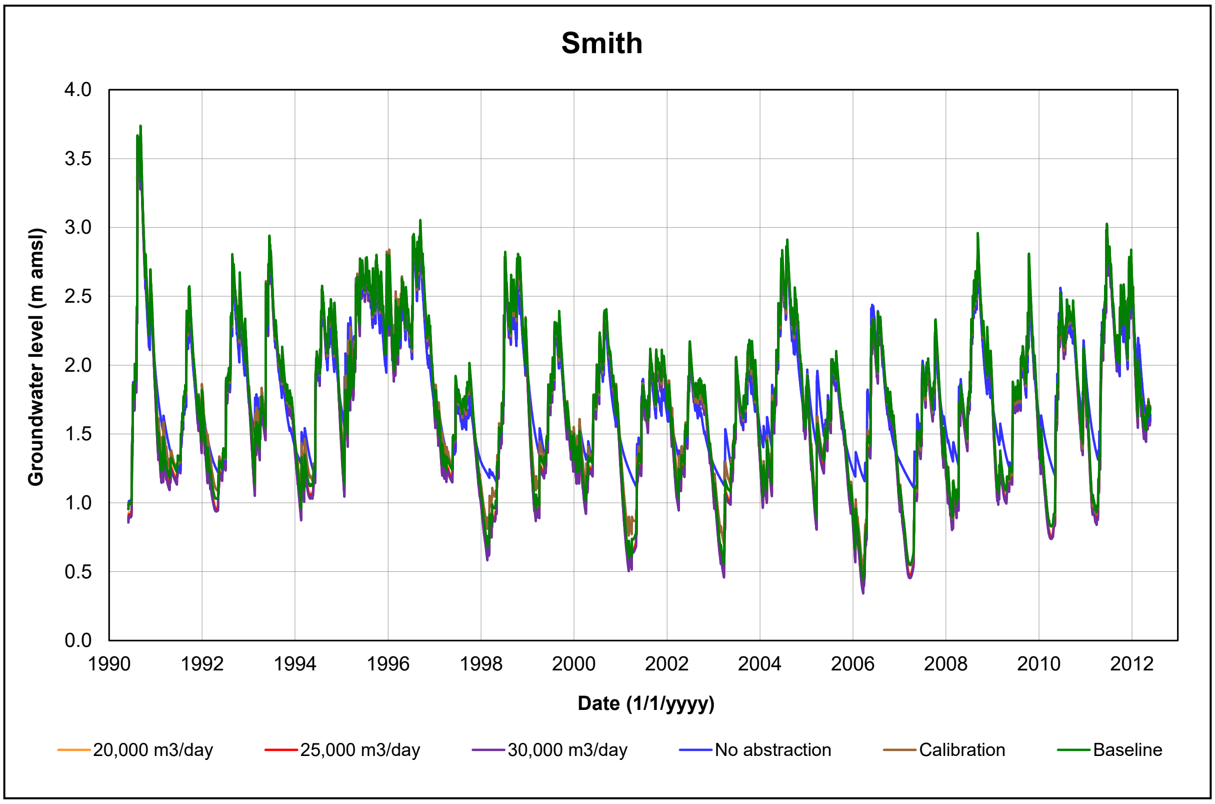

Nursery North
Groundwater level (m amsl)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
20,000 m3/day
25,000 m3/day
30,000 m3/day
No abstraction
Calibration
Baseline

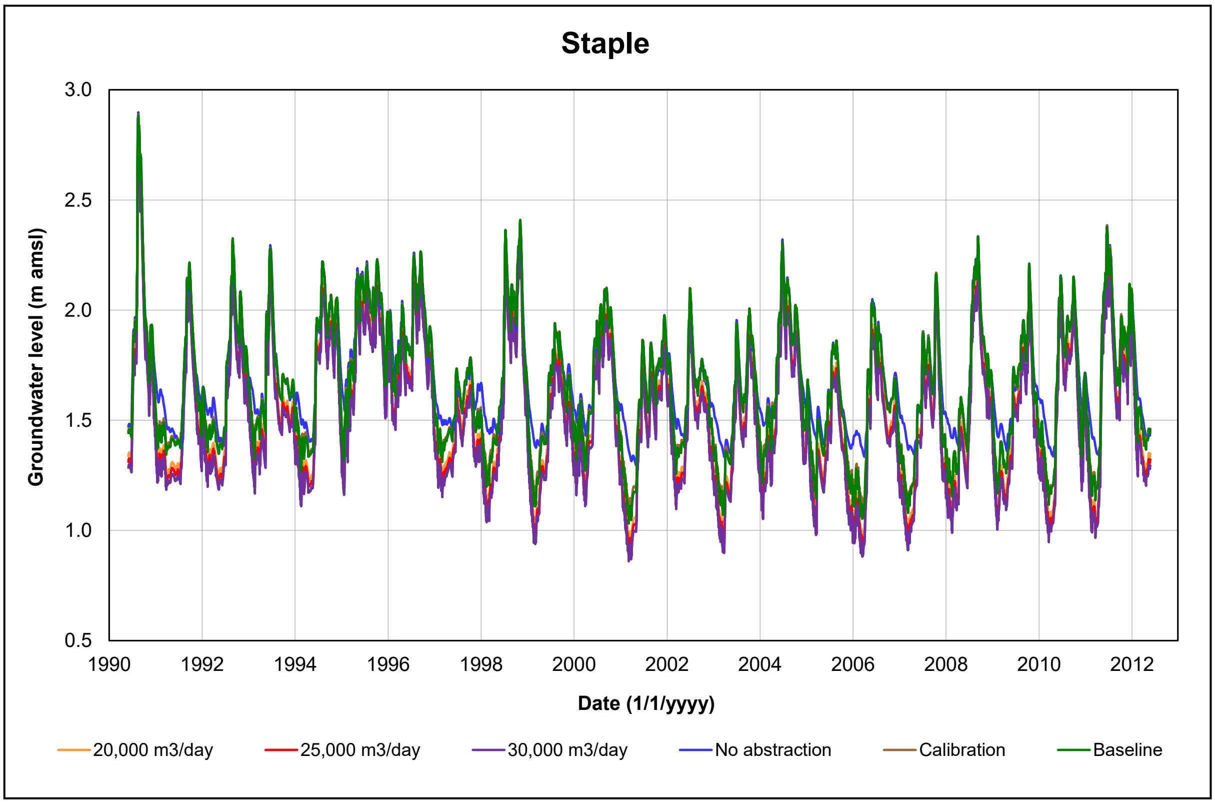

Nursery South
Groundwater level (m amsl)
6.0
5.0
4.0
3.0
2.0
1.0
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
20,000 m3/day
25,000 m3/day
30,000 m3/day
No abstraction
Calibration
Baseline

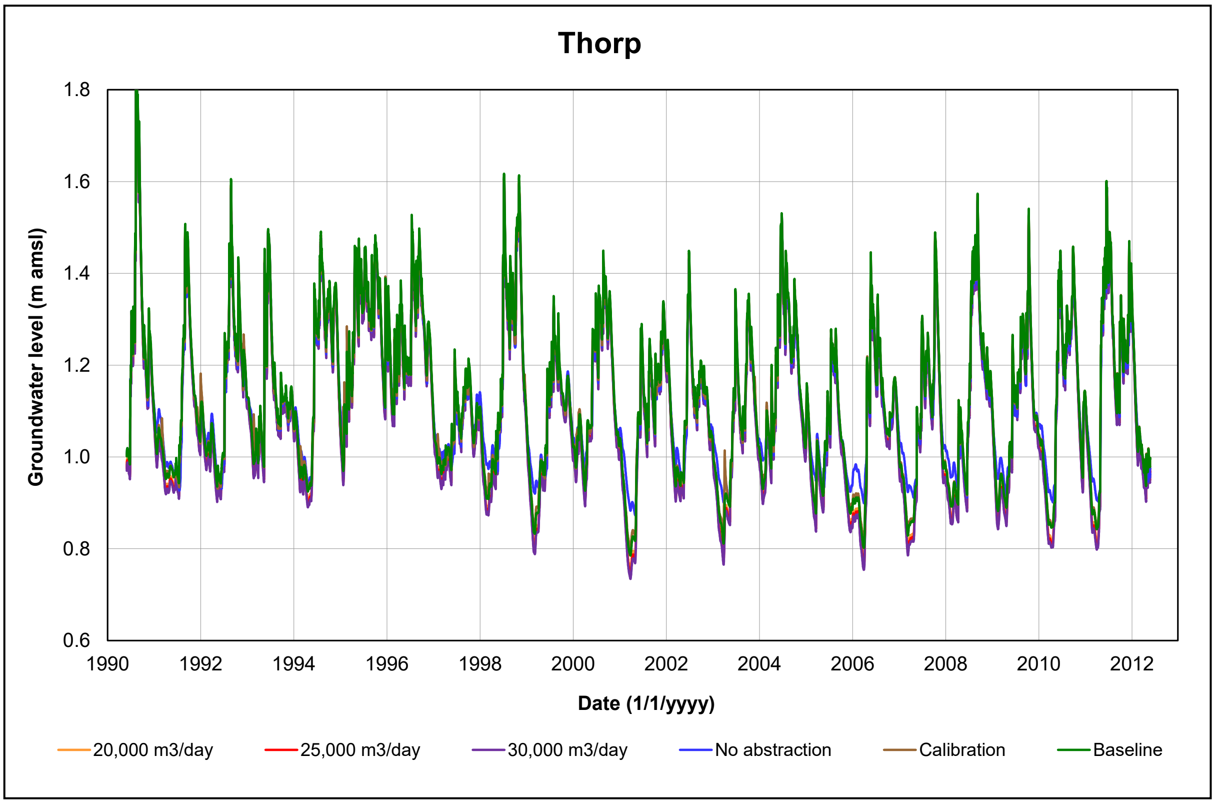

OWR
Groundwater level (m amsl)
2.5
2.0
1.5
1.0
0.5
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
20,000 m3/day
25,000 m3/day
30,000 m3/day
No abstraction
Calibration
Baseline

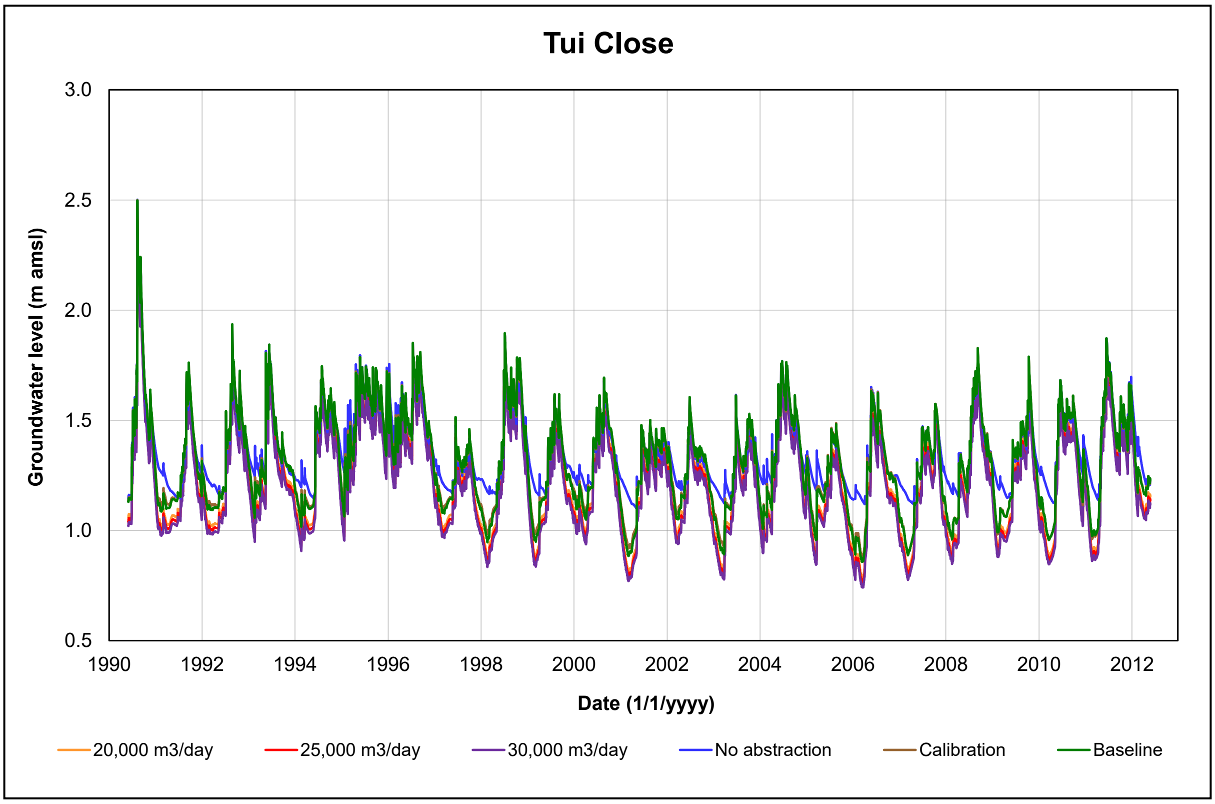

Riwaka Hall
Groundwater level (m amsl)
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
20,000 m3/day
25,000 m3/day
30,000 m3/day
No abstraction
Calibration
Baseline

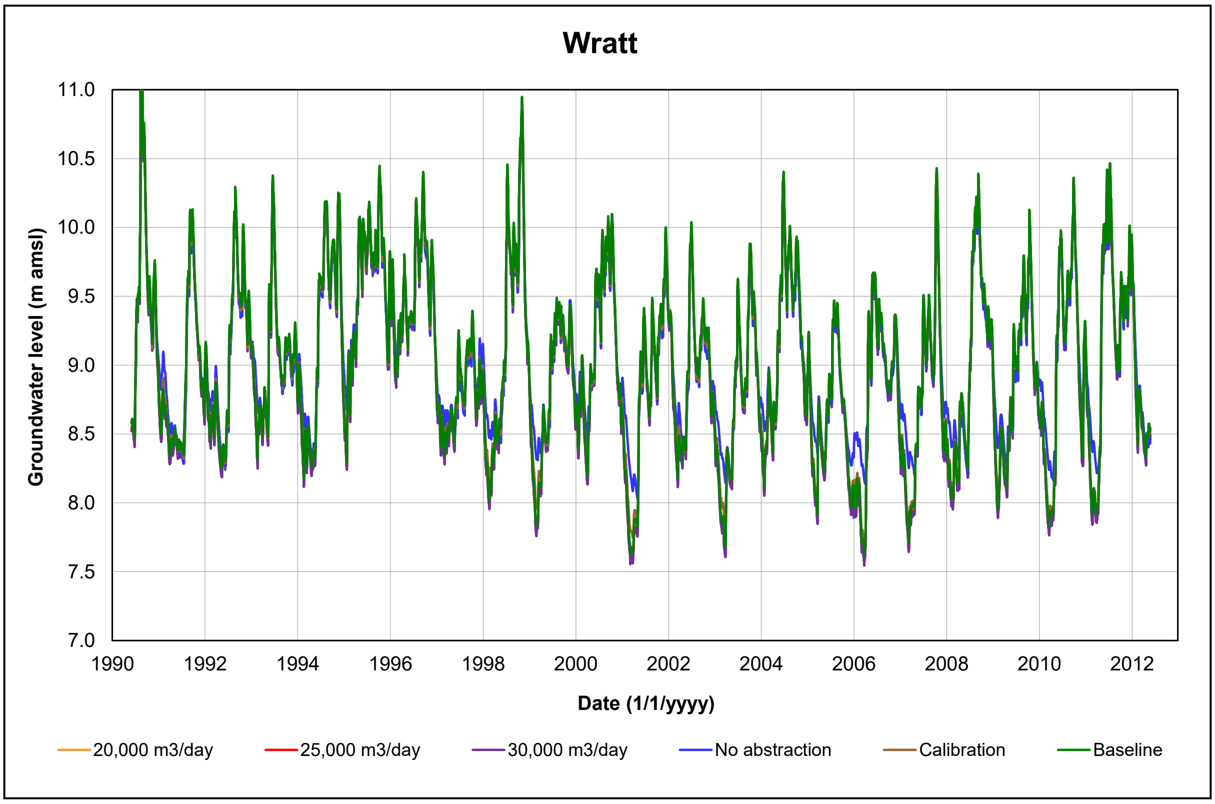

Rossiters
Groundwater level (m amsl)
6.0
5.0
4.0
3.0
2.0
1.0
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
20,000 m3/day
25,000 m3/day
30,000 m3/day
No abstraction
Calibration
Baseline


Smith
Groundwater level (m amsl)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
20,000 m3/day
25,000 m3/day
30,000 m3/day
No abstraction
Calibration
Baseline

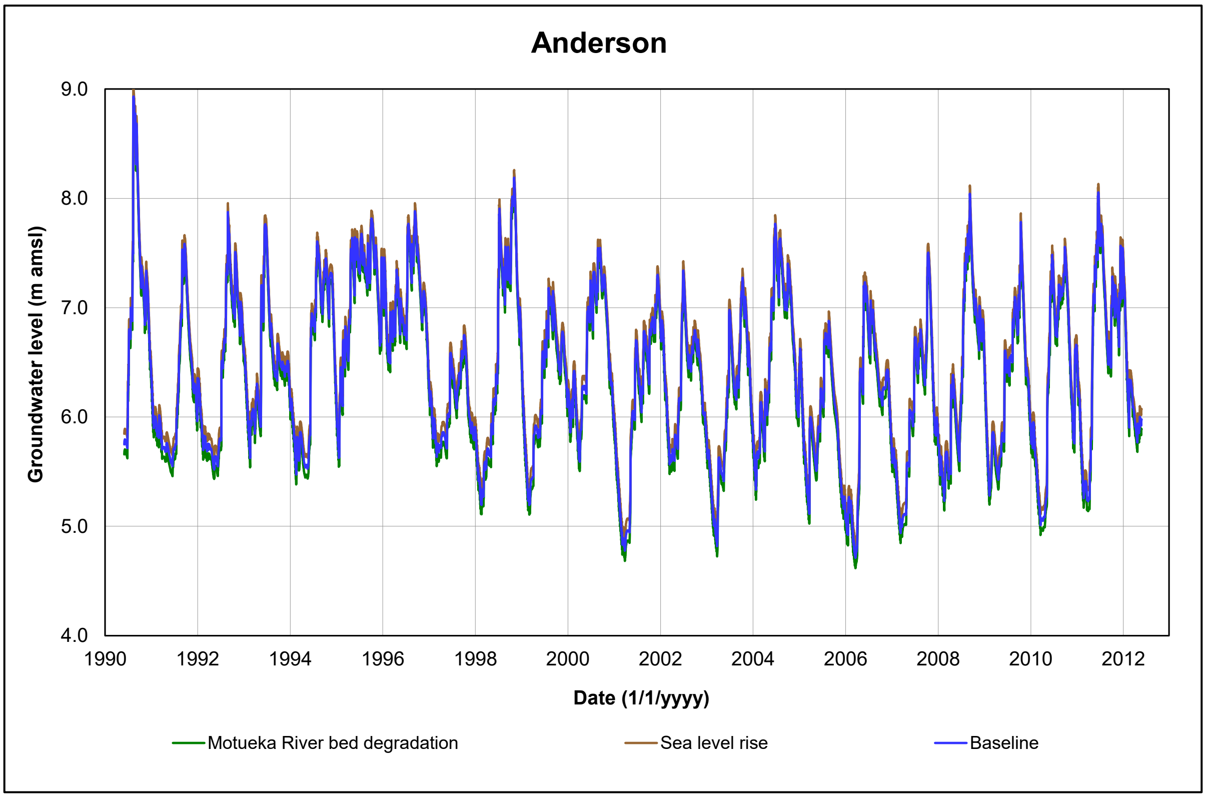

Staple
Groundwater level (m amsl)
3.0
2.5
2.0
1.5
1.0
0.5
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
20,000 m3/day
25,000 m3/day
30,000 m3/day
No abstraction
Calibration
Baseline

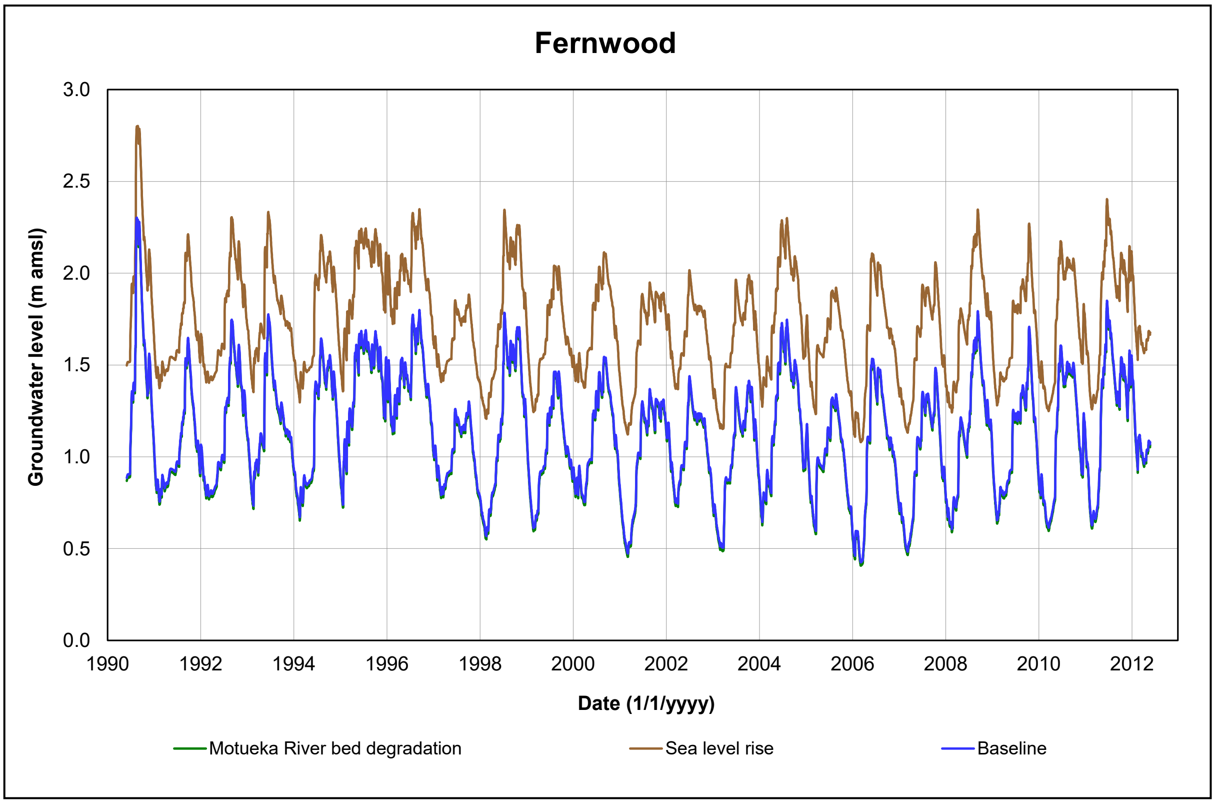

Thorp
Groundwater level (m amsl)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
20,000 m3/day
25,000 m3/day
30,000 m3/day
No abstraction
Calibration
Baseline

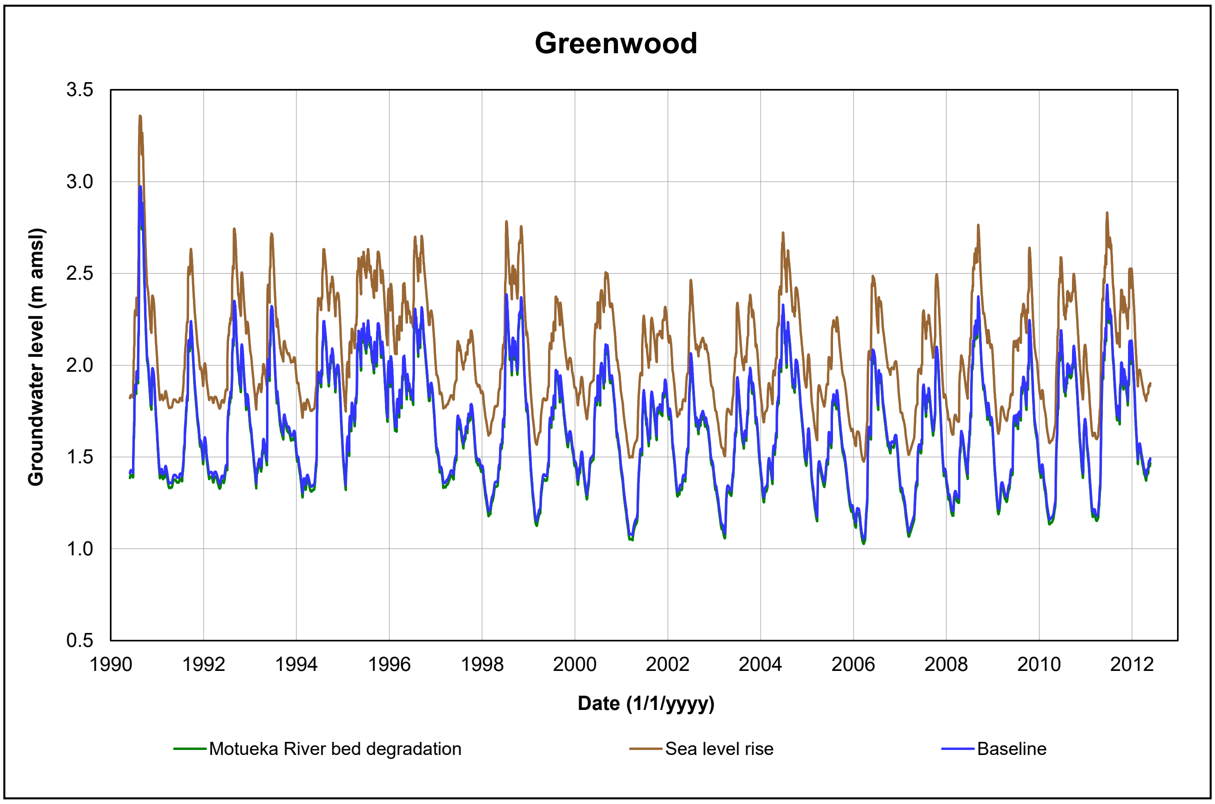

Tui Close
3.0
2.5
2.0
1.5
1.0
0.5
Groundwater level (m amsl)
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
20,000 m3/day
25,000 m3/day
30,000 m3/day
No abstraction
Calibration
Baseline

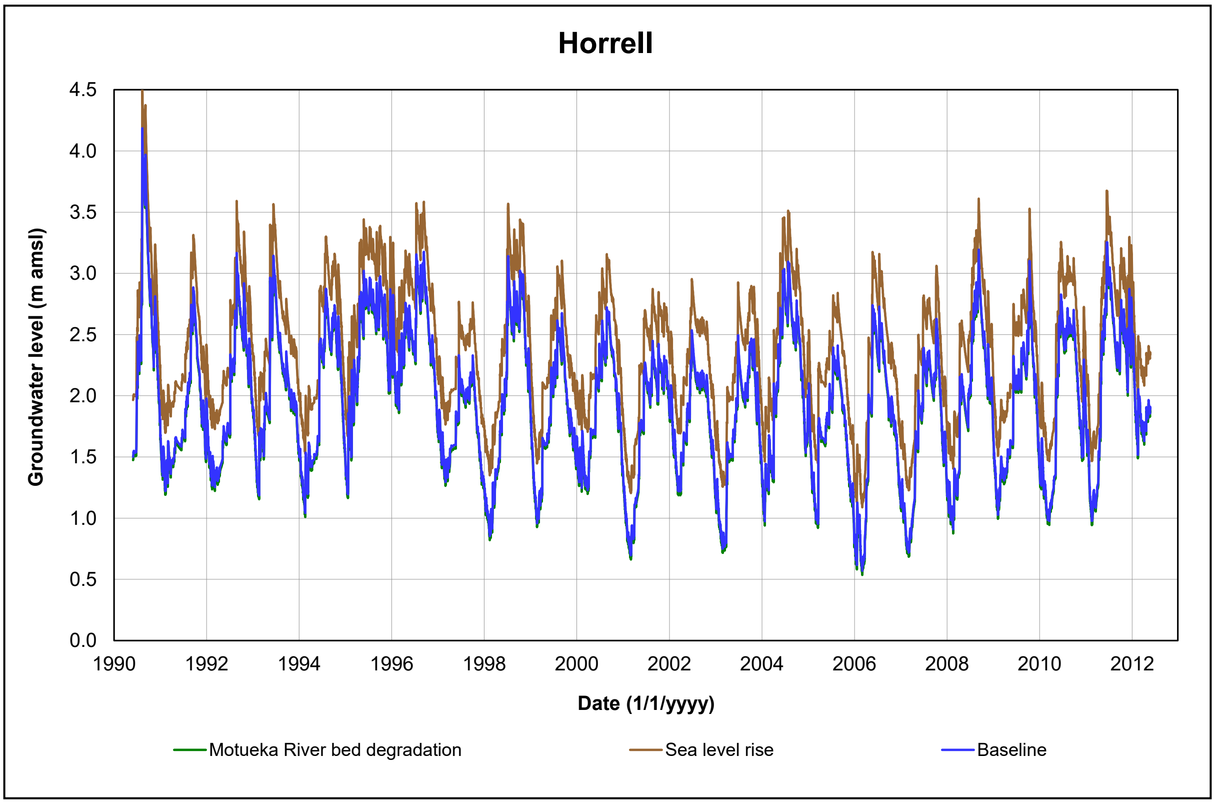

Wratt
11.0
10.5
10.0
9.5
9.0
8.5
8.0
7.5
7.0
Groundwater level (m amsl)
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
20,000 m3/day
25,000 m3/day
30,000 m3/day
No abstraction
Calibration
Baseline

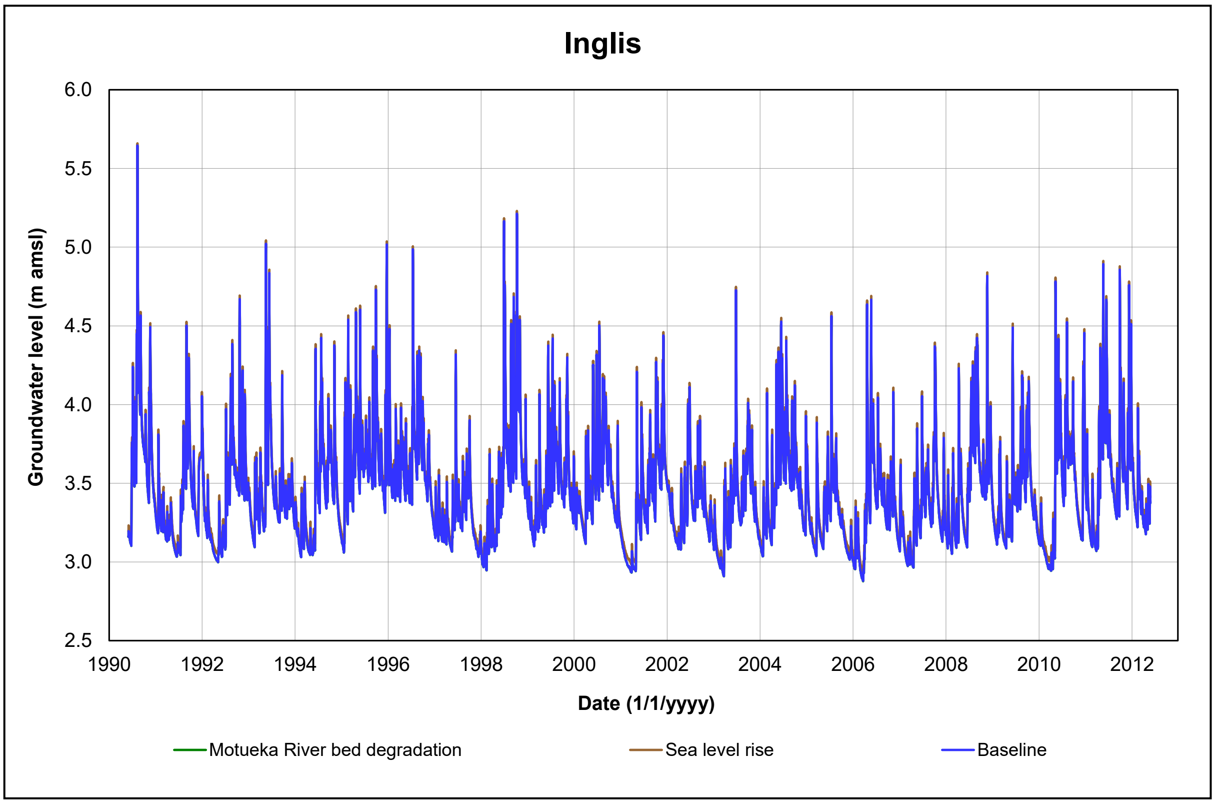
Appendix I: Hydrographs of modelled groundwater levels under scenarios 3, 9 and 10

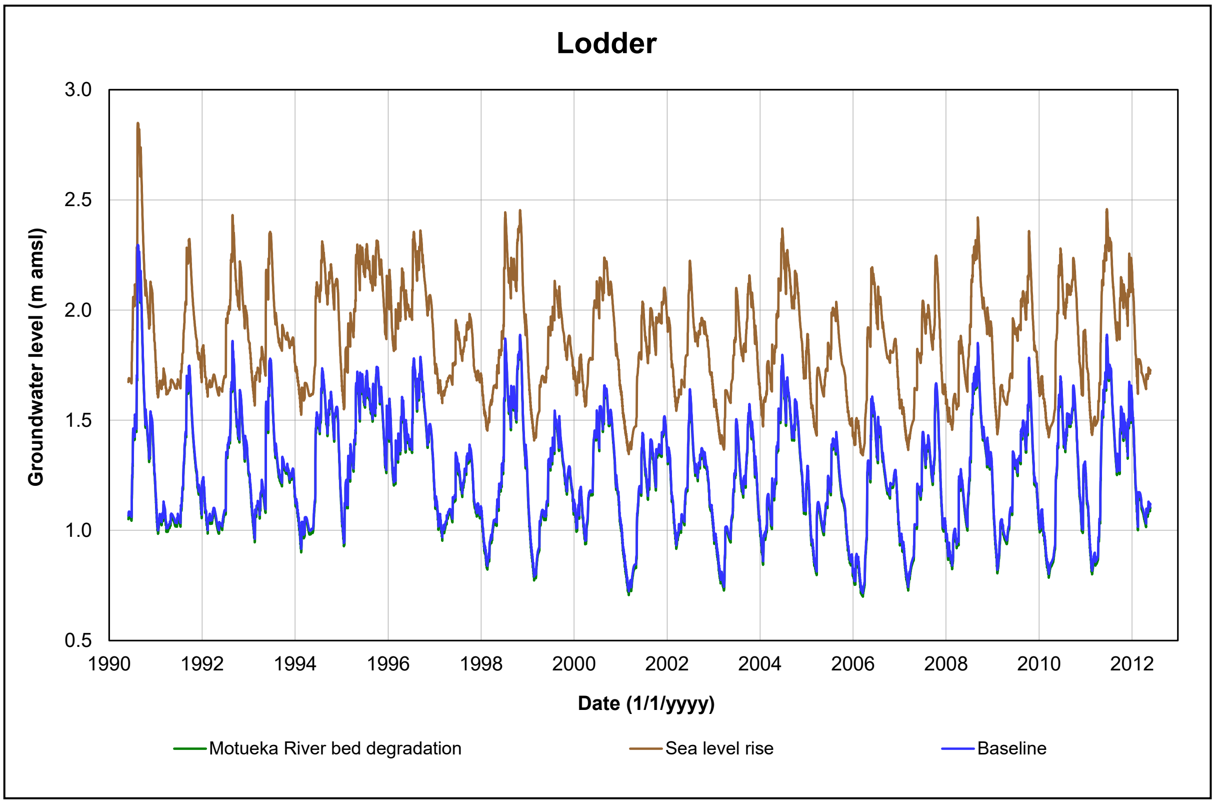


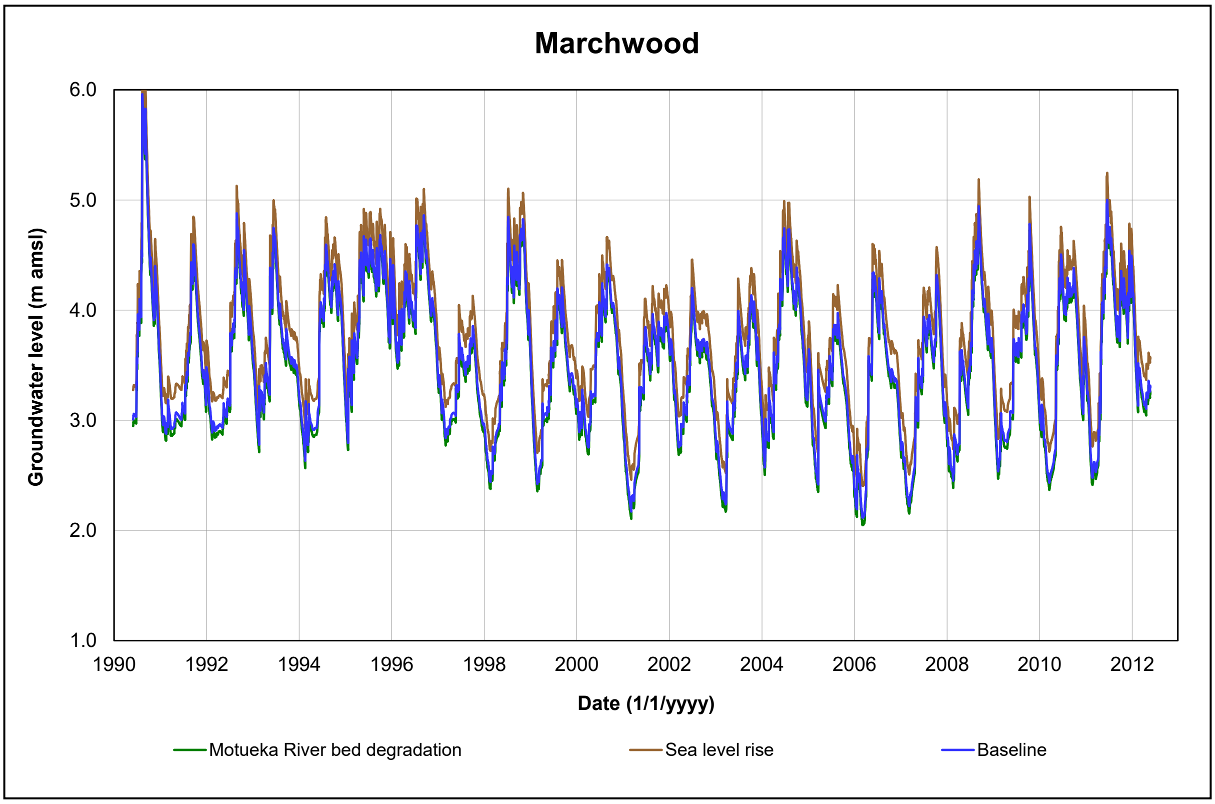


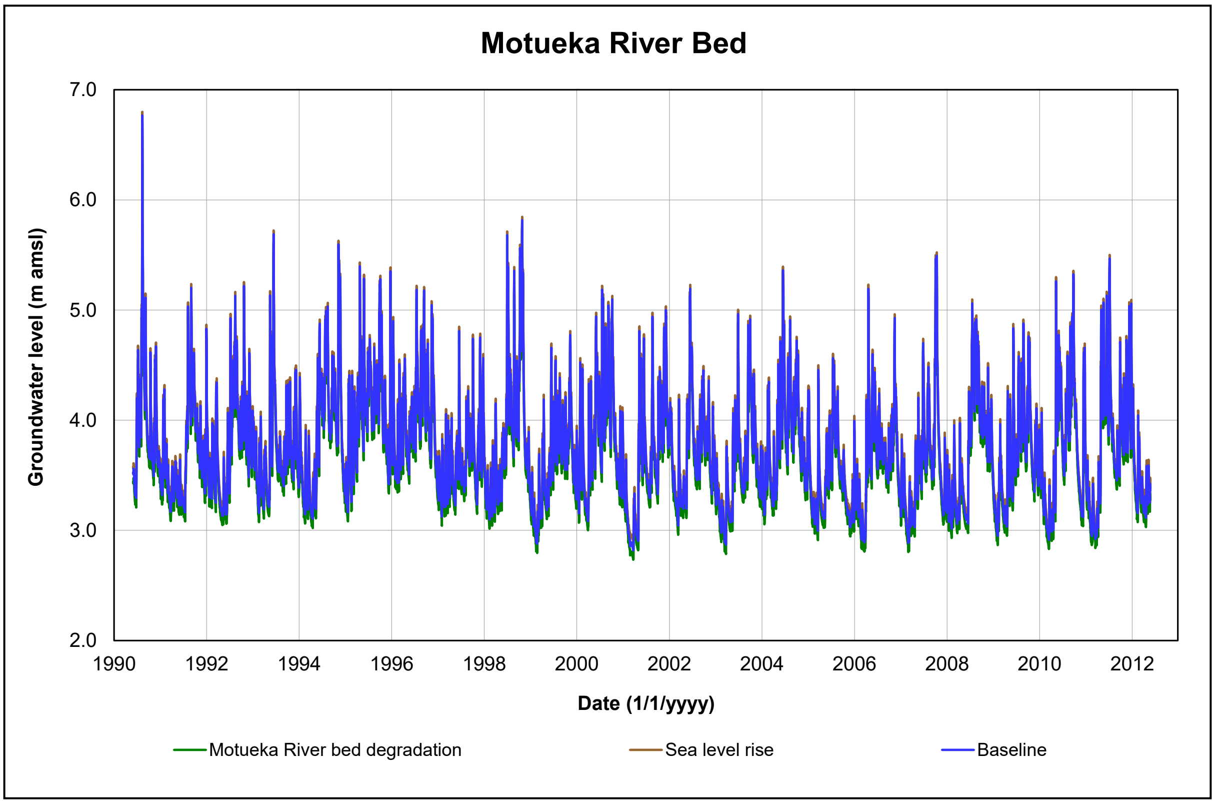

Greenwood
3.5
3.0
2.5
2.0
1.5
1.0
0.5
Groundwater level (m amsl)
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
Motueka River bed degradation
Sea level rise
Baseline

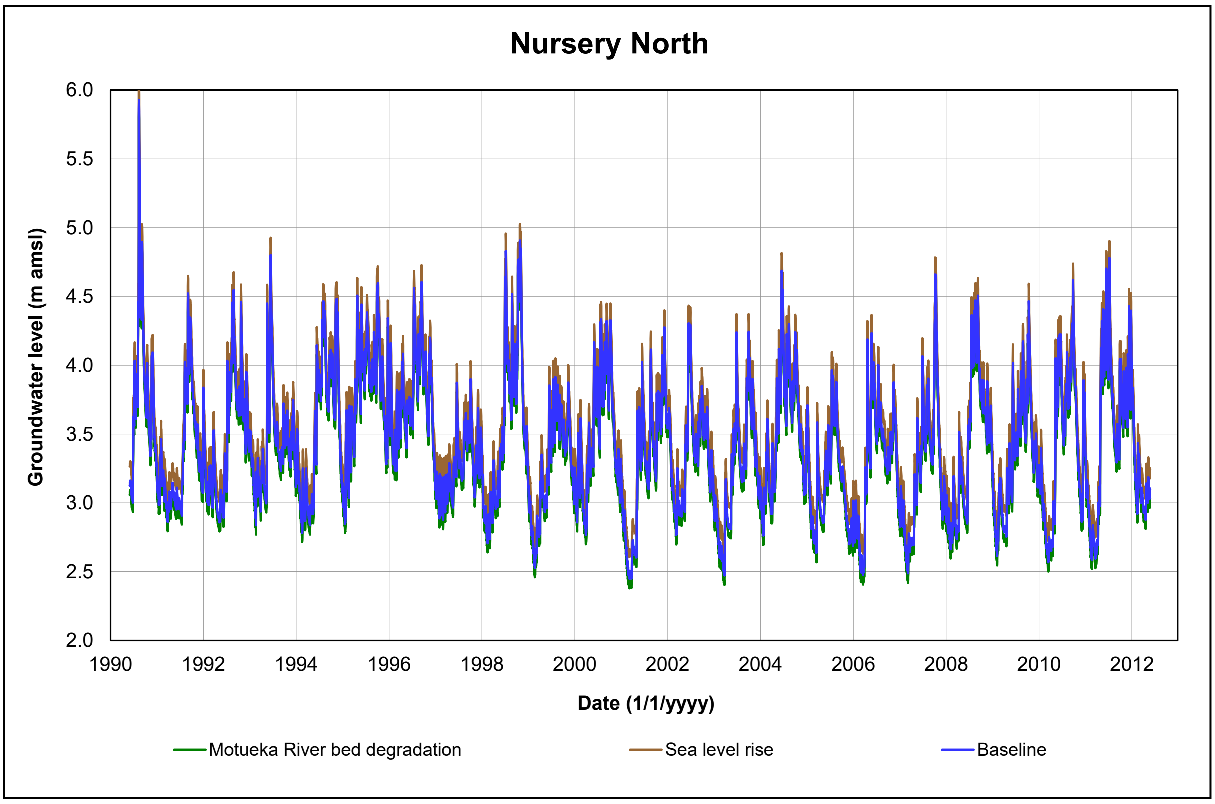

Horrell
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Groundwater level (m amsl)
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
Motueka River bed degradation
Sea level rise
Baseline

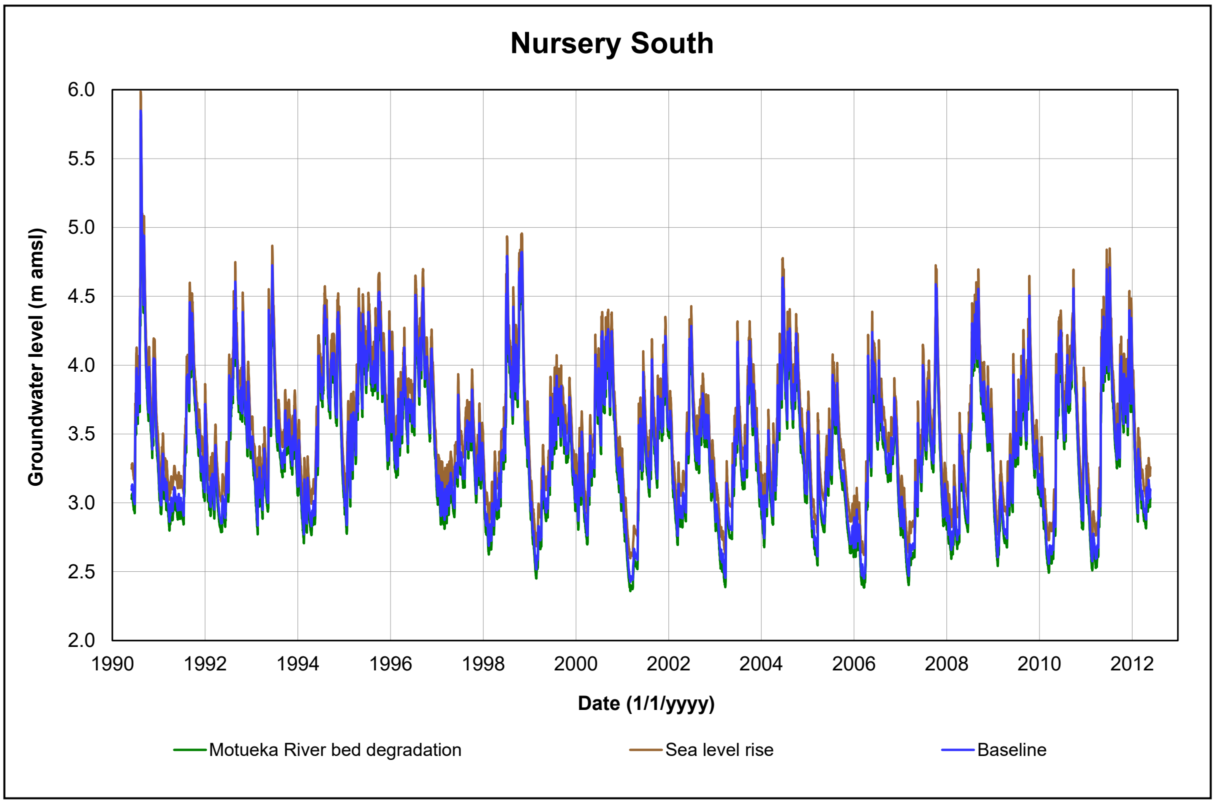

Inglis
Groundwater level (m amsl)
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
Motueka River bed degradation
Sea level rise
Baseline

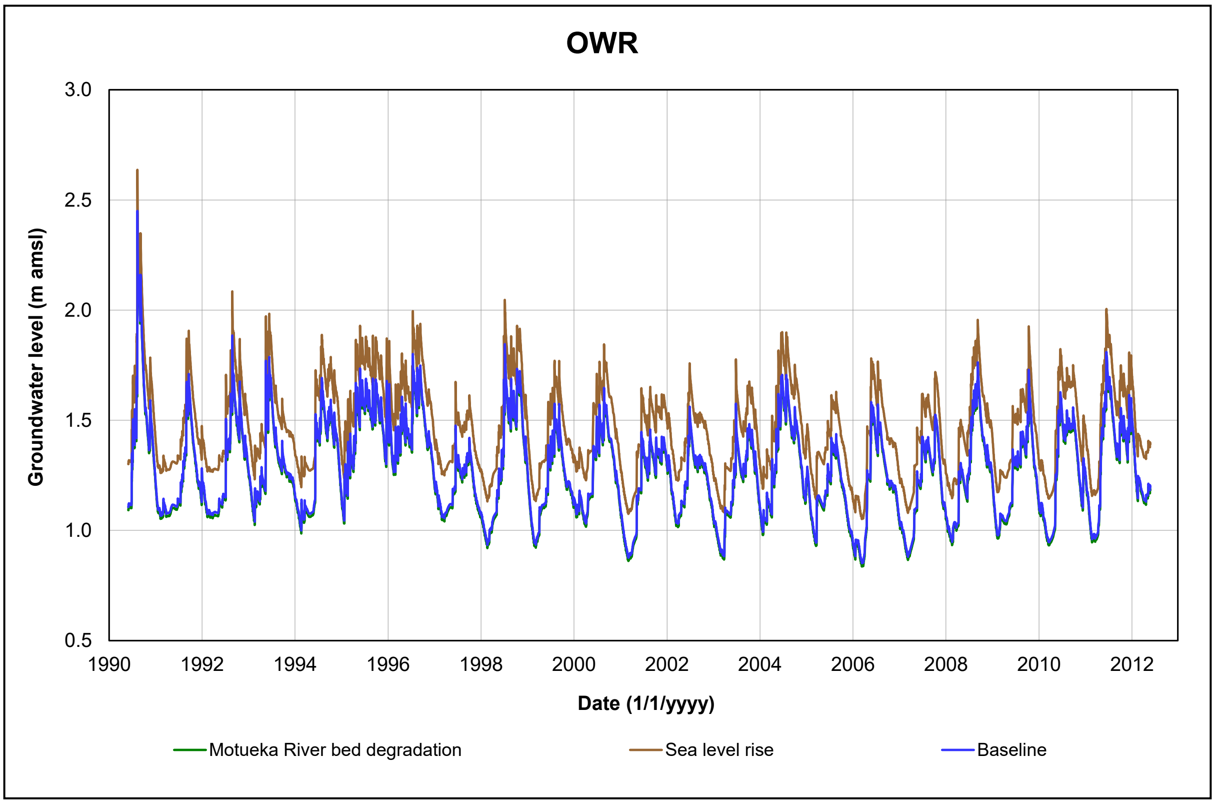

Lodder
Groundwater level (m amsl)
3.0
2.5
2.0
1.5
1.0
0.5
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
Motueka River bed degradation
Sea level rise
Baseline

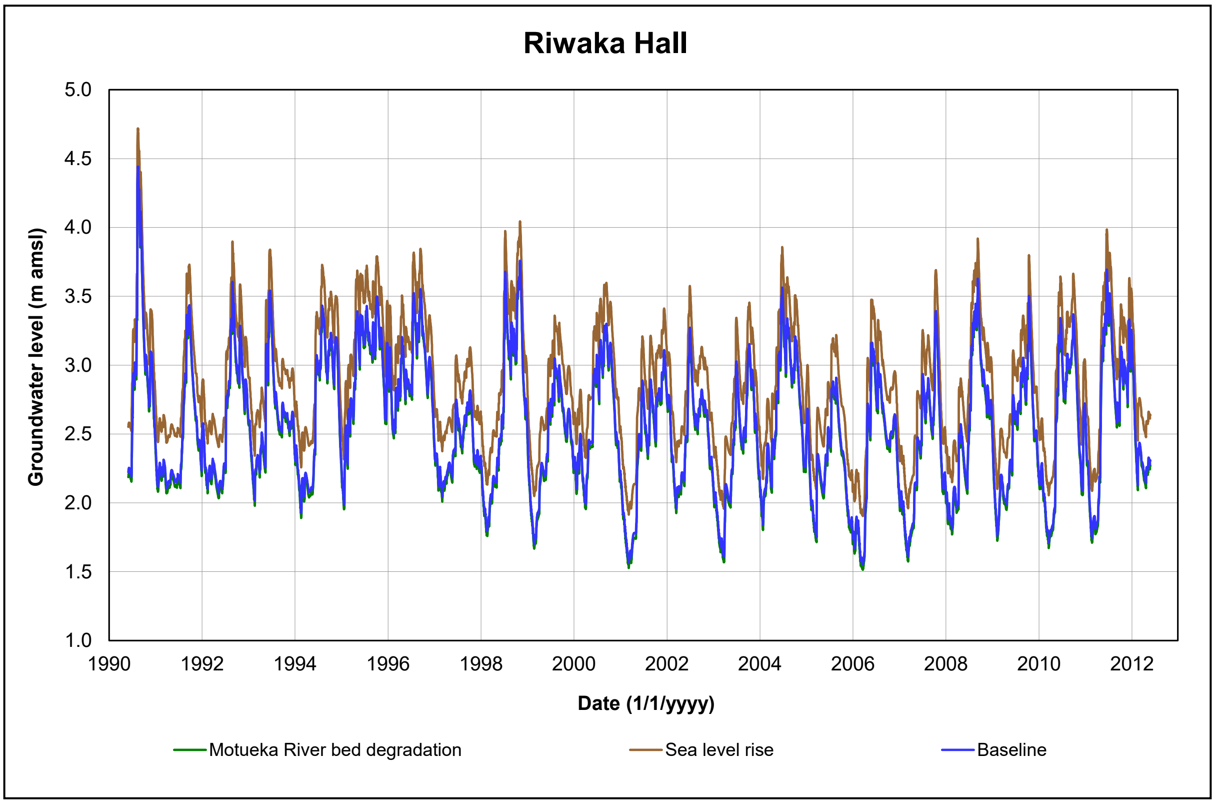

Marchwood
6.0
5.0
4.0
3.0
2.0
1.0
Groundwater level (m amsl)
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
Motueka River bed degradation
Sea level rise
Baseline

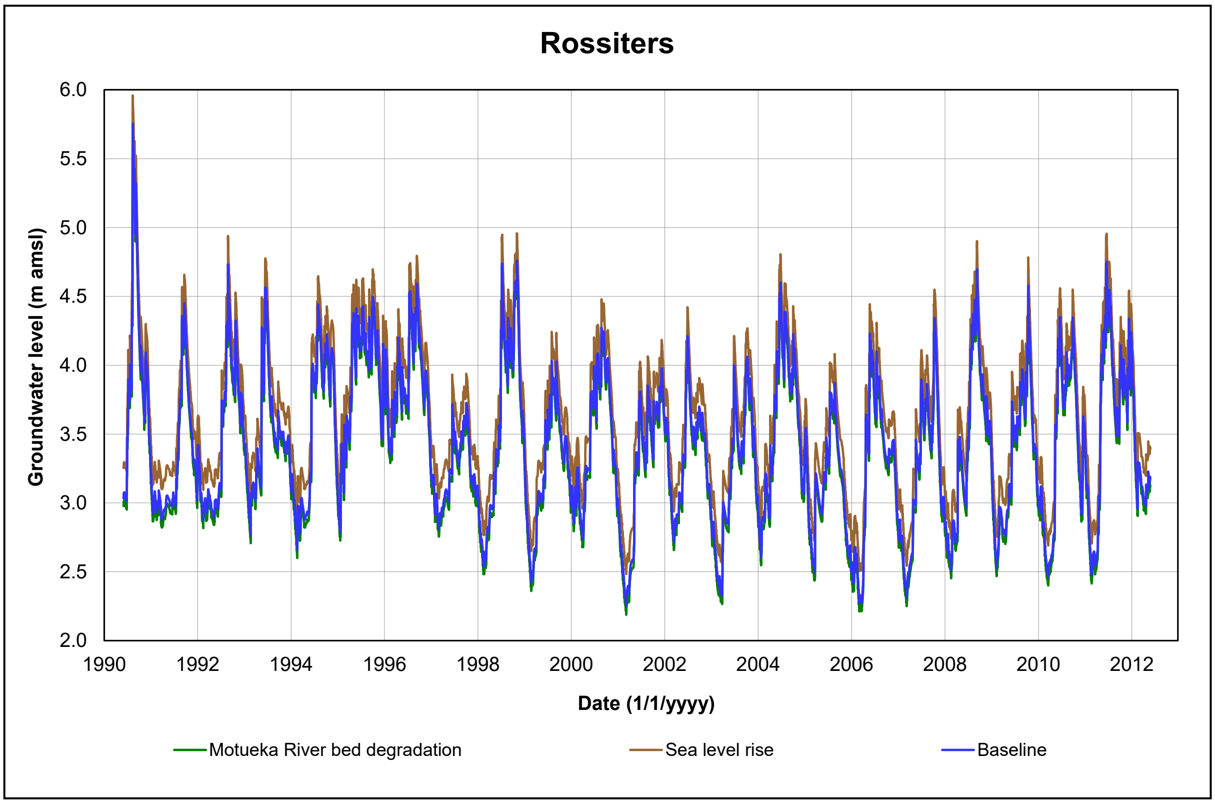

Motueka River Bed
7.0
6.0
5.0
4.0
3.0
2.0
Groundwater level (m amsl)
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
Motueka River bed degradation
Sea level rise
Baseline

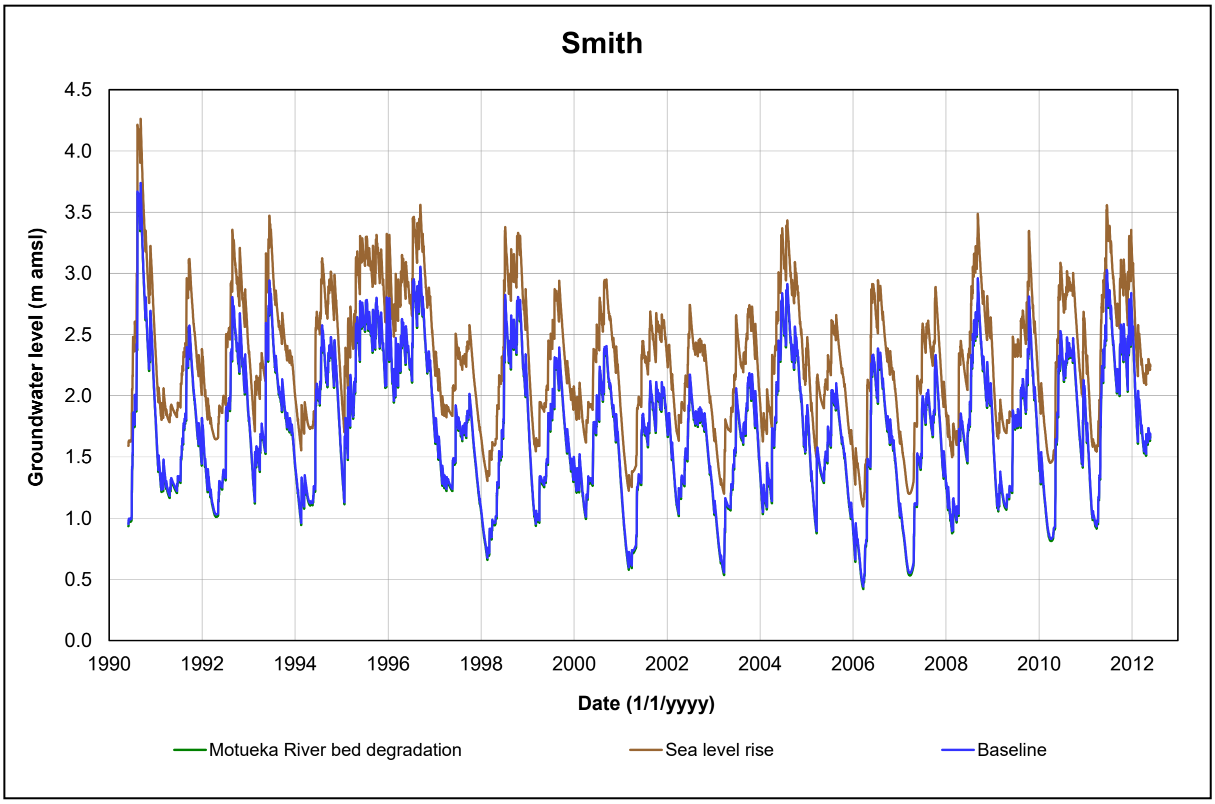

Nursery North
Groundwater level (m amsl)
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
Motueka River bed degradation
Sea level rise
Baseline

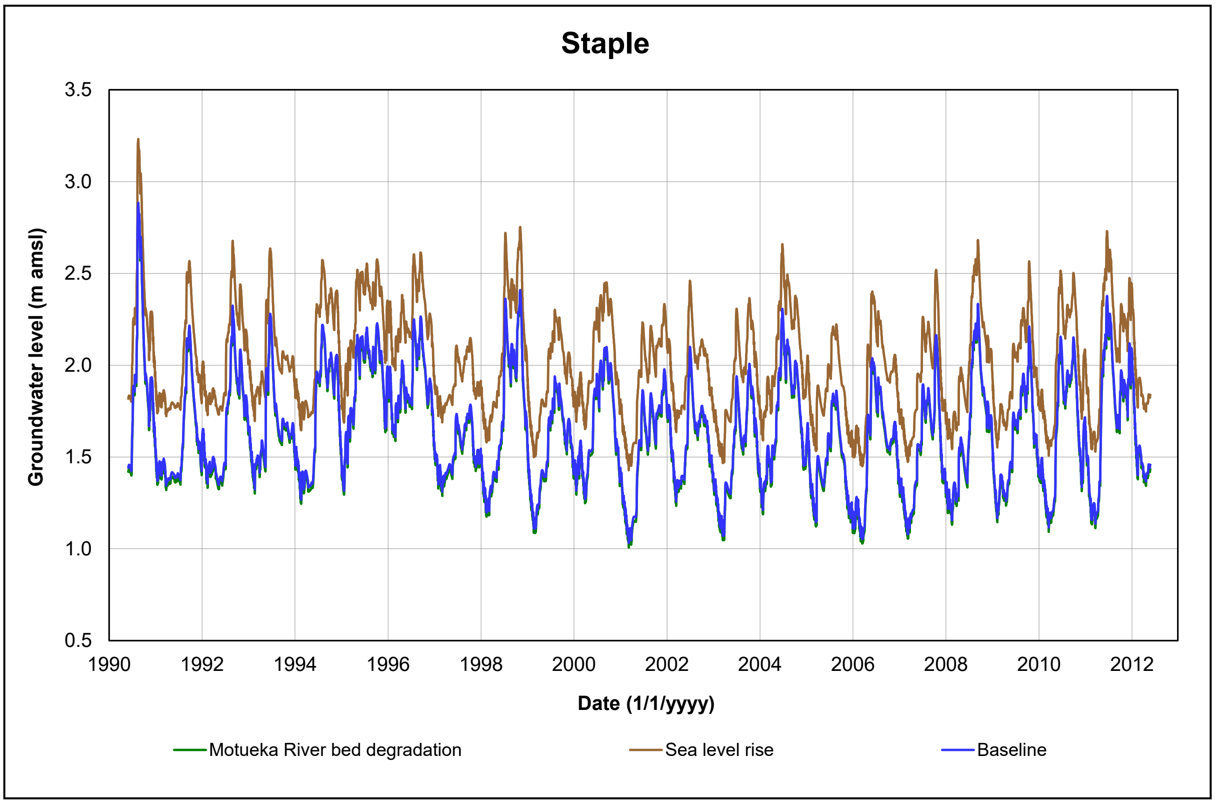

Nursery South
Groundwater level (m amsl)
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
Motueka River bed degradation
Sea level rise
Baseline

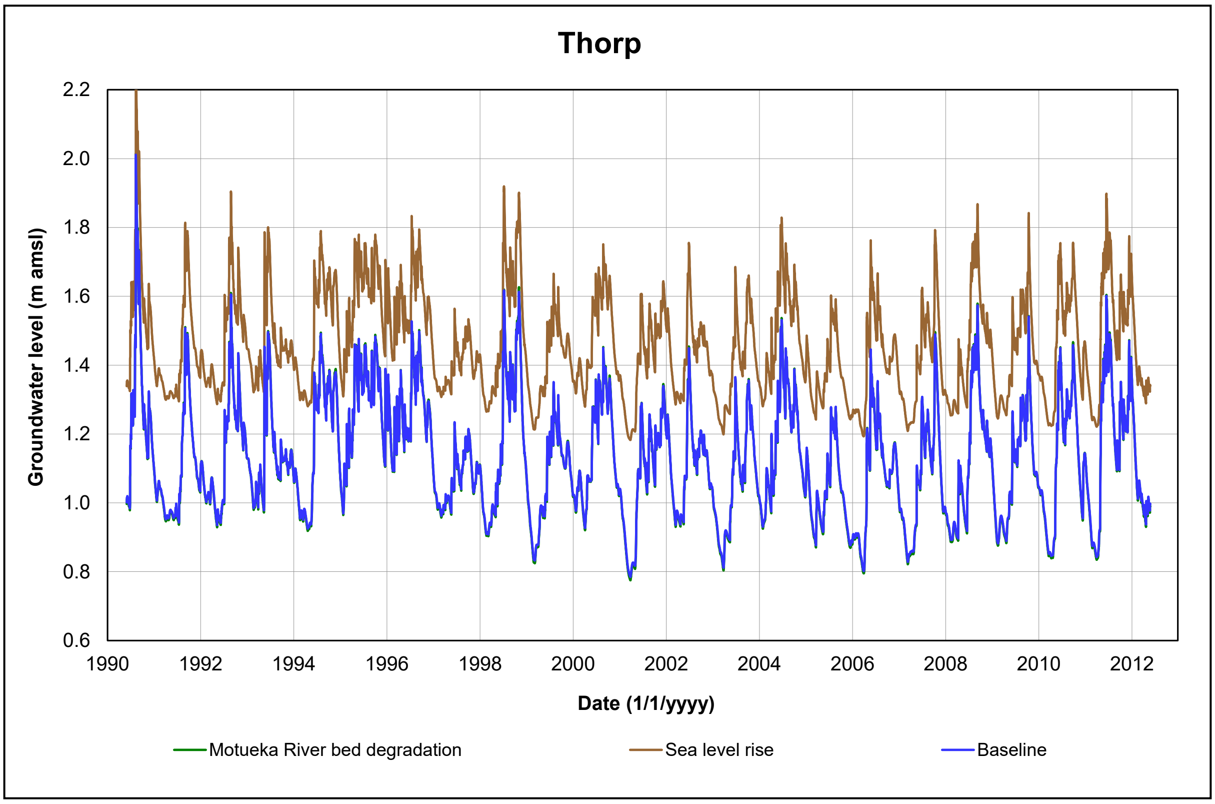

OWR
Groundwater level (m amsl)
3.0
2.5
2.0
1.5
1.0
0.5
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
Motueka River bed degradation
Sea level rise
Baseline

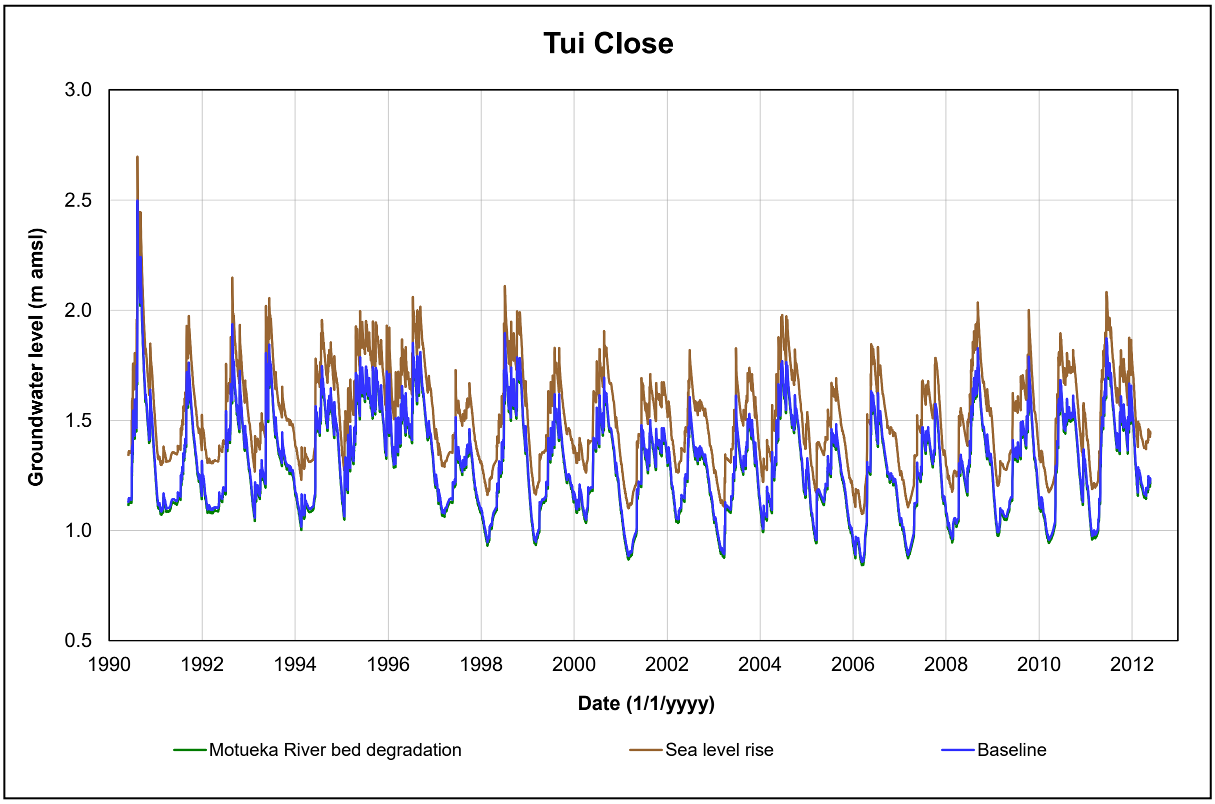

Riwaka Hall
Groundwater level (m amsl)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
Motueka River bed degradation
Sea level rise
Baseline

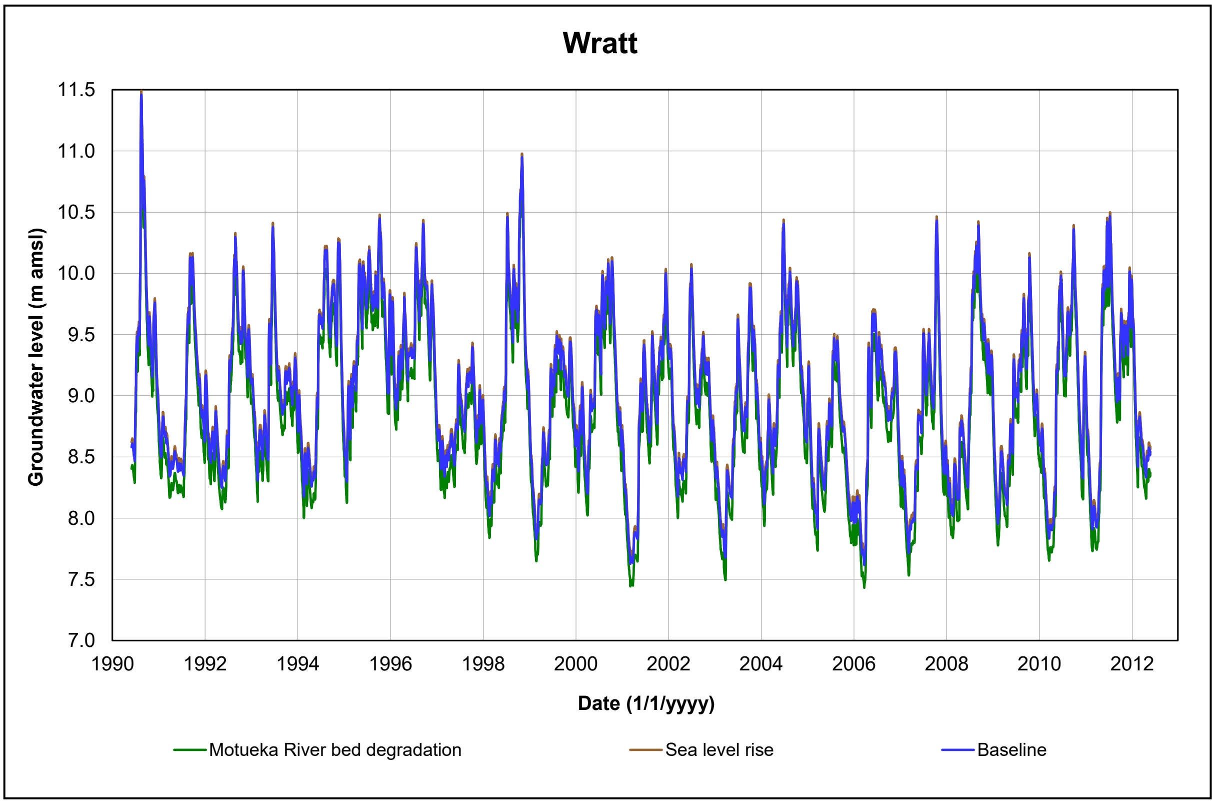

Rossiters
Groundwater level (m amsl)
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
Motueka River bed degradation
Sea level rise
Baseline


Smith
Groundwater level (m amsl)
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
Motueka River bed degradation
Sea level rise
Baseline

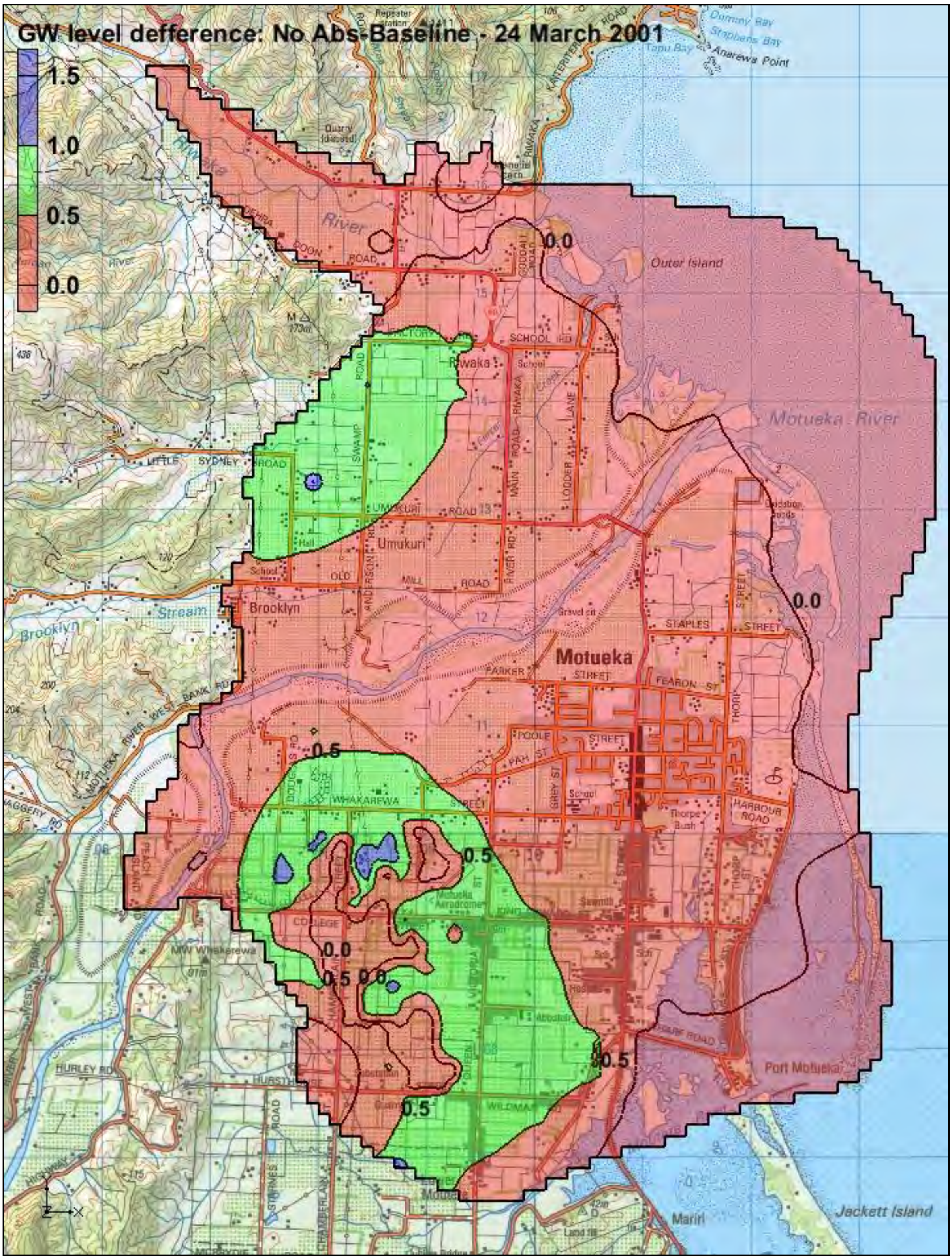

Staple
Groundwater level (m amsl)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
Motueka River bed degradation
Sea level rise
Baseline

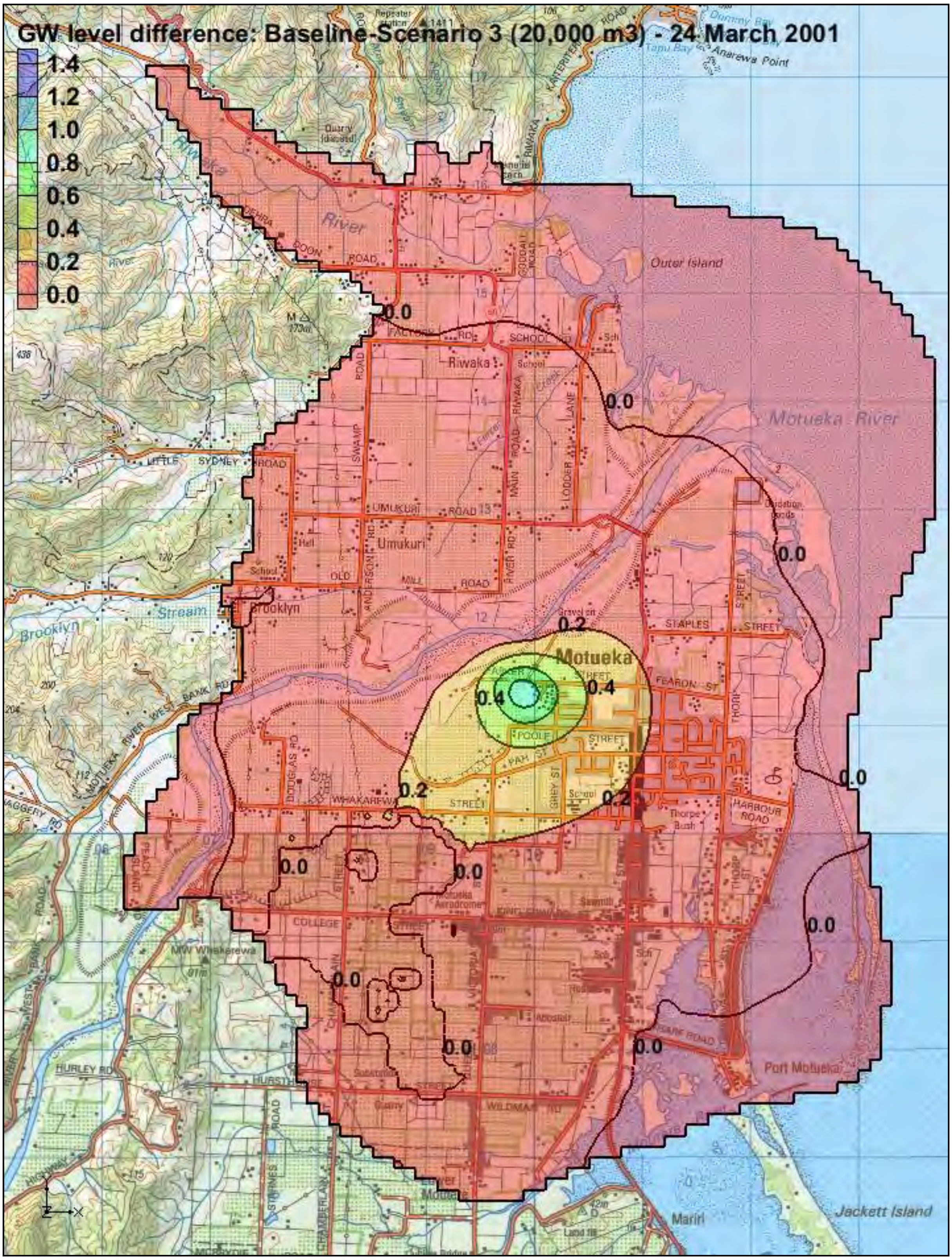

Thorp
Groundwater level (m amsl)
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
Motueka River bed degradation
Sea level rise
Baseline

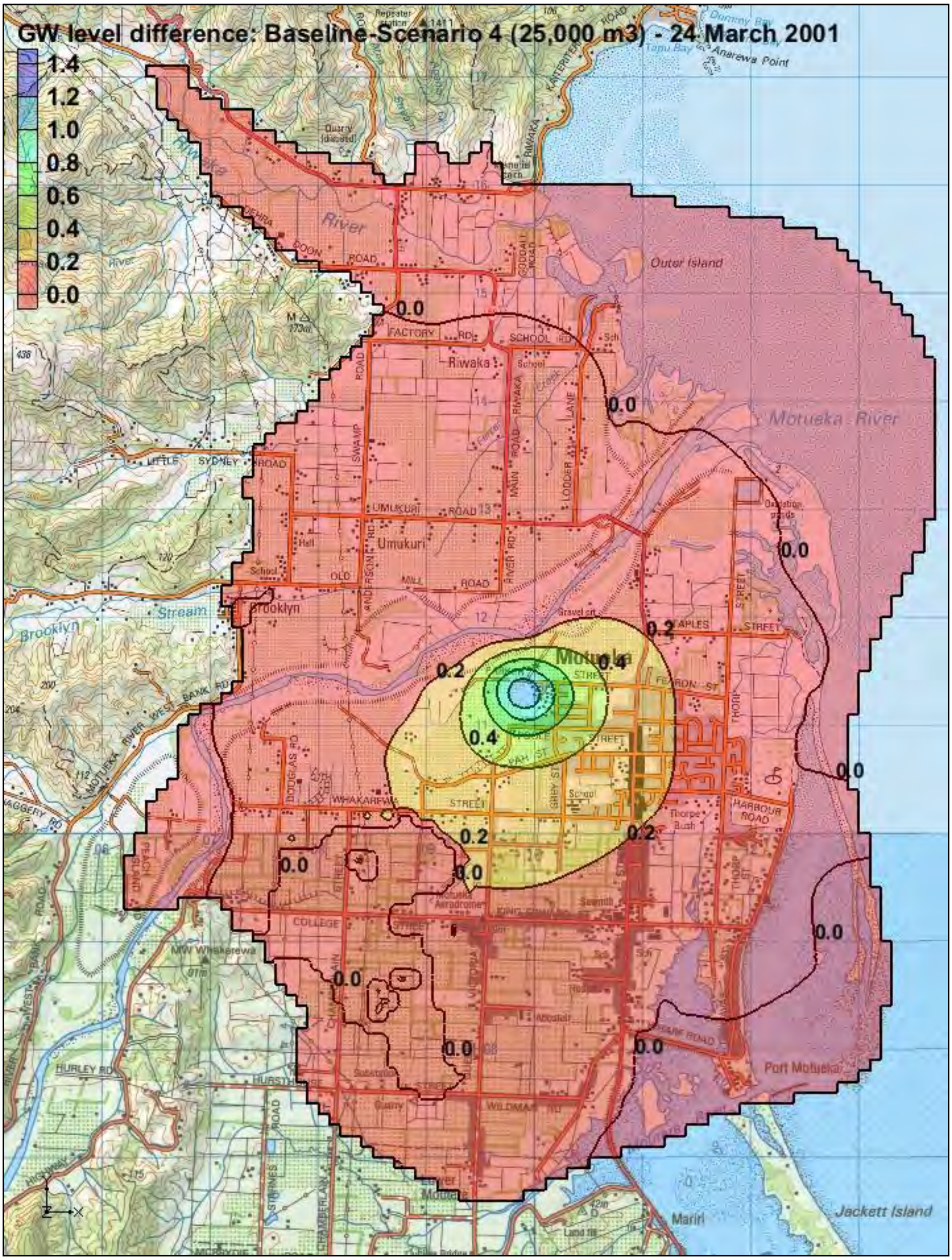

Tui Close
Groundwater level (m amsl)
3.0
2.5
2.0
1.5
1.0
0.5
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
Motueka River bed degradation
Sea level rise
Baseline

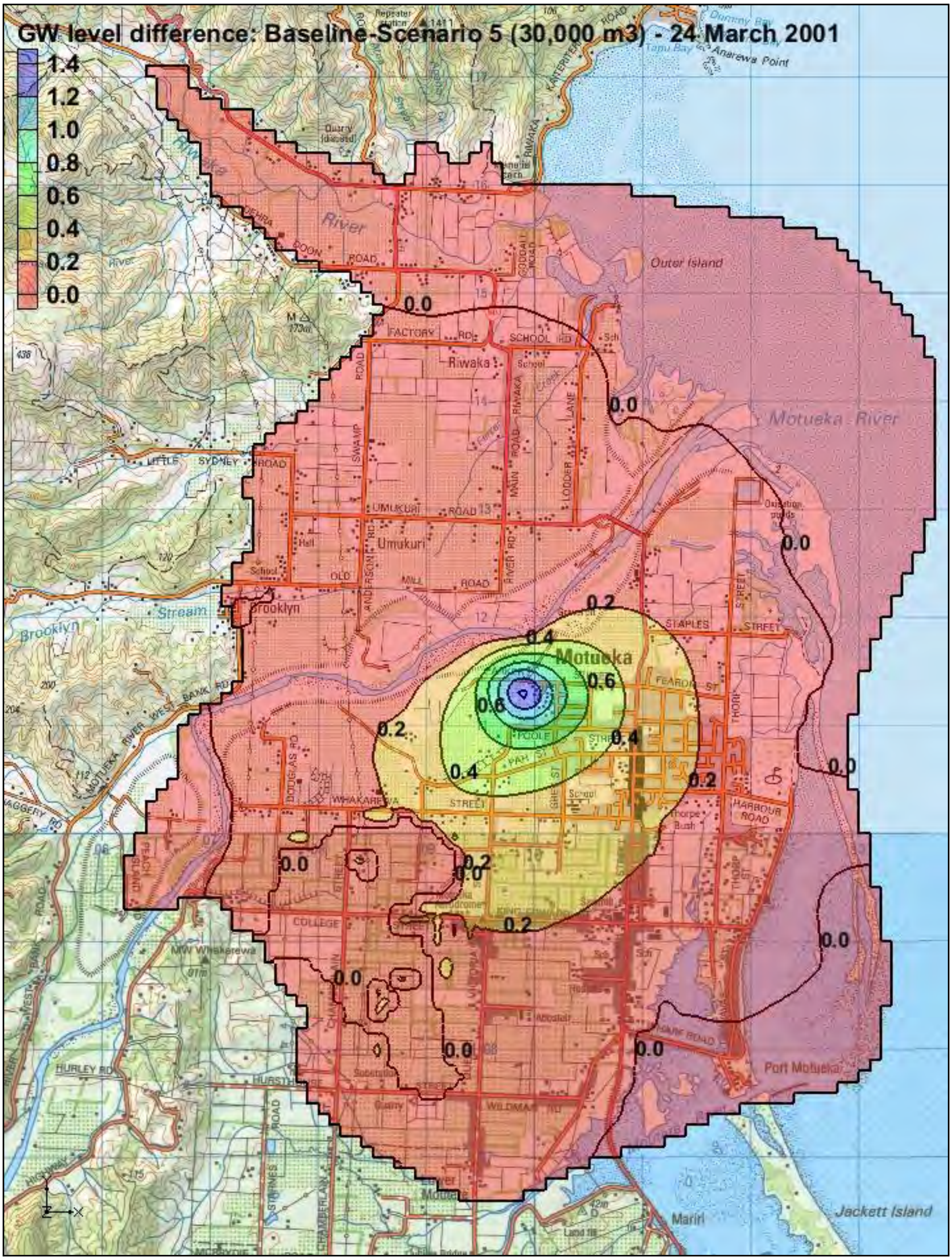

Wratt
Groundwater level (m amsl)
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0
7.5
7.0
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Date (1/1/yyyy)
Motueka River bed degradation
Sea level rise
Baseline

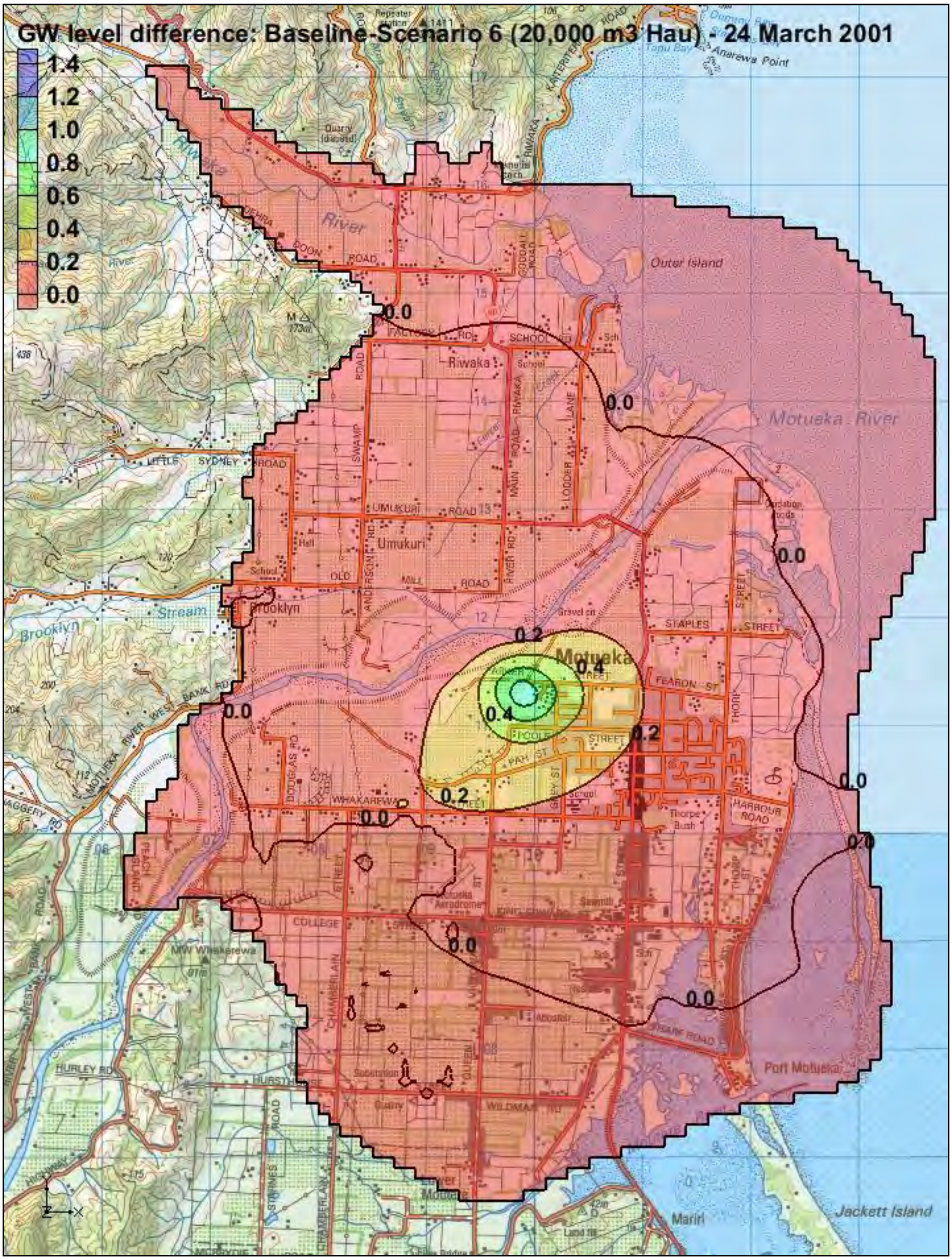
Appendix J: Maps of groundwater level changes between scenarios for 24 March 2001

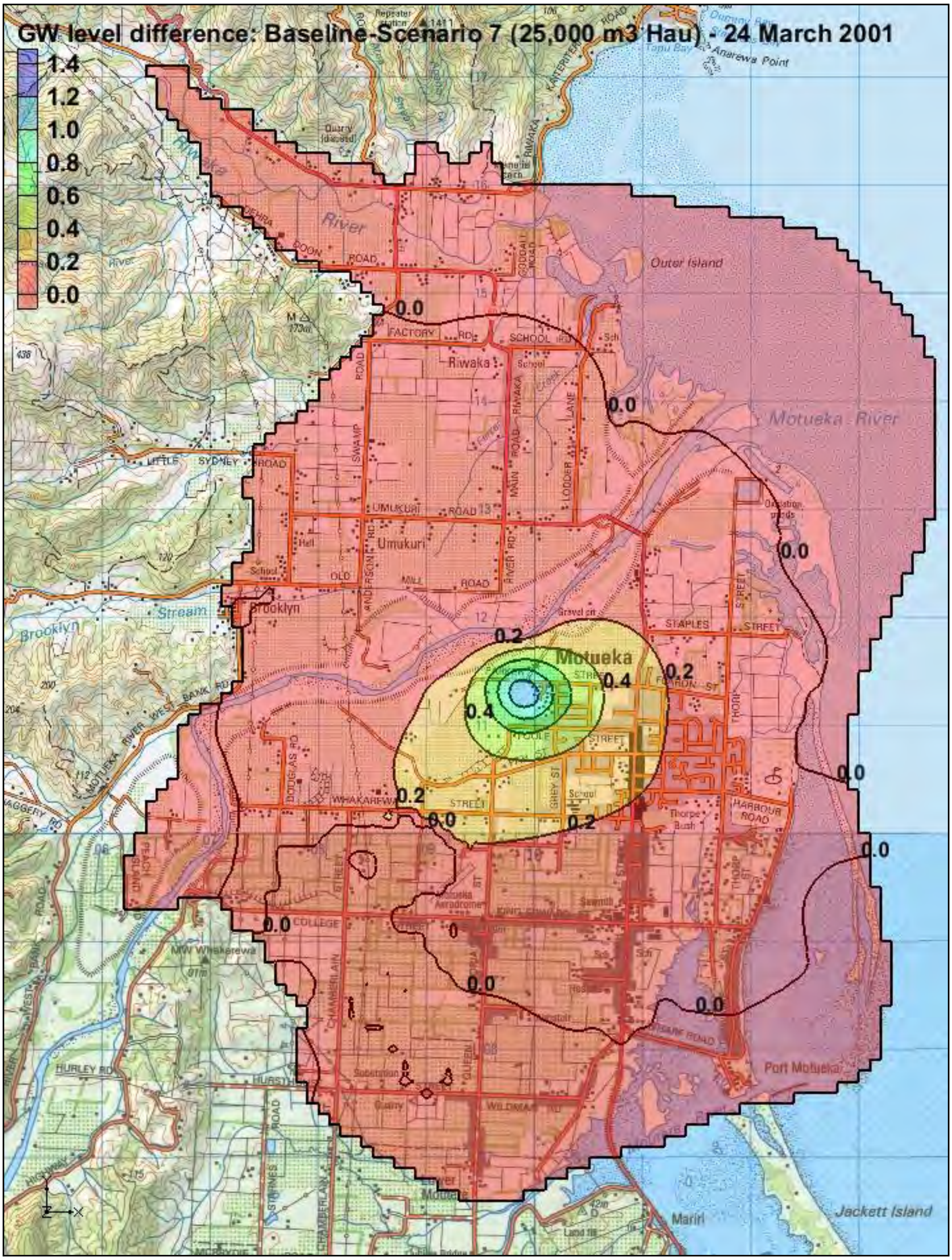


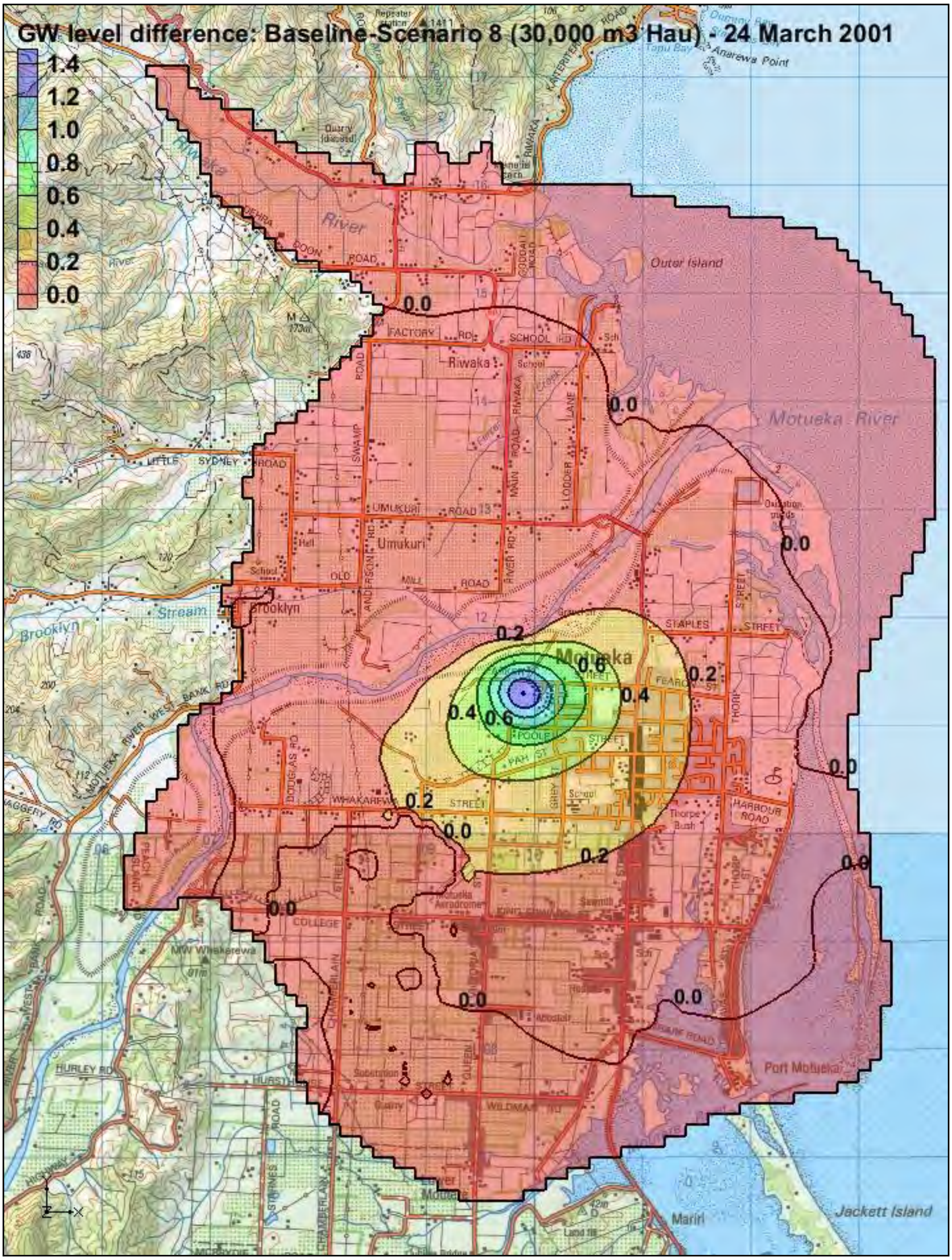

GW level difference: Baseline-Scenario 3 (20,000 m3) - 24 March 2001
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.0
0.0
0.2
0.4
0.4
0.2
0.2
0.0
0.0
0.0
0.0
0.0
0.0
0.0
Riwaka
River
Outer Island
Motueka River
Umukuri
Brooklyn
Stream
Motueka
Thorpe Bush
Port Motueka
Mariri
Jackett Island
Tapu Bay
Anarewa Point
FACTORY RD
SCHOOL RD
UMUKURI ROAD
OLD MILL ROAD
LITTLE SYDNEY ROAD
MOTUEKA RIVER WEST BANK RD
STAPLES STREET
FEARON ST
POOLE STREET
PAH ST
WHAKAREWA STREET
COLLEGE STREET
HARBOUR ROAD
HURLEY RD
WILDMAN RD

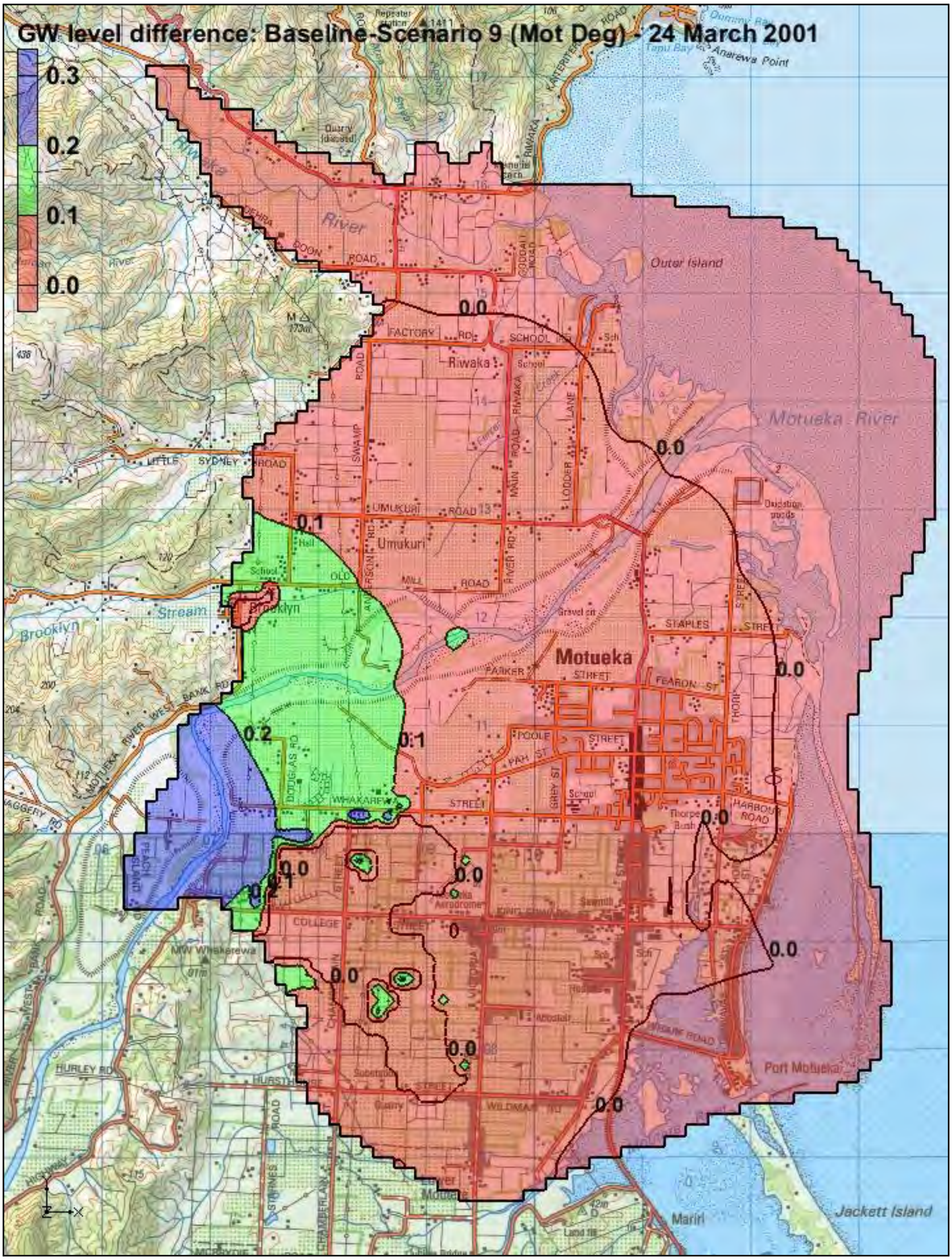

GW level difference: Baseline-Scenario 4 (25,000 m3) - 24 March 2001
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.0
0.0
0.2
0.4
0.2
0.4
0.0
0.2
0.0
0.2
0.0
0.0
0.0
0.0
0.0
0.0
Riwaka
Umukuri
Brooklyn
Motueka
Motueka River
Outer Island
Port Motueka
Jackett Island
Mariri
Riwaka River
Brooklyn Stream
Anarewa Point
Tapu Bay
SCHOOL RD
FACTORY RD
UMUKURI ROAD
OLD MILL ROAD
LITTLE SYDNEY ROAD
MOTUEKA RIVER WEST BANK RD
WHAKAREWA STREET
COLLEGE STREET
KING EDWARD
HURLEY RD
WILDMAN RD
HARBOUR ROAD
STAPLES STREET
Thorpe Bush
Motueka Aerodrome
Z
X

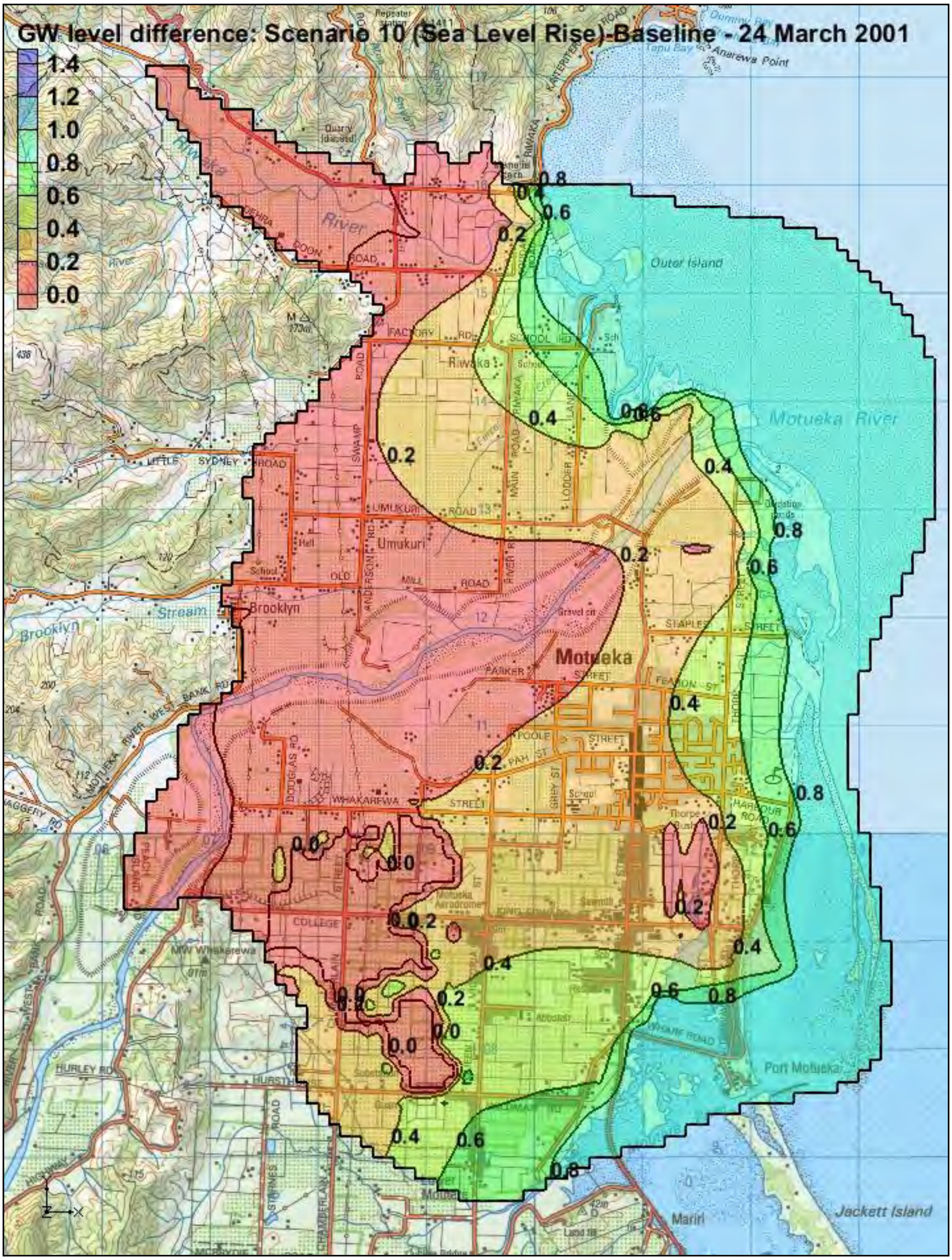

GW level difference: Baseline-Scenario 5 (30,000 m3) - 24 March 2001
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Motueka
Riwaka
Umukuri
Brooklyn
Motueka River
Outer Island
Port Motueka
Jackett Island
Mariri
Riwaka River
Brooklyn Stream

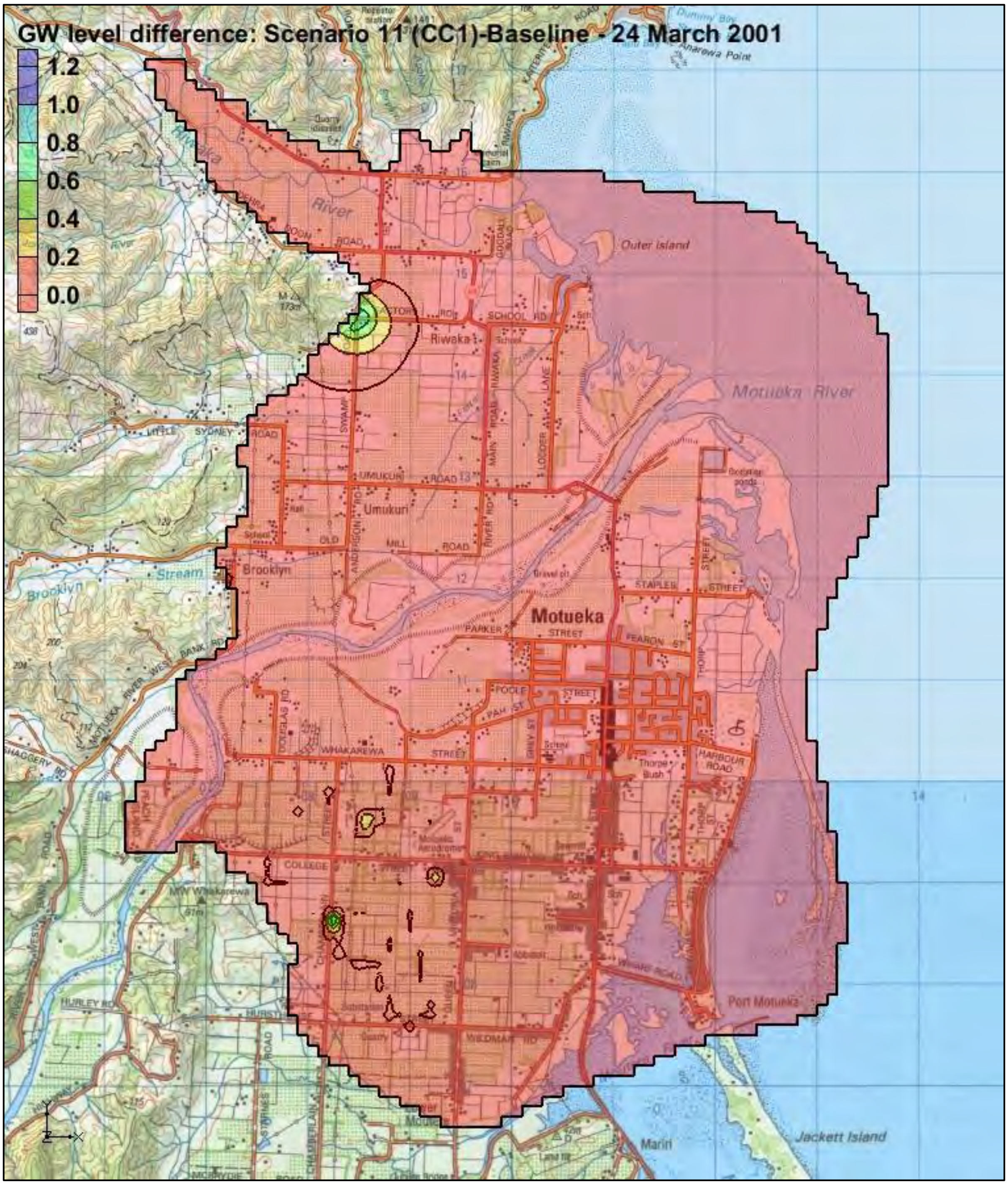

GW level difference: Baseline-Scenario 6 (20,000 m3 Hau) - 24 March 2001
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Riwaka
Motueka River
Outer Island
Umukuri
Brooklyn
Motueka
Port Motueka
Jackett Island
Mariri
0.0
0.2
0.4
0.2

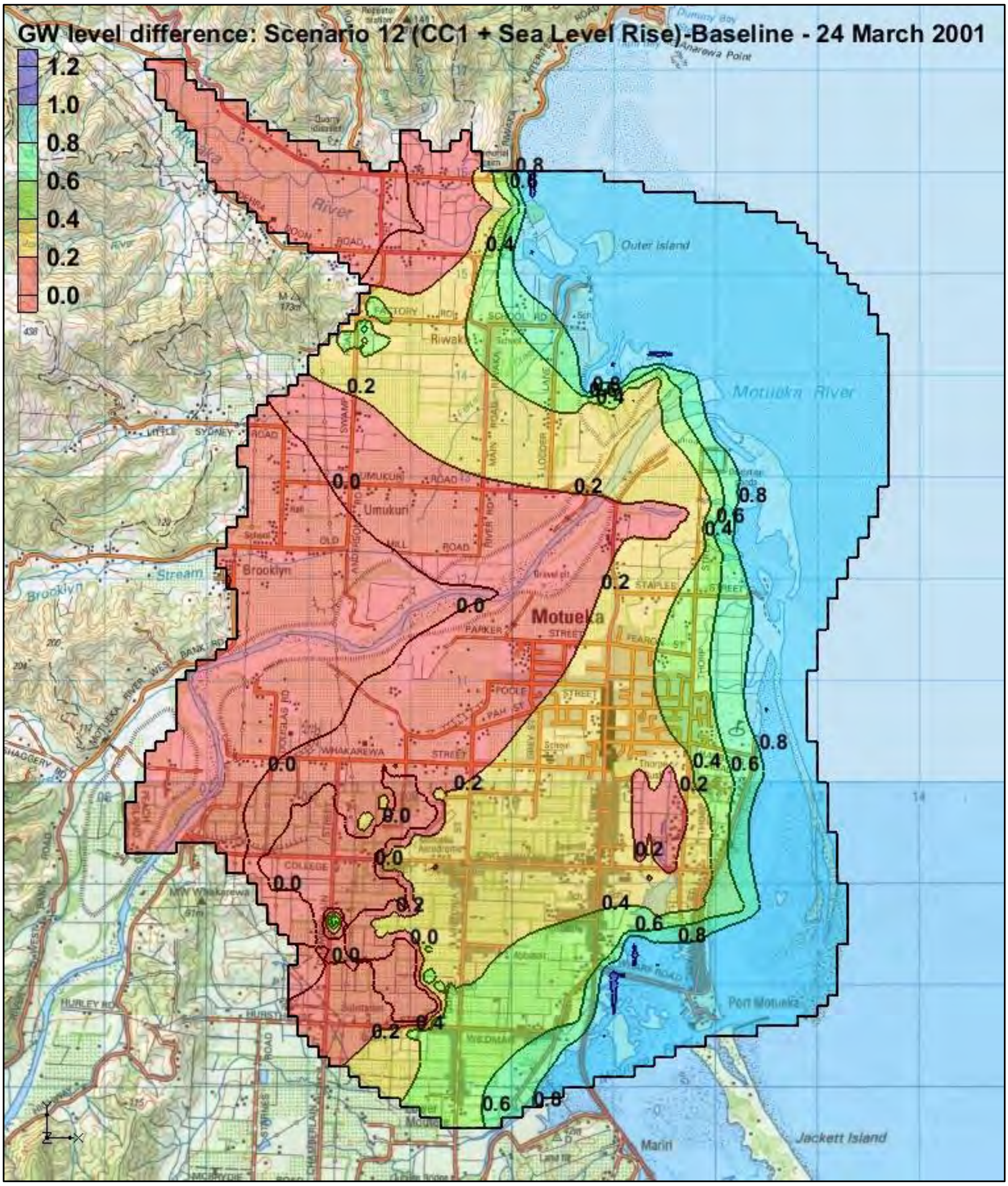

GW level difference: Baseline-Scenario 7 (25,000 m3 Hau) - 24 March 2001
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Riwaka
Umukuri
Brooklyn
Motueka
Motueka River
Outer Island
Port Motueka
Jackett Island
Mariri
0.0
0.2
0.4


GW level difference: Baseline-Scenario 8 (30,000 m3 Hau) - 24 March 2001
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Riwaka
Umukuri
Brooklyn
Motueka
Motueka River
Outer Island
Port Motueka
Jackett Island
Mariri

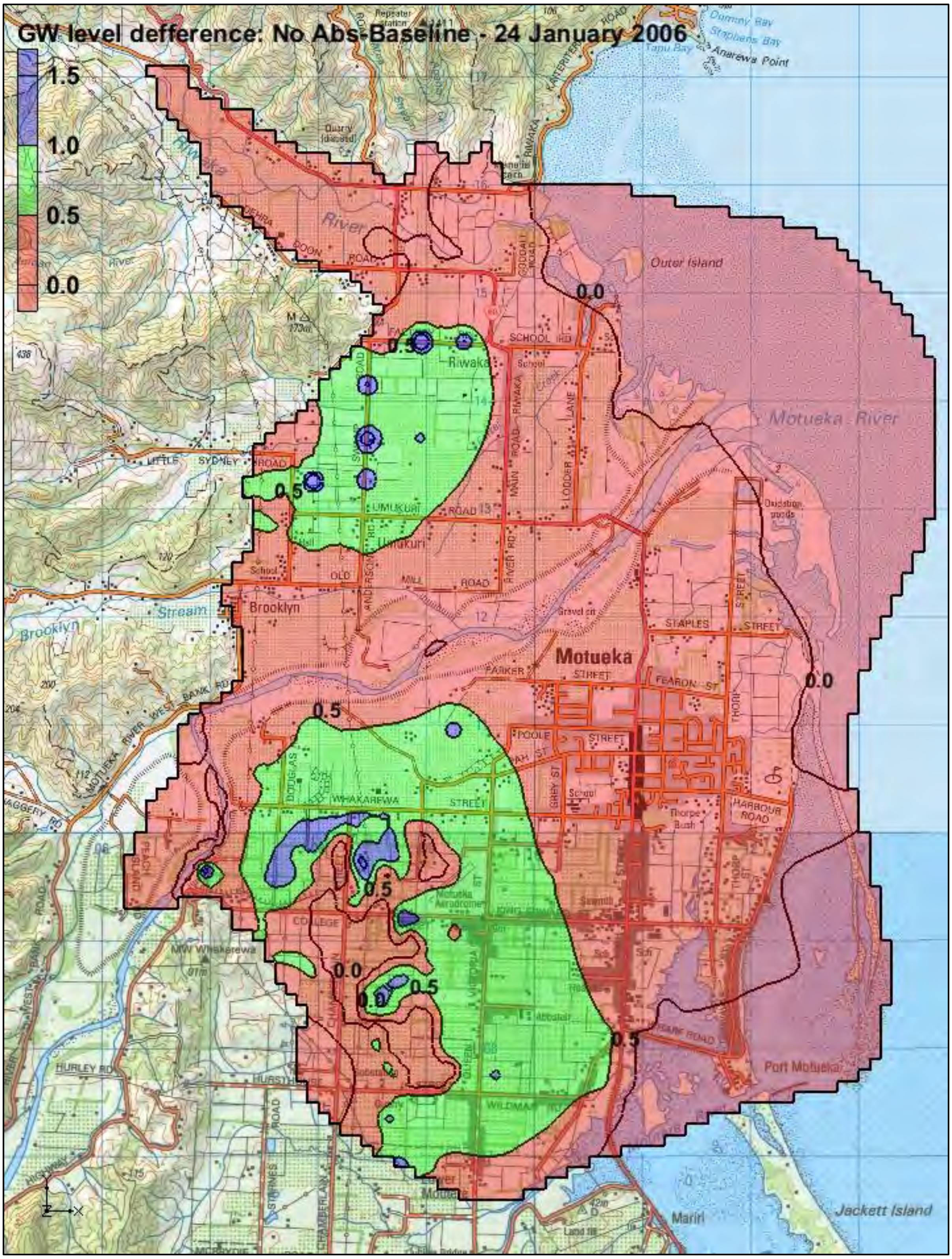

GW level difference: Baseline-Scenario 9 (Mot Deg) - 24 March 2001
0.3
0.2
0.1
0.0
Riwaka
Umukuri
Brooklyn
Motueka
Motueka River
Outer Island
Port Motueka
Jackett Island
Mariri
0.0
0.1
0.2
0.0
0.0

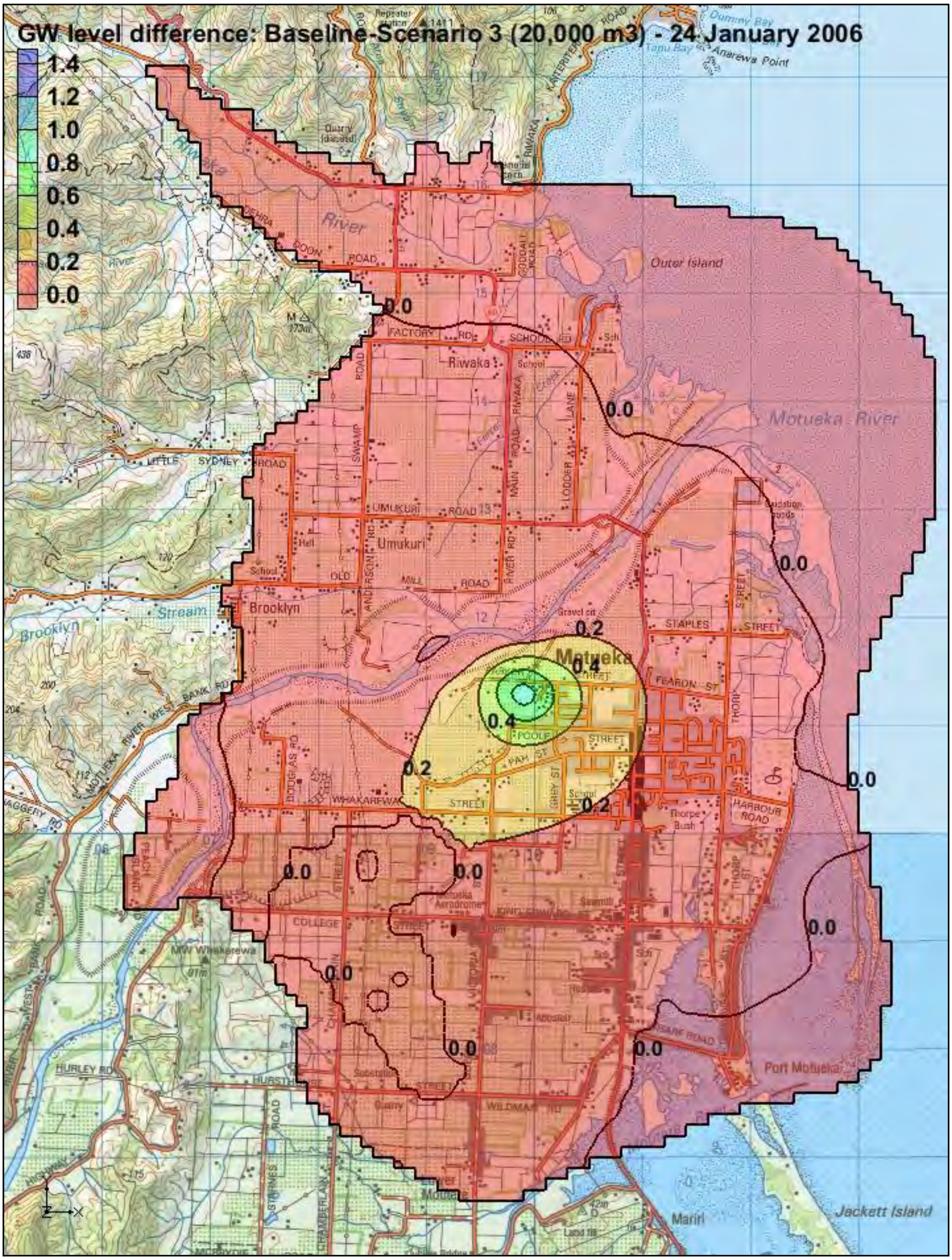

GW level difference: Scenario 10 (Sea Level Rise)-Baseline - 24 March 2001
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Riwaka
Motueka
Brooklyn
Umukuri
Outer Island
Motueka River
Port Motueka
Jackett Island
Mariri
0.0
0.2
0.4
0.6
0.8

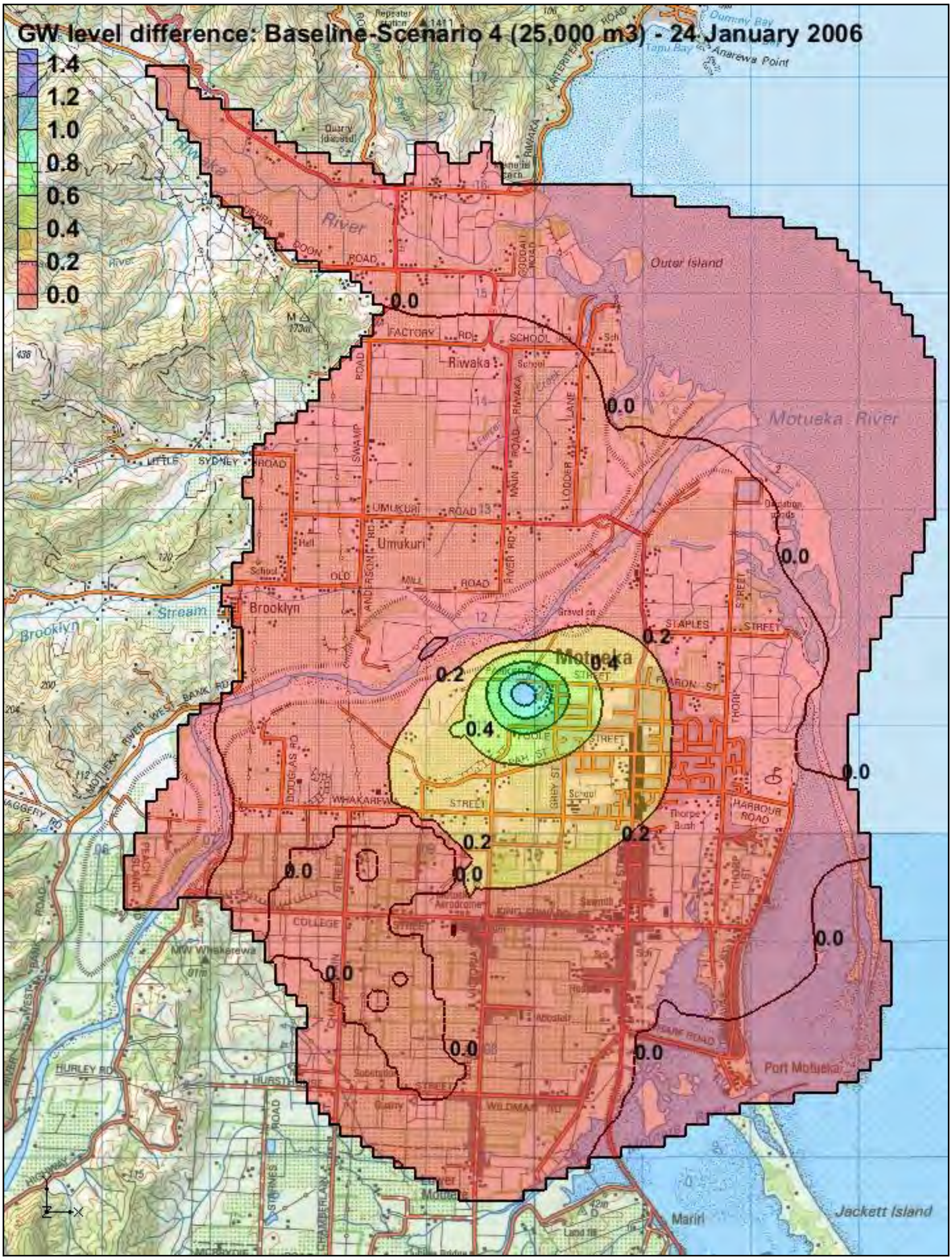

GW level difference: Scenario 11 (CC1)-Baseline - 24 March 2001
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Riwaka River
Outer Island
Motueka River
Riwaka
Umukuri
Brooklyn
Brooklyn Stream
Motueka
Port Motueka
Jackett Island
Motueka Aerodrome
Thorpe Bush
Marin
School Rd
Umukuri Road
Whakarewa Street
College Street
Pah St
Poole Street
Parker Street
Staples Street
Harbour Road
Wildman Rd
Hurley Rd
Motueka River West Bank Rd

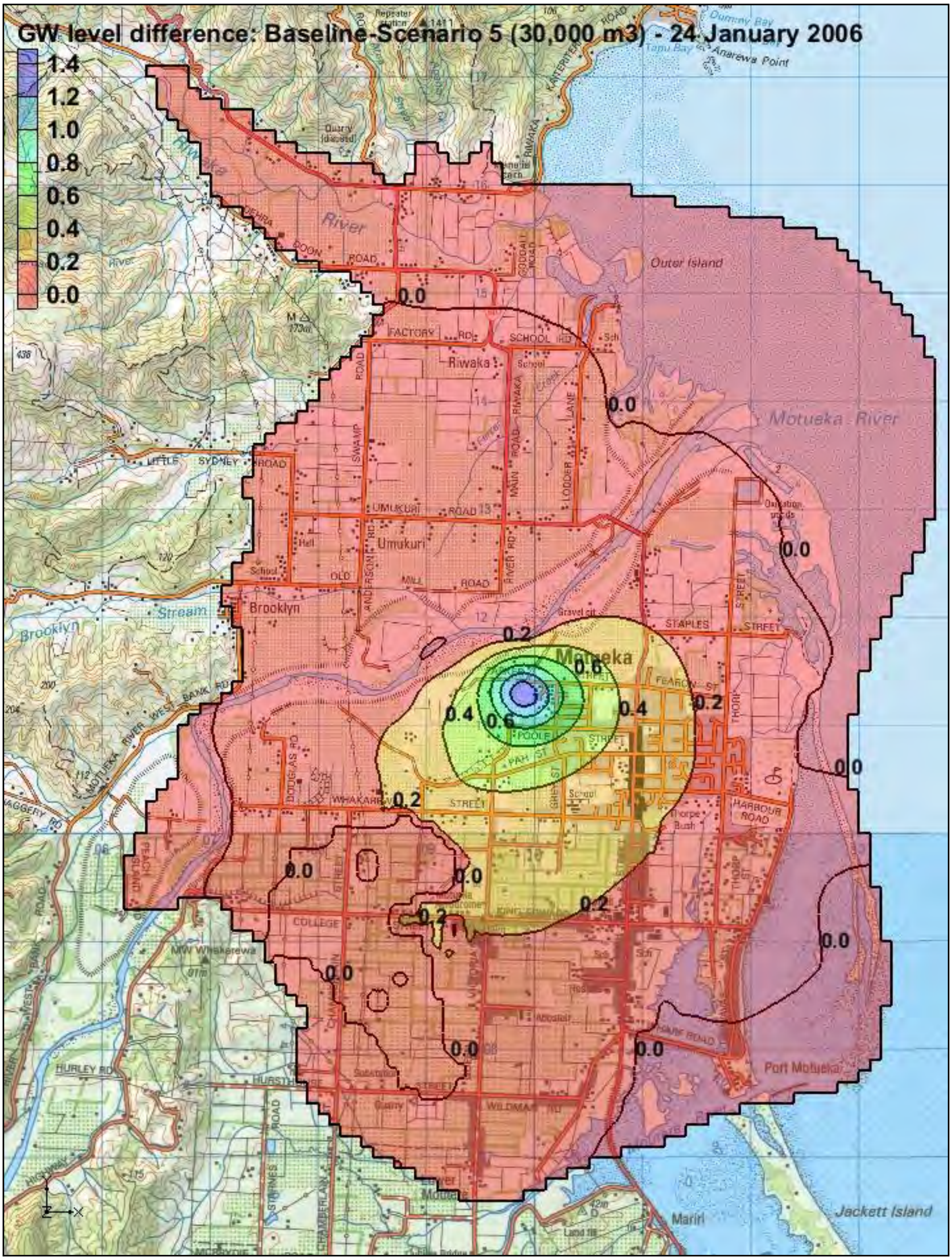

GW level difference: Scenario 12 (CC1 + Sea Level Rise)-Baseline - 24 March 2001
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Outer Island
Motueka River
Riwaka
Umukuri
Brooklyn
Motueka
Port Motueka
Jackett Island
Mariri
Anarewa Point
Riwaka River
Brooklyn Stream

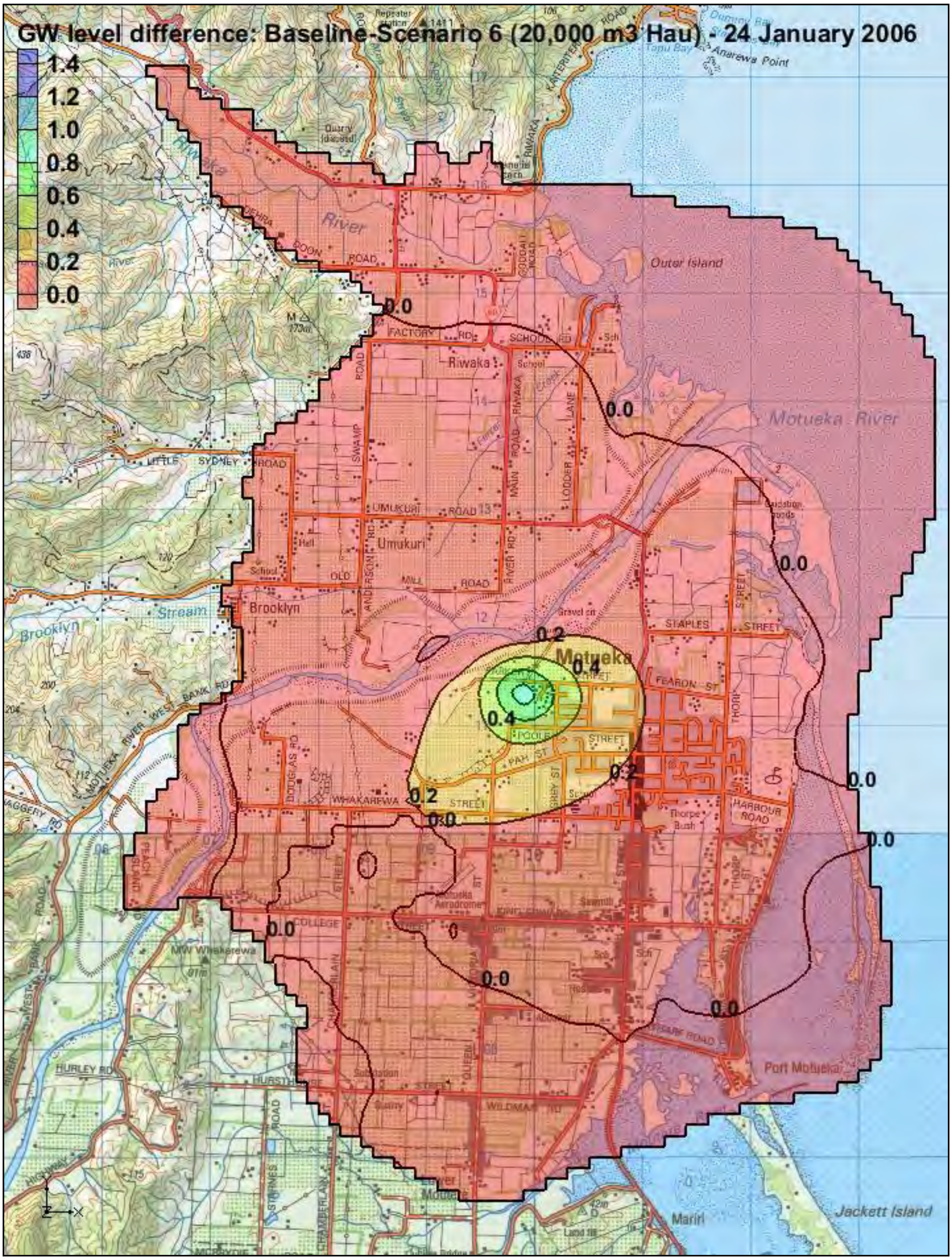
Appendix K: Maps of groundwater level changes between scenarios for 24 January 2006

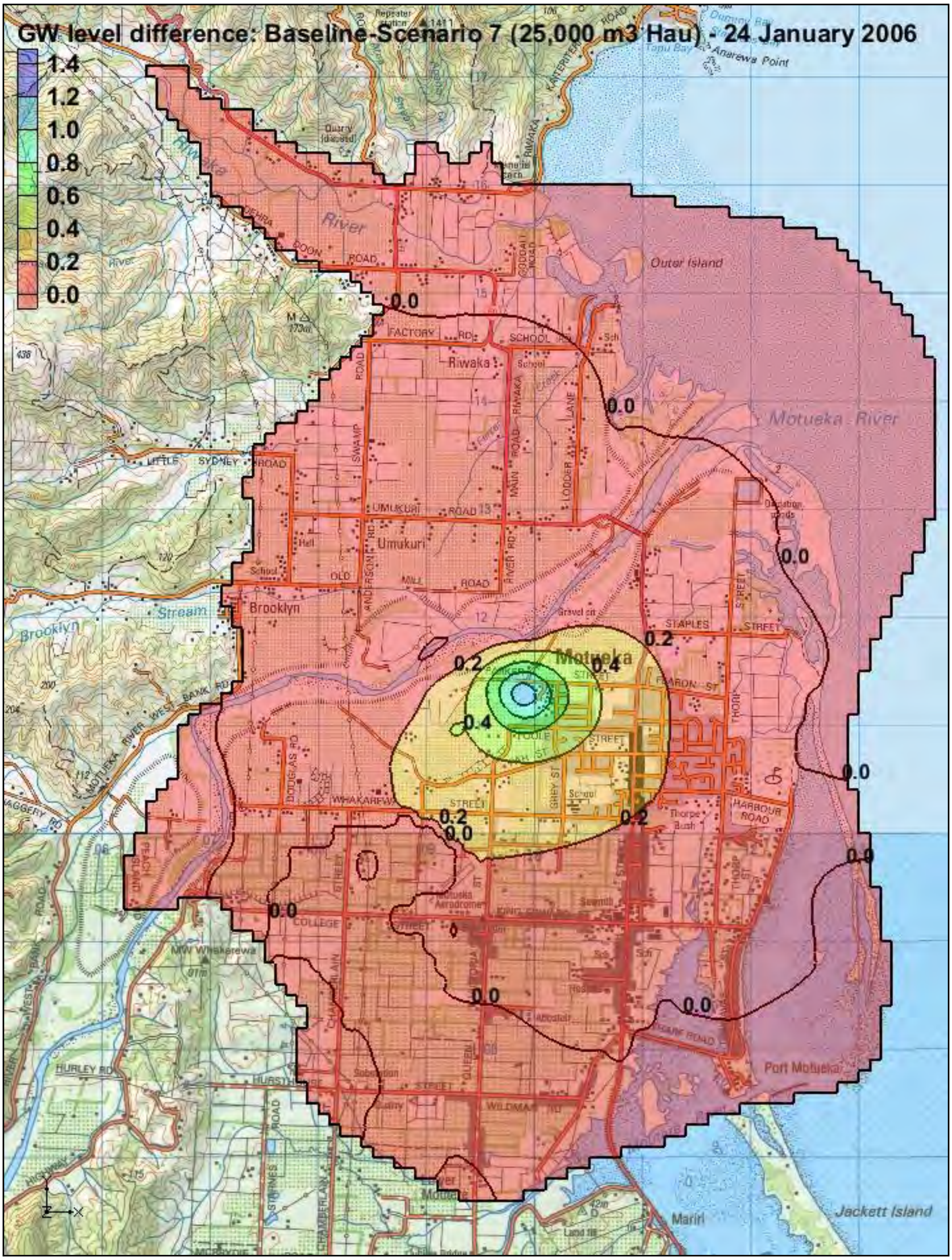


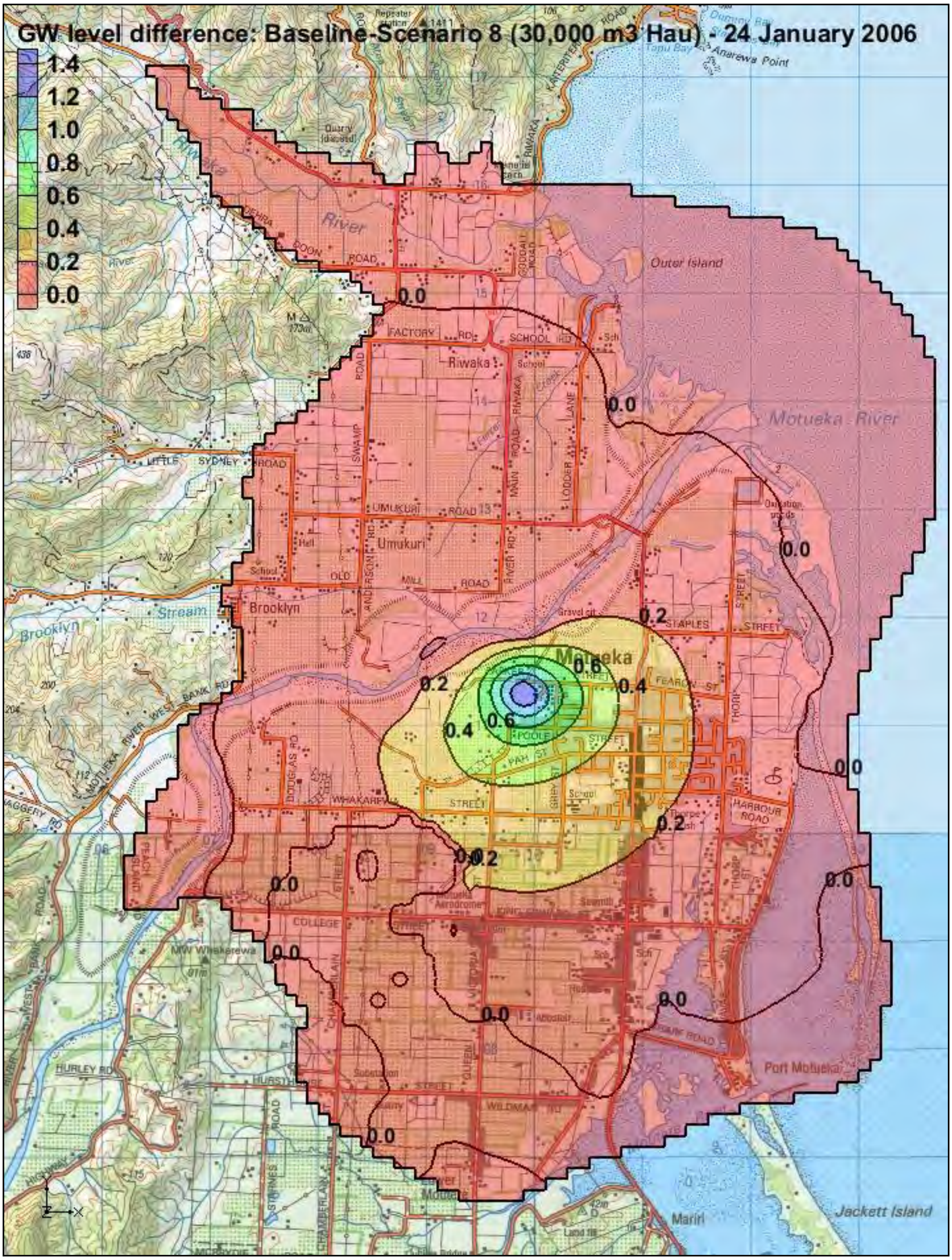

GW level difference: Baseline-Scenario 3 (20,000 m3) - 24 January 2006
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.0
0.0
0.2
0.4
0.4
0.2
0.2
0.0
0.0
0.0
0.0
0.0
0.0
0.0
Riwaka
Umukuri
Brooklyn
Motueka
Motueka River
Outer Island
Port Motueka
Jackett Island
Mariri
Andrews Point
Riwaka River
Brooklyn Stream

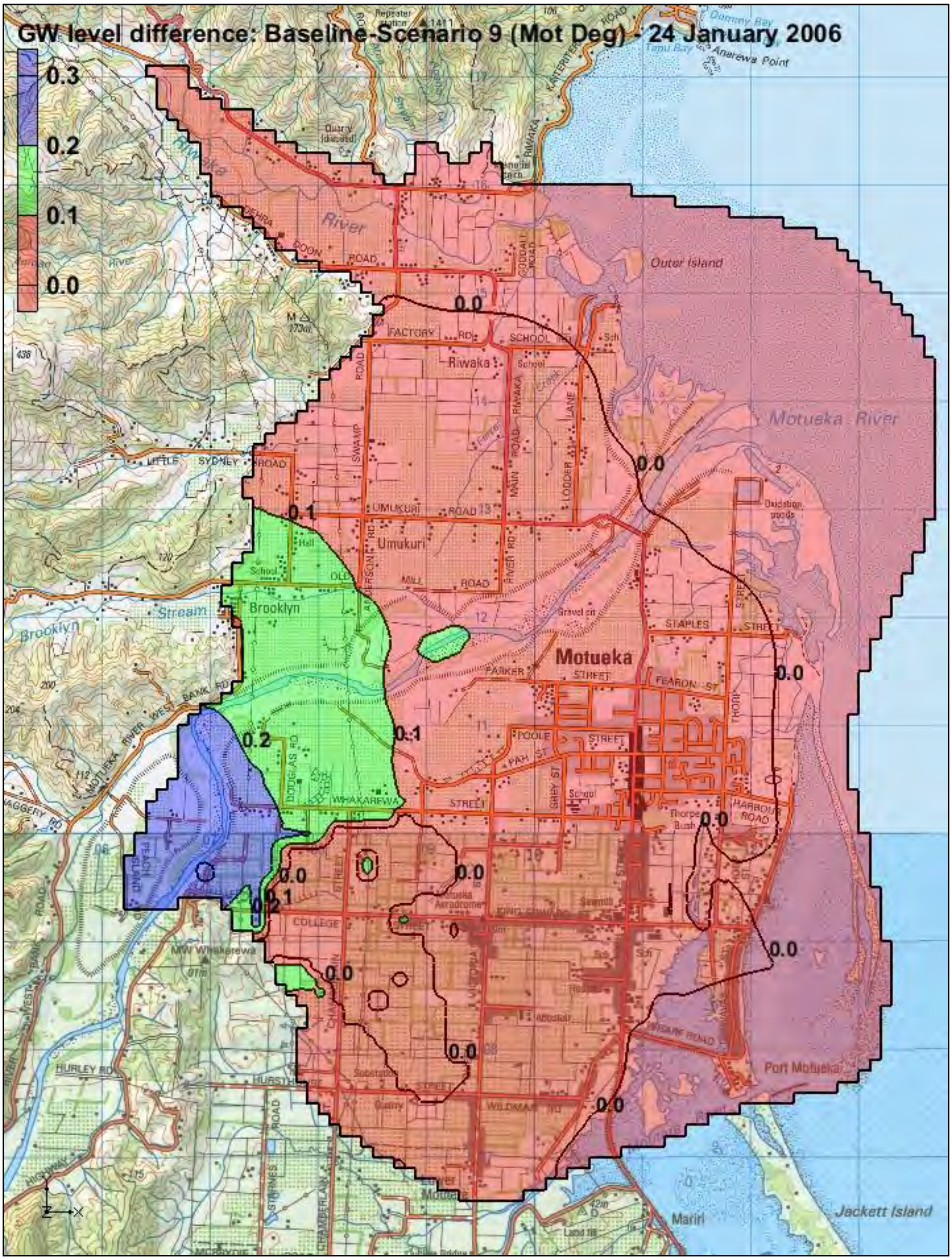

GW level difference: Baseline-Scenario 4 (25,000 m3) - 24 January 2006
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Riwaka River
Outer Island
Motueka River
Riwaka
Umukuri
Brooklyn
Brooklyn Stream
Motueka
Port Motueka
Jackett Island
Mariri
0.0
0.2
0.4

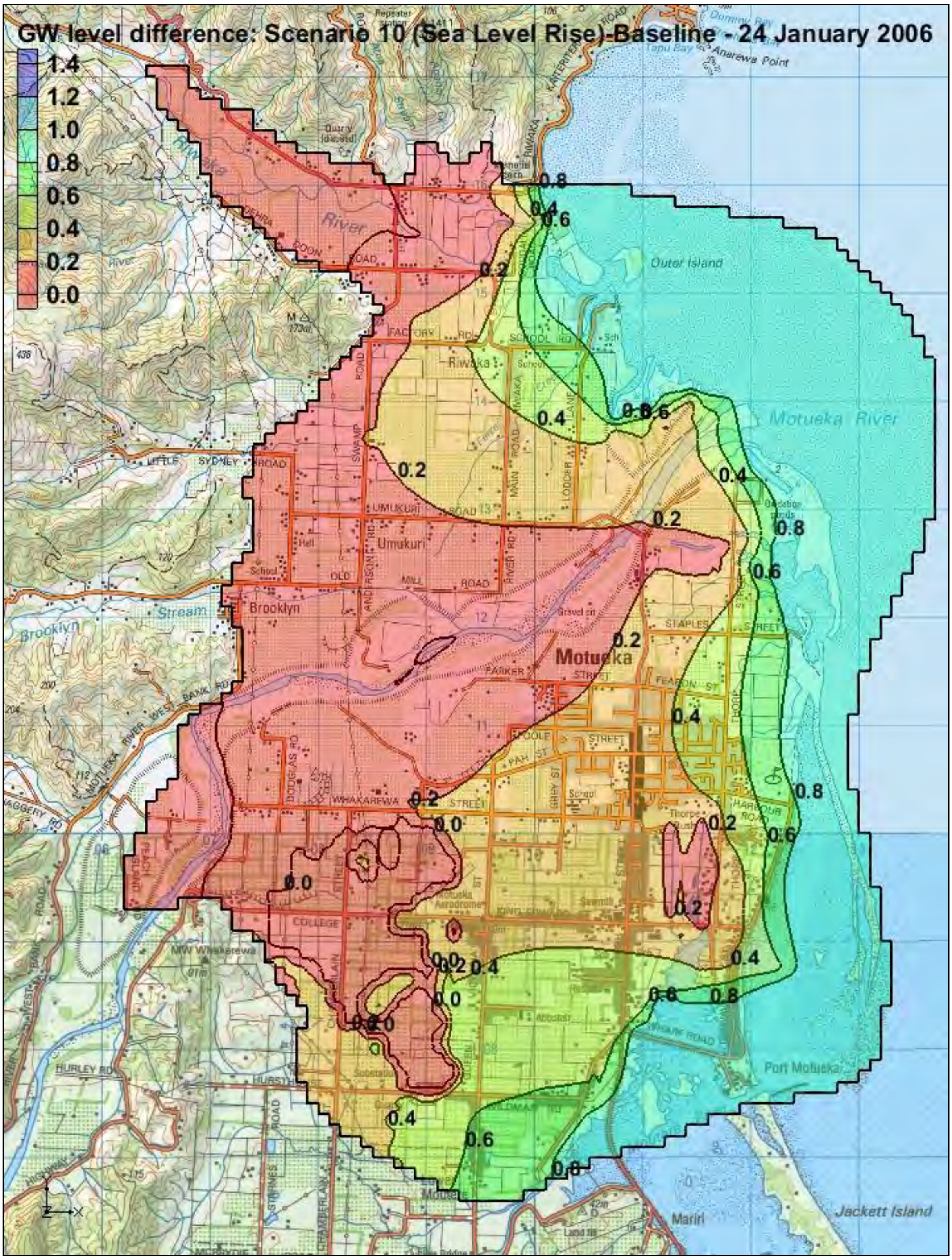

GW level difference: Baseline-Scenario 5 (30,000 m3) - 24 January 2006
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Riwaka
Umukuri
Brooklyn
Motueka
Outer Island
Motueka River
Port Motueka
Jackett Island
Mariri
0.0
0.2
0.4
0.6

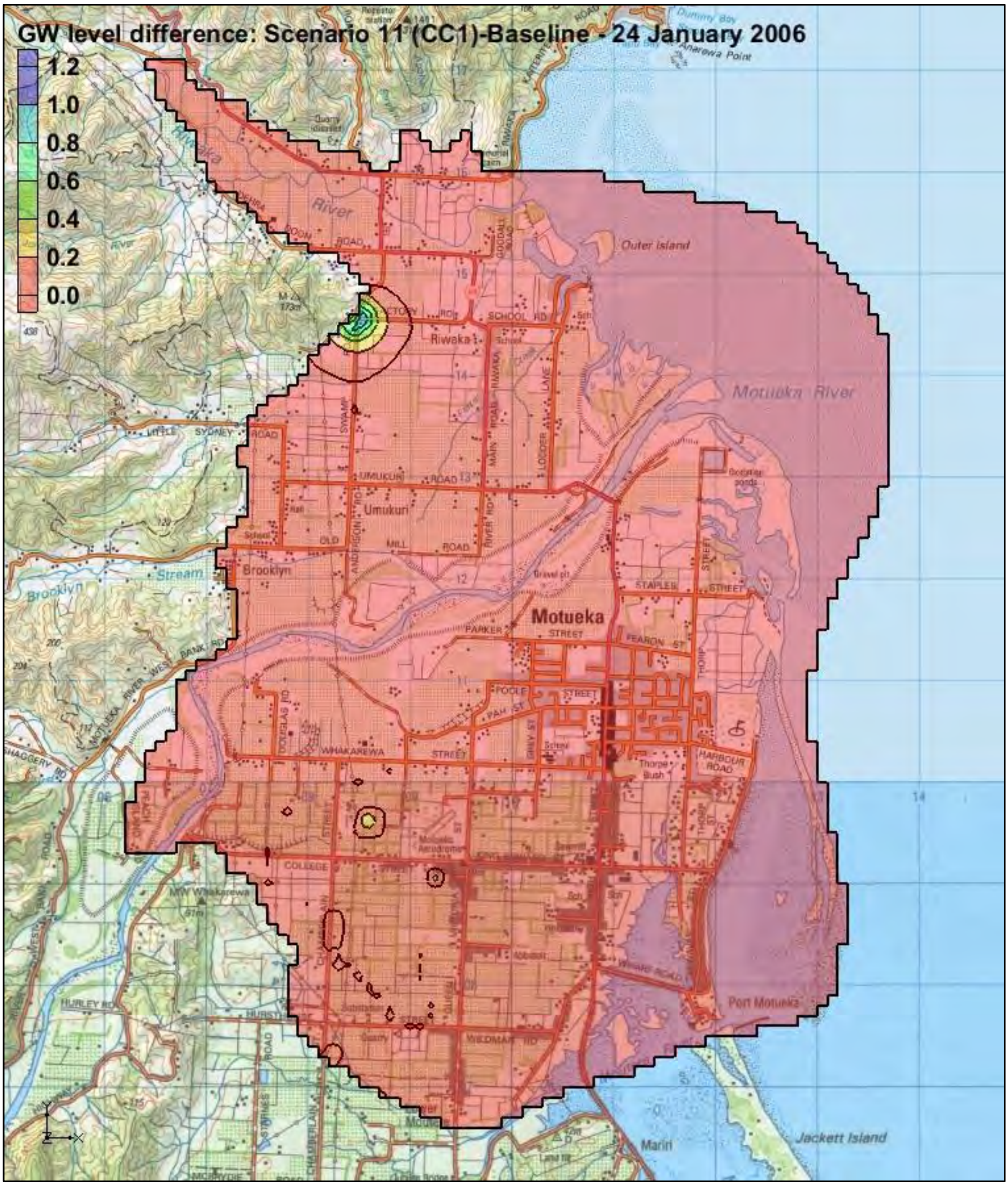

GW level difference: Baseline-Scenario 6 (20,000 m3 Hau) - 24 January 2006

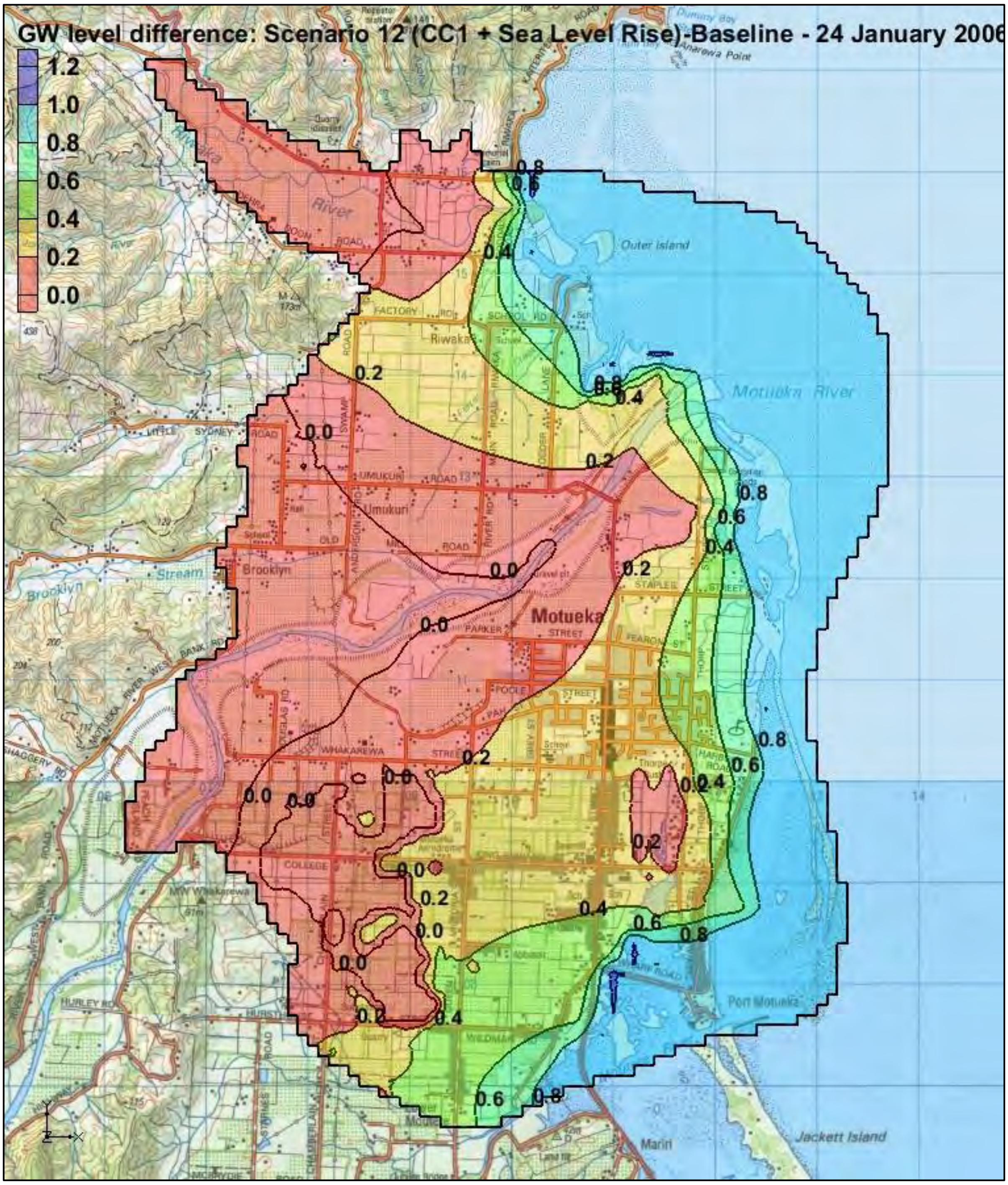

GW level difference: Baseline-Scenario 7 (25,000 m3 Hau) - 24 January 2006
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
Motueka
Riwaka
Umukuri
Brooklyn
Motueka River
Riwaka River
Brooklyn Stream
Outer Island
Port Motueka
Jackett Island
Mariri
Tapu Bay
Anarewa Point
Thorpe Bush


GW level difference: Baseline-Scenario 8 (30,000 m3 Hau) - 24 January 2006
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Riwaka
Umukuri
Brooklyn
Motueka
Outer Island
Motueka River
Port Motueka
Jackett Island
Mariri
0.0
0.2
0.4
0.6


GW level difference: Baseline-Scenario 9 (Mot Deg) - 24 January 2006
0.3
0.2
0.1
0.0
Riwaka
Motueka
Motueka River
Outer Island
Brooklyn
Umukuri
Port Motueka
Jackett Island
Mariri
0.0
0.1
0.2


GW level difference: Scenario 10 (Sea Level Rise)-Baseline - 24 January 2006
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Riwaka
Umukuri
Brooklyn
Motueka
Outer Island
Motueka River
Port Motueka
Jackett Island
Mariri


GW level difference: Scenario 11 (CC1)-Baseline - 24 January 2006
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Riwaka
Motueka
Motueka River
Outer Island
Umukuri
Brooklyn
Port Motueka
Jackett Island
Marinl


GW level difference: Scenario 12 (CC1 + Sea Level Rise)-Baseline - 24 January 2006
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Riwaka
Umukuri
Brooklyn
Motueka
Motueka River
Outer Island
Port Motueka
Jackett Island
Anarewa Point
0.0
0.2
0.4
0.6
0.8