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Groundwater REPORT

TAKAKA VALLEY GROUNDWATER MODELLING Technical Investigations

PREPARED FOR

MBIE Wheel of Water Research

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PREPARED BY
Julian Weir
Andrew Fenemor

AQUALINC

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For more information regarding this document please contact

Julian Weir
Senior Engineer
Aqualinc Research Limited
(03) 964 6514
j.weir@aqualinc.co.nz

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Aqualinc Research Ltd
Christchurch / PO Box 20 462, Bishopdale 8543, +64 (0) 3 964 6521
Ashburton / PO Box 557, Ashburton 7740, +64 (0) 3 307 6680
Hamilton / PO Box 14 041, Enderley 3252, +64 (0) 7 858 4851
www.aqualinc.com

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EXECUTIVE SUMMARY

As part of Tasman District Council (TDC)'s process for reviewing water allocation in the Takaka catchment, the Takaka Freshwater and Limits Advisory Group (FLAG) has been formed. The purpose of this group is to enable greater community involvement and consultation, and to provide a means through which the community and other stakeholders can assist TDC to develop policy which better manages the water resource of the catchment.

In order to set allocation limits, an understanding of the causes of declines in both water quantity and quality (and subsequent ecosystem health) is needed. The MBIE *Wheel of Water* research programme (Allen *et. al.*, 2012)[1] has been used to assist the FLAG develop this understanding through the following two levels of modelling:

1. Water Wheel visualisations of trade-offs among key indicators of the values and uses identified as important by the FLAG; and

2. Modelling of the flow and water quality dynamics for selected development scenarios.

This report presents the modelling development and results, contributing to item 2, for groundwater and groundwater dependent systems. Much of the hydrological and hydrogeological basis for the groundwater modelling work has been derived from Thomas & Harvey (2013)[2] as well as personal communications with Mr Joseph Thomas (TDC). The authors would specifically like to thank Mr Thomas for his contribution to, and review of, this report.

Catchment Overview and Data Sources

The groundwater system of the Takaka catchment is complex and comprises karst systems of international significance overlain by alluvial outwash gravels. There are three main water bearing aquifers within the valley which are directly related to lithology. Thomas & Harvey (2013) describe these as:

- The Arthur Marble Aquifer (AMA);
- The Takaka Limestone Aquifer (TLA); and
- The Takaka Unconfined Gravel Aquifer (TUGA) which interacts with the Takaka River and also discharges at the coast.

Various data sources have been collated to assist this study including geology, climate (both rainfall and evapotranspiration), agricultural soil properties, land coverage, surface water and groundwater measurements (levels, flow and quality) and wells and consents databases. A soil water balance model was used to calculate land surface recharge and estimate irrigation water use and scheduling.

The total average annual flow of water through the catchment (groundwater and surface water combined) is estimated at approximately 73.3 m^3/s. Of this, approximately 59.9 m^3/s is estimated to discharge off shore via surface waterways and approximately 0.2 m^3/s (annual average[3]) is removed through groundwater abstraction (primarily for irrigation and water supplies). The remaining 13.2 m^3/s discharges off shore via groundwater (sub surface). Total recharge to the groundwater system alone equates to approximately 31.9 m^3/s (through both the valley floor and the upper catchment). Approximately 8.5 m^3/s of this recharge originates from river recharge, and the remainder from land surface recharge.

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[1] Allen, W., Fenemor, A., and Wood, D. (2012): *Effective Indicators for Freshwater Management: Attributes and frameworks for Development.* Report prepared for Aqualinc Research for the MSI Wheel of Water Project. Landcare Research, Nelson. June 2012.
[2] Thomas, J. and Harvey, M. (2013): Water Resources of the Takaka Water Management Area. Tasman District Council. July 2013.
[3] The seasonal peak demand is higher than this.

Approximately 2,275 ha of land is currently irrigated in the Takaka valley with an additional 533 ha proposed (active consent applications). Of the existing irrigated area, approximately 75% is supplied from surface water and the remainder from groundwater.

By national standards, nitrate-nitrogen concentrations at a catchment scale are low in both surface water and groundwater. There are, however, some areas where local land uses have resulted in elevated concentrations.

Modelling

Interactions between the three main aquifer systems in the Takaka valley and the surface rivers and streams are complex. Furthermore, the location and details of the karst systems are generally unknown. It is therefore difficult to model these specific systems with confidence. What is known, however, is a clear hydraulic response between groundwater inflows (river recharge and land surface recharge), pumping and groundwater outflows (spring flows and off-shore discharge). Because of this, the dynamic response in groundwater levels and spring discharge has been modelled using a series of eigenmodels, as described by Bidwell & Burbery (2011)[4].

Although eigenmodels are very simplified compared to real aquifers, they are adequate for situations for which dynamic response is the primary interest (Bidwell & Burbery, 2011). They are particularly helpful in situations where the aquifer system is not known in sufficient detail to construct a more detailed numerical model, or where this is prevented by time and budgetary constraints. Consequently, they are suitable for use in the Takaka catchment.

The eigenmodels developed do not simulate contaminant transport. Instead, simple bucket-mixing models have been used to predict changes in water quality from different land use scenarios.

Multiple eigen models have been developed, one for each key observation site in the catchment, as listed in the following table.

Aquifer system	Groundwater level site	River flow site
AMA	Ball	Main Spring
	Bennett	Fish Creek
	Hamama	Spring River
	Main Spring	
	Savage	
	Sowman	
TLA	Cserney	Motupipi River
	Grove Orchard	
	Motupipi Substation	
TUGA	Fire Station (combined)	Paynes Ford
	Jefferson	
	TDC Offices	

Each model was constructed to run from 1 January 1980 through to 31 December 2014 (a total of 34 years). Calibration focussed on the period of measured data, which differed from site to site. Generally, there is little monitoring data with which to calibrate prior to approximately 1990. As a result, the reliability of calibration to this earlier period is not known and key outputs have been reported only for the period 1990-2014 (inclusive). Calibration particularly focussed on dry periods (low groundwater levels and flows).

[4] Bidwell, V. and Burbery, L. (2011): *Groundwater Data Analysis – Quantifying Aquifer Dynamics.* Prepared for Envirolink Project 420-NRLC50. Report no. 4110/1. June 2011.

Development Scenarios and Results

Once models had been calibrated, they were used to predict the response in the groundwater system from various development scenarios, as follows:

- *Scenario 1:* No consumptive use – this represents the state of the groundwater system unaffected by irrigation, other consumptive abstraction (e.g. water supplies) and subsequent use.
- *Scenario 2:* Double irrigation – this scenario represents the approximate state of the groundwater system should the existing irrigated area be doubled.
- *Scenario 3:* All existing irrigation groundwater sourced – this scenario explores the effects on the groundwater system from groundwater abstraction by assuming all existing irrigation is sourced only from groundwater.
- Scenario 4: Cobb Dam effects – this scenario represents an estimate of the state of the groundwater system if the Cobb Dam did not exist.
- Scenario 5: Waingaro River – to assess the sensitivity of the groundwater system to Waingaro River losses, all groundwater recharge from the river is removed.
- Scenario 6: No development – this scenario approximates that state of the environment, without any alteration by human activity, by removing the Cobb Dam (as per Scenario 4) and assuming all existing pasture or native grassland is instead covered in forest.
- Scenario 7: Likely irrigation 1 – this scenario is based on the calibrated model with additional irrigation in areas that are most likely to be developed in the near future, as determined by Joseph Thomas (TDC).
- Scenario 8: Likely irrigation 2 – based on the '*Likely Irrigation 1'* scenario, this scenario adds an additional 90 l/s (180 ha) of allocation taken in the upper catchment, as assessed by Joseph Thomas.
- Scenario 9: Likely irrigation 3 – Based on the '*Likely Irrigation 1'* scenario, this scenario adds an additional 150 l/s (300 ha) of allocation taken in the upper catchment, as assessed by Joseph Thomas.

A brief summary of results from these scenarios follows.

Effects of Irrigation

Groundwater abstraction for irrigation typically results in a lowering of groundwater levels. In addition, irrigation results in an increase in land surface recharge into the uppermost aquifer. If the irrigation water source is surface water (rather than groundwater), then this provides additional land surface recharge without a reduction in groundwater levels from pumping. Consequently, surface-water sourced irrigation can result in shallow groundwater levels that are higher compared to a no-irrigation scenario.

Shallow groundwater levels in the TUGA system are predicted to be lower with increased groundwater abstraction. However, when the additional irrigation is sourced from surface water, shallow groundwater levels are predicted to be higher. The shallow TUGA system directly receives the additional land surface recharge from irrigation.

The deeper AMA and TLA systems do not show this recharge effect as they are more disconnected from the surface recharge compared to the TUGA system. Specifically, the coastal TLA system is confined below the TUGA system and therefore does not receive the full benefits of direct additional recharge. As such, groundwater levels are lower with additional irrigation due to the increased abstraction.

The Likely Irrigated scenarios (scenarios 7-9) all present lesser effects than the double irrigation scenario with groundwater levels and river flows not too different from Status Quo.

Effects of the Cobb Dam

The Cobb Dam has the overall effect of raising groundwater levels, increasing low flows and reducing the number of zero-flow days. This is achieved by augmenting river flows, particular during low-flow periods, by water that has been harvested during higher flow periods (and would otherwise discharge into the sea at that time).

Effects of Groundwater Recharge from the Waingaro River

Groundwater recharge from the Waingaro River has an overall positive benefit on groundwater levels in the lower catchment and subsequent river flows.

Effects of Human Activity

Human activity has the net effect of increasing land surface recharge into the groundwater system (less water is consumed by grass compared to forest). This, combined with no regulating effects of the Cobb Dam, results in lower groundwater levels and lower river and spring flows under the No Development scenario compared to status quo.

Effects on Water Quality

Overall, land use intensification is likely to increase nitrate-nitrogen concentrations in the receiving environment, both groundwater and surface water. Doubling the irrigated area is predicted to result in a relatively small change in groundwater concentrations, but the change is more pronounced in surface waterways. The three likely irrigated area scenarios are predicted to result in very little change in predicted concentrations.

Various additional irrigation scenarios, and the effects at various monitoring sites, were modelled. Considering the impacts of additional irrigated dairying on Te Waikoropupū springs (for example), modelled nitrate-nitrogen concentrations may increase from a current concentration of approximately 0.42 g/m^3 up to approximately 0.54 g/m^3 if the full valley floor was irrigated.

1 INTRODUCTION AND BACKGROUND

Tasman District Council (TDC) are in the process of reviewing water allocation for the Takaka catchment (Figure 1). As part of this process, the Takaka Freshwater and Limits Advisory Group (FLAG) has been formed to enable greater community involvement and consultation, and to provide a means through which the community and other stakeholders can assist TDC to develop policy which better manages the water resource of the catchment.

In order to set allocation limits, an understanding of the causes of declines in both water quantity and quality (and subsequent ecosystem health) is needed. Landcare Research (Andrew Fenemor) and Aqualinc Research Ltd (Aqualinc) (Julian Weir and John Bright) are assisting the FLAG to develop this understanding through the MBIE *Wheel of Water* research programme (Allen *et. al.*, 2012). Additional assistance and local expert knowledge is provided by Joseph Thomas (TDC).

To develop this qualitative understanding of cause and effect, two levels of modelling have been considered:

1. Water Wheel visualisations of trade-offs among key indicators of the values and uses identified as important by the FLAG; and

2. Modelling of flow and water quality dynamics for selected development scenarios.

This report presents the modelling development and results, contributing to item 2, for groundwater and groundwater dependent systems. The report is structured as follows:

- Hydrological and hydrogeological summary;
- Data collection and analyses;
- Modelling concepts;
- Nitrate-nitrogen budgets; and
- Development scenarios.

1.1 Acknowledgements

The authors would specifically like to thank Joseph Thomas (Tasman District Council) for his contribution to, and review of, this report.

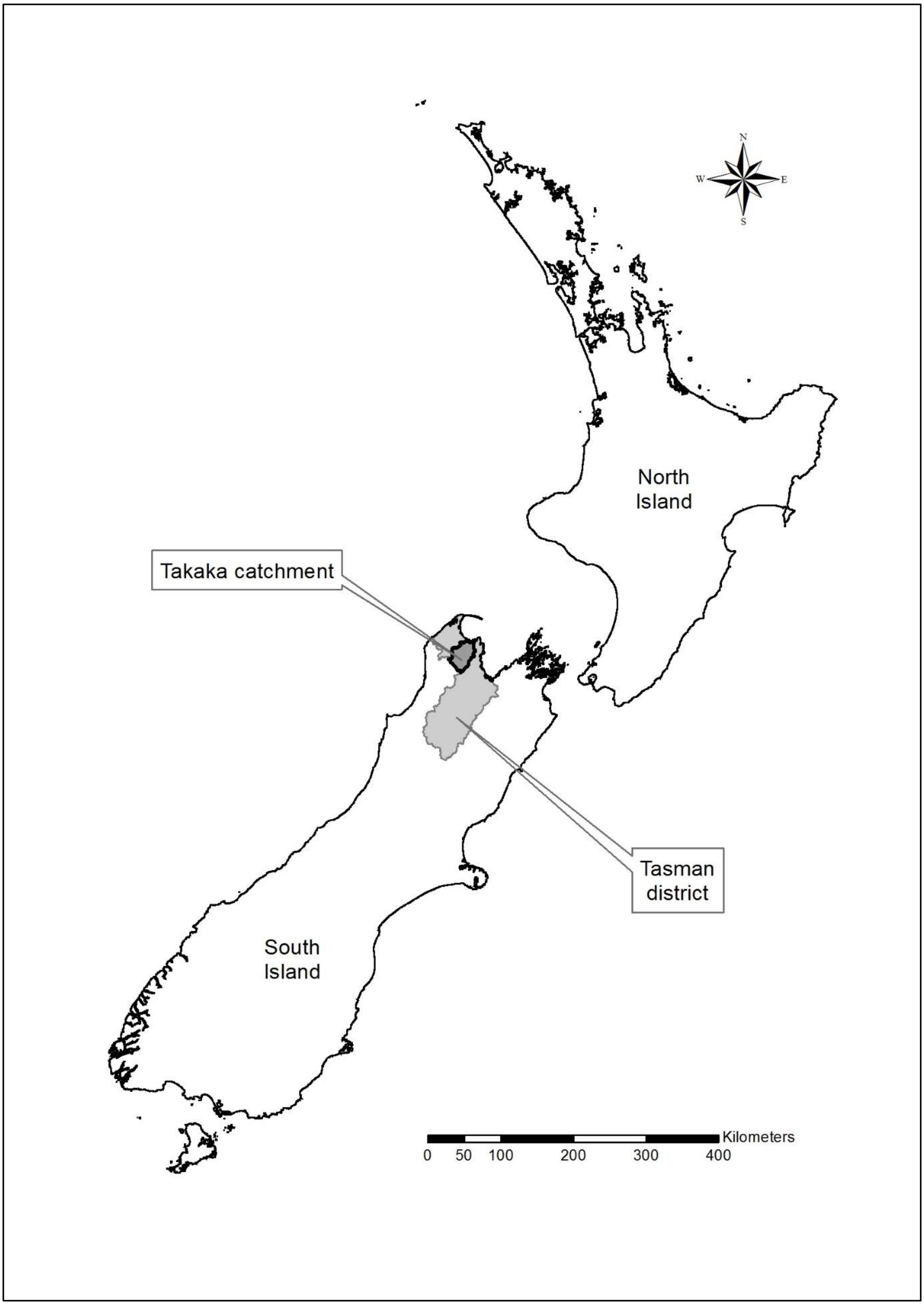

Figure 1: Location of the Tasman District and the Takaka catchment

2 HYDROLOGICAL AND HYDROGEOLOGICAL SUMMARY

Much of the hydrological and hydrogeological basis for the groundwater modelling work has been derived from Thomas & Harvey (2013) as well as personal communications with Mr Joseph Thomas (TDC). As discussed by Thomas & Harvey, TDC's water management zones (reproduced in Figure 2) encompass an area of approximately 1,012 km^2. This consists of the larger Takaka catchment (approximately 940 km^2) and the smaller Takaka North catchments (approximately 72 km^2). The Takaka North catchments are dominantly surface water systems and therefore have been excluded from this groundwater study. The remaining Takaka catchment is the focus of this study and is shown in Figure 2.

The groundwater system of the Takaka catchment is complex and comprises karst systems of international significance overlain by alluvial outwash gravels. There are three main water bearing aquifers within the valley which are directly related to lithology. Thomas & Harvey (2013) describe these as:

- The Arthur Marble Aquifer (AMA);
- The Takaka Limestone Aquifer (TLA); and
- The Takaka Unconfined Gravel Aquifer (TUGA) which interacts with the Takaka River and also discharges at the coast.

The AMA is a deeper marble-based karst system and is the principal karstic system in the Takaka valley (Thomas & Harvey, 2013). The system is found underneath the valley floor and extends from Upper Takaka through to the coast and beyond. The AMA is unconfined from Upper Takaka to approximately Hamama. Below Hamama, the AMA becomes confined by relatively impervious Motupipi coal measures that overlay the AMA. Recharge to the AMA occurs via direct infiltration on exposed marble outcrops in the upper catchment and also from infiltration of Takaka River water and land surface recharge (excess rainfall and irrigation) through the overlying TUGA. The system discharges primarily to Te Waikoropupū Springs and subsurface off shore.

The TLA occurs between East Takaka and Tarakohe and is formed from karstic Takaka limestone. The formation is folded into a series of low amplitude synclines and anticlines (Thomas & Harvey, 2013) and has a relatively impermeable lower boundary. Recharge to the TLA occurs primarily via direct infiltration on the exposed limestone outcrops along the eastern boundary and also from the southern end via Takaka River flow seeping into the TUGA and then into the limestone. The system discharges primarily to the Motupipi River and subsurface off shore. Fenemor *et al.* (2008) present a conceptual water balance for the Motupipi catchment. They calculate that approximately 30% of the nitrogen losses from the Motupipi catchment enter the TLA and that 18 tonnes/year discharge from the TLA annually.

The TUGA comprises recent river gravels and sand deposits which cover most of the Takaka valley from Upper Takaka to the sea. Recharge is primarily derived from the Takaka River and from land surface recharge (excess rainfall and irrigation). The TUGA interacts with the Takaka River and also discharges to the Motupipi River, Spring River and off shore at the coast.

The horizontal spatial extent of the three aquifer systems is shown in Figure 3.

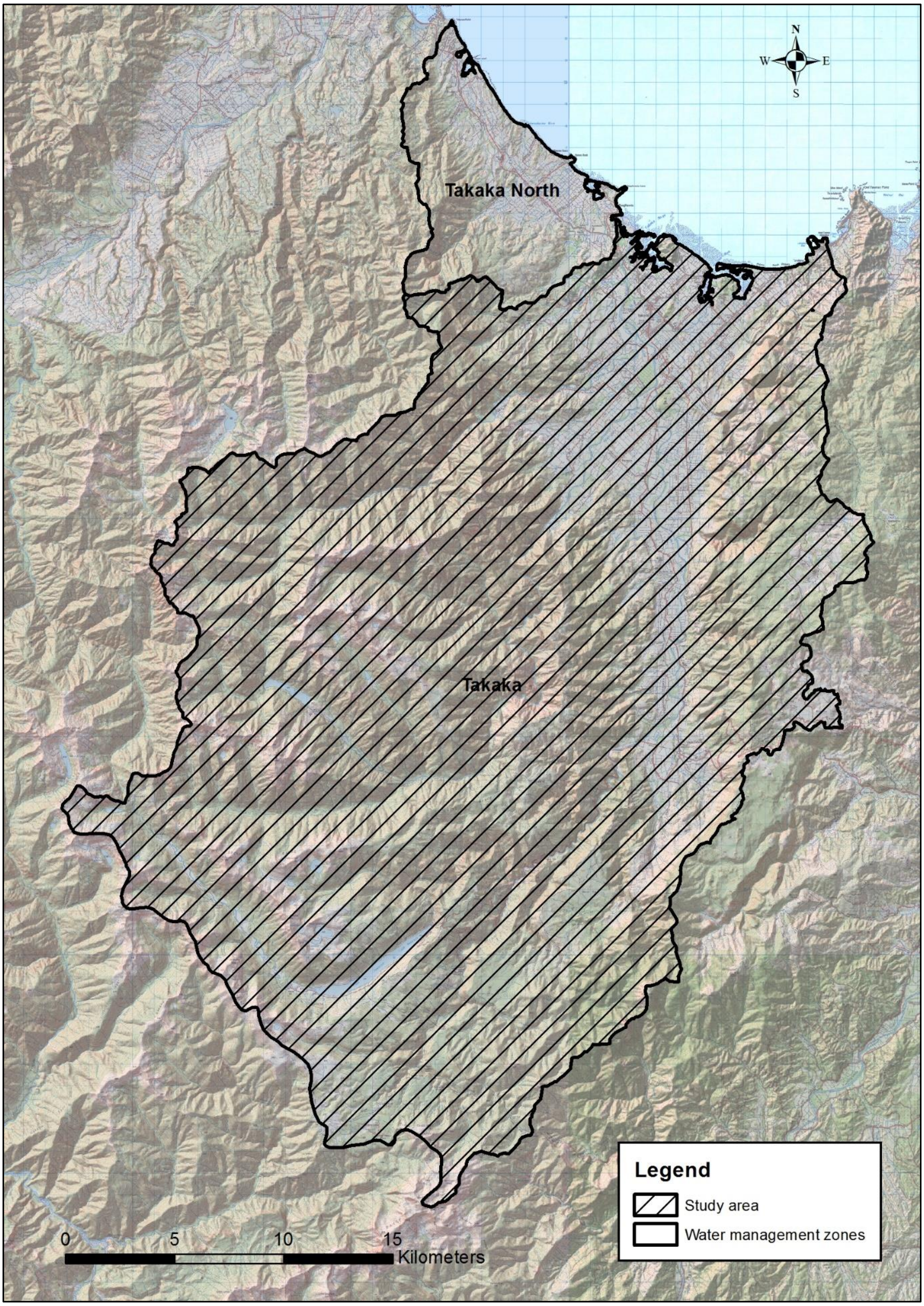

Figure 2: Takaka water management areas
(reproduced from Thomas & Harvey, 2013)

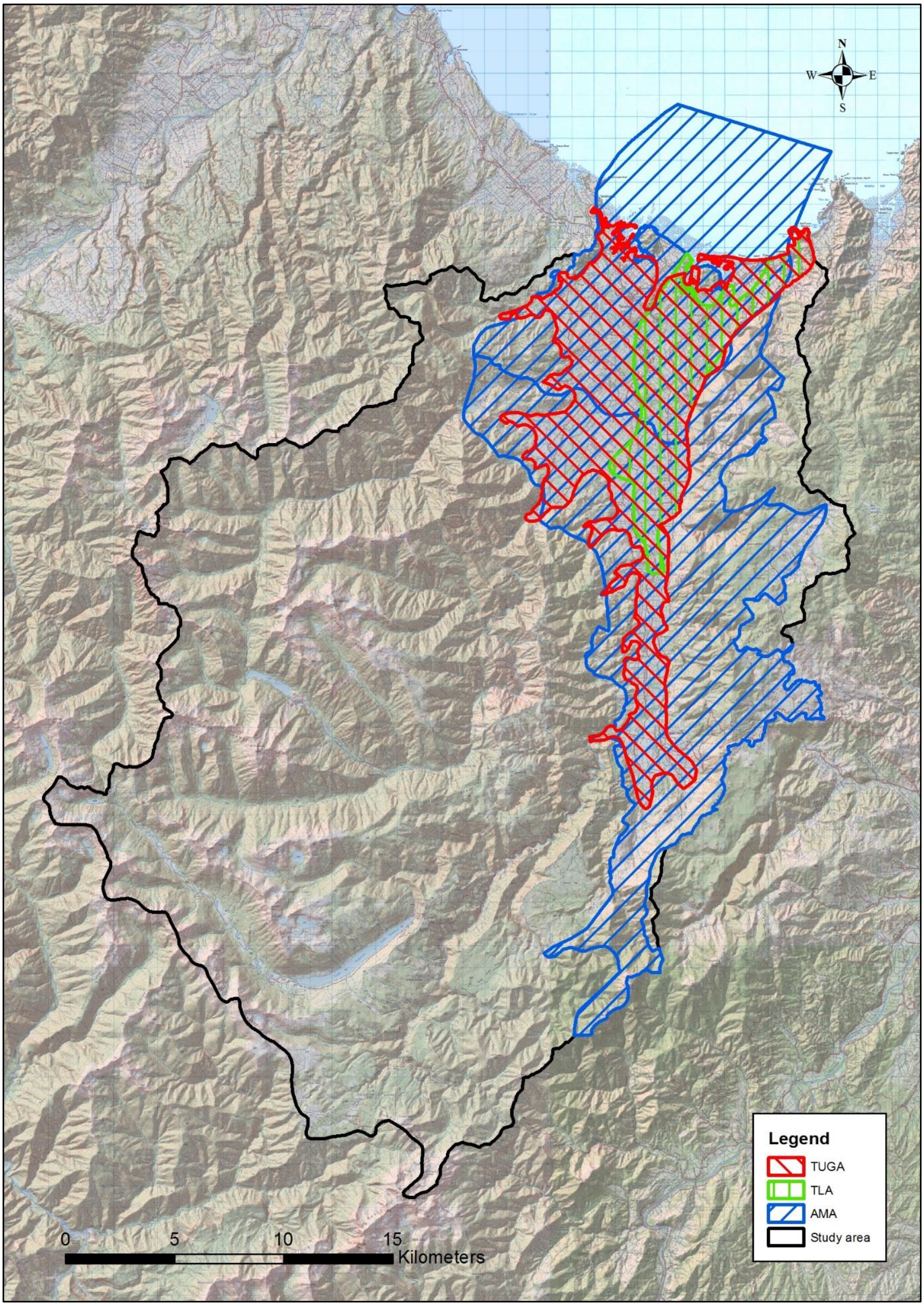

Figure 3: Spatial extent of the three aquifer systems
(reproduced from Thomas & Harvey, 2013)

3 DATA COLLECTION AND ANALYSES

Data for modelling the Takaka valley groundwater system has been collated from various sources, with Tasman District Council being the primary supplier of groundwater and surface water data. Data used for the investigation includes:

- Geological data;
- Climate data;
- Agricultural soil characteristics;
- Land cover;
- Soil water balances, quick flow separation and net land surface recharge;
- Surface water monitoring;
- River recharge;
- Existing consents and irrigated areas; and
- Groundwater level monitoring.

Brief overviews of these data sources, and the transformations applied, are presented in the following sections.

3.1 Geological Data

The study area comprises rocks of varied and complex geology (Thomas & Harvey, 2013). A simplified representation of this geology is presented in Figure 4 which describes where the individual aquifers outcrop to the ground surface. Infiltration into these areas will recharge the respective aquifers. For other areas (the unshaded areas in Figure 4), it has been assumed that any rainfall (less evapotranspiration) will run off to surface water.

A more detailed description of the catchment geology is presented in Thomas & Harvey (2013).

3.2 Climate Data

Daily time series of rainfall and potential evapotranspiration (PET) have been supplied by TDC and NIWA. In addition, a shapefile of rainfall isohyets (mean annual rainfall) has been provided by TDC (Martin Doyle, *pers. comm.*). This is shown in Figure 5.

The rainfall isohyets have been used to divide the catchment into zones of average annual rainfall against which the nearest rainfall station has been assigned to represent the time-varying (daily) rainfall. Data gaps have been filled with correlations to neighbouring rainfall sites.

PET data is more sparse, but it is not spatially highly variable. Consequently, a single time series of PET (near Kotinga) has been used to represent the entire catchment. Gaps in this data series have been filled via correlations with PET measured at Riwaka.

Time series of rainfall and PET at key stations have been collated for the period 1 January 1980 through 31 December 2014. A start date of 1 January 1980 was chosen as this is approximately the earliest data provided for the Takaka valley.

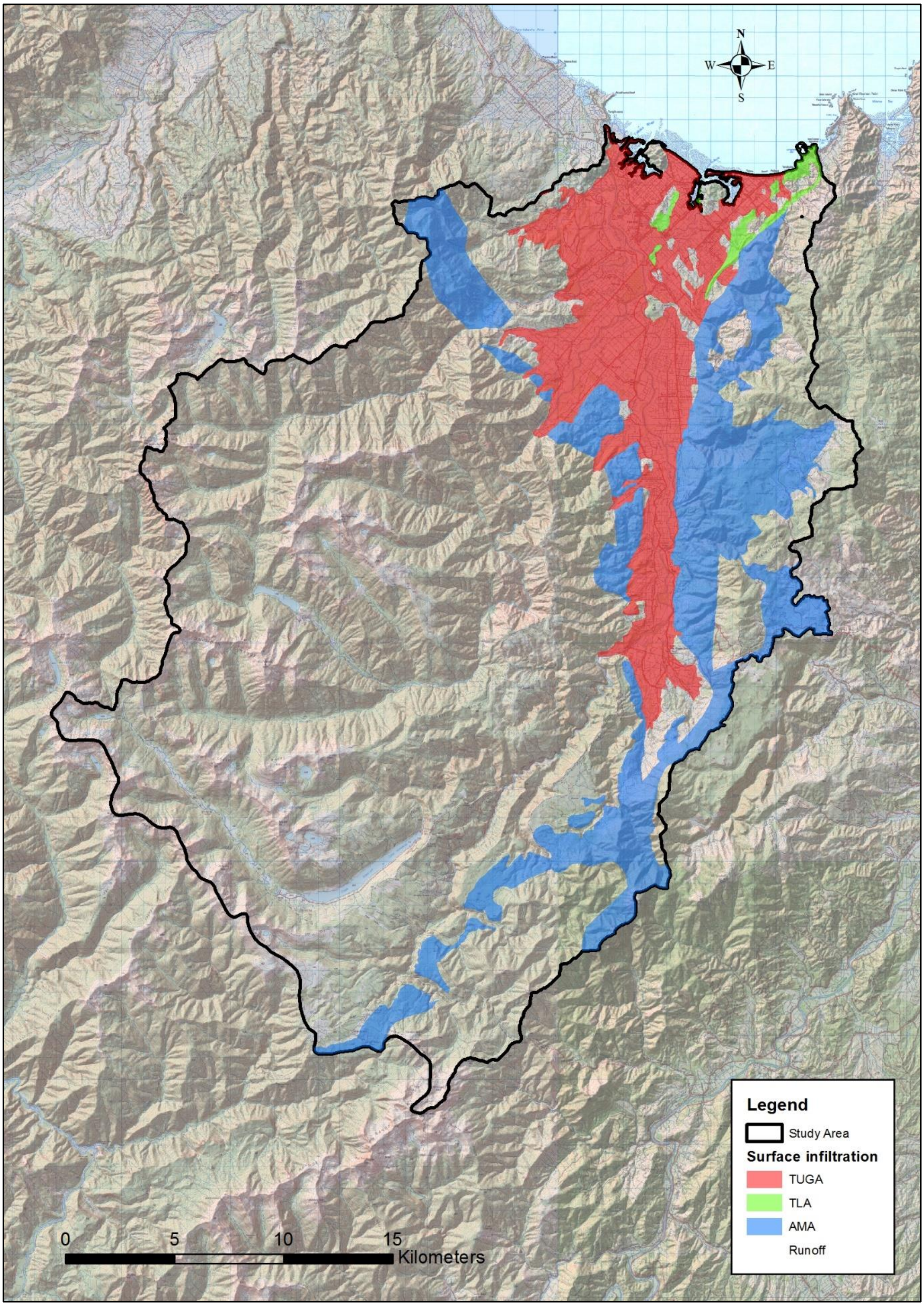

Figure 4: Simplified geology

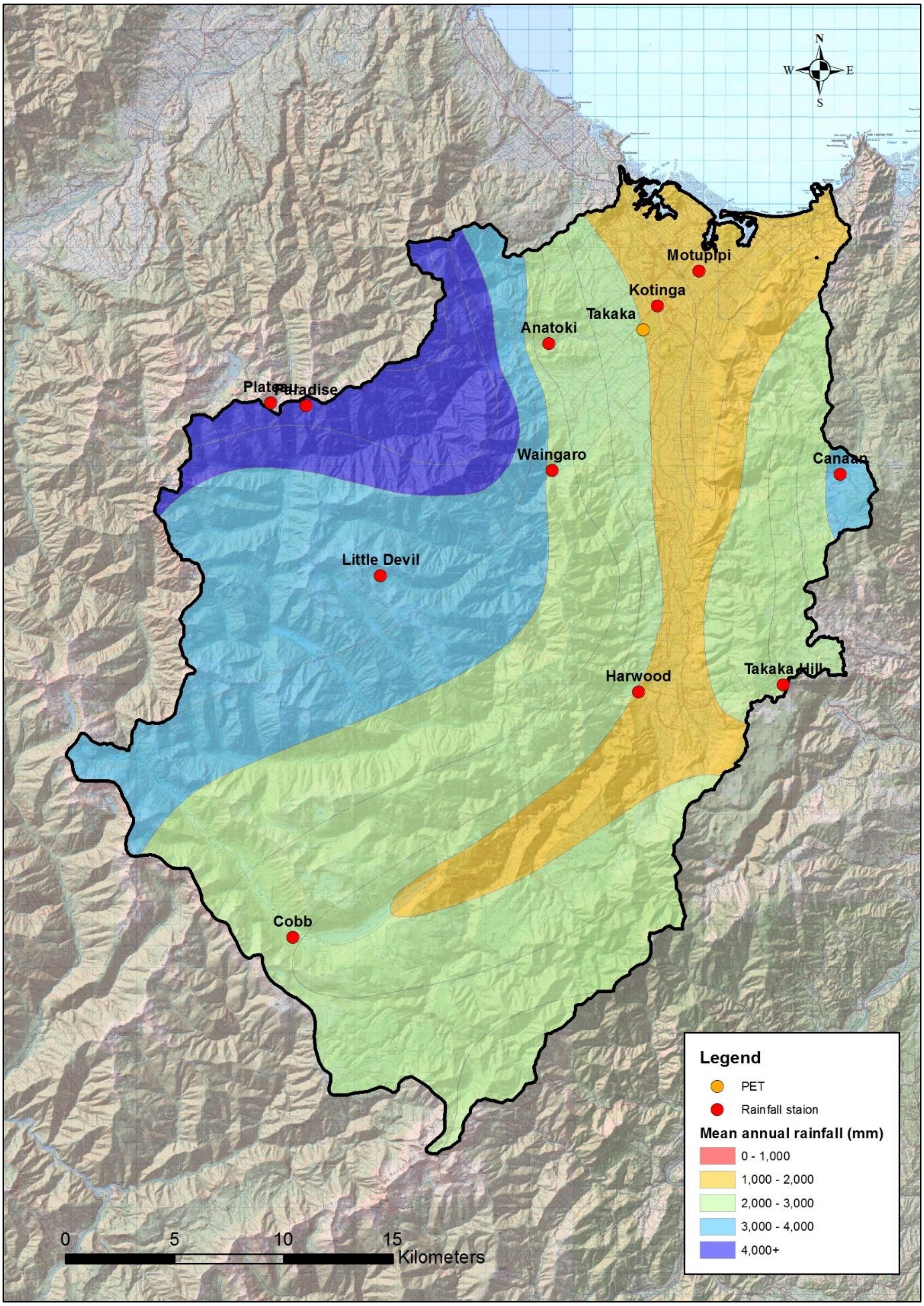

Figure 5: Rainfall and PET station locations and rainfall isohyets

3.3 Agricultural Soil Characteristics

Soils information for pasture was obtained from Landcare's S-map and Fundamental Soils Layer (FLS) coverages. These datasets were adjusted for typical rooting depths of 600 mm for pasture, 1 m for inland hill forestry and 2 m for forestry nearer the valley floor. Soils were aggregated into four plant available water (PAW) classes, as shown in Table 1.

Table 1: Soil classes

PAW class for 600 mm rooting depth (mm)	Assigned PAW for 600 mm rooting depth (mm) [1]
< 40	40
40-100	80
100-160	120
> 160	140 [2]

[1] Plants with rooting depths greater than 600 mm (e.g. forest) have access to a greater PAW depth than listed here.

[2] PAW was capped at 140 mm (for 600 mm rooting depth) due to the uncertain nature of estimating PAW for these deeper soils. This makes little difference to the calculated drainage through these soils.

The spatial distribution of soil PAW for pasture (600 mm rooting depth) is shown in Figure 6.

3.4 Land Cover

Land cover for the study area has been derived from Terralink's Land cover Database (Version 4). A simplified summary of this is provided in Table 2 and Figure 7. Land cover is dominated by grass and forest.

Table 2: Simplified existing land cover

Land cover	Area (ha)	Proportion of study area
Forest	67,400	72%
Grass	24,600	26%
Gravel or rock	1,100	1%
Water	740	0.8%
Town	170	0.2%
Total	**94,010**	**100%**

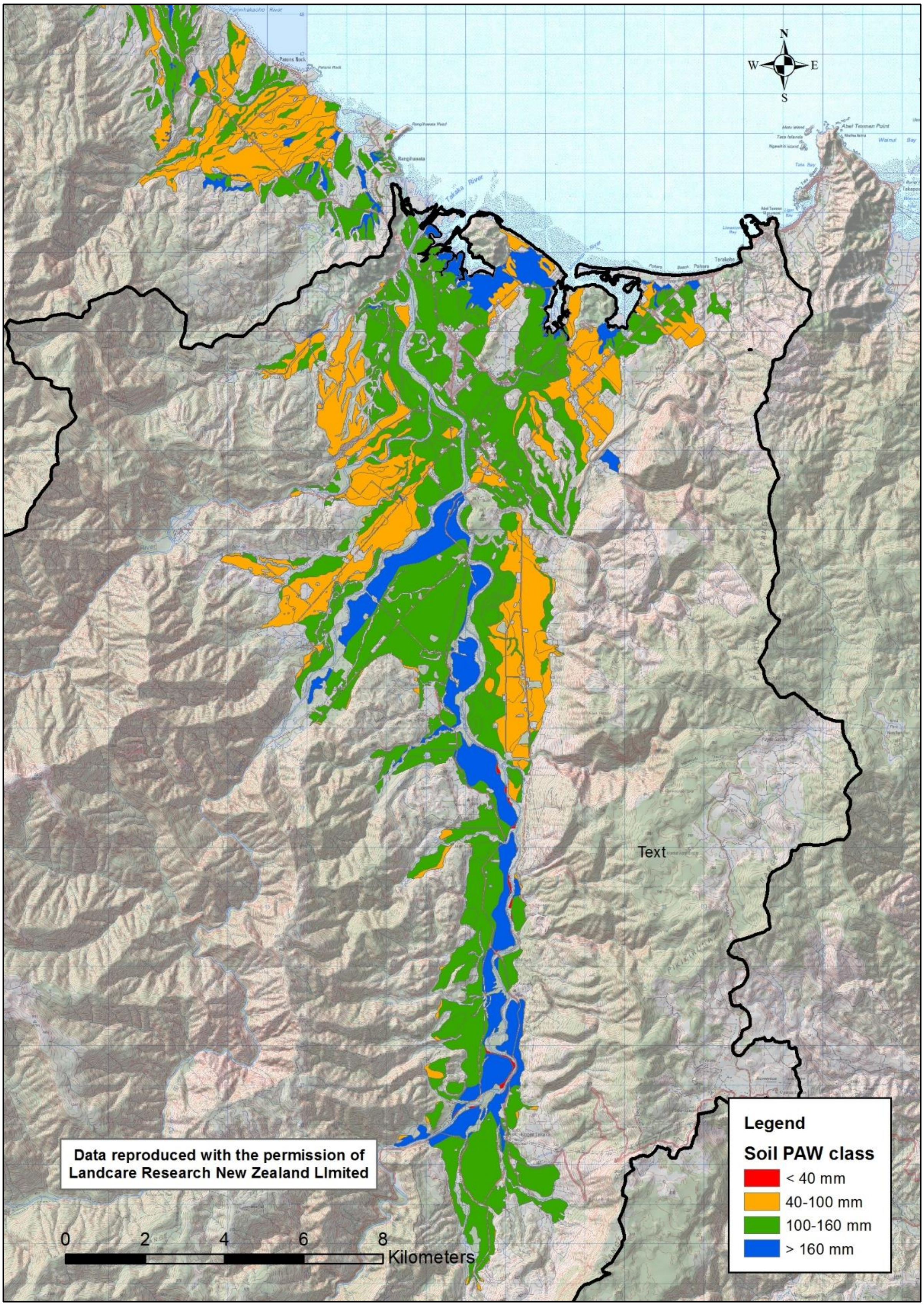

Figure 6: Soil plant available water classes for 600 mm rooting depth

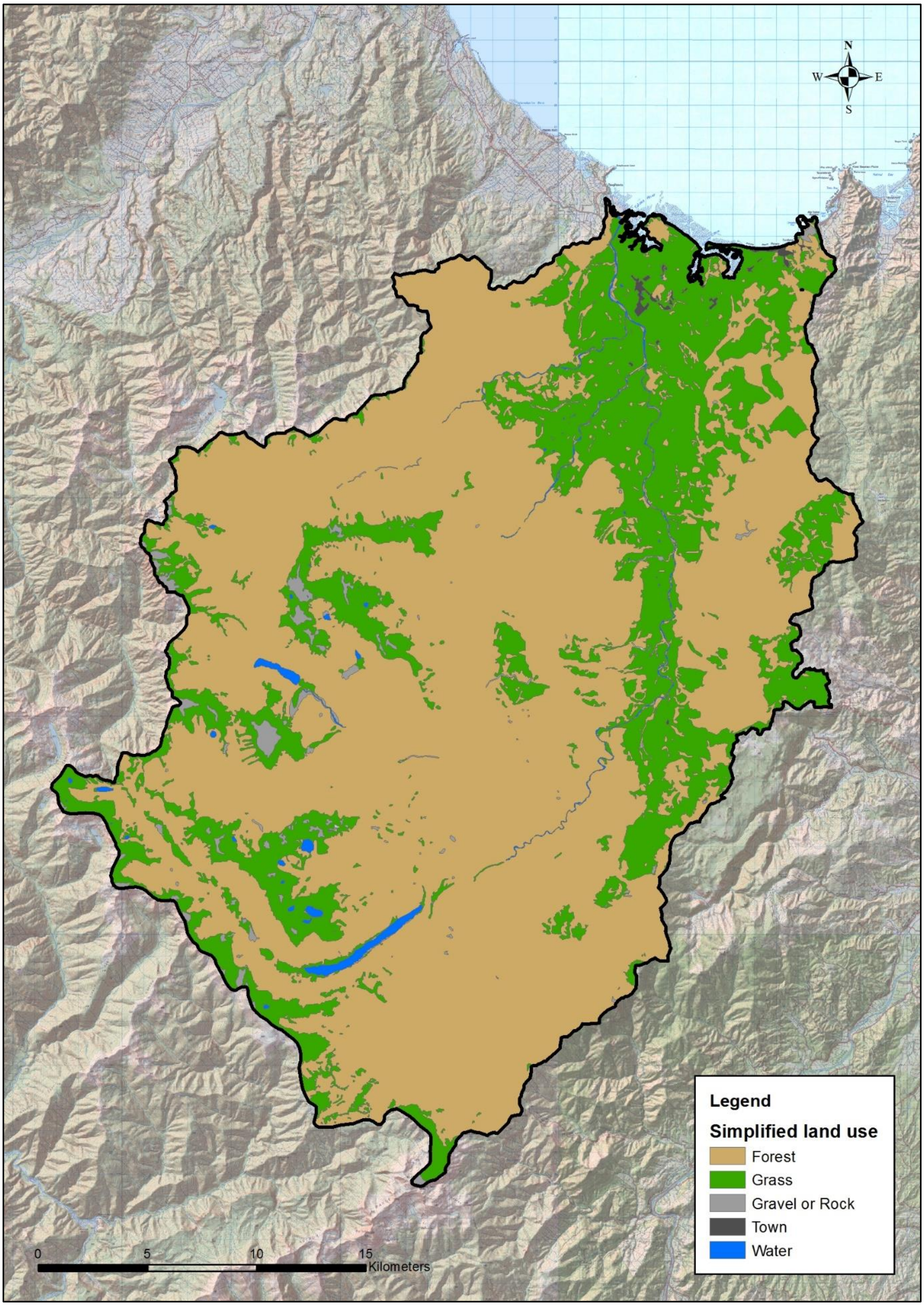

Figure 7: Land cover

3.5 Soil Water Balances, Quick Flow Separation and Net 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 accounting for differing crops, agricultural soil types, representative daily climatic conditions and irrigation strategies. The basis of the model is a daily soil moisture balance with an optional irrigation scheduling component.

For the purposes of the Takaka valley groundwater study, the soil water balance model was used to calculate groundwater recharge and irrigation water requirements. Data inputs were:

- Reference evapotranspiration (ET);
- Rainfall;
- Land cover; and
- Soil plant available water (which is a function of soil properties and rooting depth).

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

$$\text{Actual ET} = k_s \times k_c \times \text{reference ET} \tag{1}$$

Where: k_s = the water stress reduction factor; and

k_c = the evapotranspiration crop coefficient.

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

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

Where: ASM = plant available soil moisture.

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

Modelling assumes that soils were free draining, and the depth to groundwater was greater than plant rooting depths. Model simulations were run from 1 January 1980 to 31 December 2014, a total of 34 years.

3.5.1 Quick Flow Separation

IRRICALC makes the assumption that all water falling onto the land surface is either evapotranspired by plants, is stored in the soil, or drains into the underlying subsurface. For the Takaka area, some of the drainage would move laterally to nearby streams, either as direct land surface run-off or near-surface lateral flow (via preferential flow paths and other shallow discharge mechanisms). The remainder would drain to deeper recharge of the regional groundwater system. The net land surface recharge to the regional groundwater system is therefore the total land surface recharge less the contribution to river flows (referred to here as the 'quick-flow' component). This concept is consistent with the work published by Woodward *et. al* (2013) for a Taupo catchment and has been applied by Aqualinc to modelling studies in the Waikato, Ruataniwha, Waimea, central Canterbury, south Canterbury and Kakanui areas.

The quick-flow separation for the Takaka valley has been based on measured river flows in the Takaka River at both Harwoods (for the upper catchment) and at Kotinga (for the whole valley) (refer to Section

3.6). Quick flow run-off was estimated based on daily time series of land surface recharge (LSR) calculated for the catchment over the simulation period (1980-2014). The basis of the quick-flow separation is the assumption that the soils can accept only a finite rate of deep recharge, and the remaining flow is routed directly to rivers as quick-flow. The amount of LSR that is routed as quick-flow was determined by specifying a percentile of the LSR above which flow is assumed to be quick-flow. The percentile value is calibrated based on measured river flows so that average run off matched average measured river flows.

For the Takaka River catchment, the portion of land surface recharge on any day that exceeded the 89 percentile flow was routed to streams. This was based on calibration to measured average flow at Harwood's from the upper valley catchment only, and subsequently applied to the whole catchment. For the lower valley, some of this run off water has the opportunity to seep into the TUGA system as the river passes over the valley floor. The remainder stays as quick flow in the river, which equates to approximately 41.4 m^3/s.

For comparison to measured flows, an exponentially-weighted average was placed through the quick-flow run off time series to partly account for lag times and storage in the upper soils. This resulted in the flow responses shown in Figure 8 and Figure 9.

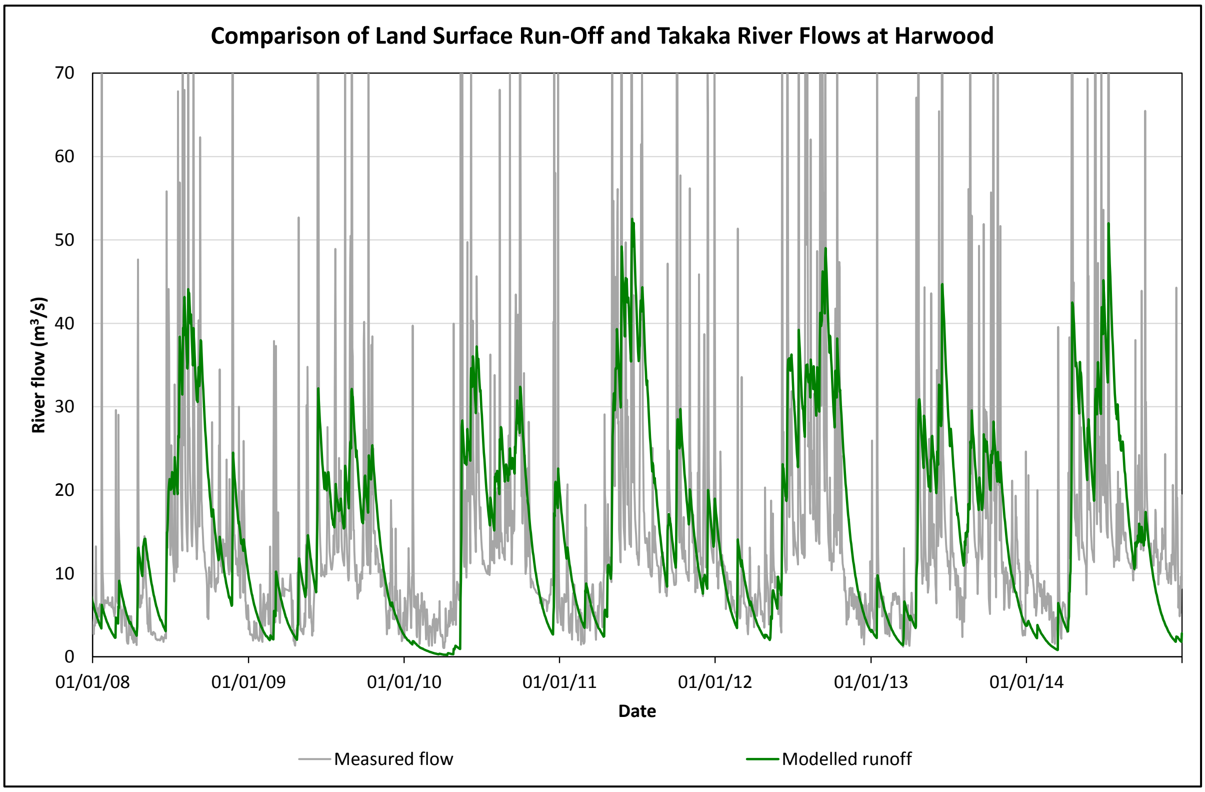

Figure 8: Flow and land surface run-off comparisons for Takaka River at Harwood

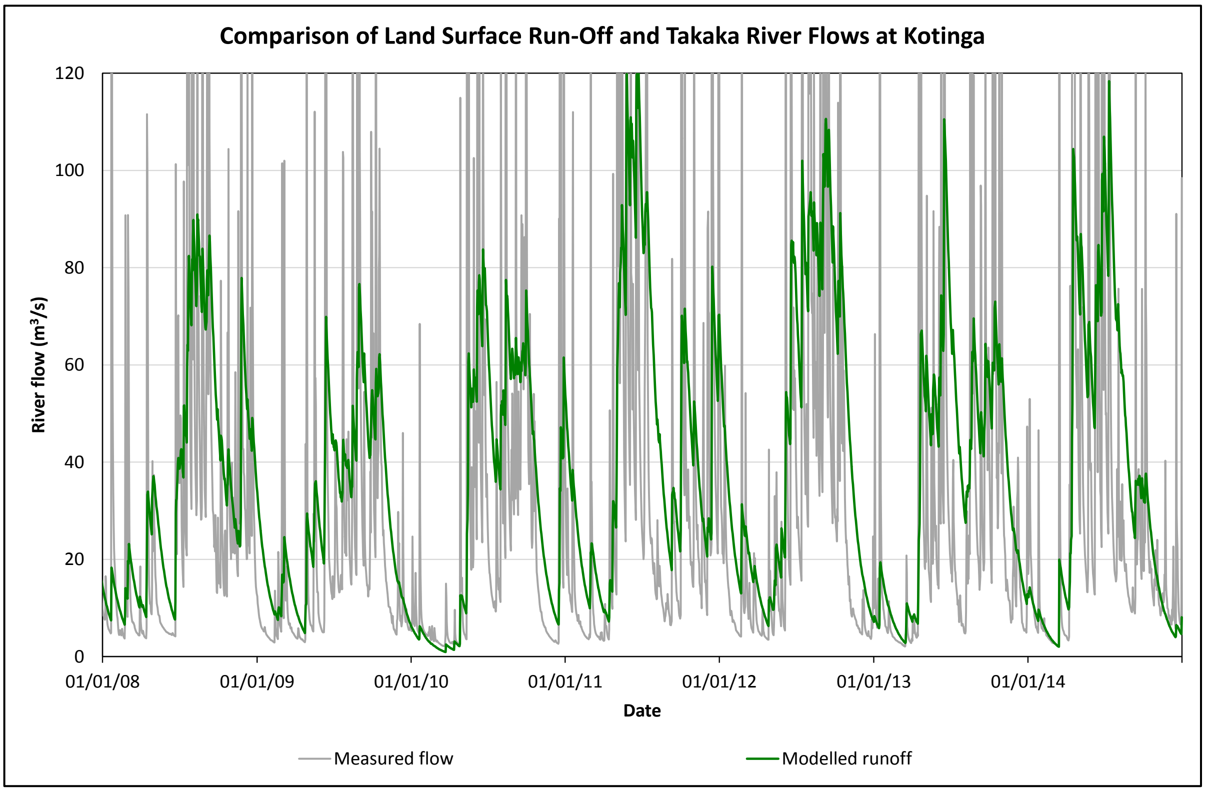

Figure 9: Flow and land surface run-off comparisons for Takaka River at Kotinga

While the assessment above sufficiently reproduces the seasonal run-off trends, it cannot reproduce the dynamics of the measured run off to the same level of accuracy as purpose-built rainfall-run-off models. However, the groundwater modelling completed for the Takaka catchment utilises measured river flow time series and therefore does not specifically use this synthesised run off time series. Instead, the purpose of this comparison is to estimate the slower regional infiltration to deeper groundwater by removing the flow that would eventually run off to rivers.

3.5.2 Resulting Land Surface Recharge

The direct land surface recharge to the groundwater system averages approximately 23.4 m^3/s over the entire study area of 940 km^2. This equates to an average annual recharge of approximately 790 mm/year. Of the 23.4 m^3/s, approximately 12.5 m^3/s is estimated to infiltrate directly to the AMA, approximately 0.7 m^3/s to the TLA and the remaining approximately 10.2 m^3/s to the TUGA. Once underground, the infiltrated water passes between aquifer systems along common boundaries. Hence, these values do not represent the total flows in each system. For example, some of the TUGA water eventually flows into the AMA and TLA systems. River recharge also contributes to groundwater flow (discussed in Section 3.7).

3.6 Surface Water Monitoring

TDC operate a series of river flow recorder sites and conduct additional spot flow gaugings throughout the catchment. In addition, Trust Power report flow at the Cobb dam (both actual and naturalised). Figure 10 shows the locations of key flow recorder sites (labelled) and the various gauging sites considered (not labelled). Table 3 summarises the stored data for the key recorder sites. Data from individual gaugings are too numerous to include herein.

Table 3: Overview of surface water flow recorder sites

River name	Monitoring site	Start date	End date	Completeness
Cobb River	Cobb Dam	6/6/85	Current	93%
Takaka River	Harwood	26/3/75	Current	~100%
Takaka River	Kotinga	9/10/70	Current	88%
Waingaro River	Hanging Rock	6/9/79	Current	99%
Anatoki River	Happy Sams	6/9/79	Current	97%
Powell Creek	U/S Motupipi River	14/12/06	Current	~100%
Motupipi River	Reillys Bridge	23/11/06	Current	99%
Fish Creek	Main Springs	5/4/85	Current	98%
Te Waikoropupū River	Spring River	13/12/74	Current	80%

3.6.1 Te Waikoropupū Main Spring Flows

A key surface water feature of the catchment is Te Waikoropupū springs. Flow from the main springs are not automatically measured by TDC. However, TDC have synthesised flows from this main spring based on adjacent groundwater levels (Main Spring groundwater) and gaugings. This flow synthesis is reliable from approximately 1999 onwards, when the Main Spring groundwater well was installed. Prior to this, the synthesis is less accurate.

Figure 11 plots a comparison between measured Fish Creek flow and synthesised flow (from Main Spring groundwater) from 1999 onwards (both daily average flow). Although there is some scatter in this correlation, the following observations are made:

- There is a relatively linear relationship between flows in Fish Creek and flows from the main spring. This suggests that the two systems are hydraulically similar.
- Fish Creek is likely to go dry at approximately the same time as flows in Te Waikoropupū main spring drop to approximately 7.8 m^3/s (and below).
- For every 1 m^3/s increase in flow from Te Waikoropupū main spring, Fish Creek increases by approximately 0.65 m^3/s.
- Fish Creek is influenced by overland flows at times of high flows, and main spring flow is not. Hence, the relationship between the two flows sites is unreliable at high flows.

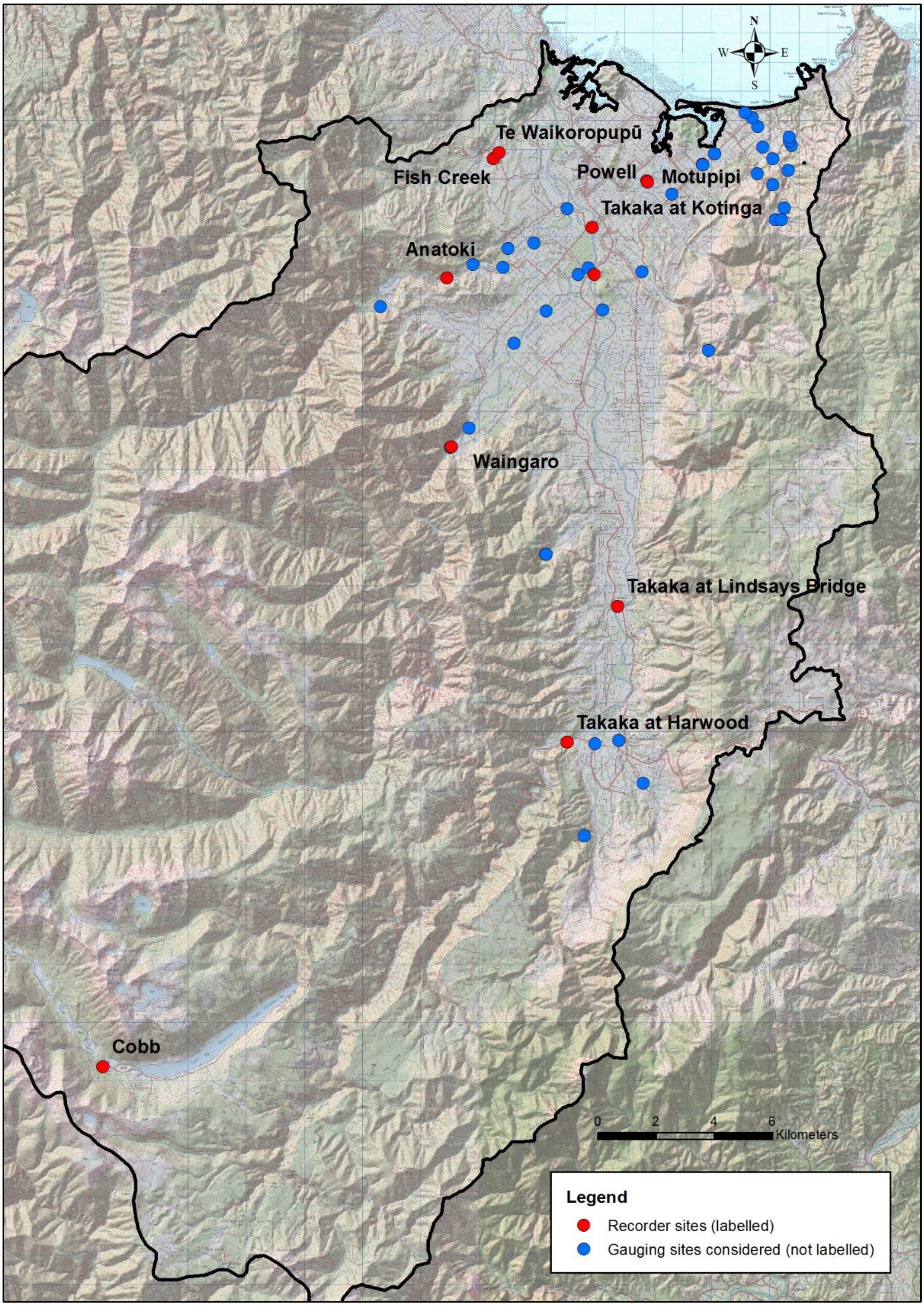

Figure 10: Key river monitoring sites

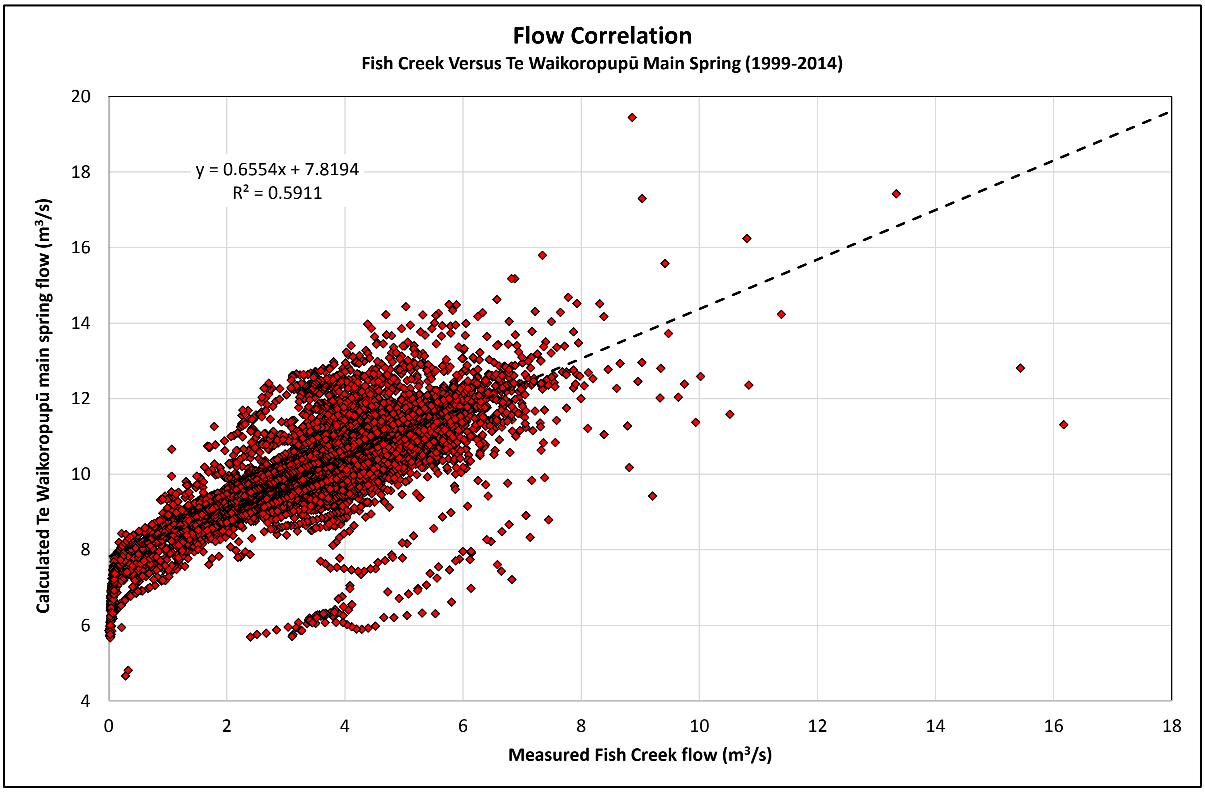

Figure 11: Comparison of measured Fish Creek flow and synthesised Te Waikoropupū main spring flow

3.6.2 Coastal Surface Water Discharge

The rate of surface water discharging into the sea from rivers has been estimated by summing the average flows in the coastal monitoring sites.

Table 4: Summation of river coastal discharge

River name	Monitoring site	Average flow (m^3/s)
Takaka River	Kotinga	33.4
Anatoki River	One Spec Bridge	~ 11.9 (1)
One Spec Creek	Takaka River confluence	~ 0.3
Motupipi River	Reillys Bridge	0.5
Te Waikoropupū main spring	Main spring	10.0
Fish Creek	Te Waikoropupū Springs	3.3
Misc. eastern streams (Motupipi through Pohara)	Various	~ 0.5
	Total	**~ 59.9**

(1) This flow is estimated as there is an insufficient range of gauged flows to accurately calculate an average (Thomas & Harvey, 2013).

3.7 River Recharge

River recharge to the groundwater system occurs primarily from the Takaka River, but also from the smaller streams and rivers. These sources are each discussed below.

3.7.1 Takaka River Recharge

The estimation of river recharge from the Takaka River to the groundwater system has been separated into two zones: above and below the Harwood recorder. The Harwood recorder is located near where the Takaka River exits the hill catchment and begins to flow along the valley floor. It is therefore a suitable location for a natural distinction between the upper (hill) catchment and the lower (valley floor) river.

Due to the distance from the monitoring locations on the valley floor, the hydraulic response of groundwater recharge from the river channels in the upper (hill) catchment is difficult to separate from the effects of land surface recharge. Consequently, it has been assumed that there is no direct recharge from river channels in this upper catchment and instead land surface recharge alone has been used, which acts as a surrogate for the combined effect of both river and land surface recharge to the groundwater system.

Below the Harwood recorder and out onto the valley floor, river recharge to groundwater is dependent (among several factors) on whether or not the river flows continuously along its entire length. If the Takaka River does not flow continuously along its entire length (even if there is only a short dry reach mid-river), then all of the river flow measured at Harwood drains into the groundwater system. When the river flows full length, some of the flow will drain to groundwater and some will remain in the river channel and discharge into the sea. Therefore, to calculate the rate of river recharge to groundwater, it is necessary to know when the river is partially dry and when it is fully flowing. There are very few recorded observations of this, so a simple relationship has been developed to predict when the river may have historically been partially dry. This relationship has been based on work presented by White *et al.* (2001) and Young *et al.* (2001). Specifically:

- An average loss of 600 l/s has been applied between Harwood recorder and Lindsay's bridge, based on gaugings. The magnitude of loss is reported by White *et al.* (2001) to be relatively independent of river flows. A constant average loss has been assumed.
- When the river does not flow full length, the loss to groundwater below Lindsay's bridge equals the remaining river flow. Young *et al.* (2001) concluded that when groundwater levels are high, river drying will occur when river flows (at Harwood) drop below approximately 7,000 l/s. However, if groundwater levels are low, then flows as high as 15,000-20,000 l/s are required to maintain full surface flow. Given this, a relationship between river drying and river flow with groundwater levels at the Sowman monitoring well (Section 3.10) has been developed to predict the days when the river dried somewhere along its each. This relationship has been further adjusted to match anecdotal evidence from local residents. Figure 12 presents the prediction of full-length flow from 1 June 2010 to 31 December 2014.
- For days when the river flows full length, it has been assumed that the losses are the same as the maximum losses for the same groundwater level.
- Provision of surface water takes for irrigation in the upper valley below the Harwood recorder have been included in the assessment. Takes have been calculated using IRRICALC (Section 3.5) for the irrigated area sourced from surface water in losing reaches of the Takaka River and adjacent tributaries.

To calculate river recharge to groundwater, the location of where the river dries does not need to be known; only if it goes dry.

Given the above methodology, the resulting recharge to groundwater from the Takaka River below Lindsay's bridge ranges between nearly zero and 14.4 m^3/s.

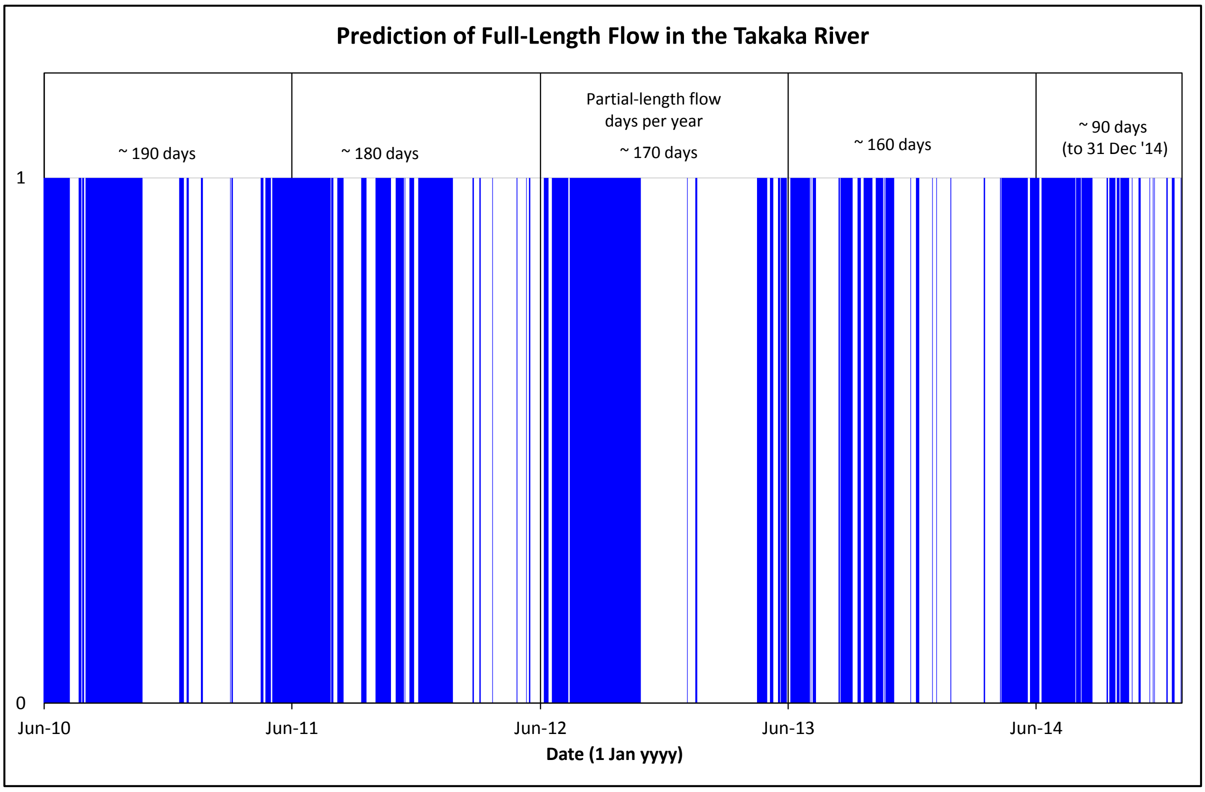

Figure 12: Prediction of full-length flow in the Takaka River
(white space (y-axis = 0) are days when the river is predicted to be partially flowing; blue space (y-axis = 1) are days when the river is predicted to be full flowing)

3.7.2 River Recharge from Smaller Streams and Rivers

In addition to groundwater recharge from the Takaka River, some of the smaller streams and rivers also contribute recharge to the groundwater system. Their contributions to groundwater recharge have been estimated based on limited spot gaugings, as follows:

- Waitui and Aaron creeks feed into the Takaka River near the Harwood recorder. Gauged flows from these two creeks sum to 334 l/s, but they go dry at times. Therefore it has been assumed that, on average, 50% of their flow (167 l/s) recharges the groundwater system.
- Waingaro River loses 646 l/s on average, with some reaches losing and some gaining at different times, largely uncorrelated to flow. A steady groundwater recharge rate of 646 l/s has been assumed, which is approximately 15% of the flow at the uppermost gauging site. This has been further adjusted for irrigation takes from the river. Half of the Waingaro River recharge has been assigned to the AMA system and half to the TUGA, as suggested by Joseph Thomas (TDC, *pers. comm.*).
- Craigieburn Creek gaugings report an average flow of 92 l/s. It is assumed that 15% of this flow recharges groundwater (assumed same as Waingaro River percentage losses), which equates to 14 l/s.
- The Anatoki River gains ~120 l/s over its length. Therefore, no groundwater recharge is assumed from this river. It will, however, receive discharge from the groundwater system.
- Smaller eastern streams accounted for as follows:
    - Ellis Creek: based on gaugings, this creek gains ~11 l/s; therefore it has been assumed that it does not contribute to groundwater recharge.

- Richmond Creek: there is insufficient gauging data for this creek; hence it has been assumed to be similar to Ellis Creek, gaining flow with no contribution to groundwater recharge.
- Gibson Creek: gauging suggests a gaining stream; hence no groundwater contribution has been assumed.
- Rameka Creek: again, insufficient gauging data; hence no groundwater contribution has been assumed.
- Dry Creek: insufficient data (measured zero flow); hence no groundwater contribution has been assumed.
- Kite Te Kahu Creek: insufficient data (measured zero flow); hence no groundwater contribution has been assumed.

Based on local knowledge, the eastern streams tend to lose flow in their upper reaches to the underlying TLA system and then gain flow again in the lower reaches as they pass over the TUGA system. However, there is insufficient data to quantity this. If this is the case, then the contribution to the TLA system is likely to be relatively small (compared to other sources) and therefore it has been conservatively assumed that the groundwater contribution is zero.

3.7.3 Combined River Recharge to Groundwater

From the above sources, the combined long-term average groundwater recharge from rivers equates to approximately 8.5 m^3/s.

3.8 Comparison of Land Surface Recharge, River Recharge and Catchment Flows

From Section 3.7.3, the long-term average groundwater recharge from rivers equates to approximately 8.5 m^3/s. As discussed in Section 3.5.2, the long-term average land surface recharge to groundwater equates to approximately 23.4 m^3/s. These combine to total 31.9 m^3/s.

Figure 13 shows time series of land surface recharge compared to river recharge. This plot has been prepared with an exponentially-weighted moving average run through the individual data sets to provide a comparison of trends and patterns. The key observations are:

- On average, land surface recharge is approximately three times larger than river recharge;
- Land surface recharge is significantly more dynamic (has larger annual variations) than river recharge; and
- The catchment experienced a period of below-average land surface recharge from 1992 through to 1995, and again from 2005 through to 2011 (approximately).

Some of the groundwater recharge re-emerges in surface waters in the lower catchment (e.g. in the Takaka River and Te Waikoropupū Spring).

The total water flowing through the catchment (groundwater and surface water combined) is estimated at approximately 73.3 m^3/s. Of this, approximately 59.9 m^3/s is estimated to discharge at the coast via surface waterways (Table 4). Approximately 0.2 m^3/s (annual average[5]) is removed through groundwater abstraction (primarily for irrigation and water supplies). The remaining 13.2 m^3/s therefore discharges off shore via groundwater (sub surface). Table 5 summarises the estimated total catchment flow balance.

[5] The seasonal peak demand is higher than this.

Table 5: Summary of total catchment flow

Flow component	Report reference	Flow (m^3/s)
	Inflows	
Land surface recharge	Section 3.5.2	23.4
River recharge	Section 3.7.3	8.5
River run off down catchment	Section 3.5.1	41.4
	Total in	**73.3**
	Outflows	
Surface water	Table 4	59.9
Pumping	-	0.2[6]
Groundwater (off shore)	Remaining balance	13.2
	Total out	**73.3**

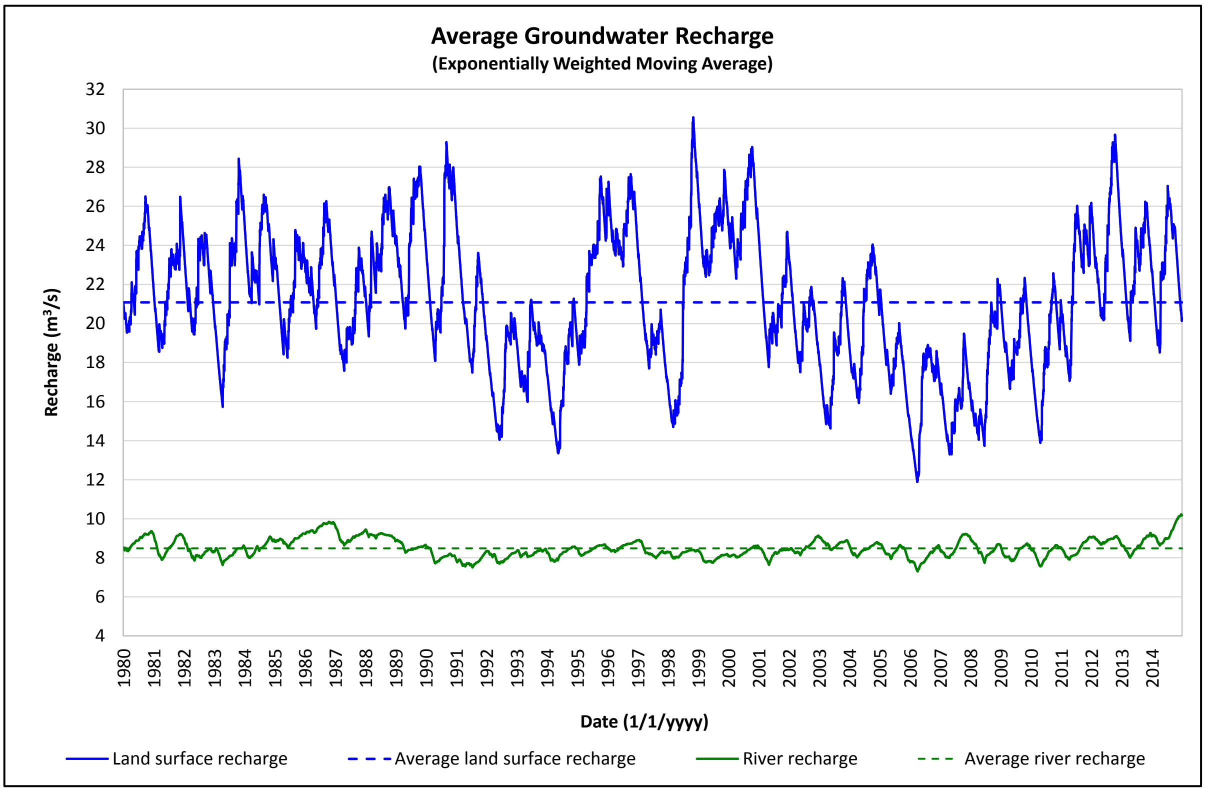

Figure 13: Comparison of land surface recharge and river recharge

[6] The seasonal peak demand is higher than this.

3.9 Existing Consents and Irrigated Areas

The locations of existing active water take consents (for both surface water and groundwater) have been supplied by TDC. These are shown in Figure 14. Many of the consents are for irrigation, but consented uses also include water supply and water storage.

Subsequently, Aqualinc has digitised the existing and proposed irrigated areas for the Takaka valley (as at April 2015). This was achieved by using a method similar to Aqualinc (2015) and utilising the following data sources:

- Farm boundary extents (as provided by LINZ);
- Aerial photographs (from different sources and different time periods including TDC, Google Maps and Bing);
- Consent locations and consented areas (as supplied by TDC); and
- Multispectural satellite imagery (mapping of the normalised difference vegetation index, NDVI) from LandSat imagery on 7 March 2015 to distinguish between actively growing areas (likely to be irrigated) and dry areas.

The digitised areas were also reviewed by the FLAG and further adjusted. Both existing and proposed consented areas were included in this analysis. Figure 15 shows the resulting mapped areas, which are summarised in Table 6. For comparison, Figure 15 also includes the peak consented rates of take for each consent.

Table 6: Summary of irrigated areas

Irrigation type	Area (ha)
K-line or long lateral	1,465
Pivot	340
Solid set	433
Gun	15
Drip/micro	22
Total existing	**2,275**
Proposed	533
Total incl. proposed	**2,808**

For comparison, TDC's calculation of current and proposed irrigated areas are 2,284 ha and 553 ha respectively, which is similar to the total listed in Table 6. Approximately 75% of the consented irrigated area is sourced from surface water, and the remainder from groundwater.

The irrigation crop water requirements and associated irrigated land surface recharge have been calculated for each consent using the IRRICALC crop-soil water balance model discussed in Section 3.5. Maximum on-farm application rates of 5 mm/day have been assumed, which is consistent with TDC's allocation methods. Restrictions to surface water takes have been applied based on river flows and typical consent conditions.

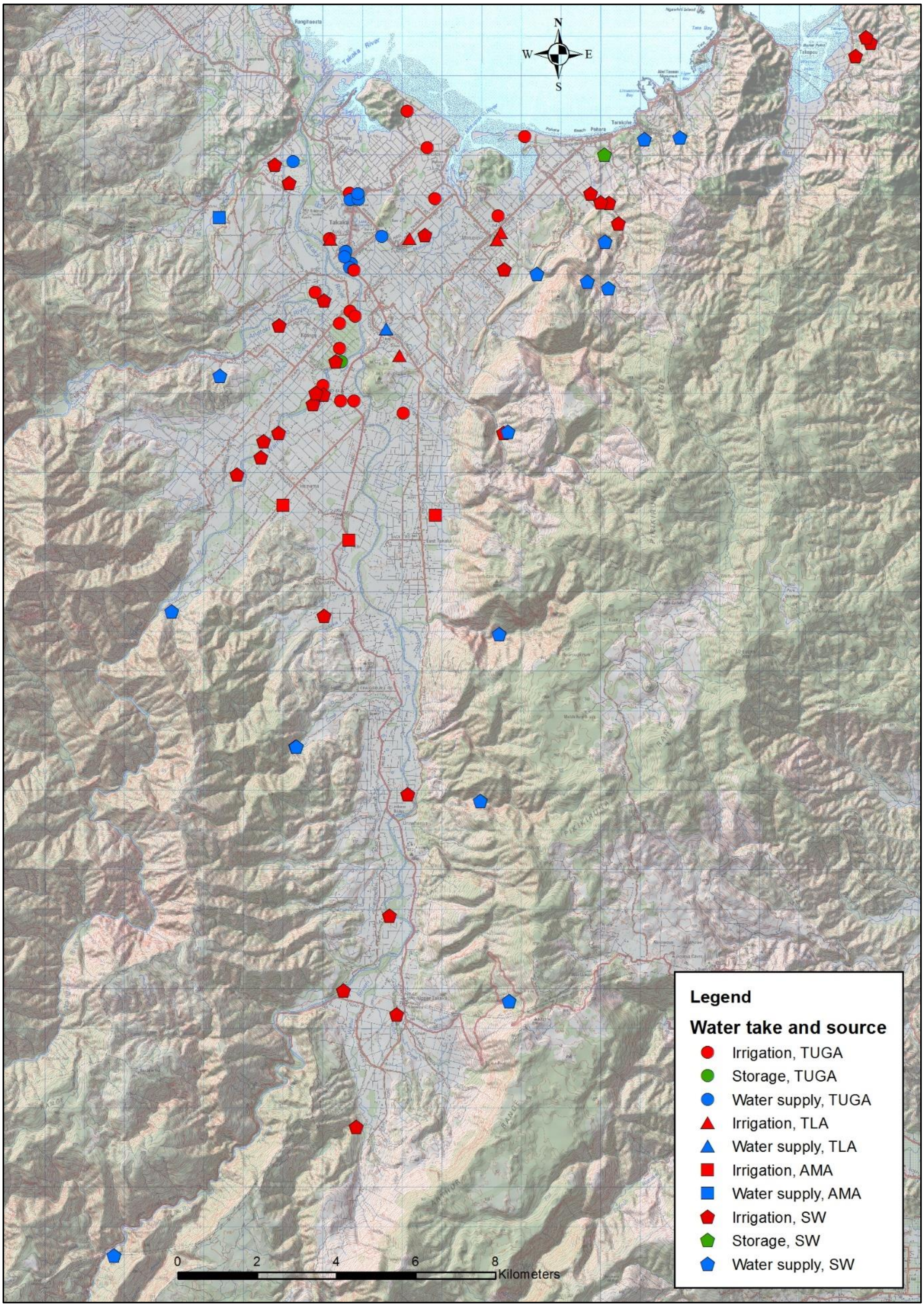

Figure 14: Existing active water take consents

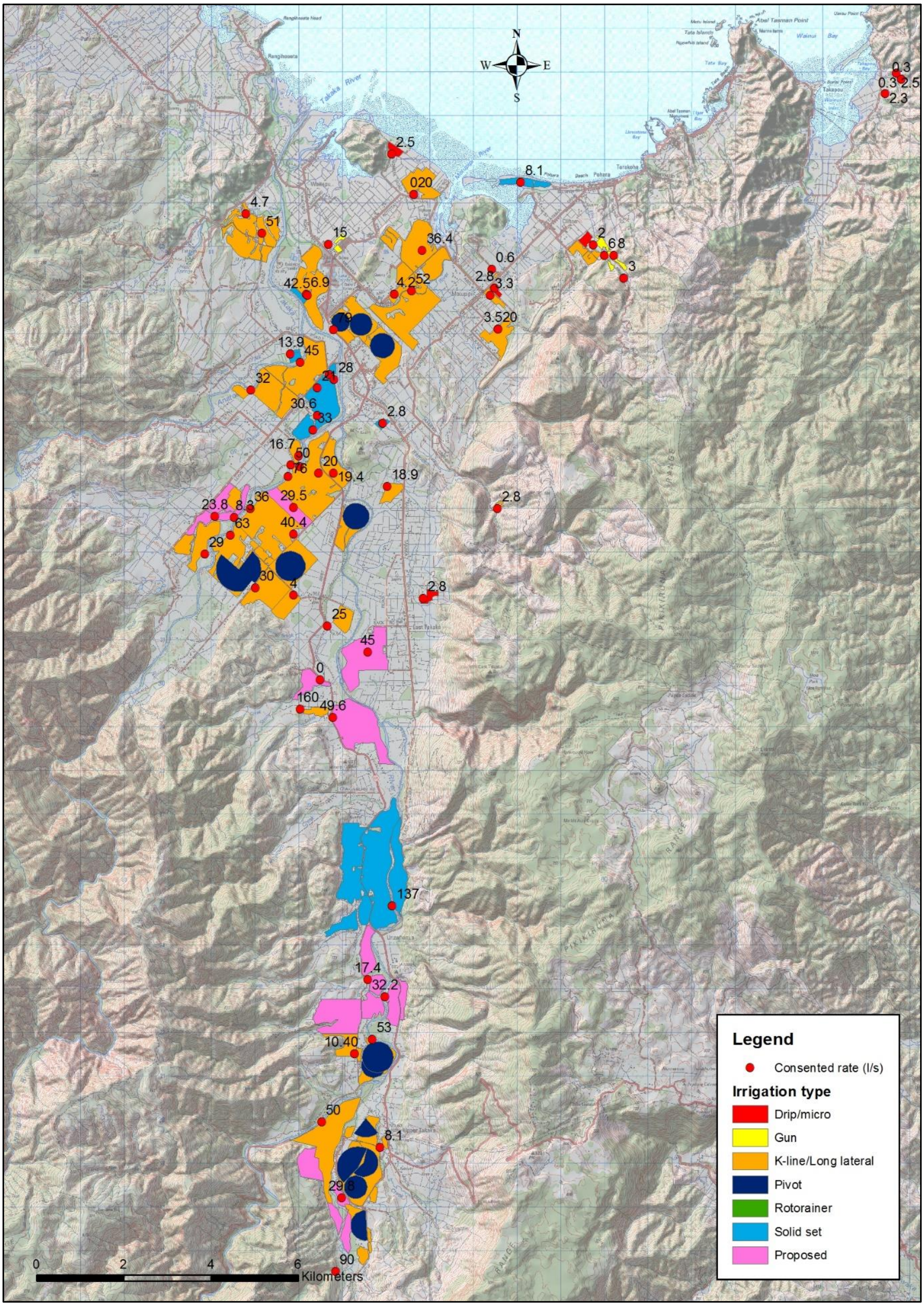

Figure 15: Existing and proposed irrigated areas and consented peak rates of take

3.10 Groundwater Level Monitoring

TDC operate a small network of groundwater level monitoring wells in the Takaka valley. The locations of these wells are shown in Figure 16. Some of these wells are currently active (i.e. TDC still record groundwater levels regularly) and some are now closed (they are no longer monitored). Table 7 summarises the stored data for each monitoring well.

Table 7: Overview of groundwater level monitoring

Well name	Well number	Aquifer	Start date	End date	Completeness
Jefferson	WWD 6829	TUGA	6/2/98	16/7/02	99%
TDC Offices	WWD 6339	TUGA	2/6/99	Current	95%
Takaka Firestation	WWD 6535	TUGA	29/7/04	4/2/11	98%
Takaka Fire 2	WWD 23648	TUGA	5/2/11	Current	98%
Cserney	WWD 6418	TLA	29/10/87	17/10/06	99%
Grove Orchard	WWD 6224	TLA	12/8/95	27/4/98	78%
Motupipi Substation	WWD 6413	TLA	3/10/81	28/1/88	52%
Ball	WWD 6011	AMA	2/6/94	22/3/04	95%
Bennett	WWD 6815	AMA	26/6/96	3/12/98	97%
Hamama	WWD 6710	AMA	25/2/88	7/4/05	82%
Te Waikoropupū Main Spring	WWD 6013	AMA	20/8/99	Current	99%
Savage	WWD 6713	AMA	18/7/02	Current	99%
Sowman	WWD 6912	AMA	26/8/99	Current	95%

Figure 17 plots the groundwater level records for the wells. Although this is a complex graph to visualise, it has been provided for the following key features:

- Groundwater levels in wells located inland have higher groundwater level elevations than those located closer to the coast;
- Wells located in the deeper AMA aquifer have larger seasonal variation in groundwater levels (25+ m range; the saw-tooth effect) compared to wells in the TLA system (5-10 m range), and wells in the TLA system have larger variation than wells located in the TUGA system (2-3 m range). The exception is groundwater levels in the Main Spring well, which is moderated by discharge to the spring.

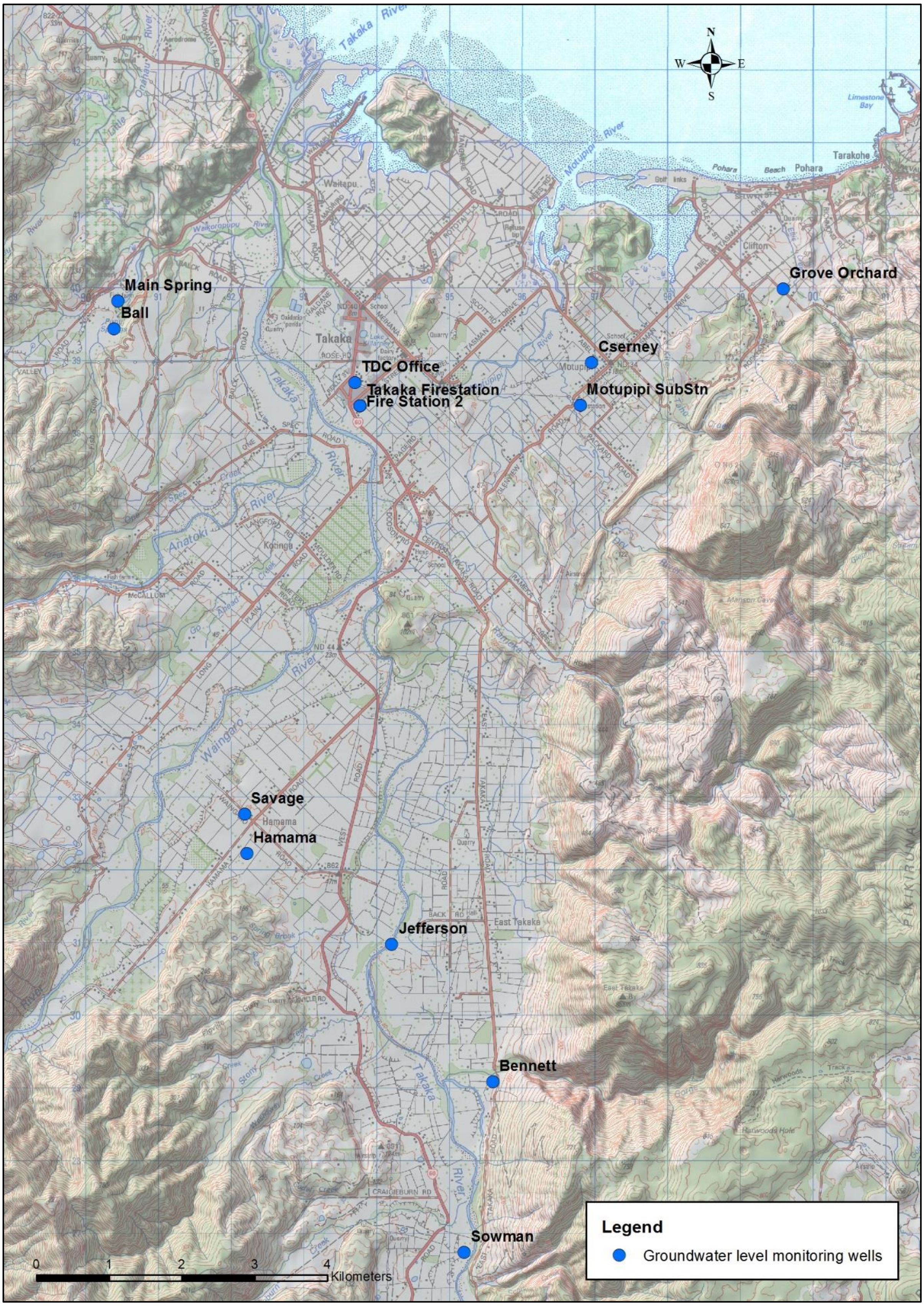

Figure 16: Groundwater level monitoring wells

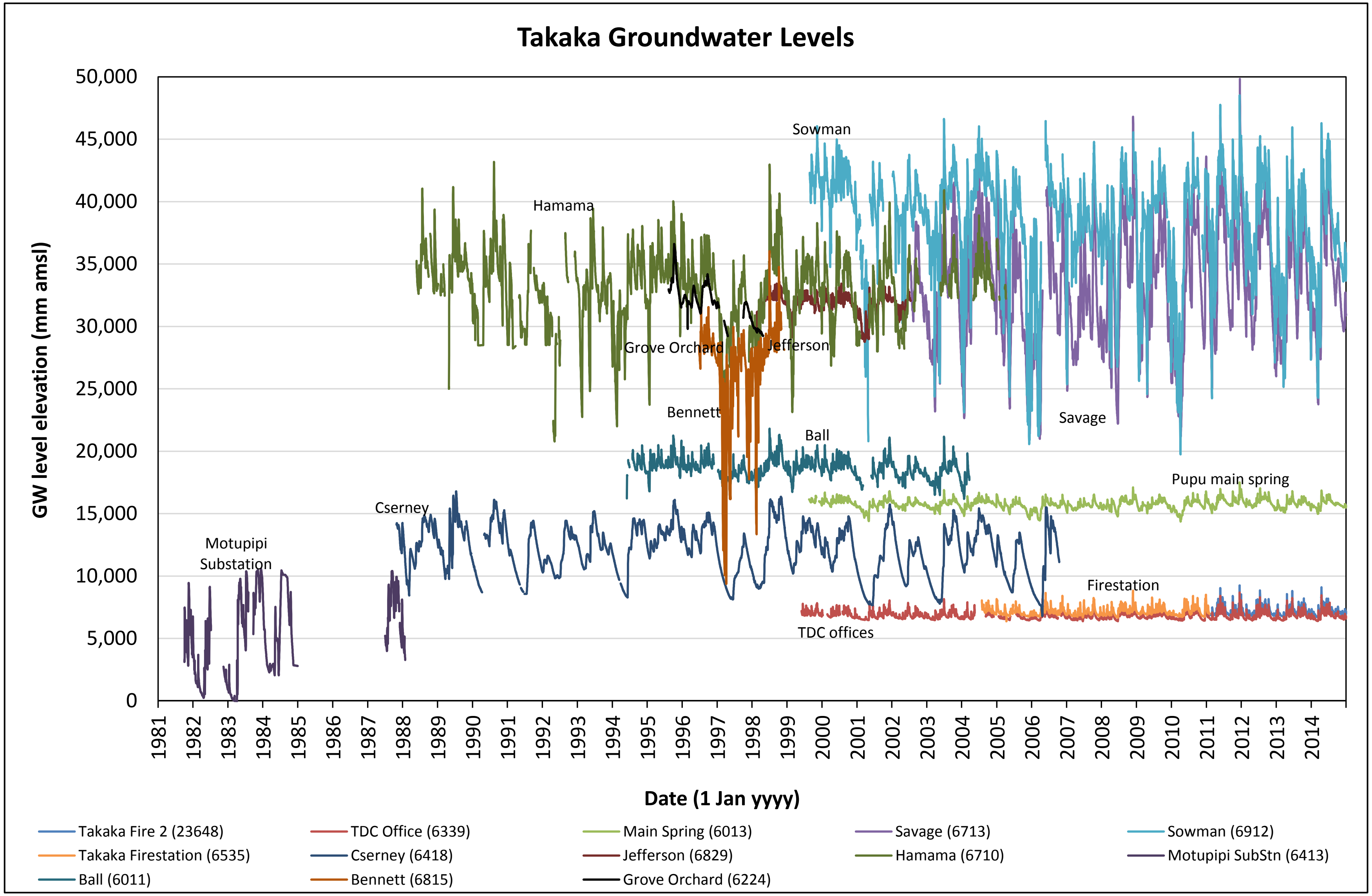

Figure 17: Groundwater level time series

3.11 Comparison of Groundwater Levels and River Flows

Groundwater levels and river flows in the Takaka valley catchment respond similarly to variations in climate. Figure 18 plots all existing AMA wells with Takaka River flows at both Harwoods and Kotinga. Key points to note are:

- Groundwater levels in Main Spring well follow very closely to variations in Takaka River base flow. The trend is a little better matched with flows at Harwood compared to Kotinga, though the difference is small. The better match to Harwood flows is possibly due to the influence of western-hill rain events that flow through to Kotinga but do not fall in the upper Takaka catchment above the Harwood recorder.
- All of the wells respond to freshes in the Takaka River, and the inland bores (Sowman and Savage) respond more promptly and with larger magnitude than the Main Spring well.
- During extended dry periods without significant river freshes (e.g. November 2013 to March 2014), Sowman and Savage groundwater levels continue to decline until a more substantial fresh occurs. Groundwater levels in Main Spring well also decline during dry periods, but the decline is significantly slower and smaller than the inland wells. These differences are due to the wells' relative proximity to the river's inland recharge (losing) reaches and also to proximity to the regulating nature of Te Waikoropupū spring discharge.

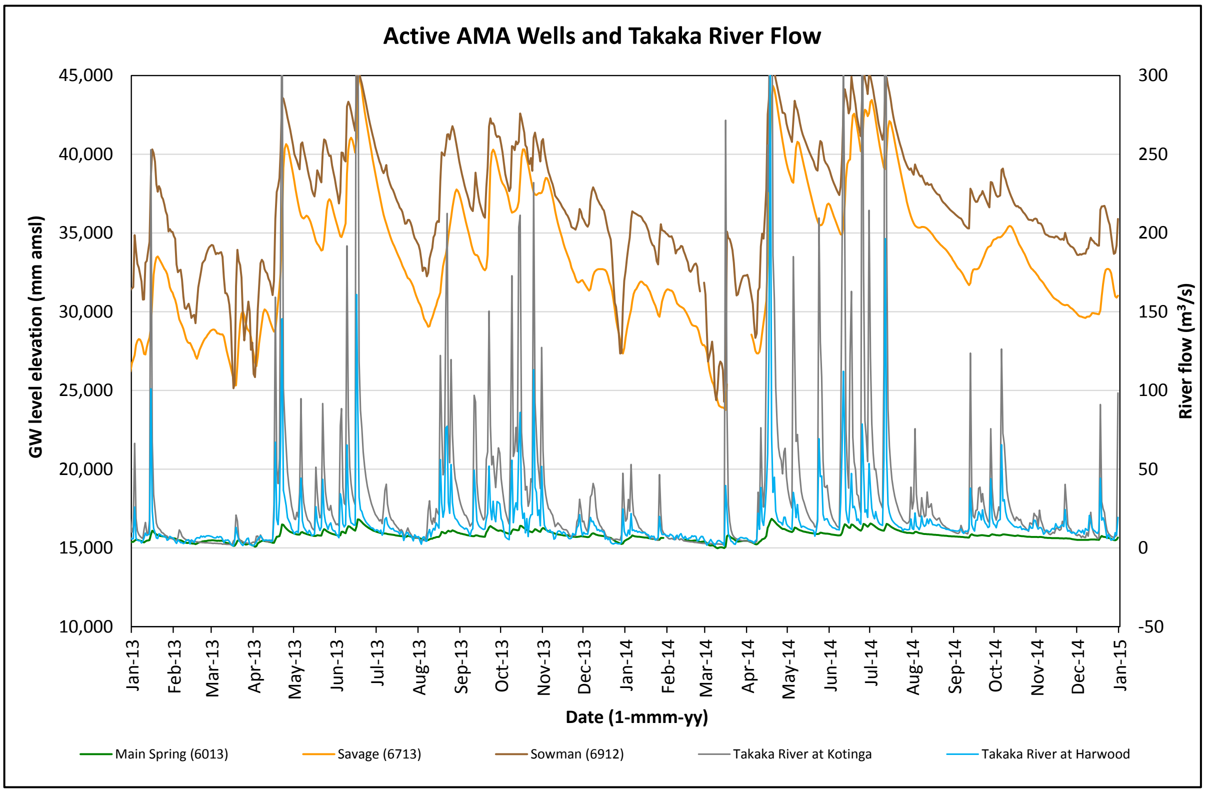

Figure 18: Comparison of groundwater levels in active AMA wells and Takaka River flows

Figure 19 presents a comparison between groundwater levels in the AMA Main Spring monitoring well and flows in Te Waikoropupū Spring. A very close correlation exists between the two data sets which further supports the statement by Thomas & Harvey (2013) that the springs are the main discharge zone for the AMA.

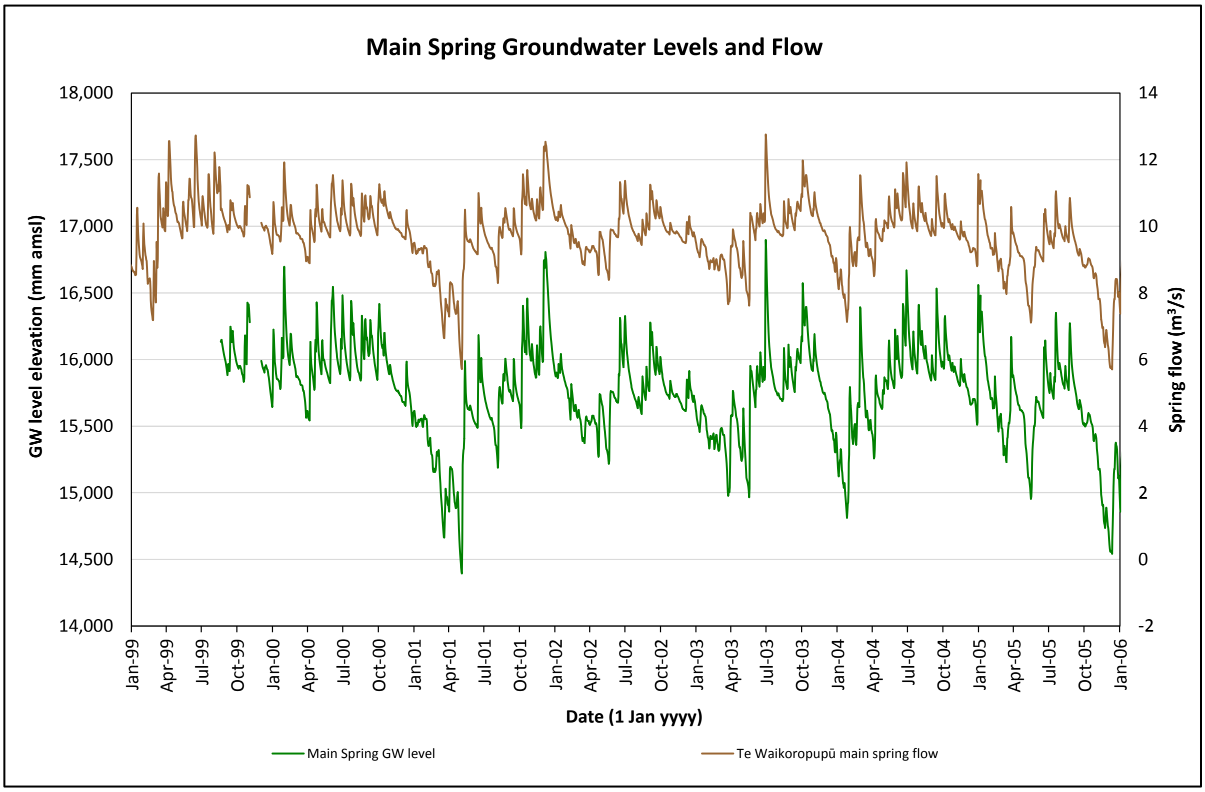

Figure 19: Comparison of Main Spring groundwater levels and flows in Te Waikoropupū spring

In the Motupipi area, shallow groundwater levels in the TUGA are closely correlated with flows in the Motupipi River. This is shown in Figure 20 which compares two TUGA wells (Takaka Fire 2 and TDC Office) and Motupipi River flows at Reillys Bridge. In addition, seasonal variations are also reflected in the deeper TLA Cserney well, but the variation is much larger (> 7 m) compared to the shallower TUGA wells (1-2 m). This is likely due to the differences in aquifer storage properties of the TUGA and TLA. By definition, the shallower TUGA is an unconfined aquifer and therefore has a larger storage capacity than the deeper more confined TLA. Consequently, any change in recharge to the TUGA will result in a much smaller change in groundwater level compared to the TLA system (i.e. more of the water is stored in the pores rather than resulting in a groundwater level change).

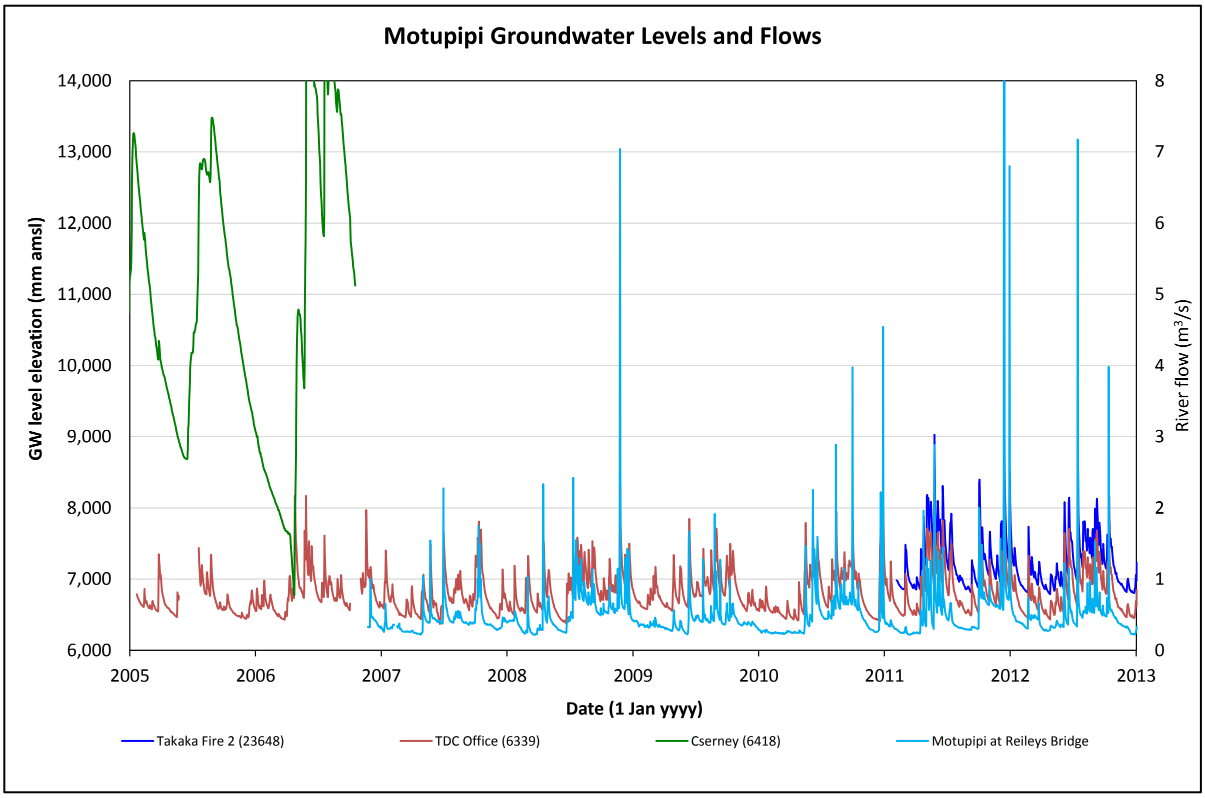

Figure 20: Comparison of Motupipi groundwater levels and river flows

3.12 Piezometric Contours

Figure 21 show groundwater level contours generated for the TUGA and Figure 22 for the AMA and TLA aquifers (combined). These contours have been derived from average groundwater levels recorded over the period 2002-2006, which encompasses a period of overlap for the majority of wells. Groundwater level monitoring is relatively spatially sparse, so it was important to include records from as many wells as possible to generate the contours. However, a common time period over which the records were averaged was needed to ensure that individual points were comparable and that records from one specific climate period did not conflict with records from another.

Due to the sparseness of measured groundwater levels, additional 'dummy' groundwater levels were added to the TUGA data set at known surface water boundaries, specifically at the coast and at rivers. This provided additional points with which to contour, resulting in a more representative result. Regardless, there is insufficient data to derive reliable piezometric contours, especially for the AMA/TLA data set. Therefore, little weight should be placed on these results.

The contours do, however, provide an indication as to the general direction of groundwater flow, this being towards the coast and off shore. Due to the influence of rivers (which follow the land surface topography), gradients in the TUGA aquifer are much steeper (contours are closer together) than in the AMA/TLA layers.

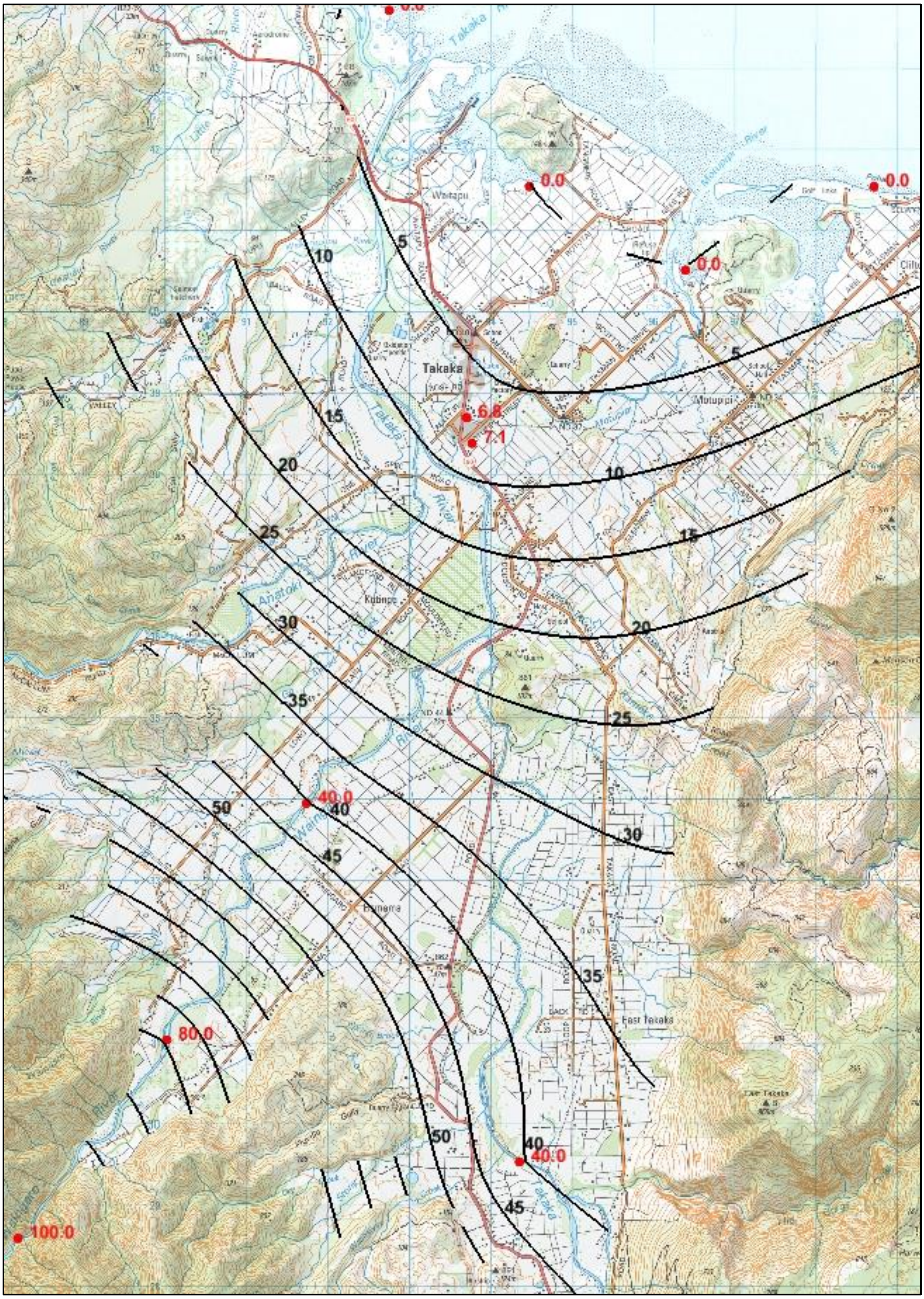

Figure 21: Groundwater level contours TUGA (2002-06 data)

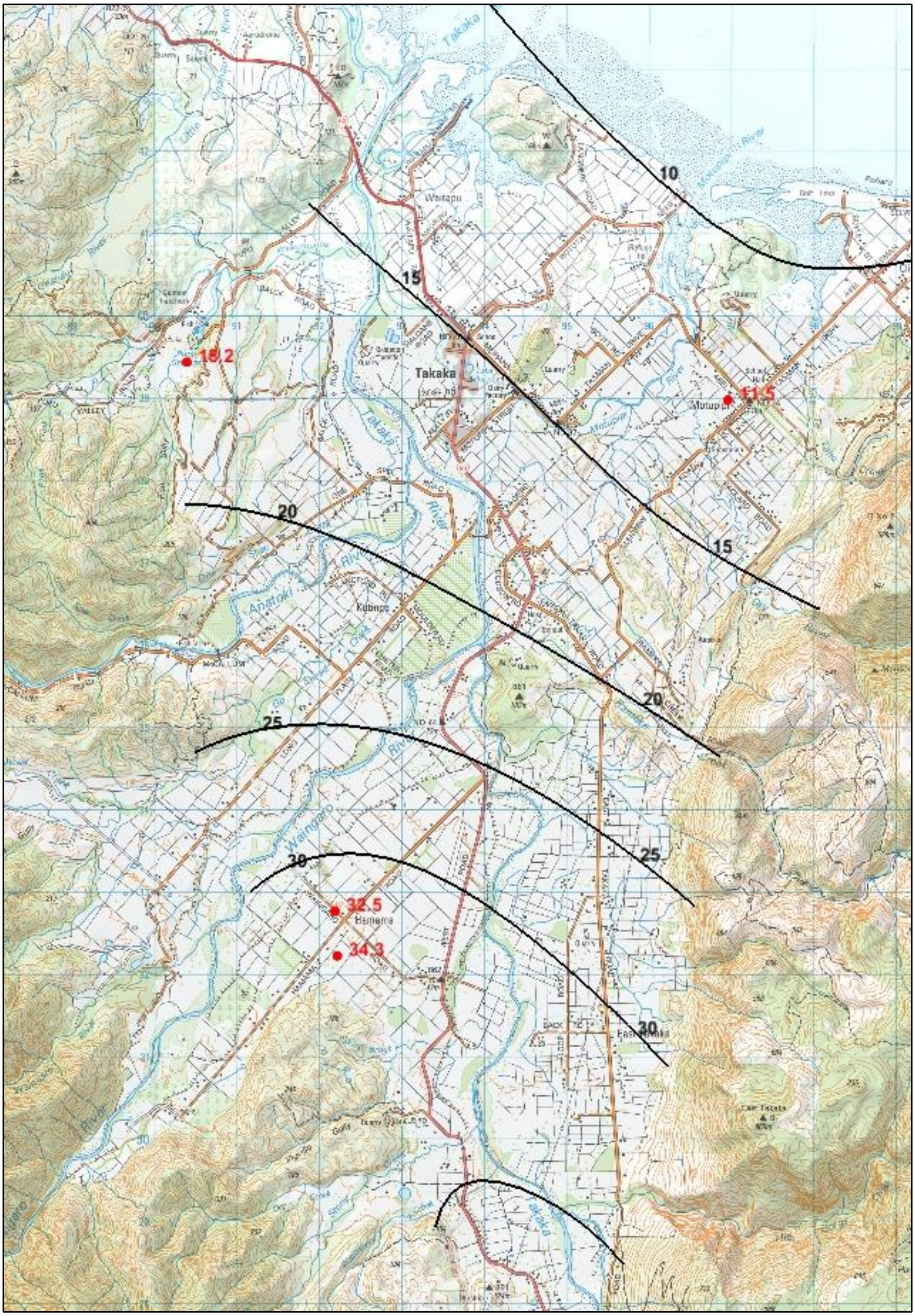

Figure 22: Groundwater level contours AMA and TLA (2002-06 data)

3.13 Nitrate-Nitrogen Monitoring

TDC have recorded measurements of nitrate-nitrogen at multiple locations throughout the catchment, in both surface water and groundwater. Figure 23 presents time series of nitrate-nitrogen concentrations in the Takaka River, both at the Harwood recorder and at the Kotinga recorder. While concentrations at Kotinga are variable and show no obvious pattern, concentrations at Harwood have been decreasing since the late 1990's. Overall, a greater concentration of nitrate-nitrogen is present at Kotinga compared to Harwood. This is due to river gains, primarily from groundwater in the lower portion of the valley floor.

Figure 24 presents average nitrate-nitrogen concentrations measured in surface water. These averages have been derived from all available measurements including 'one-offs' and longer-term records. The lower concentrations tend to occur in the larger, hill-fed rivers (Takaka, Anatoki etc.) with higher concentrations occurring in the smaller rives located in the lower plains around Motupipi.

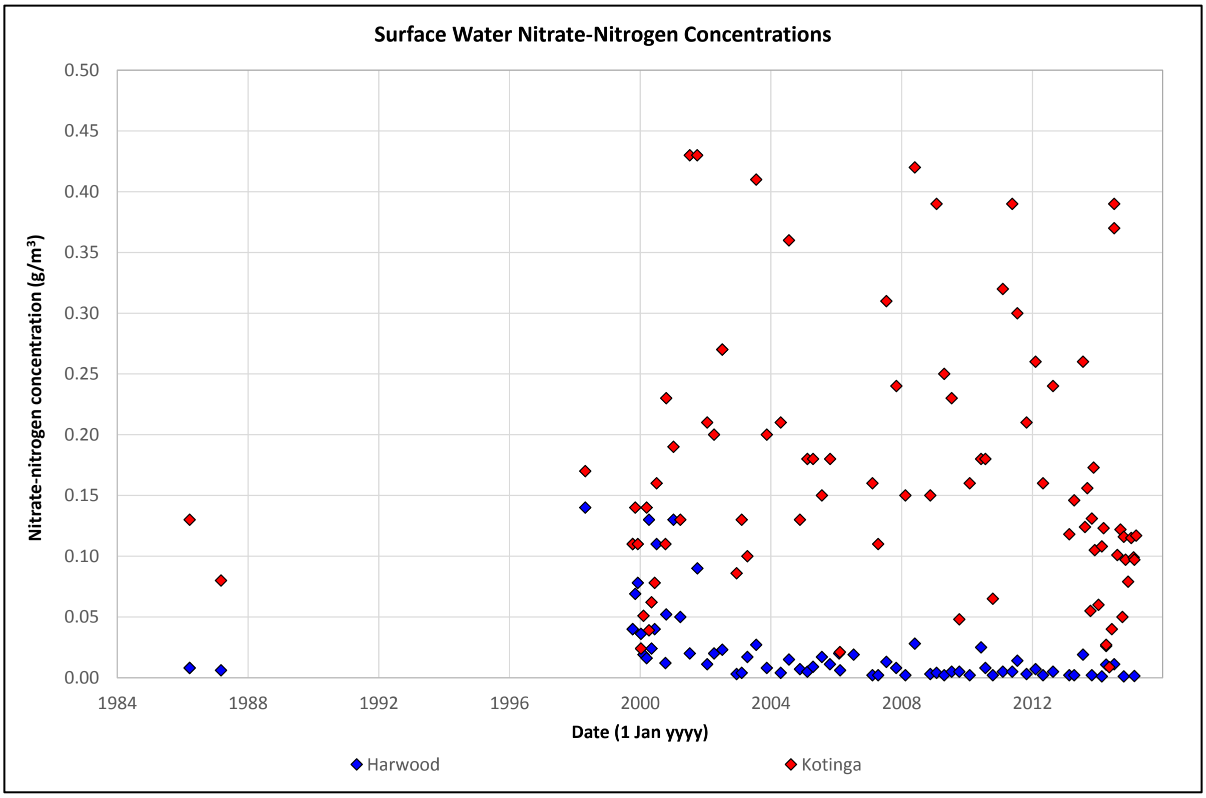

Figure 23: Nitrate-nitrogen concentrations in the Takaka River

Figure 25 presents average nitrate-nitrogen concentrations measured in groundwater. Again, these averages have been derived from all available measurements including 'one-offs' and longer-term records. Similar to surface water, the higher groundwater concentrations occurring in the Motupipi – Pohara area. The high concentrations in the Pohara, Clifton and inland Motupipi areas are likely due to local septic tank discharges, rather than agricultural effects.

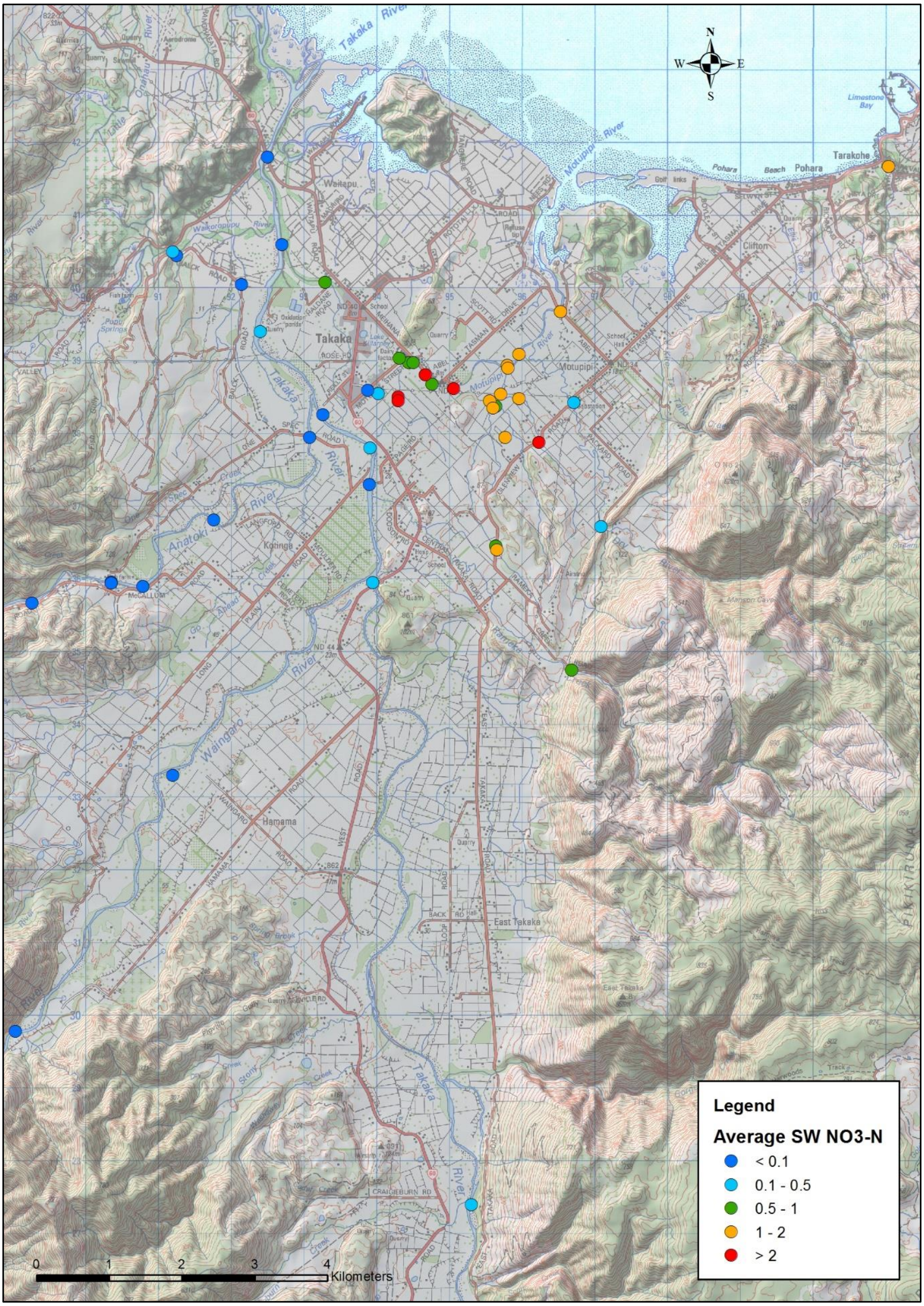

Figure 24: Surface water nitrate-nitrogen concentrations

(averages from all available measurements)

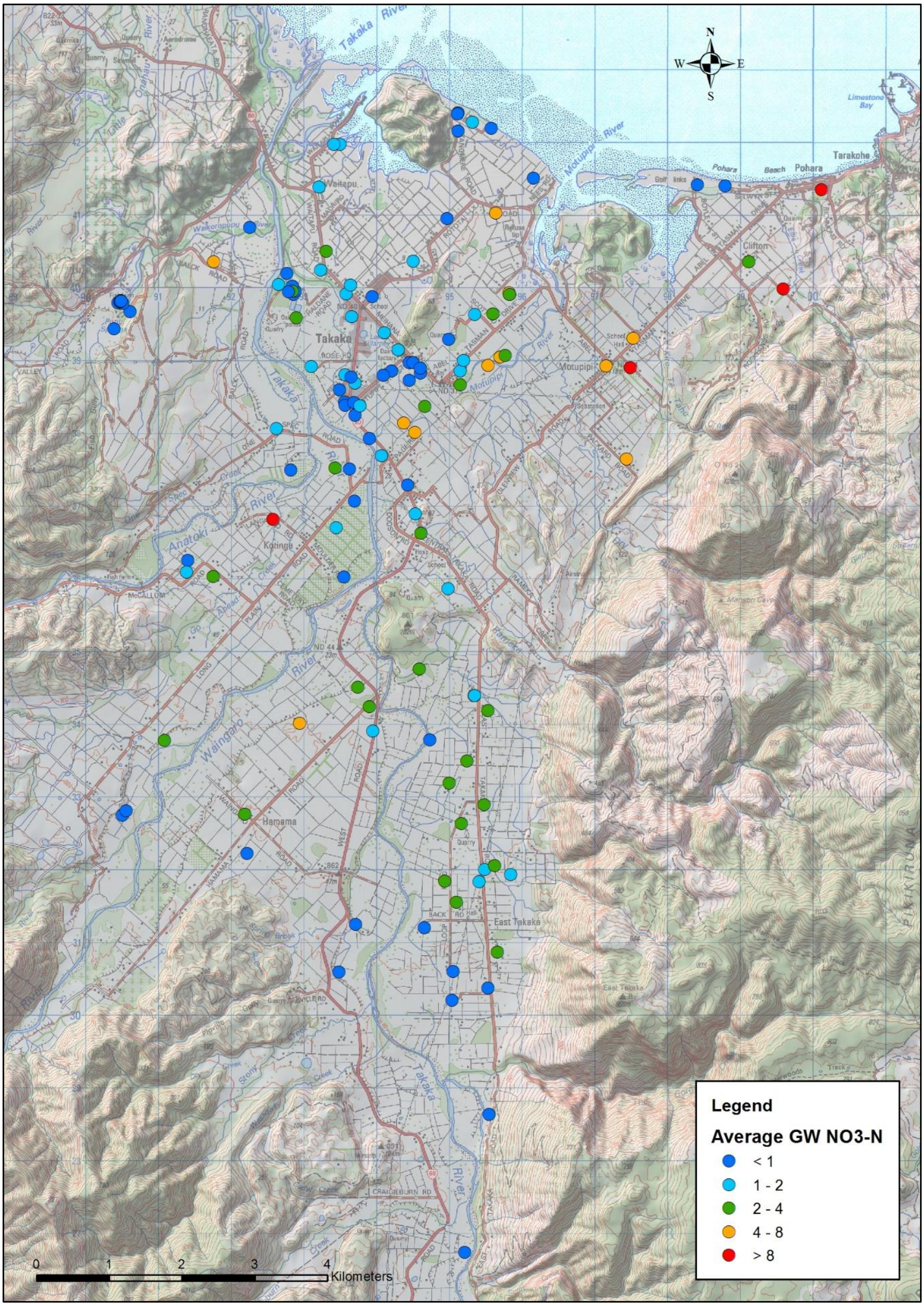

Figure 25: Groundwater nitrate-nitrogen concentrations

(averages from all available measurements)

In Figure 26, annual nitrate-nitrogen loads exiting through Te Waikoropupū main spring are presented along with average annual spring flows (see Section 3.6.1), average annual nitrate-nitrogen concentrations and average annual recharge to the AMA system. Concentration measurements have been averaged from all available measurements in Te Waikoropupū Main Spring groundwater bore, excluding outliers as presented in Appendix 2 of Stark (2015). Annual mass has been calculated as the product of flow and concentration. The main spring flows presented in Figure 26 are scaled by 1/10th, and the recharge time series by 1/20th, to allow plotting on the same axis as concentration.

The following observations are made from the data presented in Figure 26:

- Nitrate-nitrogen concentrations and annual mass have both increased over the period of record presented.
- From approximately 1999 onwards, main spring flows follow similar patterns of variation as land surface and river recharge. Prior to this, patterns in the two time series are more variable. This is likely due to the reliability of the method used by TDC to synthesise main springs flows, as briefly discussed in Section 3.6.1. Uncertainties and approximations in the land surface recharge and river recharge calculations may also contribute to the differences.
- Annual loads are a function of both flow and concentration.

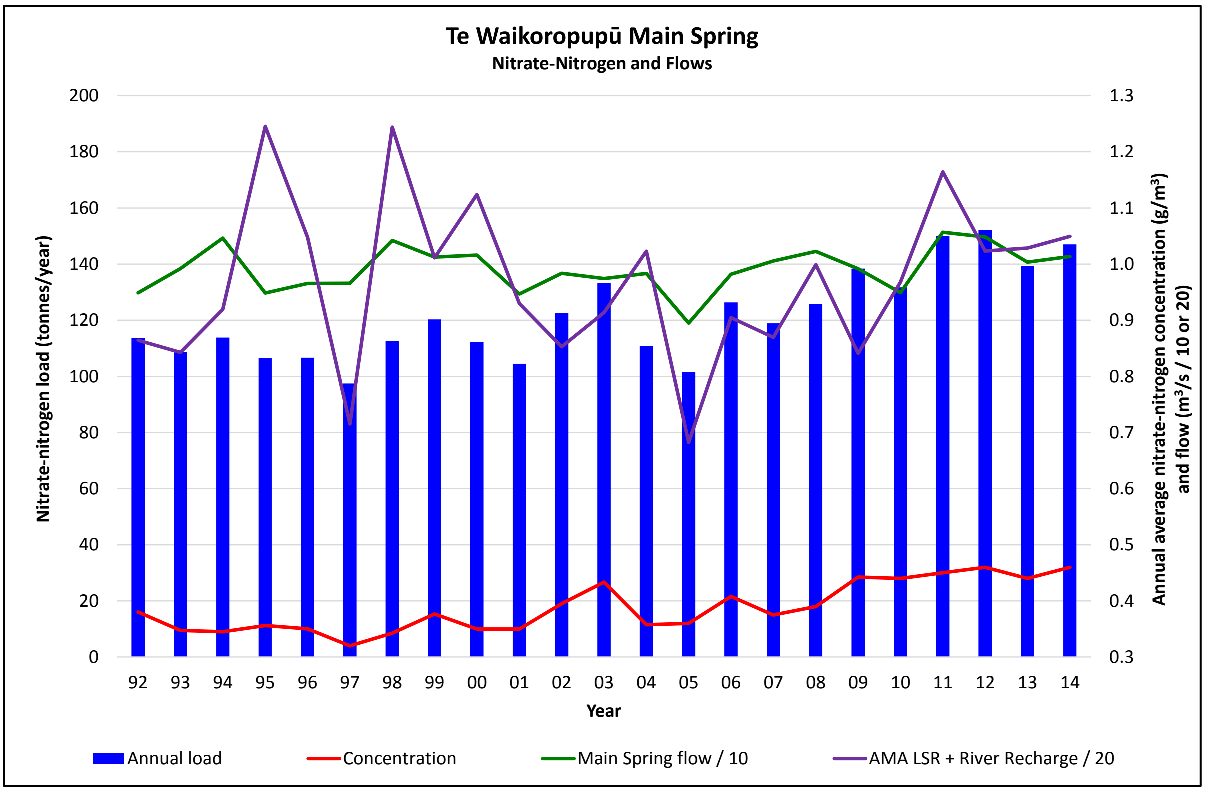

Figure 26: Annual flows and nitrate-nitrogen loads and concentrations for Te Waikoropupū main spring

4 MODELLING CONCEPTS

Interactions between the three main aquifer systems in the Takaka valley and the surface rivers and streams is complex. Furthermore, the location and details of the karst systems are generally unknown. It is therefore difficult to model these specific systems with confidence. What is known, however, is a clear hydraulic response between groundwater inflows (river recharge and land surface recharge), pumping and groundwater outflows (spring flows and off-shore discharge), as has been demonstrated in Section 3.11. Because of this, the dynamic response in groundwater levels and spring discharge has been modelled using a series of eigenmodels, as described by Bidwell & Burbery (2011).

Although eigenmodels are very simplified compared to real aquifers, they are adequate for situations for which dynamic response is the primary interest (Bidwell & Burbery, 2011). They are particularly helpful in situations where the aquifer system is not known in sufficient detail to construct a more detailed numerical model, or where this is prevented by time and budgetary constraints. Consequently, they are suitable for use in the Takaka catchment.

Eigenmodels simulate the response in groundwater levels, aquifer storage and discharge as a result of changes in ‘stresses’ (river recharge, land surface recharge, and pumping) imposed on the aquifer system. They present a 1-dimensional representation of the aquifer system. They incorporate bulk aquifer parameters which are calibrated to match the measured hydraulic response at the calibration site (groundwater levels or spring discharge). Spatial variation down the catchment is accommodated by the inclusion of zones of differing aquifer stresses.

Eigenmodels provide a prediction of total flow discharging from the aquifer system, and do not provide details on how that is divided between surface (spring) discharge and sub-surface off-shore discharge. Consequently, a simple linear relationship is assumed to scale the total modelled discharge to measured flows in these springs, with the remainder assumed to flow sub-surface off shore.

The eigenmodels developed do not simulate contaminant transport. Instead, simple bucket-mixing models have been used to predict changes in water quality from different land use scenarios.

4.1 Model Domains

Three eigen model domains have been developed, one for each of the main Takaka valley aquifers (AMA, TLA and TUGA). Each eigen model domain has been divided into stress zones within which land surface recharge, river recharge and pumping time series have been separately calculated. These are shown on Figure 27 for the AMA eigen model slice. Also shown on this figure is a generic line along which the 1-dimensional model has been formed, the spatial extend of the aquifer system, the location of relevant groundwater level monitoring wells, and relevant surface water monitoring sites. Similar domains are provided in Figure 28 and Figure 29 for the AMA and TUGA aquifers respectively.

Irrigation increases land surface recharge. Irrigation sourced from deeper layers provides additional recharge to the uppermost layer first off. As such, it has been assumed that any additional recharge from irrigation provides additional recharge into the TUGA aquifer and not directly into either the AMA or TLA systems. In addition, the AMA aquifer does not receive any land surface recharge directly into the lower (Zone 4) area due to its confined nature (Figure 27).

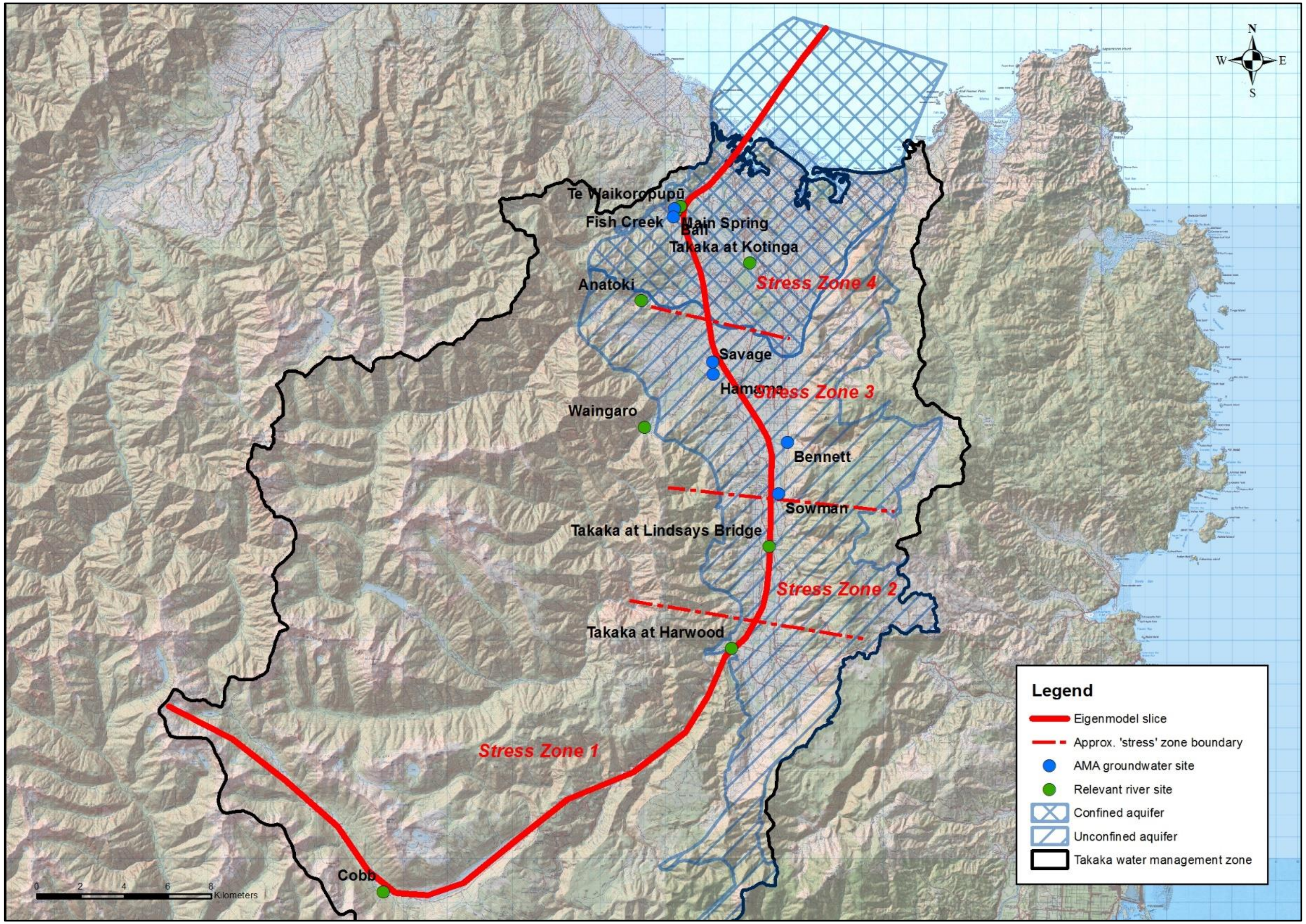

Figure 27: AMA eigenmodel domain

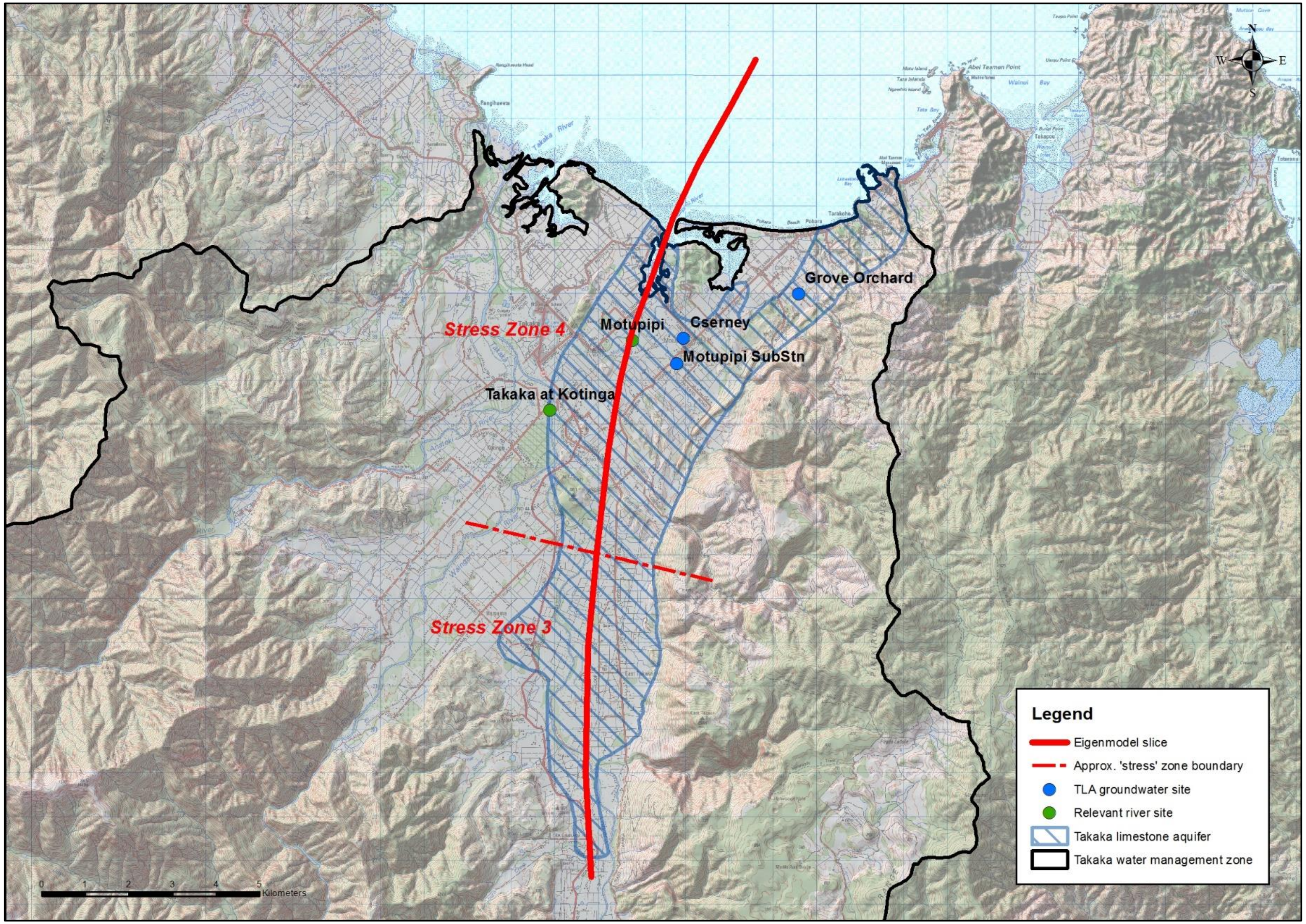

Figure 28: TLA eigenmodel domain

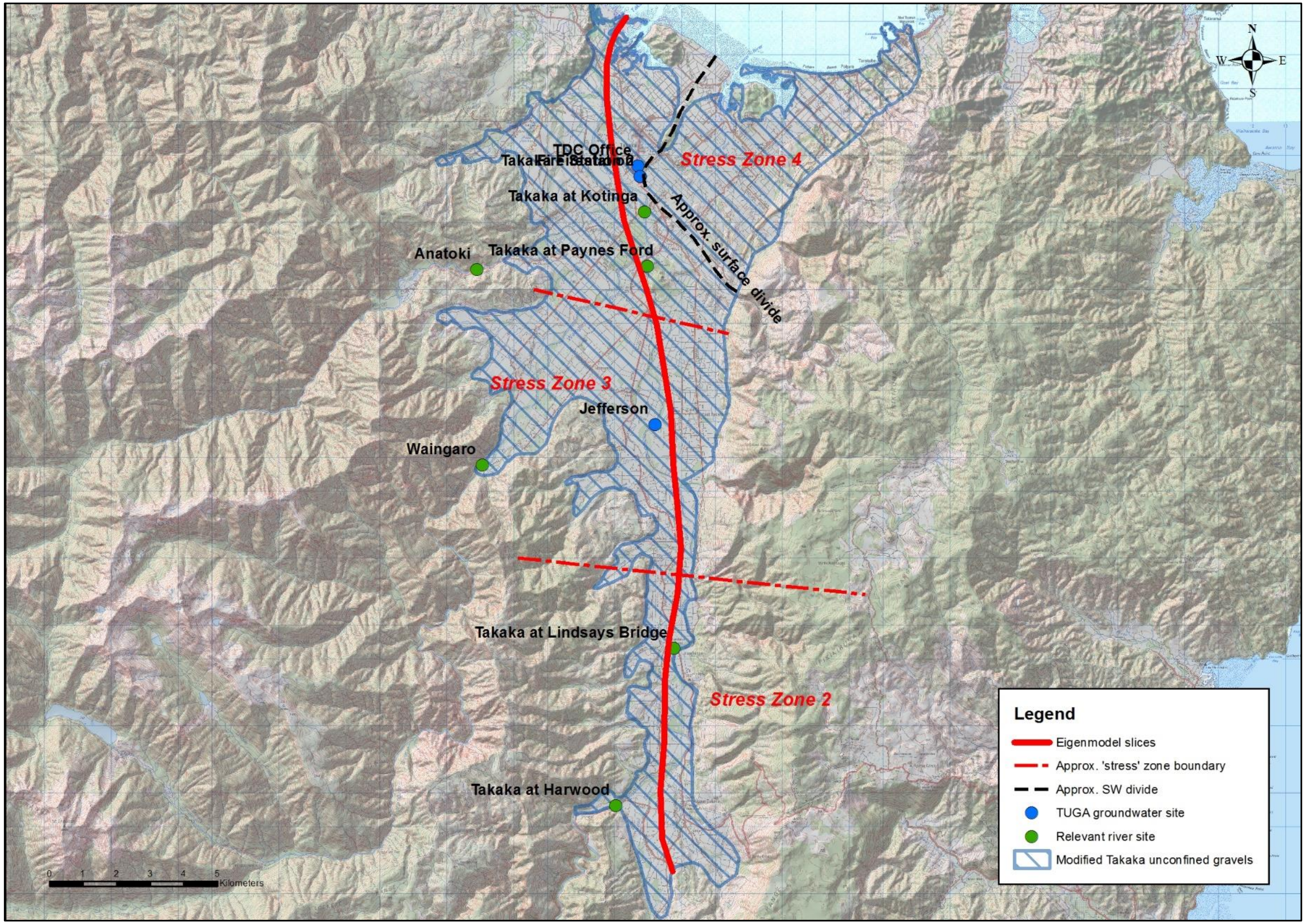

Figure 29: TUGA eigenmodel domain

Eigenmodels have been separately constructed for each monitoring well and for the key river flow sites in each of the aquifer systems, as listed in Table 8.

Table 8: List of eigenmodels developed

Aquifer system	Groundwater level site	River flow site
AMA	Ball	Main Spring
	Bennett	Fish Creek
	Hamama	Spring River
	Main Spring	
	Savage	
	Sowman	
TLA	Cserney	Motupipi River
	Grove Orchard	
	Motupipi Substation	
TUGA	Fire Station (combined)	Paynes Ford
	Jefferson	
	TDC Offices	

As discussed in Section 3.6.1, flows aren't automatically measured directly in Te Waikoropupū main spring. Therefore, calibration has been based on a main spring flow record synthesised by TDC utilising Main Spring groundwater levels. The synthesised record is most valid from 1999 onwards when the monitoring bore was installed. Prior to this date, the synthesis is less robust.

Similarly, no dedicated flow monitoring site is installed for Paynes Ford. Instead, flows at this site have been synthesised based on Takaka River flows at Kotinga less Waingaro River flows (at Hanging Rock) using a relationship provided by TDC.

Flows in the Takaka River at Kotinga are heavily dominated by surface water flowing from the Waingaro River during lows flows and additionally the Takaka River during higher flows. As such, a groundwater-based eigen model is difficult to develop for this site. Therefore, flows at Kotinga have been calculated as the sum of calculated Waingaro River flows (at the Takaka River confluence, using TDC's relationship) and modelled flows at Paynes Ford. This is an additional output to the sites listed in Table 8. Because this output is calculated based on several other model outputs, the predictions are less accurate, so should only be used to give approximately scale and direction of effect.

As discussed in Section 3.5, eigenmodels have been developed for the period 1 January 1980 to 31 December 2014 (a total of 34 years), though calibration has only been based on the period of measured data, which differs from site to site (Table 7). Calibration has particularly focussed on dry periods (low groundwater levels and flows). Specific effort was made to ensure the modelled groundwater levels matched the dynamic response of the measured data, which sometimes resulted in a poorer calibration statistic.

Calibration hydrographs for groundwater levels are provided in Appendix A and for river flow sites in Appendix B. Table 9 summarises the calibrated parameters and key calibration statistics for each site. Definitions of the parameters in Table 9 are as follows:

x/L	=	Ratio of well location to total slice length between the top of the catchment and the coastal (or off shore) boundary (dimensionless)
S	=	Bulk aquifer storativity (dimensionless)
T	=	Bulk aquifer transmissivity (m^2/day)
GW bypass	=	A base groundwater flow that remains in the groundwater system below the invert of the stream bed if the stream was to go dry; relevant only to river flow eigenmodels.
Stress zone T_v	=	Hydraulic residence time (days) for unsaturated (vadose) flow within each stress zone
% River	=	Percentage of total river recharge entering the aquifer system
R^2	=	Square of the correlation coefficient (a measure of model fit)
RMSE	=	root mean square error, defined as:

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

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

The RMSE is also reported as normalised by the range of the measured values.

There is a large degree of variability in the parameters presented in Table 9, which reflects the heterogeneity and variability of the groundwater system in the Takaka valley catchment.

Table 9: Summary of calibrated model parameters and calibration statistics

Aquifer system	Data set	Site	x/L	S	T (m^2/day)	GW bypass (m^3/s)	Stress zone Tv (days)				% River	R^2	RMSE	
							1	2	3	4			Value (m or m^3/s)	Normalised
AMA	Groundwater	Ball	0.98	0.047	22,500	-	4	3	2	1	100%	0.51	0.8	14%
		Bennett	0.67	0.520	488,000	-	4	0	0	0	100%	0.26	3.6	13%
		Hamama	0.75	0.170	292,500	-	4	3	2	1	100%	0.47	3.0	13%
		Main Spring	0.73	0.500	258,100	-	2	1	0	0	100%	0.41	0.52	17%
		Savage	0.73	0.050	217,800	-	4	3	2	1	100%	0.61	3.5	12%
		Sowman	0.70	0.040	221,300	-	4	3	2	1	100%	0.47	5.6	19%
	Flow	Fish Creek	-	0.010	313,600	1.0	4	3	3	3	100%	0.72	1.0	6%
		Main Spring	-	0.050	239,600	1.9	3	2	2	2	100%	0.42	1.4	16%
		Spring River	-	0.100	108,900	0.5	4	3	3	0.7	100%	0.60	2.1	8%
TLA	Groundwater	Cserney	0.85	0.033	201,300	-	-	-	4	3	10%	0.61	1.4	14%
		Grove Orchard	0.85	0.075	69,300	-	-	-	6	5	0%	0.68	1.2	16%
		Motupipi Substation	0.80	0.009	686,000	-	-	-	4	3	10%	0.63	2.0	19%
	Flow	Motupipi River	-	0.005	54,500	0	-	-	1	0	10%	0.27	0.5	3%
TUGA	Groundwater	Fire Station	0.98	0.150	79,700	-	-	0	0	0	100%	0.36	0.3	12%
		Jefferson	0.51	0.130	303,000	-	-	0	0	0	100%	0.22	1.1	22%
		TDC Offices	0.98	0.15	67,600	-	-	0	0	0	100%	0.30	0.3	13%
	Flow	Paynes Ford	-	0.001	653,400	2.45	-	0	0	0	100%	0.71	18.5	1%

4.2 Estimation of Sub-Catchment Flows

Through the modelling process, sub-catchment flow budgets have been estimated, which are reported in Table 10. This summary is for individual groundwater systems and does not include any river runoff down catchment (i.e. net surface water through flow).

Table 10: Summary of sub-catchment flow

Flow component	**Flow (m^3/s)**			
Aquifer	***AMA***	***TLA***	***TUGA***	***Combined***
Inflows				
Land surface recharge	12.5	0.7	10.2	23.4
River recharge	7.3	0.4	0.8	8.5
Total in	**19.8**	**1.1**	**11.0**	**31.9**
Outflows				
Surface water	13.3	0.5	4.7	18.5
Groundwater abstraction	~ 0	~ 0	0.2[(7)]	0.2
Groundwater (off shore)	6.5	0.6	6.1	13.2
Total out	**19.8**	**1.1**	**11.0**	**31.9**

[7] The seasonal peak demand is higher than this.

5 NITRATE-NITROGEN BUDGETS

The eigenmodels are not constructed to simulate transport of contaminants through the groundwater system. Instead, simple 'bucket-mixing' calculations (i.e. assuming fully mixed flow) have been constructed to estimate the effects on the groundwater system from contaminants entering via the land surface. The eigenmodels are used to predict the flows through the groundwater system and the subsequent response in groundwater levels and spring discharge. The flow predictions are then combined with the contaminant bucket-mixing calculations to estimate the long-term effects on water quality.

Below, an estimation of the catchment's current nitrate-nitrogen load is presented. The effects on water quality from future development scenarios are discussed in later sections.

5.1 Estimation of Total Catchment Nitrate-Nitrogen Loads

The current nitrate-nitrogen load exiting the Takaka valley catchment has been estimated by considering the measured concentrations of nitrate-nitrogen in both surface waters and in groundwater (Section 3.13) along with measurements and estimates of through-flows. These are discussed below.

5.1.1 Total Surface Water Nitrate-Nitrogen Loads Exiting the Takaka Valley Catchment

The load exiting the Takaka catchment has been estimated by summing the product of flow and concentration at the most coastal-located river sites. This is summarised in Table 11 and averages 334 tonnes of nitrate-nitrogen annually.

Calculations for the upper Takaka River at the Harwood recorder suggest that approximately 10 tonnes/year exit the upper catchment above the Harwood recorder. This is derived from a mean flow of 14.6 m^3/s and an average nitrate-nitrogen concentration of 0.022 g/m^3. This does not include load entering the deeper AMA system directly in the upper catchment, bypassing the Harwood recorder.

Table 11: Calculation of surface water nitrate-nitrogen loads

River	Site	Average flow (m^3/s) (see Table 4)	Average NO_3-N (g/m^3) (1)	Mass of NO_3-N (tonnes/year)
Takaka River	Kotinga	33.4	0.125	132
Anatoki River	One Spec Bridge	11.9	0.027	10
One Spec Creek	Takaka River confluence	0.3	0.027 (2)	~0
Motupipi River	Reillys Bridge	0.5	1.09	17 (3)
Te Waikoropupū main spring	Main spring	10.0	0.42 (4)	132
Fish Creek	Te Waikoropupū Springs	3.3	0.38 (4)	40
Misc. eastern streams (Motupipi through Pohara)	Various	0.5	0.2 (5)	3
			Total	**334**

(1) Averaged over available measurements from 2013-14, unless otherwise stated.
(2) There are no nitrate-nitrogen measurements for One Spec Creek. Therefore, the same concentration as Anatoki River has been assumed. This has little effect on the final catchment load from surface water.
(3) This is consistent with the findings of Fenemor *et al.* (2008), discussed in Section 2.
(4) Average from weekly measurements by Friends of Golden Bay over the period for 2016-2018.
(5) Based on measurements in Dry River.

5.1.2 Total Groundwater Nitrate-Nitrogen Loads Exiting the Takaka Valley Catchment

Calculations of nitrate-nitrogen mass exiting individual groundwater systems are discussed in Section 5.2. For the whole valley catchment these sum to approximately 380 tonnes/year.

5.1.3 Combined Nitrate-Nitrogen Loads Exiting the Takaka Valley Catchment

Combining the surface water and groundwater estimates discussed above, the total nitrate-nitrogen load exiting the Takaka valley catchment is approximately 714 tonnes/year.

5.1.4 Comparison with Land Surface Input Load Estimates

Estimates of the land surface input loads are presented in Table 12.

Table 12: Calculation of land surface nitrate-nitrogen loads

Land cover	Area (ha)	Average NO_3-N (kg/ha/year)	Loading reference	Mass of NO_3-N (tonnes/year)
Forestry	67,400	0.65	Aqualinc (2014) Table 9, and further calibrated	44
Intensive pasture/dairying	2,275 [(1)]	106	Mirka Langford (Fonterra), estimated average for Takaka valley	241
Dryland/low intensity pasture	5,465 [(2)]	68	Mirka Langford (Fonterra), estimated average for Takaka valley	372
Native grassland / hill scrubland	16,860	2.5	Hanson (2010) Tables 1-4, and further calibrated	42
		Total		**699**

(1) Existing irrigated area (Table 6).
(2) Estimated based on remaining unirrigated area on valley floor.

The average loading rates in Table 12 for forestry and grassland have been based on literature values, then slightly adjusted from these literature-based values so that modelled mass exiting the Waingaro River catchment approximately equals the measured mass (flow multiplied by concentration) over the 2013-14 period. This calibrates the loads for existing land use, based on nitrate-nitrogen concentrations measured at the Waingaro at Hanging Rock site. This was further verified for the upper Takaka River catchment down to Harwood recorder.

The average nitrate-nitrogen concentrations under the different land uses are generally consistent with values reported by Cameron *et al.* (2013), where applicable, though Cameron *et al.* reports a wide range.

Total mass estimated entering the Takaka valley system through the land surface equates to approximately 699 tonnes/year. This is approximately the same order of magnitude as the total calculated mass exiting the system (714 tonnes/year, discussed in Section 5.1.3). Differences are due to assumptions and uncertainties in the calculations and representativeness of the measurements.

5.2 Estimation of Sub-Catchment Nitrate-Nitrogen Loads

Similar calculations have been completed to estimate nitrate-nitrogen loads passing through the AMA, TLA and TUGA aquifer systems. These are presented in Table 13. This summary is for individual groundwater systems and does not include any load carried directly out of the catchment via river runoff.

Table 13: Summary of sub-catchment nitrate-nitrogen loads

Flow component	Nitrate-nitrogen (tonnes/year)			
Aquifer	***AMA***	***TLA***	***TUGA***	***Combined***
Input				
Land surface (1)	**258**	**63**	**435**	**756**
Output				
Groundwater discharged via surface water	172 (2)	15 (3)	193 (4)	380
Groundwater discharged off shore (5)	86	48	242	376
Total out	**258**	**63**	**435**	**756**

(1) Calculated using the same method as presented in Table 12, but for surface areas overlying individual aquifer systems.
(2) Calculated as the product of the flows in Te Waikoropupū main spring and Fish Creek (10.0 m^3/s and 3.3 m^3/s, respectively, consistent with Figure 21 of Thomas & Harvey, 2013), and associated nitrate-nitrogen concentrations (0.42 and 0.38 g/m^3 respectively, Table 11).
(3) Calculated as the product of Motupipi River flow (0.5 m^3/s) and Motupipi Spring concentration (1.09 g/m^3), less contribution from the TUGA system (approximately 2 tonnes/year).
(4) Calculated as the sum of individual products of the estimated TUGA groundwater flow component and concentration, estimated at various surface water sites.
(5) Individually calculated to balance the modelled land surface recharge mass loads for each aquifer system and verified as acceptable based on independent calculations of the product of calculated off-shore flow (Table 10) and a representative groundwater nitrate-nitrogen concentration at the discharge zone for each aquifer. As an example, for the AMA system, the calculated offshore flow was 6.5 m^3/s and the mean nitrate-nitrogen concentration 0.41 g/m^3 from Te Waikoropupū because there should be no further nitrate input into the confined AMA down-gradient to the coast.

The above calculations have assumed that there is no additional nitrate-nitrogen entering the groundwater systems directly from the up-catchment Takaka River. This is a reasonable assumption given the very low concentrations measured at the Harwood recorder (Section 3.13).

6 DEVELOPMENT SCENARIOS

The calibrated eigenmodels have been used to assess different management scenarios. These scenarios consider the response in both groundwater levels and spring discharge from different groundwater abstraction and land use options within the study area. The various scenarios considered are as follows:

- Scenario 1: No consumptive use
- Scenario 2: Double irrigation
- Scenario 3: All existing irrigation groundwater sourced
- Scenario 4: Cobb Dam effects
- Scenario 5: Waingaro River
- Scenario 6: No Development
- Scenario 7: Likely irrigation 1
- Scenario 8: Likely irrigation 2
- Scenario 9: Likely irrigation 3

These scenarios are discussed in further detail in the following sections.

6.1 Scenario Descriptions

6.1.1 Scenario 1: No Consumptive Use

The *No Consumptive Use* scenario represents the state of the groundwater system unaffected by irrigation, other consumptive groundwater abstraction (e.g. water supplies) and subsequent use. This scenario does not represent the true 'natural' state of the system for several reasons. Firstly, it assumes existing land cover remains (e.g. pasture and forestry). Secondly, it assumes the existing altered state of waterways remains (stop banks, channel alignments, drains, etc.). It also assumes that the Salmon Farm at Te Waikoropupū Springs and Cobb Dam operate as normal (i.e. the scenario considers actual river flows as modified by these activities). This scenario represents the dynamic state of the groundwater system should all consumptive water use cease, assuming the Cobb Dam and the Salmon Farm diversions remain.

The No Consumptive Use scenario has been founded on the calibrated model with all irrigation use (both from groundwater and surface water) switched off. All land use has been assumed to remain as existing land use with corresponding dryland land surface recharge.

6.1.2 Scenario 2: Double Irrigation

Figure 30 presents, for the whole catchment, the likely and unlikely plausible future irrigable areas (estimated by Mirka Langford (Fonterra), Corrigan Sowman, and Joseph Thomas (TDC), *pers. comms.*) overlain by the existing and proposed irrigated areas. As presented in Table 6, existing irrigated areas sum to approximately 2,275 ha with an additional 533 ha proposed. The plausible future irrigable areas shown in Figure 30 sum to an additional 1,841 ha. This, combined with the proposed irrigated areas, equates to an additional 104% of the existing irrigated area. Consequently, the *Double Irrigation* scenario represents the approximate state of the groundwater system should these proposed and plausible areas be irrigated. It also provides a feel for the sensitivity of the modelled outputs to changes in irrigated area.

This scenario is based on the calibrated model but with double the existing irrigated area and associated irrigated land surface recharge. For simplicity, it has been assumed that new irrigated areas are located in the near vicinity to existing irrigation, with the same characteristics as existing land use, irrigation methods and water sources (i.e. both groundwater and surface water sourced water). Therefore, irrigated area has simply been doubled without further consideration to location or water source.

6.1.3 Scenario 3: All Existing Irrigation Groundwater Sourced

This scenario further explores the effects on the groundwater system from groundwater abstraction if it is assumed that all existing irrigation is sourced only from groundwater. This scenario is based on the calibrated model but with all surface water takes assumed to be supplied from valley floor groundwater without additional water introduced via surface water supplied irrigation. The following assumptions are made:

- All land use and locations of irrigated areas remain unchanged, hence land surface recharge does not change. What does change is the source of water; surface water takes are now supplied from groundwater.
- Groundwater supply is assumed to be 100% reliable, so no restrictions are applied to the take.
- Changes to irrigation water sources as follows:
  - There is currently no groundwater supplied irrigation in stress zones 1 and 2; all irrigation (667 ha currently consented) is supplied from surface water. For the purpose of this theoretical scenario, it is assumed that all surface water irrigation has switched to groundwater supplied from the AMA system.
  - For stress zone 3, 80 ha is currently consented for supply from the AMA system and 236 ha from surface water. It has been assumed that all irrigated area is supplied from the AMA system.
  - In the lower valley (stress zone 4), approximately 100 ha of irrigation is currently supplied from the TLA, 484 ha from the TUGA and 1,060 ha from surface water. It has been assumed that surface water supplied irrigation will be supplied from groundwater with apportionment equivalent to existing groundwater supply. This results in approximately 282 ha irrigated from the TLA and 1,362 ha from the TUGA.
- Takes from the Takaka and Waingaro rivers are assumed to be replaced by groundwater takes. Hence, these river flows are correspondingly higher, as is the consequently groundwater recharge from those rivers.

6.1.4 Scenario 4: No Cobb Dam

The *No Cobb Dam* scenario assesses the effects of the Cobb Dam on the groundwater system. This is achieved by substituting the contribution of measured river flows from the Cobb River in the Takaka River at Harwoods with a synthesised naturalised time series of river flows (provided by Trust Power Ltd). The modelled resulting responses in groundwater levels and river flows are then compared to the calibration scenario. This represents an estimate of the groundwater system response as if the dam did not exist.

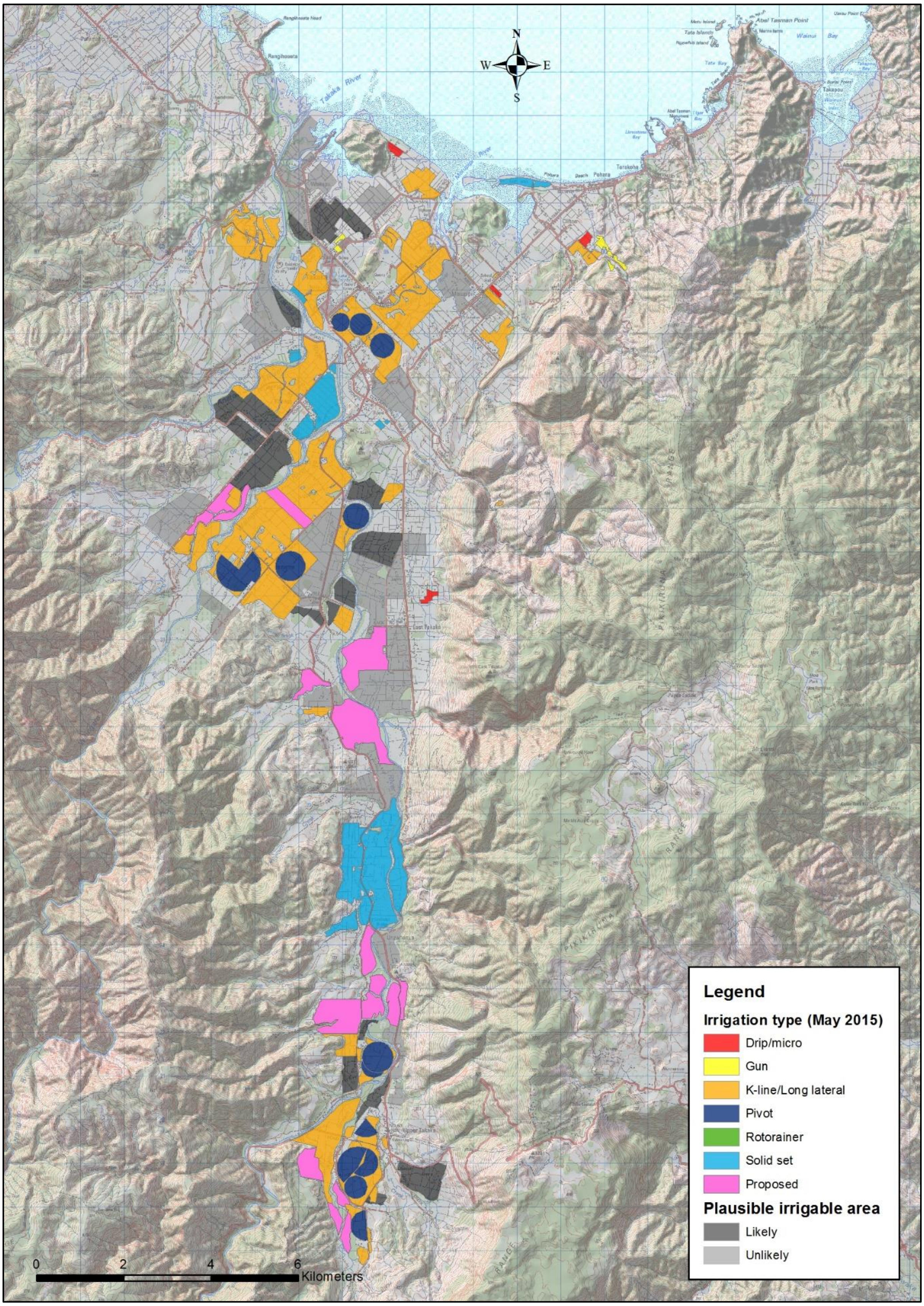

Figure 30: Existing and plausible irrigable areas
(plausible irrigable areas provided by Mirka Langford (Fonterra), Corrigan Sowman and Joseph Thomas (TDC), as at May 2015)

6.1.5 Scenario 5: Waingaro River Recharge

The *Waingaro River Recharge* scenario assesses the sensitivity of the groundwater system to Waingaro River flow losses to groundwater. This is achieved by removing the Waingaro River flow losses to groundwater, while maintaining the same river flows. The resulting responses in groundwater levels and river flows are then compared to the calibration scenario.

6.1.6 Scenario 6: No Development

The *No Development* scenario (originally labelled Natural State) approximates the state of the Takaka catchment without any alteration by human activity. This is simulated by removing the Cobb Dam (as was undertaken in Scenario 4) and assuming all existing pasture or native grassland is instead covered in forest.

6.1.7 Scenario 7: Likely Irrigation 1

The *Likely Irrigation 1* scenario is based on the calibrated model with additional irrigation in areas that are most likely to be developed in the near future, as at August 2015 (Joseph Thomas, TDC, *pers. comm*.). Figure 31 maps the existing irrigated areas and the likely irrigated areas as estimated by TDC. The additional likely irrigated areas have been added to the models to derive the subsequent aquifer response. Those areas located adjacent to the Anatoki and Waingaro rivers are assumed to be sourced from those rivers (surface water supplied irrigation); all other areas are assumed to be groundwater sourced. The total likely additional irrigated areas sum to approximately 494 ha[8] over and above existing irrigated land.

6.1.8 Scenario 8: Likely Irrigation 2

The *Likely Irrigation 2* scenario is based on the Likely Irrigation 1 scenario with an additional 90 l/s of allocation taken in the upper area above Dry Creek (stress zone 2), as assessed by Joseph Thomas (TDC, *pers. comm*.). An allocation of 90 l/s equates to an irrigated area of approximately 180 ha (based on TDC's allocation of 30 mm/week, or 0.5 l/s/ha). Hence, this irrigated area has been added to the Likely Irrigation 1 models and the subsequent response predicted.

6.1.9 Scenario 9: Likely Irrigation 3

The *Likely Irrigation 3* scenario is based on the Likely Irrigation 1 scenario with an additional 150 l/s of allocation taken in the upper area above Dry Creek (stress zone 2), as assessed by Joseph Thomas (TDC, *pers. comm*.). An allocation of 150 l/s is an additional allocation of 60 l/s over and above the Likely Irrigation 2 scenario, and equates to an irrigated area of approximately 300 ha (based on TDC's allocation of 0.5 l/s/ha). Hence, this irrigated area has been added to the Likely Irrigation 1 models and the subsequent response predicted.

[8] Subsequent to these calculations, TDC have estimated different areas of 'likely' irrigation' based on their waiting list for water permits to take water. However, the modelled hydraulic response of the groundwater system will not differ markedly from the response presented here.

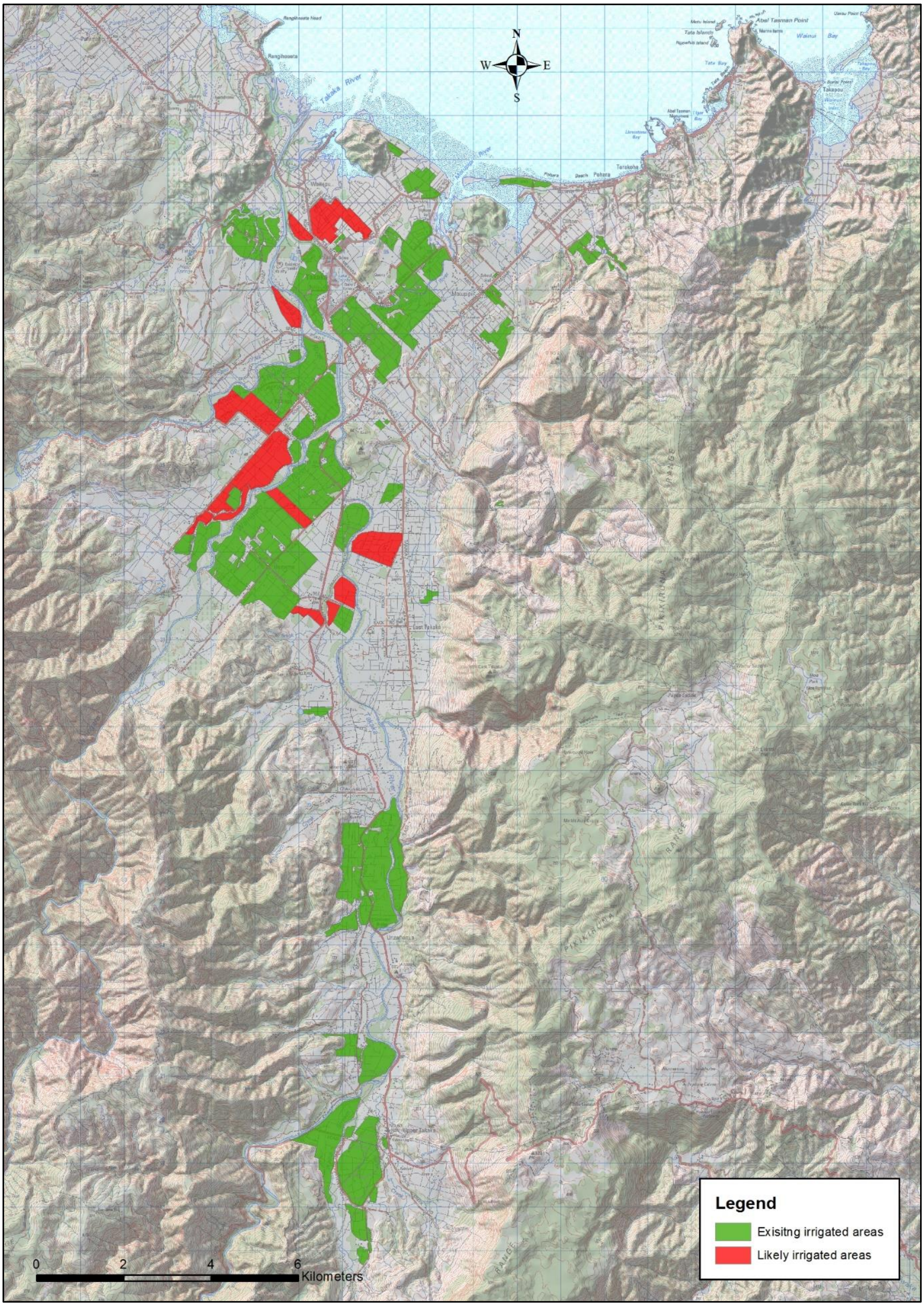

Figure 31: Likely irrigable areas
(likely irrigable areas provided by Joseph Thomas (TDC), as at August 2015)

6.2 Scenario Results

The effects of different development scenarios have been assessed by comparing modelled results, as follows:

- The effects of irrigation on groundwater levels and river flows have been assessed by comparing model outputs from scenarios 1, 2 and 3 with the calibrated (Status Quo) models;
- The effects of the Cobb Dam, Waingaro River recharge, and existing human activity have been assessed by comparing outputs from scenarios 4, 5 and 6 with the calibrated (Status Quo) models; and
- The effects of irrigating the future likely irrigated land have been assessed by comparing outputs from scenarios 7-9 with the calibrated (Status Quo) models.

These are each presented below. So as not to overwhelm the reader with many model outputs, only results from currently active sites, plus the Cserney well at Motupipi (to represent groundwater levels in the TLA system) and Paynes Ford flow (to represent discharge from the TUGA from the upper valley), have been considered.

Appendix C compares groundwater level hydrographs for the calibration scenario with results from scenarios 1, 2 and 3, zoomed-in to the period 2013-15. Similar comparisons for river flow sites are presented in Appendix D which includes hydrographs (also for the period 2013-15) and river flow-duration curves. Similarly, Appendix E and Appendix F present groundwater level and flow hydrographs (respectively) comparing scenarios 4-6 with calibration, and Appendix G and Appendix H present the same, comparing scenarios 7-9 with calibration.

Table 14 summarises the average flow, 7-day MALF and average annual zero-flow days for each of the four river flow sites considered. Also included in Table 14 are estimates of the 1-in-5 year and 1-in-10 year 7-day low-flows for the river (assuming a log-normal distribution). Average and minimum groundwater levels for the modelled wells under each scenario are listed in Table 15.

There is little monitoring data with which to calibrate prior to approximately 1990. As a result, the reliability of calibration to this earlier period is not known. Consequently, statistics below are presented only for the period 1990-2014 (inclusive).

6.2.1 Effects of Irrigation

Groundwater abstraction for irrigation typically results in a lowering of groundwater levels. In addition, irrigation results in an increase in land surface recharge into the uppermost aquifer. If the irrigation water source is surface water (rather than groundwater), then this provides additional land surface recharge without a reduction in groundwater levels from pumping. Consequently, surface-water sourced irrigation can result in shallow groundwater levels (and consequential stream flows) that are higher compared to a no-irrigation scenario.

By considering Appendix C, groundwater levels are generally lower with increased groundwater irrigation due to the net removal of water. However, shallow groundwater levels in the TUGA system are predicted to be higher under increased irrigation Scenario 2 compared to Status Quo (Calibration) due to the additional land surface recharge, primarily from surface water sourced irrigation. The shallow TUGA system directly receives the additional land surface recharge from irrigation.

The deeper AMA and TLA systems do not show this recharge effect as they are more disconnected from the surface recharge compared to the TUGA system. Specifically, the coastal TLA system is confined below the TUGA system and therefore does not receive the full benefits of direct additional recharge. As such, groundwater levels are lower with additional irrigation due to the increased abstraction with reduced additional recharge reaching this system.

The Likely Irrigated scenarios (scenarios 7-9) all present less effect than the double irrigation scenario with groundwater levels and river flows not too different from Status Quo.

Table 14: River flow statistics

River	Measured	Status Quo (Calibration)	Scenario 1 (No Consumptive)	Scenario 2 (Double Irrigation)	Scenario 3 (GW Supplied)	Scenario 4 (No Cobb Dam)	Scenario 5 (Waingaro River)	Scenario 6 (No Development)	Scenario 7 (Likely Irrig 1)	Scenario 8 (Likely Irrig 2)	Scenario 9 (Likely Irrig 3)
River flow statistics for the period 1990-2014 (unless otherwise stated)											
Average (l/s)											
Main Spring	9,910 (synthesised by TDC)	9,740	9,910	9,560	9,670	8,890	9,290	8,480	9,720	9,720	9,710
Fish Creek	3,390	3,060	3,110	3,000	2,930	2,810	2,930	2,470	3,050	3,050	3,040
Spring River	10,135	10,080	10,190	9,930	9,750	9,460	9,750	8,580	10,070	10,070	10,060
Motupipi River	470 (weedy) (2006-2014)	380	400	360	310	370	380	300	380	380	370
Paynes Ford	12,100 (synthesised)	11,820	11,680	12,260	11,660	11,110	11,430	10,310	11,810	11,810	11,800
Kotinga (calculated)	33,440	31,270	31,010	31,700	31,100	30,550	30,870	29,760	31,240	31,240	31,230
7-day MALF (l/s)											
Main Spring	7,290 (synthesised by TDC)	7,250	7,490	7,010	7,210	6,320	6,810	5,950	7,240	7,240	7,230
Fish Creek	570	530	640	430	360	290	420	230	510	510	500
Spring River	5,510	5,640	5,830	5,350	5,190	4,900	5,320	4,540	5,620	5,610	5,600
Motupipi River	210 (weedy) (2006-2014)	240	270	210	150	230	240	190	240	240	230
Paynes Ford	140 (synthesised)	70	110	50	40	0	20	0	70	70	60
Kotinga (calculated)	3,580	3,020	3,000	3,000	2,970	2,700	2,910	2,680	3,020	3,020	3,020

River flow statistics for the period 1990-2014 (unless otherwise stated)											
River	Measured	Status Quo (Calibration)	Scenario 1 (No Consumptive)	Scenario 2 (Double Irrigation)	Scenario 3 (GW Supplied)	Scenario 4 (No Cobb Dam)	Scenario 5 (Waingaro River)	Scenario 6 (No Development)	Scenario 7 (Likely Irrig 1)	Scenario 8 (Likely Irrig 2)	Scenario 9 (Likely Irrig 3)
Zero-flow days (average/year)											
Main Spring	0 (synthesised by TDC)	0	0	0	0	0	0	0	0	0	0
Fish Creek	0	1	0	3	5	6	3	6	1	1	1
Spring River	0	0	0	0	0	0	0	0	0	0	0
Motupipi River	0 (weedy) (2006-2014)	0	0	0	0	0	0	0	0	0	0
Paynes Ford	24 (synthesised)	27	22	33	31	69	37	72	28	28	27
Kotinga (calculated)	0	0	0	0	0	0	0	0	0	0	0

River flow statistics for the period 1990-2014 (unless otherwise stated)											
River	Measured	Status Quo (Calibration)	Scenario 1 (No Consumptive)	Scenario 2 (Double Irrigation)	Scenario 3 (GW Supplied)	Scenario 4 (No Cobb Dam)	Scenario 5 (Waingaro River)	Scenario 6 (No Development)	Scenario 7 (Likely Irrig 1)	Scenario 8 (Likely Irrig 2)	Scenario 9 (Likely Irrig 3)
1 in 5 year low flow (l/s) (2005/06 season) (approximate)											
Main Spring	6,385 (synthesised by TDC)	6,465	6,720	6,200	6,420	5,625	6,020	5,320	6,460	6,460	6,450
Fish Creek	70	115	260	80	115	75	170	25	110	110	100
Spring River	4,430	4,710	4,930	4,360	4,200	4,090	4,390	3,890	4,690	4,690	4,680
Motupipi River	180 (weedy) (2006-2014)	185	220	150	105	180	180	150	180	180	180
Paynes Ford	0 (synthesised)	0	0	0	0	0	0	0	0	0	0
Kotinga (calculated)	2,690	2,180	2,150	2,170	2,160	2,095	2,130	2,100	2,170	2,170	2,170
1 in 10 year low flow (l/s) (2009/10 season) (approximate)											
Main Spring	5,985 (synthesised by TDC)	6,110	6,370	5,850	6,070	5,320	5,670	5,050	6,100	6,100	6,090
Fish Creek	35	65	180	45	75	45	120	10	60	60	55
Spring River	4,005	4,330	4,560	3,960	3,810	3,760	4,010	3,620	4,310	4,310	4,300
Motupipi River	165 (weedy) (2006-2014)	165	200	130	90	160	160	140	160	160	160
Paynes Ford	0 (synthesised)	0	0	0	0	0	0	0	0	0	0
Kotinga (calculated)	2,330	1,890	1,860	1,880	1,880	1,865	1,860	1,870	1,880	1,880	1,880

Table 15: Groundwater level statistics

Groundwater level statistics for the period 1990-2014 (unless otherwise stated)												
Aquifer	Site	Measured	Status Quo (Calibration)	Scenario 1 (No Consumptive)	Scenario 2 (Double Irrigation)	Scenario 3 (GW Supplied)	Scenario 4 (No Cobb Dam)	Scenario 5 (Waingaro River)	Scenario 6 (No Development)	Scenario 7 (Likely Irrig 1)	Scenario 8 (Likely Irrig 2)	Scenario 9 (Likely Irrig 3)
Average (m above msl)												
AMA	Main Spring	15.8 (synthesised by TDC)	15.4	15.5	15.2	15.3	14.4	14.8	13.8	15.4	15.4	15.3
	Savage	33.1	33.5	33.5	33.5	33.4	32.1	32.7	29.7	33.5	33.5	33.5
	Sowman	38.3	35.2	35.2	35.2	35.1	33.8	34.5	31.3	35.2	35.2	35.2
TLA	Cserney	12.0	12.0	12.6	11.3	9.9	11.7	11.8	9.5	12.0	12.0	12.0
TUGA	Fire Station	7.2	7.5	7.4	7.8	7.3	6.9	7.1	6.2	7.5	7.5	7.5
	TDC Office	6.8	6.8	6.7	7.1	6.6	6.2	6.4	5.6	6.8	6.8	6.8
Minimum (m above msl)												
AMA	Main Spring	14.4 (synthesised by TDC)	13.1	13.3	13.0	13.1	12.5	12.6	12.0	13.1	13.1	13.1
	Savage	21.0	20.5	20.7	20.2	20.4	19.6	19.7	17.9	20.5	20.5	20.5
	Sowman	19.7	19.9	20.2	19.7	19.8	19.1	19.2	17.5	19.9	19.9	19.9
TLA	Cserney	6.8	6.3	7.0	5.3	3.5	6.1	6.1	5.4	6.3	6.3	6.3
TUGA	Fire Station	6.4	6.7	6.5	7.0	6.4	5.9	6.3	5.4	6.7	6.7	6.7
	TDC Office	6.4	6.1	6.0	6.3	5.9	5.6	5.8	5.1	6.1	6.1	6.1

6.2.2 Effects of the Cobb Dam

The Cobb Dam has the overall effect of raising groundwater levels, increasing low flows and reducing the number of zero-flow days in Fish Creek and the Takaka River at Paynes Ford. This is achieved by augmenting river flows, particular during low-flow periods, by water that has been harvested during higher flow periods (and would otherwise discharge into the sea during those periods).

6.2.3 Effects of Groundwater Recharge from the Waingaro River

Groundwater recharge for the Waingaro River has an overall positive benefit on groundwater levels in the lower catchment and subsequent Takaka River flows at Kotinga, similar to the Cobb Dam, but to a lesser magnitude.

6.2.4 Effects of Human Activity

Comparing the outputs from Scenario 6 with calibration, human activity has the net effect of increasing land surface recharge into the groundwater system (less water is consumed by grass compared to forest). This, combined with no regulating effects of the Cobb Dam, results in lower groundwater levels and lower river and spring flows under the No Development scenario compared to status quo.

6.2.5 Effects on Water Quality

The effects on water quality for individual aquifer systems have been estimated and are summarised below. These calculations assume full mixing in both groundwater and surface water. If the aquifer systems are not fully mixed, then the concentration predictions will be different to what is discussed below.

6.2.5.1 Additional Scenarios

Since the original draft of this report, further scenarios were run to inform recommendations by the Takaka FLAG on flow and nitrate-nitrogen triggers or limits for water bodies in the Takaka catchment. These additional scenarios are discussed in the following sections.

Figure 32 (supplied by TDC) shows the locations of additional irrigable land in the valley floor and has been used to inform additional scenarios. Criteria for this mapping included topography, land suitability for irrigation, access to water sources[9], and land ownership. These areas are similar to those shown in Figure 30 and Figure 31 but with small differences due to revisions by local members of the Takaka FLAG after the earlier figures were created. The results of these additional scenarios are presented below and are consistent with the results from Scenarios 7-9 discussed above.

Although the future irrigated land uses may change, it has been assumed that the valley land uses are exclusively for dairy farming under current land management practices, as dairying is effectively a 'worst case land use' scenario in terms of both seasonal water use and nitrogen leaching.

'Proposed irrigation' corresponds to potentially irrigable land represented by TDC's waiting list for irrigation water permits. 'Plausible irrigation' represents potentially irrigable land meeting the criteria listed above, but not on TDC's waiting list. 'Unlikely irrigation' represents potentially irrigable land but one or more of the above criteria mean that this land would be unlikely to be irrigated in the medium term.

[9] For example, some areas in the valley with streams or the river drying out regularly and without other potential water sources were excluded.

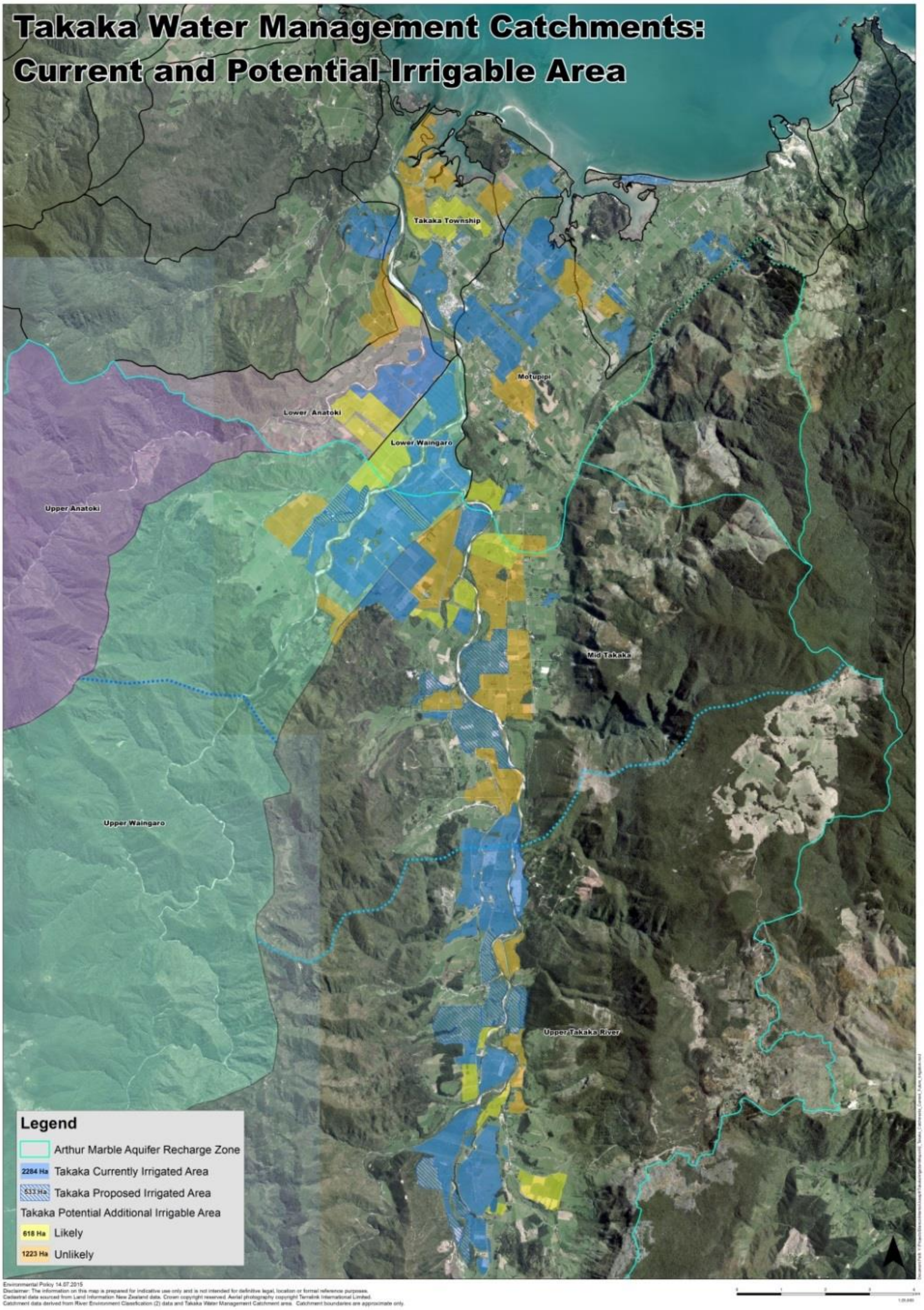

Figure 32: Current and potential irrigation areas in Takaka Valley (supplied by TDC)

A further scenario labelled '*766 l/sec AMA recharge zone allocation limit*' has also been included as an option raised, but not unanimously adopted, by the Takaka FLAG in their discussions about allocation triggers or limits for the Te Waikoropupū Springs. For modelling purposes, it was assumed that additional allocations would be used for dairy irrigation, even though other water uses would also be possible.

6.2.5.2 Effects on AMA Groundwater and Te Waikoropupū River Water Quality

Considering groundwater nitrate-nitrogen concentrations, irrigation on the valley floor results in a nitrate nitrogen load through the AMA system of an additional 38 tonnes/year (approximately) over and above dryland pasture (assumed). This, combined with the catchment's background nitrate-nitrogen load, results in a mean groundwater concentration in Te Waikoropupū main spring of 0.42 g/m^3 (based on measurements taken by Friends of Golden Bay over 2016-2018).

Based on a groundwater system through-flow of approximately 19.8 m^3/s (Table 10), if the 38 tonnes/year load were to be eliminated (under Scenario 1, No Consumptive Use), then the concentration in Te Waikoropupū main spring would be approximately 0.36 g/m^3.

Under Scenario 2 (Double Irrigation), an additional 38 tonnes/year load is estimated to contribute to Te Waikoropupū main spring groundwater, which would increase the concentration to approximately 0.47 g/m^3.

Under Scenario 6 (No Development), the load entering the AMA system assuming the catchment has natural land cover (predominantly forest) is estimated to be approximately 8 tonne/year. Assuming no change to load from the upper catchment, then the concentration in Te Waikoropupū main spring bore is estimated to be approximately 0.01 g/m^3.

Projected nitrate-nitrogen concentrations at Te Waikoropupū Springs are summarised for the various scenarios in Table 16 and plotted in Figure 33. Also include in Table 16 are the irrigated and dryland areas within the AMA recharge zone for each of these scenarios.

Table 16: Modelled nitrate-nitrogen concentrations at Te Waikoropupū Springs for various development scenarios

Scenario	Area of irrigated dairy (ha)	Area of dryland dairy (ha)	Nitrate-nitrogen concentration (g/m^3)		
			AMA fully mixed	Main springs	Fish Springs
Current Dairy (Status Quo)	993	2,063	0.41	0.42 (1)	0.38 (1)
Current+Proposed	1,462	1,594	0.44	0.44	0.40
Current +Proposed+Plausible	2,045	1,011	0.47	0.48	0.44
Current+Proposed+Plausible +Unlikely	3,056	0	0.54	0.54	0.50
766 l/sec AMA upper allocation limit from FLAG deliberations	1,544	1,512	0.44	0.45	0.41
Double current irrigation (Scenario 2)	1,986	1,070	0.47	0.47	0.43
100% dryland dairy (Scenario 1)	0	3,056	0.35	0.36	0.32
No Development - AMA recharge zone (Scenario 6)	0	0	0.002	0.01	-0.03 (2)

(1) Equivalent to measured mean nitrate-nitrogen concentration from Friends of Golden Bay (FOGB) weekly data 2016-2018. Only FOGB data has been used in this analysis to avoid any uncertainties created by use of different laboratories or analytical methods. However, the inclusion of all data makes little difference to the average values.

(2) These calculations are based on an incremental change from the status quo and this negative result reflects the uncertainty margins of the modelling. A value of approximately zero is pragmatic.

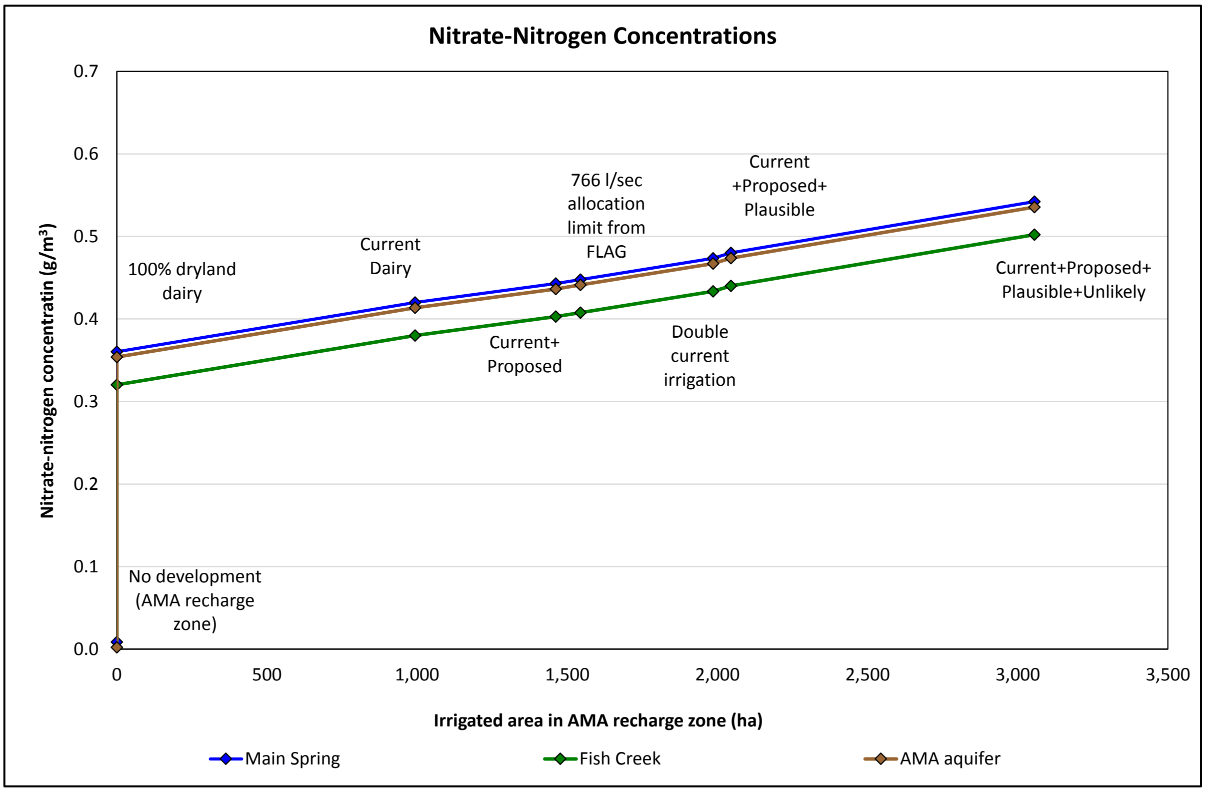

Figure 33: Modelled nitrate-nitrogen concentrations at Te Waikoropupū Springs for scenarios shown in Table 16

6.2.5.3 Effects on TLA Groundwater and Motupipi River Water Quality

Similarly, current irrigation on the valley floor results in a nitrate nitrogen load through the TLA system of an additional 9 tonnes/year (approximately) over and above dryland pasture (assumed). This, combined with the catchment's background nitrate-nitrogen load, results in a mean groundwater concentration in the TLA bores of approximately 2.4 g/m^3 (averaged from several TLA bores).

Based on a groundwater system through-flow of approximately 1.1 m^3/s (Table 10), if the 9 tonnes/year load were to be eliminated (under Scenario 1, No Consumptive Use), then the concentration in TLA bores would be approximately 2.15 g/m^3.

Under Scenario 2 (Double Irrigation), an additional 9 tonnes/year load is estimated to contribute to TLA groundwater, which would increase the concentration to approximately 2.65 g/m^3.

Under Scenario 6 (No Development), the load entering the TLA system assuming all forestry is estimated to be approximately 2 tonne/year. Assuming no change to load from the upper catchment, then the concentration in TLA groundwater is estimate to reduce to approximately 0.69 g/m^3.

Of the 9 tonnes/year of additional nitrate-nitrogen, approximately 4 tonnes/year is estimated to discharge to the Motupipi River. This, along with contribution from local nitrate-nitrogen run off and mixing, results in its existing average concentration of approximately 1.00 g/m^3 (based on 2014 data). Under Scenario 1 (No Consumptive Use), if 4 tonnes/year is removed from the Motupipi River, this is estimated to reduce river concentrations to approximately 0.75 g/m^3. Similarly, under Scenario 2 (Double Irrigation), Motupipi River concentrations are estimated to increase to 1.25 g/m^3. Under Scenario 6 (No Development), river concentrations are predicted to be close to zero.

6.2.5.4 Effects on TUGA Groundwater Quality

Similarly, current irrigation on the valley floor results in a nitrate nitrogen load through the TUGA system of an additional 60 tonnes/year (approximately) over and above dryland pasture (assumed). This, combined with the catchment's background nitrate-nitrogen load, results in a mean groundwater concentration in the TUGA bores of approximately 1.25 g/m^3 (estimated from measurements from multiple wells).

Based on a groundwater system through-flow of approximately 11.0 m^3/s (Table 10), if the 60 tonnes/year load were to be eliminated (under Scenario 1, No Consumptive Use), then the concentration in TUGA bores would be approximately 1.08 g/m^3.

Under Scenario 2 (Double Irrigation), an additional 60 tonnes/year load is estimated to contribute to TUGA groundwater, which would increase the concentration to approximately 1.42 g/m^3.

Under Scenario 6 (No Development), the load entering the TUGA system assuming all forestry is estimated to be approximately 13 tonne/year. Given this, the concentration in TUGA groundwater is estimate to reduce to approximately 0.06 g/m^3.

Of the 60 tonnes/year of additional nitrate-nitrogen, approximately 26 tonnes/year is estimated to discharge to surface water, primarily the Takaka River. This, along with contribution from local nitrate-nitrogen run off and mixing, results in its existing average concentration of approximately 0.13 g/m^3 (based on 2014 data at Kotinga).

Under Scenario 1 (No Consumptive Use), if 26 tonnes/year is removed from the Takaka River, this is estimated to reduce river concentrations to approximately 0.10 g/m^3. Scenario 2 (Double Irrigation), Takaka River concentrations are estimated to increase to 0.15 g/m^3. Under Scenario 6 (No Development), river concentrations are predicted to be close to zero.

6.2.5.5 Summary of Effects

Figure 34 and Figure 35 graphically summarise the above predicted effects on groundwater and surface water quality, respectively. For comparison and for scale, the New Zealand Drinking Water standard for nitrate-nitrogen (11.3 g/m^3, derived from a nitrate concentration limit of 50 g/m^3) is shown on the groundwater graph. For scenarios located between the scenarios presented, a simple linear interpolation can be used to estimate corresponding concentrations.

The assessments do not allow for lag and travel times in the groundwater system. They assume that a change in land use is instantaneously reflected in a change in discharge concentration. Consequently, the predicted changes will be zero if there are no changes in land use, but in reality, measured concentrations may still change while the system rebalances from a historical change.

The assessments also assume that any change in nitrate-nitrogen mass (from a change in land use) is uniformly mixed in the receiving groundwater system. However, if certain areas change and others do not, then the resulting response in groundwater will not be uniform. For example, if there is no land use change between the Takaka River and Takaka town, then there will be no change in groundwater quality underlying the town. Also, if land use changes to the north of the town (down gradient), then concentrations from there and towards the coast may change also without affecting the town's water quality.

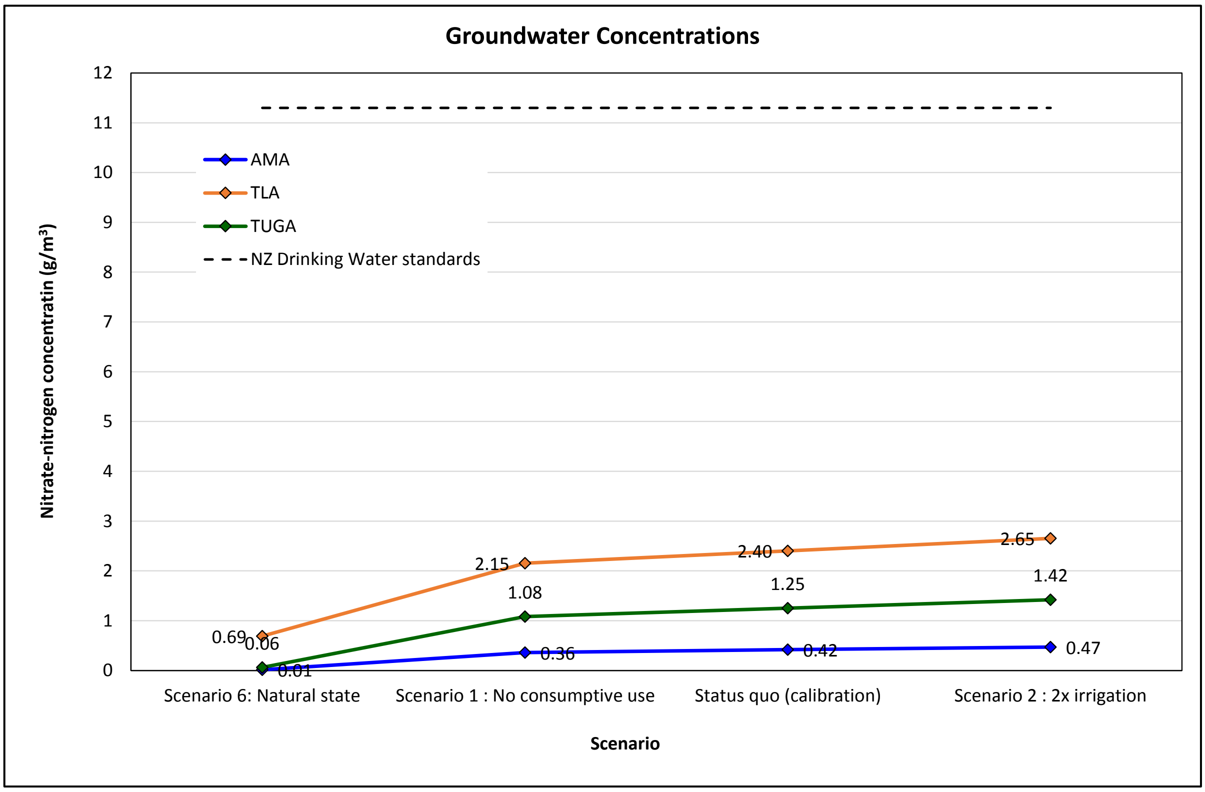

Figure 34: Existing and predicted groundwater nitrate-nitrogen concentrations under various scenarios

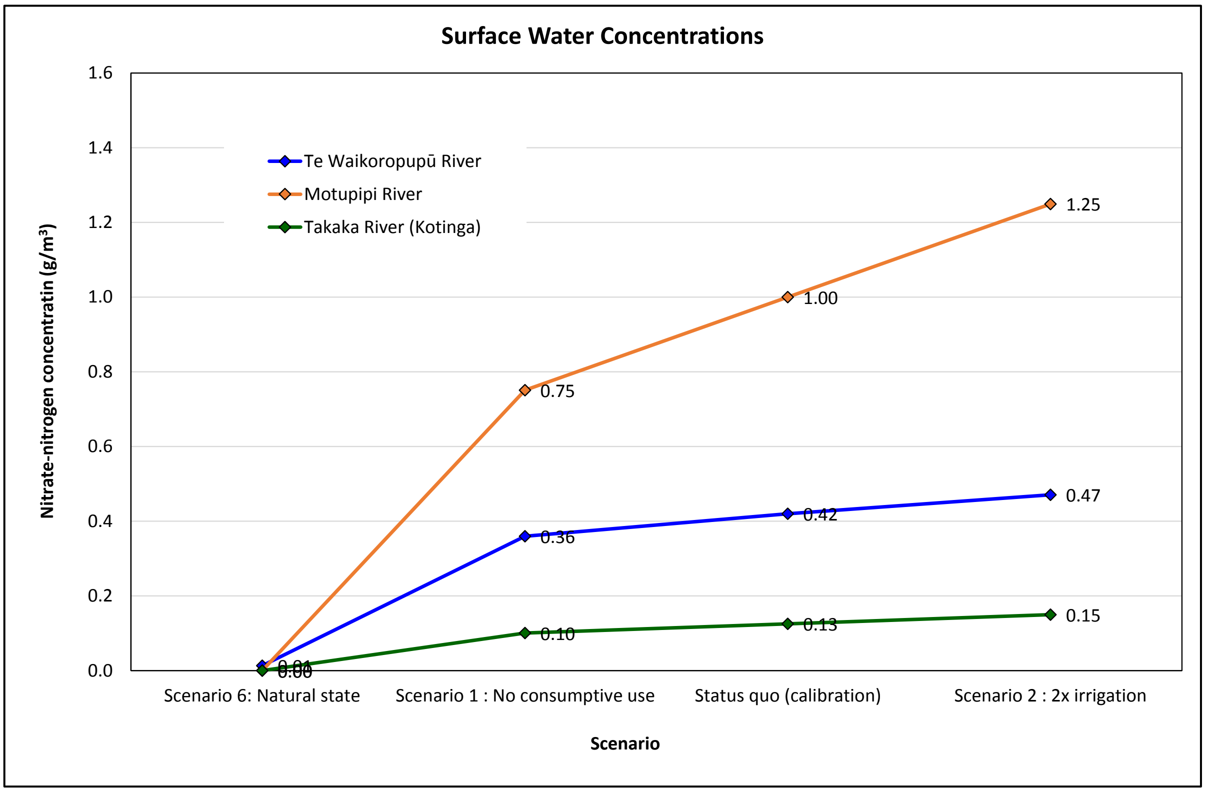

Figure 35: Existing and predicted surface water nitrate-nitrogen concentration under various scenarios

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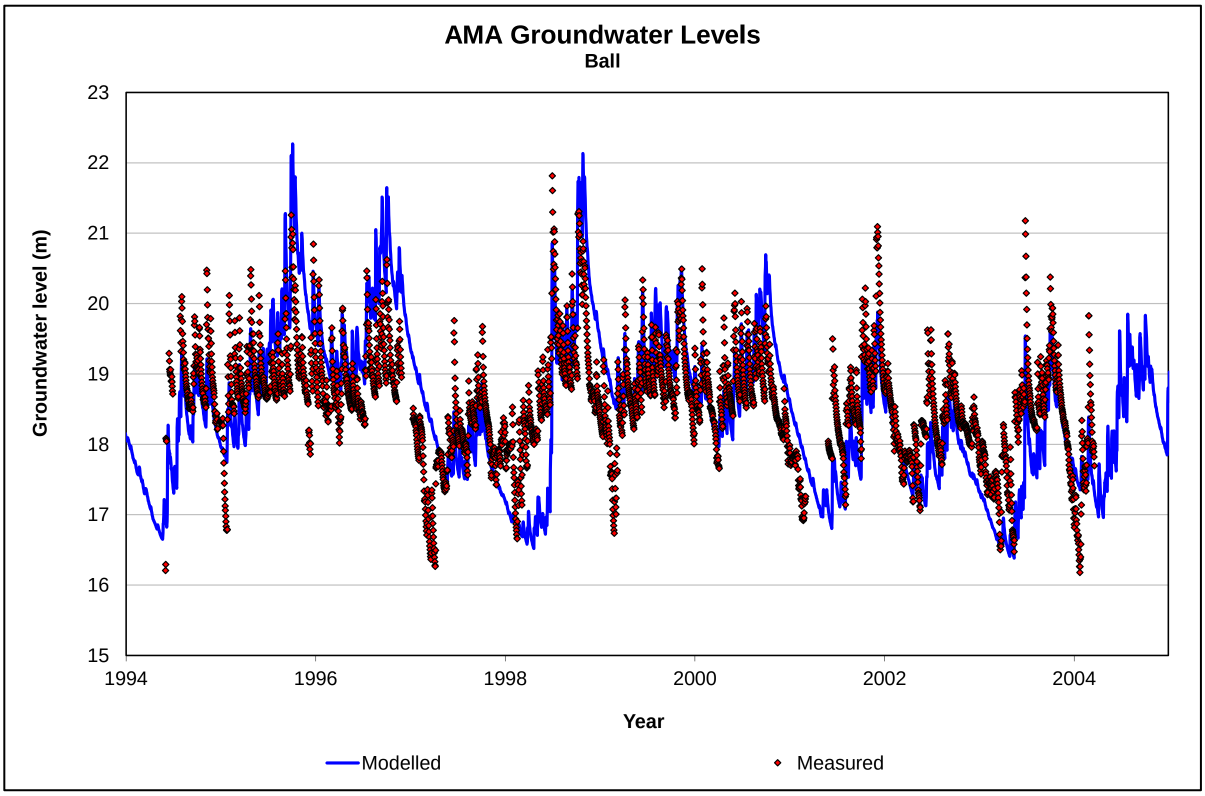
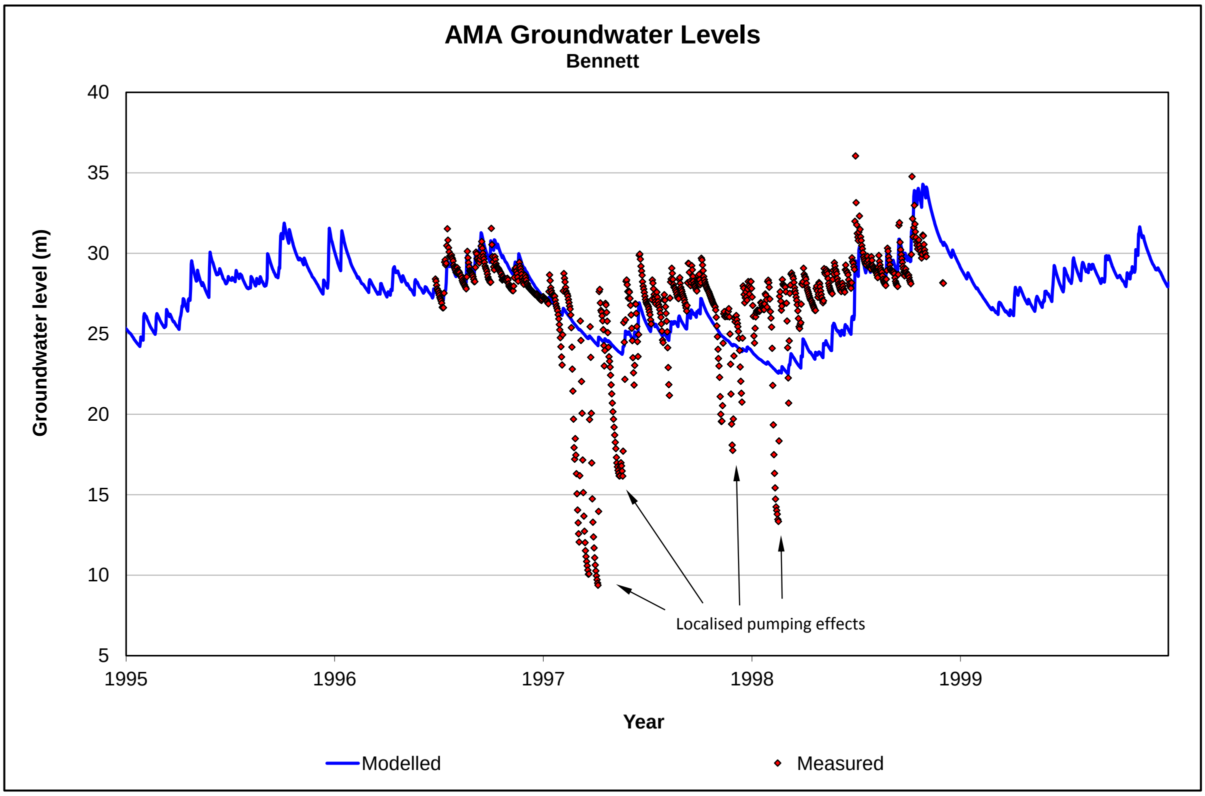
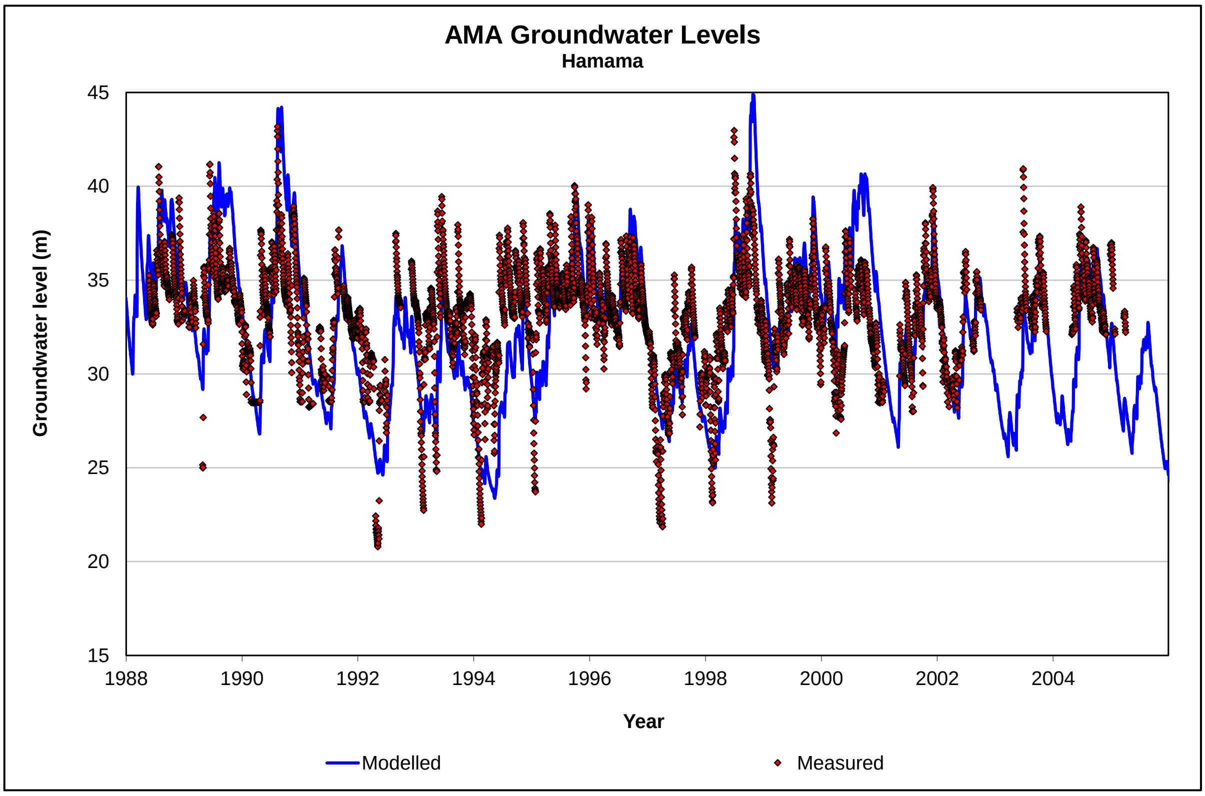
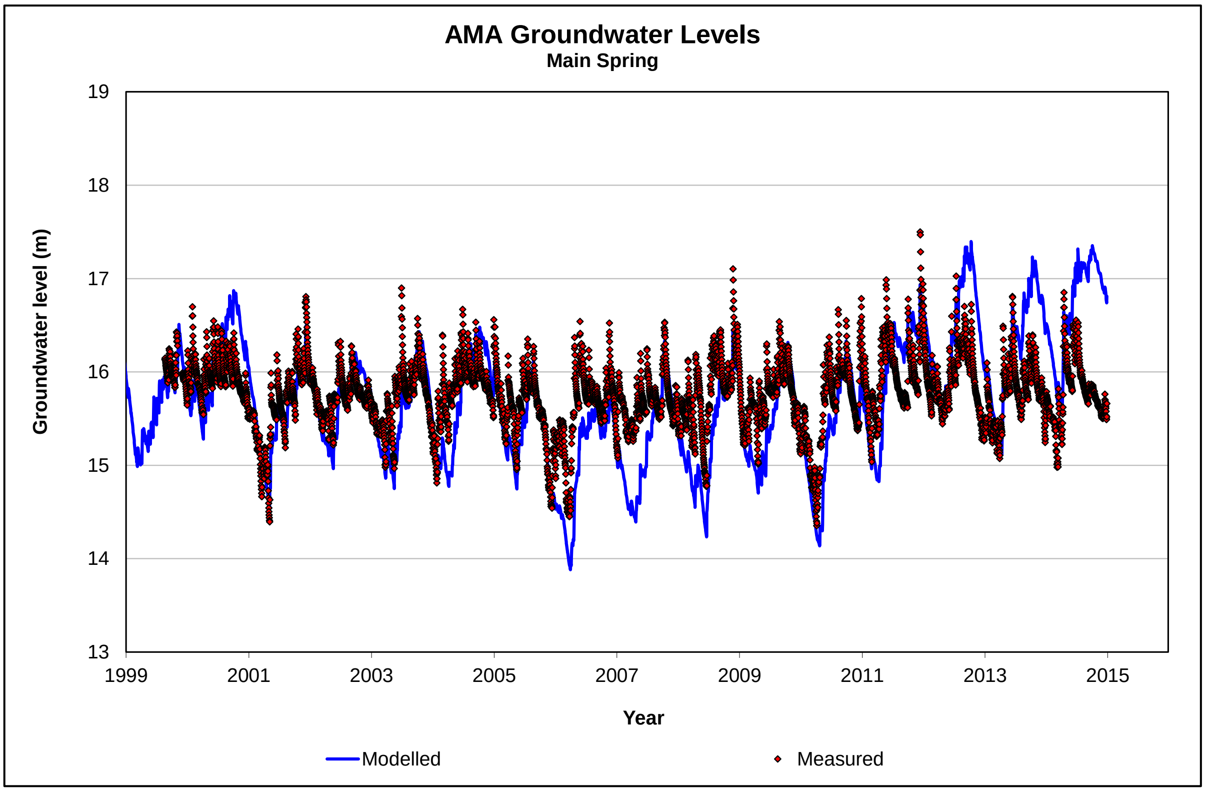
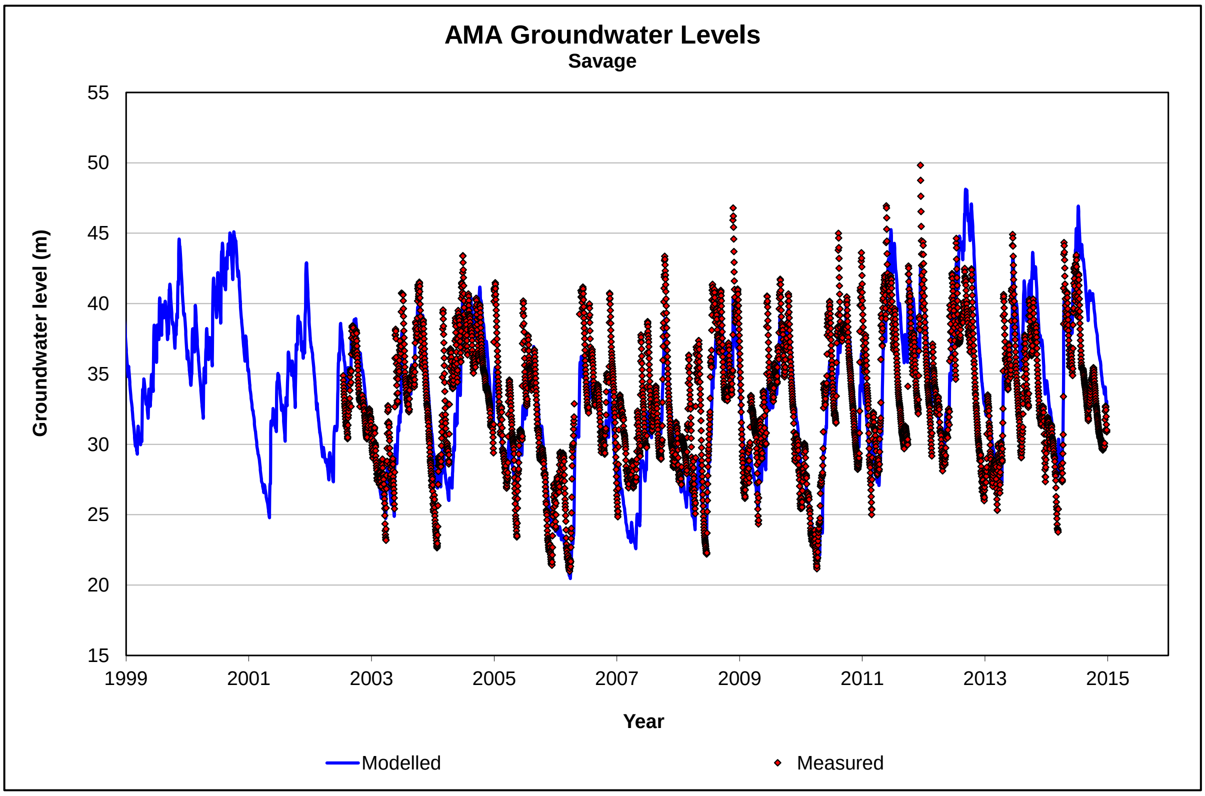
Appendix A: Calibration groundwater level hydrographs

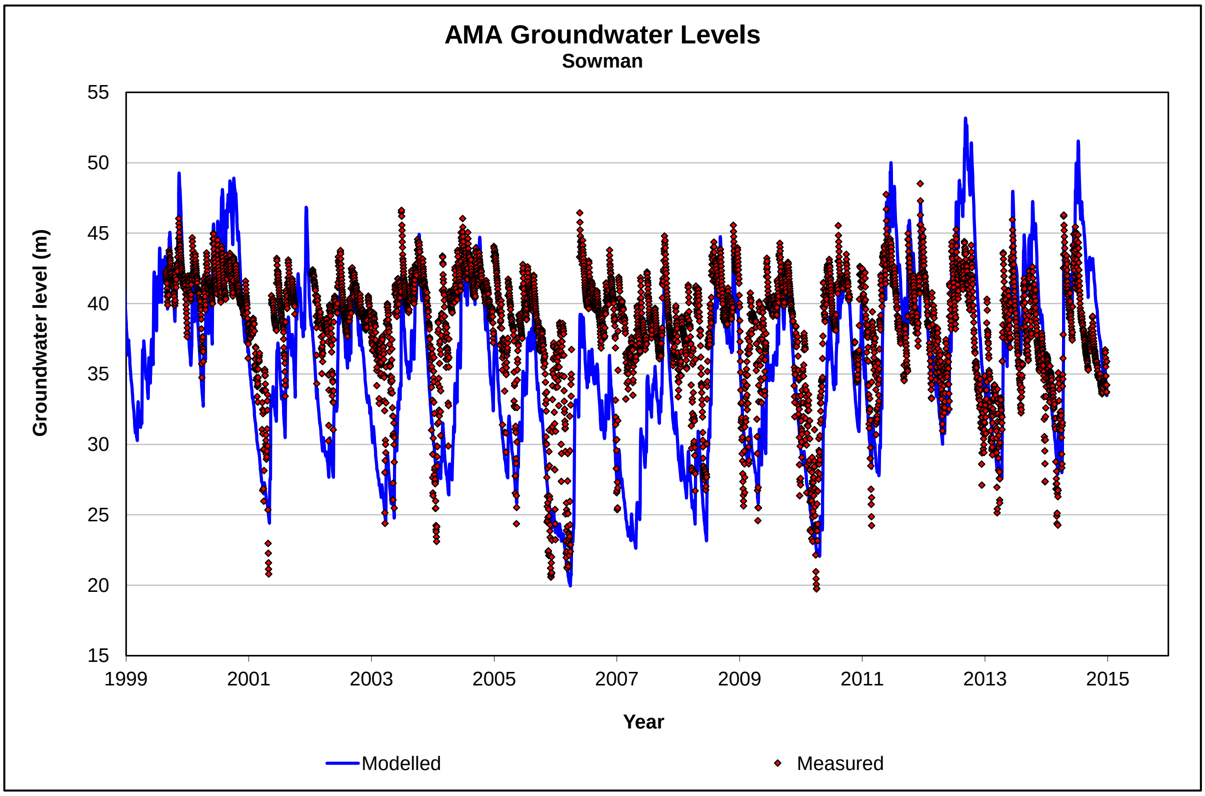

AMA Groundwater Levels
Ball
Groundwater level (m)
23
22
21
20
19
18
17
16
15
1994
1996
1998
2000
2002
2004
Year
Modelled
Measured

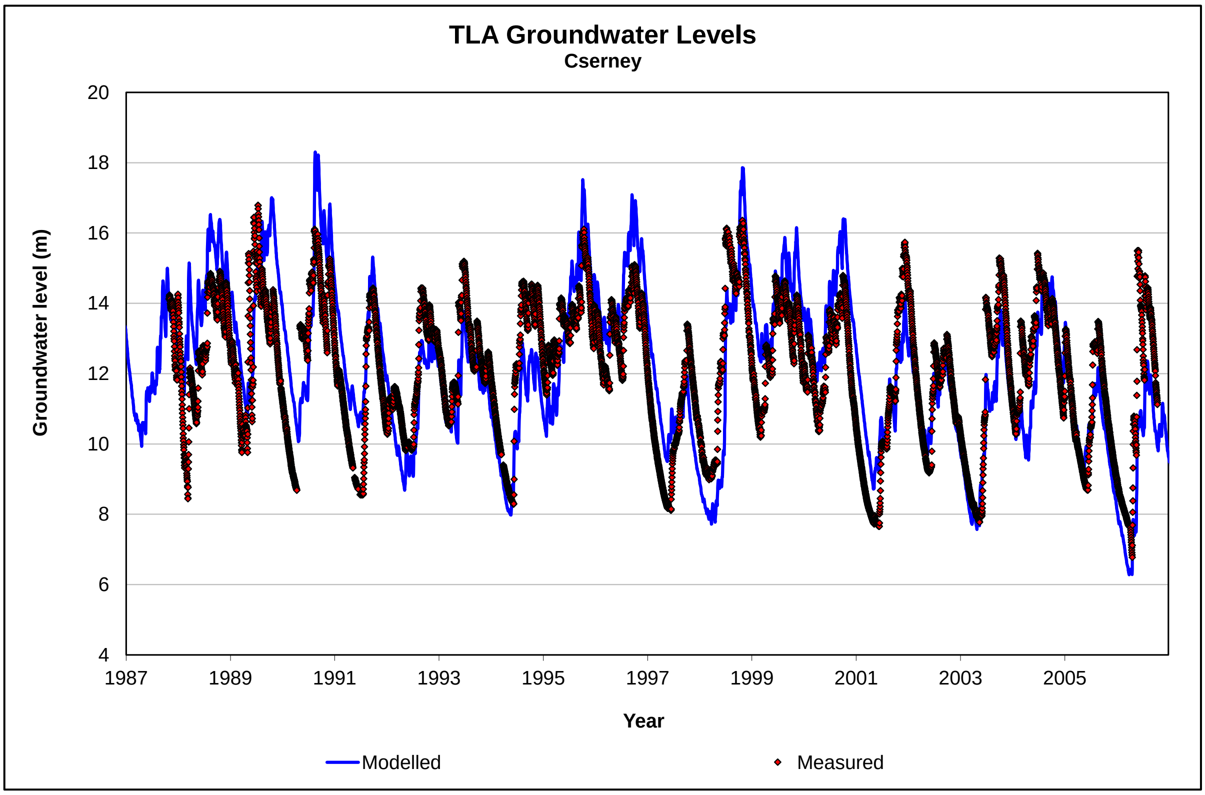

AMA Groundwater Levels
Bennett
Groundwater level (m)
40
35
30
25
20
15
10
5
1995
1996
1997
1998
1999
Year
Localised pumping effects
Modelled
Measured


AMA Groundwater Levels
Hamama
Groundwater level (m)
45
40
35
30
25
20
15
1988
1990
1992
1994
1996
1998
2000
2002
2004
Year
Modelled
Measured

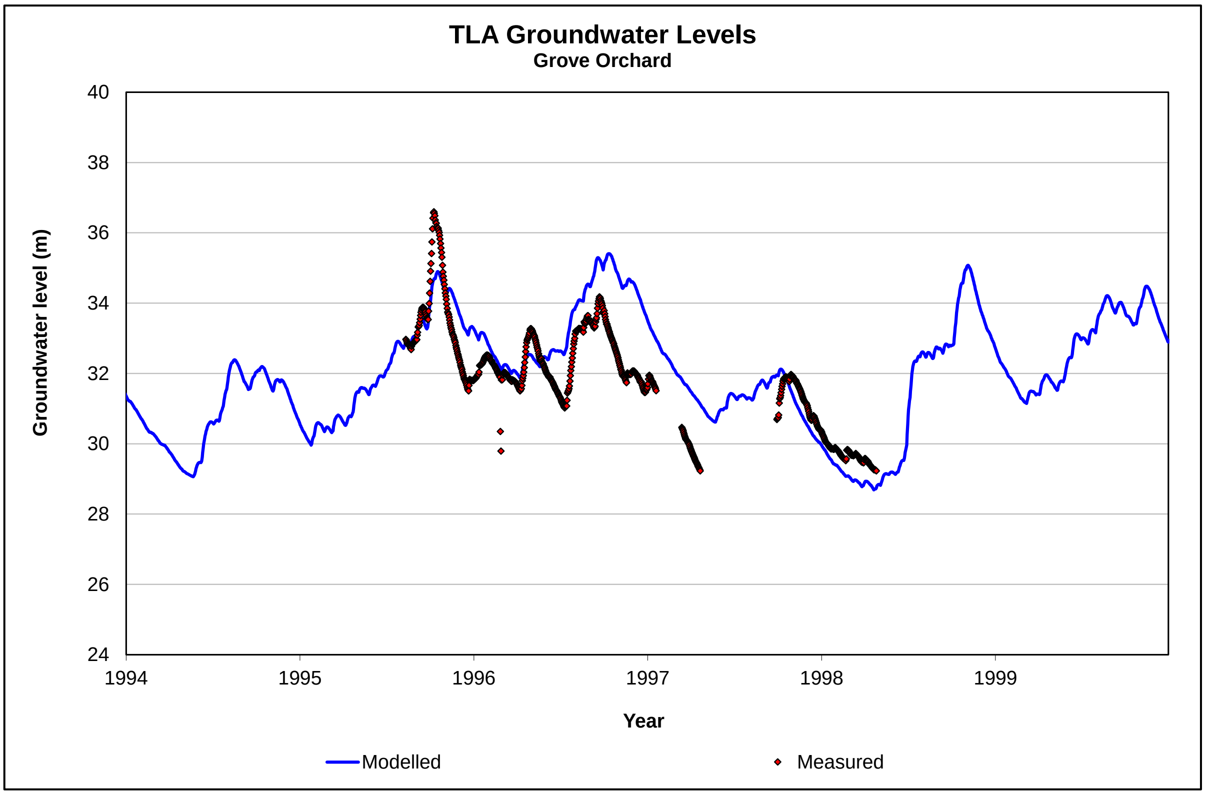

AMA Groundwater Levels
Main Spring
Groundwater level (m)
19
18
17
16
15
14
13
1999
2001
2003
2005
2007
2009
2011
2013
2015
Year
Modelled
Measured


AMA Groundwater Levels
Savage
Groundwater level (m)
55
50
45
40
35
30
25
20
15
1999
2001
2003
2005
2007
2009
2011
2013
2015
Year
Modelled
Measured

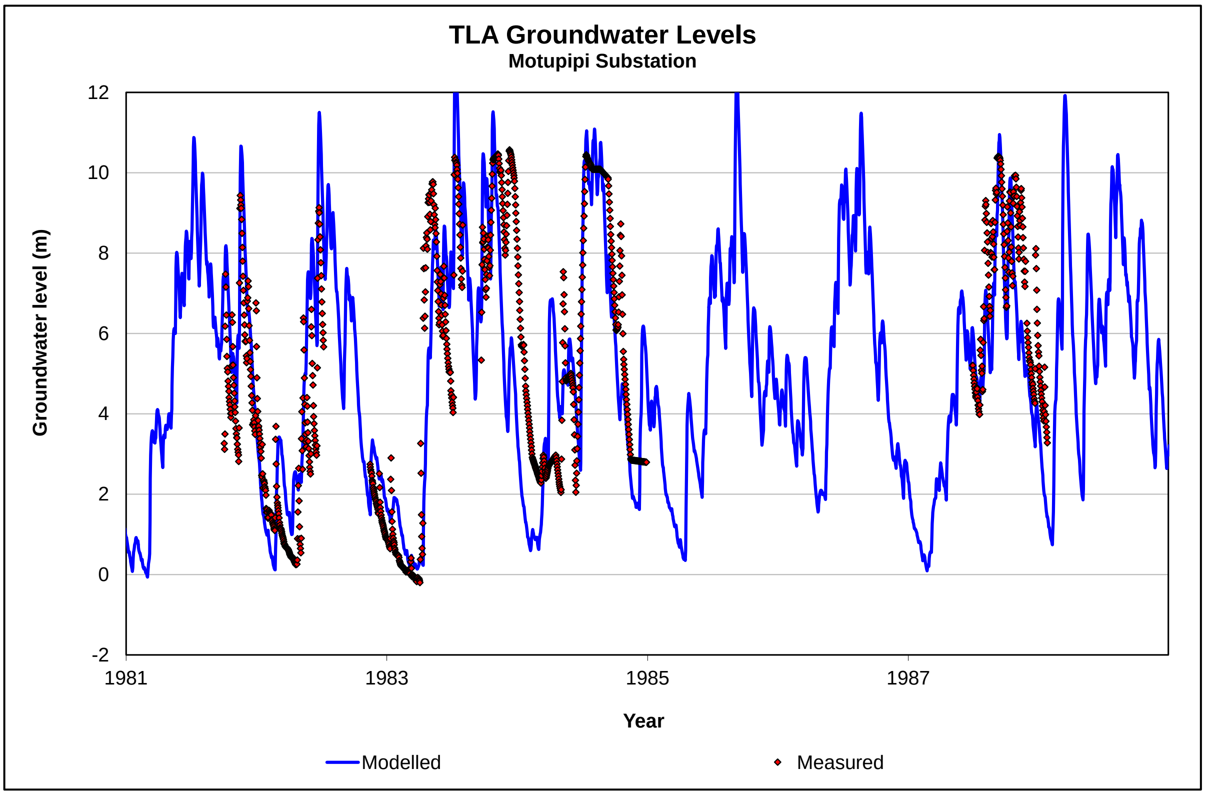

AMA Groundwater Levels
Sowman
Groundwater level (m)
55
50
45
40
35
30
25
20
15
1999
2001
2003
2005
2007
2009
2011
2013
2015
Year
Modelled
Measured



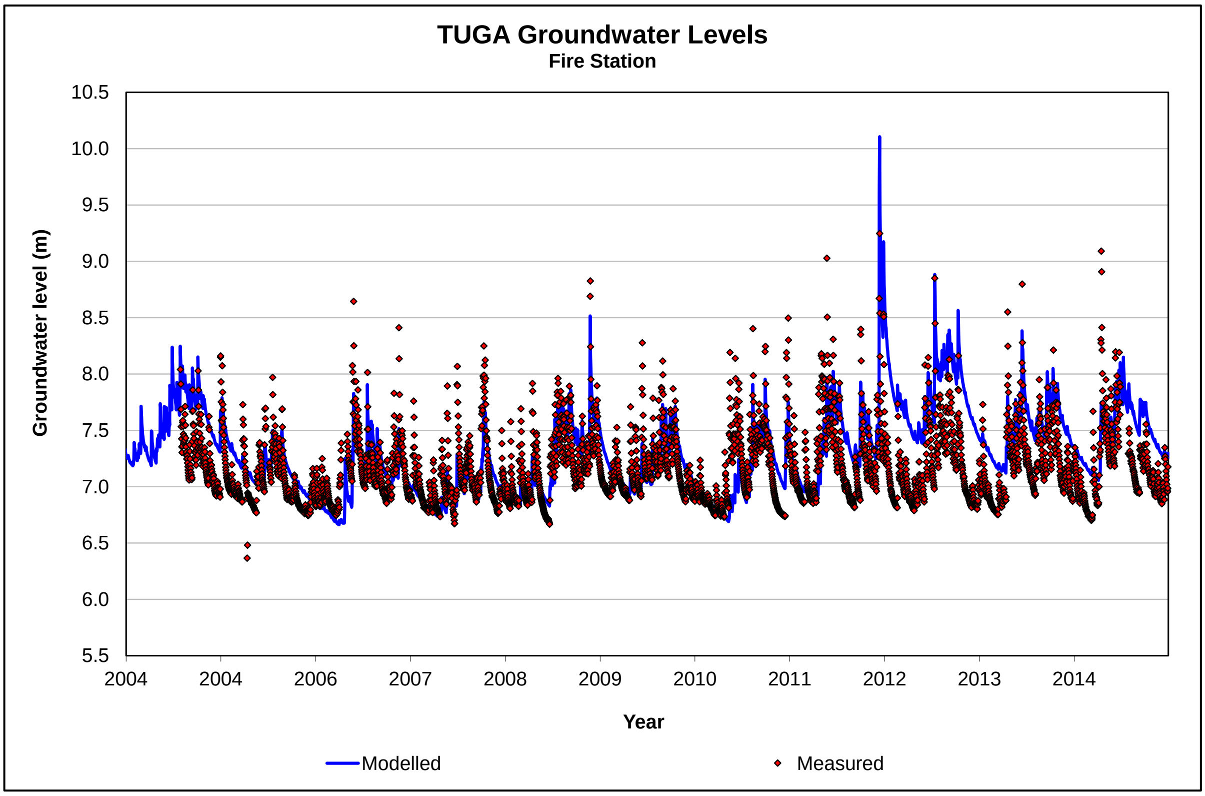
TLA Groundwater Levels
Cserney
Groundwater level (m)
20
18
16
14
12
10
8
6
4
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
Year
Modelled
Measured



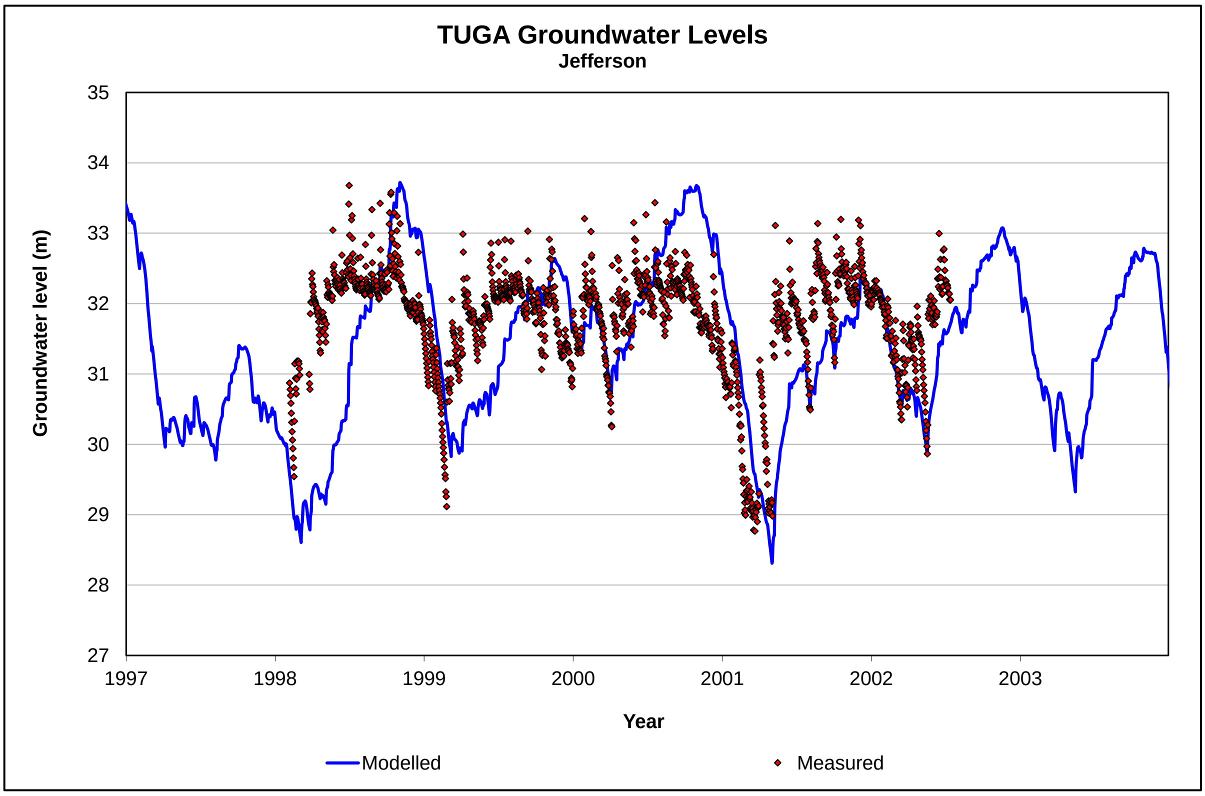
TLA Groundwater Levels
Grove Orchard
Groundwater level (m)
40
38
36
34
32
30
28
26
24
1994
1995
1996
1997
1998
1999
Year
Modelled
Measured

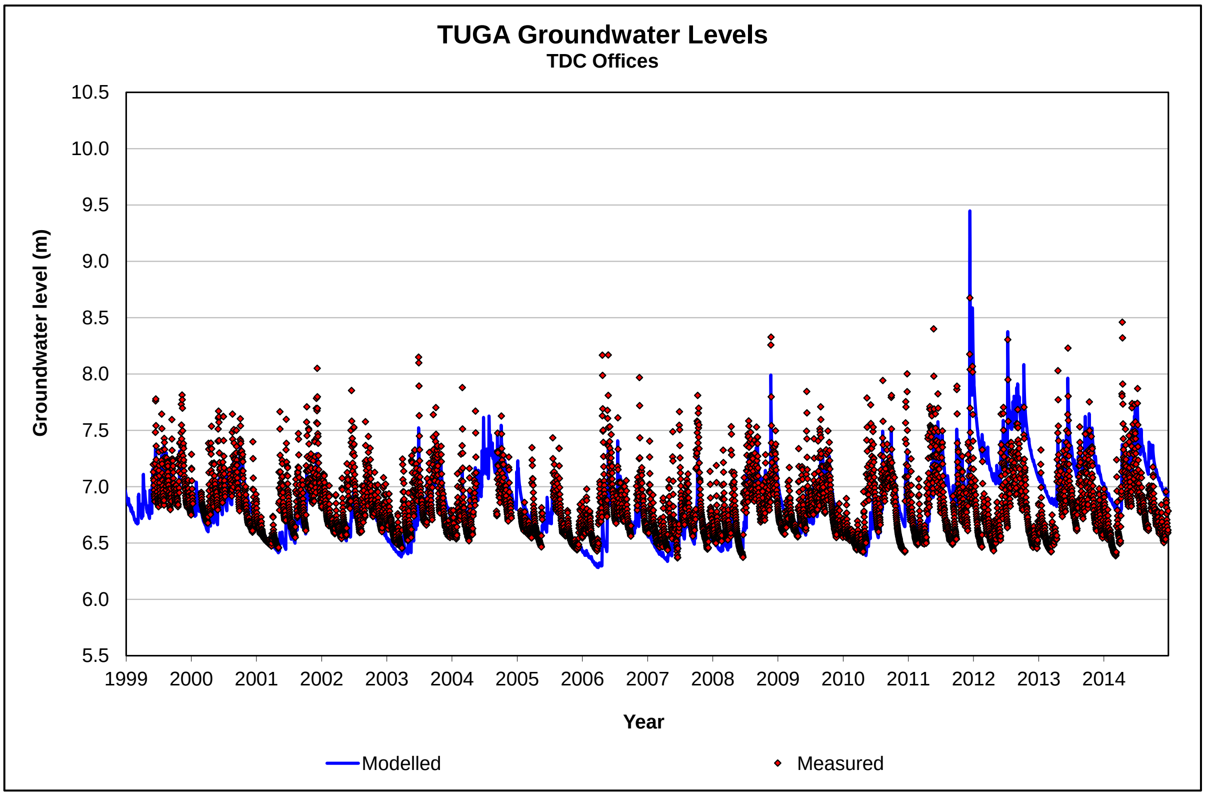


TLA Groundwater Levels
Motupipi Substation
Groundwater level (m)
12
10
8
6
4
2
0
-2
1981
1983
1985
1987
Year
Modelled
Measured

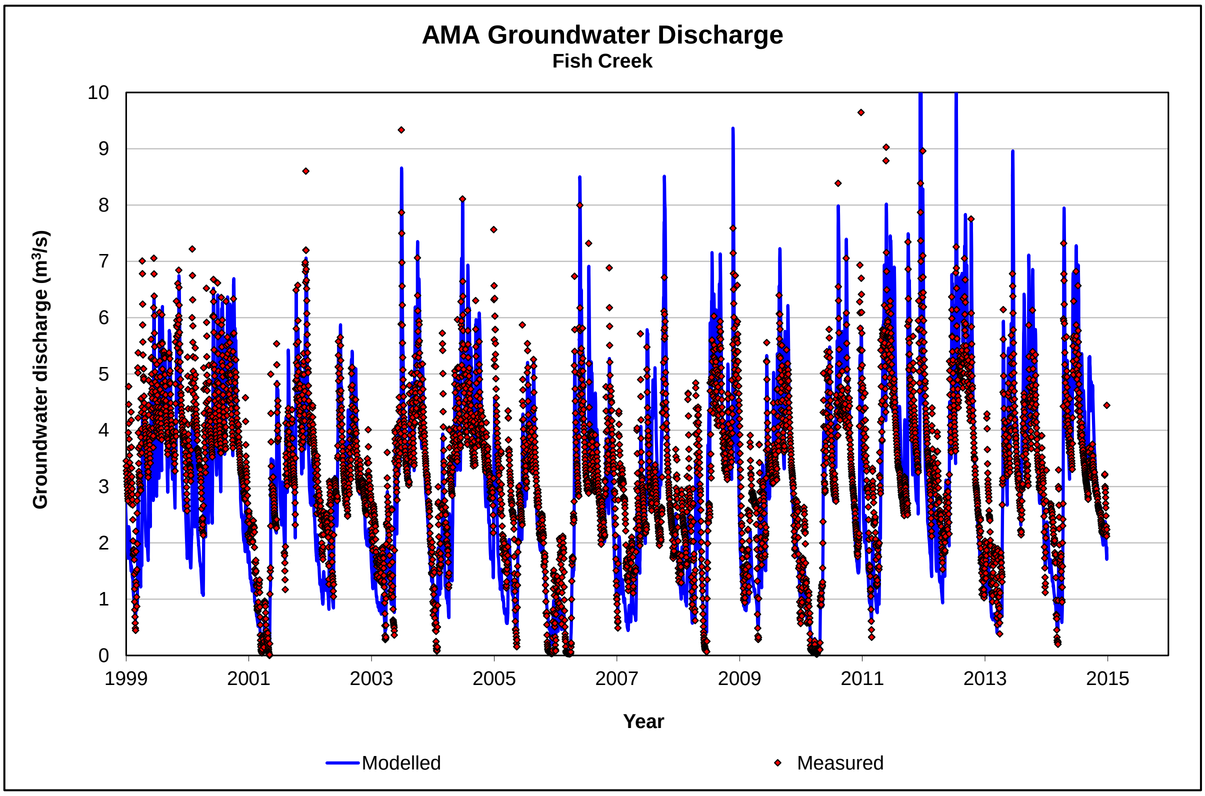


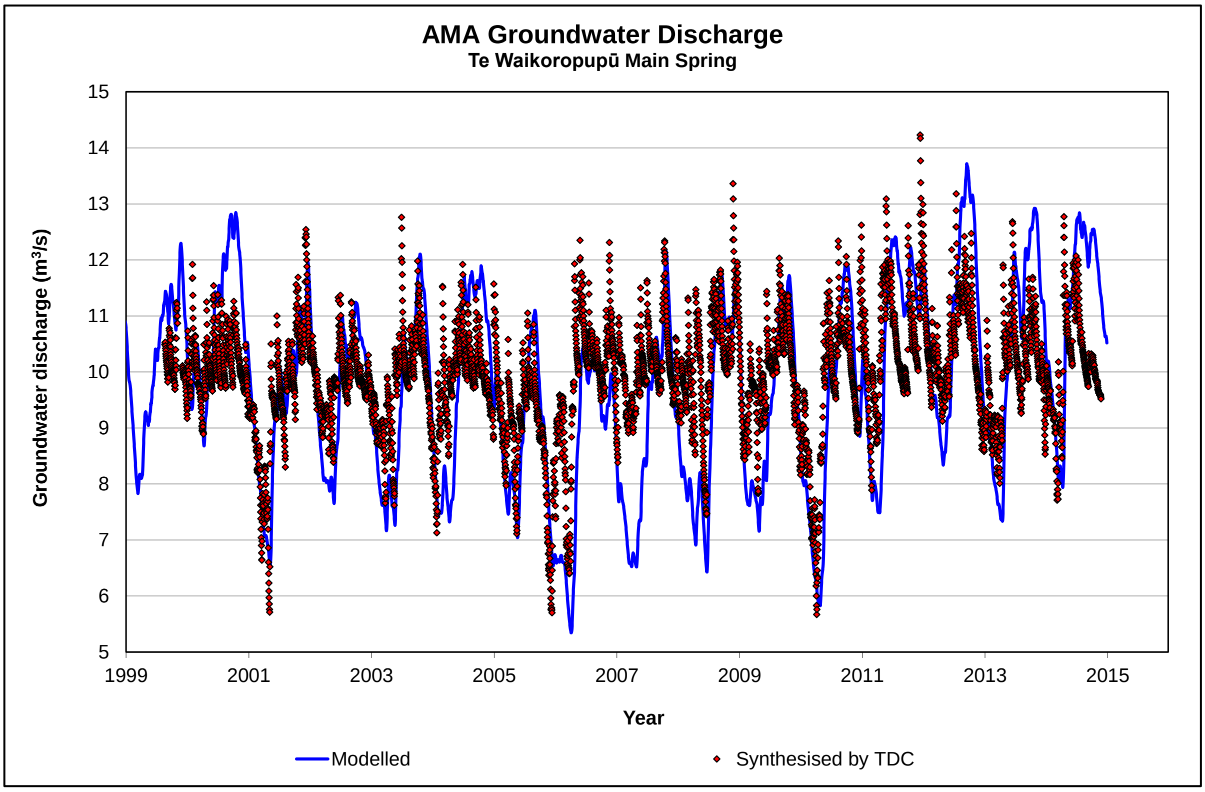
TUGA Groundwater Levels
Fire Station
Groundwater level (m)
10.5
10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
2004
2004
2006
2007
2008
2009
2010
2011
2012
2013
2014
Year
Modelled
Measured

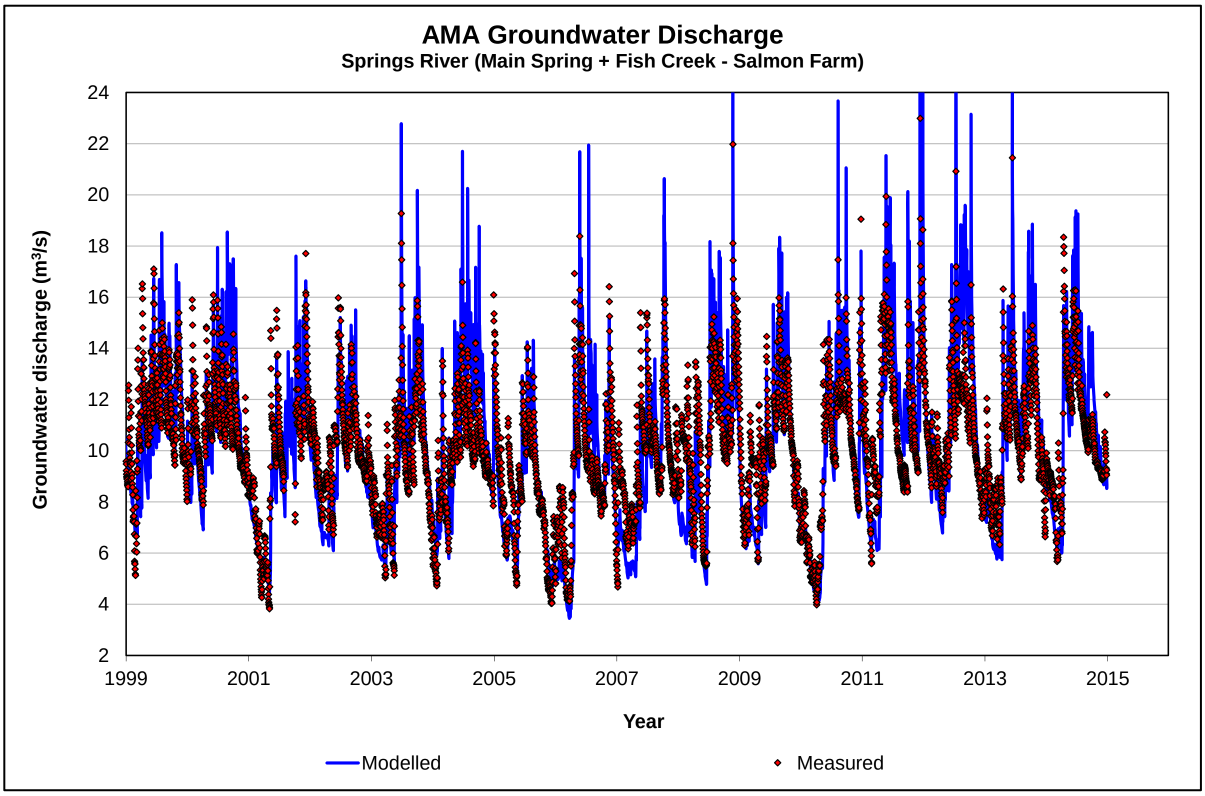

TUGA Groundwater Levels
Jefferson
Groundwater level (m)
35
34
33
32
31
30
29
28
27
1997
1998
1999
2000
2001
2002
2003
Year
Modelled
Measured

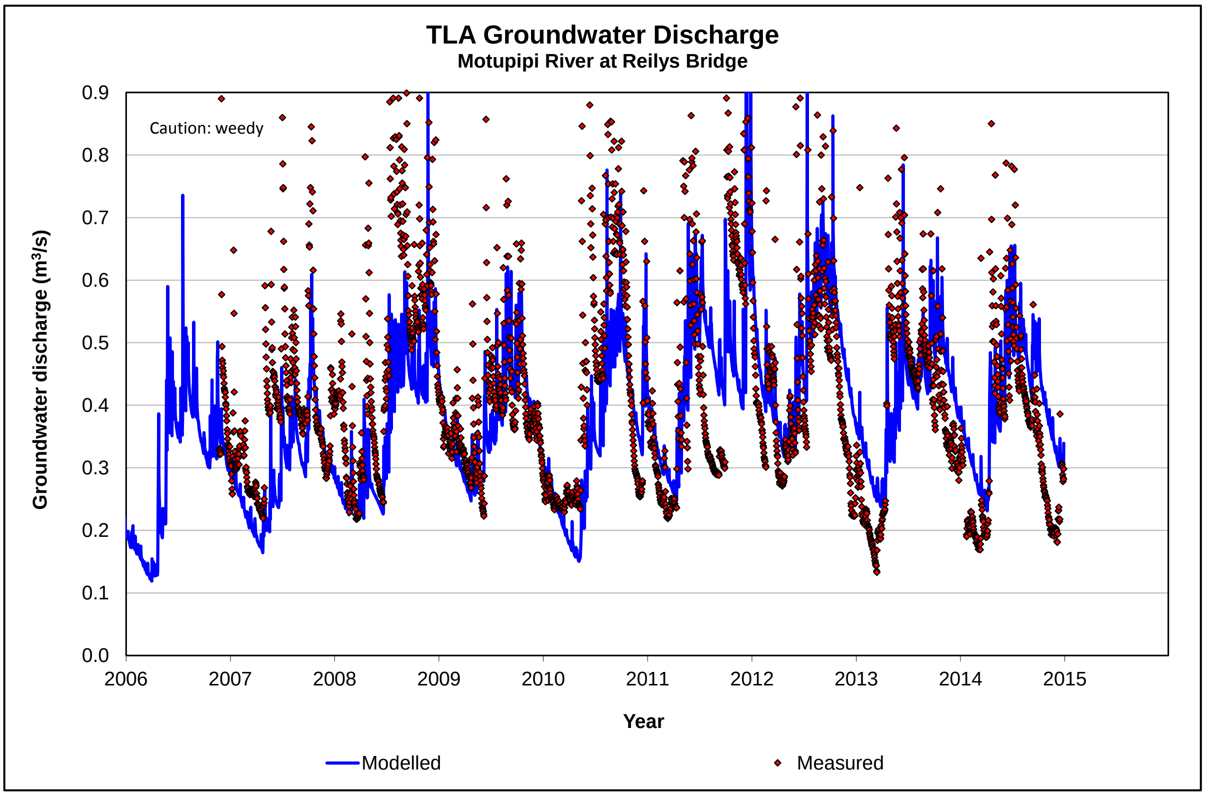

TUGA Groundwater Levels
TDC Offices
Groundwater level (m)
10.5
10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
Year
Modelled
Measured

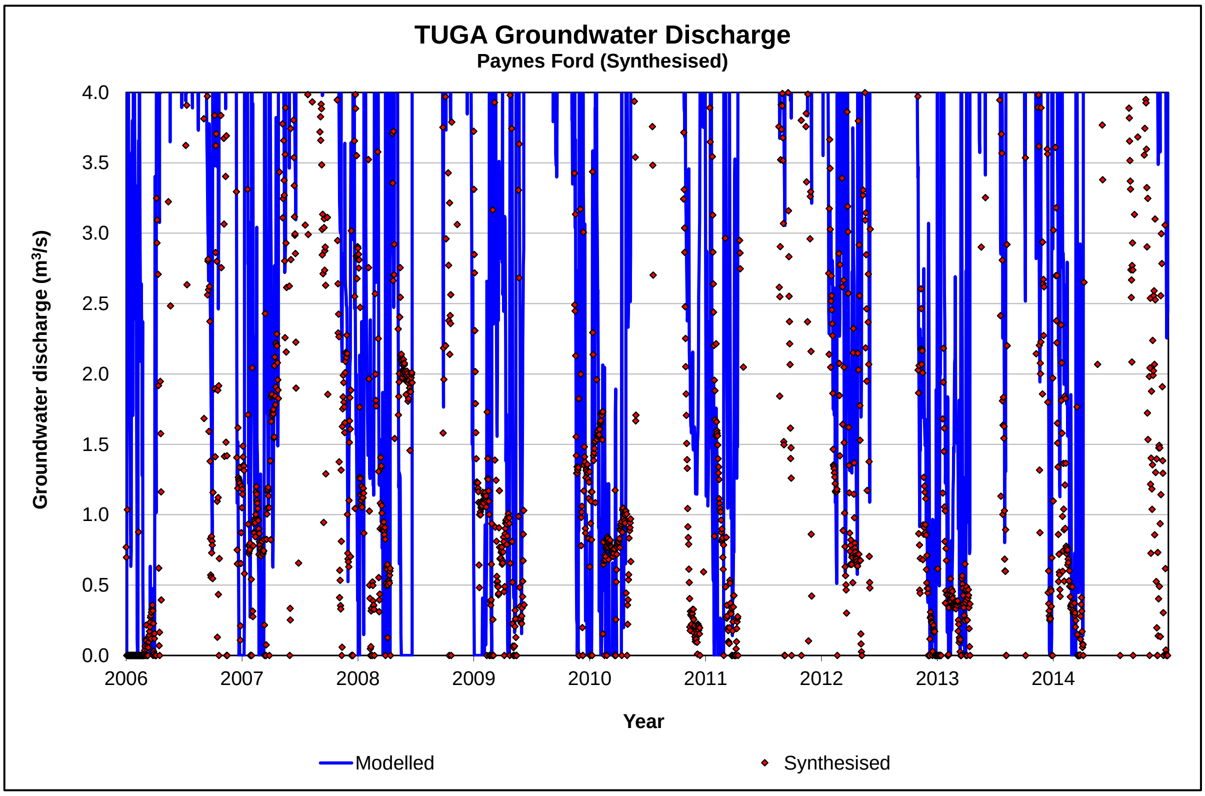
Appendix B: Calibration river flow hydrographs


AMA Groundwater Discharge
Fish Creek
Groundwater discharge (m³/s)
0
1
2
3
4
5
6
7
8
9
10
1999
2001
2003
2005
2007
2009
2011
2013
2015
Year
Modelled
Measured


AMA Groundwater Discharge
Te Waikoropupū Main Spring
Groundwater discharge (m³/s)
5
6
7
8
9
10
11
12
13
14
15
1999
2001
2003
2005
2007
2009
2011
2013
2015
Year
Modelled
Synthesised by TDC

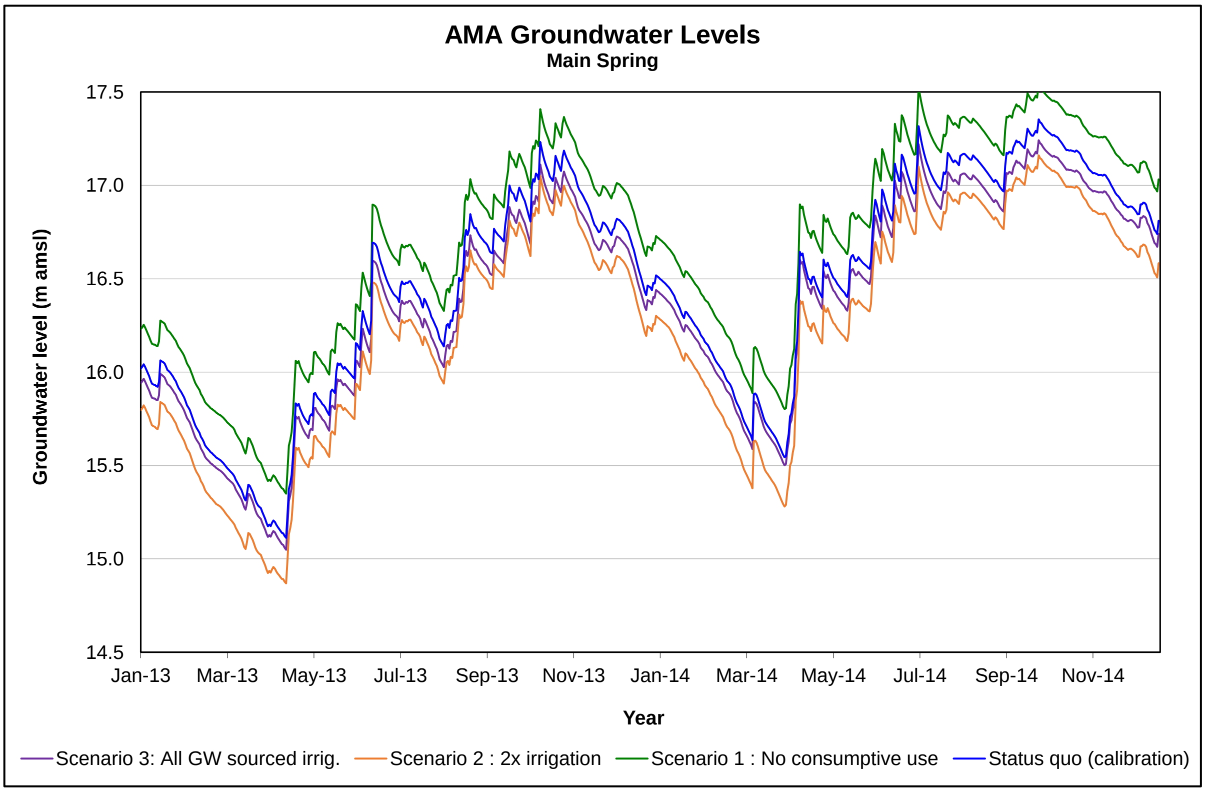

AMA Groundwater Discharge
Springs River (Main Spring + Fish Creek - Salmon Farm)
Groundwater discharge (m³/s)
24
22
20
18
16
14
12
10
8
6
4
2
1999
2001
2003
2005
2007
2009
2011
2013
2015
Year
Modelled
Measured

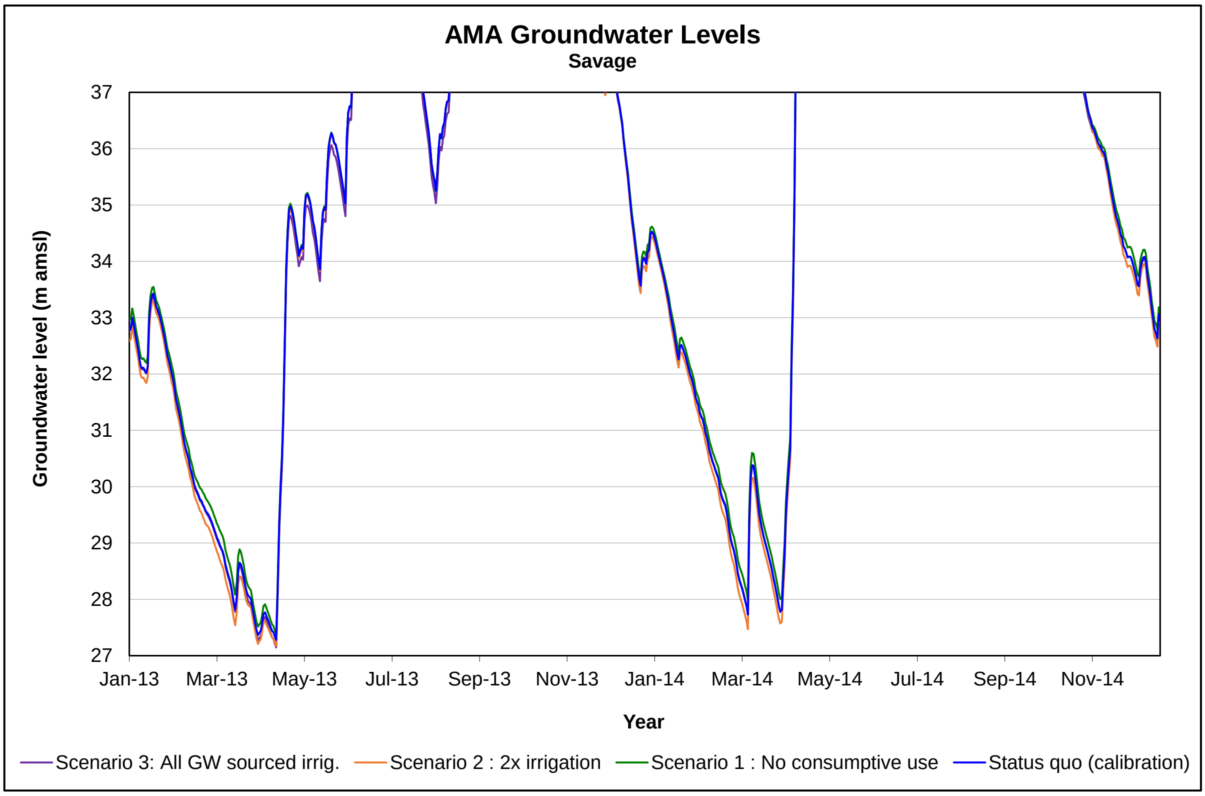

TLA Groundwater Discharge
Motupipi River at Reilys Bridge
Caution: weedy
Groundwater discharge (m³/s)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
Year
Modelled
Measured

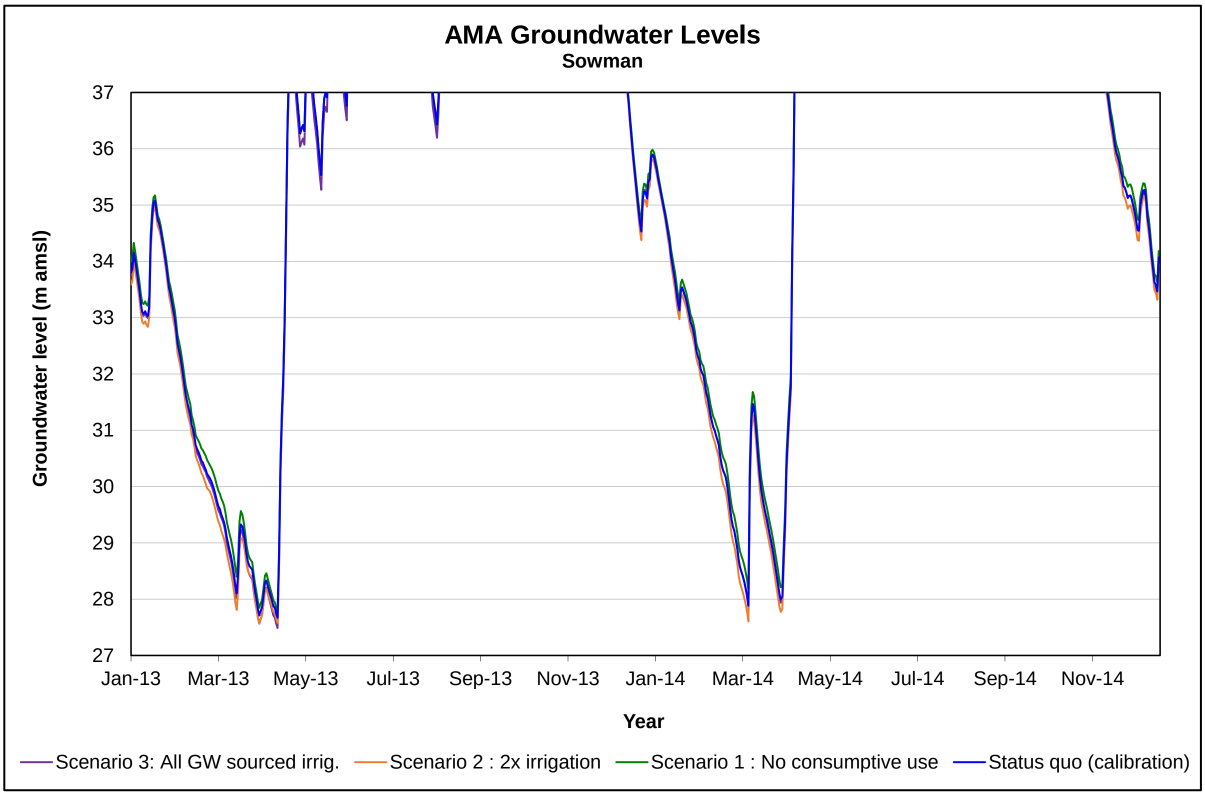


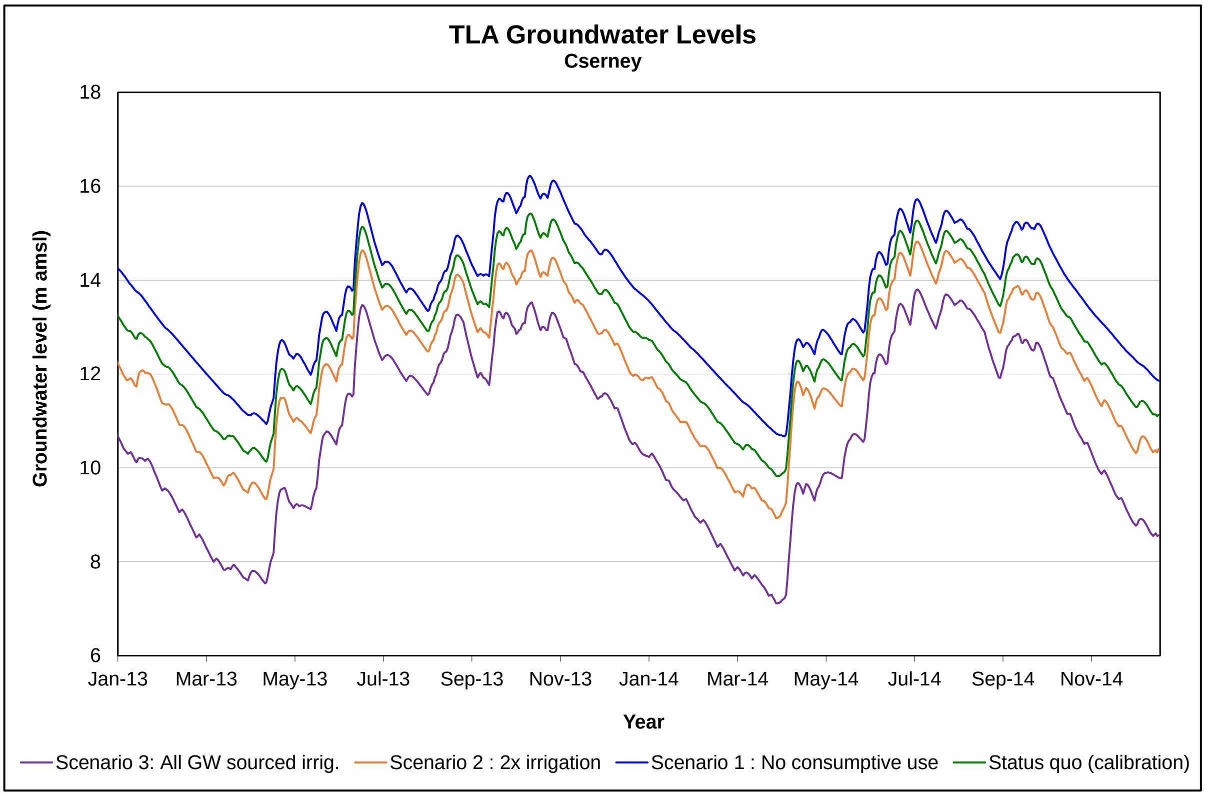
TUGA Groundwater Discharge
Paynes Ford (Synthesised)
Groundwater discharge (m³/s)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
2006
2007
2008
2009
2010
2011
2012
2013
2014
Year
Modelled
Synthesised

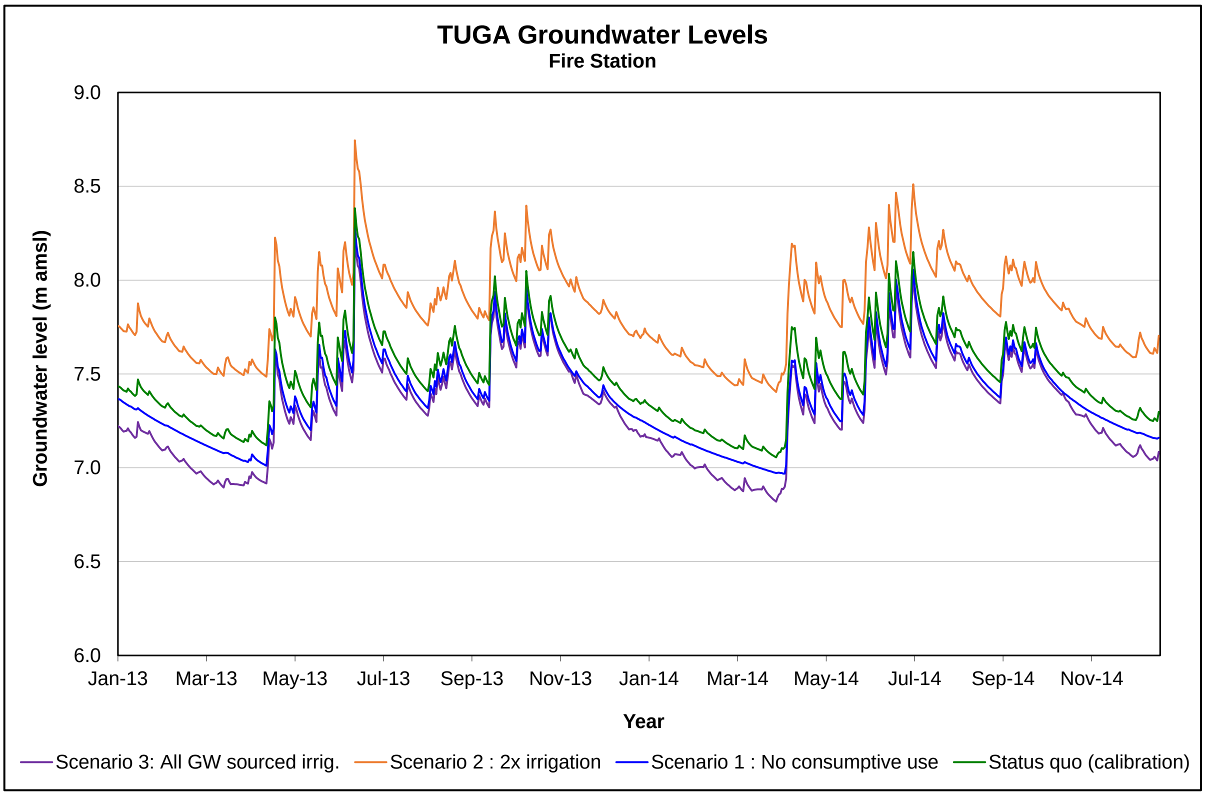
Appendix C: Groundwater level hydrographs comparing calibration with Scenarios 1, 2 and 3

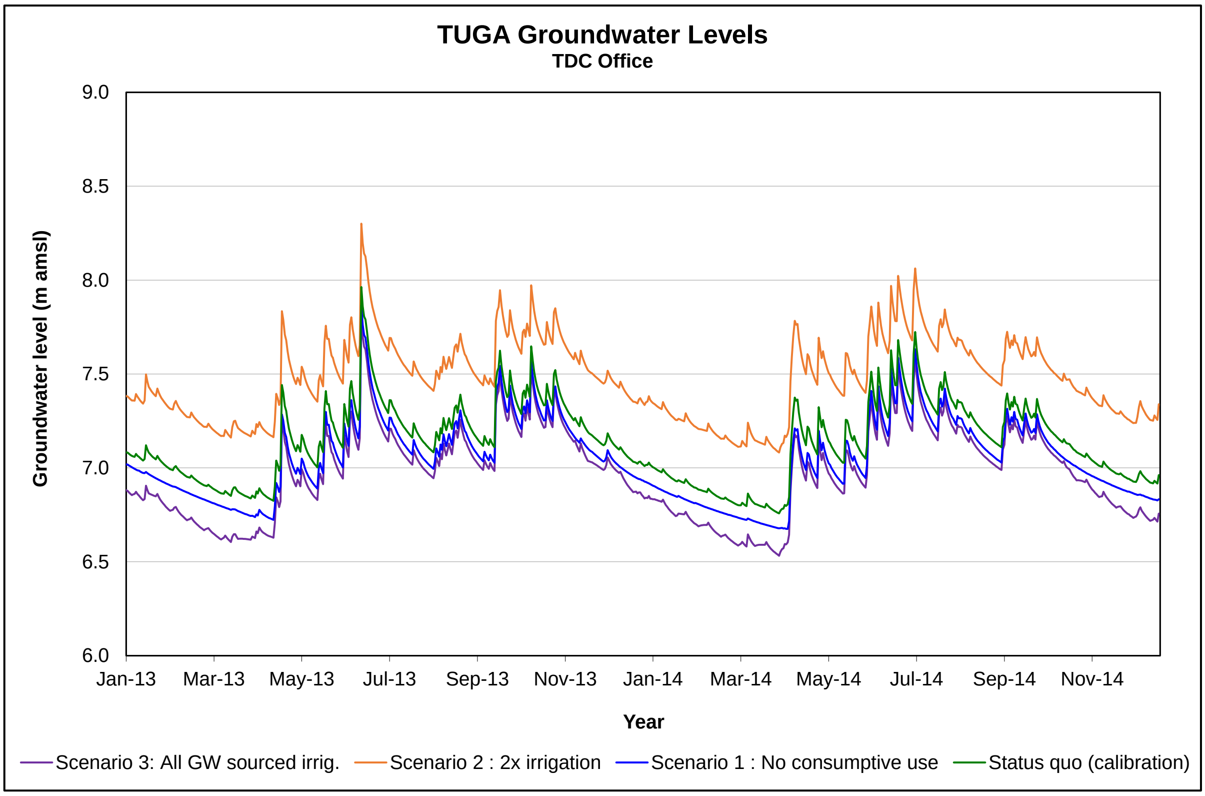

AMA Groundwater Levels
Main Spring
Groundwater level (m amsl)
17.5
17.0
16.5
16.0
15.5
15.0
14.5
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Year
Scenario 3: All GW sourced irrig.
Scenario 2 : 2x irrigation
Scenario 1 : No consumptive use
Status quo (calibration)


AMA Groundwater Levels
Savage
Groundwater level (m amsl)
37
36
35
34
33
32
31
30
29
28
27
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Year
Scenario 3: All GW sourced irrig.
Scenario 2 : 2x irrigation
Scenario 1 : No consumptive use
Status quo (calibration)

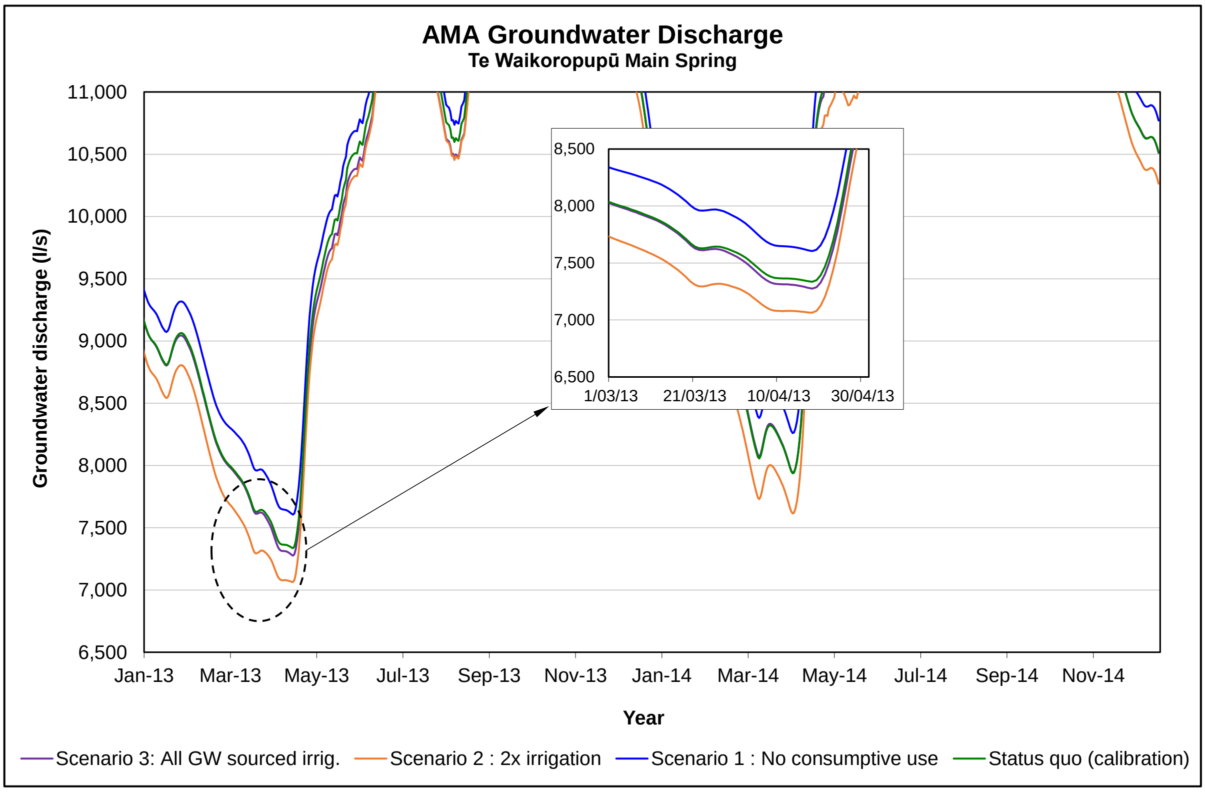

AMA Groundwater Levels
Sowman
Groundwater level (m amsl)
37
36
35
34
33
32
31
30
29
28
27
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Year
Scenario 3: All GW sourced irrig.
Scenario 2 : 2x irrigation
Scenario 1 : No consumptive use
Status quo (calibration)

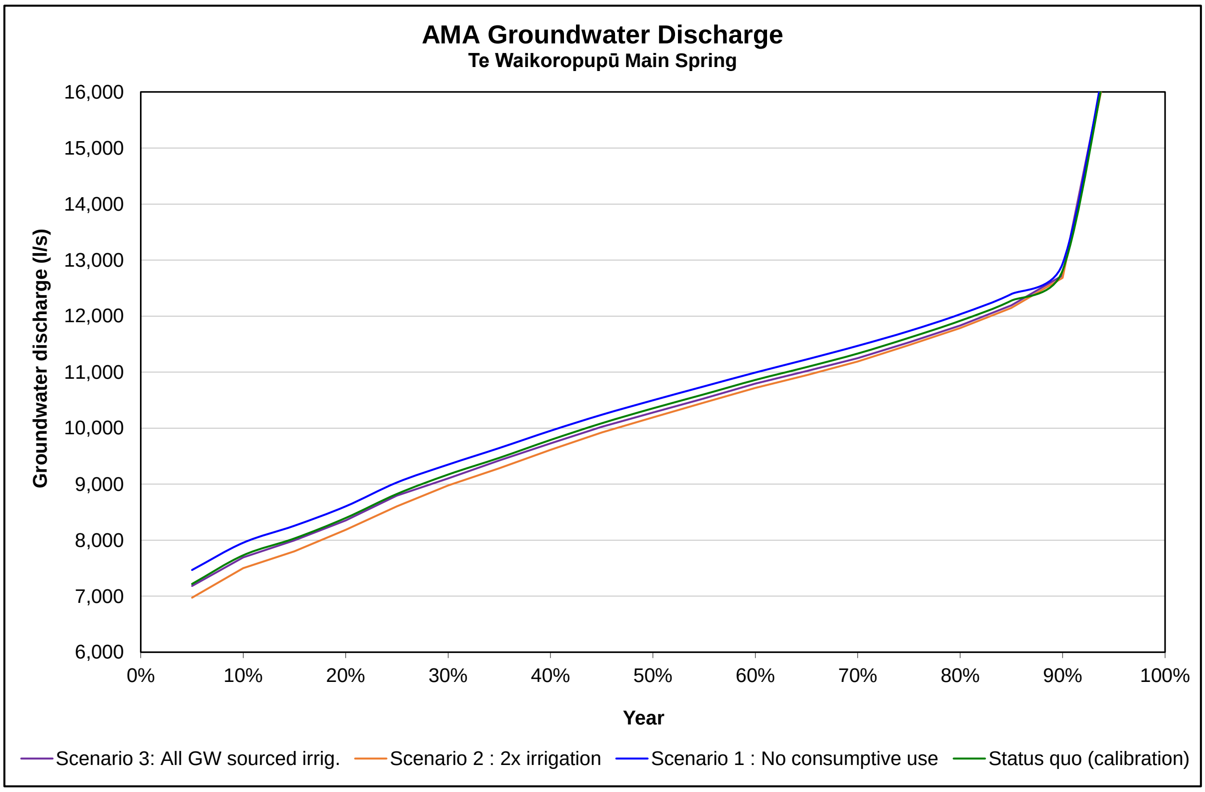

TLA Groundwater Levels
Cserney
Groundwater level (m amsl)
18
16
14
12
10
8
6
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Year
Scenario 3: All GW sourced irrig.
Scenario 2 : 2x irrigation
Scenario 1 : No consumptive use
Status quo (calibration)

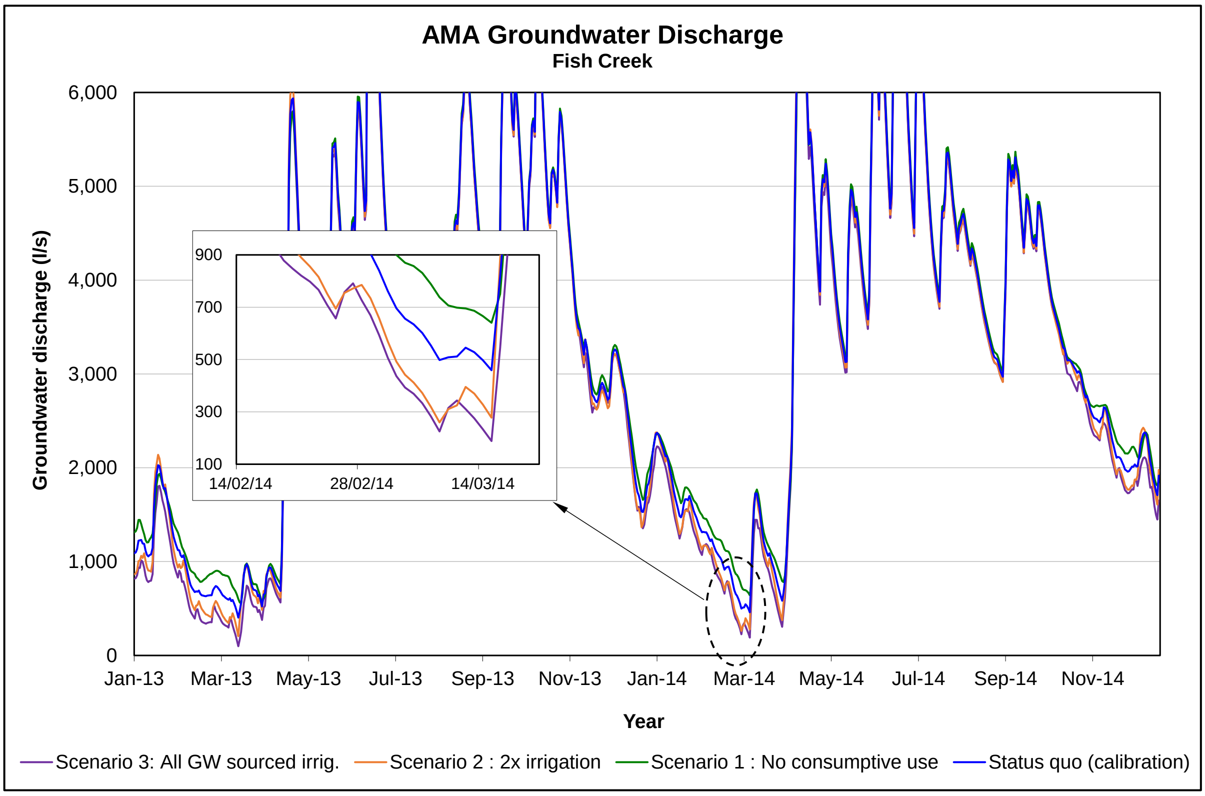

TUGA Groundwater Levels
Fire Station
Groundwater level (m amsl)
9.0
8.5
8.0
7.5
7.0
6.5
6.0
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Year
Scenario 3: All GW sourced irrig.
Scenario 2 : 2x irrigation
Scenario 1 : No consumptive use
Status quo (calibration)

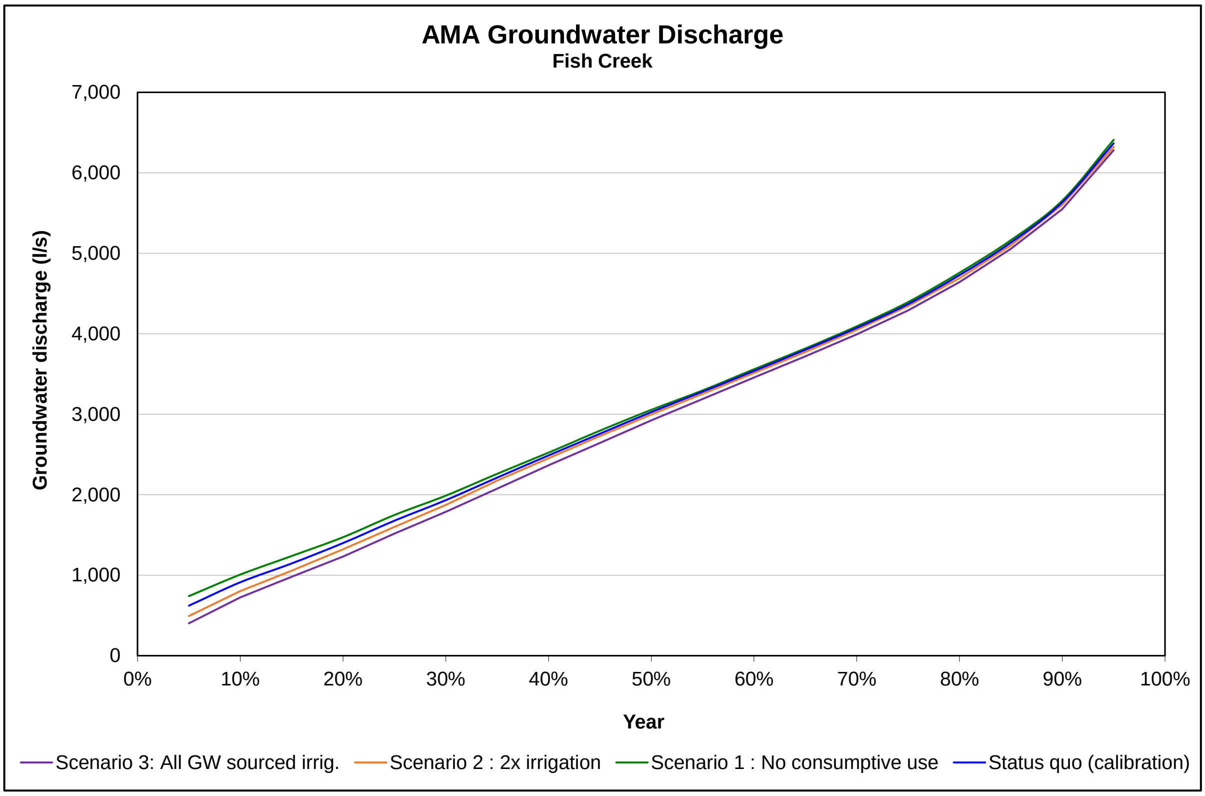

TUGA Groundwater Levels
TDC Office
Groundwater level (m amsl)
9.0
8.5
8.0
7.5
7.0
6.5
6.0
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Year
Scenario 3: All GW sourced irrig.
Scenario 2 : 2x irrigation
Scenario 1 : No consumptive use
Status quo (calibration)

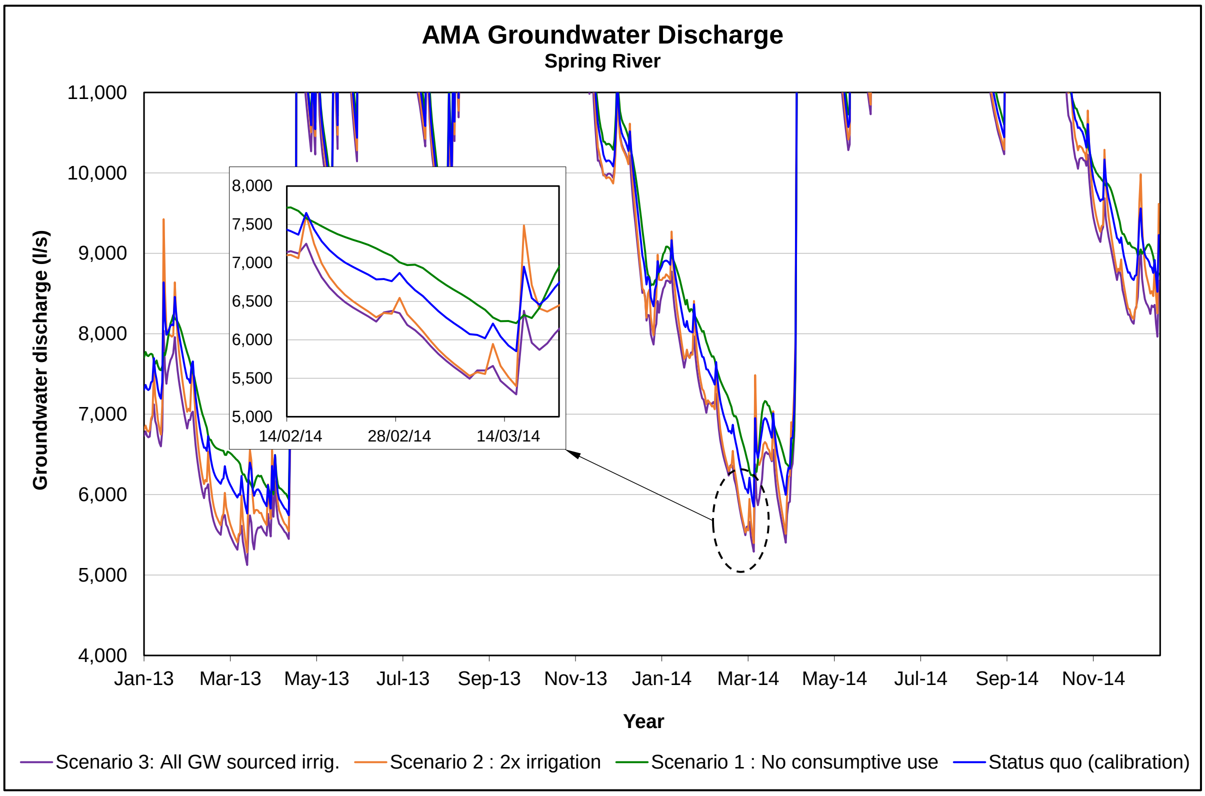
Appendix D: Flow hydrographs and flow duration curves comparing calibration with Scenarios 1, 2 and 3


AMA Groundwater Discharge
Te Waikoropupū Main Spring
Groundwater discharge (l/s)
11,000
10,500
10,000
9,500
9,000
8,500
8,000
7,500
7,000
6,500
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Year
8,500
8,000
7,500
7,000
6,500
1/03/13
21/03/13
10/04/13
30/04/13
Scenario 3: All GW sourced irrig.
Scenario 2 : 2x irrigation
Scenario 1 : No consumptive use
Status quo (calibration)

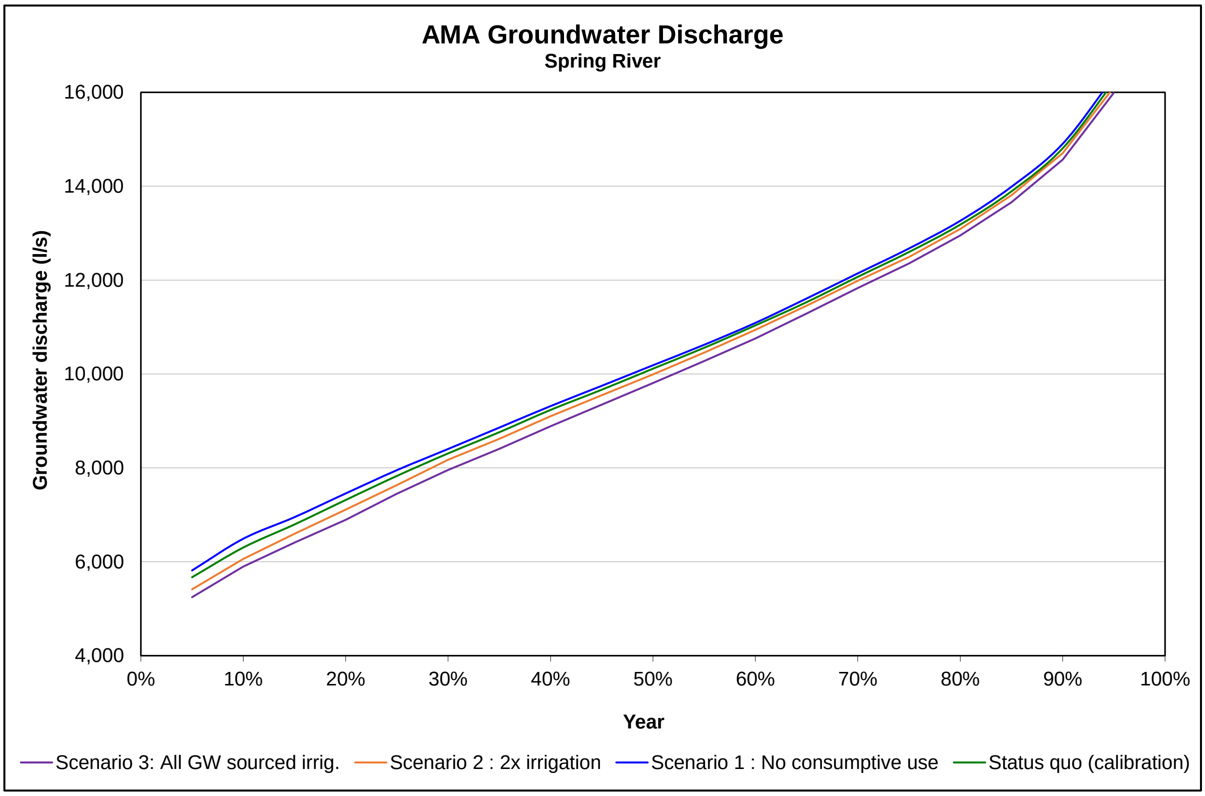

AMA Groundwater Discharge
Te Waikoropupū Main Spring
Groundwater discharge (l/s)
16,000
15,000
14,000
13,000
12,000
11,000
10,000
9,000
8,000
7,000
6,000
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Year
Scenario 3: All GW sourced irrig.
Scenario 2 : 2x irrigation
Scenario 1 : No consumptive use
Status quo (calibration)


AMA Groundwater Discharge
Fish Creek
Groundwater discharge (l/s)
6,000
5,000
4,000
3,000
2,000
1,000
0
900
700
500
300
100
14/02/14
28/02/14
14/03/14
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Year
Scenario 3: All GW sourced irrig.
Scenario 2 : 2x irrigation
Scenario 1 : No consumptive use
Status quo (calibration)

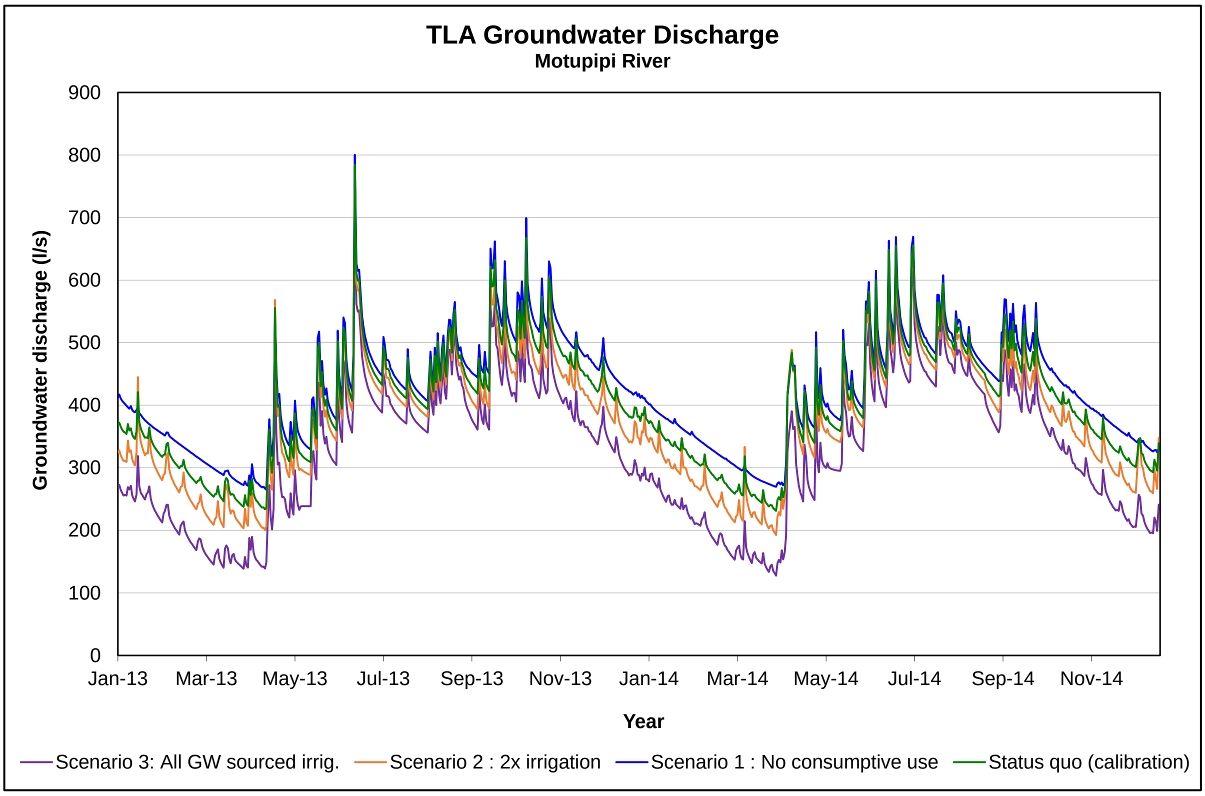

AMA Groundwater Discharge
Fish Creek
Groundwater discharge (l/s)
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Year
Scenario 3: All GW sourced irrig.
Scenario 2 : 2x irrigation
Scenario 1 : No consumptive use
Status quo (calibration)

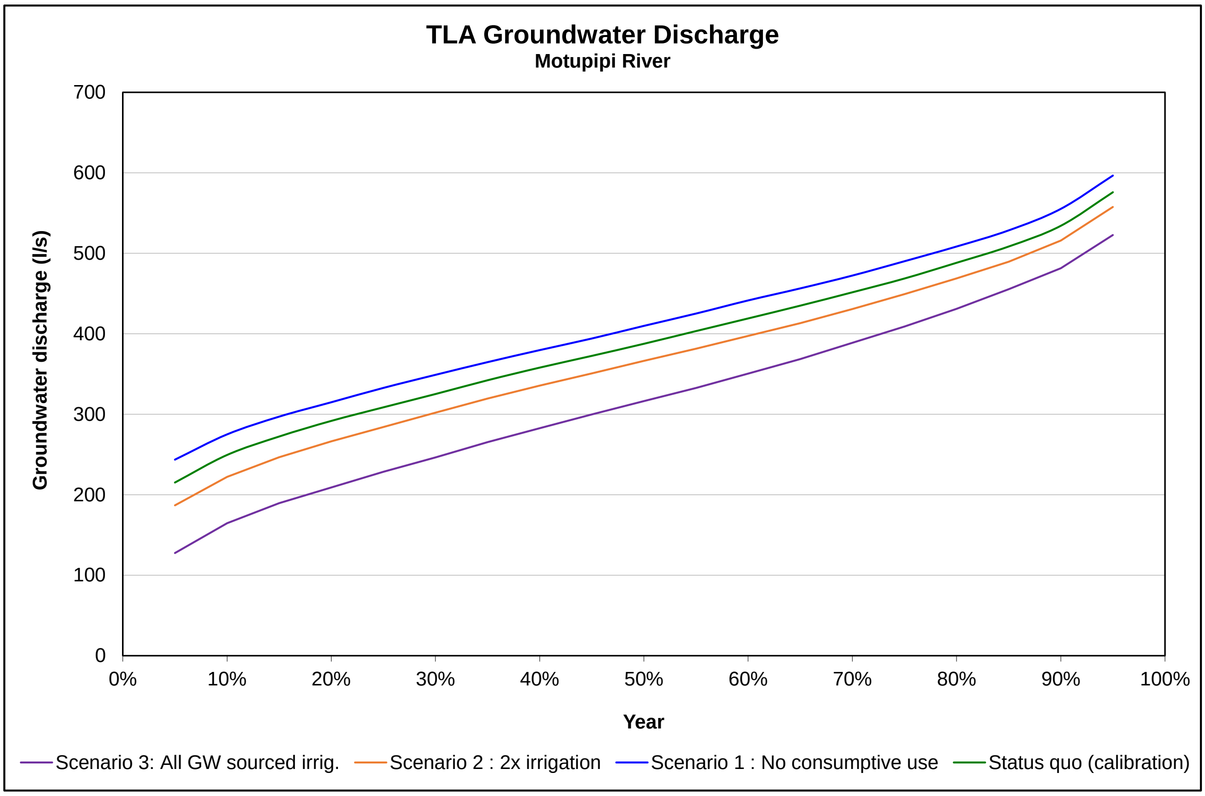


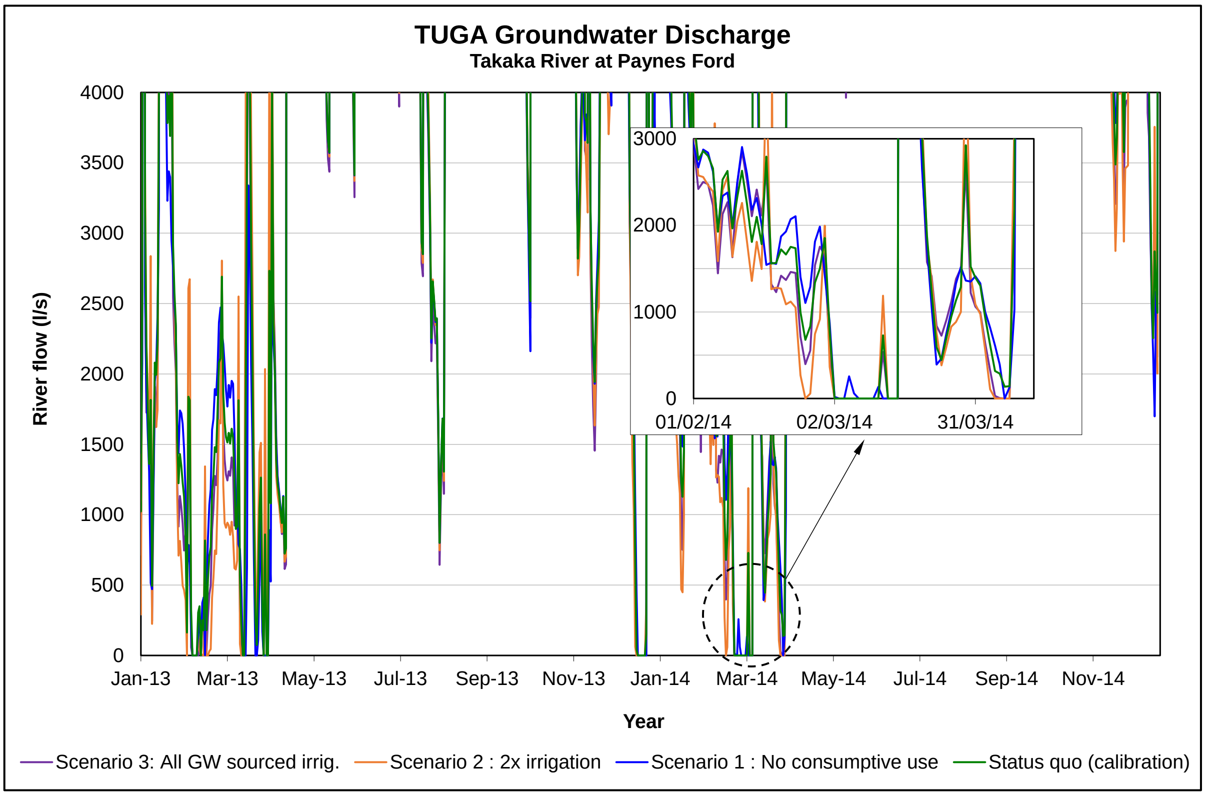
AMA Groundwater Discharge
Spring River
Groundwater discharge (l/s)
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
8,000
7,500
7,000
6,500
6,000
5,500
5,000
14/02/14
28/02/14
14/03/14
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Year
Scenario 3: All GW sourced irrig.
Scenario 2 : 2x irrigation
Scenario 1 : No consumptive use
Status quo (calibration)

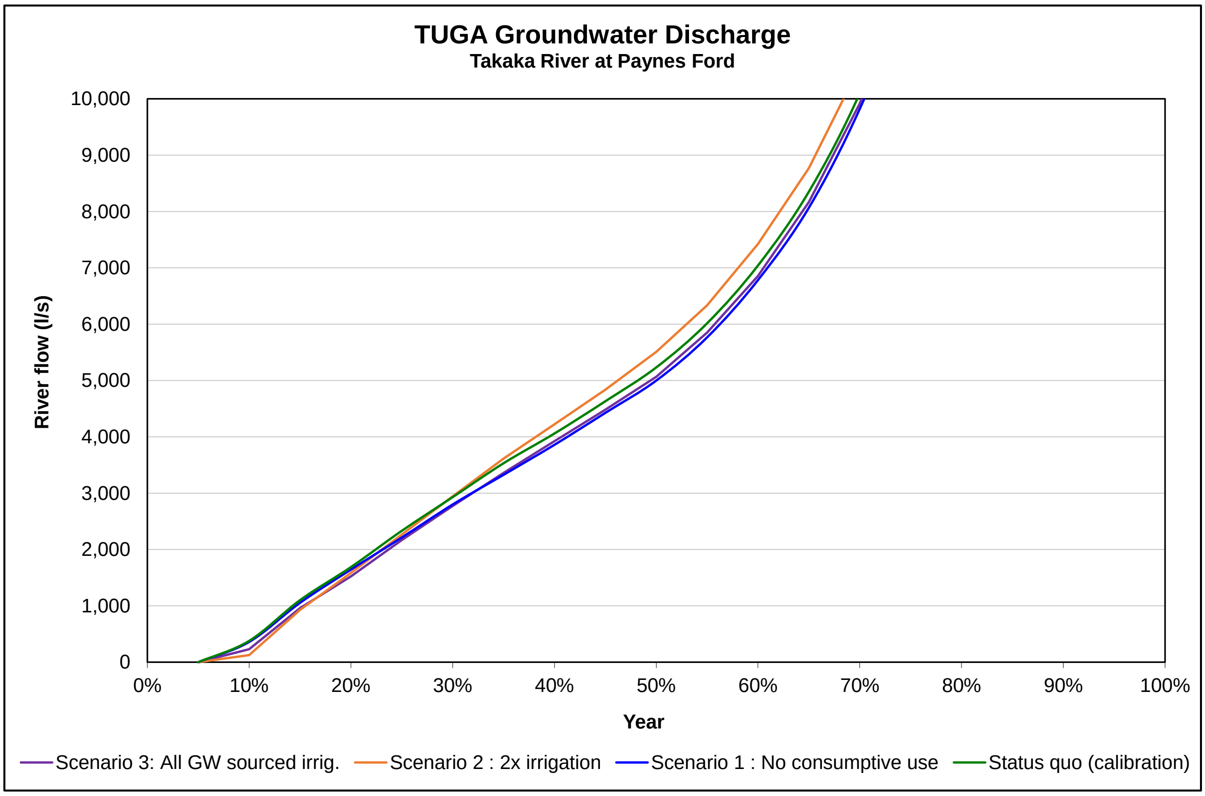


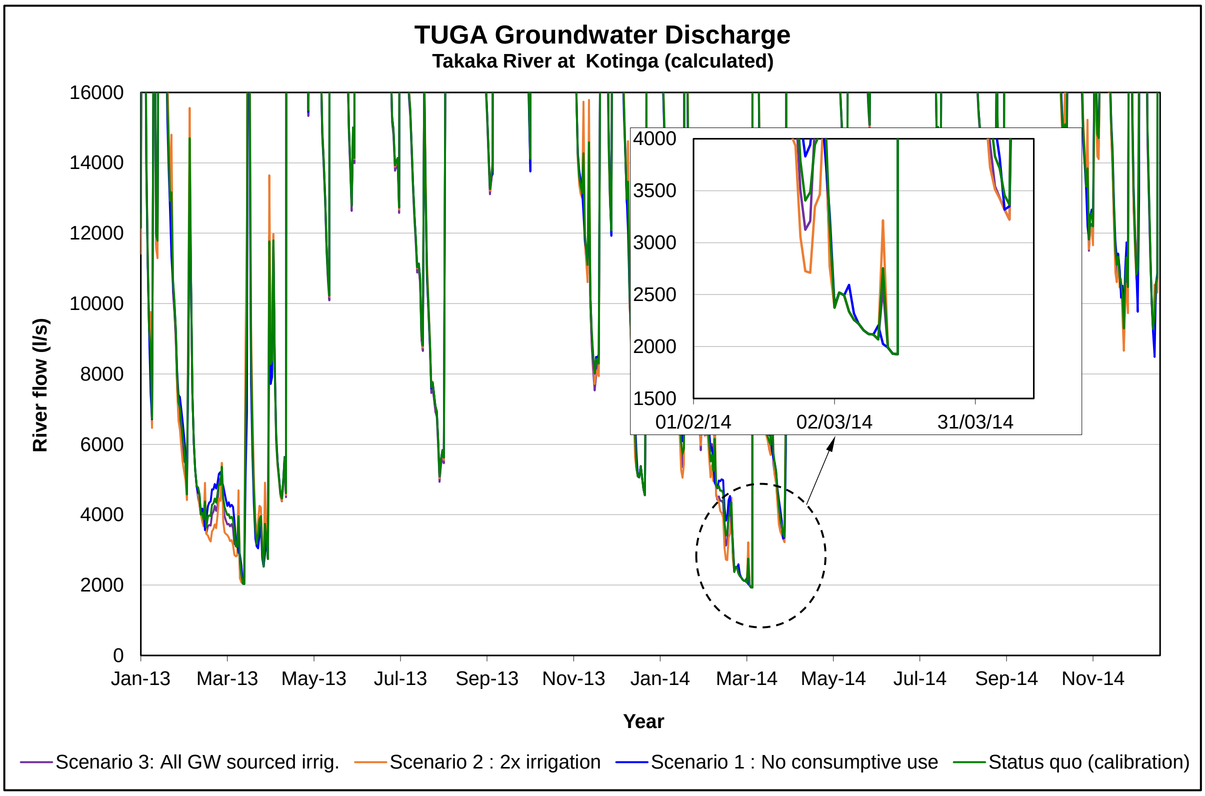
AMA Groundwater Discharge
Spring River
Groundwater discharge (l/s)
16,000
14,000
12,000
10,000
8,000
6,000
4,000
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Year
Scenario 3: All GW sourced irrig.
Scenario 2 : 2x irrigation
Scenario 1 : No consumptive use
Status quo (calibration)

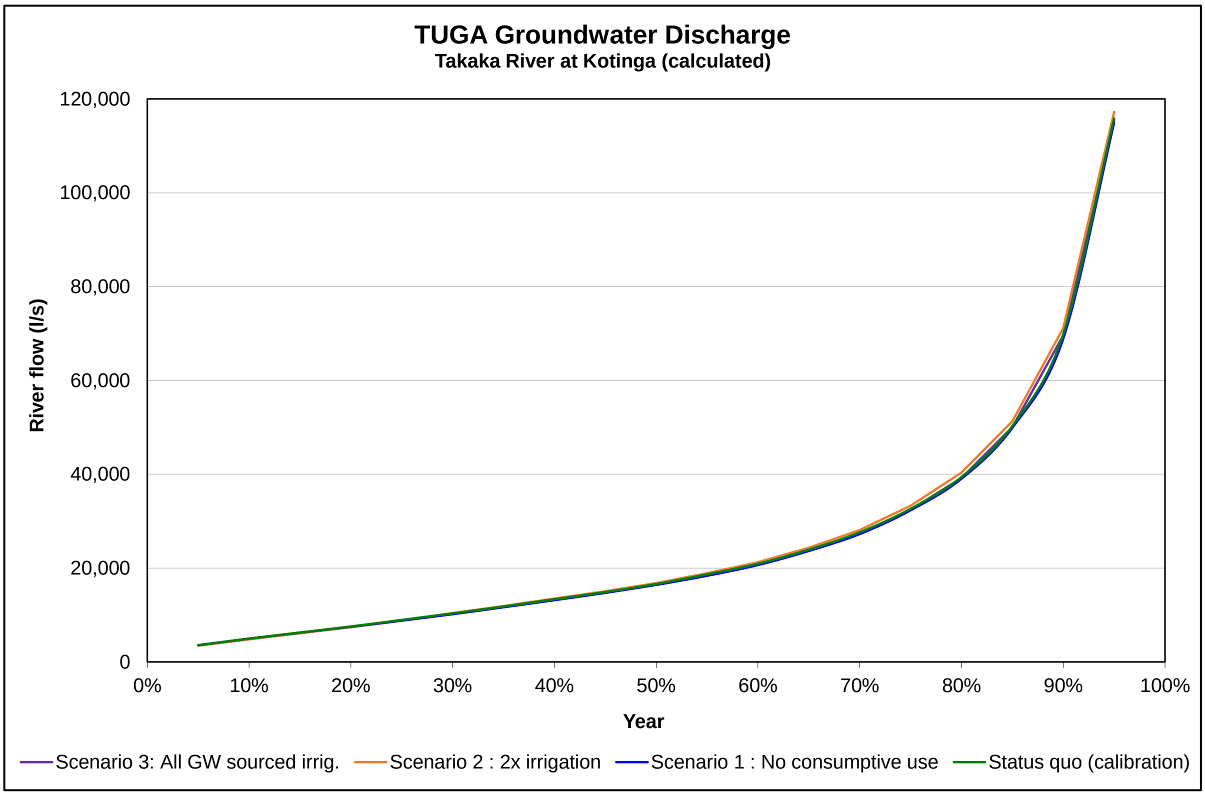

TLA Groundwater Discharge
Motupipi River
Groundwater discharge (l/s)
0
100
200
300
400
500
600
700
800
900
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Year
Scenario 3: All GW sourced irrig.
Scenario 2 : 2x irrigation
Scenario 1 : No consumptive use
Status quo (calibration)


TLA Groundwater Discharge
Motupipi River
Groundwater discharge (l/s)
0
100
200
300
400
500
600
700
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Year
Scenario 3: All GW sourced irrig.
Scenario 2 : 2x irrigation
Scenario 1 : No consumptive use
Status quo (calibration)

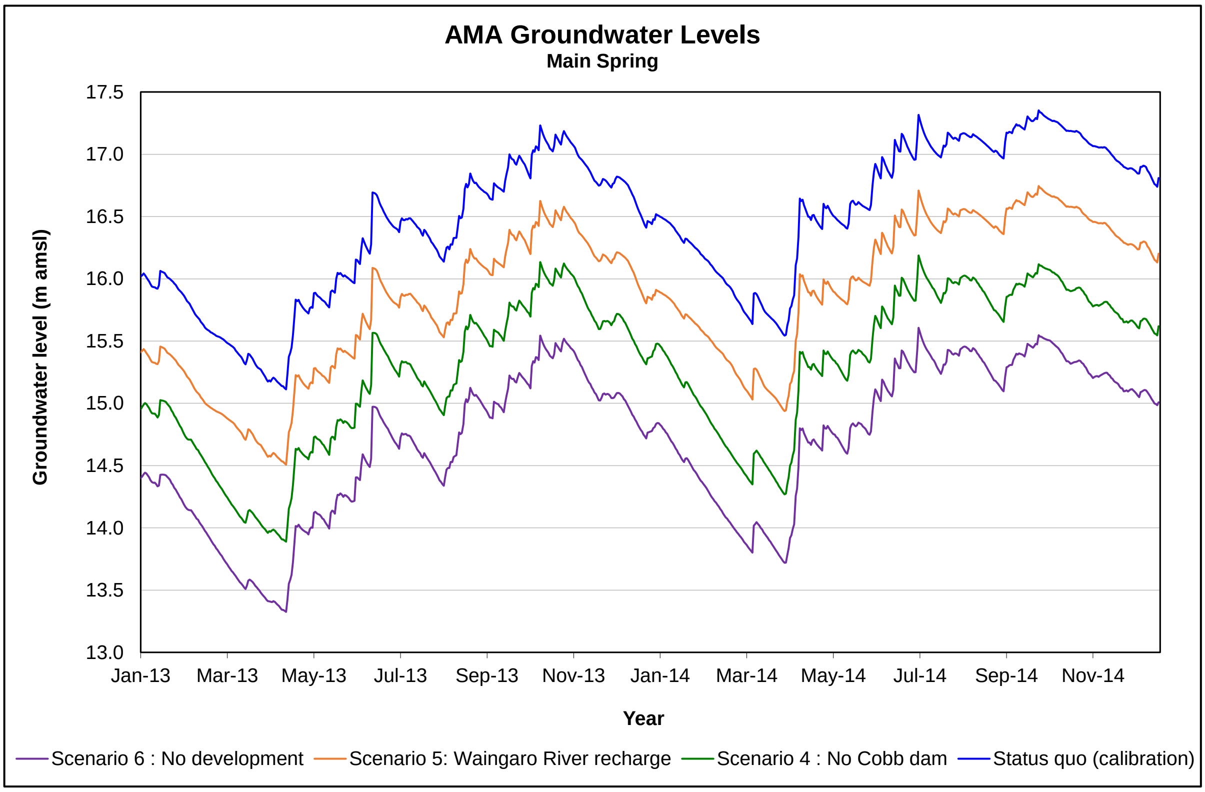

TUGA Groundwater Discharge
Takaka River at Paynes Ford
River flow (l/s)
4000
3500
3000
2500
2000
1500
1000
500
0
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Year
3000
2000
1000
0
01/02/14
02/03/14
31/03/14
Scenario 3: All GW sourced irrig.
Scenario 2 : 2x irrigation
Scenario 1 : No consumptive use
Status quo (calibration)

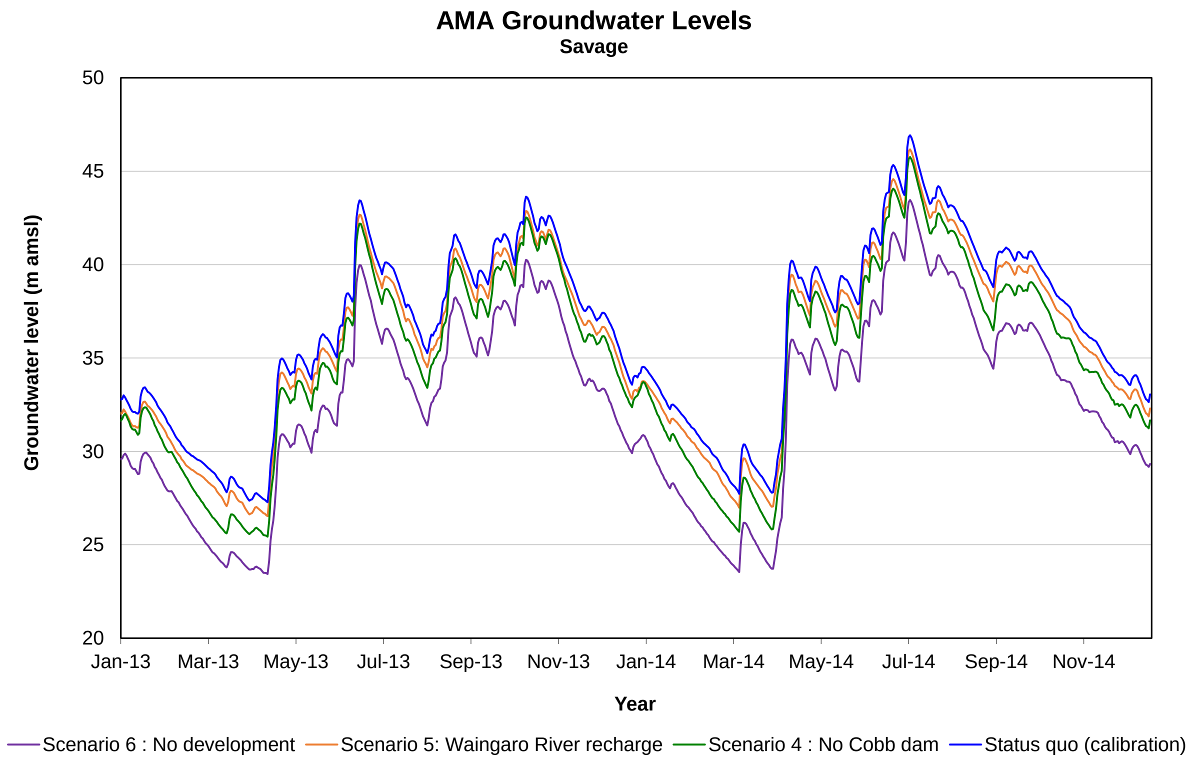

TUGA Groundwater Discharge
Takaka River at Paynes Ford
River flow (l/s)
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Year
Scenario 3: All GW sourced irrig.
Scenario 2 : 2x irrigation
Scenario 1 : No consumptive use
Status quo (calibration)

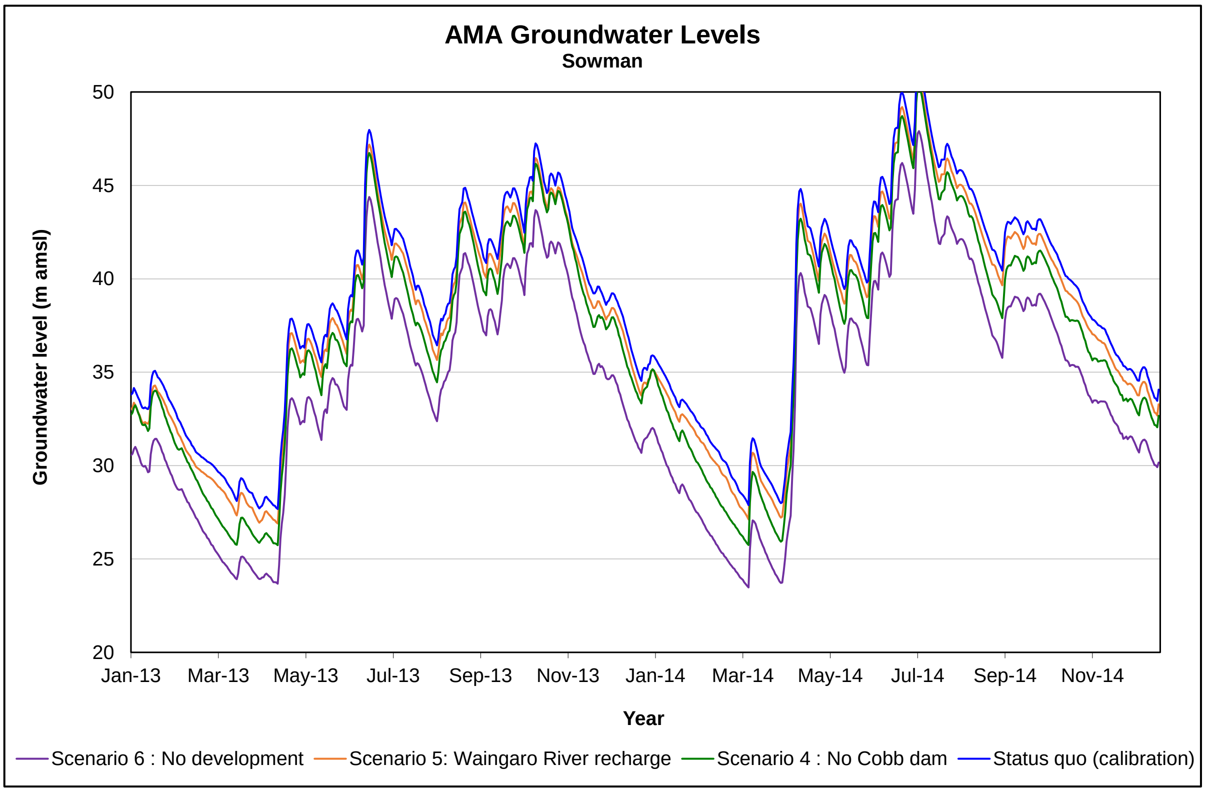

TUGA Groundwater Discharge
Takaka River at Kotinga (calculated)
River flow (l/s)
16000
14000
12000
10000
8000
6000
4000
2000
0
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
4000
3500
3000
2500
2000
1500
01/02/14
02/03/14
31/03/14
Year
Scenario 3: All GW sourced irrig.
Scenario 2 : 2x irrigation
Scenario 1 : No consumptive use
Status quo (calibration)


TUGA Groundwater Discharge
Takaka River at Kotinga (calculated)
River flow (l/s)
120,000
100,000
80,000
60,000
40,000
20,000
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Year
Scenario 3: All GW sourced irrig.
Scenario 2 : 2x irrigation
Scenario 1 : No consumptive use
Status quo (calibration)

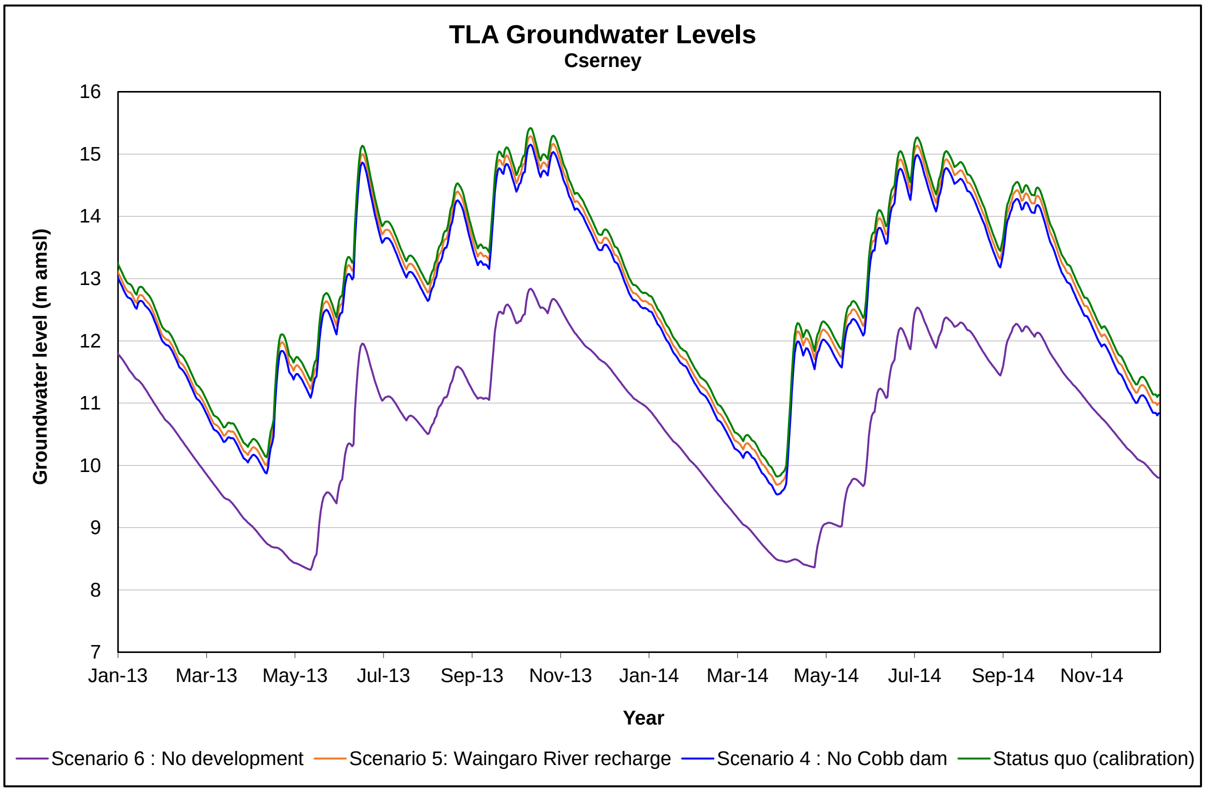
Appendix E: Groundwater level hydrographs comparing calibration with Scenarios 4-6


AMA Groundwater Levels
Main Spring
Groundwater level (m amsl)
17.5
17.0
16.5
16.0
15.5
15.0
14.5
14.0
13.5
13.0
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Year
Scenario 6 : No development
Scenario 5: Waingaro River recharge
Scenario 4 : No Cobb dam
Status quo (calibration)

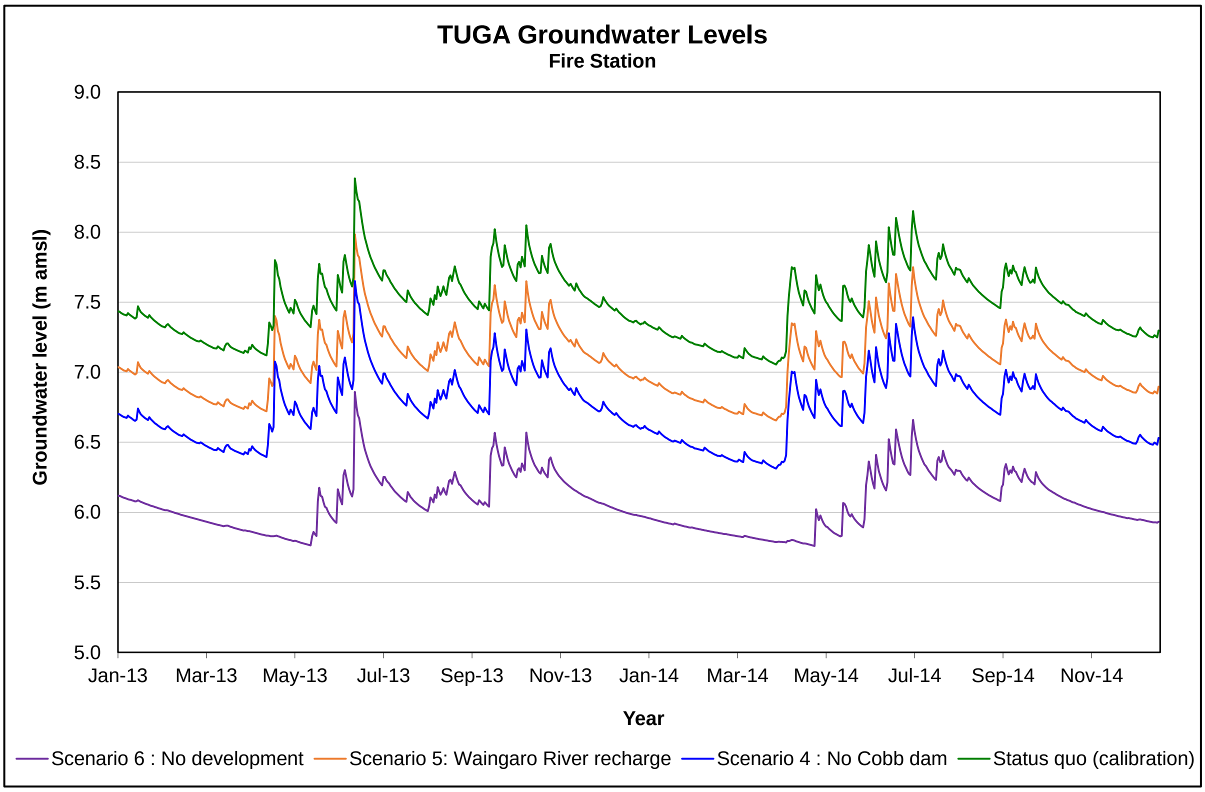

AMA Groundwater Levels
Savage
Groundwater level (m amsl)
50
45
40
35
30
25
20
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Year
Scenario 6 : No development
Scenario 5: Waingaro River recharge
Scenario 4 : No Cobb dam
Status quo (calibration)

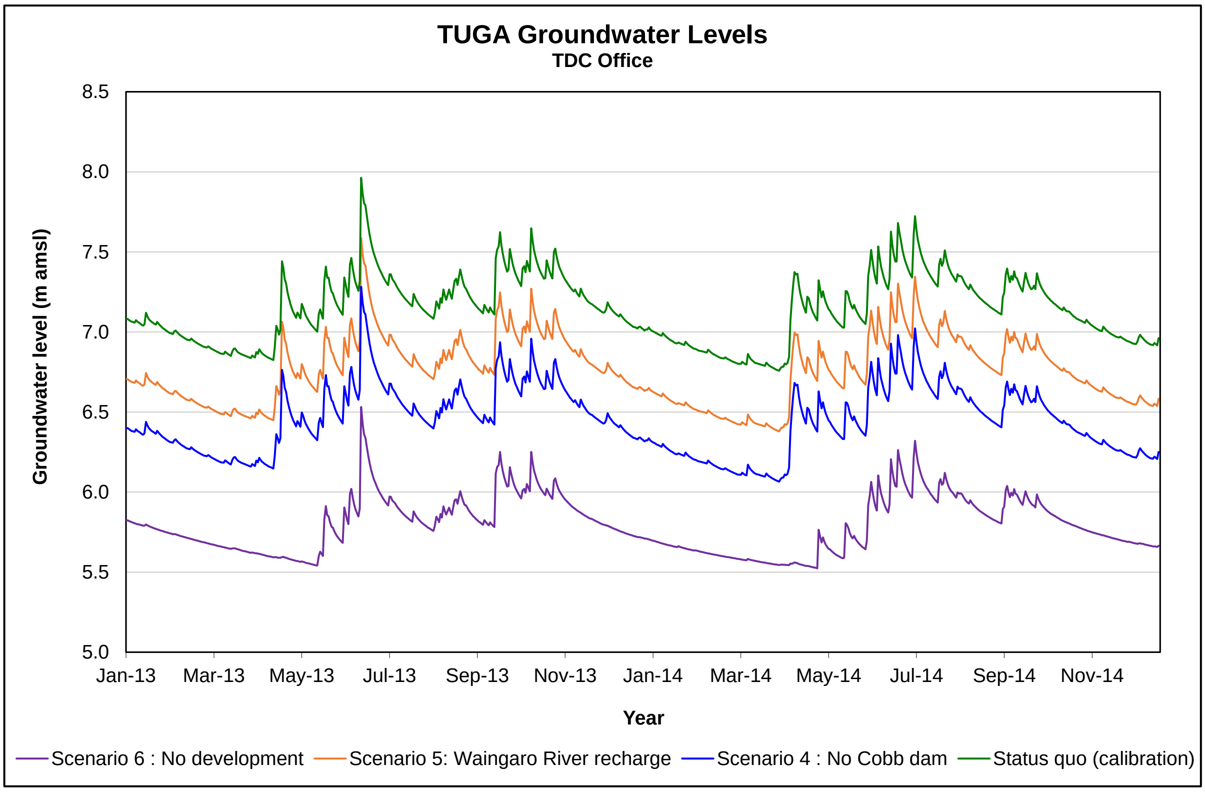


AMA Groundwater Levels
Sowman
Groundwater level (m amsl)
50
45
40
35
30
25
20
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Year
Scenario 6 : No development
Scenario 5: Waingaro River recharge
Scenario 4 : No Cobb dam
Status quo (calibration)

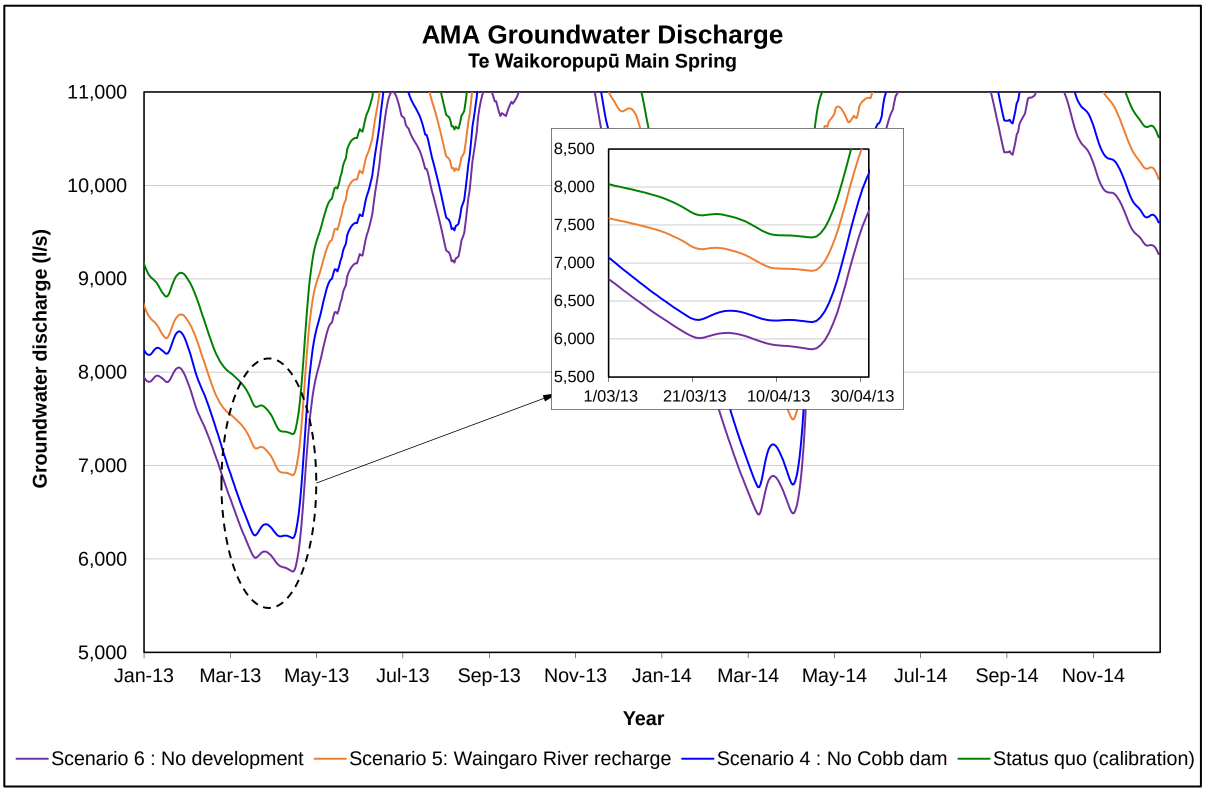


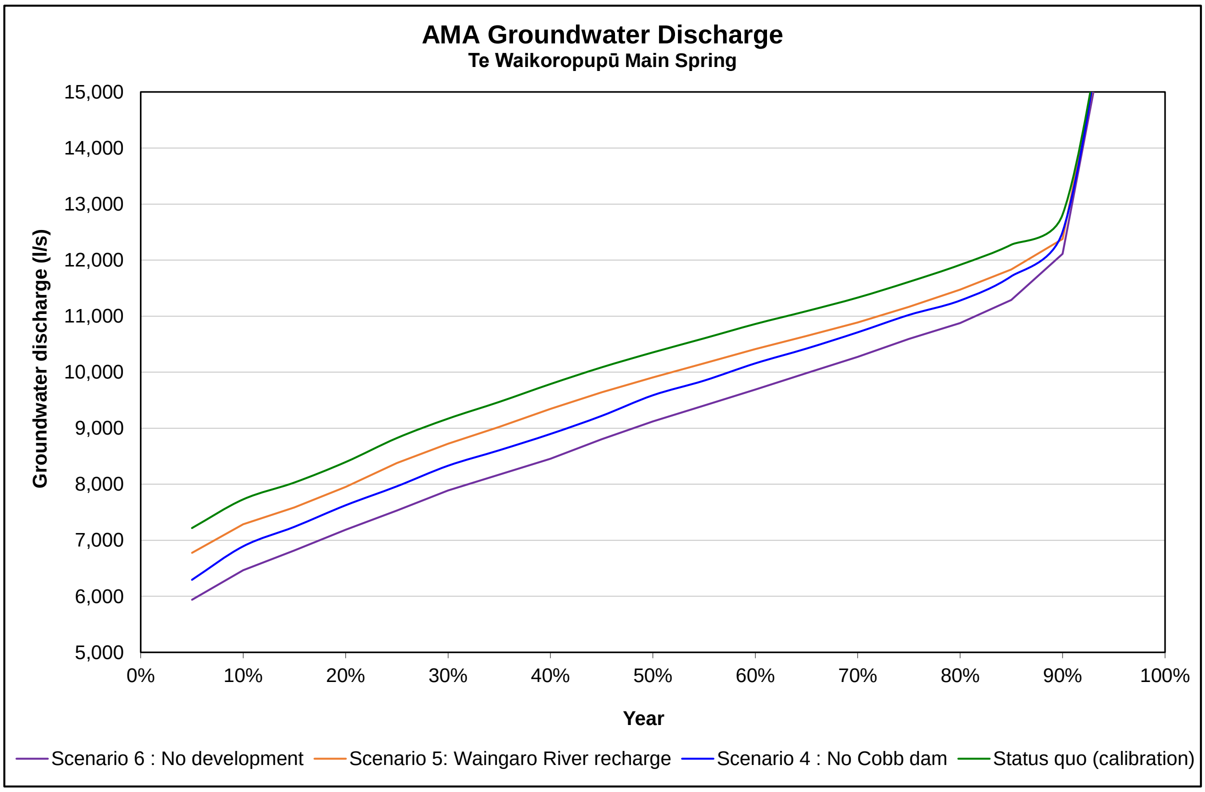
TLA Groundwater Levels
Cserney
Groundwater level (m amsl)
16
15
14
13
12
11
10
9
8
7
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Year
Scenario 6 : No development
Scenario 5: Waingaro River recharge
Scenario 4 : No Cobb dam
Status quo (calibration)

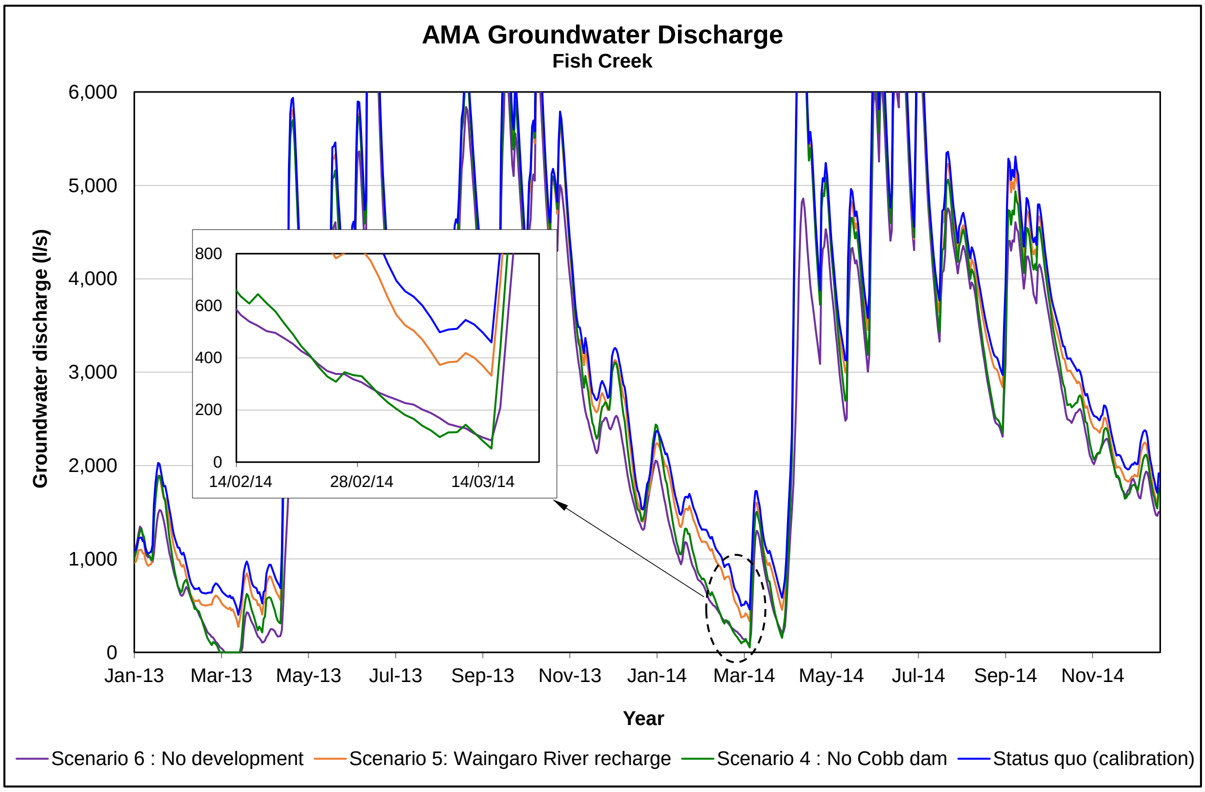

TUGA Groundwater Levels
Fire Station
Groundwater level (m amsl)
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Year
Scenario 6 : No development
Scenario 5: Waingaro River recharge
Scenario 4 : No Cobb dam
Status quo (calibration)

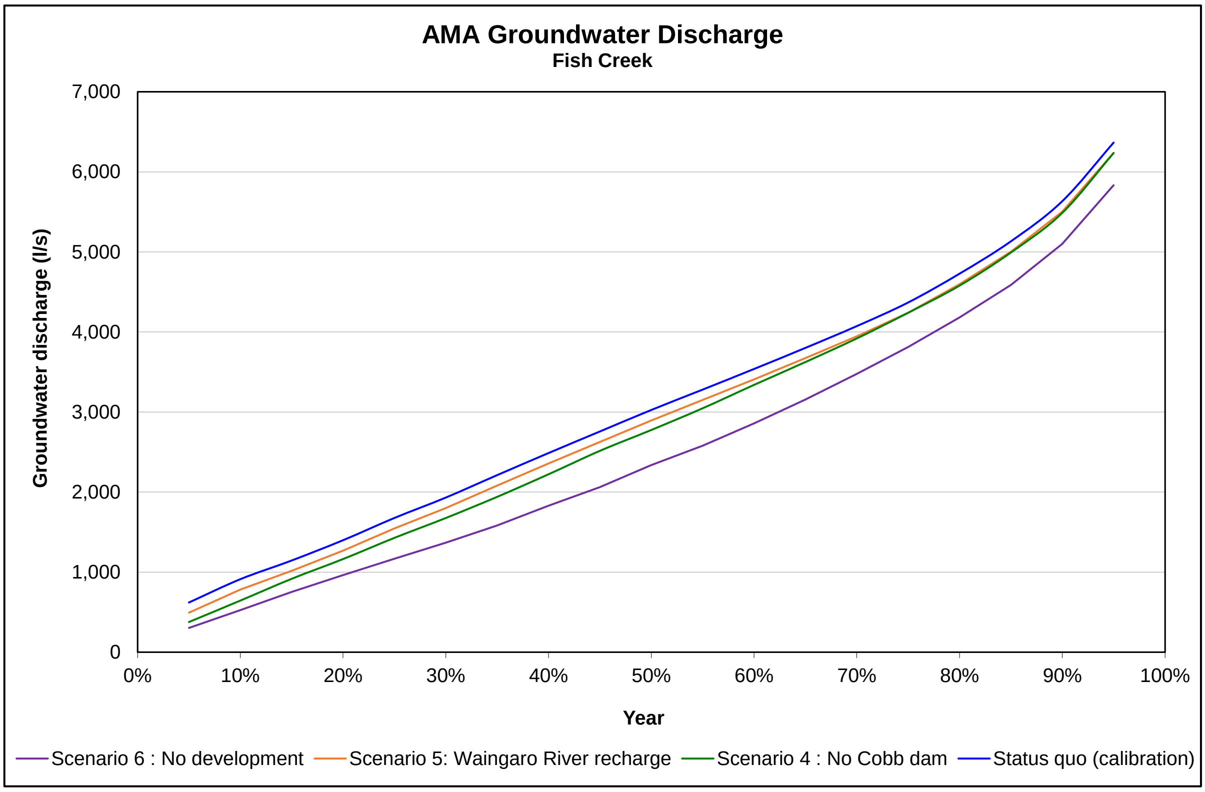

TUGA Groundwater Levels
TDC Office
Groundwater level (m amsl)
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Year
Scenario 6 : No development
Scenario 5: Waingaro River recharge
Scenario 4 : No Cobb dam
Status quo (calibration)

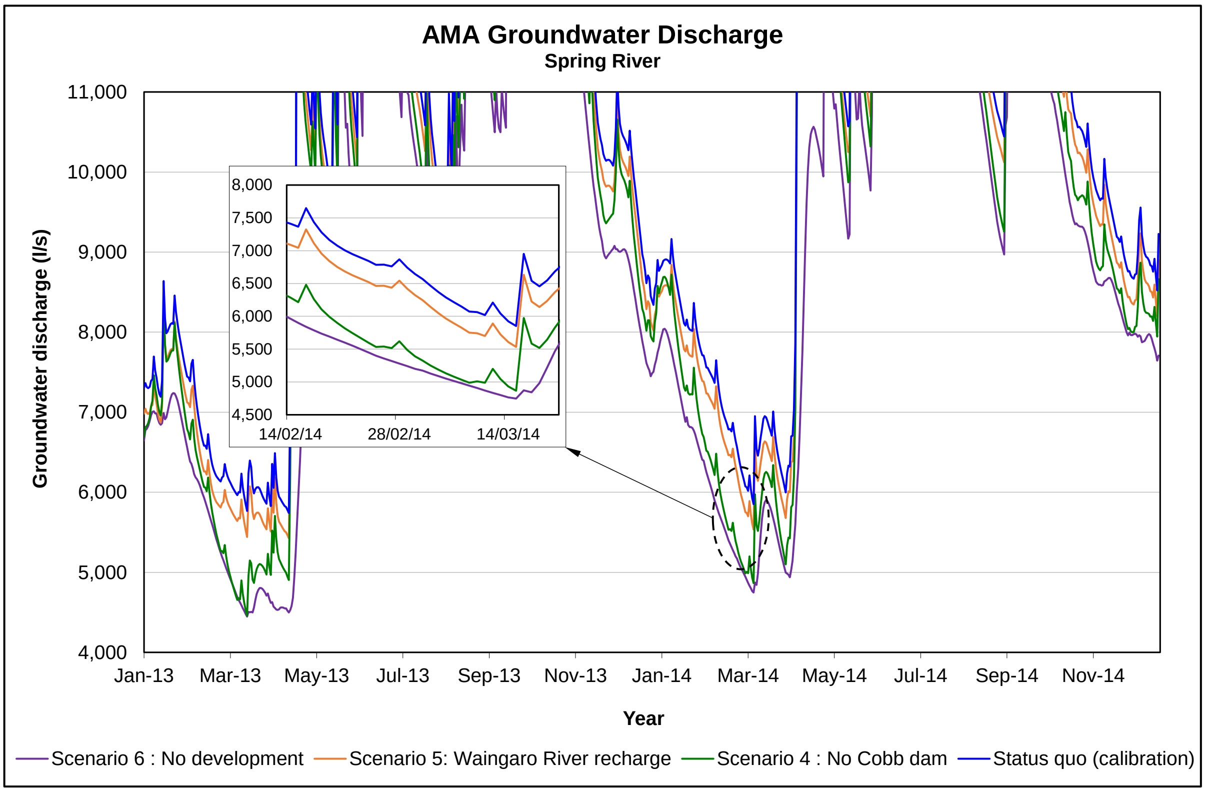
Appendix F: Flow hydrographs and flow duration curves comparing calibration with Scenarios 4-6


AMA Groundwater Discharge
Te Waikoropupū Main Spring
Groundwater discharge (l/s)
11,000
10,000
9,000
8,000
7,000
6,000
5,000
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Year
8,500
8,000
7,500
7,000
6,500
6,000
5,500
1/03/13
21/03/13
10/04/13
30/04/13
Scenario 6 : No development
Scenario 5: Waingaro River recharge
Scenario 4 : No Cobb dam
Status quo (calibration)

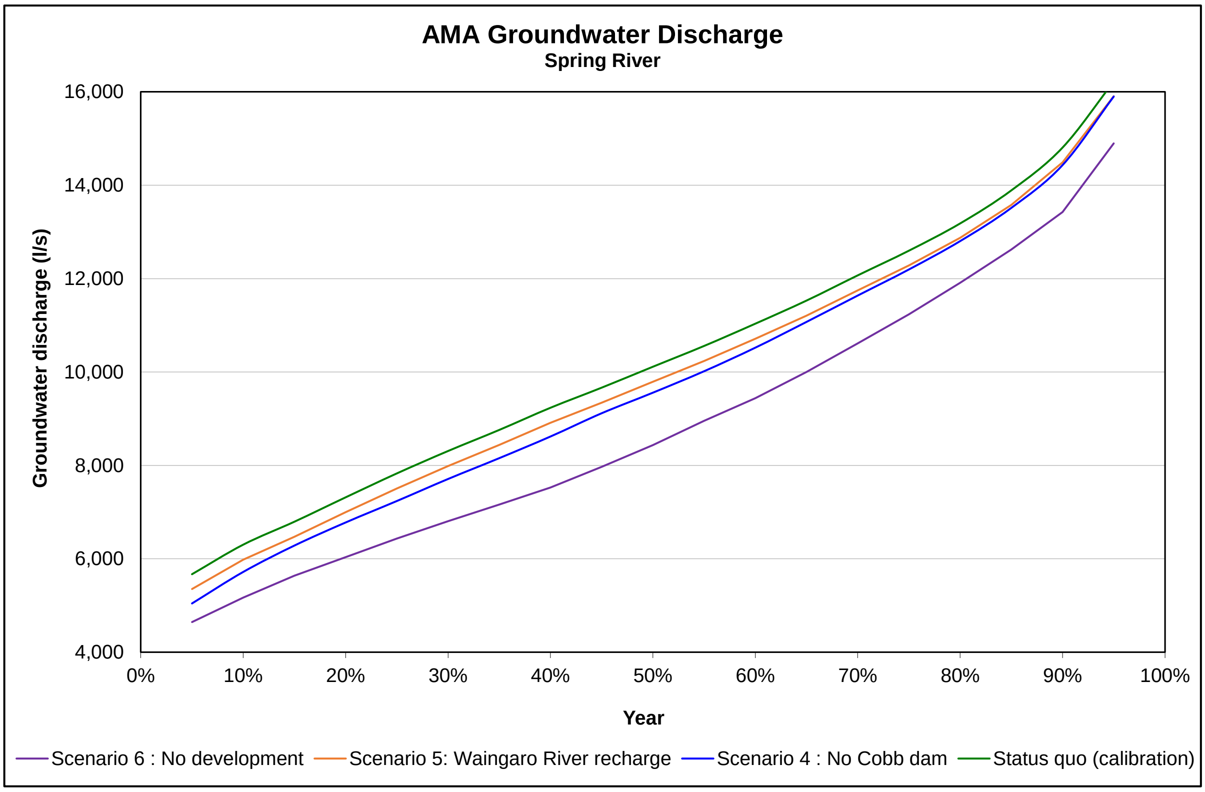

AMA Groundwater Discharge
Te Waikoropupū Main Spring
Groundwater discharge (l/s)
15,000
14,000
13,000
12,000
11,000
10,000
9,000
8,000
7,000
6,000
5,000
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Year
Scenario 6 : No development
Scenario 5: Waingaro River recharge
Scenario 4 : No Cobb dam
Status quo (calibration)


AMA Groundwater Discharge
Fish Creek
Groundwater discharge (l/s)
6,000
5,000
4,000
3,000
2,000
1,000
0
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Year
800
600
400
200
0
14/02/14
28/02/14
14/03/14
Scenario 6 : No development
Scenario 5: Waingaro River recharge
Scenario 4 : No Cobb dam
Status quo (calibration)

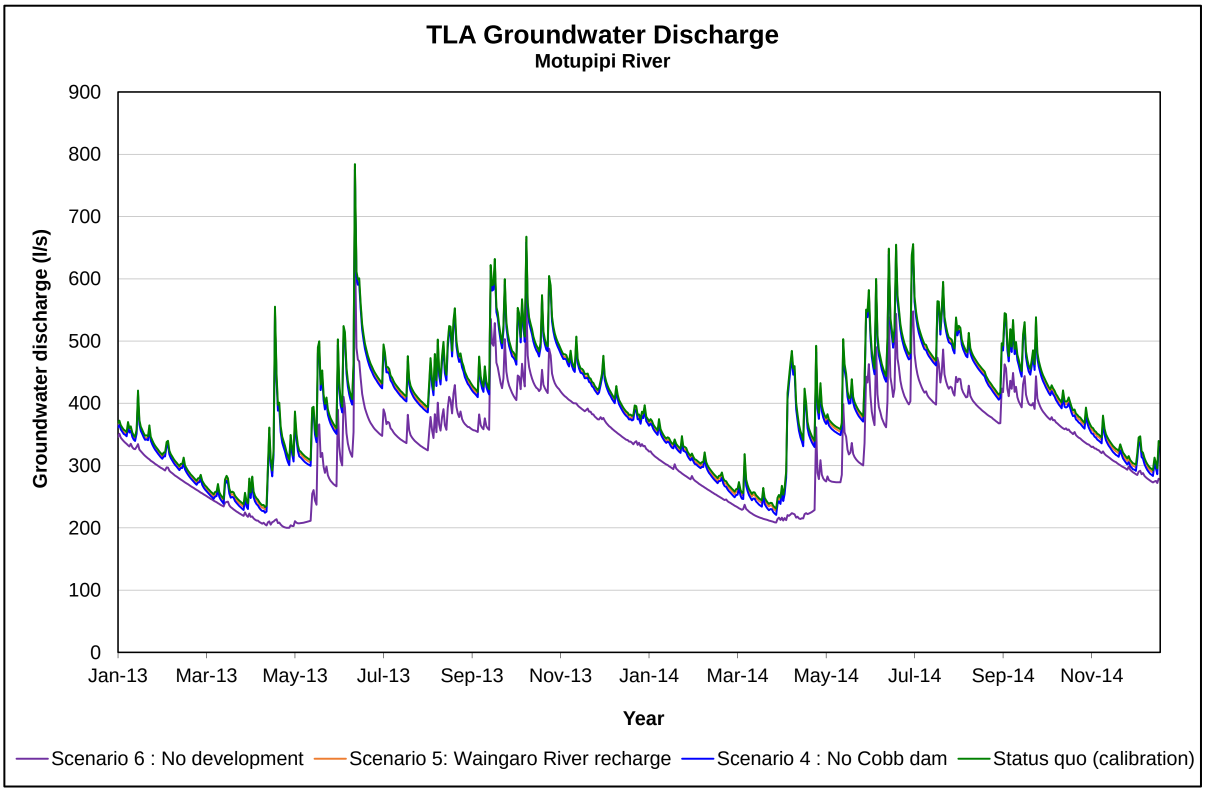

AMA Groundwater Discharge
Fish Creek
Groundwater discharge (l/s)
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Year
Scenario 6 : No development
Scenario 5: Waingaro River recharge
Scenario 4 : No Cobb dam
Status quo (calibration)

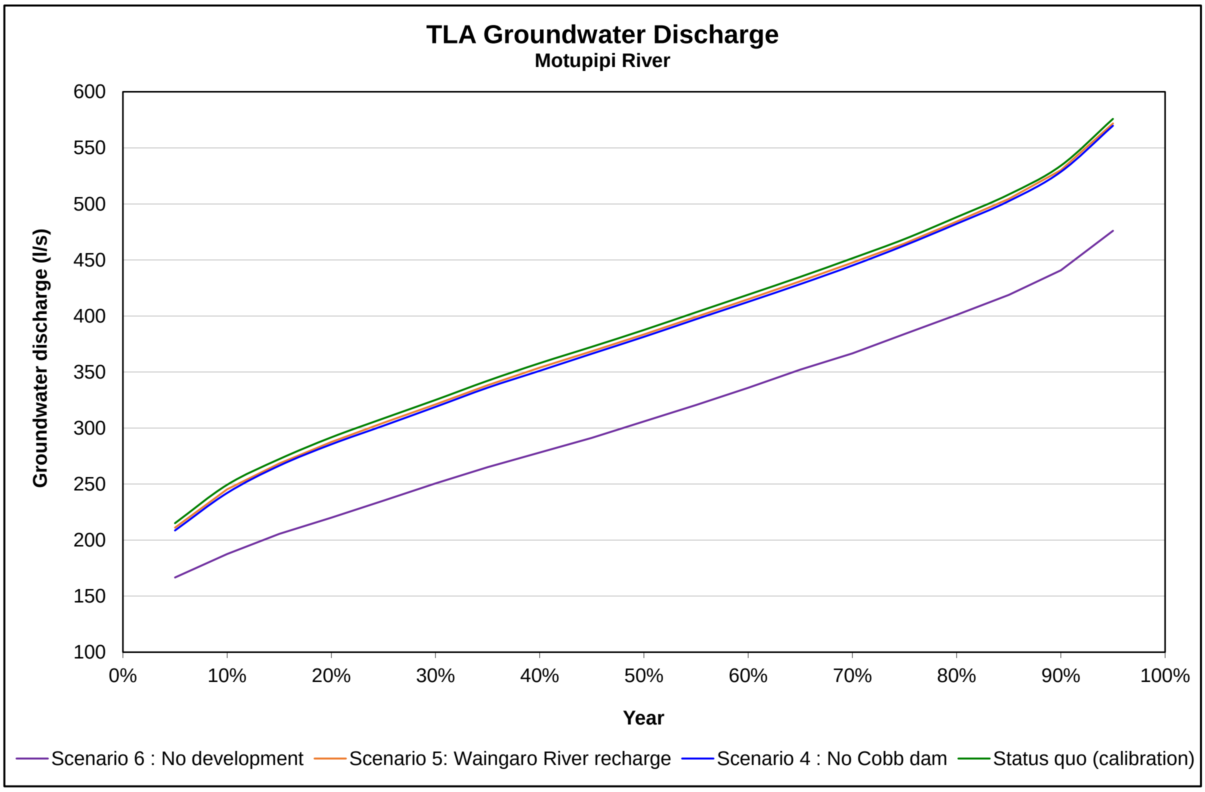


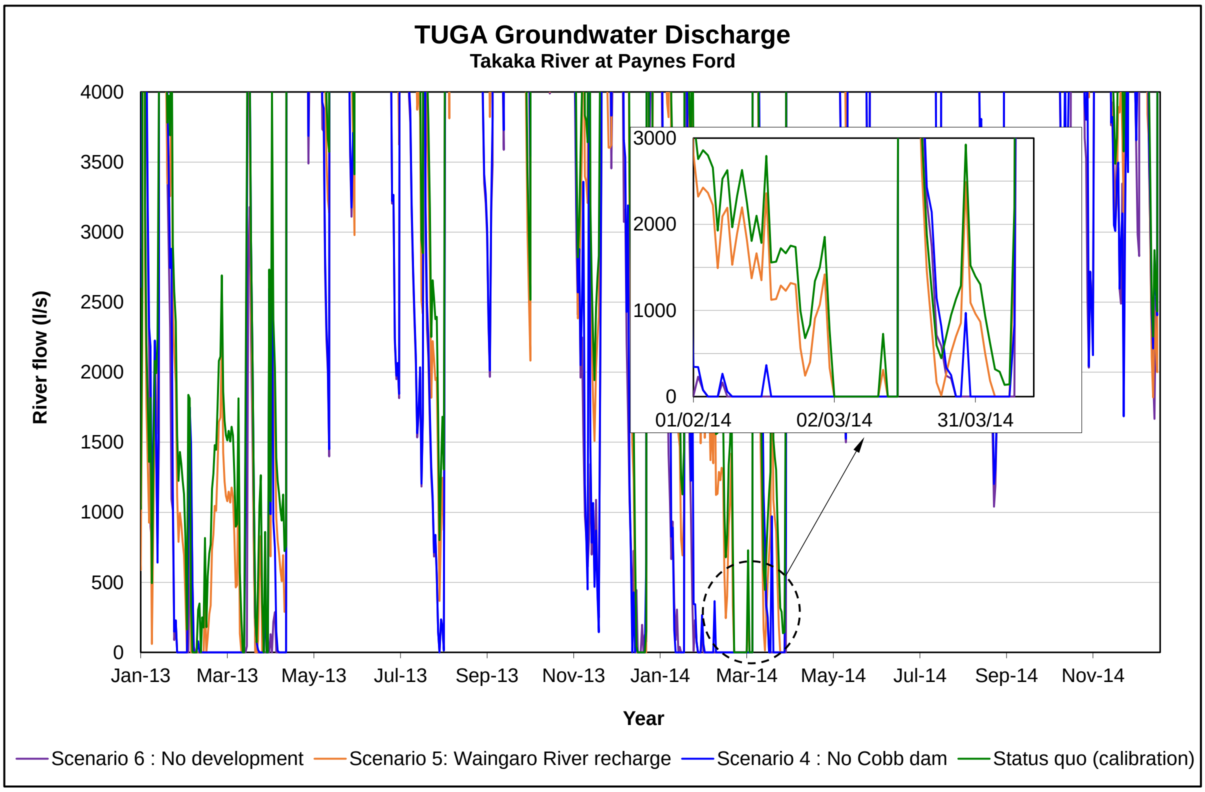
AMA Groundwater Discharge
Spring River
Groundwater discharge (l/s)
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Year
8,000
7,500
7,000
6,500
6,000
5,500
5,000
4,500
14/02/14
28/02/14
14/03/14
Scenario 6 : No development
Scenario 5: Waingaro River recharge
Scenario 4 : No Cobb dam
Status quo (calibration)



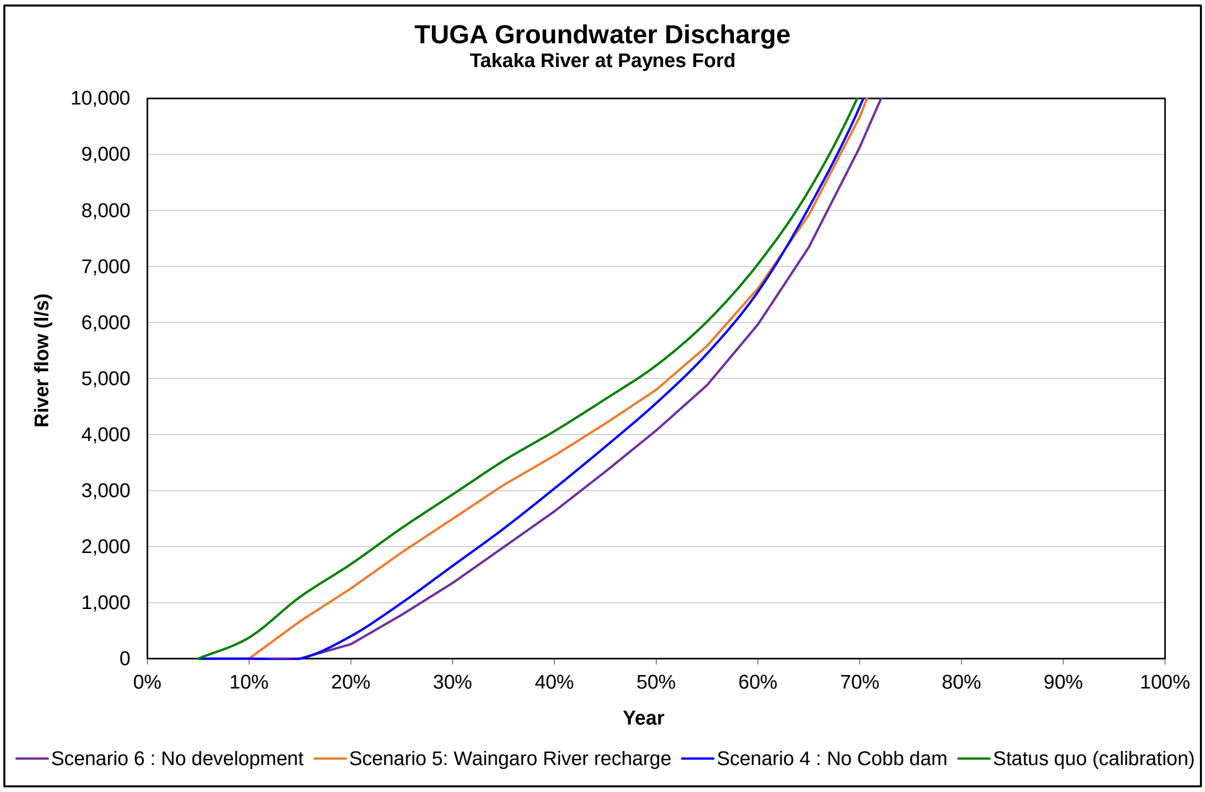
AMA Groundwater Discharge
Spring River
Groundwater discharge (l/s)
16,000
14,000
12,000
10,000
8,000
6,000
4,000
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Year
Scenario 6 : No development
Scenario 5: Waingaro River recharge
Scenario 4 : No Cobb dam
Status quo (calibration)


TLA Groundwater Discharge
Motupipi River
Groundwater discharge (l/s)
900
800
700
600
500
400
300
200
100
0
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Year
Scenario 6 : No development
Scenario 5: Waingaro River recharge
Scenario 4 : No Cobb dam
Status quo (calibration)

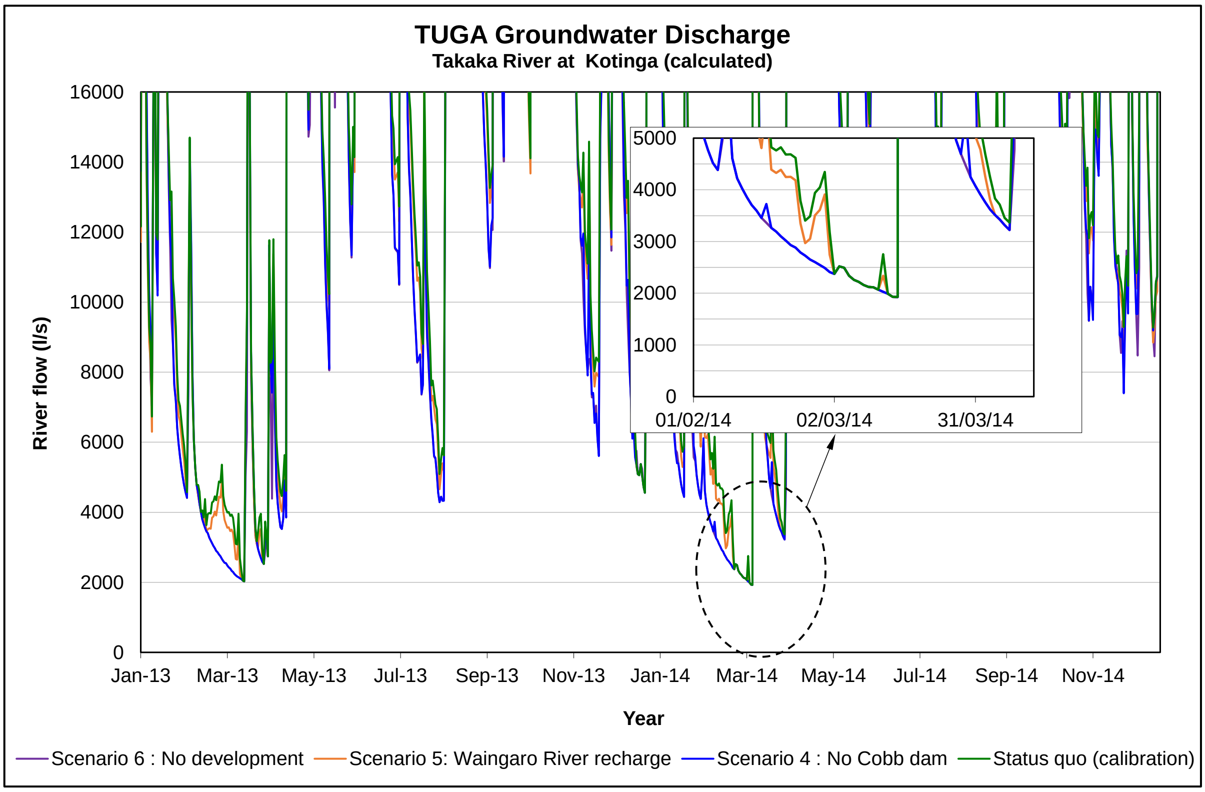

TLA Groundwater Discharge
Motupipi River
Groundwater discharge (l/s)
600
550
500
450
400
350
300
250
200
150
100
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Year
Scenario 6 : No development
Scenario 5: Waingaro River recharge
Scenario 4 : No Cobb dam
Status quo (calibration)

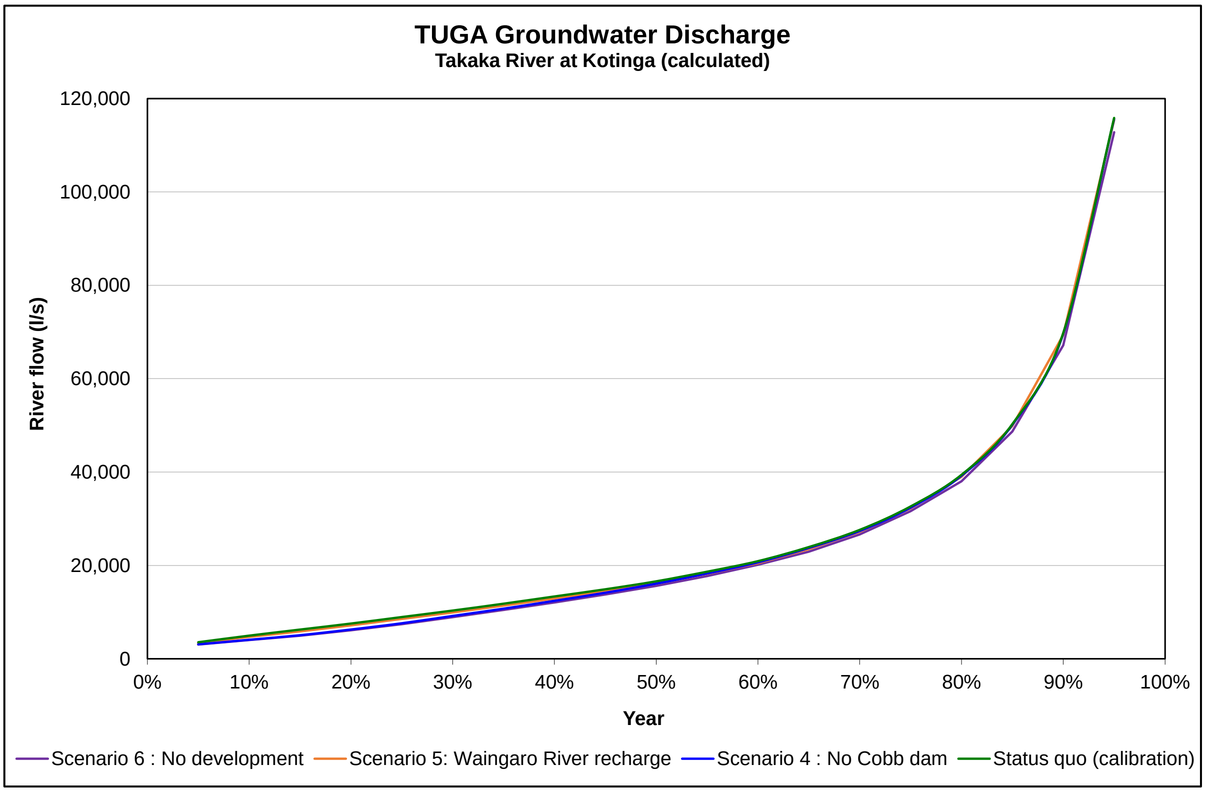


TUGA Groundwater Discharge
Takaka River at Paynes Ford
River flow (l/s)
4000
3500
3000
2500
2000
1500
1000
500
0
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Year
3000
2000
1000
0
01/02/14
02/03/14
31/03/14
Scenario 6 : No development
Scenario 5: Waingaro River recharge
Scenario 4 : No Cobb dam
Status quo (calibration)

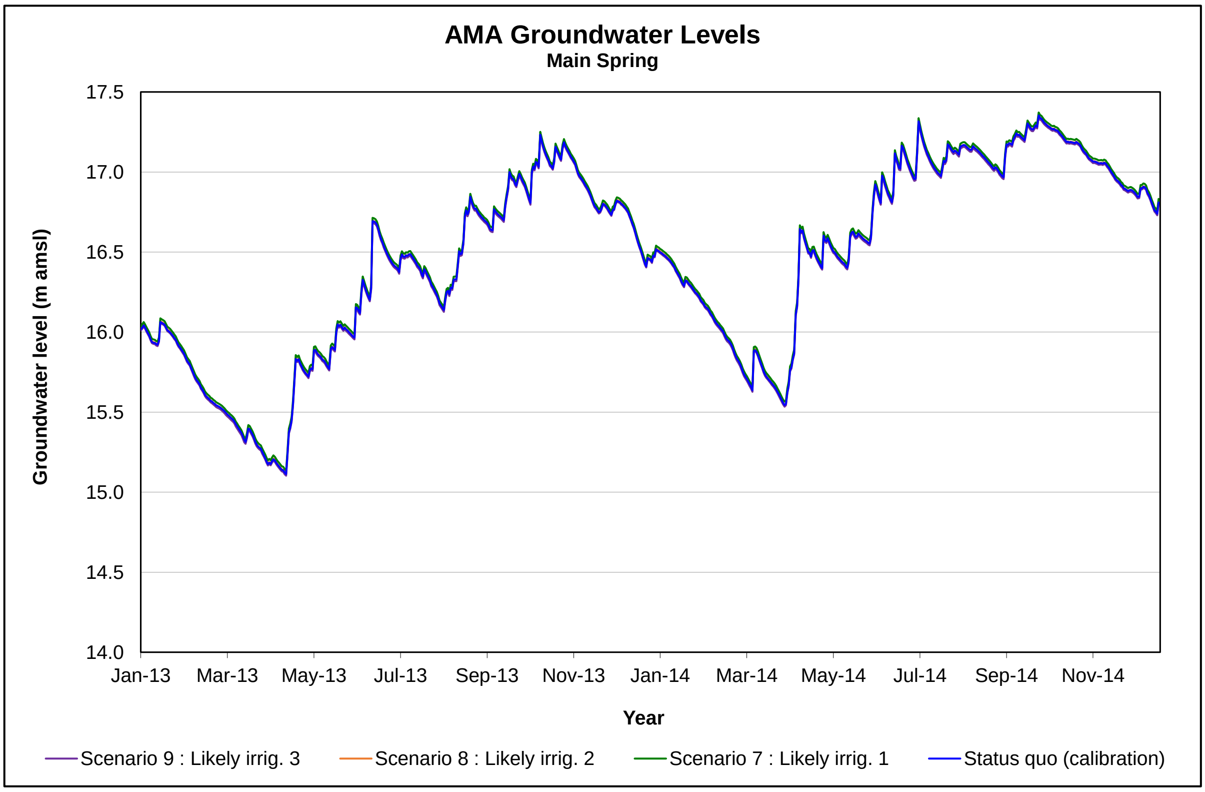


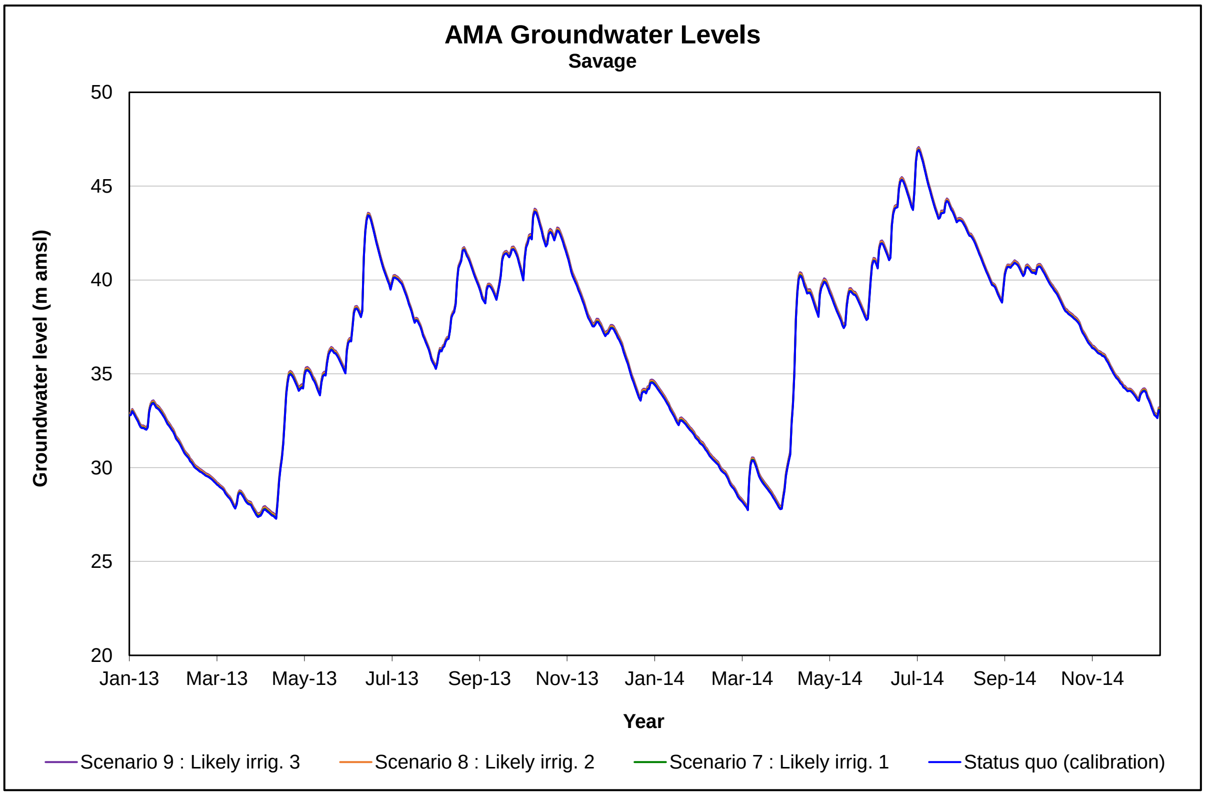
TUGA Groundwater Discharge
Takaka River at Paynes Ford
River flow (l/s)
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Year
Scenario 6 : No development
Scenario 5: Waingaro River recharge
Scenario 4 : No Cobb dam
Status quo (calibration)

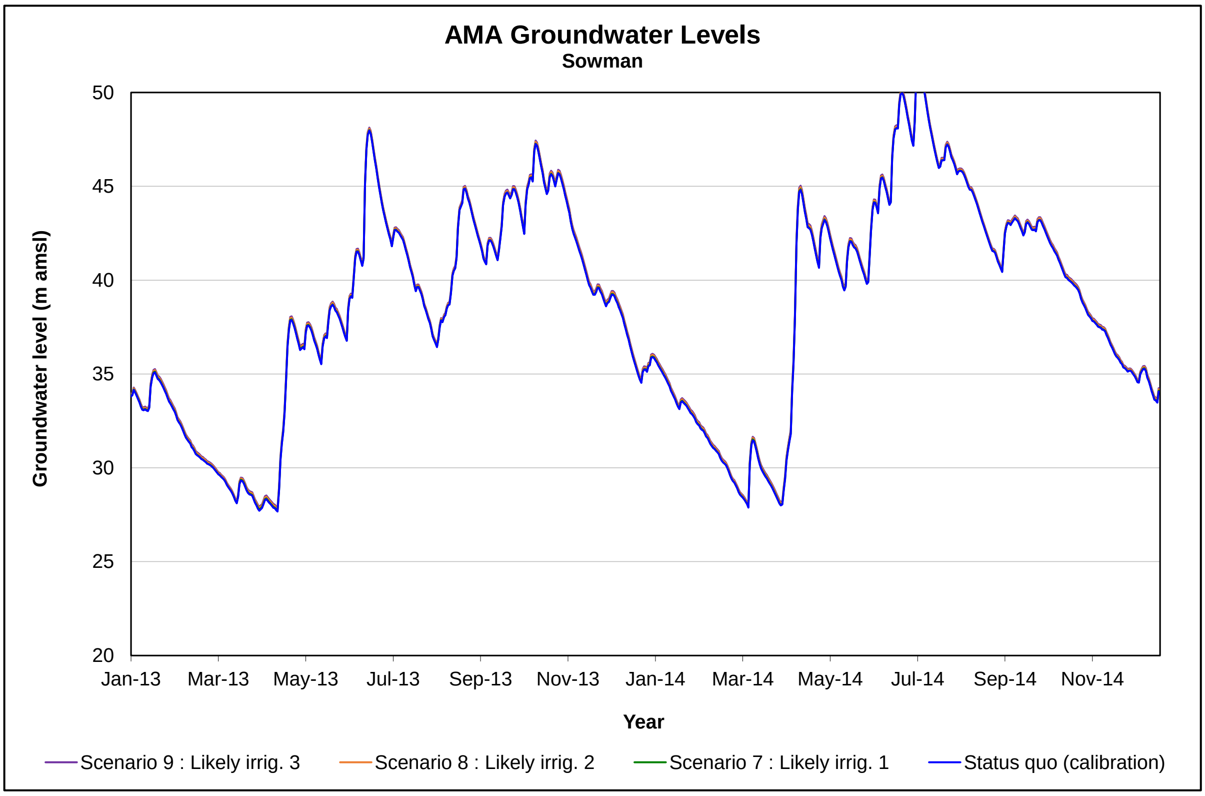

TUGA Groundwater Discharge
Takaka River at Kotinga (calculated)
River flow (l/s)
16000
14000
12000
10000
8000
6000
4000
2000
0
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
5000
4000
3000
2000
1000
0
01/02/14
02/03/14
31/03/14
Year
Scenario 6 : No development
Scenario 5: Waingaro River recharge
Scenario 4 : No Cobb dam
Status quo (calibration)

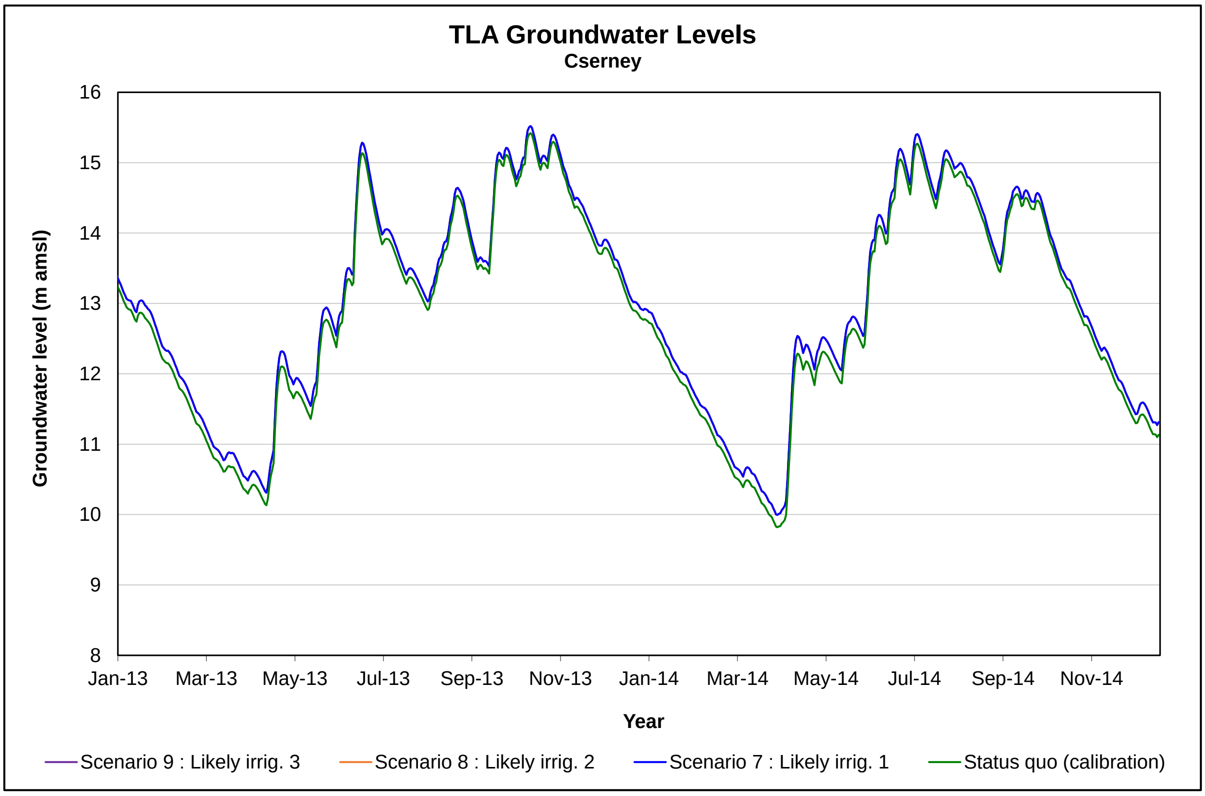

TUGA Groundwater Discharge
Takaka River at Kotinga (calculated)
River flow (l/s)
120,000
100,000
80,000
60,000
40,000
20,000
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Year
Scenario 6 : No development
Scenario 5: Waingaro River recharge
Scenario 4 : No Cobb dam
Status quo (calibration)

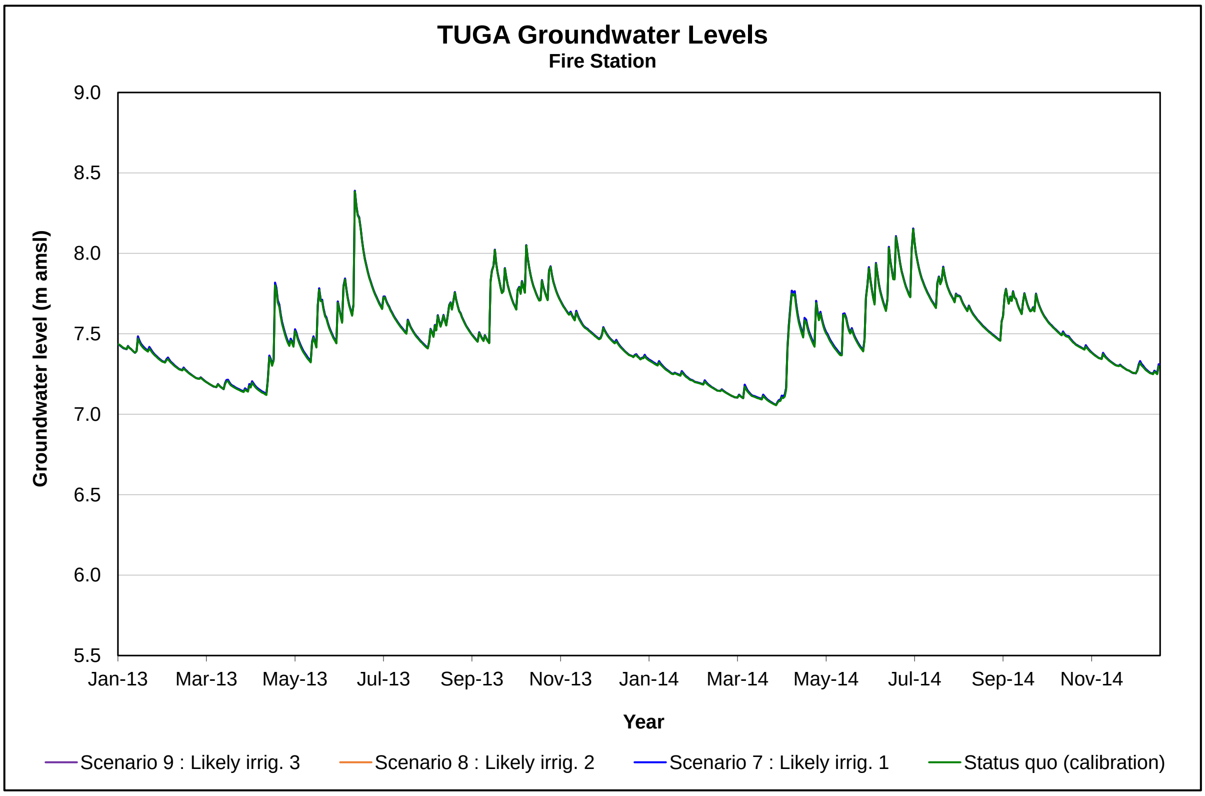
Appendix G: Groundwater level hydrographs comparing calibration with Scenarios 7-9

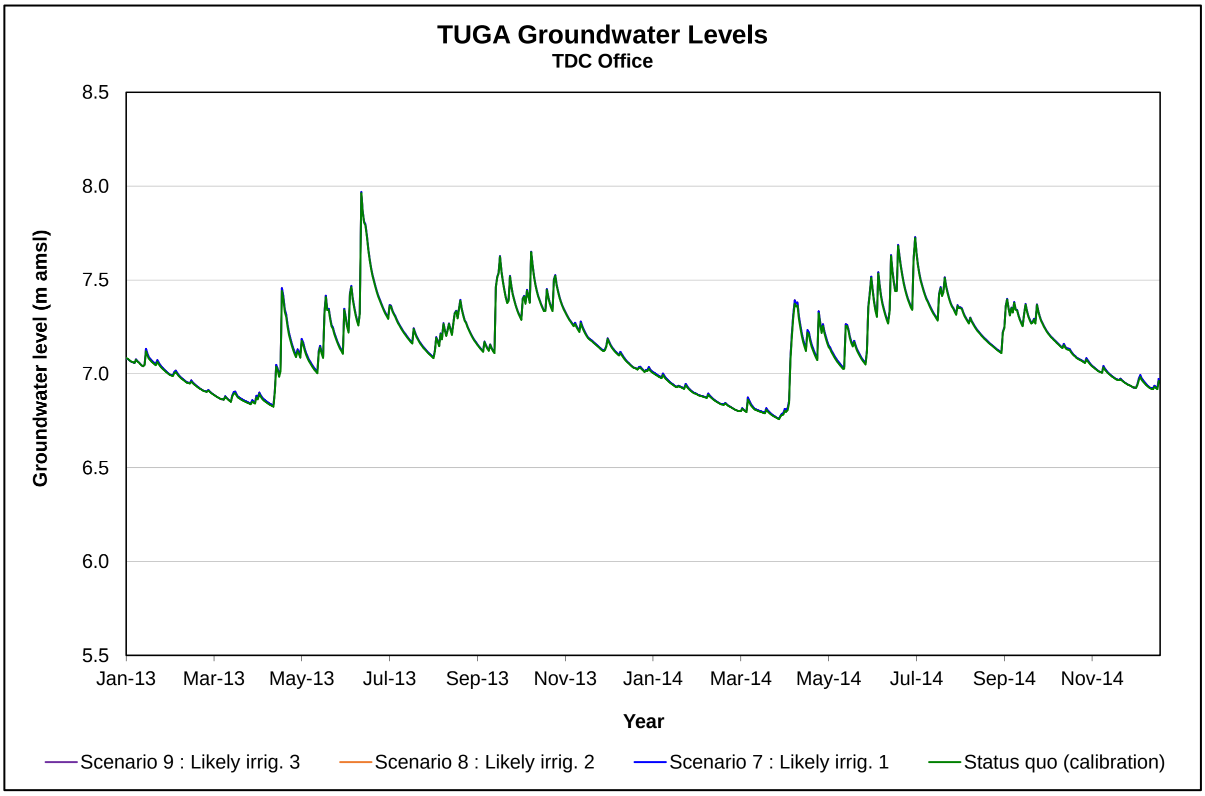

AMA Groundwater Levels
Main Spring
Groundwater level (m amsl)
17.5
17.0
16.5
16.0
15.5
15.0
14.5
14.0
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Year
Scenario 9 : Likely irrig. 3
Scenario 8 : Likely irrig. 2
Scenario 7 : Likely irrig. 1
Status quo (calibration)


AMA Groundwater Levels
Savage
Groundwater level (m amsl)
50
45
40
35
30
25
20
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Year
Scenario 9 : Likely irrig. 3
Scenario 8 : Likely irrig. 2
Scenario 7 : Likely irrig. 1
Status quo (calibration)

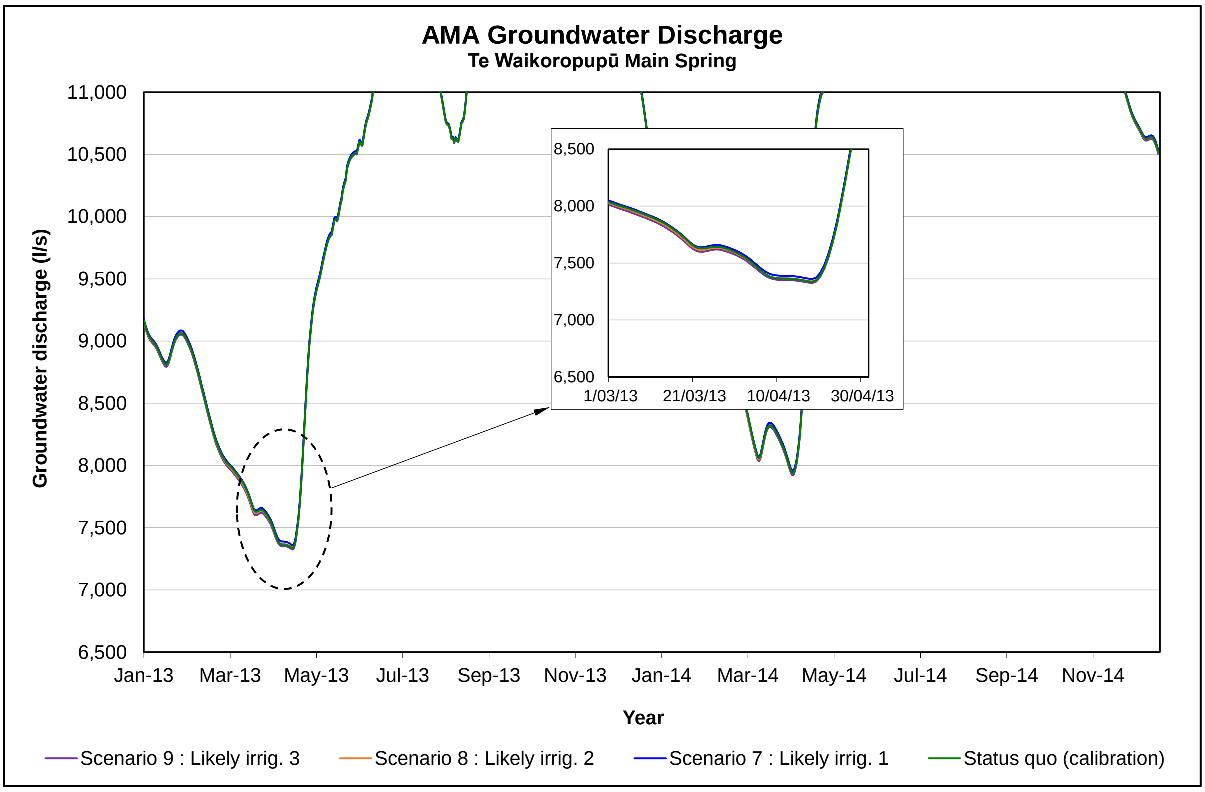

AMA Groundwater Levels
Sowman
Groundwater level (m amsl)
50
45
40
35
30
25
20
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Year
Scenario 9 : Likely irrig. 3
Scenario 8 : Likely irrig. 2
Scenario 7 : Likely irrig. 1
Status quo (calibration)


TLA Groundwater Levels
Cserney
Groundwater level (m amsl)
16
15
14
13
12
11
10
9
8
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Year
Scenario 9 : Likely irrig. 3
Scenario 8 : Likely irrig. 2
Scenario 7 : Likely irrig. 1
Status quo (calibration)

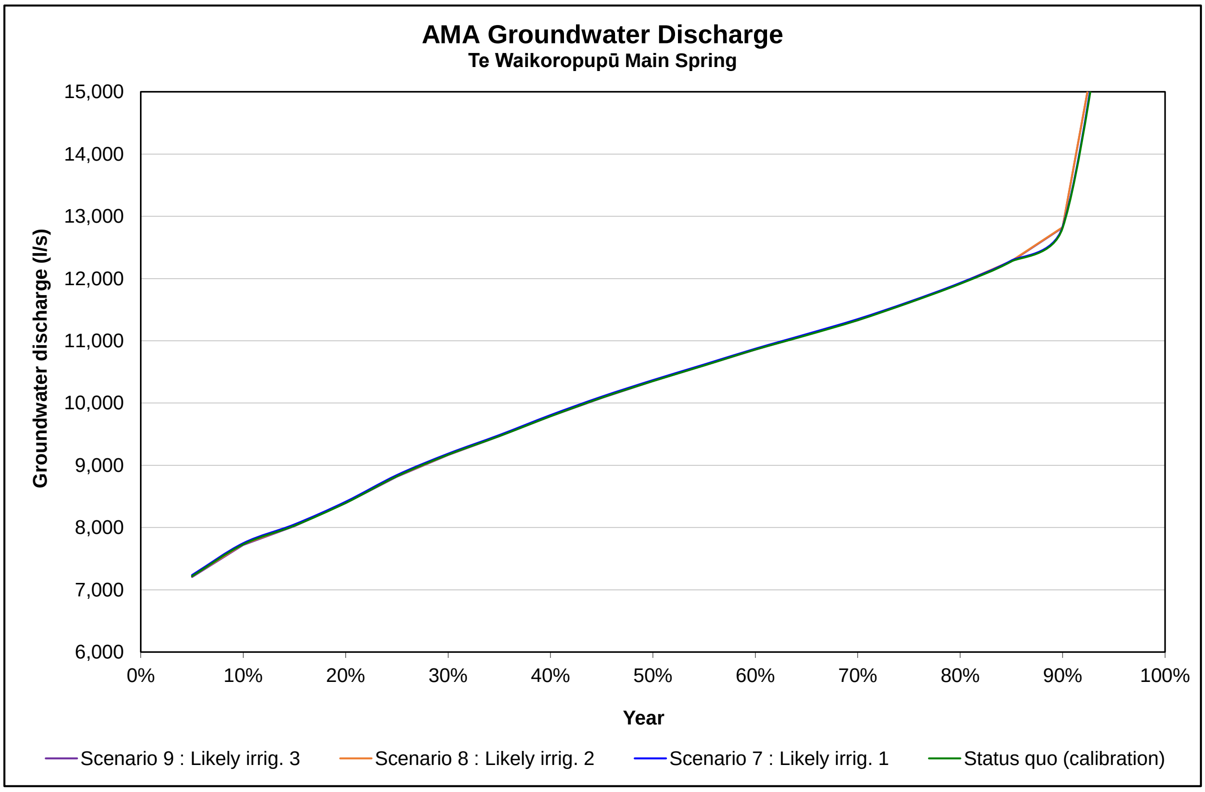

TUGA Groundwater Levels
Fire Station
Groundwater level (m amsl)
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Year
Scenario 9 : Likely irrig. 3
Scenario 8 : Likely irrig. 2
Scenario 7 : Likely irrig. 1
Status quo (calibration)


TUGA Groundwater Levels
TDC Office
Groundwater level (m amsl)
8.5
8.0
7.5
7.0
6.5
6.0
5.5
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Year
Scenario 9 : Likely irrig. 3
Scenario 8 : Likely irrig. 2
Scenario 7 : Likely irrig. 1
Status quo (calibration)

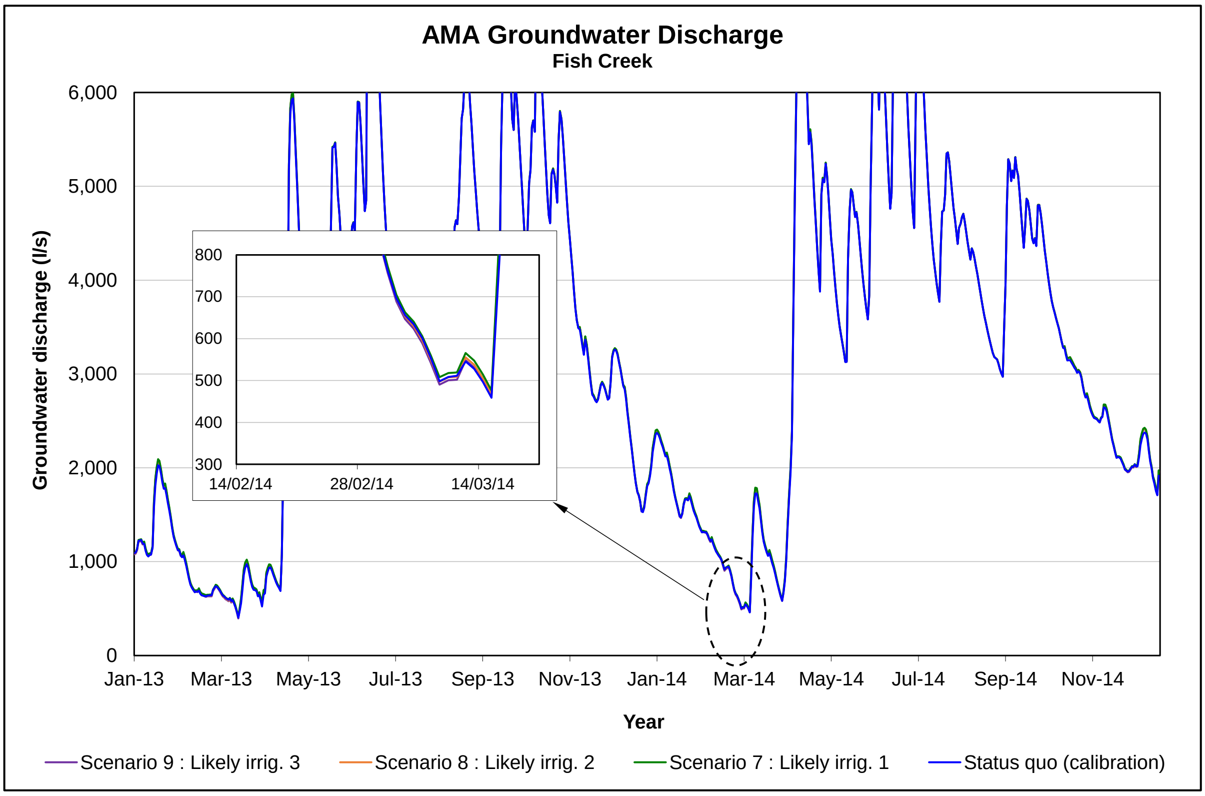
Appendix H: Flow hydrographs and flow duration curves comparing calibration with Scenarios 7-9



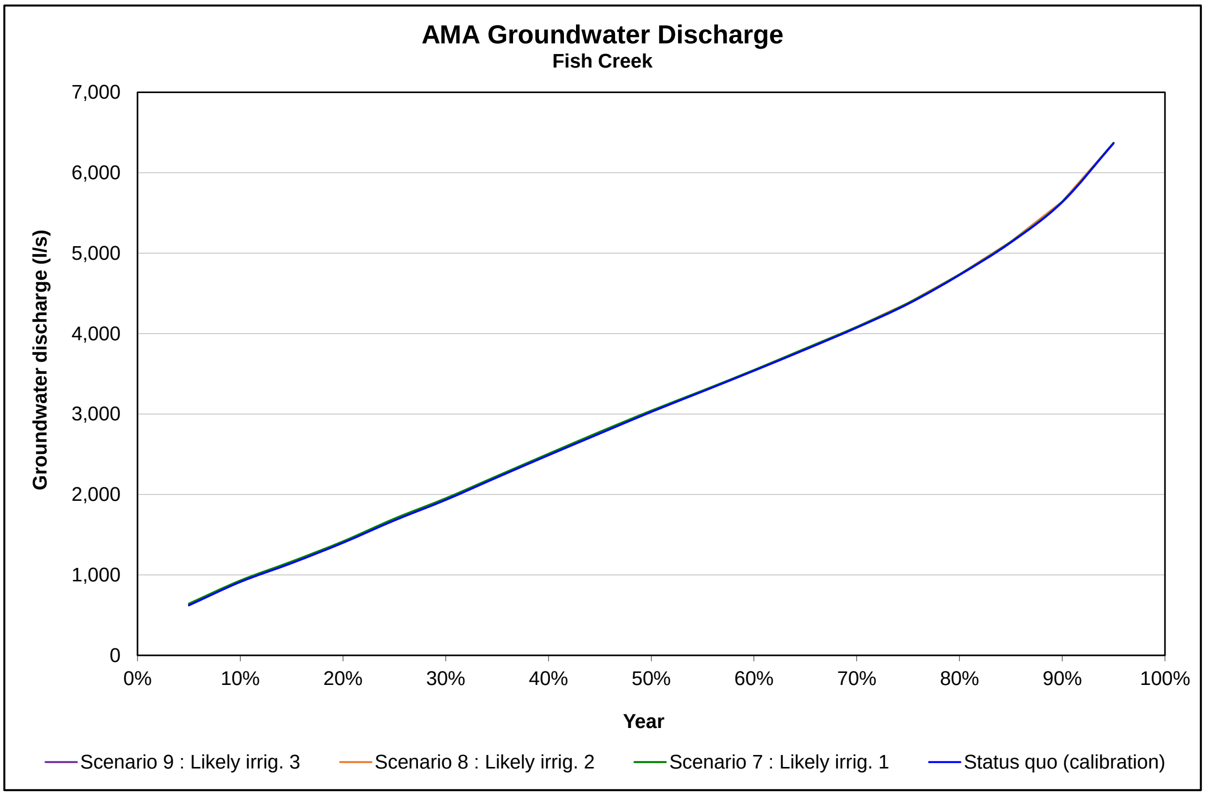
AMA Groundwater Discharge
Te Waikoropupū Main Spring
Groundwater discharge (l/s)
11,000
10,500
10,000
9,500
9,000
8,500
8,000
7,500
7,000
6,500
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Year
8,500
8,000
7,500
7,000
6,500
1/03/13
21/03/13
10/04/13
30/04/13
Scenario 9 : Likely irrig. 3
Scenario 8 : Likely irrig. 2
Scenario 7 : Likely irrig. 1
Status quo (calibration)



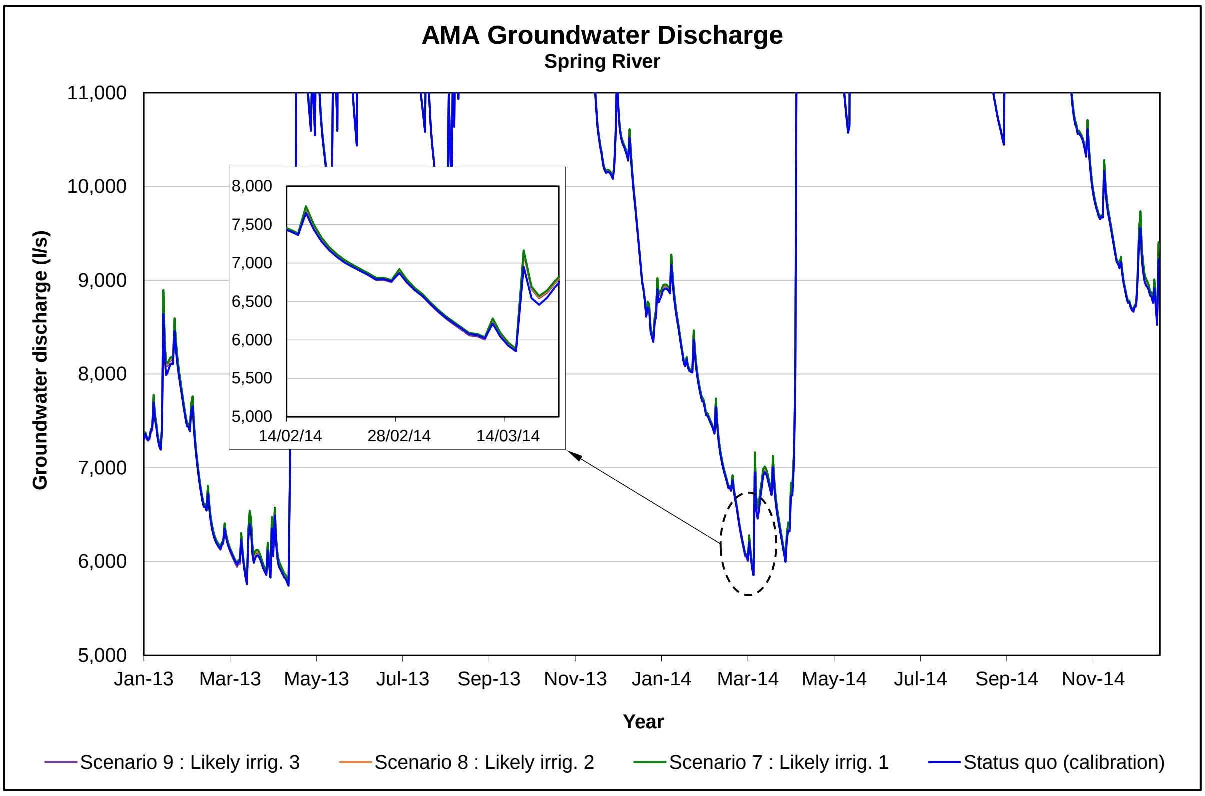
AMA Groundwater Discharge
Te Waikoropupū Main Spring
Groundwater discharge (l/s)
15,000
14,000
13,000
12,000
11,000
10,000
9,000
8,000
7,000
6,000
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Year
Scenario 9 : Likely irrig. 3
Scenario 8 : Likely irrig. 2
Scenario 7 : Likely irrig. 1
Status quo (calibration)

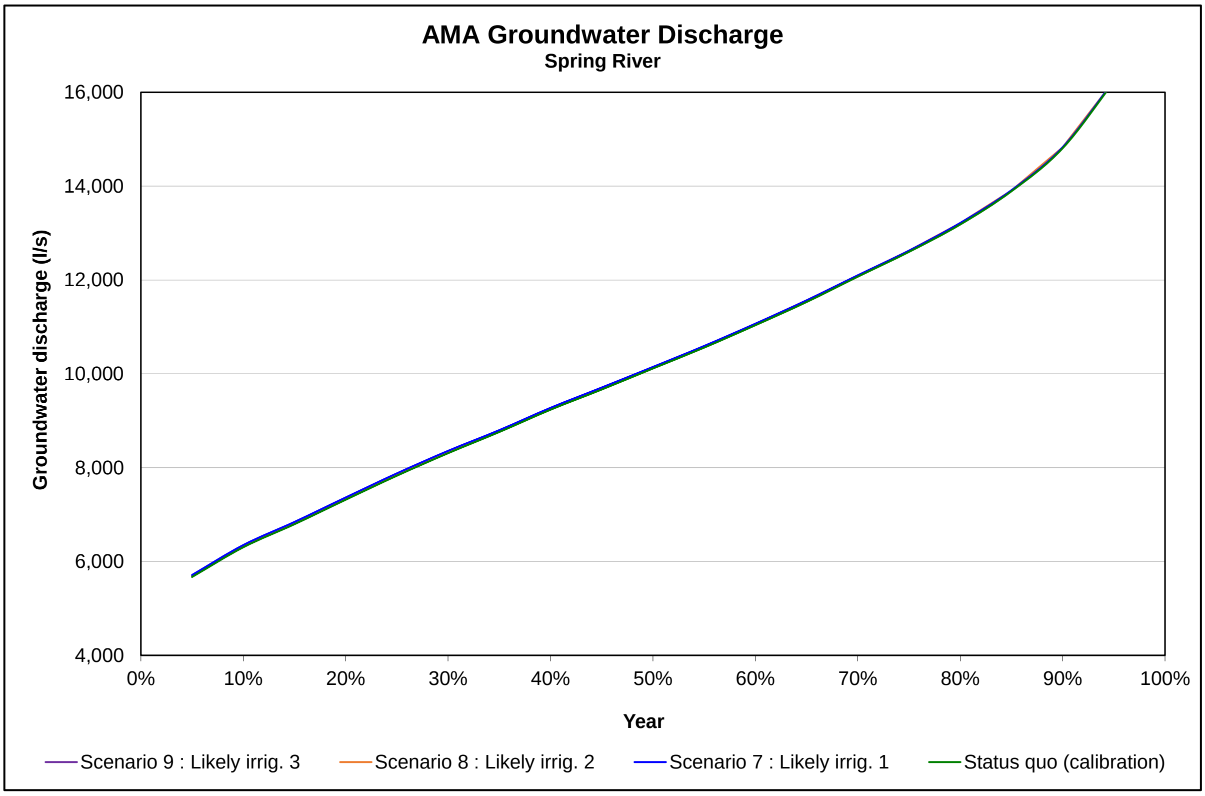


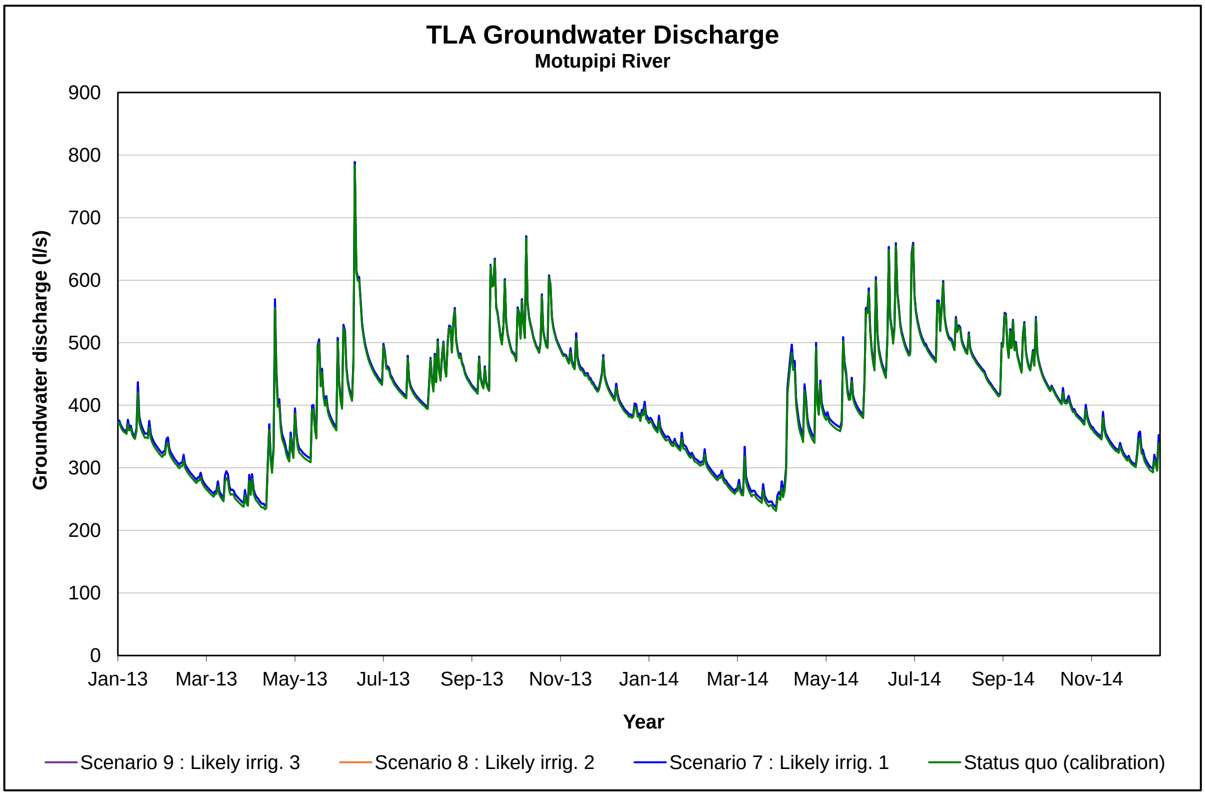
AMA Groundwater Discharge
Fish Creek
6,000
5,000
4,000
3,000
2,000
1,000
0
Groundwater discharge (l/s)
800
700
600
500
400
300
14/02/14
28/02/14
14/03/14
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Year
Scenario 9 : Likely irrig. 3
Scenario 8 : Likely irrig. 2
Scenario 7 : Likely irrig. 1
Status quo (calibration)



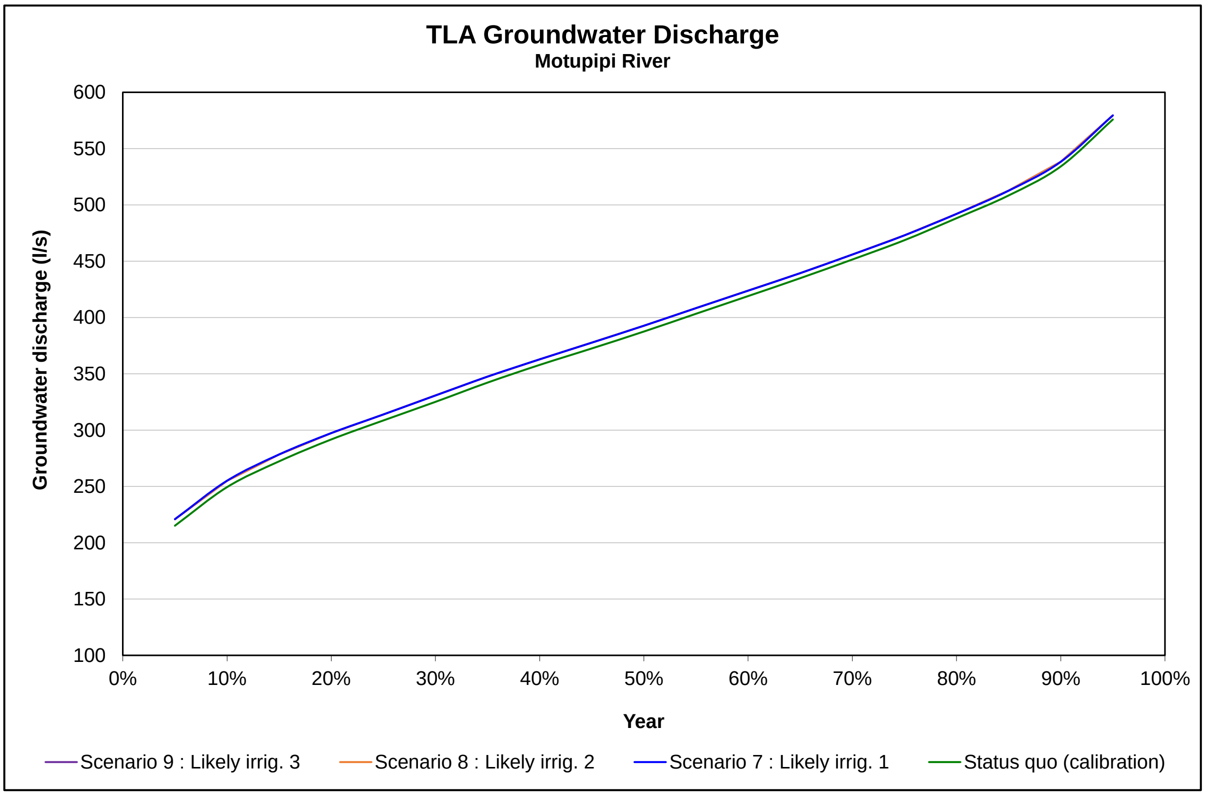
AMA Groundwater Discharge
Fish Creek
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
Groundwater discharge (l/s)
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Year
Scenario 9 : Likely irrig. 3
Scenario 8 : Likely irrig. 2
Scenario 7 : Likely irrig. 1
Status quo (calibration)


AMA Groundwater Discharge
Spring River
Groundwater discharge (l/s)
11,000
10,000
9,000
8,000
7,000
6,000
5,000
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Year
8,000
7,500
7,000
6,500
6,000
5,500
5,000
14/02/14
28/02/14
14/03/14
Scenario 9 : Likely irrig. 3
Scenario 8 : Likely irrig. 2
Scenario 7 : Likely irrig. 1
Status quo (calibration)

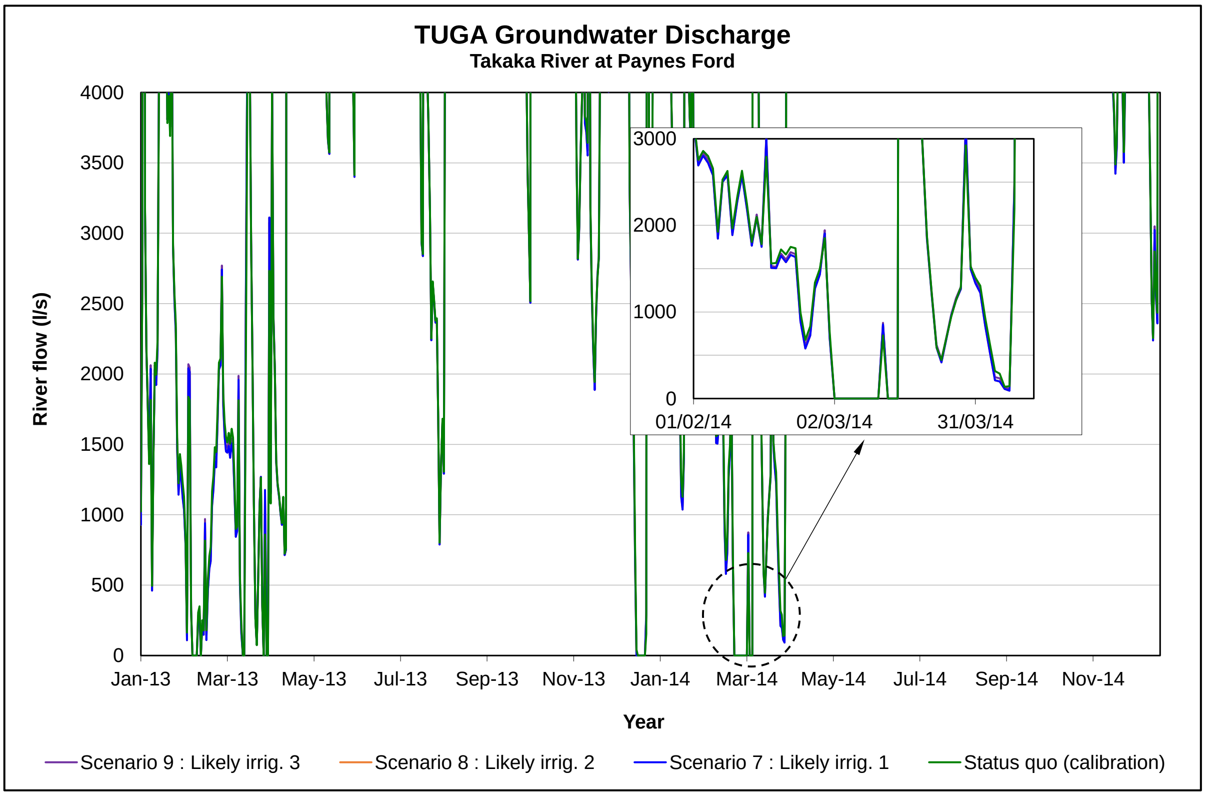

AMA Groundwater Discharge
Spring River
Groundwater discharge (l/s)
16,000
14,000
12,000
10,000
8,000
6,000
4,000
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Year
Scenario 9 : Likely irrig. 3
Scenario 8 : Likely irrig. 2
Scenario 7 : Likely irrig. 1
Status quo (calibration)



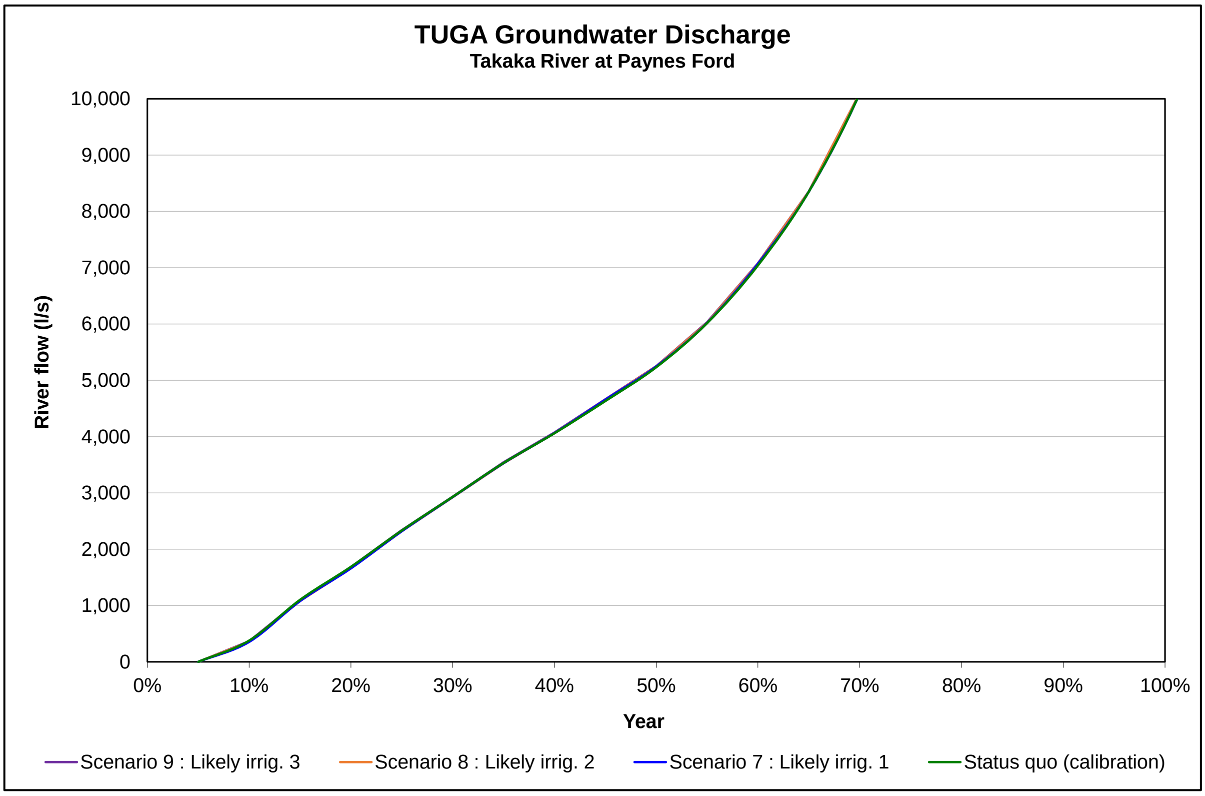
TLA Groundwater Discharge
Motupipi River
Groundwater discharge (l/s)
900
800
700
600
500
400
300
200
100
0
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Year
Scenario 9 : Likely irrig. 3
Scenario 8 : Likely irrig. 2
Scenario 7 : Likely irrig. 1
Status quo (calibration)



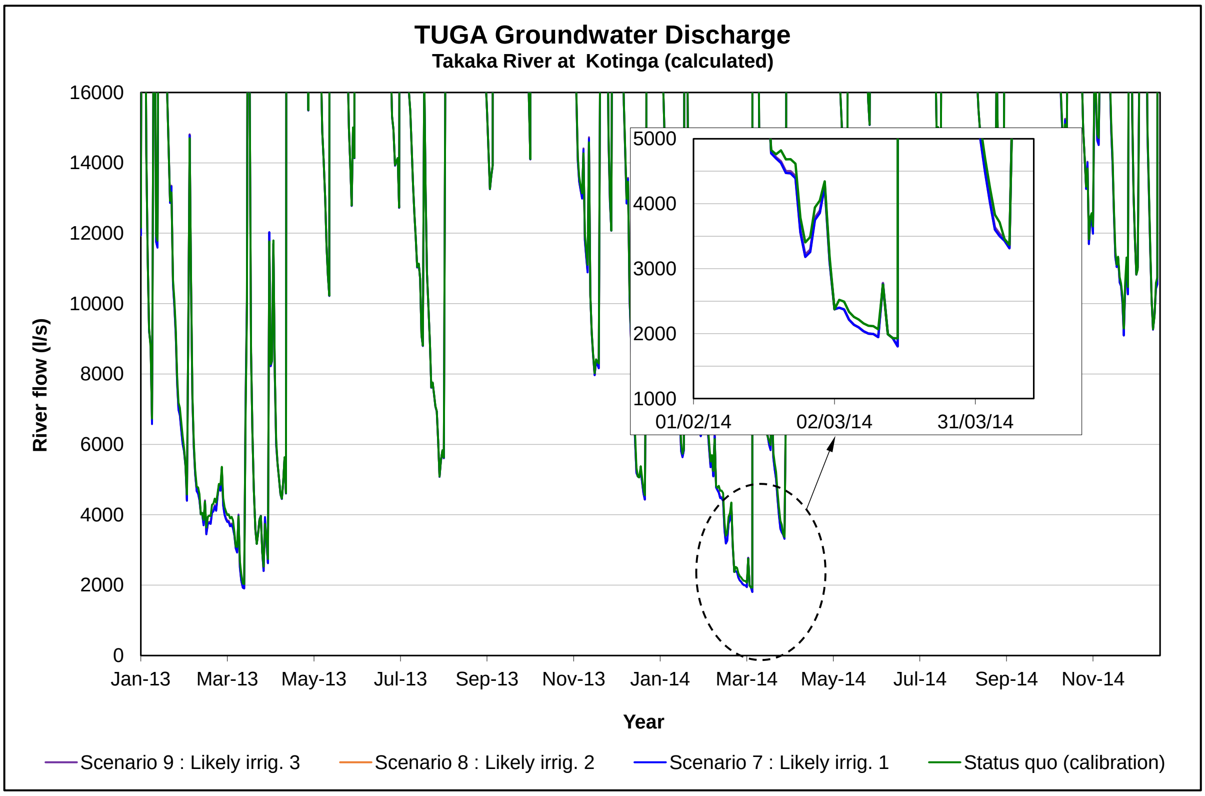
TLA Groundwater Discharge
Motupipi River
Groundwater discharge (l/s)
600
550
500
450
400
350
300
250
200
150
100
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Year
Scenario 9 : Likely irrig. 3
Scenario 8 : Likely irrig. 2
Scenario 7 : Likely irrig. 1
Status quo (calibration)



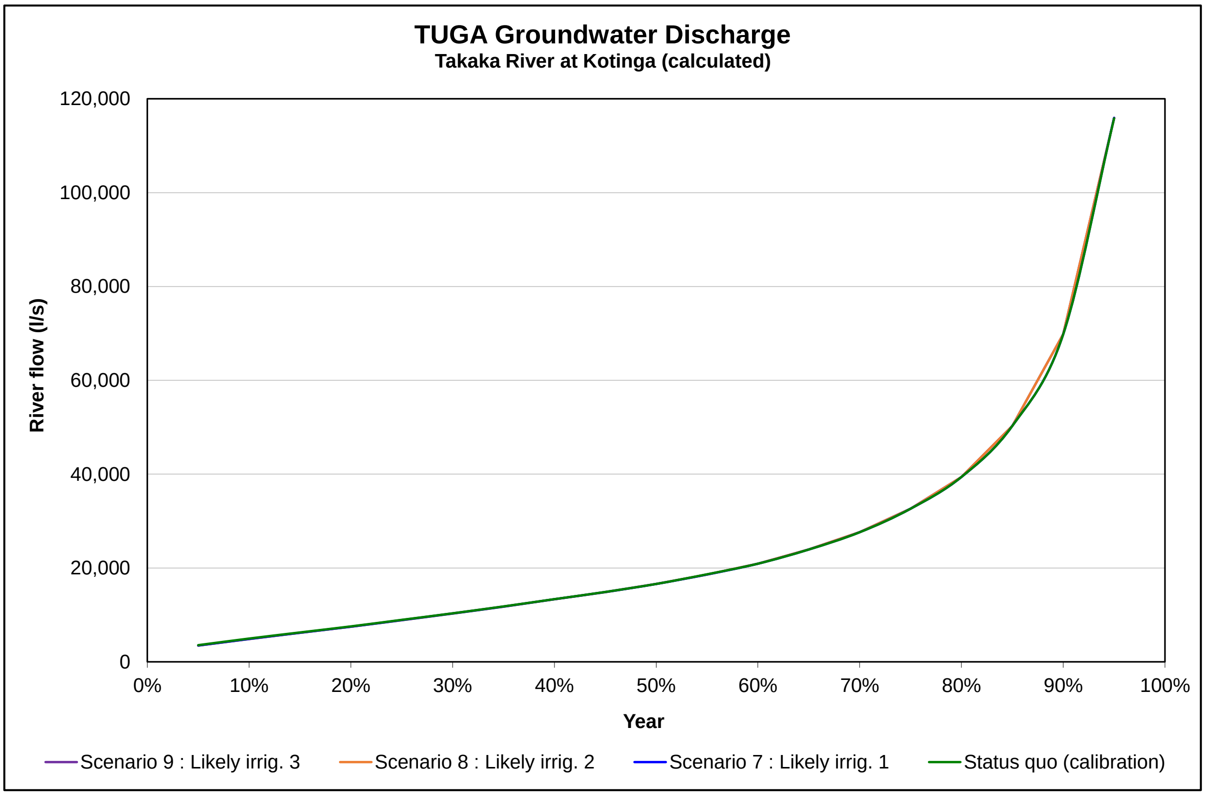
TUGA Groundwater Discharge
Takaka River at Paynes Ford
River flow (l/s)
4000
3500
3000
2500
2000
1500
1000
500
0
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Year
3000
2000
1000
0
01/02/14
02/03/14
31/03/14
Scenario 9 : Likely irrig. 3
Scenario 8 : Likely irrig. 2
Scenario 7 : Likely irrig. 1
Status quo (calibration)



TUGA Groundwater Discharge
Takaka River at Paynes Ford
River flow (l/s)
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Year
Scenario 9 : Likely irrig. 3
Scenario 8 : Likely irrig. 2
Scenario 7 : Likely irrig. 1
Status quo (calibration)



TUGA Groundwater Discharge
Takaka River at Kotinga (calculated)
River flow (l/s)
16000
14000
12000
10000
8000
6000
4000
2000
0
Jan-13
Mar-13
May-13
Jul-13
Sep-13
Nov-13
Jan-14
Mar-14
May-14
Jul-14
Sep-14
Nov-14
Year
5000
4000
3000
2000
1000
01/02/14
02/03/14
31/03/14
Scenario 9 : Likely irrig. 3
Scenario 8 : Likely irrig. 2
Scenario 7 : Likely irrig. 1
Status quo (calibration)



TUGA Groundwater Discharge
Takaka River at Kotinga (calculated)
River flow (l/s)
120,000
100,000
80,000
60,000
40,000
20,000
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Year
Scenario 9 : Likely irrig. 3
Scenario 8 : Likely irrig. 2
Scenario 7 : Likely irrig. 1
Status quo (calibration)