Delineation of the Rangitata riparian zone

Report No. R12/65

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Report prepared for Environment Canterbury by

Lee Burbery
Lincoln Ventures Limited

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24 Edward Street, Lincoln
PO Box 345
Christchurch 8140
Phone (03) 365 3828
Fax (03) 365 3194

75 Church Street
PO Box 550
Timaru 7940
Phone (03) 687 7800
Fax (03) 687 7808

Website: www.ecan.govt.nz
Customer Services Phone 0800 324 636

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Report No 1050-9-R1

June 2012

By Lee Burbery

LINCOLN VENTURES LIMITED

Community Summary

A riparian zone aquifer is a groundwater system that is closely related to a surface water body. Water resource management rules within a riparian zone might be tailored differently from rules outside such a zone, to account for the strong surface water/groundwater connection.

The riparian aquifer zone of the lower section of the Rangitata River which divides the Mayfield-Hinds groundwater allocation zone (GWAZ) and Rangitata-Orton GWAZ has been delineated based on the review of available geological, hydrological and water chemistry data.

The Rangitata riparian aquifer zone is conceived to include both shallow and deep groundwater that underlies the margin of land between the Rangitata River and Kapunatiki Creek (encompassing Rangitata Island and the Rangitata South Branch). The historic flood plain on the north side (true-left) of the Rangitata, directly south of Coldstream, is also considered to be part of the riparian zone. Covering 17,388 hectares, the riparian aquifer zone is approximately three times the area of the active Rangitata River channel.

61 million m^3 of groundwater is currently consented to be pumped from the riparian aquifer zone, annually. This is four times more than what can conceivably be supplied by rainfall recharge, the deficit of which must be made up from river water flow losses. Consequently, groundwater abstractions from within the riparian zone have potential to significantly impact flows in the Rangitata River system and in particular the spring-fed McKinnons Creek.

McKinnons Creek and Ealing Springs constitute features of the Rangitata River system that are protected under the Rangitata River Conservation Order for their salmon spawning properties and cultural significance to Ngāi Tahu. Elevated nitrate levels in these surface waters pose a potential environmental risk to the ecological qualities for which these spring-fed water systems are recognised.

There is technical merit in defining a riparian aquifer zone for the Rangitata River, although the resource management implications of doing so are not clear, particularly given the Rangitata River is already subject to a conservation order. The relatively small spring-fed McKinnons Creek would likely stand to benefit the most from the establishment of a riparian aquifer management zone on the Rangitata.

There is an obvious need for further field investigation work to be undertaken that would assist in the technical refinement of the Rangitata riparian zone, and is required before any changes to groundwater allocation resource management in the Rangitata region might be made.

Executive Summary

A riparian aquifer zone has been delineated for the lower Rangitata River based on review of available geological, hydrological, hydrogeological and water chemistry data. A water balance has been evaluated for the riparian zone, as have the potential stream depletion effects of consented groundwater takes within the zone.

The Rangitata riparian aquifer zone is conceived to include both shallow and deep groundwater that underlies the margin of land between the Rangitata River and the paleo-channel that is the Kapunatiki Creek. It encompasses Rangitata Island and the Rangitata South Branch, on the true-right of the river. On the true-left of the river, the riparian boundary follows the main river terrace to within 7 km of the river mouth where a relatively small 102 hectare area comprising the lower river terrace directly south of Coldstream is also considered to be riparian. The total area of the riparian aquifer zone is 17,388 hectares, 5,495 hectares of which is active river channel.

Although influences of Rangitata River water can be traced beyond the riparian zone, e.g. under much of the Orton plain, groundwater there is not deemed to be strictly riparian. Similarly, the aquifers under Mayfield-Hinds plain have a conceivable natural hydraulic connection with the river, but indications are they are dominated by LSR (LSR) that is augmented by irrigation schemes, which operate using diverted river water. Some water from the Mayfield-Hinds irrigation scheme drains into to the riparian aquifer zone.

Rainfall is estimated to provide $15x10^6$ m^3 of recharge water to the riparian aquifer annually. This is less than a quarter of the $61x10^6$ m^3 of groundwater that is currently consented to be abstracted from the zone for irrigation. The difference in the annual water balance is assumed to be made up by recharge contributions from the Rangitata River system.

The general potential stream depletion effect of groundwater abstraction within the riparian zone is estimated to be in the region of 1.4 - 2.0 m^3/s. This is a significant proportion of the river's managed residual low flow of: 20.1 m^3/s (summer); 15.1 m^3/s (winter). McKinnons Creek is conceived to be most adversely affected by the seasonal pumped abstraction.

McKinnons Creek and Ealing Springs constitute features of the Rangitata River system that are protected under the Rangitata River Conservation Order for their salmon spawning properties and cultural significance to Ngāi Tahu. Elevated nitrate levels in these surface waters pose a potential environmental risk to the ecological qualities for which these spring-fed water systems are recognised.

There is technical merit in defining a riparian aquifer zone for the Rangitata River, although the resource management implications of doing so are not clear, particularly given the Rangitata River is already subject to a conservation order. The relatively small spring-fed McKinnons Creek would likely stand to benefit the most from the establishment of a riparian aquifer management zone on the Rangitata.

There is a need for further field investigation work to be undertaken that would assist in the technical refinement of the Rangitata riparian zone, and is required before any changes to groundwater allocation resource management in the Rangitata region might be made. A piezometric survey - particularly of deep groundwater beneath the Orton plain - and modern river gauging measurements are identified as a priority. This would help determine the natural character of the hydrological system between the Rangitata and Orari rivers, and might also inform whether the increase in pumped abstraction over the past decade has invoked river losses. It is recommended that such investigations should be completed before the Rangitata South Irrigation Scheme becomes operational in 2014, because this activity will invoke new hydraulic changes to the natural environment.

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1 Introduction

1.1 Background to the Rangitata Riparian Project

Riparian zones are land areas that adjoin, directly influence, or are influenced by, a body of water (Ministry for the Environment, 2001). Generally, riparian zones include: a) land immediately alongside streams, rivers and lakes, including the riverbank itself; or b) river floodplains and associated wetlands and seepage zones which interact with the river permanently or in times of flood. In the context of this review, a riparian zone aquifer is inferred to be a groundwater system that has a high degree of hydraulic connectivity with a surface water body - a zone from which groundwater yields are primarily sustained by river recharge; the effects of aquifer storage and LSR effects are secondary.

In 2005 Environment Canterbury determined that shallow groundwater in the vicinity of the Rakaia River is supported by river recharge. This finding prompted a reassessment of the Rakaia – Selwyn Groundwater Allocation Zone (GWAZ). Furthermore, it sparked a riparian study project that aimed to establish the existence of groundwater zones in Canterbury that are dominated by river recharge effects, and to delineate these ‘riparian zone aquifers’.

The lower section of the Rangitata River, located at the southern end of the Canterbury Plains was earmarked as one of the river systems for which a riparian aquifer zone would be investigated. At the present time, the Rangitata River separates two groundwater management zones: on the true left of the river is the Mayfield-Hinds GWAZ, and on the true-right is the Rangitata-Orton GWAZ (Figure 1-1). Any natural hydraulic characteristics of the integrated Rangitata River and groundwater systems were not explicitly taken into account when the GWAZs were defined (Aitchison-Earl *et al.,* 2004).

In 2007, as a preparatory stage of the Rangitata Riparian investigation project, Environment Canterbury reviewed topographic, water chemistry and pumping test data and from this mapped a preliminary riparian zone boundary (Vincent, 2007). Environment Canterbury has subsequently contracted Lincoln Ventures to undertake a comprehensive evaluation of the hydrogeology of the lower Rangitata catchment, and to delineate a Rangitata riparian zone. This report constitutes a documentation of that technical work and in effect is an update of the preliminary assessment undertaken by Vincent (2007). The methodology for delineating the riparian zone and structure of this report attempts to follow a set of guidelines developed by Environment Canterbury, and which emanated from the inaugural Rakaia River riparian study conducted by Williams (2009) – a copy of the ‘riparian zone study and report template’ guidelines is included as Appendix A.

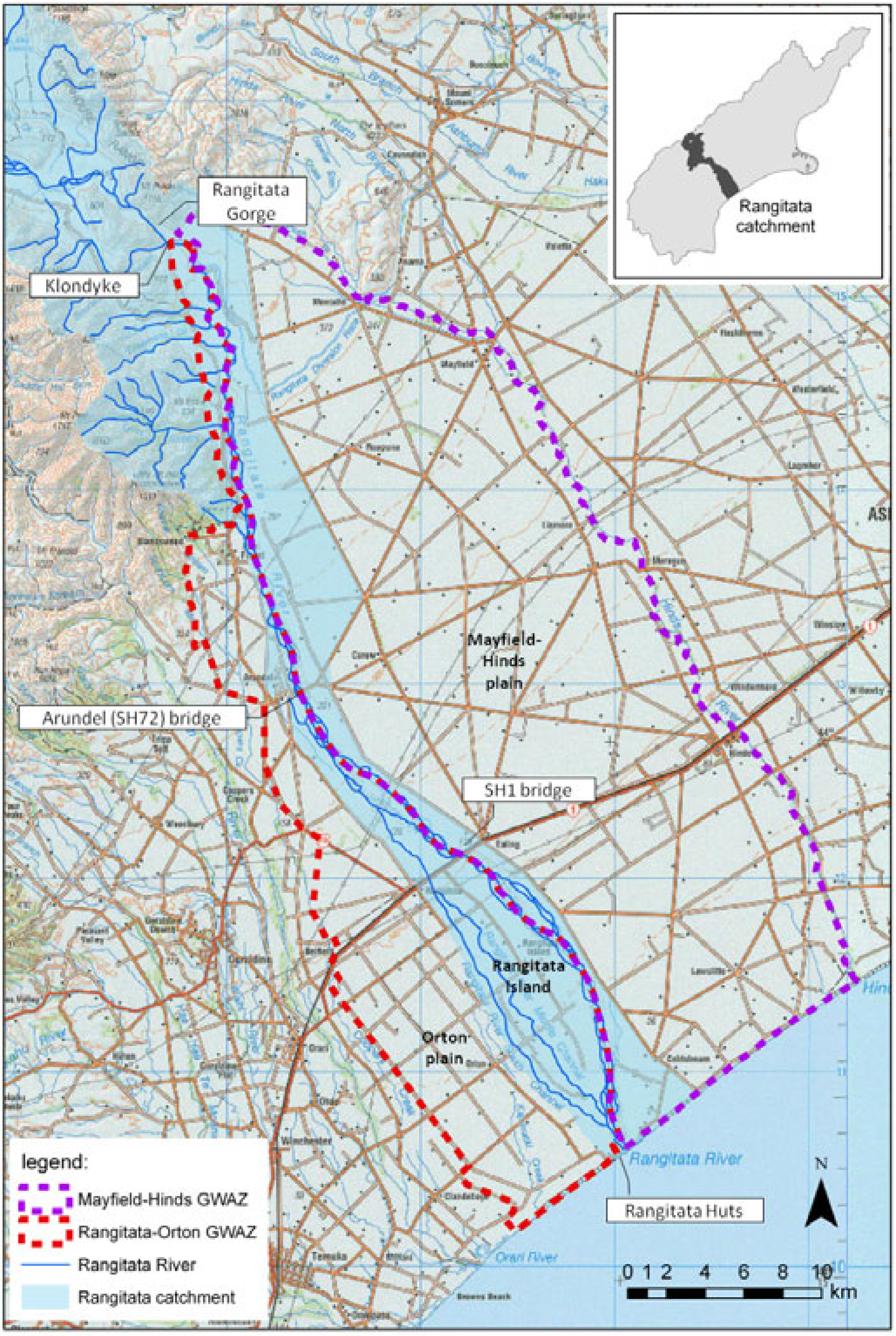

Figure 1-1: **Location map of the Rangitata River (lower section)**

Existing groundwater allocation zone boundaries and geographic points of interest marked

1.2 Previous work and data sources

Compared to the integrated surface water and groundwater systems of the Rakaia and Selwyn rivers that were reviewed by Williams (2009) when he delineated the Rakaia riparian aquifer zone, there has been relatively little historic field work undertaken in the Rangitata River area. A bibliographic list of key published technical reports relating to the Rangitata River and neighbouring groundwater systems, which collectively constitute the reference for much of the knowledge about the hydrogeology in the Rangitata area, is provided here:

- Walsh, RP, 1975. Resource and Usage of Water in the Rangitata Catchment. South Canterbury Catchment and Regional Water Board.
- Scarf, F and Waugh, JR, 1986. Rangitata River Water Management Plan 1986-1996. South Canterbury Catchment Board and Regional Water Board Publication No. 46, March 1986.
- Ingles, C, 2000. The Magnitude and Extent of Hydraulic Connection of the Rangitata River – Subsequent Gaugings 1999 – 2000. Environment Canterbury Report No. U00/47, September 2000.

> Walsh (1975) provided a general overview of the water resources in the catchment, including detailed analysis of river flow statistics. At the time, only 8 rights for groundwater abstraction had been issued, for a total of 34 L/sec. Walsh (1975) also reviewed 8 sets of river flow measurements carried out between Klondyke and the sea, from which '*an interim conclusion ... would seem to be that only in unusually wet years, when groundwater tables rise appreciably, does any substantial accretion to the Rangitata River discharge rate occur in its lower reaches.'*
>
> Both Scarf and Waugh (1986) and Ingles (2000) report on additional Rangitata River flow gauging data; each arrived at the same general conclusion about flow gains and losses as Walsh (1975).
>
> Scarf and Waugh's (1986) report outlined a 10-year water management plan for the Rangitata River. The plan specified that groundwater abstractions from less than 15 m depth and within 400 m of the main river channels (i.e. the 'fairway margin') or 50 m of any minor tributary channel would be managed similar to surface water abstractions and subject to minimum flow restrictions. The 'fairway margin' management zone concept described by Scarf and Waugh (1986) is similar to that of a 'riparian zone aquifer' zone. The water management plan has been superseded by Environment Canterbury's Natural Resources Regional Plan (NRRP) and the over-ruling Rangitata River Conservation Order made in 2006, as explained below.

- Brooks, T, 1996. Ashburton – Rangitata Plains: Groundwater Information, Review, Issues and Recommended Future Investigations. Canterbury Regional Council Technical Report U96(29)
- Environmental Consultancy Services, 1997. Rangitata – Temuka Groundwater Review, Issues and Recommendations. Canterbury Regional Council Technical Report U97(34)

> Both of the above reports reviewed the state of technical understanding of the groundwater systems that border each side of the Rangitata River. Each identified there was a general lack of understanding of by what means local groundwater was recharged, and neither report mentioned anything of the potential hydraulic relationship between the Rangitata River and groundwater. Report U97(34) contained a reproduction of the South Canterbury Catchment Board's (SCCB) drawing W57 – a piezometric map of shallow groundwater across the Rangitata-Orton-Orari plain surveyed in 1978.

- Mosley, MP, 2001. Rangitata River: Natural Character, Amenity Values and Flow Regime, revised edition. Environment Canterbury Report R01/23.

- Te Runanga O Arowhenua and Gail Tipa, 2001. Rangitata River Tangata Whenua Values. Environment Canterbury Report R01/9.
- Aitchison-Earl, P, 2001: Effects of groundwater abstraction on surface water flows in the Rangitata River and tributaries, revised edition, Environment Canterbury technical report U01/76.

  These reports were compiled to assist Environment Canterbury in preparing a NRRP and at the time a Water Conservation Order on the Rangitata River was being sought. Report R01/23 focuses primarily on the fluvial environment and mentions nothing of riparian/groundwater systems below the Rangitata Gorge. Mosley (2001) did, however, note that the Rangitata is probably the least studied of the braided rivers systems on the Canterbury Plains. In Report R01/9 there is mention that historically the land between SH1 and the lagoon at the mouth of the Rangitata was swampy. Numerous creeks are reported to have existed on the south branch of the Rangitata (including Kapunatiki Creek and McKinnons Creek) that were important mahinga kai areas. Dewatering of these creek systems is perceived by Arowhenua to have coincided with the construction of the stop bank diverting water from the South Branch.

  The aim of Aitchison-Earl's (2001) work was to investigate a technically defensible way of evaluating stream depletion effects. The 30-day, stream depletory effect of groundwater takes from less than 15 m depth and within 2 km of the Rangitata River and its tributaries was evaluated using the Jenkins (1977) approach. At the time, within that zone, there were 23 groundwater permits with a combined effective rate of take equal to 1445 L/s. Aitchison-Earl (2001) estimated that the stream depletion effect would be 943 L/s, 469 L/s of which would directly affect McKinnons Creek. In her conclusion, Aitchison-Earl (2001) cautioned that groundwater takes on the Mayfield-Hinds plain might adversely affect Rangitata River flows by reducing the groundwater pressure at Ealing Springs.

  A Water Conservation Order was made on the Rangitata River in 2006 (Ministry for the Environment, 2006). The order imposes low flow restrictions on resource consents to take water within the Rangitata River catchment, tied to a naturally occurring flow of 110 m^3/s at Klondyke. In particular, no consent to abstract groundwater in the lower catchment will be granted if it is assessed to have a stream depletion effect of more than 5 L/s on the Rangitata River, McKinnons Creek or Ealing Springs. Equally, the cumulative stream depletion effect of all water abstractions within the entire catchment is capped at 33 m^3/s for periods when the Rangitata River flows are less than 110 m^3/s at Klondyke.

- Dommisse, J, 2006. Hydrogeology of the Hinds Rangitata Plain and the Impacts of the Mayfield Hinds Irrigation Scheme. MSc Thesis, University of Canterbury.

  Dommisse's (2006) thesis constitutes the most comprehensive hydrogeological investigation of the Rangitata region and focussed on characterising the impacts of the Mayfield-Hinds Irrigation Scheme on the groundwater system situated between the Rangitata and Hinds rivers, i.e. on the true-left of the Rangitata River. Using the methods developed by Davey (2006), Dommisse conceived there to be at least four distinct aquifers within the fluvio-glacial sediments deposited from Rangitata River over the millennia. Groundwater levels in the uppermost aquifer and discharges from various drains were monitored over the course of the field study and a catchment water balance was derived for the 2005/06 irrigation year. Chemistry data obtained for samples collected from groundwater, springs and water emerging from drains were used to determine the origin of these waters. Generally, Dommisse (2006) could not find any evidence to suggest the Rangitata River contributes any significant recharge to the groundwater system on the north-side of the river. Instead, rainfall and water from the Rangitata Diversion Race were identified as the main recharge sources and the Rangitata River supposedly gains flow from the 40 groundwater-fed springs that emerge from the foot of the terraces lining the north bank of the river. Dommisse (2006) did however conclude that there were multiple lines of evidence to suggest that downstream of Storriers

> Road (within approximately 7 km of the coast) the Rangitata River probably loses water to the adjacent shallow aquifer. Dommisse (2006) recommended piezometric surveys coupled to river flow gauging measurements be undertaken to refine understanding of the hydraulic linkage between the Rangitata River and neighbouring aquifers.

- Vincent, C, 2007: Identification of Rangitata riparian sub-area boundaries, review of previous work and recommendations for future investigations, Environment Canterbury internal memorandum IN6C/364, 30 June 2007.

> Vincent's work of 2007 was intended to serve as a planning and preparation step of a more comprehensive field investigation for the Rangitata riparian area. Vincent (2007) mapped out a tentative Rangitata riparian aquifer zone based on review of topography, chemistry, isotope and aquifer test data (see Appendix B). To improve the reliability of his assessment, Vincent (2007) recommended: i) further hydrochemical analysis of shallow groundwater in various areas and of McKinnons Creek be undertaken; ii) stream depletion effects be reassessed based on consideration of his marked riparian sub-area boundaries; iii) on-going monitoring of shallow groundwater levels from which the hydrodynamics of the groundwater system might be characterised, iv) survey the groundwater table from which groundwater flow paths might be inferred, and v) aquifer testing of the shallow groundwater system.
>
> Since 2007, Environment Canterbury has continued to routinely monitor groundwater levels in selected bores within both the Rangitata–Orton and Mayfield–Hinds GWAZ's, and in 2010 a relatively small survey of groundwater chemistry was undertaken as part of the Rangitata riparian project to address Vincent's (2007) first recommendation. This report summarises the scope of any practical Rangitata riparian zone investigations to date. The chemical analytical results from the 2010 survey remain to be interpreted.

- Scott *et al.,* 2011. Groundwater Quality Investigation of the Rangitata-Orari area. Environment Canterbury report R11/56.

> Recently, as a separate project, Scott *et al.* (2011) evaluated nitrate contamination in groundwater between the Rangitata and Orari rivers. Hydrochemistry, including stable isotope analyses, was applied to interpret groundwater recharge and flow patterns within the region. Scott *et al.* (2011) concluded that: '*the Rangitata River influences groundwater adjacent to the river, especially in the Rangitata Island area and can reach depths of over 100 m'.*

1.3 Purpose and scope of work

The purpose of the work reported here is to undertake a comprehensive desk-top review and analysis of available geological, hydrological and hydrochemical data with the objectives of characterising and delineating a riparian aquifer zone for the lower section of the Rangitata River, i.e. where it crosses the Canterbury Plains. The scope of work closely follows that prescribed in Environment Canterbury's Riparian Zone Study and Report Template (Appendix A), using methods similar to those applied in the Rakaia riparian sub-area assessment (Williams, 2009).

The report is divided into the following chapters:

Chapter 1:	Introduction
Chapter 2:	Geology
Chapter 3:	Surface Water Hydrology
Chapter 4:	Groundwater Hydrology
Chapter 5:	Hydrochemistry
Chapter 6:	Delineation of a Riparian Zone
Chapter 7:	Water Budget and Stream Depletion Assessment

Chapter 8: Conclusions and Recommendations
Chapter 9: References

Chapters 2 through 5, provide reviews and analyses of independent geological, hydrological and chemical datasets, from which the inter-relationship between the Rangitata River and the groundwater resource is inferred. In Chapter 6, the separate lines of technical evidence are brought together and a Rangitata riparian zone is delineated. The resulting zone is compared to that proposed by Vincent (2007) (Appendix B).

Chapter 7 contains a water budget for the resulting Rangitata riparian zone, including an account of consented water takes within the zone. Finally, an assessment is made of whether the establishment of a separate Rangitata riparian aquifer sub-zone has any technical merit given the current state of knowledge and likely resource management implications. This is presented in Chapter 8, accompanied by recommendations for future investigations to fill any residual knowledge gaps identified from the review. Chapter 9 is a compilation of references mentioned in this report.

2 Geology

2.1 Geomorphology

The Rangitata River is the southernmost of the large braided alpine rivers whose coalesced alluvial fan deposits formed during successive Quaternary glacial and interglacial periods to collectively make up the Canterbury Plains. The Rangitata fan itself is elongated NW-SE and covers an area of 900 km^2 (Barrell *et al.,* 1996). At the time of the last glacial maximum (18,000 years ago) the fan would have extended a further 70 km beyond the present day coastline and has undergone constant coastal erosion since then (e.g. Browne and Naish, 2003). The present day Rangitata River is naturally confined to the south-western side of the fan where it has incised below the main surface of the fan, forming noticeable terrace features.

The geomorphic features of the Rangitata fan were surveyed by GNS in 1996 (a copy of the resulting map is enclosed in Appendix C). The survey described the main surface of the plains as a composite feature of six geomorphic units (RG0:RG5) of different ages (Barrell *et al.,* 1996). The youngest unit (RG0) constitutes the modern day flood plain and includes the south and middle channels of Rangitata Island. Following the Ministry for the Environment’s (2001) definition, the RG0 unit would correspond to the Rangitata riparian zone.

2.2 Geology

Barrell *et al.* (1996) describe the geology of the RG0 unit as unweathered clasts of grey gravels within an uncemented sandy matrix. Similar geological materials make up the RG1 geomorphic unit, which rests a few meters above the modern floodplain (RG0), has negligible soil cover and exhibits no evidence of loess accumulation.

Sediments in older geomorphic units (RG2:RG5) that were deposited mostly during the Otira glacial period comprise unweathered clasts of grey-brown gravels in a slightly weathered matrix composed of iron-stained silty sand. Incorporated within these strata are loess beds (wind-blown deposits of silt and clay sediments transported from dried out glacial river beds). Although loess generally forms as a blanket layer, Barrell *et al.* (1996) suggest that loess is thin (<0.5 m) or absent on most of the Rangitata fan, in contrast to the thicker and more extensive deposits of the Rakaia and Waimakariri sectors of the Canterbury Plains. Discontinuous loess units up to 2 m thickness have been mapped for some young terraces (RG2 and RG3) alongside the Rangitata River close to the coast. The RG2 geomorphic unit described by Barrell *et al.* (1996) corresponds in age to the Springston Formation described by Williams (2009) in the Rakaia riparian aquifer study.

Of note on the geomorphic map (Appendix C) is that Rangitata Island and Coldstream (north of the Rangitata River mouth) are founded on RG2 fan material, i.e. sediments from the last glacial episode, rather than recent alluvial deposits. These regions were incorporated in the tentative Rangitata riparian aquifer zone delineated by Vincent (2007) (Appendix B).

Information gathered from Barrell *et al.'s* (1996) geomorphic survey has subsequently been incorporated into GNS's modern geological QMap (shown as Figure 2-1). QMap units coded Q1a and Q2a are young alluvium and late last glacial alluvium, respectively (equivalent to the RG1 and RG3:RG5 geomorphic units described by Barrell *et al.* (1996). Q1a_af marks the active river bed (RG0 unit) and Q2-1a the latest last glacial alluvium (RG2).

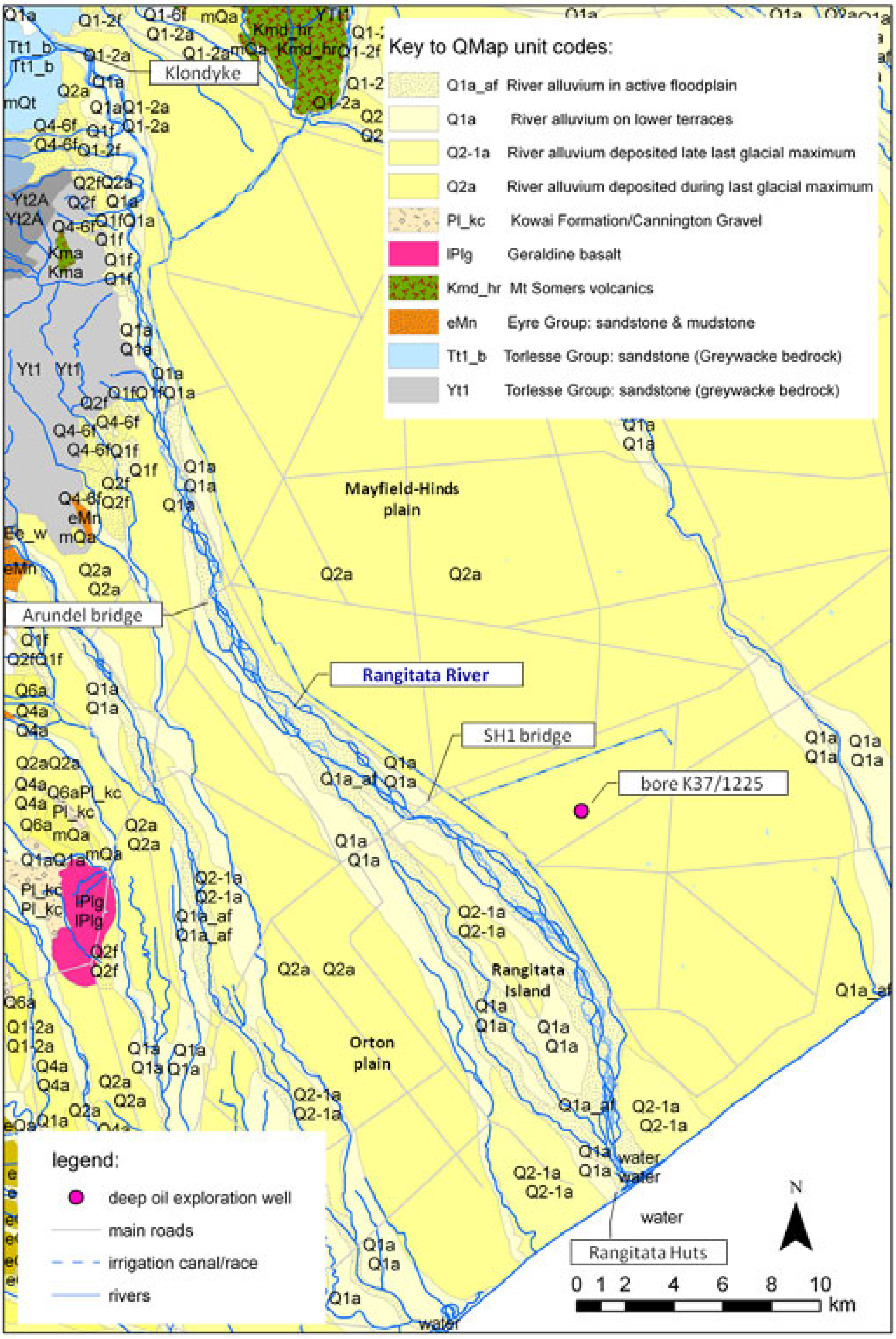

Figure 2-1: GNS geological Qmap

At Ealing on the north bank of the Rangitata River, 14 km from the coast, ‘outwash gravels’ have been recorded down to 673 m in bore K37/1225 where they were reported to rest upon claystone/sandstone. There is no record of any marine sediments occurring within the Rangitata fan, such as are associated with the Christchurch Formation occurring between the Waimakariri and Rakaia rivers and which act there to form a confined aquifer condition near the coast.

In an effort to identify common potential geological markers, the Environment Canterbury software XSect was applied to generate geological transects along and tangential to the Rangitata River based on automatic plotting of select borelog data within Environment Canterbury’s Wells Database. A total of four transects were plotted and are contained in Appendix D. In lieu of any mathematical analyses of the geological data to correlate geological markers, interpretation of the transects is reliant on visual inspection. From this, it is possible to vaguely identify a concentration of strata either containing fractions of silt or clay, or described as claybound, below the approximate 20 m depth mark on the transect (A-A’) following the Rangitata River across the plain, particularly down-gradient of SH1. This would concur with Davey’s (2006) suggestion of a possible aquitard separating two aquifer units. However, no discrete geo-facies can be identified within the logged sand or gravel units, nor can any distinction be made from borelog data between material deposited in the modern day river channels and the more aged adjacent terraces (see transects C-C’ and D-D’ in Appendix D). The reasoning for any hydraulic disconnection between the Rangitata River and adjoining groundwater system therefore cannot be argued based on the available geological evidence.

2.3 Soils

Most soils on the Rangitata fan are shallow, stony and free-draining, however peaty loam and silt loam soils occur near the coast for example on Rangitata Island and at Lowcliffe, which were historically swampy areas at the time of European settlement (e.g. Barrell *et al.,* 1996) (Figure 2-2).

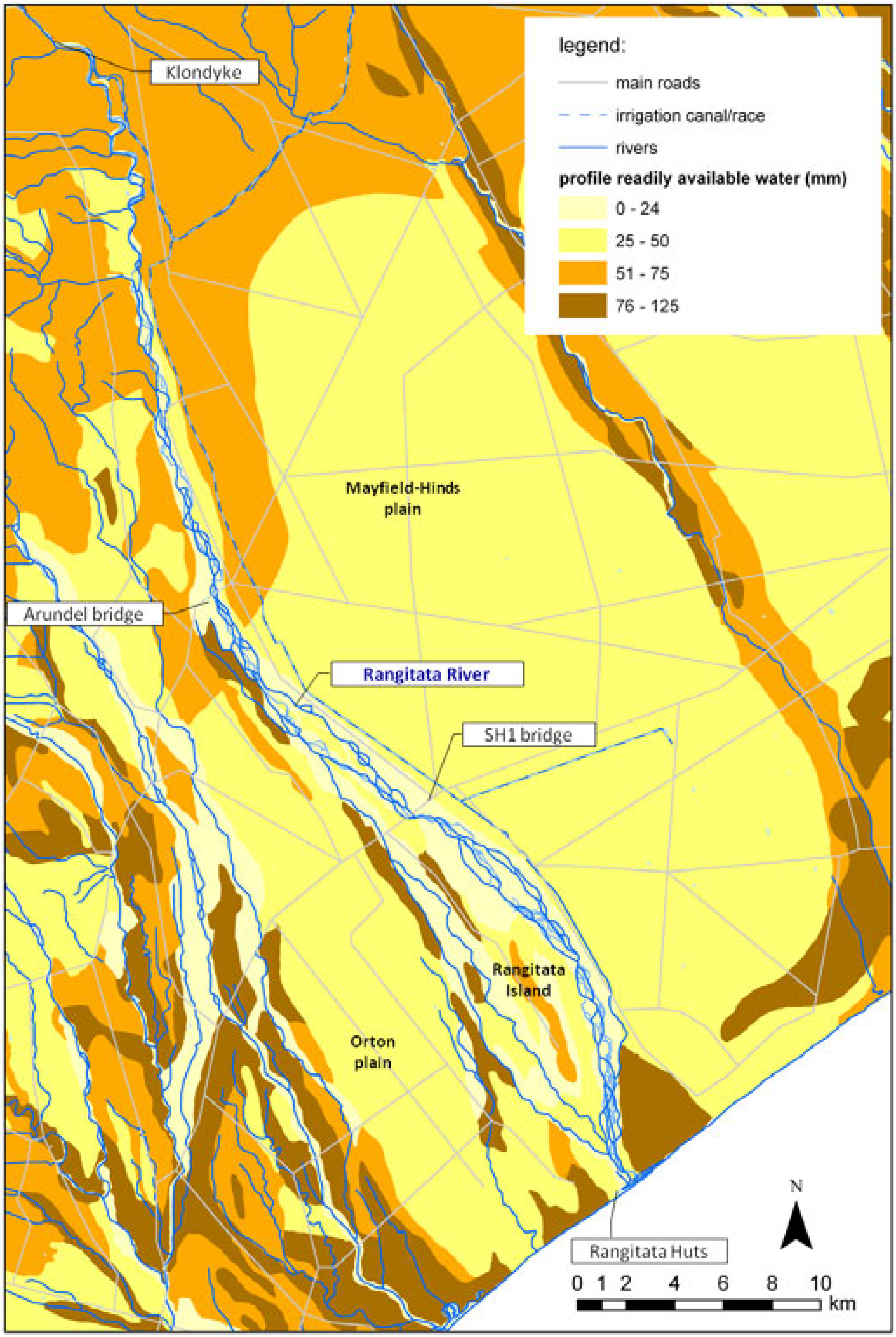

Figure 2-2: **Map of soil drainage properties**

Data obtained from Landcare Research (http://lris.scinfo.org.nz/#/layer/100-fsl-profile-available-water/)

3 Surface water hydrology

3.1 Rangitata River

The Rangitata is a substantial alpine river draining a total catchment area of 1772 km^2. The elevation range above the Rangitata Gorge is from 440 m to 2835 m above sea level (asl), approximately 2.6% of which is glaciated (Mosley, 2001). The catchment area of the lower section of the river, below the gorge where it flows out across the Canterbury Plains (and the main focus area of this riparian zone study), is approximately 278 km^2 - the reach length being 55 km to the sea.

The river has a sinuous and meandering form with a relatively narrow flood plain for approximately 7 km below the gorge. Downstream this develops into a multi-threaded sinuous pattern and over the final 36 km reach to the sea the river is a fully braided system (e.g. Figure 3-1). The braided nature of the river, spiritual and cultural significance, and ecology are all factors that are valued through the Rangitata River Conservation Order (2006).

Between Arundel and State Highway 1 (SH1), the river divides into two main channels known as the North Branch and the South Branch. The land lying between the North and South branches is known as Rangitata Island (Figure 3-1). In Environment Canterbury's asset management report it is noted that historically the distribution of flows between the North and South branches varied from year to year and that the size of the South Branch appeared to have increased over the period 1870 to 1920. However subsequent flood mitigation works prevent any river flows of less than 1500 m^3/s entering the South Branch (Environment Canterbury, 2008).

Kapunatiki Creek is similarly marked on topographic maps as a surface water feature despite it being little more than a paleo channel, only likely to wet-up if it were to transmit Rangitata River storm water in the most extreme flood events.

Flows in the Rangitata are recorded continuously at Klondyke Corner, within the gorge (e.g. Figure 3-1) where the river is funnelled onto the plain. Lynn Stream, which drains the eastern flank of Mount Peel (43 km from the coast) and which is ungauged, is the only significant tributary of the Rangitata River, below the gorge (see Figure 3-1).

3.2 Surface water irrigation schemes

The Rangitata River supplies two large independent irrigation systems: The Rangitata Diversion Race (RDR) and the Rangitata South Irrigation Scheme (RSIS). The RDR has been in operation since 1945, whereas the RSIS is currently under construction with plans to become operational in 2014.

The RDR (Environment Canterbury resource consent: CRC011237) diverts up to 30.7 m^3/s of water from the Rangitata River, almost continuously, 2 km below Klondyke. The race supplies irrigation water to the Mayfield-Hinds irrigation scheme located on the Rangitata fan, on the true left of the river (Figure 3-1). The RDR equally supplies water to both the Valetta and Ashburton-Lyndhurst irrigation schemes further afield. Outside of the irrigation season (between 10th May and 9th September) priority is given to water in the RDR to feed the Montalto and Highbank hydro-electric power stations, from where it discharges into the Rakaia River.

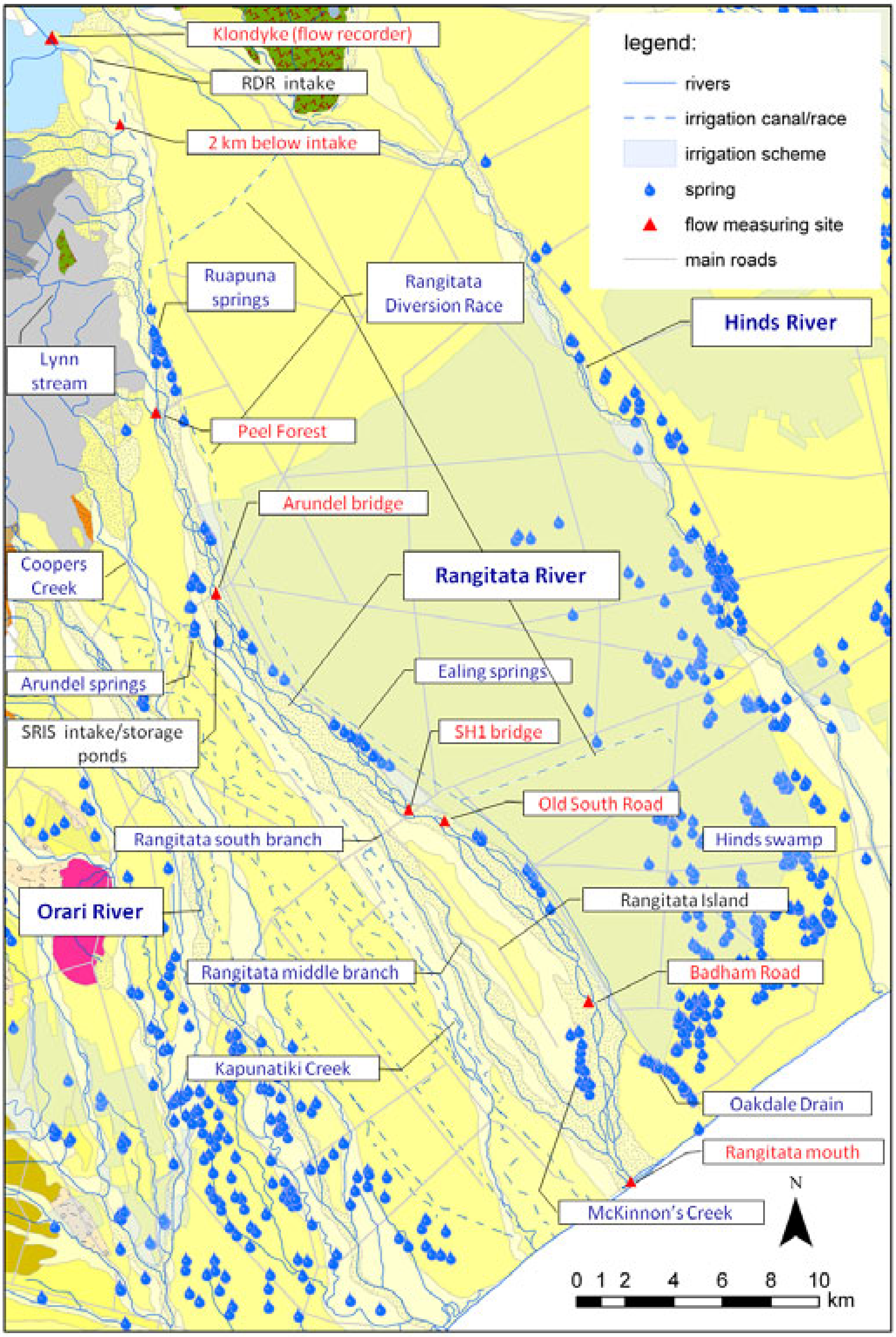

Figure 3-1: **Hydrological features of the lower Rangitata**

Flow gauging sites referenced in the report are marked in red.

Dommisse's (2006) thesis focused on studying the impacts of the Mayfield-Hinds irrigation scheme on the hydrogeology of the Hinds-Rangitata plain. It identified that the groundwater system (within the Rangitata fan) under the Rangitata-Hinds plain is strongly affected by the Mayfield-Hinds irrigation scheme. In particular, the irrigation scheme provides significant recharge water to the underlying aquifers. In computing an annual water balance for the 2005 – 2006 irrigation year, Dommisse estimated that the Mayfield-Hinds irrigation scheme probably contributes 111 $x10^6$ m^3 of water (or 64%) to the regional aquifer recharge. The only hydraulic linkages between the Rangitata River and groundwater system conceived by Dommisse (2006) was irrigated LSR using Rangitata River water transferred via the RDR and an efflux of groundwater from the aquifer via springs that discharge to the Rangitata River (discussed in the next section).

Resource consent for the construction of the RSIS was issued in 2010. The RSIS (consents CRC001229, CRC042094 and CRC070924) will harvest water from the Rangitata River upstream of Arundel Bridge at varying rates (maximum 20 m^3/s) when river flows are above 65.2 m^3/s and store it in ponds covering 280 ha, to a maximum volume of $16.5x10^6$ m^3. Water will then be distributed via stockwater races to farms across the Rangitata-Orton-Orari plain. Up to $3x10^6$ m^3 of water will also be stored in on-farm storage reservoirs. The water distribution network for the RSIS appears as a dashed blue line in Figure 3-1.

3.3 Springs and spring-fed streams

Environment Canterbury has records of at least 86 individually mapped springs within the lower Rangitata catchment that are distributed as approximately six clusters. Most of the knowledge about springs in the area was accrued by Davey (2003), some of which was refined by Dommisse (2006). Almost half of the springs are terrace-riser springs that are located along the true-left bank of the river. The most significant of these is a set known as Ealing Springs (located at or about New Zealand Map Grid ref: 238240E-568310N), which are explicitly mentioned in the Rangitata River Conservation Order (2006) for their salmon spawning feature and significance to Ngāi Tahu (see Figure 3-1). There is anecdotal evidence that the flows of many of these terrace riser-springs are linked to irrigation activities and operation of the RDR (i.e. the Mayfield-Hinds irrigation scheme). Thus, it is generally believed that the terrace-riser springs are a groundwater seepage feature associated with the Rangitata fan terrace, i.e. driven by LSR (LSR) rather than associated with re-emergent Rangitata River water. Water chemistry evidence studied as part of this review tends to support this theory (see Section 5).

Davey (2003) proposed that the cluster of springs below the Rangitata River terrace near Ruapuna, towards the upper end of the catchment, comprise a mixture of terrace-riser springs hydraulically driven by LSR water seeping from the river terrace and springs probably hydraulically driven by the Rangitata River.

The spring-fed stream known as McKinnons Creek is another waterway that is explicitly itemised in the Rangitata River Conservation Order (2006), again valued for its salmon spawning features and cultural significance to Ngāi Tahu. McKinnons Creek emerges in the lower reach of the Rangitata River, to the east of Rangitata Island and joins the Rangitata River at or about grid reference: 238930E-567020N. A line of springs associated with the creek are mapped at a location known as Wallaces Bridge, which coincides with the location at which the gradient of the Rangitata River steepens as a consequence of river incision promoted by the eroding coastline (Barrell *et al.,* 1996).

On the opposing (north) side of the Rangitata is Oakdale Drain, which is sourced from a stockwater race just 4 km from the coast and flows through Coldstream. A number of terrace-riser springs, and some springs classified as depression springs (Davey, 2003) equally discharge into the drain. Oakdale Drain discharges direct to the ocean via a gravel bar.

3.4 Hydrologic regime

3.4.1 Rangitata River mainstem

The mean flow of the Rangitata River (when computed from 19 complete annual datasets available between 1981 and 2011) is 93.6 m^3/s. Absolute minimum and maximum recorded flows at Klondyke are 30.9 m^3/s (1993) and 2964 m^3/s (1995), and the 7-day Mean Annual Low Flow (MALF) is 41.6 m^3/s. In 1957, a significant flood event (flows estimated to be 2400 m^3/s) caused widespread flooding across the Rangitata-Orton plain and prompted an investment in flood engineering works that included limiting flows to the South Branch. From an Environment Canterbury flood assessment report it appears that since 1957, the Rangitata River has entered the South Branch at least nine times.

The Rangitata has an annual flow regime characteristic of a glacial-fed system, i.e. lowest monthly flows occur during the winter and the highest flows are attributed to early summer snowmelt episodes. The flow pattern, however, varies considerably between years. A plot of the river flow regime for the last five years is included as Figure 3-2. The largest floods are commonly associated with 'rain-on-melting-snow' events and tend to occur in December and January (Mosley, 2001). Long periods of sustained flow are not uncommon during winter when there is snow accumulation in the mountains. Mosley (2001) estimated the average monthly 7-day low flow between July and August to be between 45 and 50 m^3/s, compared to over 90 m^3/s between November and January (during snowmelt). As can be seen in Figure 3-2, the general regime of river flows and rainfall (i.e. the two natural sources for potential aquifer recharge) are closely matched. However when evapo-transpirative losses are factored in it can be seen that the amount of rain that would be active in recharging groundwater (i.e. LSR[1]) is relatively low. One would expect to notice this divergence between LSR and river recharge signals in the riparian zone aquifer. Such analyses are covered in Section 4.3.

The diversion of river water by the RDR has a continuous impact on the Rangitata's natural flow regime. Although the RDR is consented to take and divert water from the river at a continuous rate not exceeding 30.7 m^3/s, restrictions attached to the consent ensure a minimum of between 20.1 and 22.0 m^3/s of flow is retained in the Rangitata River during the irrigation season (1 September to 31 May) and between 15.1 and 17.0 m^3/s at other times. Rather than continuously abstract from the river, the RSIS has been designed to harvest water from the Rangitata when flows are above 110 m^3/s.

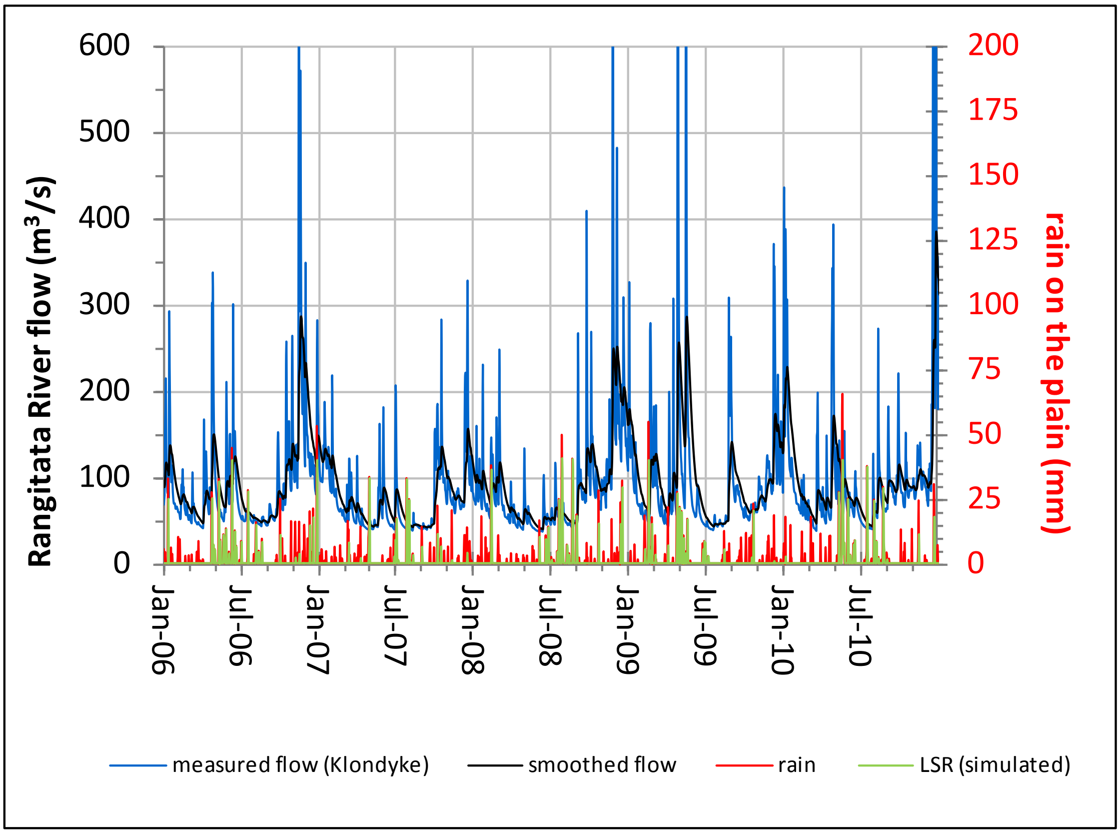

Figure 3-2: Flow and rainfall regime for the lower section of the Rangitata River

Display limited to 2006-2011 records only. Note: Flows recorded at Klondyke are upstream of any RDR water take effects.

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[1] LSR has been calculated using the soil water budget model employed by Scott (2004) and described in Bidwell and Burbery (2011). Model assumptions are provided in Section 7.1 of this report.

3.4.2 Spring-fed surface waters

The flow regime of the tributaries and springs within the Rangitata catchment are poorly studied. It has been reported that the Ealing Springs discharge between 400 and 800 L/s to the Rangitata River, upstream of SH1 (Dommisse (2006) referencing Fish and Game (2001)). Results from Dommisse's own effort to gauge flows in Ealing Springs during March 2006 were subject to significant uncertainty, and as a consequence add little to the knowledge of flows measured by Fish and Game (2001).

Flows in Oakdale Drain were measured periodically by Dommisse (2006) throughout 2005 and 2006. Lowest flows were measured during the winter (72 L/s in September 2005) and proceeded to steadily rise from January onwards, peaking at 283 L/s in late June 2006. Dommisse (2006) inferred that flow in Oakdale Drain was primarily driven by rainfall recharge with a minor contribution from LSR associated with the Mayfield-Hinds Irrigation Scheme. Dommisse (2006) did not assume any hydraulic connection between Oakdale Drain and the Rangitata River.

Forty-one individual flow measurements at Wallaces Bridge on spring-fed McKinnons Creek have been analysed from Environment Canterbury's river gauging database. The data are biased towards low flow measurements made during the irrigation season, although creek flows appear to have been monitored on an approximately monthly basis over 2001/02. The overall flow range is 100 – 500 L/s. A seasonal pattern based on reasonably high and stable winter flows (typically between 400 and 440 L/s, over June to September) and low summer flows can be seen in the data. The low flows do not match the general flow regime of the Rangitata River, from which it can be inferred that McKinnons Creek has no direct hydraulic connection with the Rangitata River, thus is sensitive to local groundwater levels. The lows flows observed during summer months are presumed to be an effect of pumped abstraction for irrigation – Aitchison-Earl (2001) has previously noted that stream depletion effects of groundwater abstraction on McKinnons Creek are potentially significant.

3.5 Rangitata River gaugings (flow gains and losses)

Rangitata River flow gauging data are reported in Walsh (1975), Scarf and Waugh (1986), and Ingles (2000). Altogether, it appears there have been 17 individual gauging runs completed on the Rangitata River, some of which were split over two days. Table 3-1 provides a compilation of the river flow gauging results from the three separate reports.

Table 3-1: Summary of published Rangitata River flow gauging data

Gauging site	Rangitata Gorge / Klondyke	Below RDR	Peel Forest	Arundel bridge	SH1 bridge	Old Main South Road	Badham Rd	Rangitata Mouth
distance from coast (km)	58	55	41	30	20	17	7	0
Date								
24/06/1970	-	13.8	-	-	12.4	-	-	-
20/08/1971	-	10	-	9	7.1*	-	-	-
25/08/1971	-	8.7	8.8	7.7*	-	-	-	8.5
5/04/1973	48.9	-	29.7	28.7	-	28.4	-	-
19/06/1973	50.3	22.9	24.4	-	-	-	-	-
20/06/1973	48.9	-	-	-	-	22.6	23.8	-
16/07/1973		10.7	10.6	10.7	10.6	-		10.5
24/07/1973	38.4	8.3	9	8.9	-	8.5	8.3	-
30/10/1973	-	69	-	62.1	59.5	-	-	-
20/05/1974	45.4	-	21.7	21.9	-	-	-	-
21/05/1974	-	-	-	-	-	21.4	20.1	-
6/06/1974	-	13.9	-	-	16	-	-	19.3
19/08/1974	-	13.6	-	16.4	16.6	-	-	17.2
30/08/1974	-	13.3	-	14.6	16.8	-	-	16.3
28/07/1975	-	23.6	-	-	23.5	-	-	-
20/03/1984	75.4	-	42.6	41.8	-	-	-	-
21/03/1984	-	-	-	40.5	42*	-	-	-
12/02/1999	54.7	-	-	25.0	27.4	-	25.9	26.2
3/08/1999	45.2	-	-	24.6	25.1	-	24.21	31.5
20/08/1999	-	19.1	-	19.1	17.1	17.8	-	18.5

(signifies result reported to be erroneous. Red/green font denotes general observed loss/gain of more than 10% of measured flow.)*

As Scarf and Waugh (1986) suggested, overall measured net flow losses or gains along the Rangitata are in relative terms small and the results of the majority of gauged gains/losses lie within the standard confidence limits of +/- 10% of gauged river flow. There is no apparent consistent loss or gain in the small sample set of data.

In 1970 and 1971 estimated flow losses were less than 1.4 m^3/s. In October 1973 the river was flowing at over 60 m^3/s (the highest at which it's ever been gauged) and losses were calculated to be as high as 9.5 m^3/s. In contrast, net gains in river flow (in the realm of 3.0 – 5.4 m^3/s) were observed over the 3 gauging runs carried out between June and August 1974. According to the water level monitoring records of well K38/0129 located on the Orton plain, the groundwater table was relatively high throughout the winter of 1974, which may have been a contributing factor. A relatively large gain in flow measured along the bottom 7 km reach of the river in 1999 was suspected to be associated with tidal effects and a consequence of delayed release of water stored in the lagoon at the river mouth.

The flow gauging data do not paint a consistent picture of the integrated surface water – groundwater system. The variability in the gauging data raises questions about their reliability, especially if the scale and braided nature of the river are also considered. There are insufficient historic groundwater level data to understand the groundwater condition at the time of each gauging event (something Ingles (2000) attempted to do). Furthermore, 10% uncertainty in flow measurement on the 7-day MALF of 41.6 m^3/s equates to 4.2 m^3/s, which is a significant amount of water. More flow gauging data would help reduce this uncertainty.

It is worth noting that since the last Rangitata River gauging in 1999, groundwater abstraction for irrigation has significantly increased, e.g. the consented maximum daily volume of groundwater abstraction between Rangitata and Orari rivers is up from 1.7 m^3/s (1999) to 7.4 m^3/s (2010) (Scott *et al.,* 2011). It is conceivable that the increased utilisation of the groundwater resource will have invoked a stress on the Rangitata River, and quite possibly upset the effective flow equilibrium observed in historic gauging data.

4 Groundwater hydrology

The gravels of the Rangitata fan constitute the aquifer from which groundwater is yielded. They have been described as: '*either massive or poorly stratified, with a silty sand matrix. Bedforms within the gravels include metre-scale trough cross bedding and planar cross bedding, and clast imbrication is common*' Barrell *et al.* (1996). This translates to a non-uniform, highly heterogeneous aquifer setting comprised of innumerable hydrostratigraphic units of varying shape and size.

Davey (2006) attempted to delineate the aquifers of the Canterbury Plains, including those associated with the Rangitata fan, based on spatial analysis of various parameters recorded on borelog information stored electronically in Environment Canterbury's Wells Database (Wilson and Ettema, 2010). Based on the distribution of well screens, descriptions of water-bearing zones, iron staining, free gravel and claybound gravel, Davey (2006) identified what appear to be three definable aquifers common to the Rangitata fan.

Across the fan there is a shallow unconfined aquifer within 20 m of the land surface. A relatively thick aquitard feature often described in borelogs as claybound, tight or cemented gravel separates the uppermost aquifer from a deeper system that has been inferred between 40 and 90 m. Davey (2006) postulated that a third aquifer unit can be distinguished from well information, located below 90 m depth, possibly in the depth region of 90 - 150 m. Hydrogeological data are studied here to determine the hydraulic relationship between surface water and groundwater systems in the lower Rangitata region.

4.1 Piezometric gradients

Table 4-1 lists groundwater levels measured for clusters of wells (marked on Figure 4-1) that screen various depths and located at different distances from the coastal boundary. The piezometric data suggest that a downward potential hydraulic gradient exists throughout most of the length of the Rangitata fan aquifer. This vertical gradient is reversed towards the coastal boundary, consistent with the model of a system discharging to the sea. Dommisse (2006) recognised similar pressure gradients across the entire Rangitata-Hinds plain, and noted that water pressures in the deeper aquifers were higher than those in the unconfined shallow aquifer seawards of Emersons Road (i.e. within approximately 4 km of the coast). Interestingly, free-flowing artesian conditions do not prevail near the coastal margin, as they do close to the mouth of the Orari River. One could infer from this that there is no extensive truly confining layer occurring within the fan material.

With sufficient piezometric data it is possible to plot groundwater contours and vectors of groundwater flow direction, hence identify whether, under steady-state conditions, groundwater is influent or effluent along a river reach. In the preparatory stage of the Rangitata riparian project Vincent (2007) recommended a piezometric survey should be completed as part of any riparian field investigation. However, such a survey remains to be undertaken. For his MSc thesis, Dommisse (2006) surveyed and contoured groundwater levels within the Mayfield-Hinds groundwater allocation zone, on the northern side of the Rangitata River. The last time groundwater levels were surveyed across the Rangitata-Orton plain was in 1978, by the SCCB. A copy of the piezometric map for the southern aspect of the Rangitata (SCCB drawing W57) can be found in the 1996 report by Environmental Consultancy Services. An annotated version of the map is included in Appendix E of this report, together with a copy of Dommisse's (2006) piezometric map for aquifer 1. Based on the age of the SCCB map, it can be inferred that it is a reflection of the water table in the uppermost, shallow unconfined aquifer. Piezometric contours at a regional scale are available on Environment Canterbury's GIS database and are the only dataset that integrates piezometric data from both sides of the Rangitata River. However, because these contours have been generated by processing water levels monitored from both shallow and deep wells, the piezometric surface they map is unreliable for inferring knowledge of hydraulics at a local scale (pers. comm. Marc Ettema, Environment Canterbury, January 2012).

Table 4-1: Piezometric levels recorded at select clusters of wells that screen various depths and follow the general flow path along the coastal plain, from the Gorge to the sea

Well ID	Easting	Northing	Ground level (m asl)	Screen elevation (m asl)	Well depth (m)	Groundwater level (m asl)	Observation date
Arundel (true-right):							
K37/1641	2374516	5687811	168	168	6	167	26/02/2002
K37/0304	2374700	5687800	166	166	n/a	164	24/08/1979
K37/1332	2373627	5686942	172	137	83	159	10/06/2009
K37/1392	2374080	5687979	171	101	96	138	16/07/2009
K37/1755	2374950	5687620	163	53	145	126	16/07/2009
K37/1623	2374580	5687030	163	50	120	110	10/06/2009
Rangitata Island, above SH1 (true-right):							
K37/2171	2377500	5683400	126.17	126.17	10	124.47	19/06/2007
K37/1305	2379141	5684048	120.66	115.16	81.16	110.30	19/06/2007
K37/1306	2378210	5683440	122.72	49.25	119.27	109.61	19/06/2007
K37/2706	2377255	5683351	128.11	45.58	102.53	102.2	19/06/2007
Ealing, above SH1 (true-left):							
K37/2897	2379310	5687173	156.1	156.1	n/a	148.89	8/05/2006
K37/0250	2379300	5687200	159.12	159.12	23.75	139.91	3/06/1983
K37/0251	2379400	5687200	158.12	158.12	23.77	141.61	2/06/1992
K37/1391	2379488	5686968	153.81	93.81	145.8	136.61	4/07/2006
Rangitata Island, below SH1 (true right):							
K38/1381	2383680	5679370	82.87	61.37	22.5	74.62	2/07/2003
K38/1380	2383680	5679370	82.87	9.37	75	74.34	2/07/2003
K38/1379	2383680	5679370	82.87	-46.13	131	71.14	2/07/2003
Coldstream (true-left):							
K38/1050	2391814	5669698	17.443	17.443	6.3	15.11	24/08/2006
K38/0366	2390774	5669282	6.8	6.8	11.1	5.16	12/10/2010
K38/1842	2390769	5669268	9.11	-88.84	118.67	6.21	20/05/2007
K38/1262	2390882	5669760	15.12	-99.88	121	8.49	10/05/2006
Rangitata Huts (true-right):							
K38/1821	2389390	5667312	7.1	-9.8	19.4	2.61	23/08/2010
k38/1707	2389390	5667312	9.18	-19.82	34	5.38	23/08/2010
k38/1706	2389390	5667312	9.18	-59.32	72.5	5.97	23/08/2010
K38/1705	2389390	5667312	9.18	-95	100	7.07	23/08/2010

(n/a = not available; presumed to be shallow)

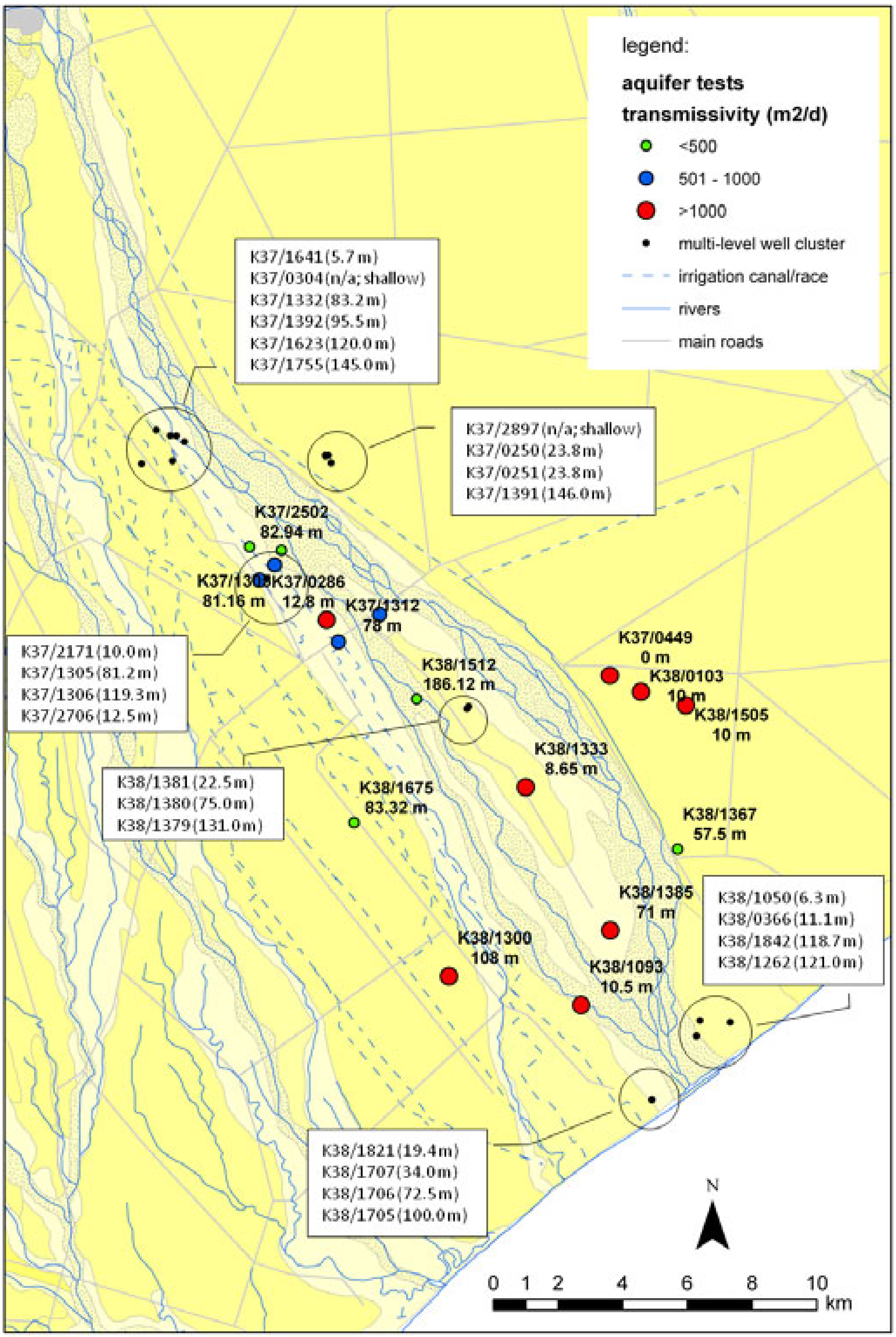

Figure 4-1: Measured aquifer transmissivities

Relates to wells listed in Table 3-3 and localities of multi-level piezometric data listed in Table 3-2. Depths of wells that have been pump-tested are labelled; well screen details can be found in Table 3-3

Dommisse's (2006) plotted contours tend to show groundwater within the uppermost aquifer (measured from wells <50 m deep) on the north side of the river flows into the Rangitata River starting above SH1 (Appendix E). This observation is consistent with the hypothesis that springs at the base of the river terrace, such as at Ealing, are derived from groundwater discharging from the Mayfield plain rather than associated with re-emergent river water. The piezometric contours also suggest the Rangitata River supplies water to the shallow aquifer within approximately 5 km of the coast in the region where sediments from the latest stage of the last glaciation are lain (Q2-1a in Figure 2-1). The piezometric data Dommisse (2006) collated for aquifer 2 tend to suggest groundwater in the deeper aquifer flows parallel to the Rangitata River, discharging towards the coast. Oakdale Drain at Coldstream and numerous springs associated with Hinds swamp are evidently sinks for the regional groundwater system (see Figure 3.18 in Dommisse (2006)).

There are no obvious indications from the piezometric surface of shallow groundwater under the Rangitata - Orton plain, mapped by the SCCB, that the Rangitata River influences recharge of the shallow aquifer across the Rangitata - Orton plain. Contours tend to suggest that above the 135 m topographic contour line, i.e. about Arundel, some groundwater drains towards the river (Appendix E). The springs mapped at the foot of the Rangitata River terrace at Arundel (e.g. Figure 3-1) are likely to be this weak sink. Between the 135 m and 85 m topographic contours, however, the piezometric surface along the margin of the Rangitata River does indicate a losing river system. Geographically, this region corresponds to the bifurcation of the Rangitata, and head of the Rangitata South Branch. Thus, it would appear that some Rangitata River water flows into the South Branch, as groundwater. There are no obvious signs that the river continues to lose water to ground along the Rangitata Island reach, an observation that suggests the RG2 geomorphic unit that makes up Rangitata Island is less permeable than the recent RG0 and RG1 modern floodplain material, as was postulated by Barrell *et al.* (1996). Furthermore, groundwater contours in the vicinity of the Rangitata South Branch towards the south-east corner of the Island at about the 70 m topographic contour start to reflect the overall pattern of a gaining river system. Given this area coincides with the head of Kapunatiki Creek, it might follow that the paleo-river channel mapped as Kapunatiki Creek has relatively high permeability and influences the drainage of shallow groundwater.

4.2 Aquifer permeability

The specific capacity of wells has been mapped in an attempt to identify any spatial patterns that might indicate areas where groundwater is directly influenced by river recharge (Figure 4-2). Wells drawing groundwater that is directly recharged by the Rangitata River are likely to exhibit high specific capacities, since the effects of a river recharge boundary is to reduce the drawdown observed in the pumped well. However, the reliability of specific capacity data for inferring knowledge about the aquifer formation is compromised by factors such as the well installation design and the fact that specific capacity values are obtained from pumping tests that examine the system at no fixed scale.

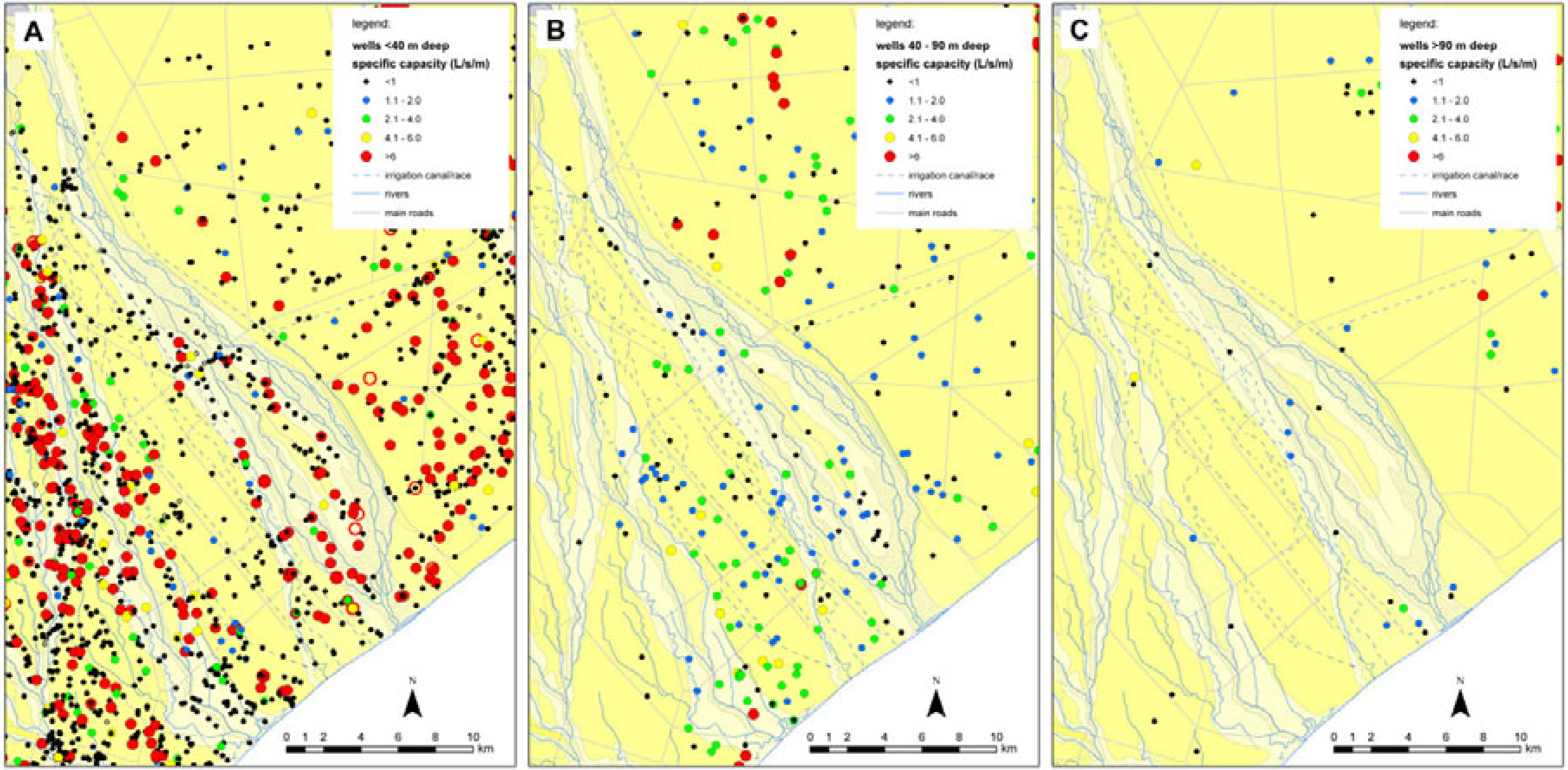

Figure 4-2: **Specific capacities of wells in the defined depth ranges**

[A] <40 m deep; [B] 40-90 m deep and; [C] >90 m deep. Depth measurements refer to top of well screen. Hollow circles in Figure 4-2A denote galleries

From Figure 4-2 it appears that relatively high specific capacities have been measured in wells shallower than 40 m deep positioned within the modern day flood plain, that is: the main North channel (most notably close to McKinnons Creek), the Rangitata South Branch, and parts of Kapunatiki Creek. A reasonable proportion of wells that screen Q2-1a alluvium close to the mouth on the northern side of the river (i.e. near Coldstream) have high specific capacities, which corroborates with the region where shallow groundwater appears to be sourced from the river, based on piezometric data (Section 4.1; Appendix E). Only a couple of wells that screen similar geological material on the opposite bank of the river have high measured specific capacities, hence it is likely that there is no significant hydraulic connection with the river on the south side. Equally, for the most part, wells screening the older Q2-1a (RG2 geomorphic units) on Rangitata Island have relatively low specific capacities.

A large number of shallow wells towards the lower (south-eastern) end of the Mayfield-Hinds irrigation scheme have relatively high specific capacities, even though these wells are relatively distant from any modern Rangitata River geomorphic features, or likely riparian zone. The hydrogeology in this region is significantly affected by the RDR and many of the wells are located either close to mapped spring features or irrigation races, which most probably accounts for the high specific capacities measured.

Not surprisingly, specific capacities are, on the whole, smaller for wells screening below 40 m (i.e. in aquifer 2 or 3 defined by Davey (2006)). Spatial patterns in these data are less apparent than for the shallow well data. The highest specific capacity values have been recorded for deep wells located near to Kapunatiki Creek, and on the Mayfield-Hinds plain, inland of SH1. Rather than contrasting high (>6 L/s/m) or low (<1 L/s/m) specific capacity values mapped for the shallow wells, the spread of values for the deep wells seems more uniformly distributed (generally ranging from <1 L/s/m to 4 L/s/m). From the scatter in the specific capacity data for deep wells it is not possible to infer any local river recharge influences on the measured hydraulic properties.

Table 4-2 lists the hydrogeological parameters of Rangitata fan deposits as determined from aquifer tests. Included are specific capacity values for comparison. Relatively consistent aquifer transmissivity values in the range 1700 – 2860 m^2/day (average 2296 m^2/day) have been measured for shallow gravel strata (all test wells screening less than 13 m deep). The pumping test data do not support the theory that aquifer transmissivity is inversely proportional to set-back distance from the river, nor does it reveal any significant differences exist in hydrogeological properties between RG1 or RG2 geomorphic units. The data highlight weaknesses in the use of specific capacity data for inferring information about aquifer hydrogeological properties.

The measured transmissivities of strata screened at depth (wells deeper than 50 m) is more variable and has been evaluated within the range 150 - 1600 m^2/day. Relatively low storage coefficients determined in pumping tests performed from deeper wells indicates some degree of aquifer confinement, although the pumping test data confirm that the deeper aquifer units examined below 50 m depth function as leaky systems, i.e. water can permeate vertically through the hydrogeological system. The results of the pumping tests, which are an examination of the groundwater system at a local-scale, seem to support the hydrogeological picture portrayed by the piezometric levels (Section 4.1), that there are no extensive truly confining strata within the Rangitata fan.

The two deep wells for which relatively high transmissivities exceeding 1000 m^2/day have been reported (K38/1385 screening 65 – 71 m and K38/1300 screening 61 – 108 m) are both located within 7 km of the coast. Although K38/1385 is located close (<1 km) to the modern day Rangitata River, K38/1300 is over 6 km (south-west) from the river where RG2 geomorphic units are mapped on the surface. There are seven deep wells located close to SH1 that have been pump-tested, several of which are positioned within the modern day river flood channel. One might suspect, given the proximity to the Rangitata River, that these wells could be susceptible to river recharge effects which might manifest themselves in the hydraulic parameter values determined from pump tests. However, no effective river recharge boundary effects have been reported for any of the aquifer tests and measured aquifer transmissivity values do not correlate with variables such as the set-back distance from the river. The transmissivity of sedimentary strata below 51 m depth within the mid-reaches of the Rangitata River has typically been measured as less than 600 m^2/day (see Figure 4-1 and Table 4-2).

Table 4-2: Reported hydrogeological properties of Rangitata fan sediments

Well ID	Screened interval (m bgl)	Transmissivity (m2/d)	Storativity	K'/B' (1/day)	Model	Duration (mins)	Reliability[2]	Specific capacity (L/s/m)
K37/0449	n/a	2840	n/a	n/a	Eden-Hazel	660	3	6.2
K38/0103	n/a-10.0	2860	n/a	n/a	Eden-Hazel	960	3	24.4
K38/1505	0.3-5.0	1974	n/a	n/a	Eden-Hazel	270	2	156.5
K38/1333	0.0-8.65	1700	n/a	n/a	n/a	4305	2	n/a
K37/0286	9.5-12.8	2400	0.11	n/a	n/a	450	2	5.4^{+}
K38/1093	3.6-10.0	2000	0.1*	n/a	Theis	1359	2	15.8
K38/1367	51.5-57.5	150	n/a	n/a	Eden-Hazel	253	2	1.7
K37/1315	51.4-57.4	515	n/a	n/a	Eden-Hazel	240	3	3.0
K38/1385	65.0-71.0	1100	0.0046	0.00804	Hantush-Jacob	n/a	1	0.7
K37/1312	65.9-78.0	882	0.00056	0.000443	Hantush-Jacob	1411	2	1.2
K38/1675	65.3-83.3	390	0.00039	0.00047	Hunt-Scott	2420	1	2.4
K37/2502	70.9-83.0	240	1x10^{-5}	6x10^{-6}	n/a	5800	3	1.0
K37/1305	72.7-81.2	573	0.00017	0.00035	Hantush-Jacob	3000	2	0.3
K37/1310	76.0-89.0	265	0.0002	6x10^{-5}	n/a	4374	3	0.5
K38/1300	60.8-108.0	1600	0.0002	n/a	n/a	n/a	2	2.1
K37/2706	82.5-100.5	577	0.0014	1x10^{-5}	n/a	4284	3	0.9
K38/1512	114.0-136.0; 180.1-186.1	441	0.00106	0.000301	Hantush-Jacob	1620	2	1.8

(denotes assumed value; n/a = not available; + = gallery. All data from Environment Canterbury's aquifer test database.)*

4.3 Groundwater dynamics

In a riparian zone aquifer, one would expect groundwater levels to be sensitive to the variations in river levels (i.e. possibly experience bank storage effects) due to the strong hydraulic connection with the river. Also, drawdowns from groundwater pumping are likely to be buffered by the river recharge boundary condition. With increasing distance from the river, any variable river recharge signal in the groundwater system will be damped, to the extent that it becomes unmeasurable. Far from the river, such as beyond the riparian zone margin, LSR and pumped abstraction are the only mechanisms responsible for dynamism exhibited in groundwater levels. Groundwater level monitoring well records were therefore reviewed for the purpose of assessing whether river recharge signals are detectable in any of the datasets, from which inferences could be made regarding riparian zonation.

Environment Canterbury routinely monitors groundwater levels at seven locations within 5 km of the Rangitata River (Figure 4-3). The observations cover: Rangitata Island, sandwiched between the Rangitata River channels (wells K38/1379-21 and K38/0135); shallow groundwater under Mayfield-Hinds plain on the north-bank (wells K38/0384 and K38/1571); shallow groundwater on Orton plain, adjacent to Kapunatiki Creek (wells K38/0129 and K38/2111); and aquifers at variable depths close to the river on the south-bank and near to the river mouth (wells K38/0117, K38/1705-1707 and K38/1821). There are other monitoring wells further afield, including deep and shallow wells located in the middle of the Orton plain, far beyond any conceivable river influence (e.g. wells K38/0013 and K38/1081) (Figure 4-3).

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[2] Environment Canterbury score aquifer test data according to perceived potential error in the resulting hydraulic parameter estimates. Reliability rankings range from 5 (poor) to 1 (most reliable). See Aitchison-Earl and Smith (2008) for more details.

Piezometric levels are monitored at varying depths at two of the locations (Rangitata Island and Rangitata Huts), using multi-level well arrays, which permits study of groundwater pressure variations in the various aquifer units defined by Davey (2006). The multi-level well cluster on Rangitata Island (wells K38/1379-81) is sited most central to a likely riparian zone as defined by Vincent (2007) (e.g. Appendix B), hence is in a prime position to provide the most useful information in relation to the riparian zone hydraulics. However, the structural integrity of the well installations on Rangitata Island are damaged (Aitchison-Earl, 2004) and the wells provide a measure only of the piezometric response integrated over three aquifers, down to 131 m.

Groundwater under the Mayfield-Hinds plain is so highly affected by the irrigation scheme that the aquifer recharge signal from irrigation completely masks the underlying climate-driven signal, let alone any potential river recharge signal. Dommisse (2006) concluded that groundwater levels in the upper-most aquifer (i.e. wells <30 m deep) across all of the Mayfield-Hinds plain are driven predominantly by irrigation scheme inputs, and that rainfall recharge is secondary. The only river recharge effect Dommisse (2006) noticed from groundwater level data he collected was in wells K38/0517 and K38/1050 (e.g. Figure 4-3) that both screen the shallow aquifer adjacent to the river (within 6 km of the coast), and in the region where piezometric contours are suggestive of river losses to groundwater (as were covered in Section 4.1; Appendix E).

Groundwater levels for Environment Canterbury's shallow monitoring wells K38/0384 and K38/1571 demonstrate how the groundwater system within Rangitata fan material on the true-left of the river is out of sync with the natural hydrological cycle patterns (see Figure 4-4). Dommisse (2006) suggests groundwater pressures in the deeper aquifer units under the Mayfield-Hinds plain are driven by LSR, even though observations were made in excess of 4 km from the river boundary. No additional groundwater level monitoring data on the true left of the river suitable for analysis have been identified.

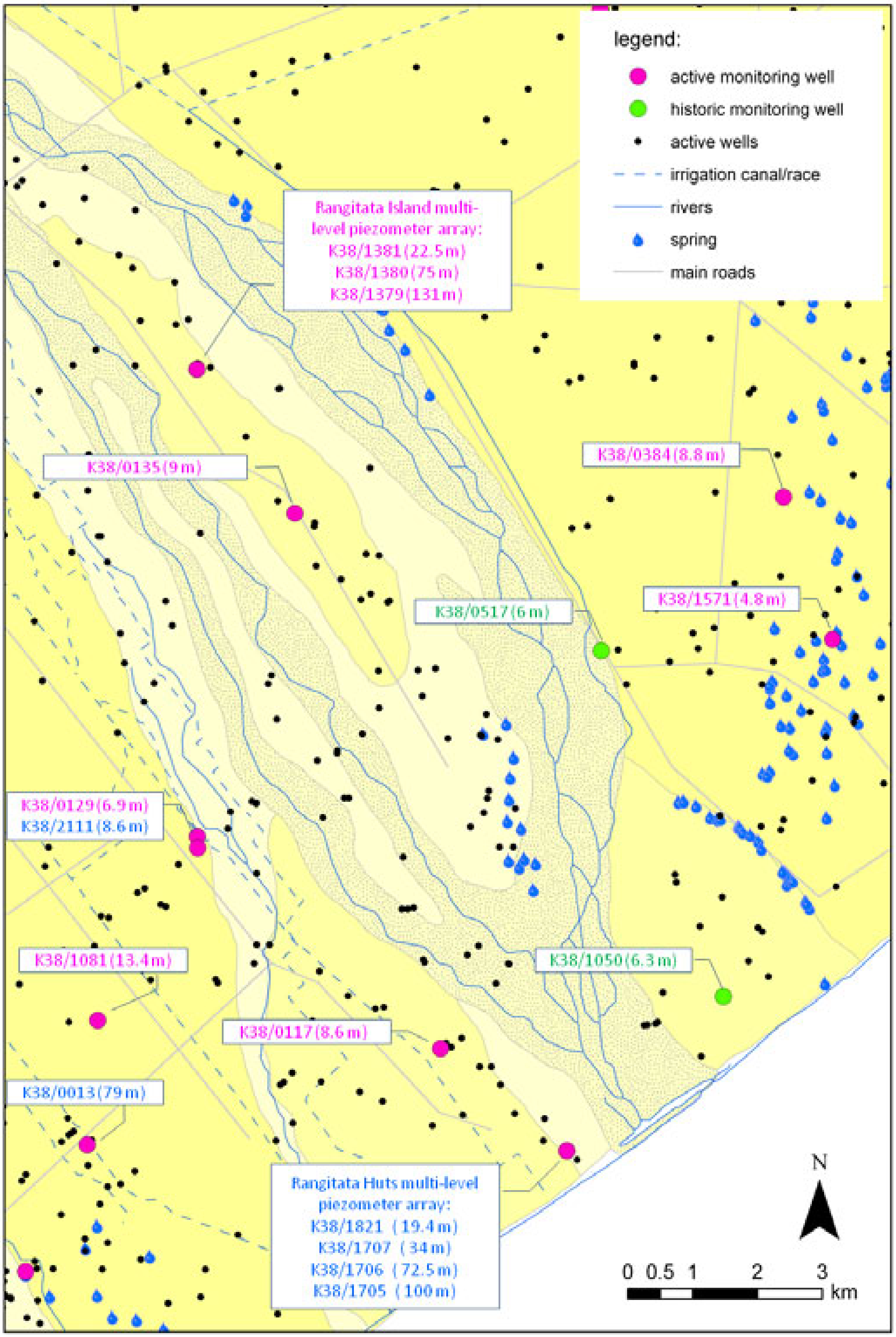


Figure 4-3: Groundwater level monitoring well coverage

Wells with continuous pressure recording devices are labelled in blue; bracketed value denotes well depth. Active wells with resource consents to take water are marked, as are historic monitoring wells reported by Dommisse (2006) to be sensitive to river flows

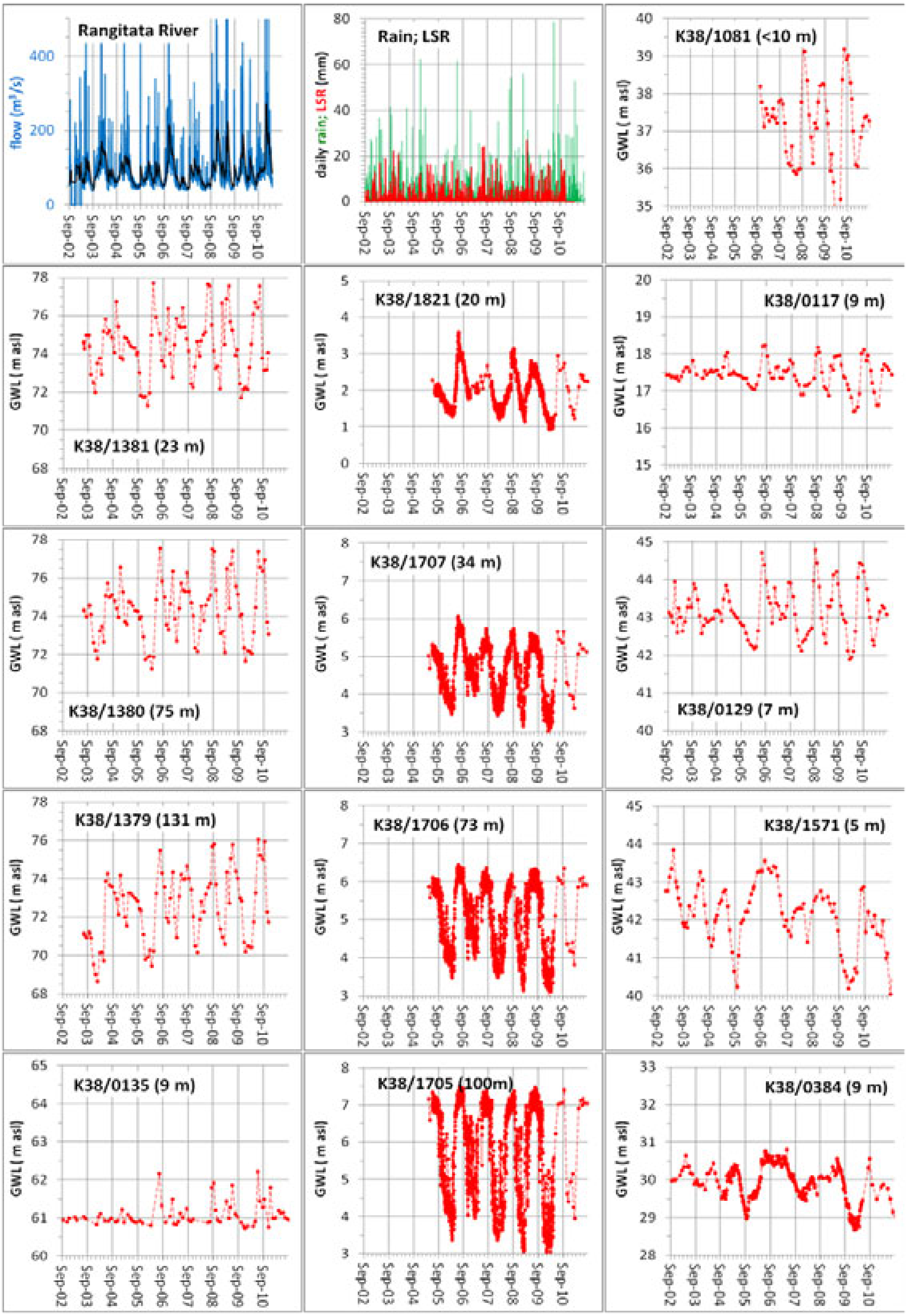


Figure 4-4: **Hydrographs for monitoring wells in Figure 4-3**

Record for potential (river and rainfall) recharge mechanisms included - black line is a smoothed river recharge signal. K38/1081 provides a reference dataset for shallow aquifer beneath the Orton plain, devoid of potential river effects

4.3.1 Analysis of monthly monitoring records

Owing to its setting within the centre of the riparian zone mapped by Vincent (2007), an attempt was made to mathematically analyse the groundwater level signal monitored in the shallowest of the multi-level piezometers (K38/1381) on Rangitata Island. This analysis is detailed in Appendix F. The overall conclusion of the analysis was that reliable observation data were too sparse and, being of near-monthly measurement frequency, of too low a resolution to detect potential dynamic river recharge signals based on the information available. There is weak, semi-quantitative evidence to suggest that the dynamism exhibited in the shallow aquifer beneath the island is caused by LSR (LSR) effects, i.e. active rainfall. From the analyses conducted, it has been determined that most aquifer recharge from LSR tends to be concentrated between April and August. Occasional heavy rainfalls occurring during the summer season (i.e. between December and March) appear to provide less sustained, yet significant recharge events (e.g. Figure F-3 in Appendix F). It follows that any potential hydraulic connection the aquifer has with the river is effectively a basal component of the groundwater store and river recharge signals are sufficiently damped to be unnoticeable in water level data.

All the groundwater level data collected from wells that are monitored at near-monthly intervals are subject to the same problem of uncertainty, attributed to low sampling resolution, i.e. insufficient detail to filter potential river recharge effects from the LSR response signal. Thus, their usefulness in characterising a riparian zone is limited and no attempt was made to analyse those records mathematically. As an alternative, the records were subjected to a visual analysis, whereby hydrograph patterns were compared against that for well K38/1381 (see Figure 4-4), which, being located on the Orton plain, was assumed to provide a reference dataset for non-riparian zone effects (i.e. water level fluctuations driven mainly by LSR).

If pumped abstraction effects that occur from September to June are overlooked, visual inspection of the hydrograph data in Figure 4-4 confirms that all monitored groundwater levels (other than the two wells K38/0384 and K38/1571 on the Mayfield-Hinds plain that are known to be affected by the irrigation scheme) exhibit a similar form. The obvious difference in amplitude (see Figure F-1 in Appendix F) can be explained by the effect of localised heterogeneity of the aquifer formation and position of the wells in relation to potential discharge boundaries. For example, the small (generally <1 m) variance in groundwater levels observed in wells K38/0135 and K38/0117 is characteristic of wells located close to some fixed hydraulic boundary. Since, the two wells are different distances from the coastal discharge boundary, but both within 1.5 km of the active river channel, it is conceivable that the Rangitata River is the hydraulic boundary condition common to both wells. Comparatively larger amplitudes (up to 2 m) are seen in groundwater level records from wells K38/0129 and K38/1081, which are located farther (>5 km) from the river.

Despite it screening across what Davey (2006) defines as aquifer 1, and being the monitoring well situated closest to the Rangitata River, very large groundwater level fluctuations are seen in the hydrograph record of well K38/1381, located on Rangitata Island (Figure 4-3; Figure 4-4). This appears to be at odds with the argument provided above about constant head boundary effects. However, in this case, the large amplitude of the groundwater recharge response observed at K38/1381 is believed to be attributed to the 23 m deep well screening material with lower storativity properties than the other monitoring wells, most of which provide piezometric measurements at depths shallower than 10 m below ground level.

The similarity in the overall groundwater level patterns observed between the monitoring well datasets (that include reference well K38/1081) implies the groundwater system at all the observation points is driven by the same recharge processes. If a well were in a zone where variable river recharge effects were active (as might occur in a riparian zone), one could expect to see a phase shift in the signal from wells not in the zone, or some anomalous recharge spikes resulting from river storm flows. The phase shift would be related to bank storage effects, which do not apply to systems distant from rivers. This finding suggests that none of the wells Environment Canterbury routinely monitor monthly screen aquifers in close enough proximity of the Rangitata River for bank storage effects to be effective, or contain any information relevant to the riparian zone delineation problem.

4.3.2 Analysis of continuous monitoring records at the coast

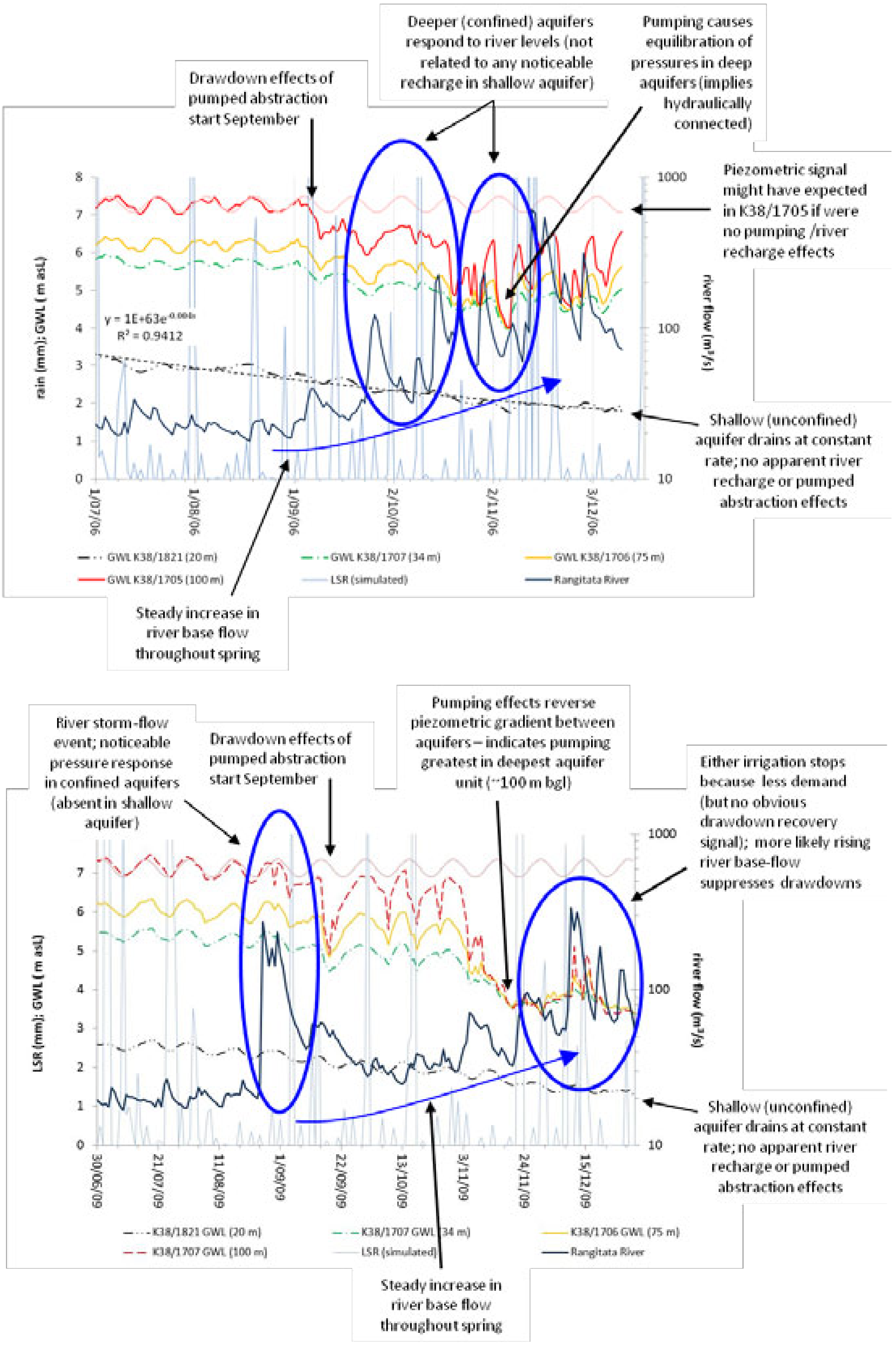
Groundwater pressures are recorded at 15 minute intervals in the multi-level piezometer cluster at Rangitata Huts, as they are also in the unconfined shallow aquifer at K38/2111 on the Orton plain (on the margin of Kapunatiki Creek). The high monitoring frequency makes these data more conducive to hydrodynamic analyses than the monthly monitoring data.

The usefulness of the piezometric data from the coastal cluster of wells K38/1705:K38/1707 and K38/1821 for understanding potential river recharge effects is however compromised, since the groundwater pressures at this location are affected by tidal effects. An attempt was made to filter the piezometric data for tidal effects, for the purpose of providing a base-line dataset from which potential LSR and river recharge might be analysed. Unfortunately, tidal effects could not be subtracted with any reliability and when compounded with significant noise associated with unknown pumped abstraction, restricted interpretation of groundwater level patterns to a subjective visual inspection (similar to that conducted for the monthly monitoring data). Details of the tidal-signal processing applied can be found in Appendix F.

Large water level changes attributed to aquifer confinement can be seen in the piezometric level data from deep wells of the Rangitata Huts coastal cluster (K38/1705-7) (Figure 4-4; Figure 4-5). All three deep wells (K38/1705-1707) exhibit the same piezometric pattern and are highly affected by drawdown effects (typically 2-3 m) during the irrigation season due to low storage properties. From comparing the tidal signals observed in piezometric data monitored over the winter periods of 2006 and 2009 (when the average piezometric level was relatively stable), the relative difference in tidal efficiencies has been calculated (see Appendix F).

Tidal effects are greatest in the deepest well K38/1705 that screens the aquifer 95.0-100.0 m bgl. The tidal response is in the realm of 50-65% of the actual ocean tidal amplitude (see Appendix F). Although of similar phase, the tidal signal is approximately 10% less in the well screened 68.5-72.5 m (K38/1706) and 30-40% less at 34 m depth (K38/1707). This measured difference in tidal response reflects the lower storage properties of the aquifer with increasing depth.

Tidal effects are equally noticeable in groundwater level responses of the shallow aquifer at Rangitata Huts (well K38/1821), although these are more difficult to characterise owing to groundwater level variations attributed to variable LSR inputs and relatively fast aquifer drainage. The tidal signal is more damped in the unconfined aquifer compared to the deeper system, as a consequence of the higher storage properties.



Drawdown effects of pumped abstraction start September

Deeper (confined) aquifers respond to river levels (not related to any noticeable recharge in shallow aquifer)

Pumping causes equilibration of pressures in deep aquifers (implies hydraulically connected)

Piezometric signal might have expected in K38/1705 if were no pumping /river recharge effects

Shallow (unconfined) aquifer drains at constant rate; no apparent river recharge or pumped abstraction effects

Steady increase in river base flow throughout spring

River storm-flow event; noticeable pressure response in confined aquifers (absent in shallow aquifer)

Drawdown effects of pumped abstraction start September

Pumping effects reverse piezometric gradient between aquifers – indicates pumping greatest in deepest aquifer unit (~100 m bgl)

Either irrigation stops because less demand (but no obvious drawdown recovery signal); more likely rising river base-flow suppresses drawdowns

Shallow (unconfined) aquifer drains at constant rate; no apparent river recharge or pumped abstraction effects

Steady increase in river base flow throughout spring

Figure 4-5: Hydrographs for piezometric levels recorded at the coastal multi-level well cluster at Rangitata Huts

Interpretative comments included [Top: winter-spring 2006; Bottom: winter-spring 2009]. Note: pink line is modelled tidal effect in K38/1705, assuming no other recharge/discharge influences, i.e. effective baseline piezometric level

Examination of daily hydrograph data for the multi-piezometers at the coast focussed strongly on the winter-spring periods of 2006 and 2009 for which continuous piezometric records were available (Figure 4-5). Deciphering a potential dynamic river recharge signal is complicated because most of the storm flow events resulting from snow-melt in the upper catchment that can be separated from rainfall events on the plains occur during the irrigation season when groundwater monitoring records contain irrigation noise. Furthermore, because river flows are measured at the gorge they do not include potential storm-flow draining from the plains. Thus it is possible that for rainfall recharge events on the plain there is a coincident (unmonitored) rise in river levels that has potential to affect the groundwater system. The detection of any passive recharge effect potentially associated with the near-doubling of river baseflows from August to January is compromised by uncharacterised drawdown effects arising from pumped abstraction.

Throughout the data record (Figure 4-5) there are rainfall events that corroborate with immediate increases in the piezometric water pressure in excess of tidal noise when no noticeable increase in river flow has been recorded at the gorge (e.g. July 2006). Equally, there are rainfall events around the same season that have failed to invoke a piezometric response (e.g. August 2006, October 2006). Most significant is the observation that on occasions piezometric levels in the deeper wells appear to have responded to river flow events when no rainfall has been measured on the plains (e.g. September 2006, November 2009). It is unlikely increases in river flows would prompt cessation of irrigation that would cause a recovery of piezometric levels, thus one can assume the aquifer response is most probably related to river effects. It is conceived that these effects however are primarily pressure responses to mass loading of river water on a semi-confined aquifer, much like the tidal-effects, rather than attributed to any direct aquifer recharge event/drained response. Further technical assessment is required to test this hypothesis and to potentially quantify hydraulic properties of the multi-layered aquifer system from the routine monitoring data.

Notwithstanding the incomplete technical knowledge, the conclusion drawn from the piezometric data collected from the Rangitata Huts is that water pressures in the deep aquifer are sensitive to the river flow condition. During the summer, irrigation season it appears that the higher seasonal river flow bolsters up the groundwater pressures, mitigating the observed effects of pumped abstraction. The presence of aquitard strata and general positive vertical pressure gradient tend to suggest the deep aquifers have limited hydraulic connectivity with the river. Furthermore, the observation from groundwater level monitoring data that any active recharge process is insufficient to completely suppress groundwater abstraction effects, adds doubt as to whether the system should be classified as riparian or not. Nonetheless, drawdown effects of pumped abstraction are evidently distributed over all the three individually screened deeper aquifer units (see Figure 4-5) highlighting the leaky characteristics of the system, which one might reasonably presume extend to the surface, hence hydraulically link the deep groundwater to the river.

Water levels monitored in the shallow aquifer of the uppermost 20 m of ground level and comprising sediments mapped as young alluvium (e.g. Figure 2-1) exhibit a steady decline throughout each irrigation season, albeit no obvious localised drawdown effects (Figure 4-5). This is in contrast to the opposing steady increase in river base-flows and therefore suggests that dynamism observed in the shallow aquifer is dominated by LSR, not any bank storage, river recharge effect. This does not preclude the shallow groundwater from being hydraulically connected to the river.

5 Hydrochemistry

In this section, chemical analytical data available from Environment Canterbury's SQUALARC water quality database (Ettema, 2011) are reviewed because hydrochemical data can indicate likely recharge sources, permit the tracing of water flow-paths and reveal information about hydrological mixing. Dommisse (2006) and Scott *el al.* (2011) have previously undertaken comprehensive reviews of water chemistry within the groundwater allocation zones on opposing sides of the Rangitata River. This is a revision of their analyses and incorporates water chemistry data purposely collected in 2010 as part of the Rangitata riparian project. It expands on the review of hydrochemical data completed by Vincent (2007).

5.1 Methods of assessment

Major ion composition, electrical conductivity, Ca/Mg ratio, dissolved silica, nitrate and oxygen-18 stable isotope data are the hydrochemical variables that have been analysed here. The first four variables all reflect mineral dissolution, hence tend to increase as water evolves during any passage through the soil zone or increased hydraulic residence time underground. The ion composition and consequently, conductivity can also be impacted by contamination resulting from land-use. Elevated nitrate concentrations in particular are a good indication of land-use impacts, and were used here to positively identify active LSR processes. Oxygen-18 is useful for determining the potential source of groundwater.

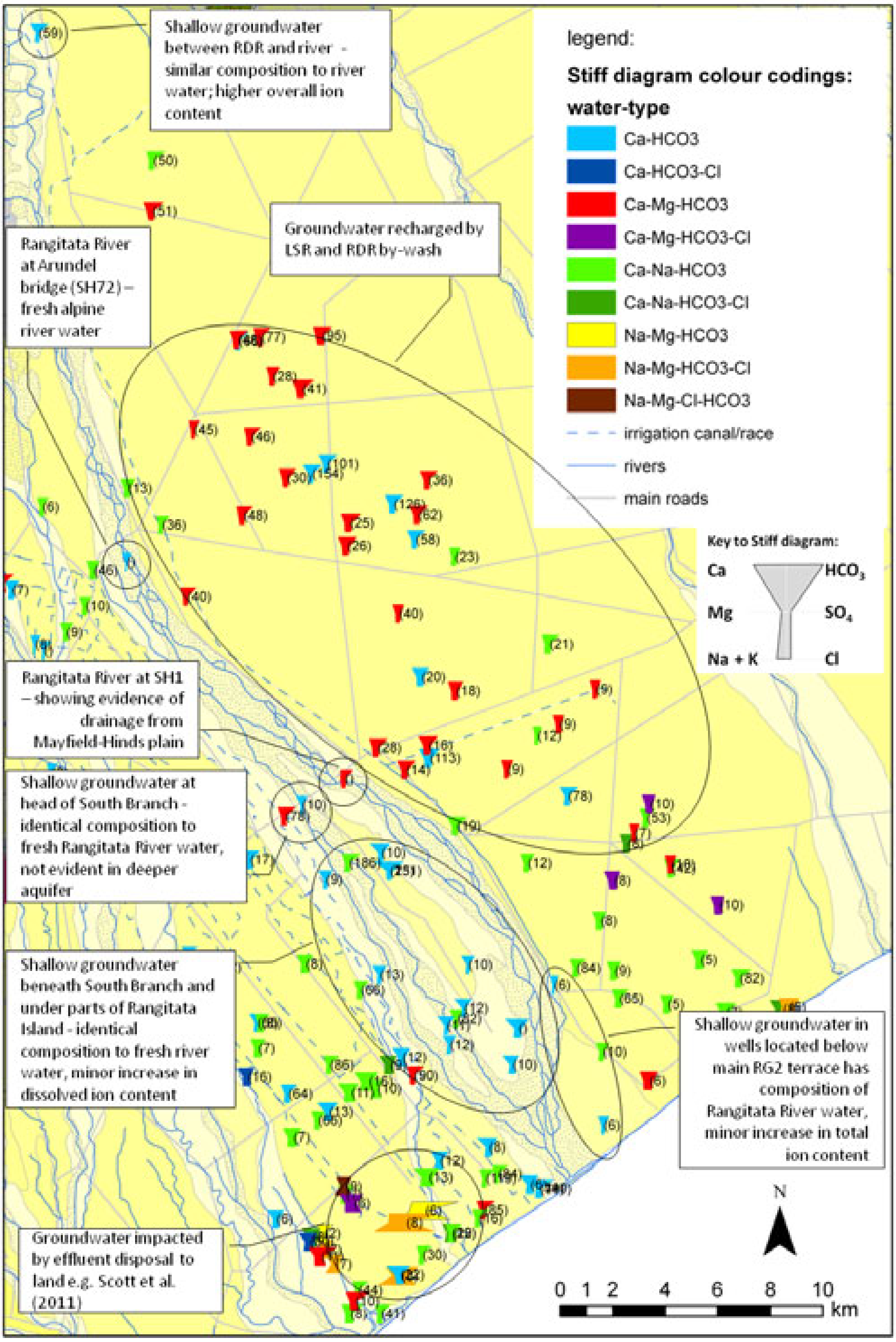
To plot possible hydrochemical facies, water samples were classified into 'water-types' based on their major ion chemistry and mapped using Stiff diagrams (e.g. Domenico and Schwartz, 1990) (Figure 5-1). Only analytical data for which the ion mass balance had been measured to within 5% accuracy were processed. The overall shape and colour of the Stiff diagram denotes a specific water-type based on its major ion composition (a key to which is provided in Figure 5-1). A single ion is dominant only if it constitutes more than 50% of the overall cation or anion balance when assessed in meq/L, otherwise a water is classified as a mixed water-type (with ions listed in order of equivalent mass).

Figure 5-2 to Figure 5-5 plot the distribution of average electrical conductivity, Ca/Mg ion ratios, silica and nitrate concentrations. Censored nitrate data, with concentrations below the laboratory method detection limit, were processed using the probability plotting procedure described by Helsel and Cohn (1988). The data can be found in tabular form in Appendix G. Findings are discussed in the next section.

Natural isotope enrichment processes determine that δ^{18}O signatures are measurably different for recharge water originating from different geographic regions. In this case snow and rain draining from a cold, mountainous alpine environment in the upper catchment that is westward, versus rainfall recharge on a warmer, eastward coastal plains setting. Thus, oxygen-18 can be a reliable chemical tracer for mapping the extent of alpine river water but, as Dommisse (2006) discovered, because the RDR has highly modified the natural hydrogeological system under the Mayfield-Hinds plain, natural δ^{18}O signals in this area are distorted. δ^{18}O data are plotted in Figure 5-6.

Figure 5-7 plots δ^{18}O and Ca/Mg results along three vertical transects (SH1, Rangitata Island, and close to the coast) to study any stratification in the groundwater chemistry and delineate the probable depth of a Rangitata riparian aquifer zone. A map showing the exact location of the transects is included in Appendix I, together with piezometric profiles.

It is assumed that water in a riparian zone aquifer will be of relatively young age. Information contained in Stewart *et al.* (2006) and Aitchison-Earl (2004) on the age of groundwater determined from fifteen sampled wells within the Rangitata region was reviewed. A summary of the groundwater age data can be found in Figure 5-8.


Shallow groundwater between RDR and river - similar composition to river water; higher overall ion content

Groundwater recharged by LSR and RDR by-wash

Rangitata River at Arundel bridge (SH72) – fresh alpine river water

Rangitata River at SH1 – showing evidence of drainage from Mayfield-Hinds plain

Shallow groundwater at head of South Branch - identical composition to fresh Rangitata River water, not evident in deeper aquifer

Shallow groundwater beneath South Branch and under parts of Rangitata Island - identical composition to fresh river water, minor increase in dissolved ion content

Shallow groundwater in wells located below main RG2 terrace has composition of Rangitata River water, minor increase in total ion content

Groundwater impacted by effluent disposal to land e.g. Scott et al. (2011)

Figure 5-1: Stiff plot showing hydrochemical facies of groundwater and surface water

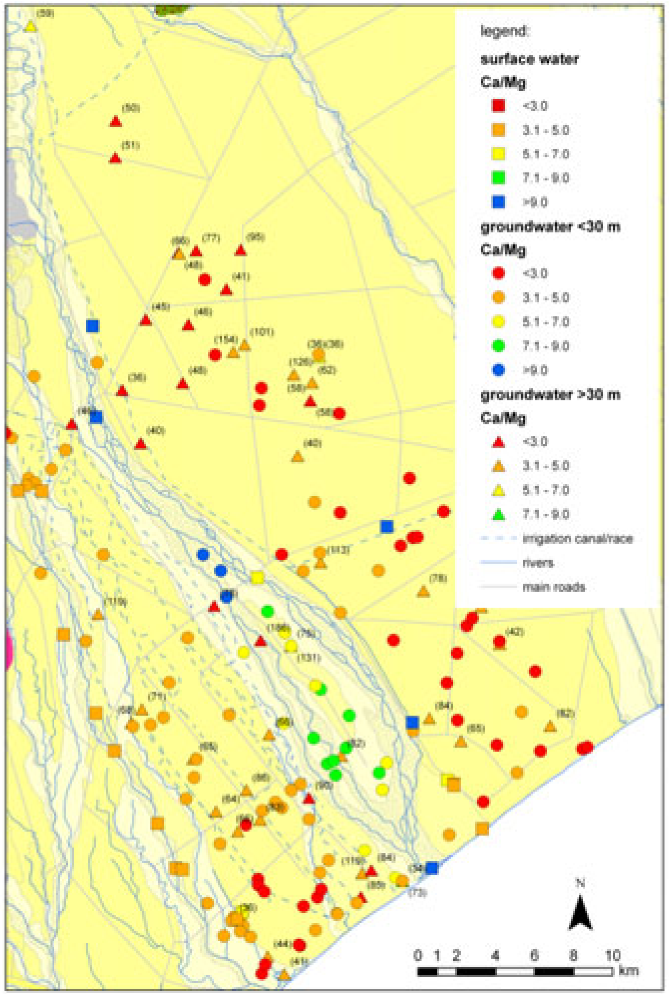


Figure 5-2: **Ca/Mg ratios**

Labels mark depth (in metres) of sampled wells over 30 m.

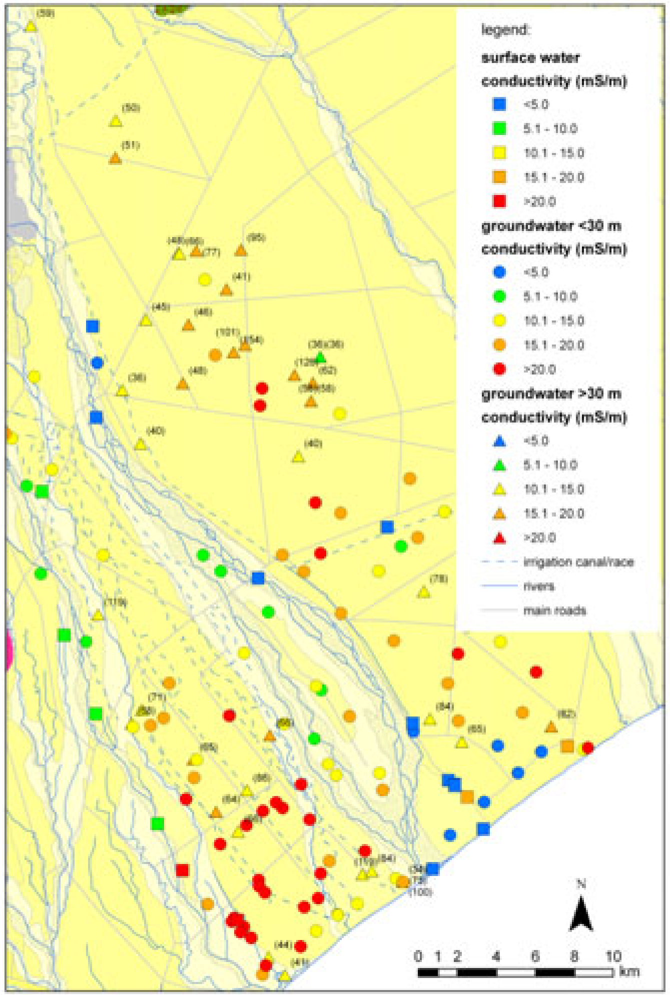


Figure 5-3: **Electrical conductivity (field measurement)**

Labels mark depth (in metres) of sampled wells over 30 m.

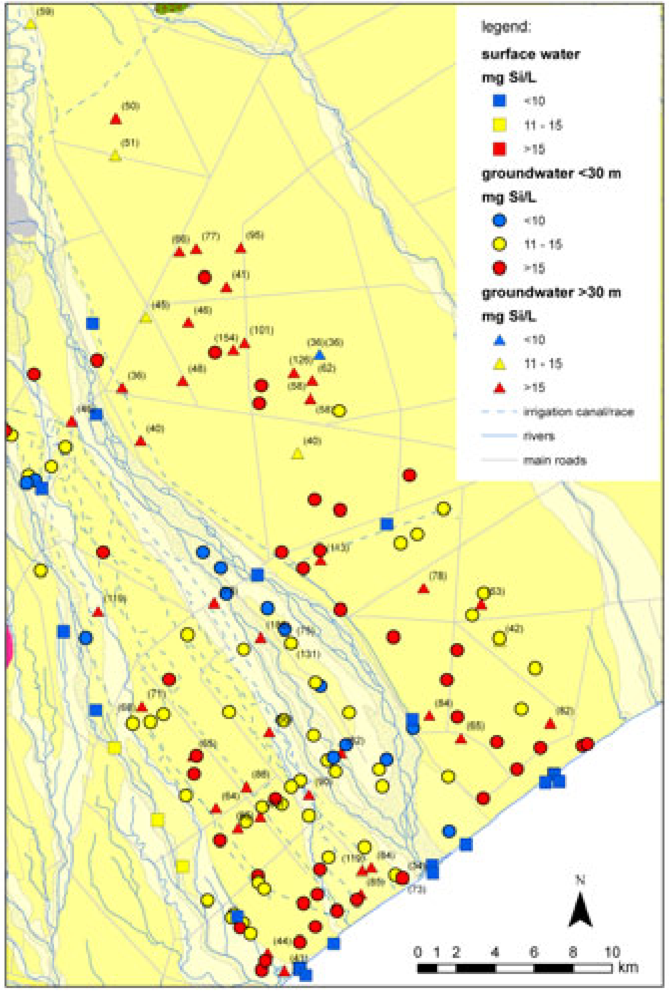


Figure 5-4: **Dissolved silica**

Labels mark depth (in metres) of sampled wells over 30 m.

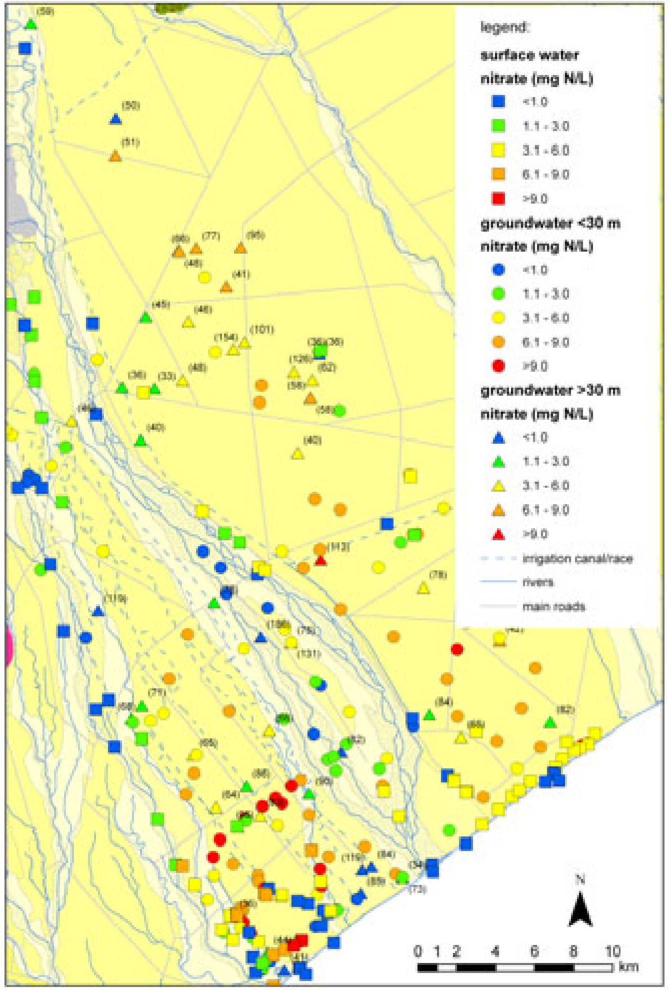


Figure 5-5: **Nitrate concentrations**

Labels mark depth (in metres) of sampled wells over 30 m.

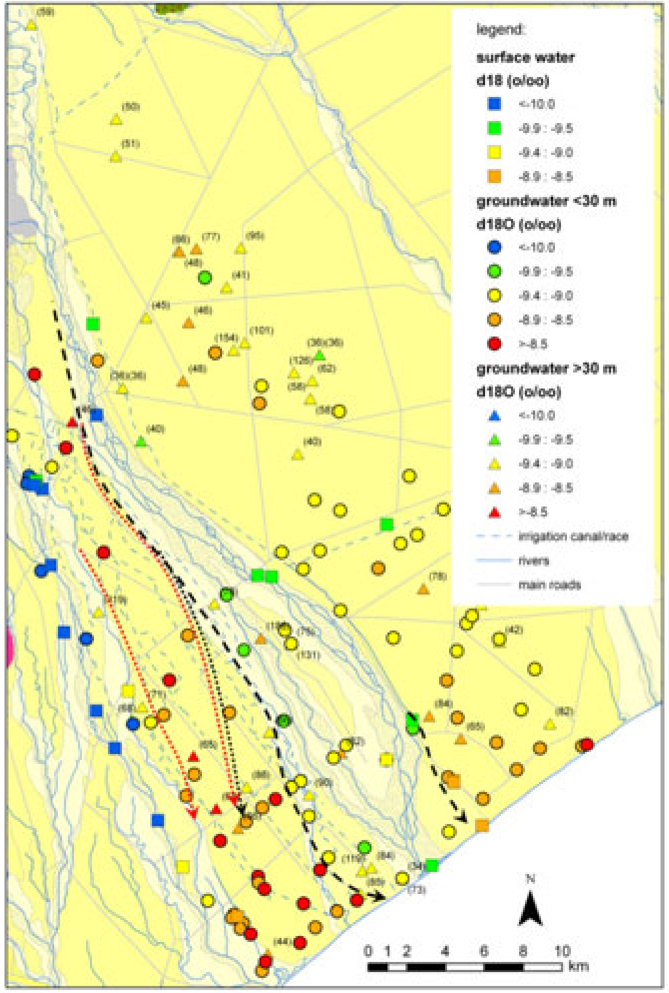


Figure 5-6: **δ^{18}O values**

Labels mark depth (in metres) of sampled wells over 30 m.

Long, black hatched arrows delineates zone over which Rangitata River water, distributed by natural processes can be traced. Smaller hatched black line traces similar zone, for deeper (>30 m) groundwater. Red hatched lines mark inferred diffuse hydraulic boundary of deep groundwater sourced from Rangitata River and Orari River, and influenced by LSR.

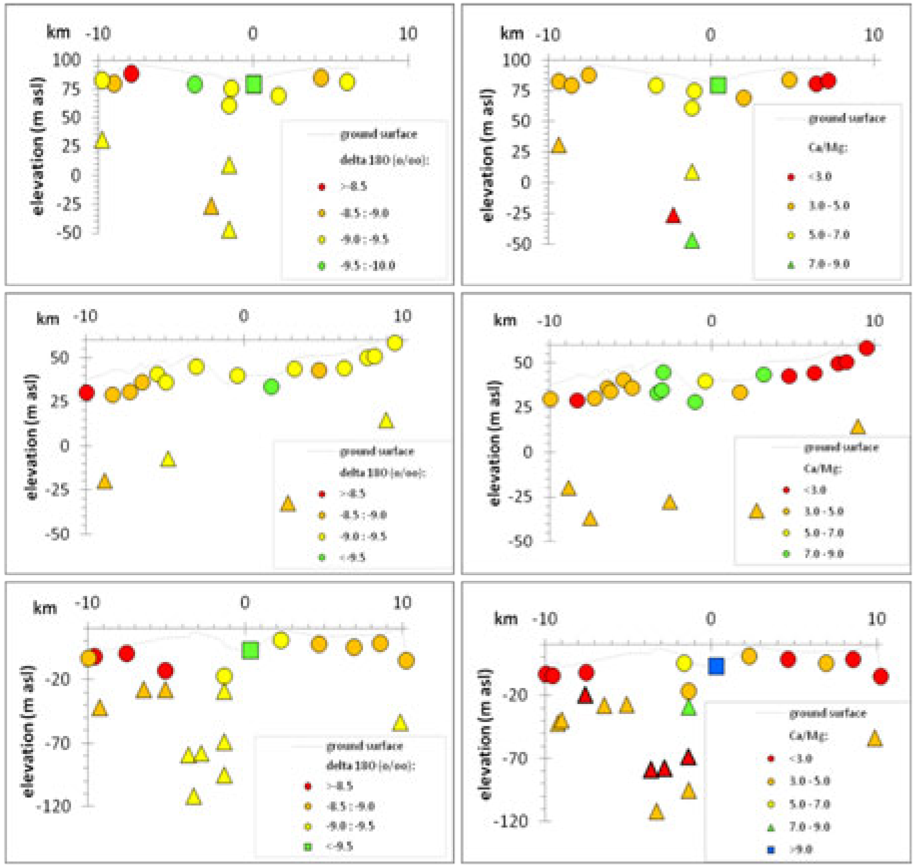


Figure 5-7: **Hydrochemical transects, central to the Rangitata River**

Top: SH1 transect; Middle: Rangitata Island transect; Bottom: coastal transect. See Appendix I for map of transect locations.

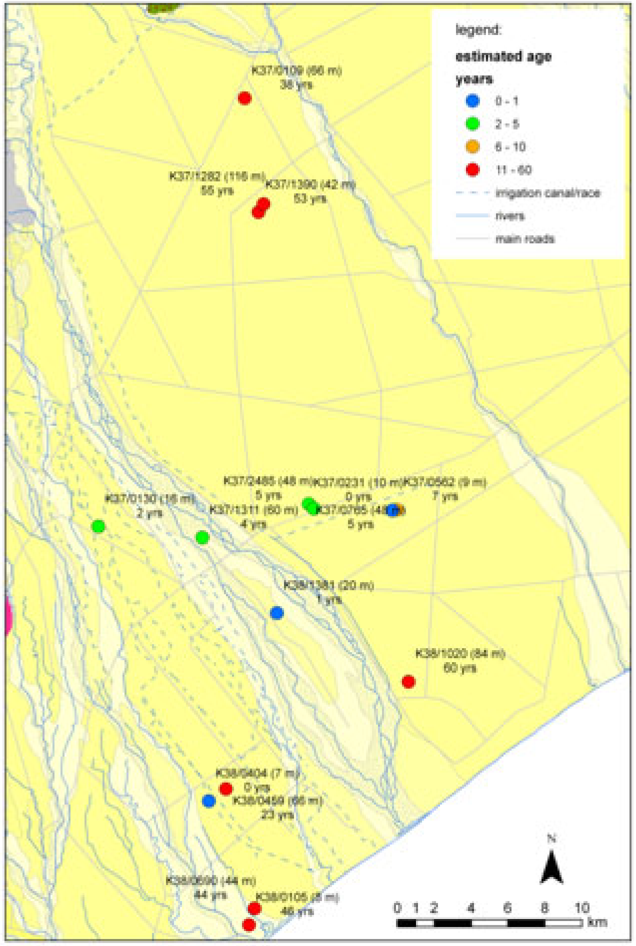


Figure 5-8: **Plot of groundwater age data**

Compiled from information contained in Stewart et al. (2006) and Aitchison-Earl (2004). Bracketed value denotes well depth.

5.2 Findings of hydrochemical assessment

The composition of fresh Rangitata River water draining from the upper catchment is typical of Canterbury alpine river waters. It is calcium bicarbonate ($Ca\text{-}HCO_3$) type water, contains few dissolved ions, has a relatively high Ca/Mg ratio (11.4 - 12.1), low silica (5.2 - 5.6 mg/L) and is free of nitrate. It is defined by blue, skinny Stiff plots in Figure 5-1. $\delta^{18}O$ values for the alpine river water are seasonally dependent, but in the general range of -9.7 to $-10.6^{o}/_{oo}$ (average $-10.2^{o}/_{oo}$; n = 6). By comparison, water originating from rainfall on the coastal plain in the Rangitata region typically has a $\delta^{18}O$ signature of greater than $-9^{o}/_{oo}$.

5.2.1 Mayfield-Hinds (true left)

As Dommisse (2006) showed, groundwater throughout the Mayfield-Hinds plain exhibits a complicated chemistry due to operation of the surface water irrigation scheme. From the oxygen isotope evidence, most of the groundwater (at all depths) is a composite of Rangitata River and rain water. All signs are that where groundwater may have originated from the river, it has been distributed via the irrigation scheme. The exception to this case however is shallow groundwater close to the river mouth, down-gradient of Rangitata Island where Barrell *et al.* (2006) mapped RG2 fan deposits, which has chemical characteristics similar to the Rangitata River's. The lack of nitrate impacts and low silica content (suggestive of relatively young water) (Figure 5-4) distinguish groundwater in this region from that elsewhere along the coastal margin, north-east from Coldstream. The water chemistry evidence therefore supports the hydrological evidence that the shallow aquifer between Coldstream and the Rangitata channel is closely hydraulically connected with the river. The same inferences were made by Vincent (2007). Furthermore, the failure to detect any signs of land-use impacts to the shallow groundwater resource could be an indication that significant subterranean through flow of river water occurs in this region.

The water chemistry data are consistent with the piezometric evidence and show that water emanating from the springs at Ealing has clearly drained from the Mayfield-Hinds plain, from which it leaches nitrate. There is the possibility that on occasions, groundwater contributions from the Mayfield-Hinds plain to the Rangitata River above SH1 (which includes Ealing Springs) makes up a significant proportion of the total river flow, since dilution effects are noticeable in the nitrate, Ca/Mg and oxygen-18 chemistry of river water sampled from the main channel at SH1 (e.g. Figure 5-2, Figure 5-6).

5.2.2 Orton plain (true right) including South Branch and Rangitata Island

Chemistry data are relatively sparse for groundwater on the true right of the river between Arundel and SH1, yet the general picture portrayed by the data (Figure 5-1 to Figure 5-7) tends to be that all groundwater on the true right of the Rangitata River, from the gorge down to where the river splits into the North and South branches is dominated by LSR. Rainfall at the foothills is typically 1100 mm/year (versus 600 mm at the coast) and Burbery and Ritson (2010) estimated LSR in the upper Orari plain to be approximately 427 mm/year. Thus, it is postulated LSR provides significant recharge to the groundwater system beneath the Orton plain, which probably suppresses the influence of the Rangitata River.

All the hydrochemical evidence reviewed shows that shallow groundwater within the young alluvial sediments that form the Rangitata South Branch channel originates from the Rangitata River. Collectively, the ion chemistry and oxygen-18 isotope chemistry (which shows minor rainfall recharge contributions) indicate groundwater in the older RG2 fan material (that forms Rangitata Island and the divide between the south and middle channels) has a longer hydraulic residence time than water within the younger RG0 and RG1 geomorphic units. This backs up Barrell *et al.*'s (1996) conceptual model of the older, more weathered fan units having a lower effective permeability due to higher fines. Nonetheless, shallow groundwater beneath the island maintains the same $Ca\text{-}HCO_3$ water-type characteristic associated with the river water, thus it can be presumed that the bulk of water is river-related. This seems contradictory to the inferences made about groundwater dynamics under the Rangitata Island that were that the shallow aquifer is most sensitive to LSR. What it suggests is that the river water probably makes up a basal component to the groundwater system, as was alluded to in Appendix F.

Nitrate concentrations in groundwater beneath Rangitata Island typically register within the range 3 – 6 mg $N\text{-}NO_3/L$ suggesting impacts from land-use. A large proportion of the island is utilised for dairy farming and there are numerous on-site sewage systems and dairy effluent discharge consents across the Island, which are probable sources (e.g. Scott *et al.,* 2011).

The observation that water analysed from McKinnons Creek is not characteristic of fresh alpine river water, yet exhibits similar chemical characteristics to shallow groundwater beneath Rangitata Island tends to suggest that flows in McKinnons Creek are related to groundwater discharging from the Island, i.e. water at the spring-heads is not necessarily sourced directly from the Rangitata River. The piezometric data clearly show a positive head differential between the water table beneath the Island and the level of the river, which could drive this (e.g. Appendix I).

Effluent disposal across the lower Orton plain impacts shallow groundwater chemistry about Kapunatiki Creek (e.g. Scott *et al.,* 2011) hence reduces the usefulness of hydrochemical data for inferring information about the Rangitata River. Similarly, the Kapunatiki Creek area is a discharge point for Timaru District Council's stockwater race that distributes Orari River water across the Orton-Orari plain. The Stiff plots (Figure 5-1), electrical conductivity (Figure 5-3) and oxgen-18 data (Figure 5-6) however appear to show chemical traces of Rangitata River (albeit diluted by LSR water) in some shallow sample locations between Kapunatiki Creek and the river. For example, the shallow piezometer K38/1821 near Rangitata Huts is consistent with the inference made about shallow groundwater hydraulics at this locality, based on analysis of the groundwater level monitoring record (in Section 4.3). The contribution groundwater up-welling from depth contributes to the shallow groundwater chemical signal close to the coast is not known.

Other than from the multi-level well cluster (K38/1379-1381), Environment Canterbury hold no records of deep groundwater directly beneath Rangitata Island having been sampled for chemical analysis. Due to the poor construction of the multi-level wells, deep groundwater sampled from them is not representative of the natural aquifer system, thus these data were omitted from this review. The age of groundwater in these wells has been estimated to be anywhere between 1 and 5 years old. It is believed this likely reflects groundwater age in the shallow aquifer.

Substantially more deep wells whose water chemistry has been analysed are located west of Rangitata Island - in the Rangitata South and Middle branches, Kapunitiki Creek and land in between, as well as across the Orton plain. It is inferred from δ^{18}O data that the Rangitata River most probably contributes recharge to much of the deep (below 30 m at least) groundwater system across the Rangitata-Orton plain, consistent with the distribution of Rangitata fan material. A plume of Rangitata River water spreading laterally at depth can be seen in the hydrochemical transects in Figure 5-7. The extensive area across which deep groundwater related to the Rangitata River has been traced is sketched on Figure 5-6 – it is more extensive than the zone of influence in the shallow (<30 m) groundwater system that extends no further than Kapunatiki Creek. Although Orari River water is also strongly depleted in oxygen-18, the diffuse hydrological boundary between the Rangitata and Orari rivers can be identified in the δ^{18}O data, separable by LSR inputs derived from rainfall on the Orton plain. The distribution of δ^{18}O values supports the model of the Rangitata River being effectively the, steady-state base recharge component of groundwater within the Rangitata fan sediments, on top of which is superposed LSR water. Silica concentrations and Ca/Mg ratios in groundwater sampled from depths greater than 30 m tend to suggest the deep water is aged. Although the age of deep groundwater along the general flow path sketched in Figure 5-6 has never been quantified, Stewart *et al.* (2006) have found that deep groundwater in the Rangitata fan is typically <60 years old, even at 85 m depth (Figure 5-8). At the head of Rangitata Island, groundwater sampled from 57-60 m depth and related to river water has been dated at less than 4 years old, indicating significant vertical leakage.

6 Delineation of the riparian zone

In this section the results of the review and data analyses are processed into a mapped Rangitata riparian zone, marked in Figure 6-1. The findings of the technical evidence presented in the preceding three chapters and from which the riparian zone has been delineated are summarised as follows. The delineation draws heavily on geological and hydrochemical evidence:

a) The modern day Rangitata River is entrenched through Rangitata fan deposits of varying ages, and which cover an extensive area, stretching between the Hinds and Orari rivers. There is no geological evidence to suggest significant stratification within the fan material that might form extensive aquifer confinement or justify unique hydro-stratigraphic units of major-scale. However, Davey (2006) has previously defined at least three aquifer units at varying depths within the Rangitata fan. The uppermost aquifer 1 is generally contained within the top 20 m, below which silty, sandy gravels of lower permeability are more prolific and form an aquitard, separating the shallow unconfined aquifer system from an apparent second aquifer system in the depth range of 40 - 90 m. Groundwater has also been yielded in usable quantities from gravel strata within the depth range 90 - 150 m, which Davey (2006) defined as aquifer 3.

b) The vertical head differential in the groundwater system across most of the coastal plain is one of a positive downward gradient, hence there is potential for groundwater to seep vertically downwards, i.e. be lost from the surficial hydrological systems (that include the Rangitata River). The vertical piezometric gradient is reversed close to (within approximately 4 km of) the coast where deep groundwater up-wells, due to the coastal boundary, although not under free-flowing artesian conditions. All the hydrogeological evidence indicates the deep aquifers function as leaky systems and are hydraulically-connected with each other and the overlying, shallow unconfined aquifer. There is no reason to suspect that the groundwater systems in the Rangitata are hydraulically-disconnected from either the river or the sea.

c) It is conceived that deep groundwater on the true-left of the river (under the Mayfield-Hinds plain) shares some hydraulic connection with the Rangitata River. However the hydrogeology has been highly affected by irrigation schemes affiliated with the Rangitata Diversion Race and that have been operational since 1945. In effect, the Rangitata fan on the true-left of the river is artificially recharged at the surface, which limits the potential for the Rangitata River to lose water northwards (the best evidence for this can be seen in the piezometric transects contained in Appendix I. The evidence is that there is actually a net discharge of groundwater to the river along the terrace that forms the northern river bank. The most prominent discharge is Ealing Springs, which is explicitly mentioned as a protected water feature in the Rangitata River Conservation Order (2006). No reliable measurement has been made of the rate at which the numerous groundwater springs collectively feed the river system. Dommisse (2006) has previously assumed it to be $8x10^6$ m^3/year (equivalent to 0.25 m^3/s, although rates vary seasonally). It is fair to state this rate is no more than a 'best-guess' and from the hydrochemical evidence the groundwater inputs to the river system constitute a reasonable proportion of river flows since they are sufficient enough to alter the composition of the river water chemistry. It is assumed that the riparian margin on the true-left of the river follows the line of the distinct Q2a (RG4) terrace from the gorge to within 7 km of the coast.

d) Close to the coast, immediately south of Coldstream, there is a sector of sediments that were deposited by the river late in the last glacial melt-period that GNS classify as Q2-1a. Piezometric contours indicate the Rangitata River loses water to these sediments and hydrochemical data which indicates that groundwater in this area originates from the Rangitata River and being relatively 'fresh', suggests reasonable through-flow of river water. Vincent (2007) incorporated this area in his tentative riparian zone and it is similarly included in the delineations made here.

e) The Rangitata South and Middle branches are paleo-flood channels of the Rangitata River that now rarely receive any surface water inputs as a consequence of flood control engineering works. Conceptually, these are prime areas for classification as a riparian zone. Both piezometric evidence and hydrochemical evidence support the notion that river water is lost to groundwater at the bifurcation of the (main) North Channel and South Branch, strengthening the case for riparian classification. In analysing the available groundwater level data, no apparent dynamic river recharge or bank storage effects have been detected, although admittedly, none of the groundwater level monitoring sites are located directly in the modern flood plain channels (Q1a_f geological; RG0 geomorphic units). Equally, owing to the braided characteristic of the Rangitata River, it can be expected that the river stage is not directly proportional to river flow, which reduces the potential for variable river recharge effects.

f) The permeability of the remnant fan material that constitutes Rangitata Island, sandwiched between the South Branch and Rangitata (main) North Channel seems to be less than that of the younger gravels in the paleo-flood channels. Evidence for this is derived from well-specific capacity data, piezometric contours and ion chemistry. This concurs with the interpretations made by Barrell *et al.* (1996) based on geomorphic evidence and related to considerations about particle size distributions. Hydrochemical evidence, both in the form of ionic composition and oxygen-18 isotope chemistry demonstrate that shallow groundwater within Rangitata Island bears many similarities with that sampled from within Kapunatiki Creek channel. Kapunatiki Creek is in fact a paleo-flood channel of the Rangitata River, albeit of apparently older age than either the South or Middle channels. The general chemical characteristic of shallow groundwater beneath Rangitata Island and along the trace of Kapunatiki Creek is of water sourced from the Rangitata River, yet subject to some dilution by LSR. The exact degree of dilution has not been determined since the δ^{18}O values of the river and rainfall end-members are not reliably constrained. The over-riding impression is that the Rangitata River supports the steady-state base component of shallow groundwater across the region between Kapunatiki Creek and the main river channel. The water is relatively young in age and chemically un-evolved, which suggests there could be reasonably high flux of river water transmitted through this region – more transmitted through the youngest alluvial channels than the older geomorphic units under Kapunatiki Creek and Rangitata Island. All the same, the riparian margin has been extended to incorporate all these paleo-features. The riparian margin does not follow Kapunatiki Creek all the way to the coast, but in light of the δ^{18}O evidence collated from shallow groundwater chemistry and extrapolated along what on topographic maps, it appears to be a less obvious paleo-channel that returns back towards the Rangitata River. The riparian zone mapped in Figure 6-1 incorporates slightly more of Kapunatiki Creek than was in the tentative zone mapped in 2007 (Appendix B), aside from this the two zones are near identical.

g) In terms of the depth of the riparian zone, evidence of deep groundwater is sparse and hence conclusions are uncertain. However, it is conceived at this stage that Rangitata River water most likely supplies a constant, near steady-state basal component to the deeper groundwater system, given the regional aquifer is historically related to the river and the modern day river is incised into strata of varying depositional age. Owing to the noise associated with long-standing irrigation of the Mayfield-Hinds plain using Rangitata River water, it is not possible to infer any detail about the natural association of deep groundwater with the Rangitata River on the true-left of the river, although it is conceived that there is some that is probably comparable with that on the true-right (i.e. with the Orton plain). The piezometric contour data published by Dommisse (2006) are not suggestive of significant hydraulic connection between the Rangitata River and the deeper aquifers under Mayfield-Hinds. On the southern-side of the river, however it has been possible from δ^{18}O and electrical conductivity data to trace the flow path of what is believed to be water sourced from the Rangitata River across much of the Rangitata-Orton plain at depth (> 30 m bgl). The influent Rangitata River water appears to mix with LSR-derived water, forming a diffuse hydraulic boundary between the Rangitata River and Orari River. Water sourced from LSR on the Orton plain flows across the top of the deep, underlying groundwater infiltrated from the Rangitata River. An estimate of the extended riparian zone for deeper groundwater under the Orton plain is marked in Figure 6-1 by a red hatched line. Knowledge of the piezometric surface of deep groundwater, characterisation of recharge potentially derived from run-off from the foothills into the Orton plains aquifer and more hydrochemical evidence are required to improve the reliability of these assumptions.

h) The lowest leakage factor from the available aquifer test data is calculated as L = 370 m (e.g. Lough and Williams, 2009), which suggests that deep groundwater is most likely recharged by the mechanism of pervasive and extensive vertical leakage. Nonetheless, Rangitata River water younger than approximately 4 years has been sampled from 60 m depth at the bifurcation of the (main) North Channel and South Branch (well K37/1311, Figure 5-8). Based on ion chemistry, it is inferred that elsewhere deep groundwater is likely to have a longer hydraulic residence time. Williams (2009) proposed treating deep wells the same as shallow wells in his assessment of the Rakaia riparian zone. It might be technically correct to term the deep groundwater system beneath the Orton plain as riparian, given its association with the river, but whether it should be managed as a 'special' riparian zone is debatable. The passive stream depletory effect of abstracting deep groundwater (related to the Rangitata River) beneath the Orton plain is unlikely to be any more severe than abstracting shallow groundwater from regions believed to potentially drain to the river, e.g. Mayfield-Hinds plain in the vicinity of Ealing or Ruapuna springs, or the high terrace at Arundel (that is sourced by LSR). Thus from the context of managing the integrated surface water – groundwater system, for now deep groundwater is included, but only within the coverage of the shallow riparian zone (black hatched line in Figure 6-1).

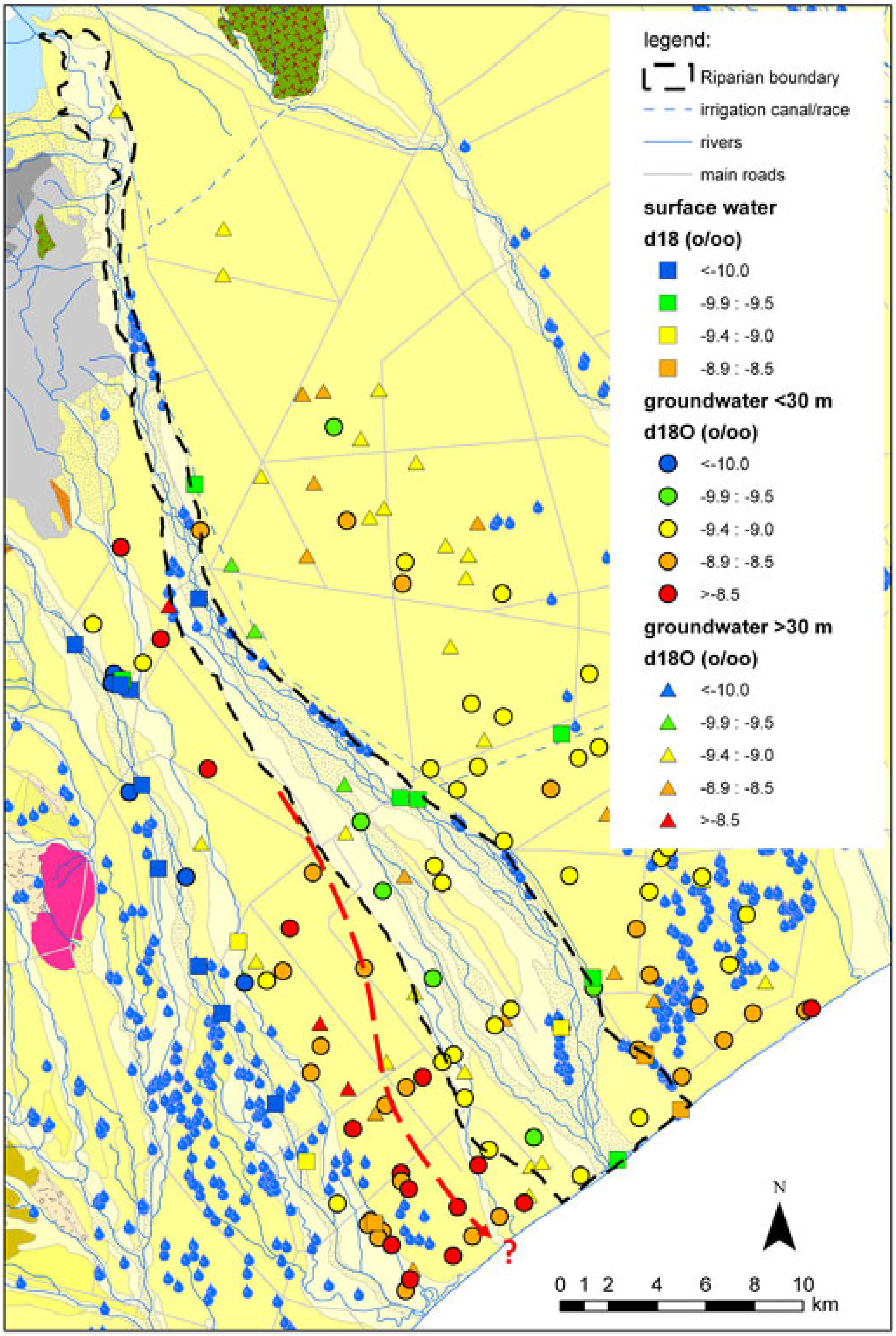


Figure 6-1: Delineated riparian zone boundaries

(— —) primary riparian zone for surficial hydrological system;
(— —) likely riparian margin for deep (>30 m) groundwater system.

7 Water budget and stream depletion

An annual water budget has been calculated for the riparian zone, for the purpose of obtaining a general perspective of the potential stresses consumptive water use for irrigation pose to the Rangitata River. Unlike the water budget Williams (2009) completed for the Rakaia riparian zone assessment, the external hydrological inputs and outputs on the Rangitata are limited, both in their natural character, and in terms of their data availability.

The piezometric and hydrochemical data suggest some river flow must be lost below SH1 and feed the riparian zones identified on both sides of the river. It is conceived from the geomorphology however that much of the river water that flows as groundwater in the phreatic aquifer under Rangitata Island and the South Branch would likely return to the river system under natural conditions. Certainly, no obvious consistent flow gains or losses have ever been detected through river gauging measurements from which it is presumed they are relatively small, although even small losses via mechanisms such as leakage can sum to large volumes of water over a substantial time period. It is assumed that under natural conditions the Rangitata River steadily leaks water to the deep groundwater system at some slow, as of yet undetermined, rate. From the apparent flowpath plot from δ^{18}O data (Figure 5-6), some of the losses to the deep groundwater system are suspected to flow southwards in the direction of Orari Lagoon, beyond the margins of the primary riparian zone. It is suspected this deep groundwater discharges to the sea, either directly or via the overlying shallow aquifer. As a consequence of the developments in pumped abstraction since the last time the river was gauged in 1999, it is anticipated that the effective river leakage rate may potentially have increased.

It is hypothesised that any river gains from the Mayfield-Hinds aquifer on the northern-side (which Dommisse (2006) has previously assumed are 8×10^6 m^3/yr) are offset by natural losses to groundwater on the southern-side, to the Rangitata-Orton aquifer. Being relatively small in comparison to actual river flows, they are implicit to river gauging errors. Thus in the absence of groundwater abstraction for irrigation, although there is an exchange of water between the systems, overall the Rangitata River and connected groundwater system, probably maintain a general pseudo-steady-state hydrological condition.

Although conceived to be secondary to river recharge effects in a riparian zone, rainfall still contributes an input to the system. Average annual dry-LSR estimates have therefore been calculated as part of the water budget based on analysis of NIWA's virtual climate data. The second component of the water budget that has been analysed is the annual consented volume of water for irrigation. It is presumed any difference between LSR and pumped abstraction must be made up by recharge from the Rangitata River, since the groundwater storage capacity of the riparian zone is conceived to be limited, particularly for the shallow aquifer that has a high hydraulic connection with the river. No attempt has been made to account for potential return irrigation water, i.e. irrigated-LSR, errors in which area assumed implicit to errors in the assumptions regarding water usage.

To factor in the temporal dynamics of the hydraulic stresses imposed on the river system from irrigation water demand, beyond an annual water budget, a stream depletion assessment has also been completed, using similar methods to those employed by Aitchison-Earl (2001).

7.1 Land surface recharge calculations

The total area of the riparian zone delineated in Figure 6-1 is 17,388 ha. Of this, 5,495 ha is mapped as active river bed associated with the Rangitata main-stem and North Branch, equivalent to the RG0 geomorphic unit defined by Barrell *et al.* (1996). The active river bed is very permeable, comprises no soil cover and according to Landcare Research's SMap has no available water holding capacity. It has been assumed here that the active river channel has no role to play in water storage or aquifer recharge and any rainfall falling within the river channel immediately drains away as river flow.

Although the flood plain that forms the Rangitata South Branch is mapped as a similar geology and soil profile as that of the main river channel, much of the flood plain is farmed and covered in pasture. This has been incorporated in the LSR calculations for the 11,893 ha portion of the total 17,388 ha riparian zone. The calculation of long-term average annual LSR was made using the simple LSR-model implicit to the Groundwater Data Analysis tool (Bidwell and Burbery, 2011). This was applied in the mathematical analyses of hydrograph data (see Appendix F). The model is identical to that employed by Scott (2004) to estimate LSR for the Canterbury region.

The optimised LSR-model parameter values listed in Table F1 were assumed in the calculations. At 20 mm, the available water holding capacity (AWHC) estimated in the coupled LSR-model-eigen-model inversion problem of water level data from K38/1821 is at the lower end of the range of profile readily available water (PRAW) values mapped by Landcare Research (Figure 2-2). In assuming a lower value, marginally more LSR will be predicted.

Inputs of daily rainfall and potential evapotranspiration were obtained from NIWA's virtual climate database (http://cliflo.niwa.co.nz/). Records of virtual climate stations that cover the riparian zone in Figure 6-1 were spatially averaged. The average annual recharge statistic was calculated from processing 32-years of daily data (September 1979 – September 2011).

The LSR results are summarised in Table 7-1. From the average annual rainfall of 692 mm/yr, it is estimated 469 mm falls during the 8-month irrigation season (September to April, inclusive) with the remaining 223 mm falling outside this period. However, because of higher evapo-transpiration rates during the growing season, it is estimated that as little as 10% of the rain falling during the irrigation season (49 mm) is active in groundwater recharge, compared to 36% (80 mm) between May and August (inclusive). The characteristic winter recharge pattern is evident in the groundwater level monitoring data (e.g. Figure 4-4 and Figure 4-5).

Table 7-1: Summary of annual volumetric LSR and consented groundwater takes within primary riparian zone

	Area [ha]	Rain [mm/yr]	AET [mm/yr]	LSR [mm/yr]	Recharge volume [10^6 m^3/yr]	Consented groundwater takes [10^6 m^3/yr]
Active river channel	**5495**	**692**	**n/a**	**n/a**	**38.0**	**n/a**
Primary riparian zone (excl river bed)	**11893**	**692**	**-365**	**129**	**15.3**	**-61**
Total riparian zone	**17388**	**692**	**-365**	**129**	**53.3**	**-61**

Negative values indicate an output from the hydrological system.

7.2 Consented water use

Information on consented water takes was obtained from Environment Canterbury's Resource Management Act Database. Only currently active consents have been analysed. Although the riparian aquifer study is directed to groundwater resource management, surface water consents have been analysed for completeness.

7.2.1 Surface water

Fourteen individual consents to take surface water from the lower sector of the Rangitata River and its tributaries within the riparian zone have been identified. These are listed in Table 7-2 and marked on Figure 7-1.

Table 7-2: Details of current consents to take surface water in the riparian zone

Note: by comparison, there are only two current surface water take consents (CRC092108 and CRC981744.2) in the upper Rangitata catchment, i.e. upstream of the gorge. The maximum rate of those two consents is 1610 L/s and both are subject to low flow restrictions.

Consent #	Surface water	Maximum rate of take [L/s]	Subject to low flow restriction?	Low flow reference site	Comment
CRC011237	Rangitata main-stem	30,700	Yes	Klondyke recorder	Main RDR scheme
CRC110225	Rangitata main-stem	3,000	Yes	Klondyke recorder	Supplemental to main RDR scheme
CRC961755	Rangitata main-stem	200	No	n/a	Consent held by RDR Management Ltd.
CRC082520	Rangitata tributary	26	Yes	can only operate concurrent with Mayfield-Hinds irrigation scheme	Dams seepage water from Mayfield-Hinds irrigation scheme
CRC970991	Rangitata tributary	38	Yes	Klondyke recorder	3 spring-fed tributaries
CRC962182.1	Rangitata main-stem	37.5	Yes	Klondyke recorder	Rangitata Island
CRC093723	Kapunatiki Creek	250	No	n/a	Water actually pumped from bore K38/2348
CRC961093	McKinnons Creek	110	Yes	Wallace Bridge, McKinnons Creek	Priority given to salmon hatchery consent, downstream
CRC070765.1	McKinnons Creek	150	No	n/a	Water diverted to salmon hatchery and returned to creek
CRC020325.4	Oakdale Drain	29	Yes	Oakdale Drain	n/a
CRC110486	Oakdale Drain	29	Yes	Oakdale Drain	n/a
CRC001229.1; CRC070924.1; CRC042094.1	Rangitata main-stem	20,000	Yes	Klondyke recorder	RSIS; primarily aimed at harvesting storm flows

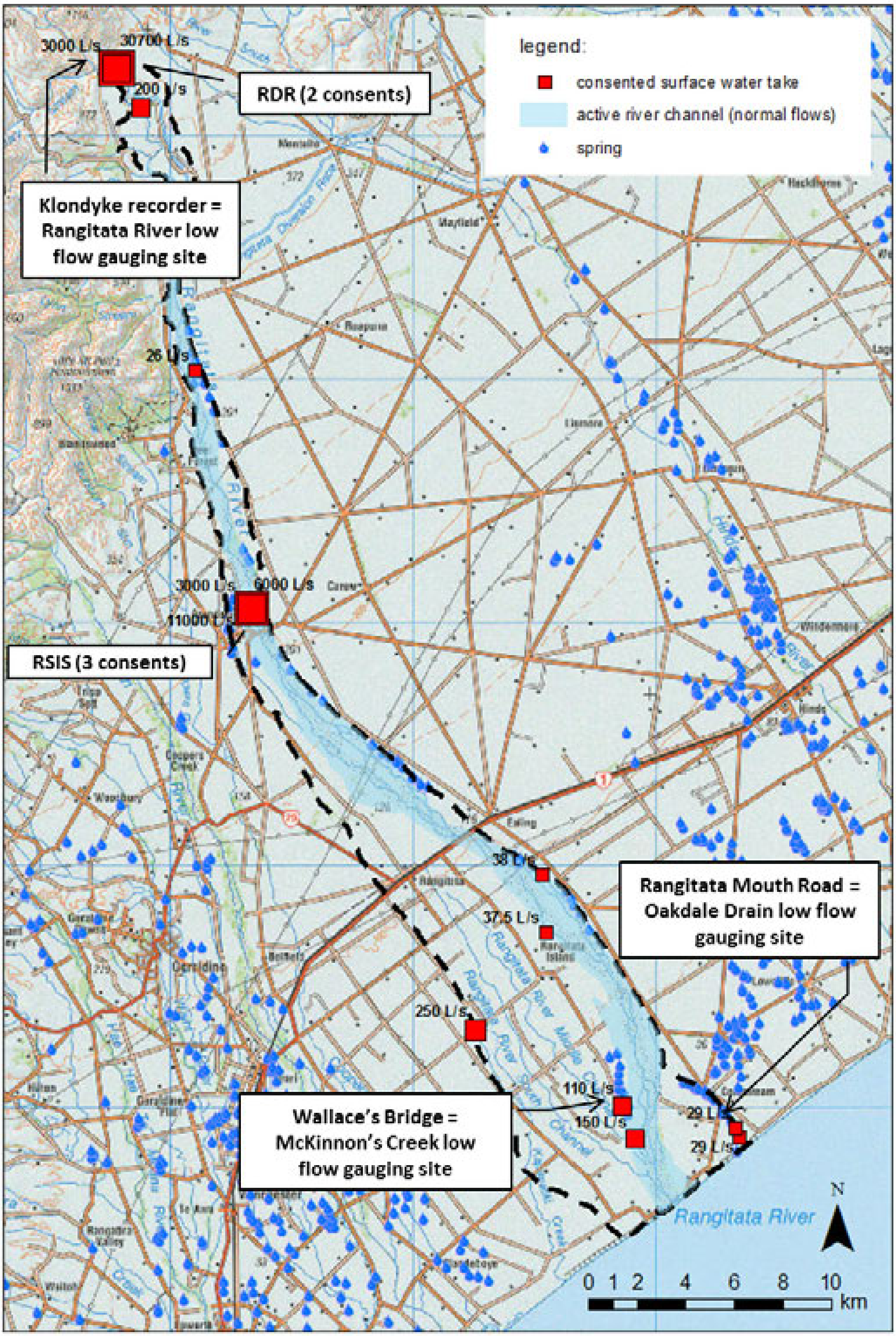


Figure 7-1: Active consents to take surface water within the riparian zone

Seven consents in the riparian zone are for takes directly from the Rangitata River, six of which relate to the two surface water irrigation schemes described in Section 3.2. There are two consents related to each of McKinnons Creek, Oakdale Drain and small tributaries along the base of the north river terrace that drain the Mayfield-Hinds plain. There is a current surface water take consent related to Kapunatiki Creek, although technically the abstraction is of shallow groundwater (riparian water).

It is difficult to evaluate annual volumes for surface water takes since their conditions generally refer to maximum rate of take from run-of-river, values of which are provided in Table 7-2 and Figure 7-1. To complicate matters further, eleven of the fourteen surface water takes have some form of low flow restriction written into their consent conditions, tied to one of the three separate flow gauging reference sites within the riparian zone (Figure 7-1).

The RSIS is exceptional since it is designed to harvest water at high flows, yet is permitted to take a maximum of 392 L/s when the Rangitata River flow is between 66 and 110.1 m^3/s, below which various restrictions apply. It was beyond the scope of this study to review low flow restrictions in detail, conditions of which vary between individual consents. However, in lieu of any annual quantum of abstracted surface water, low flow restrictions have been factored in to an assessment of Rangitata River flows at two reference states, these being the 7-day MALF and 110 m^3/s (which is a low flow threshold applied in the Rangitata River Conservation Order). It has been determined that:

- when the Rangitata River is at its 7-day MALF of 41.6 m^3/s, current surface water take consents in the lower Rangitata permit water abstraction direct from the Rangitata River at a rate of 19.10 m^3/s. 18.90 m^3/s (i.e. 99%) is attributed to the main RDR take. If consents in the upper Rangitata catchment are added in, the total abstraction rate is 19.16 m^3/s.
- when the Rangitata River is at 110 m^3/s, current surface water take consents in the lower Rangitata permit water abstraction direct from the Rangitata River at a rate of 31.37 m^3/s. 30.7 m^3/s (i.e. 98%) is attributed to the main RDR take. If consents in the upper Rangitata catchment are added in, the total abstraction rate is 31.43 m^3/s.

7.2.2 Groundwater

There are 68 active groundwater take consents within the primary riparian zone delineated in Figure 6-1. Collectively they are consented to pump $61x10^6$ m^3 over the course of a year (Table 7-1). A further 10 consents and $6.7x10^6$ m^3/yr can be added to this if the more distant deep groundwater beneath the Orton plan believed to be related to the river is incorporated in the budget.

The 68 consents in the primary zone are operated from 137 wells. 68 (50%) of these are shallower than 30 m, 44 (32%) are installed to a depth between 30 and 90 m, and the remaining 24 (17%) terminate deeper than 90 m depth. It is not possible to infer the exact depth from which water is pumped where a water take is consented to be taken using a combination of wells of varying depths. Assuming the well located closest to the Rangitata River is representative of the depth from which a water take is exercised then it is estimated that volumetrically, 56% of the ($61x10^6$ m^3/yr) consented volume of water is from shallow wells (<30 m deep); 31% is abstracted from wells in the depth range 30 – 90 m, and; 13% of the consented groundwater is drawn from deep wells (>90 m).

It is evident that at $61x10^6$ m^3/yr, the volume of groundwater consented to be drawn from the primary riparian zone far exceeds the $15.3x10^6$ m^3 of rain considered to infiltrate to the water table outside of the bounds of the main active, braided river channel (Section 7.1). The annual volume of water drawn indirectly from the river is thus potentially significant - at least $45.7x10^6$ m^3/yr, which equates to 1.5 m^3/s; or $52.4x10^6$ m^3/yr; 1.7 m^3/s if the deep groundwater abstractions across the Orton plain are counted.

7.3 Stream depletion assessment

Unlike the simple annual water budget computed above, a stream depletion assessment considers the temporal nature of abstraction effects. The potential stream depletion effect upon the Rangitata River, arising from groundwater abstraction within the primary riparian zone, was assessed for both a 7-day and 150-day period of continuous pumping at the full consented rate (Q7 and Q150). A simplifying assumption was that for any individual consent, all water is taken from the well listed on the consent conditions that is positioned closest to the river. Figure 7-2 shows the distribution of sites with resource consents to take water from within the riparian zone and from which wells that were considered in the stream depletion assessment can be identified.

No compensation was made to try and split a consented take between shallow and deep wells, should there be a mix of wells on the consent. The active river bed of the main river, as determined from the shape of the Q1a_af surface defined by GNS was applied as the river target the distance to which was the assumed separation distance for any individual well. Although conservative, this assumption acknowledges that the Rangitata River is a dynamic braided fluvial system, the course of which varies. The assumed active river is shaded blue in Figure 7-2.

The analytical solution to a stream depletion problem considering a well abstracting from a leaky aquifer provided by Hunt (2012) was applied in the assessment. The transmissivity values of the overlying unconfined and underlying confined aquifers in the mathematical problem were assumed from the geometric mean transmissivity determined from the aquifer test data in Table 4-2, assuming 30 m depth defined the depth to the top of the dividing aquitard. A specific yield of 0.06 was assumed to characterise the unconfined aquifer and the arithmetic mean storativity from the deep aquifer tests was applied to the confined aquifer system. Instead of making any assumptions about low permeability aquitard strata with uniform properties, the aquitard conductance (*K'/B'*) was assumed to be variable and a function of the well screen height. For the case of all wells with screens set deeper than 30 m, the effective vertical hydraulic conductivity of the aquitard was assumed to be 0.001 m/day, which is obtained from the harmonic average of *K'/B'* determined from aquifer test data with B' assumed to be the top of well screen depth less 30 m. *K'/B'* was evaluated for every deep pumped well with similar assumptions regarding the effective aquitard thickness *B*' related to individual well designs. In the stream depletion assessment of wells shallower than 30 m, a constant *K'/B'* value of $2\text{x}10^{-5}$ /day was assumed, which is the harmonic mean of *K'/B*' determined from leaky aquifer pump test interpretations in Table 4-2. No assumptions were made regarding possible streambed conductance effects, and λ was set to 109 m/day. The aquifer parameters in the stream depletion problem are summarised in Table 7-3.

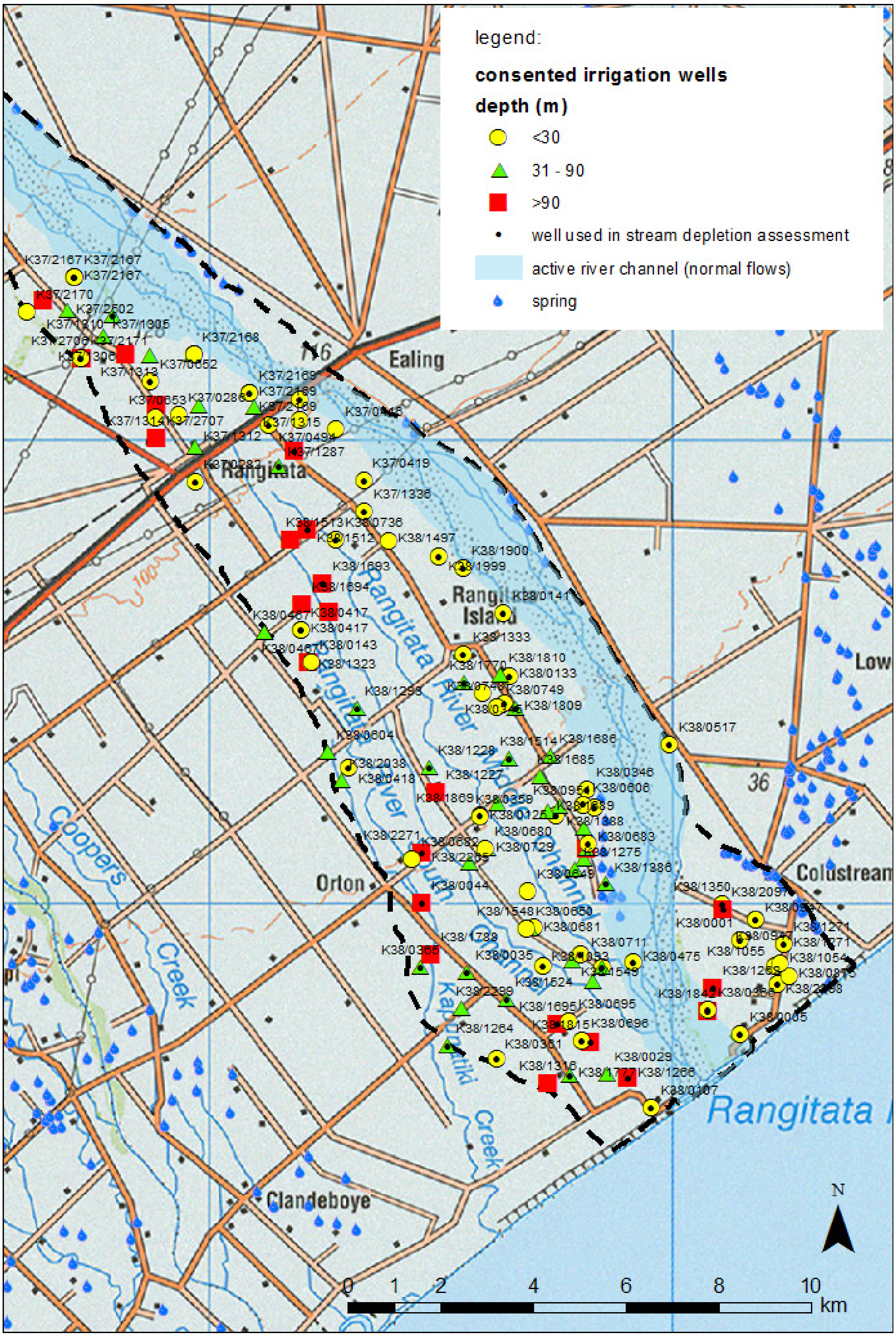


Figure 7-2: Active consents to take groundwater in the (primary) riparian zone

Wells used in stream depletion assessment are highlighted. One consent to take groundwater from 58.5 m depth, upstream of SH1 is outside the frame

Table 7-3: General aquifer properties assumed in stream depletion assessment
(evaluated using the functions W_15 and W_16 in Hunt (2012))

Parameter	Transmissivity of unconfined aquifer, $T1$ [m^2/d]	Transmissivity of semi-confined aquifer, $T2$ [m^2/d]	Specific yield unconfined aquifer, $S1$ [-]	Storativity semi-confined aquifer, $S2$ [-]	Aquitard conductance K'/B' (assessment of wells <30 m) [1/day]	Aquitard conductance K'/B' (assessment of wells >30 m) [1/day]
Assumed value	2253	493	0.06	0.0012	2.7×10^{-5}	0.001 / (screen height - 30 m)
Comment	Geometric mean from shallow aquifer tests	Geometric mean from deep aquifer tests where leakage assumed	Optimised from Eigen-model analysis of piezometric data for well K38/1821 (Appendix F)	Arithmetic mean from deep aquifer tests where leakage assumed	Harmonic mean from deep aquifer tests where leakage assumed	K'= 0.001 is harmonic mean from deep aquifer tests where leakage assumed, with B'= screen height – 30 m

Table 7-4 contains the results from the stream depletion assessment, from which it is apparent that shallow irrigation wells present the greatest potential impact to the river flows. The results highlight that as much as 53% of the total consented groundwater takes (from all depths) within the riparian zone could reasonably manifest themselves as stream depletion impact over the course of an irrigation season. In the mathematical modelling, the remaining 47% of the pumped groundwater is assumed to be sourced from aquifer storage, although in reality due to mass balance considerations it will more likely manifest itself as an indirect, cumulative stream depletion impact distributed over a long time period.

Table 7-4: Results from the stream depletion assessment considering wells only within the primary riparian zone

	Q7 **7-days pumping**	**Q150** **150-days pumping**
Effective abstraction rate from wells <30 m deep [m^3/s]	3.02	2.28
Effective abstraction rate from wells 30 - 90 m deep [m^3/s]	1.24	1.05
Effective abstraction rate from wells >90 m deep [m^3/s]	0.48	0.40
Total effective abstraction rate from all wells [m^3/s]	**4.73**	**3.73**
Stream depletion rate: wells <30 m deep [m^3/s]	1.33	1.68
Stream depletion rate: wells 30 - 90 m deep [m^3/s]	0.06	0.25
Stream depletion rate: wells >90 m deep [m^3/s]	0.01	0.05
Total stream depletion rate: all wells [m^3/s]	**1.41**	**1.98**
Stream depletion rate: wells <30 m deep [% of pumped rate]	44	73
Stream depletion rate: wells 30 - 90 m deep [% of pumped rate]	5	24
Stream depletion rate: wells >90 m deep [% of pumped rate]	3	13
Total stream depletion rate: all wells [% of pumped rate]	**30**	**53**

Although not shown, when the stream depletion assessment was repeated for 10 current consents to take deep groundwater believed to be sourced from the Rangitata River, from beneath the Orton plain and beyond the perimeter of the primary riparian zone, the resulting 150-day stream depletion effect was zero. At least 2.8 km (and more often more than 4 km) separated these wells from the Rangitata River and the result supports the exclusion of the wells from the riparian aquifer zone.

At potentially 1.98 m^3/s, the resulting 150-day stream depletion assessment evaluated here is considerably more than the 0.94 m^3/s determined previously by Aitchison-Earl (2001). In 2001 only 23 resource consents to take shallow groundwater (from <15 m deep) were assessed and for a 30-day pumping period, assuming a combined effective rate of take equal to 1.45 m^3/s. In this latest 2012 assessment there are currently 68 consents (shallow and deep) and the effective rate of take is almost double (3.73 – 4.73 m^3/s), depending upon whether 7-day or 150-day effective abstraction rates are considered. Unlike Aitchison-Earl (2001), no effort has been made in this assessment to examine discrete potential effects on any of the tributaries, for example McKinnons Creek.

If, from the conditions written into RDR's resource consent to divert surface water, 20.1 m^3/s is assumed to be a low residual river flow in the irrigation season, then the direct 150-day stream depletory effect assessed here of 1.98 m^3/s is close to 10% of the residual river flow, hence could be considered significant. Ten percent is also the generally accepted margin of error applied to river flow gauging data, which has practical implications should there ever be a proposition to attempt to measure stream depletion rates in the future.

Furthermore, when the potential (1.98 m^3/s) stream depletion effect of groundwater takes in the riparian zone is compounded with the (31.43 m^3/s) maximum consented rate of surface water takes direct from the Rangitata River the resulting 33.41 m^3/s exceeds the 33.0 m^3/s cap prescribed in the Rangitata River Conservation Order (2006).

8 Conclusion and recommendations

8.1 Conclusions

Available geological, hydrological and hydrochemical data for the lower section of the Rangitata River have been reviewed. From this a Rangitata riparian aquifer zone has been delineated and the following conclusions made:

1) The Rangitata riparian aquifer zone mapped here is near identical to the shape of the tentative riparian zone previously mapped by Vincent (2007). In total, it has an area of 17,388 ha, of which 5,495 ha constitutes the active Rangitata River channel.

2) The riparian zone includes all groundwater located under and between the paleo river channels on the true-right of the Rangitata. That is the margin of land between the main river channel and Kapunatiki Creek, which encompasses the Rangitata South Branch and Rangitata Island.

3) On the true-left of the river, the riparian boundary follows the main Rangitata River terrace to within 7 km of the river mouth where it extends northwards to Coldstream, to include a relatively small 102 hectare area comprising river alluvium deposited late in the last glacial period. Although numerous terrace-riser springs are incorporated in the riparian zone on the north side of the river, no consideration has been given to explicitly addressing them as a riparian feature, for the reason that they are not directly driven by river processes (but they do contribute to the river system).

4) Hydrological records proved ineffective for the determination of a riparian zone. No significant or consistent flow losses have been recorded on the Rangitata River. Similarly, no river recharge effects are evident in any of Environment Canterbury's groundwater level monitoring wells – in all cases any potential river recharge signal is obscured by drawdown effects of uncharacterised pumped abstraction. However, based on other lines of evidence, it is believed that there must be pervasive leakage of water from the river, quite probably at a rate within the margin of river flow gauging error. It is conceived that Rangitata River water provides a steady basal component to the groundwater resource within the riparian zone.

5) Although Rangitata River water appears to be traceable beyond the riparian zone, e.g. under much of the Orton plain, groundwater there is not considered to be riparian. Large gaps remain in our technical understanding of aquifer recharge processes active on the Orton plain, which are currently conceived to comprise components of rainfall recharge,

river recharge and recharge associated with run-off from the foothills. The RSIS that is due to come on-line in 2014 is set to significantly alter the hydrological state of the groundwater system on the Orton plain.

6) Aquifers under the Mayfield-Hinds plain have a conceivable natural hydraulic connection with the Rangitata River, but indications are that they are dominated by LSR that is augmented by irrigation schemes, which operate using diverted river water. Drainage from the Mayfield-Hinds plain is the source of the terrace-riser springs that drain into the riparian aquifer zone, such as Ealing Springs (which are protected under the Rangitata River Conservation Order). Although uncertain, best-estimates are that the springs might collectively contribute $8x10^6$ m^3 recharge to the riparian zone, each year. A hypothesis is that effective gains to the Rangitata River from groundwater/springs draining from Mayfield-Hinds (i.e. from the north) may operate to counter-balance river flow losses to the groundwater system under the Orton plain (i.e. to the south), which could partly explain the apparent pseudo-steady state flow condition observed in historic river gauging data.

7) From the geological evidence under natural conditions, most of the subterranean river flow down the Rangitata South Branch is likely to be returned to the river system. I conclude that the significant increase in pumped groundwater abstraction on the south-side of the river over the past decade may have induced groundwater leakage, and as a consequence quite possibly promoted river losses from those last measured in 1999.

8) Elevated nitrate concentrations are consistently found in the spring-fed McKinnons Creek (maximum 13 mg $N\text{-}NO_3/L$; mean and median 4.4 mg $N\text{-}NO_3/L$), suggesting that the creek is sensitive to land-use practices on Rangitata Island. These nutrient levels are within the chronic toxicity to freshwater organisms bracket and indicative of a highly disturbed system (Hickey and Martin, 2009). They suggest that values for McKinnons Creek, recognised in the Rangitata River Conservation Order, are not being protected.

9) It is concluded from a relatively simple water balance that in the region of 75% (if not more) of the $61x10^6$ m^3/year of groundwater that is permitted to be pumped from the riparian zone annually might reasonably be expected to stem from the river. This effectively equates to a long-term average potential cumulative stream depletion effect of 1.5 – 1.7 m^3/s.

10) A more technical assessment of potential stream depletion effects made using the analytical stream depletion model of a layered, leaky aquifer system (Hunt, 2012) with various generalised assumptions, has determined that consented groundwater takes from within the riparian zone have potential to impact flows in the Rangitata River system within the region of 1.41 - 1.98 m^3/s, based on respective 7-day and 150-day irrigation scenarios. This is substantially more than the 0.93 m^3/s previously determined by Aitchison-Earl (2001) at the time the Rangitata River Conservation Order was being prepared.

11) Potential stream depletion effects attributed to consented groundwater abstractions within the riparian aquifer zone translate to a significant proportion of the Rangitata River's managed residual flow of 20.1 m^3/s (summer) or 15.1 m^3/s (winter). Furthermore, when they are compounded with the consented rate at which surface water might be taken from the Rangitata River (for a reference river flow state of 110 m^3/s) the potential stream depletion effect on the Rangitata River is 33.43 m^3/s, which exceeds the 33 m^3/s cap specified in the Rangitata River Conservation Order.

12) McKinnons Creek is considered to be particularly vulnerable to stream depletion effects from local groundwater abstraction, particularly those on Rangitata Island. This opinion is consistent with that of Aitchison-Earl (2001) who formerly assessed potential stream depletion effects on McKinnons Creek to be significant.

13) From an analytical perspective, once the Rangitata South Irrigation Scheme becomes operational and starts distributing Rangitata River water across the Rangitata-Orton plain, the same problems that impact on the Mayfield-Hinds plains aquifer will impact on the Rangitata-Orton hydrogeological system, i.e. it will become increasingly difficult to

characterise any natural hydrogeological processes, such as potential river recharge characteristics, owing to substantial noise from irrigation practices.

8.2 Recommendations

The following are recommendations for future work required to improve the technical understanding of the Rangitata riparian system that are relevant to future groundwater resource management. Recommendations are listed in order of technical importance.

1) **Rangitata river gaugings.** The Rangitata River suffers from a paucity of flow measurement data (17 flow gauging runs, the latest of which was 1999). It is recommended that a comprehensive set of flow gauging data are collected for the river as this would greatly improve the understanding of the hydraulic nature of the Rangitata riparian zone. Flow data should be corroborated with groundwater level data. Multiple gauging runs would reduce uncertainty. Table 8-1 provides a list of gauging sites that would provide the most useful information based on current conceptions of the river system.

Table 8-1: Recommended river flow gauging sites

Site #	Description
1	Below RDR inlet = reference inflow to plains
2	Above Ruapuna springs
3	Below Ruapuna Springs/Lynn Stream inlet
4	SH72, Arundel
5	Above Ealing Springs/South Branch bifurcation
6	SH1
7	Midway along Rangitata Island
8	Above McKinnons Creek (e.g. Bradley Rd)
9	Rangitata River mouth = reference outflow to sea

2) **Piezometric survey**. Several reports have previously mentioned a need for a piezometric survey across the Rangitata - Orton plain (e.g. Environmental Consultancy Services, 1997; Vincent, 2007; Burbery and Ritson, 2010). I support this recommendation. It is recommended that a piezometric survey of both the shallow unconfined aquifer (i.e. <20 m deep) and of the deeper groundwater system be undertaken, from the Rangitata River to Coopers Creek/the Orari River. Deep survey wells should target a common depth (e.g. within the range: 50 – 90 m) to reduce bias from vertical pressure gradients. The results would help refine the groundwater flowpaths that have so far been inferred from $\delta^{18}O$ data. The survey should comprise as many wells as possible close to the river boundaries, as well as a survey of the river level itself, to help constrain the groundwater vectors at these potential groundwater sources/sinks. It is recommended the survey be completed between the months of July and August when irrigation is not active and ideally before the RSIS comes on line. Maximum information can be yielded from the survey if it is completed concurrent with the river flow gauging recommended above.

3) **Flow measurements of McKinnons Creek**. McKinnons Creek stands to benefit most from establishment of a riparian aquifer management zone. As a surface water body protected under the Rangitata River Conservation Order and identified as sensitive to stream depletion effects, it is recommended resource management of McKinnons Creek could be improved if its hydrological properties were better characterised. To achieve

this, it is recommended that flow measurements be conducted on the creek, either continuously using a weir, or frequent gauging over the course of at last one year. At the same time, groundwater levels should be recorded (daily) in a shallow bore (not used for irrigation) close to the springs that are the source of the creek, and water usage on Rangitata Island should be recorded (daily). From these data, a correlation between groundwater level and creek flow can be made, together with an understanding of the potential spring-depletion effects of groundwater abstraction.

4) **Characterisation of McKinnons Creek water.** Elevated nitrate concentrations measured in McKinnons Creek suggest land-use impacts from Rangitata Island. Further (seasonal) δ^{18}O analyses of the creek water and comparison against Rangitata River water and strict LSR water from somewhere on the Orton plain (not affected by Fonterra's effluent disposal practice) would enable potential dilution factors of river recharge and LSR components to be evaluated. It is recommended the creek might benefit from a reform of the current land and water management, such as establishment of a Rangitata riparian management zone.

5) **Flow measurements of Ealing Springs**. Ealing Springs is similarly a protected surface water body under the Rangitata River Conservation Order (2006). It would be useful to determine the magnitude of flow in these springs reliably, to ascertain with confidence their natural flow condition and influence on the Rangitata River. Given the springs' dependency on groundwater draining off the Mayfield-Hinds plain, it is recommended they are managed as part of an integrated Rangitata River/Mayfield-Hinds groundwater plan. Like McKinnons Creek, consistently elevated levels of nitrate are measured in the spring water from which it is recognised that land-use practices on the Mayfield-Hinds plains potentially threaten the ecological values of the springs, hence it might be prudent to investigate or monitor this threat.

6) **Hydrochemical surveying on Orton plain and around Coldstream.** It is recommended that δ^{18}O sampling be extended to deep wells between Arundel and Badham Road and at the foothills for the purpose of improving knowledge about how the deep aquifer beneath Orton plain is recharged. Similarly, some additional hydrochemical surveying of groundwater in the riparian zone mapped between Coldstream and the river would improve the reliability of the assumptions about riparian water in this area and possibly improve the understanding of how connected water in Oakdale Drain is to the shallow riparian water.

7) **Further consents analysis**. The resource management implications and operational issues of establishing a riparian aquifer zone are yet to be ascertained and were beyond the scope of this review. However, it is recommended that a useful task would be to examine the current consents with water restrictions and compare the cumulative stream depletion effect based on summing their WQN9 assessments evaluated under the NRRP against the cumulative effect determined in this study. This would provide some perspective of a potential impact factor of any resource management reforms.

8) **Investigate water usage data and efficient use of water.** Monitored groundwater level data contain noise from groundwater abstraction for irrigation that currently cannot be characterised with any reliability owing to a lack of knowledge regarding water usage. It is anticipated that this problem will be rectified with the National Water Measuring Standards that are in the process of being implemented. There appears to be a common pattern in the groundwater level hydrograph records reviewed that suggests groundwater abstraction in the riparian zone commences early September each year. The regularity in the pattern tends to suggest water is likely being used inefficiently in the riparian area, i.e. not necessarily being managed based on actual crop demand. It is therefore recommend

that when they become available, water usage data be compared to hypothetical water demand and actions taken to rectify any inefficient usage of water to reduce potential stream depletion rates.

9) **Characterise the tidal effects at the Rangitata Huts monitoring wells.** There is scope for the coastal cluster of multi-level wells at Rangitata Huts to be used to monitor changes in potential piezometric pressures from which the potential risk of unsustainable groundwater abstraction, i.e. groundwater mining and sea water intrusion might be monitored. However, the use of these wells for this purpose first requires some reliable characterisation of tidal effects, which itself posses an interesting technical challenge that it is recommended is addressed.

9 Acknowledgements

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Appendix A: Riparian zone study and report template

Section	**Heading title**	**Scope – questions to be answered**	**Purpose**
1	Introduction	Introduces general issues, location of study area, historical perspective, itemises previous work	To set the scene and alert reader to what is contained in the report; specific scene setting, to alert reader to why the report is necessary and any potential outcome from any changes made; to detail confidence that the reader may assign to conclusions
1.1	Issues and scope of the report	Details specific issues, why the study was undertaken	
1.2	Data used to compile this report	What data are used, perhaps comments on reliability	
2	Geology, geomorphology and aquifer structure	Regional and then local geology	To place hydrogeology in perspective; To form basis for later discussion on hydrogeology To place aquifer property assessment in constraints of localised geology To erect hydro-stratigraphic units and determine their continuity To determine via 3-D modelling the dynamics of groundwater flow and leakage on basis of the geological and hydro-stratigraphic structure To aid understanding of the geological environment in order that it may be used later when riparian zones are erected or modified
2.1	Description of geology based on geological survey maps	Mapped geology	
2.2	Geology and aquifer structure		
2.2.1	Inland aquifer structure		
2.2.2	Coastal aquifer structure		
2.3	Geological cross sections		
2.3.1	Bore log results	Bore log geology	
2.4	Correlation between strata		
2.5	Confining layers	Based on bore log geology	
2.6	Production of 3-D model	Use of ARANZ or other visualisation tool	
2.7	Sedimentological model	Is a model available, or necessary? Does it help understanding of the geology and hydrogeology?	
3	Surface water hydrology	Description of rainfall distribution and magnitude, surface water bodies, monitoring records and derived data, basis for environmental flows (discharge, habitat, recreation, etc.)	To show how the surface water system works, its seasonal and inter-annual variability
3.1	Analysis of rainfall and surface water flow data		
3.2	NIWA or other reports on low flows		
3.3	Conclusions	Based on reported data	To determine the origin, state and variability of the resource
4	Groundwater Hydrology	Brief description of the knowledge of groundwater in the study area	To set the scene
4.1	Groundwater level data	Monitoring records, maps showing spring distribution, spatial and discharge relationships with waterways, project-specific data may need to be collected, perhaps for a year prior to publication of report if it is not already available	To describe the groundwater levels and how they interact with spring and surface flows
4.2	Relationship between surface water flows in streams and groundwater levels		
4.3	Springs		
4.4	Groundwater flow and its spatial and temporal variation	Using groundwater levels, distribution of surface water, springs and other information, determine contours, flow directions and potential for other sources of recharge	To describe qualitative understanding of groundwater dynamics, origins of recharge sources
4.5	Relationship between groundwater levels and Rakaia River flow		
4.6	Aquifer properties	Aquifer test review with maps showing distribution of parameters and then discussion on variation	To describe understanding of dynamics of groundwater flow, recharge and discharge (abstraction)

4.7	Groundwater age determinations	Assess or commission work to inform groundwater dynamics	To describe the time-scale of groundwater flow and possible recharge sources
4.8	Issues of scale dependency of processes	Assess the timing of recharge and abstraction against the aquifer dynamics	To determine what recharge may be used in the season and to determine the importance of storage within the system
5	Groundwater and surface water chemistry	Geochemical and age determination data can aid in understanding of groundwater dynamics, existing data may be insufficient, so plan of geochemical study needs to be done at least a year before report published	To define recharge sources, flow directions, mean residence times, discharge zones, helps in the water budget assessment
5.1	Use of groundwater chemistry		
5.2	Exploratory geochemical project		
5.3	Follow-up groundwater project		
5.4	Further geochemistry, stable isotope analysis, age determinations		
5.5	Analysis of geochemical data		
5.6	Conclusions from water chemistry		
6	Groundwater recharge sources	Using data from groundwater levels, chemistry, surface water distribution, temporal variation	To describe understanding of groundwater dynamics. Make significant comments, to be used later in the report, about the inputs to the resource
6.1	Spatial variation		
6.2	Temporal variation		
6.3	Conclusions		
7	Water budget	Based on previous section illustrating recharge and dynamics. Calculate land-based recharge, also that produced by surface water schemes, leakage from races, etc. Calculate or determine metered abstraction volumes. Calculate or estimate discharge to surface waterways, and through coast. Either model the budget, or create spreadsheet showing mean year values. Determine hydraulic connection, determine whether stream depletion conditions should apply everywhere, or at varying magnitudes dependent upon distance from major and minor waterways. Does storage vary wildly year to year, or is the system largely buffered by the nearby river?	To erect a water budget to support or determine allocation, or a change in allocation amount and mechanism.
7.1	Inputs		
7.1.1	Analysis of recharge data		
7.1.1.1	Rainfall recharge estimates for RRZ and remainder of RS zone by creating a sub-zone.		
7.2	Outputs		
7.2.1.1	Discharge of groundwater to streams and to Rakaia River		
7.2.1.2	Discharge of groundwater under coastline		
7.2.1.3	Consented water use		
7.2.1.4	Effects of water use on surface water flows		
7.3	Storage		
7.3.1	Temporal and spatial variation in storage		
7.4	Water budget discussion		
8	Discussion, conclusions and recommendations	Especially on issues of hydraulic connection, how much of the groundwater resource is derived largely from the river, how much extra recharge is induced by pumping, should takes be constrained by environmental low flow in river, and if so, to what degree?	To indicate the uncertainty in the calculations and conclusions; to determine the applicability of hydraulic connection and associated conditions; to determine what changes in planning may be required; to determine an environmental outcome should the allocation limit or zone boundaries be changed.
8.1	Uncertainties involved and suggestions for management options		
8.2	Review and discussion of the implications should a change in zone be proposed.		
8.2.1	Will all consent holders need to have minimum flow conditions		
8.2.2	Is proposed change in zone boundary consistent with recommendations in any previous report on allocation issues?		
8.3	Potential outcomes from this report		
8.3.1	Formal recognition of a riparian zone with its own groundwater allocation and management mechanism		
8.3.2	A change in the allocation limit for the remainder of the allocation zone		

8.3.3	Is proposed change in zone boundary consistent with the options outlined in any report on allocation issues? (e.g. stream depletion / hydraulic connection with the river)		
8.4	Recommendations		
9	Acknowledgements		
10	References		

Appendix B: Riparian zone from Vincent, 2007

Figure B-1: Preliminary riparian sub-area boundary, delineated by Vincent (2007) at preliminary stage of Rangitata Riparian project (Figure 1 in Vincent, 2007)

Appendix C: Geomorphic map of the Rangitata fan

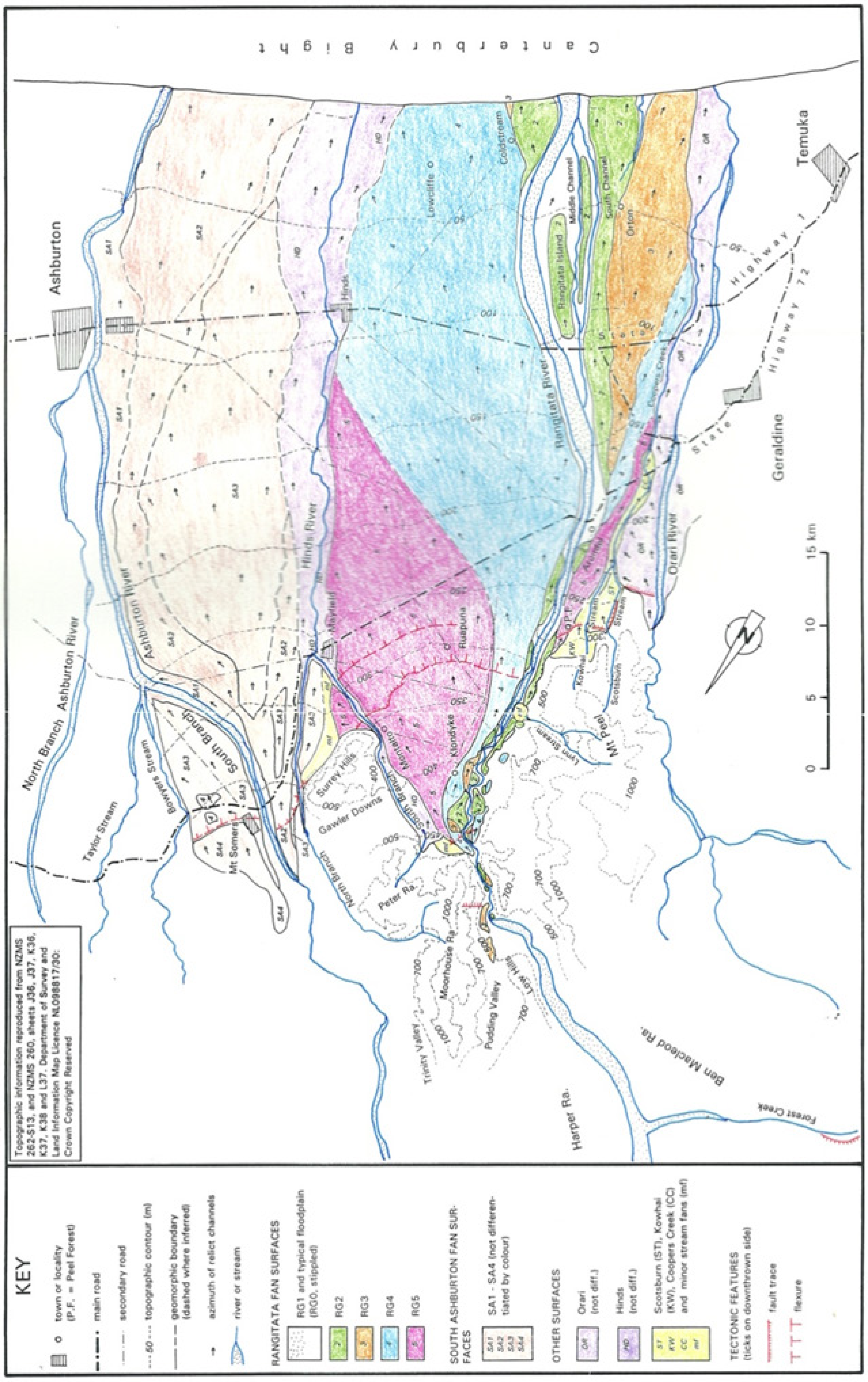
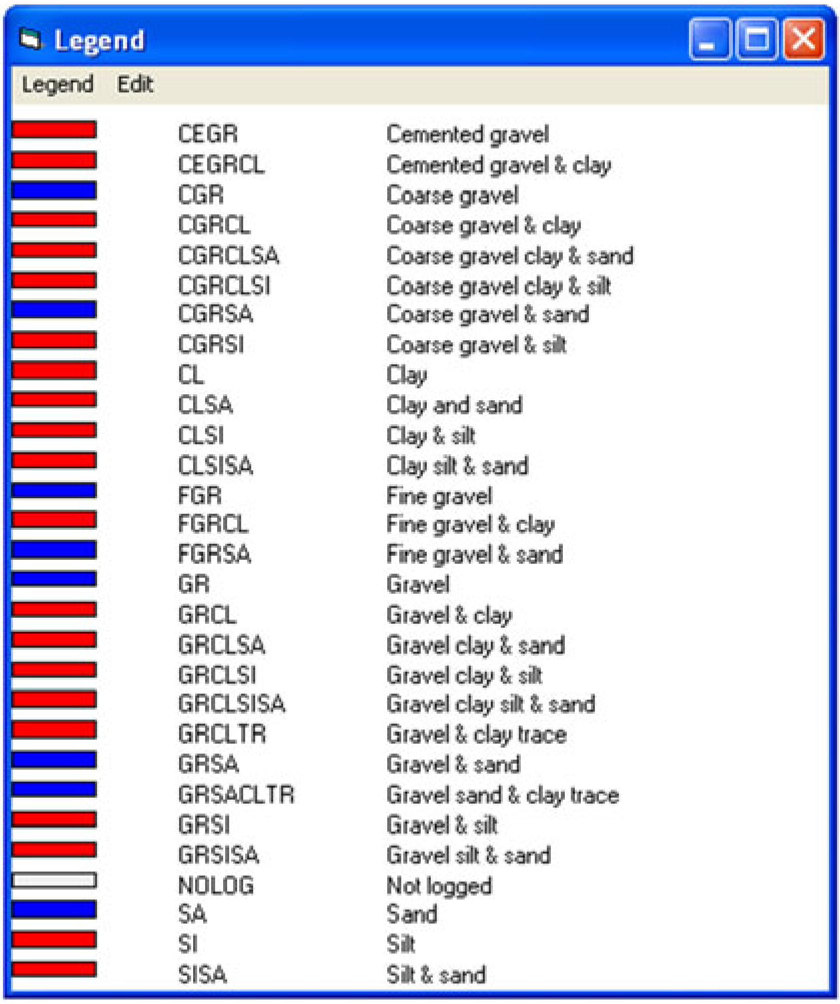


Figure C-1: Geomorphic map of the Rangitata fan, showing correlation of fluvial surfaces of the fan and adjacent catchments (Figure 8 in Barrell *et al.*, 1996)

Appendix D: Geological transects

The following figures in this appendix show the geological transects produced using Environment Canterbury's XSect software. A 10 km buffer was applied to transect A-A' that follows the main NW-SE orientation of the Rangitata fan, along the path of the present day river. A 2 km buffer was applied in the generation of transects B-B' and C-C', and 5 km buffer to transect D-D'. C-C' and D-D' are tangential to and intersect the Rangitata River.

Blue colours in the transects denote geological strata logged as: gravel and/or sand. Red denotes any unit logged as comprising any fraction of clay or silt, or described as cemented (see Figure D-1).



🟥	CEGR	Cemented gravel
🟥	CEGRCL	Cemented gravel & clay
🟦	CGR	Coarse gravel
🟥	CGRCL	Coarse gravel & clay
🟥	CGRCLSA	Coarse gravel clay & sand
🟥	CGRCLSI	Coarse gravel clay & silt
🟦	CGRSA	Coarse gravel & sand
🟥	CGRSI	Coarse gravel & silt
🟥	CL	Clay
🟥	CLSA	Clay and sand
🟥	CLSI	Clay & silt
🟥	CLSISA	Clay silt & sand
🟦	FGR	Fine gravel
🟥	FGRCL	Fine gravel & clay
🟦	FGRSA	Fine gravel & sand
🟦	GR	Gravel
🟥	GRCL	Gravel & clay
🟥	GRCLSA	Gravel clay & sand
🟥	GRCLSI	Gravel clay & silt
🟥	GRCLSISA	Gravel clay silt & sand
🟥	GRCLTR	Gravel & clay trace
🟦	GRSA	Gravel & sand
🟦	GRSACLTR	Gravel sand & clay trace
🟥	GRSI	Gravel & silt
🟥	GRSISA	Gravel silt & sand
⬜	NOLOG	Not logged
🟦	SA	Sand
🟥	SI	Silt
🟥	SISA	Silt & sand

Figure D-1: Colour legend used in XSect geological transects

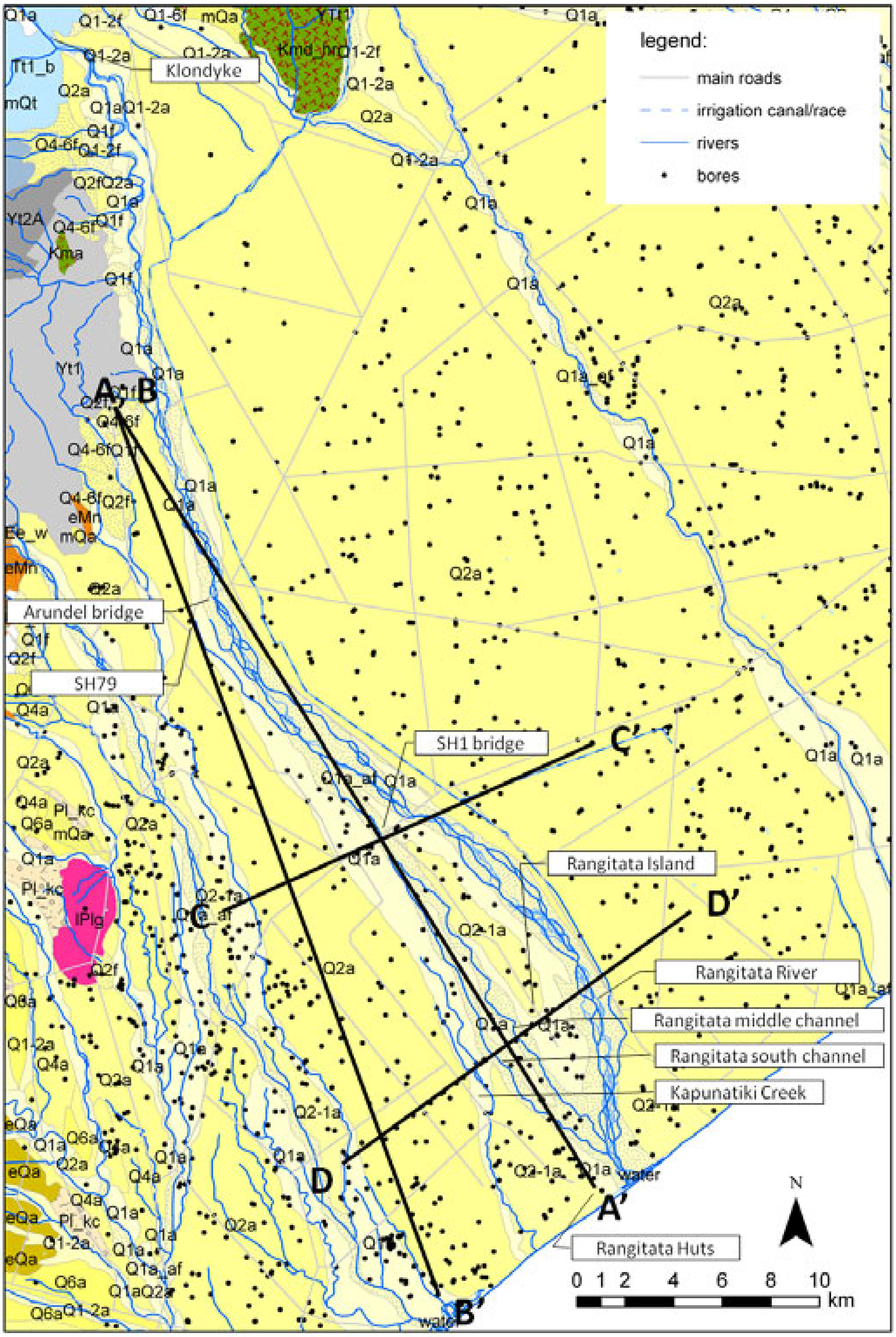


Figure D-2: Map of geological transects generated using Environment Canterbury's XSect software

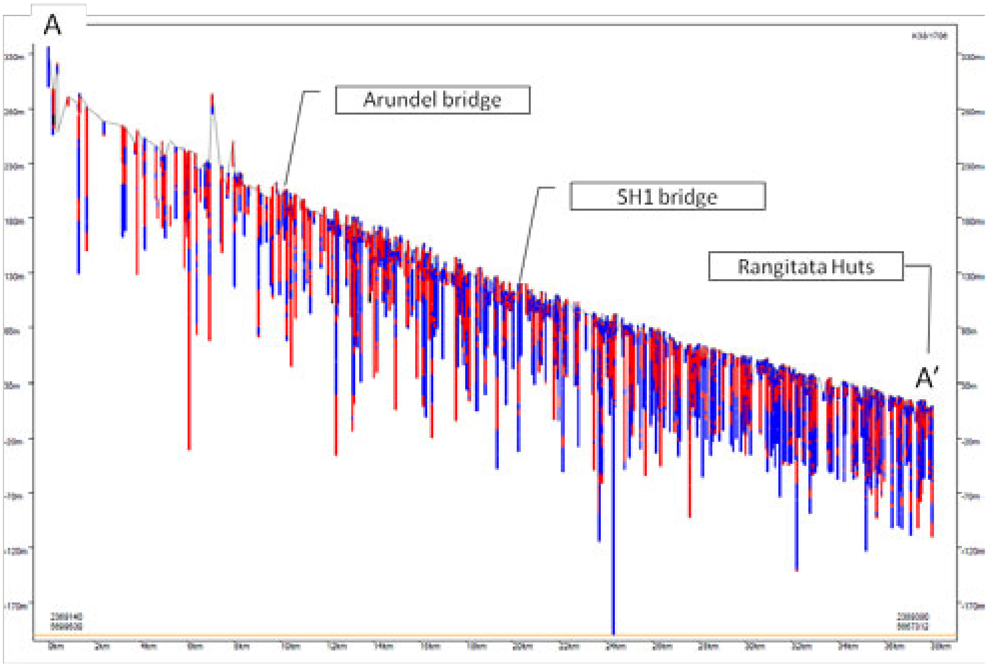


Figure D-3: **Geological transect A-A', running along length of Rangitata fan. Rangitata Gorge to the Rangitata River mouth**

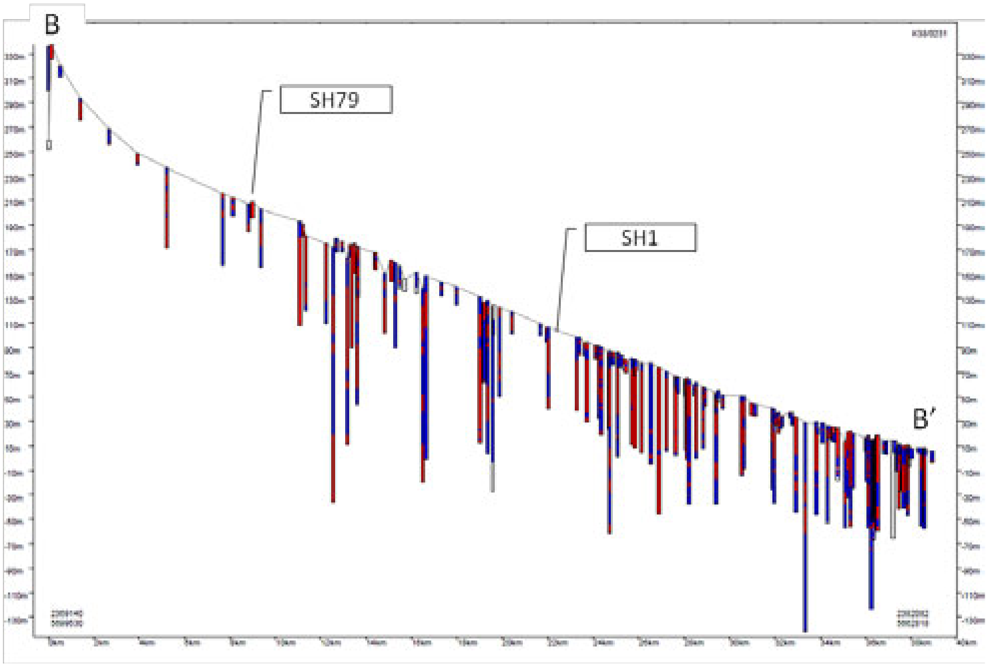


Figure D-4: **Geological transect B-B', running along length of the Rangitata fan. Rangitata Gorge to Orari River mouth**

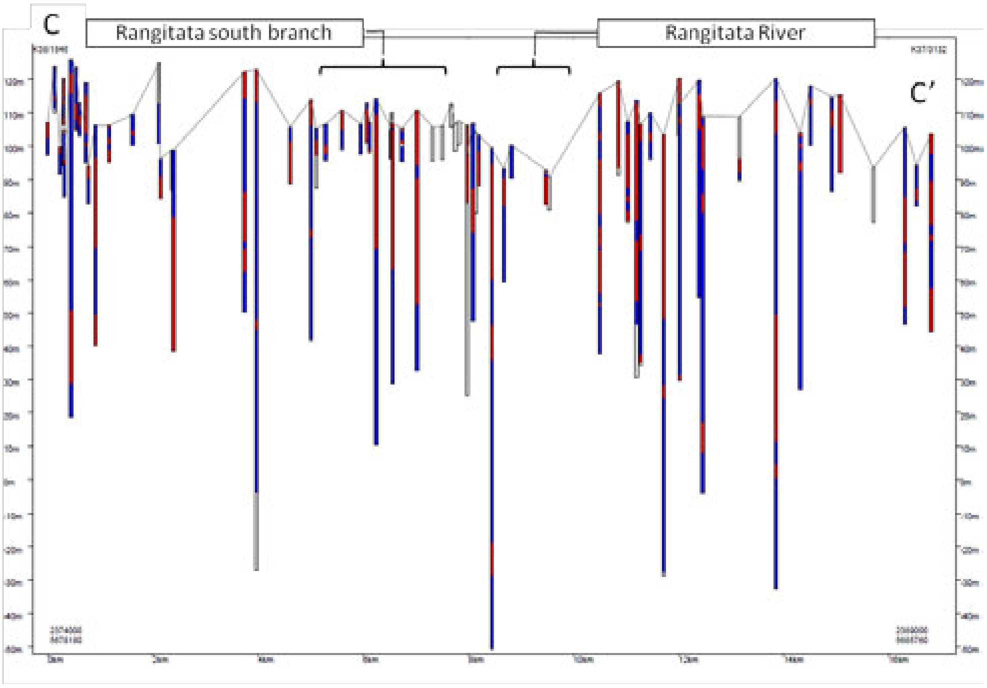


Figure D-5: Geological transect C-C', cutting across the Rangitata fan

Follows approximate line of State Highway 1.

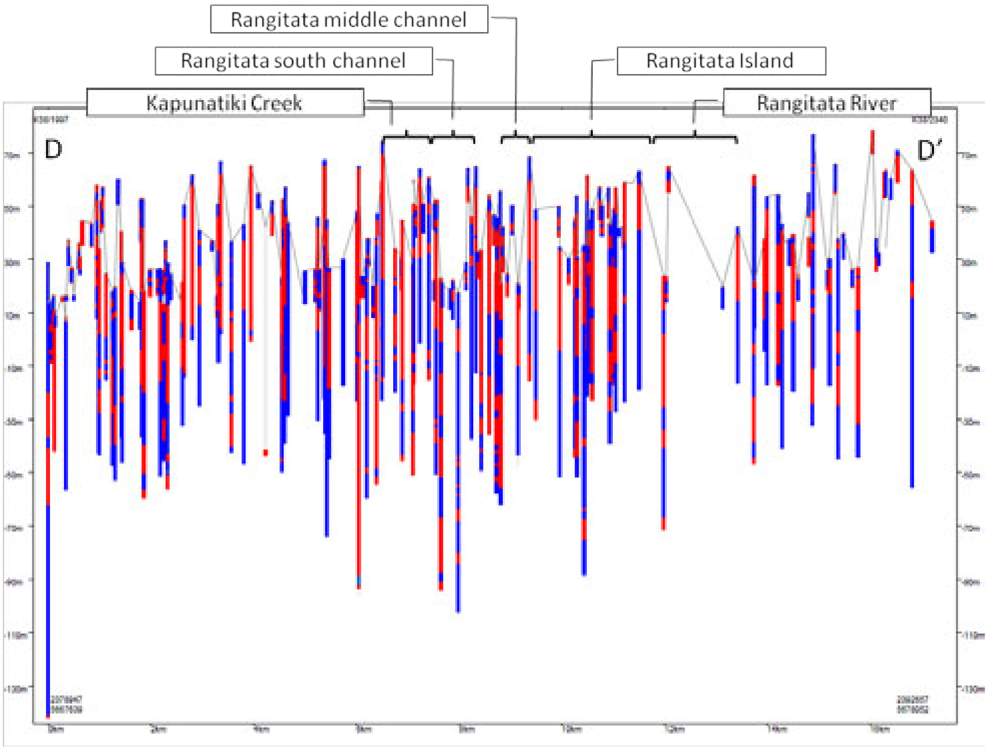
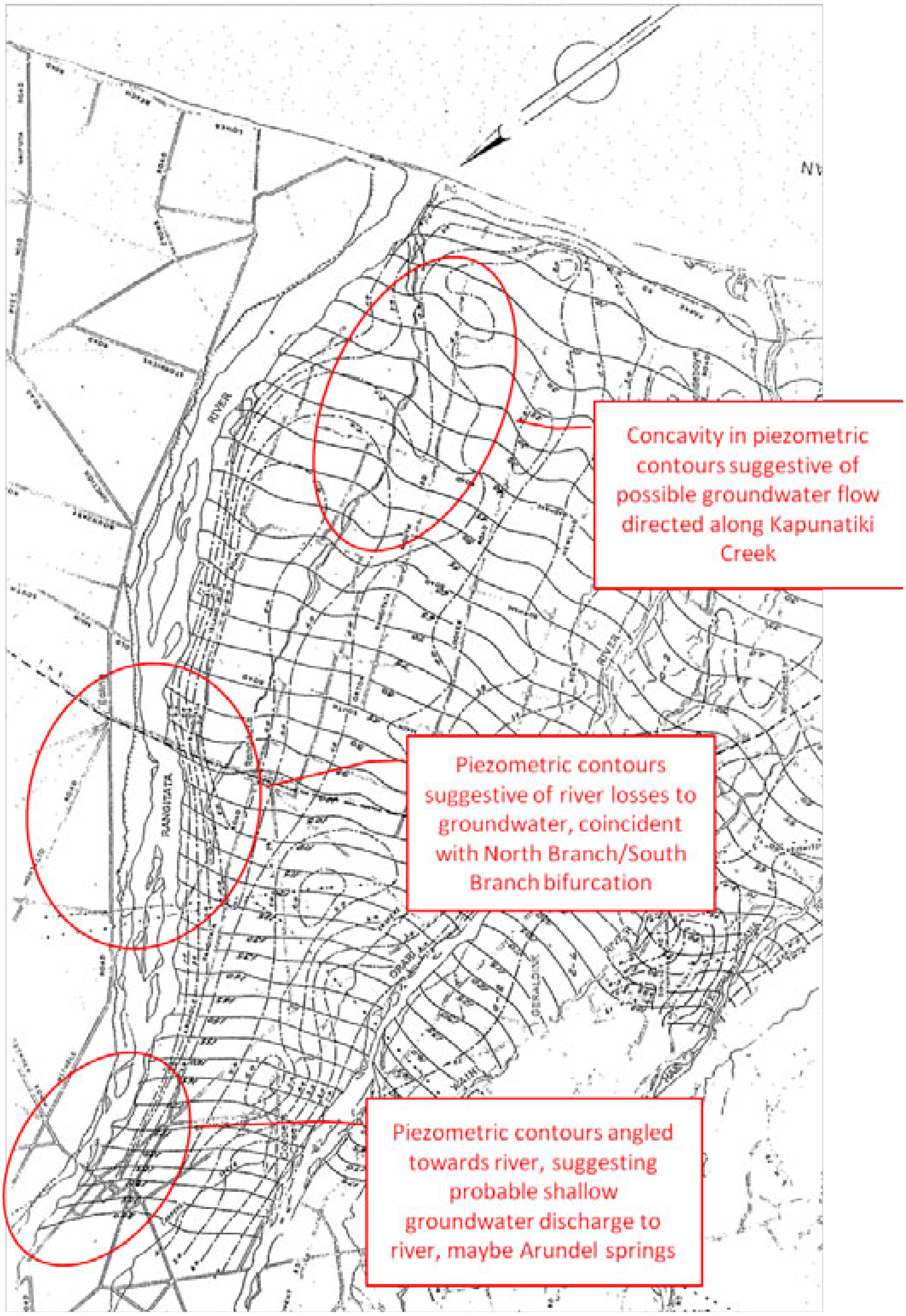


Figure D-6: Geological transect D-D', cutting across the Rangitata fan

Dissection of paleo flood channels and Rangitata Island on the true-right.

Appendix E: Historic piezometric maps

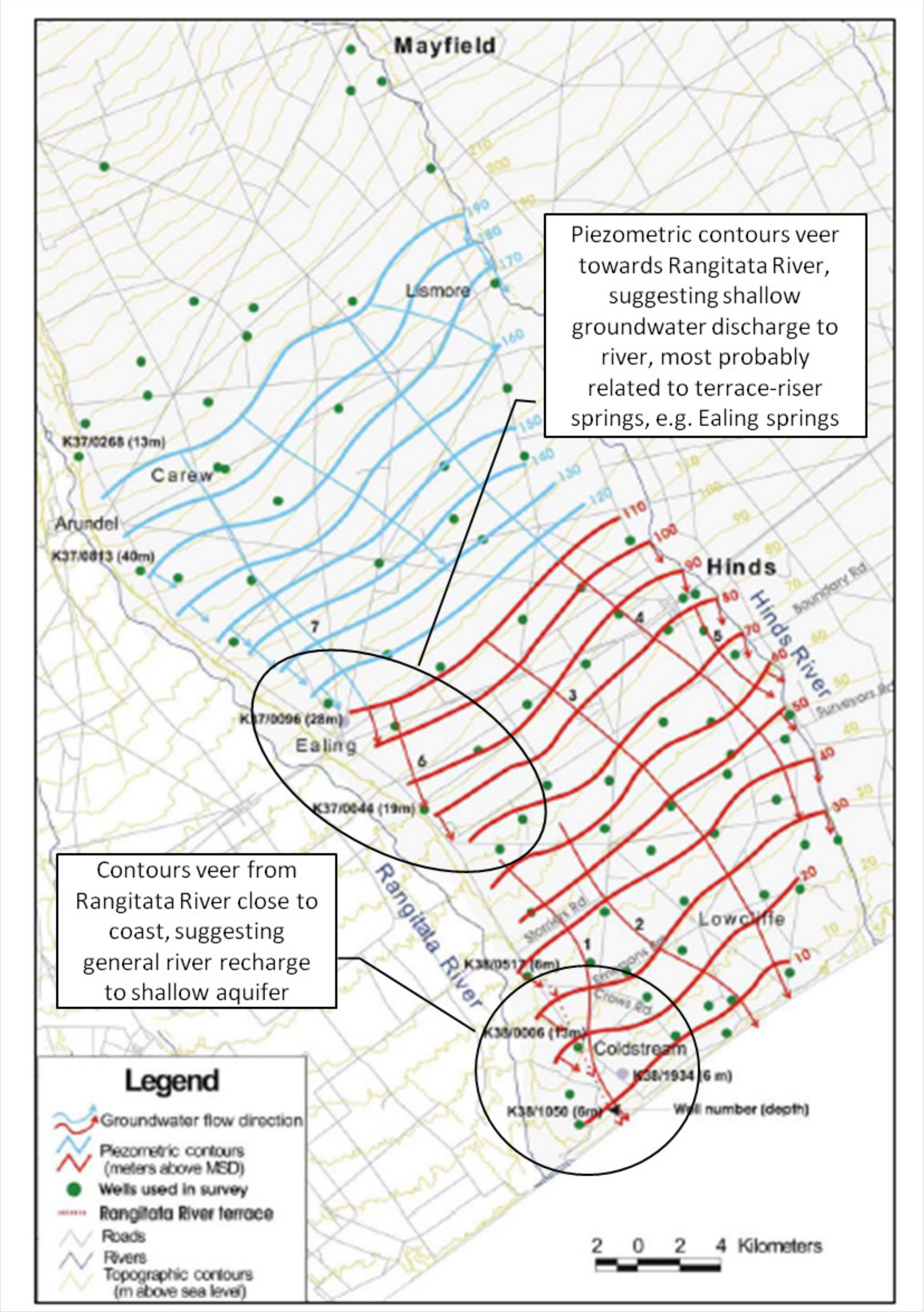


Concavity in piezometric contours suggestive of possible groundwater flow directed along Kapunatiki Creek

Piezometric contours suggestive of river losses to groundwater, coincident with North Branch/South Branch bifurcation

Piezometric contours angled towards river, suggesting probable shallow groundwater discharge to river, maybe Arundel springs

Figure E-1: **Piezometric contours for shallow groundwater, surveyed in 1978, original scale 1:63,360 (modified from SCCB Drawing W57; Figure 4 in De Joux (1997))**



Piezometric contours veer towards Rangitata River, suggesting shallow groundwater discharge to river, most probably related to terrace-riser springs, e.g. Ealing springs

Contours veer from Rangitata River close to coast, suggesting general river recharge to shallow aquifer

Figure E-2: **Piezometric contours for shallow groundwater on Mayfield-Hinds plain, surveyed in 2006 (modified from Figure 3.17 in Dommisse, 2006)**

Note: Dommisse (2006) identified a slight increase in topographic gradient midway across the plain, which he displays on his piezometric map through use of red and blue contour lines.

Appendix F: Analyses of groundwater hydrographs

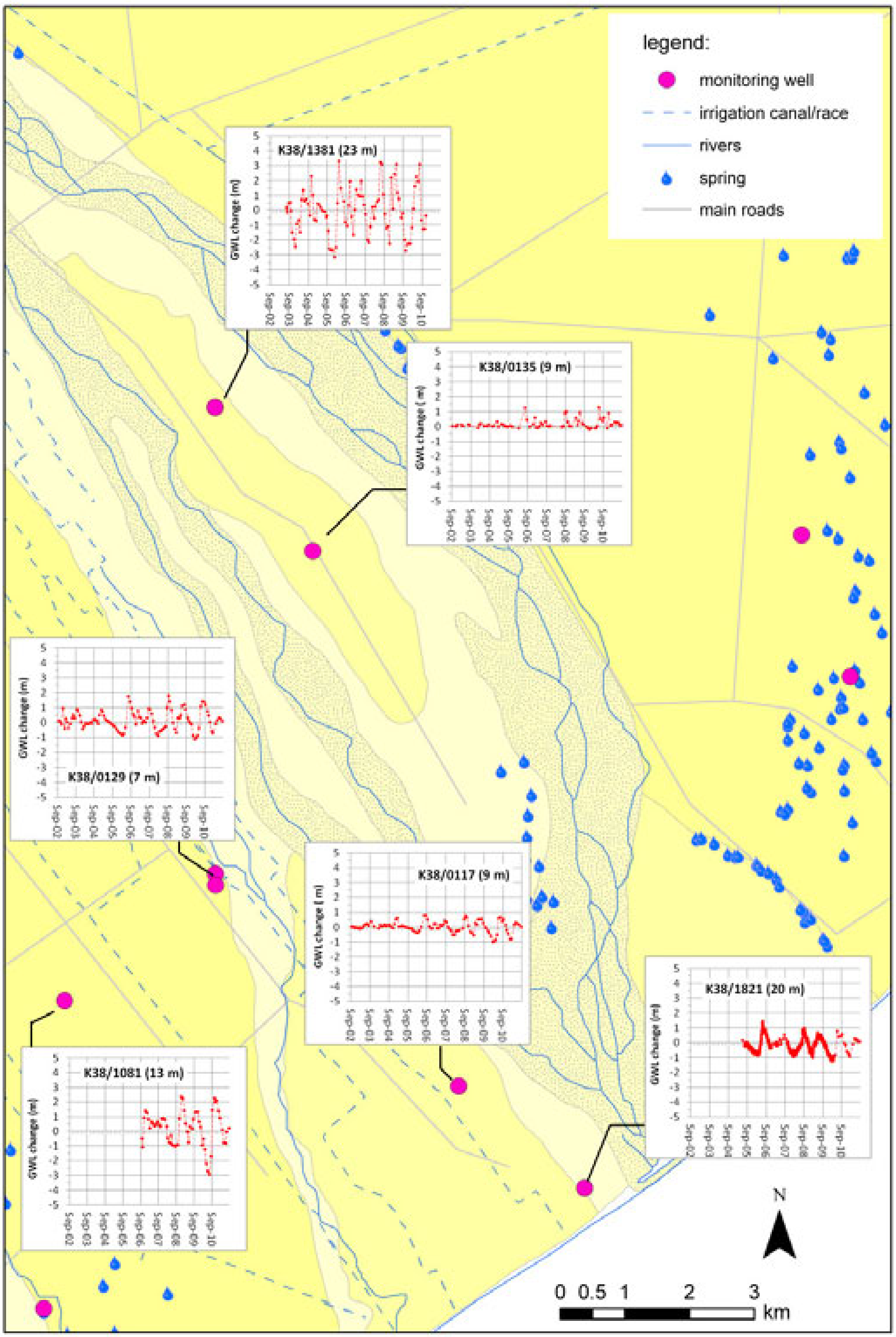


Figure F-1: Monitored changes in groundwater levels, relative to spot water level measurement taken in August 2003

Shallow groundwater under Rangitata Island

Mathematical analysis of groundwater level data focussed on the levels monitored in well K38/1381 that screens older (RG2) fan material between the depths of 21.5 and 22.5 m, on Rangitata Island. The well is located 1 km from the modern day Rangitata River channel (Figure 4-3). It is known that the shallow aquifer formation here is hydraulically inter-connected with the deeper aquifer units screened by wells K38/1379 (129 – 131 m) and K38/1380 (73.5 – 74.5 m) as a fault of the bore drilling. The vertical hydraulic gradient at this locality is downward and there is definite leakage of shallow groundwater to the deeper system, via the connection formed at the time of well installation (Aitchison-Earl, 2004). The water levels are representative of those occurring in the shallow aquifer and are replicated in the hydrographs for the two deeper wells.

Time series analysis of the groundwater level data was undertaken using two methods outlined in Bidwell and Burbery (2011). These being an exponentially weighted moving average (EWMA) model and an eigen-model approach, respectively. EWMA methods were applied to smooth (river) recharge data in the study of groundwater level – surface water relationships completed in the original Rakaia River Riparian project (Williams, 2009).

All mathematical analyses were restricted to evaluating only observation data collected from outside the irrigation season, since it can be assumed these observation data do not contain noise arising from pumped abstraction (for which no records are available). Based on this auditing criterion, only 28 individual observation data-points from the seven years of monitoring record were suitable for analysis.

EWMA analyses

For the EWMA analyses, groundwater levels were correlated with EWMA of recharge data time-series data. Mathematically, the EWMA model is defined as:

$$y(t) = \alpha\, y(t-1) + (1-\alpha) r(t); \qquad 0<\alpha<1 \qquad (1)$$

$$h(t) = g \times y(t) + d \qquad (2)$$

In equation (1), *y(t)* is the EWMA at time *t*, α is the weighting coefficient in the EWMA model, *y(t-1)* is the EWMA for the preceding time step and *r(t)* is the observed recharge at the current time-step *(t)*. Note: as α tends to zero, more weight is given to current observed recharge, as α tends to 1, more weight is given to previous observations and the data are smoothed.

Equation (2) calculates the groundwater level as a function of time - *h(t)*. It provides an offset *(d)* and a gain term *(g)* to the EWMA which aims to scale the recharge data to the common scale of the observation data - in this case groundwater level, which is measured as metres above sea level (m asl). Thus, *h(t)* provides a simulation of the groundwater level that can be compared against the observed levels. The EWMA process involved using an iterative numerical solver to find optimal α*, g* and *d* terms to match observed with simulated levels.

For comparison, basic daily rainfall, Rangitata River flow and LSR (LSR) data were all separately employed as experimental time-series recharge datasets (*r(t)* in equation (1)). LSR data were generated using a basic soil moisture budget model, comparable to that used by Scott (2004). The model processes daily rainfall and potential vapour-transpiration (PET) inputs. An available soil water holding capacity value of 20 mm (a value identified as optimal by the GDA-tool and within the typical range of profile water value for soils on Rangitata Island (25 – 75 mm) (e.g. Figure 2-2) was assumed, as was an evaporation reduction function value of 5, and crop factor value of 0.8 (see Bidwell and Burbery, 2011 for an explanation of these parameters). Daily rainfall and PET data for the Rangitata Island region were obtained from NIWA's virtual climate station database (http://cliflo.niwa.co.nz/).

The over-riding conclusion of the EWMA model analyses was that the model provided no better explanation to observed groundwater patterns than might otherwise be estimated from taking a simple average observed groundwater level. One of the many limiting factors to the analyses lay in the lack of reliable data points with which to attempt to match the model.

Figure F-2 provides EWMA modelled examples of the three recharge time-series data-sets analysed: river flows, measured rainfall and hypothetical LSR, super-posed with the groundwater level data of K38/1381 that the model was in each case aiming to match to. Note: the recharge data have no scalable dimension. $\alpha = 0.9$ applies in all cases. The failure of the EWMA mathematical model to correlate with the groundwater level data is clearly evident.

Scrutiny of potential recharge and water level signals shown in Figure F-2 allows for some discussion about the hydrological system:

1) Potential rainfall and river recharge events outside of the irrigation season tend to occur in unison thus cannot be separated with any reliability based on visual assessment.

2) River base-flows generally rise over the spring-summer when there are multiple flashy river flow events that are separate from rainfall on the plain. The usefulness of these events for assessment of aquifer recharge is unfortunately compromised by untimely drawdown effects from pumped abstractions for which no data is available.

3) There is evidence that on at least two occasions, groundwater levels rose when there were no reported increases in flows at the Klondyke recorder. These are ringed in Figure F-2. From the rainfall data it seems likely that the groundwater level response was driven by LSR effects.

4) In the absence of any further evidence, it seems reasonable to assume that LSR is responsible for the dynamism exhibited in groundwater levels of the shallow aquifer beneath Rangitata Island. It is feasible that there is a basal, less variable component that is supported by the river, the signal of which is too damped to notice.

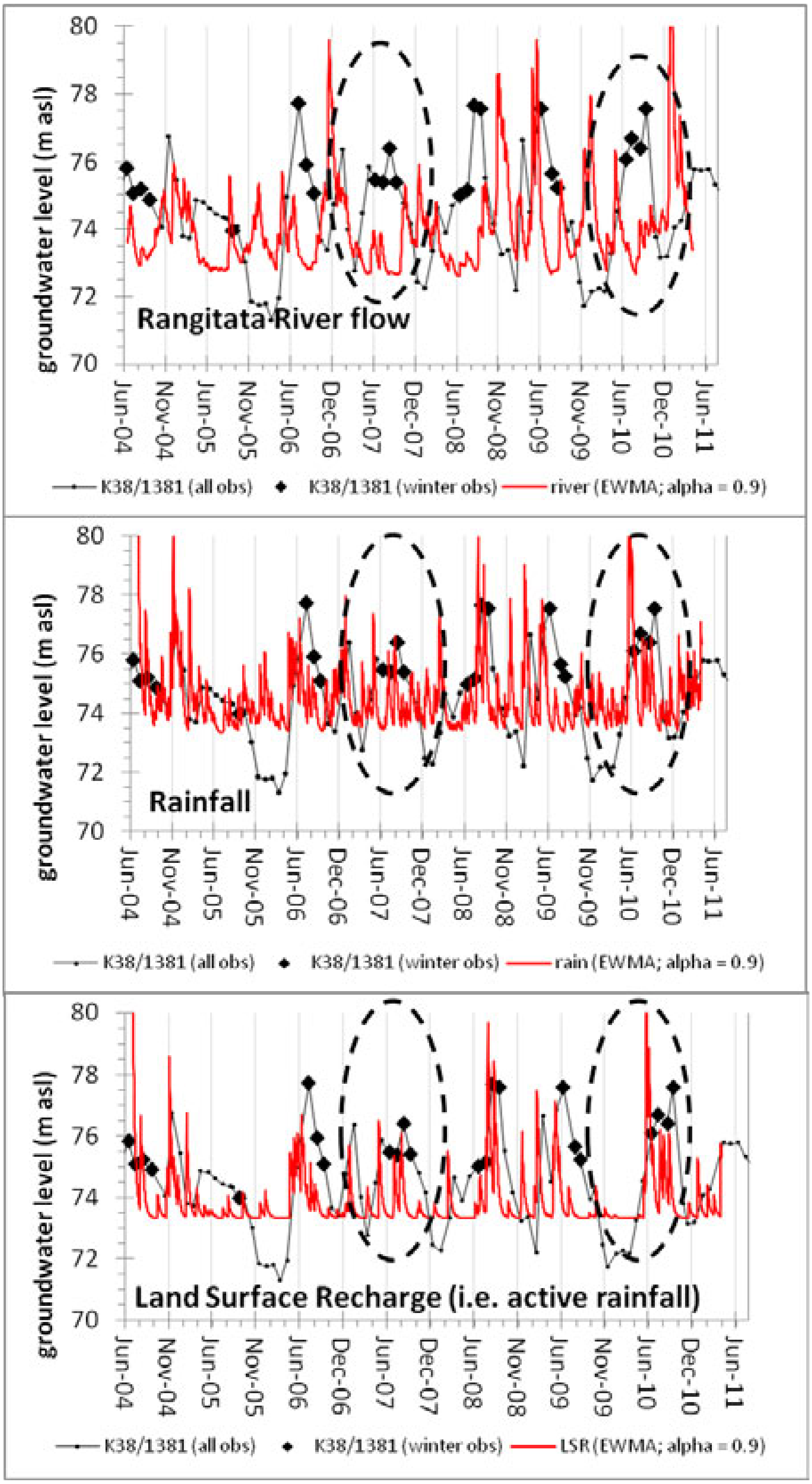


Figure F-2: Example of EWMA model of different potential aquifer recharge sources attempts of which were made to correlate with the groundwater levels monitored at K38/1381

Although dimensions of recharge signal are purposely omitted, it is useful to note rainfall and LSR bottom out at zero (i.e. there are periods of no recharge).

Eigen-model analysis

Given the mathematical limitations of the EWMA analyses the water level monitoring data from K38/1381 were also processed using an eigen-model approach, which involves a direct solution to the transient groundwater flow equation, hence provides a more realistic representation of aquifer dynamics. The Groundwater Data Analysis tool (GDA-tool) package (Burbery *et al.,* 2011) that comprises a LSR model coupled to the eigen-model was applied for this purpose.

Without elaborating on the complexities of the analyses, in brief, the GDA-tool is a signal filter. Daily rainfall and PET time-series datasets that constitute the potential aquifer recharge signal are processed to generate a response function that is a direct simulation of groundwater levels. The GDA-tool provides a means by which simulated groundwater levels are automatically matched to observed levels. Details can be found in Burbery *et al.* (2011).

The outcome of the eigen-model analyses mirrored the findings of the EWMA analysis. That is the lack of frequent observation data precluded any reliable assessment. Figure F-3 shows the resulting modelled groundwater levels based on the assumption that rainfall recharge is the only active recharge mechanism and it is distributed uniformly over the aquifer. The measured model-fit is a significant improvement on the EWMA model assessment, albeit still not convincing. The parameter values optimized by the calibration routine completed by the GDA-tool are summarised in Table F-1. The values show some questionable results, e.g. x/L = 0.01, which seems conceptually wrong and tends to imply the mathematical solver in the GDA-tool maybe failed to find a unique mathematical solution, most probably due to strong-correlation of the mathematical parameters. Applying mathematical constraints to parameters such as x/L in the eigen-model however is difficult given the boundary conditions of the shallow aquifer beneath Rangitata Island do not strictly conform to those assumed in the eigen-model, rendering the problem quite abstract.

Regardless, of this error, a river recharge component was incorporated into the model, modelled as a finite recharge zone in which the time variant head signal was proportional to the exponentially weighted moving average of river flow recorded at Klondyke. The proportionality constant, as well as the EWMA weighting coefficient were automatically estimated by the GDA-tool. With exception of the available water holding capacity, the parameter values in the LSR model were held fixed at their previous estimate. What was found was that no improvement in the replication of groundwater levels could be achieved when a river recharge component was incorporated into the model. Although not robust, the finding tends to support the inferences made from the qualitative assessment of EWMA data, i.e. rainfall recharge is responsible for much, if not all, the dynamism exhibited in shallow groundwater levels under the middle of Rangitata Island.

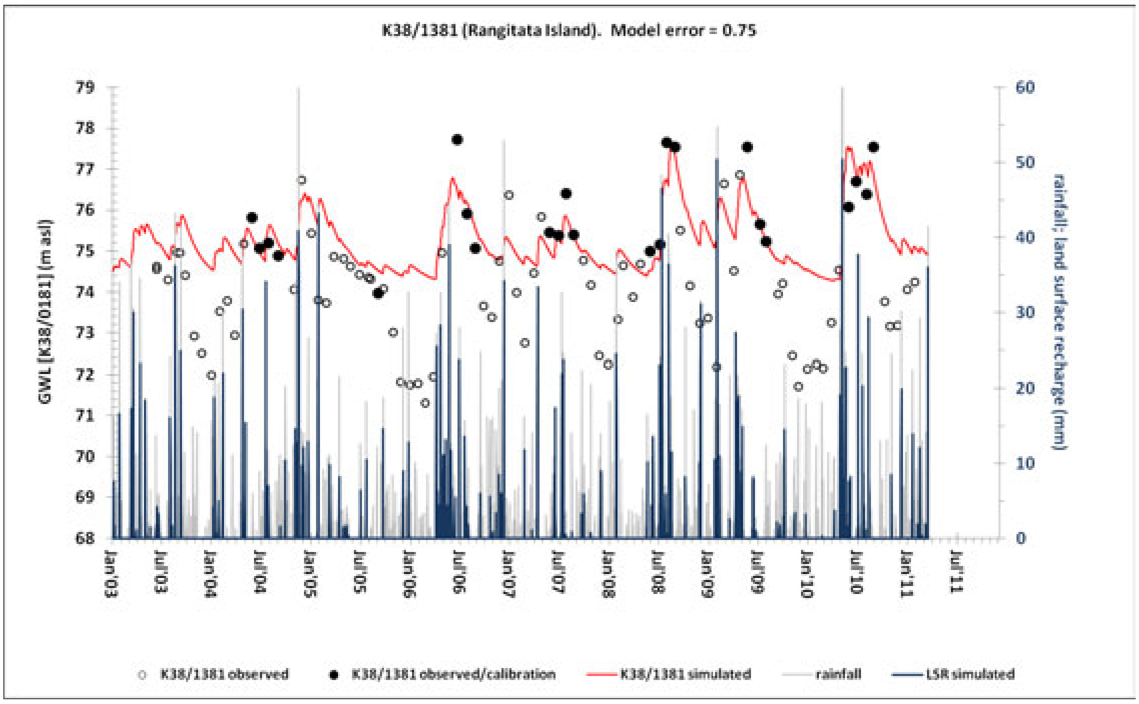


Figure F-3: Modelled groundwater levels at K38/1381 based on GDA-tool analysis

Note: hollow symbols are observation made during irrigation season and are assumed to be affected by pumped abstraction effects, for which no compensation has been made in the model.

Table F-1: Optimised parameters of the coupled LSR-eigen-model that produced the groundwater level response curve in Figure F3

	Eigen-model				**LSR-model**			
Parameter	*T/SL*^{2} (1/day)	*S*	H_0 (m asl)	*x/L*	*AWHC* (mm)	α	*C*	D_t (mm)
Description	Effective aquifer diffusivity	Aquifer storage coefficient	Base-head	Effective location of well	Available water holding capacity	Evaporation reduction coefficient	Crop factor	Drainage threshold
Optimised value	0.0059	0.06	74.18	0.01	20.0	4.9	0.8	50.

Recorder wells at Rangitata Huts

Environment Canterbury monitors groundwater levels at 15-minute intervals in the multilevel piezometers (K38/1705 - K38/1707 and K38/1821) at Rangitata Huts. The data are integrated over a daily time-step to provide an average daily groundwater level. The wells are located 500 m from the coastline and the data are subject to tidal effects as a consequence. The groundwater level hydrographs for the wells are presented in Figure F-4, along with the Rangitata River flow records. It is evident in the data that the groundwater levels do not follow the general regime of the river – groundwater levels tend to be highest over the winter months, which coincides with the time when river flows are relatively low and stable.

The general temporal pattern of piezometric levels in the Rangitata Huts multi-level well cluster is common to that observed in the monthly record of other monitoring wells across the region (see Figure 4-4 in Section 4.3 of this report). Given no variable river recharge signal could be identified in those records, it is assumed that the low groundwater levels observed between spring-autumn are a result of pumped abstraction and minimal LSR rather than a time lag-effect associated with possible river recharge.

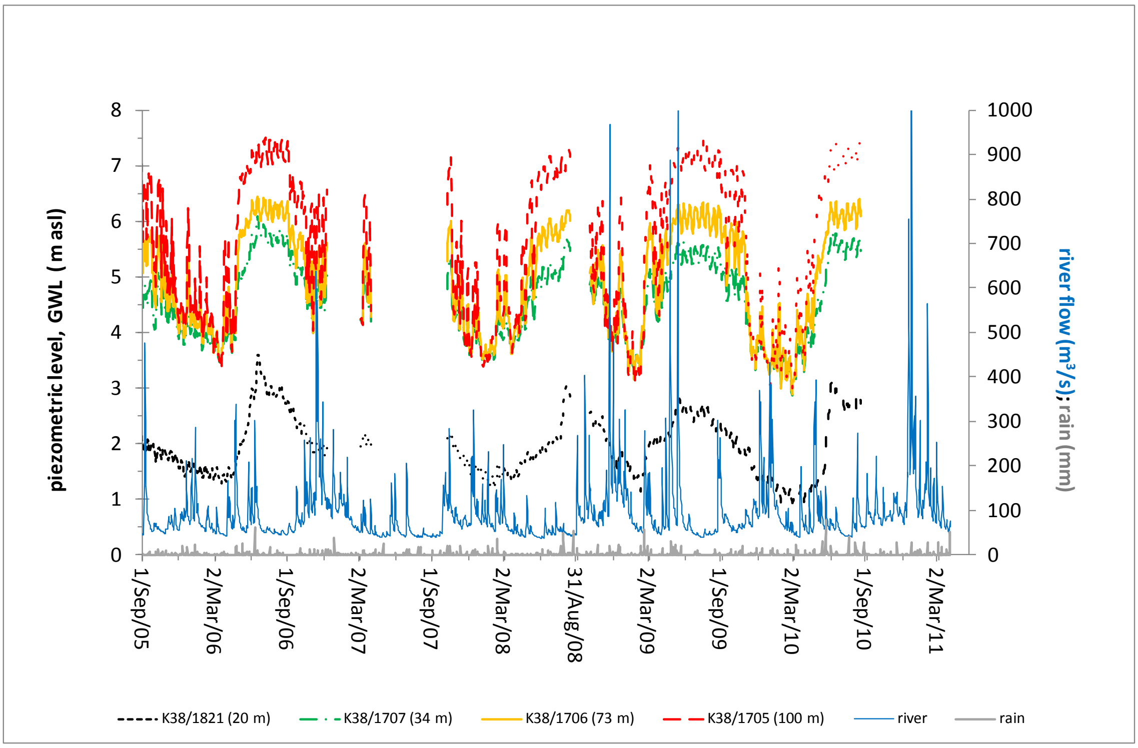


Figure F-4: Piezometric levels monitored in the multi-level well cluster at Rangitata Huts

For the winter periods of 2006 and 2009, groundwater levels were relatively stable and the records contained no gaps. These fragments of the groundwater level data were used for the study of tidal effects. A tidal model (e.g. Serfes, 1991) was applied to process the tidal signal in piezometric data collected July–August:

$$GWL(x,t) = GWL_{ave} + h_0 \exp\left(-x\sqrt{\pi S/t_p T}\right) \cdot \sin\left(\frac{2\pi t}{t_p} - x\sqrt{\pi S/t_p T}\right) \qquad (3)$$

The variables in equation (3) are: $GWL\ (x,t)$, the simulated piezometric level at time t, GWL_{ave} is the average piezometric level over the period of analysis, h_0 is the tidal amplitude, x is the distance from the tidally varying boundary, S/T is the aquifer diffusivity, t_p is the tidal period. Values for h_0 and t_p were obtained from NIWA's on-line tide-prediction tables (http://www.niwa.co.nz/services/online-services/tide-forecaster) and assumed to be 0.79 m and 0.517 days, respectively. Note: no account was made to accurately correct for spring and neap tidal effects, or model storm surges that might have occurred contributed to higher than average tidal amplitudes. A value of 500 m was assumed for x - equal to the distance the wells are from the coastline. The aquifer diffusivity value, T/S was therefore the unknown variable in the problem and estimated based on curve-matching the function given by equation (3) to the appropriate sub-set of observed groundwater levels.

In the analyses of groundwater levels from well K38/1821, representative of the shallow unconfined aquifer, the tidal model was superimposed on a linear model, to filter out the apparent steady decline in observed water levels. The Nash-Sutcliffe (1970) model efficiency index, which is comparable to the coefficient of determination (R^2) was applied as an objective function in the inversion problem. A model efficiency of one implies a perfect model fit, whereas a value of zero suggests the model is a poor descriptor and no more effective than assuming the mean of the observation data represents the entire time-series dataset. The model-fitting results are summarised in Table F-2 and shown in Figure F-5 to Figure F-7.

Table F-2: Results of signal processing piezometric data for tidal effects

Well	**K38/1705**		**K38/1821**	
Screen depth (m bgl)	95-100		16.9-18.9	
Piezometric levels analysed for period	Jul-Dec 2006	May-Sep 2009	Jul-Dec 2006	
Interpretive model	Tidal model		Linear trend	Linear trend + tidal model
Estimated aquifer diffusivity, *T/S* [m^2/day]	2.28E-06	8.47E+05	n/a	2.24E+05
Model efficiency index, *E*	0.654	0.693	0.935	0.944
Mean error (m)	0.077	0.106	0.112	0.104

Owing to uncharacterised recharge effects, the filtering of the tidal signal observed in shallow groundwater at well K38/1821 was relatively unsuccessful, as can be seen by the marginal improvement of the model efficiency index, between the linear trend and linear trend + tidal model interpretations listed in Table F-2. Equation (3) provided a better yet still relatively crude representation of the tidal signal observed in well K38/1705.

Aquifer diffusivity values determined from the analyses can be translated to transmissivity or storativity values provided one of these parameters can be constrained. In the absence of such knowledge, no attempt has been made to quantify these physical properties. As can be seen in the hydrograph data shown in Figure 4-5 (Section 4.3), the tidal effects are trivial compared to drawdown effects and potential recharge effects, which remain uncharacterised.

A tidal efficiency was calculated for each of the three deep piezometers. The average tidal range in both 2006 and 2009 was the same: 1.58 m (e.g. Table F-3). The baseflow of the Rangitata River (as measured at Klondyke) was also comparable: 52 m^3/d and 47 m^3/s, respectively. The tidal effect in the observation wells however varied between years. In 2006 the range observed in K38/1705 was 0.79 m (i.e. 50% tidal efficiency) and 1.03 m in 2009 (65% tidal efficiency). The tidal efficiency is variable owing to the variability in the pre-condition of the aquifer. In 2006, groundwater levels were slightly higher than experienced in 2009 by between 0.15 m and 0.44 m (depending on aquifer depth), and this additional water pressure suppressed the tidal effects by between 0.24 m and 0.26 m. The relative tidal efficiency between aquifers remains effectively constant independent of the pre-existing condition of the groundwater levels. Monitoring of the difference in piezometric pressure between the various well screen provides useful insight into the changes in groundwater flow with time, however to achieve this, characterisation of tidal effects is first required. With sufficient data, a correlation between the pre-existing groundwater level condition and tidal efficiency should be feasible and it is recommended this be attempted, after which the piezometric data from the cluster wells can be used a monitoring wells for detecting changes attributed to pumped abstraction.

Table F-3: Tidal efficiencies

Well ID	K38/1705	K38/1706	K38/1707
Well screen (m bgl)	95-100	68.5-72.5	29.0-34.0
8 July – 21 August, 2006			
Range of tidal effect (m)	0.79	0.69	0.45
Tidal efficiency (%)	50	44	78
Relative to K38/1705 range	1.0	0.90	0.59
Average piezometric level (m asl)	7.28	6.20	5.70
9 June – 27 August, 2009			
Range of tidal effect (m)	1.03	0.95	0.70
Relative to K38/1705 range	1.0	0.93	0.68
Tidal efficiency (%)	65	59	44
Average piezometric level (m asl)	7.13	6.05	5.36
Average tidal efficiency wrt that of K38/1705	1.0	0.91	0.64

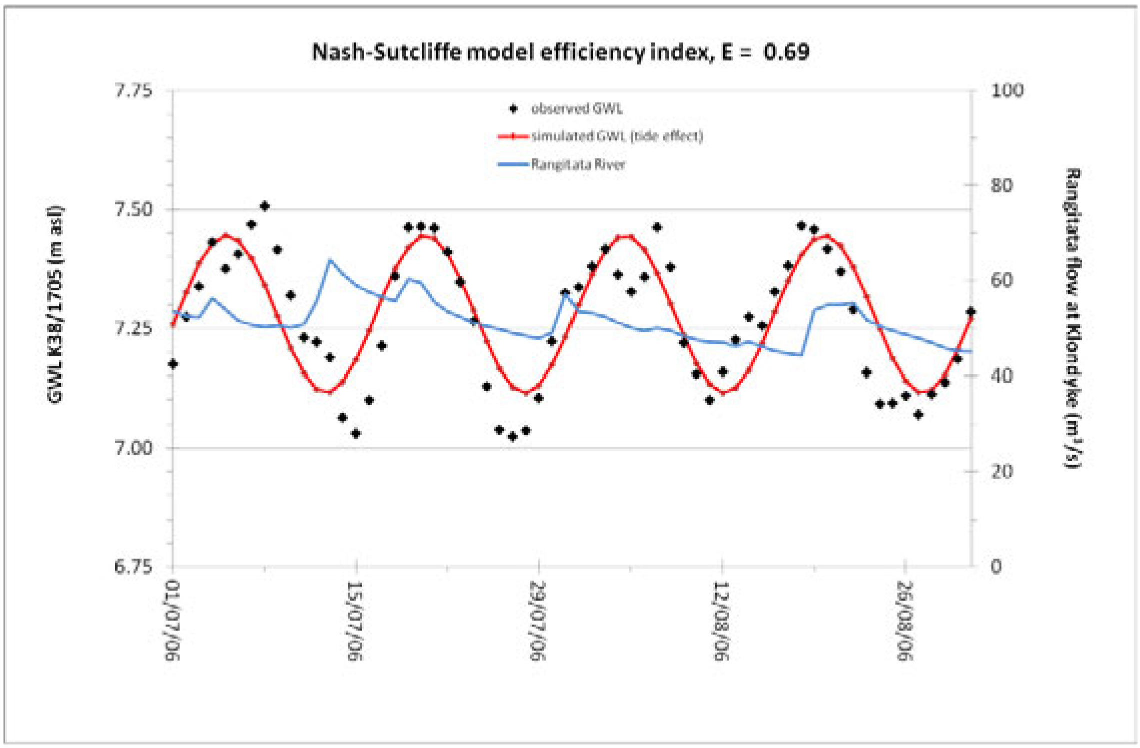


Figure F-5: **Processed tidal signal of piezometric levels monitored in 100 m deep well K38/1705 (winter-spring 2006)**

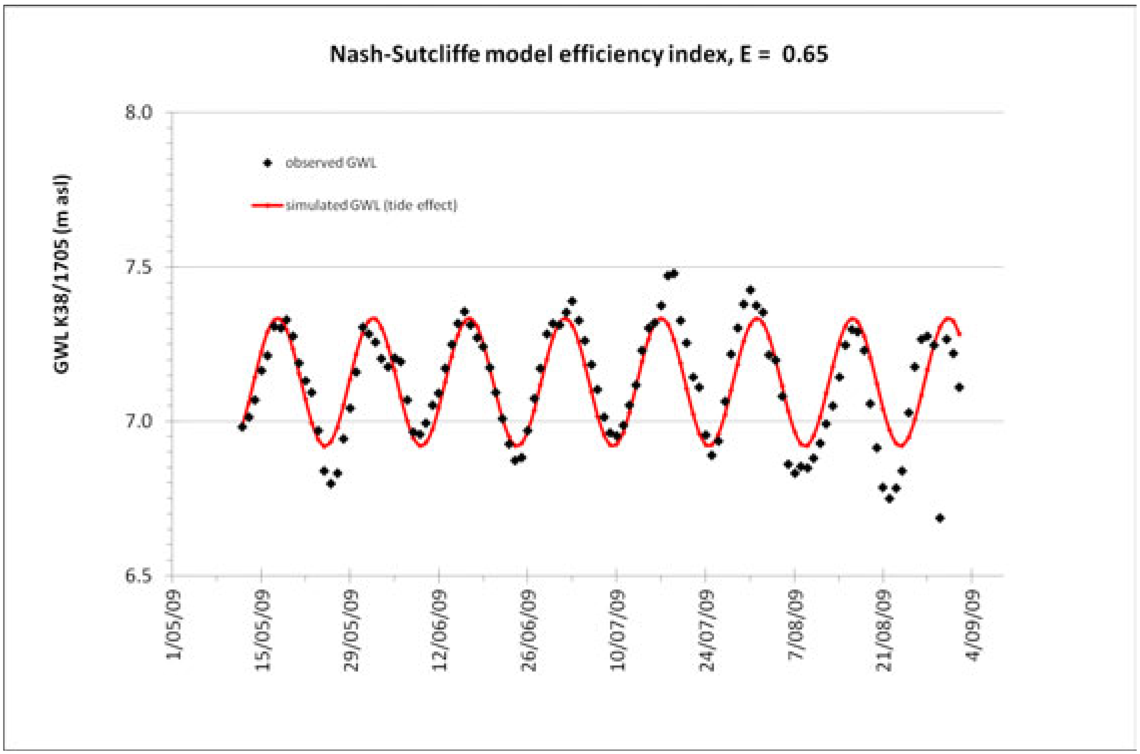


Figure F-6: **Processed tidal signal of piezometric levels monitored in 100 m deep well K38/1705 (winter-spring 2009)**

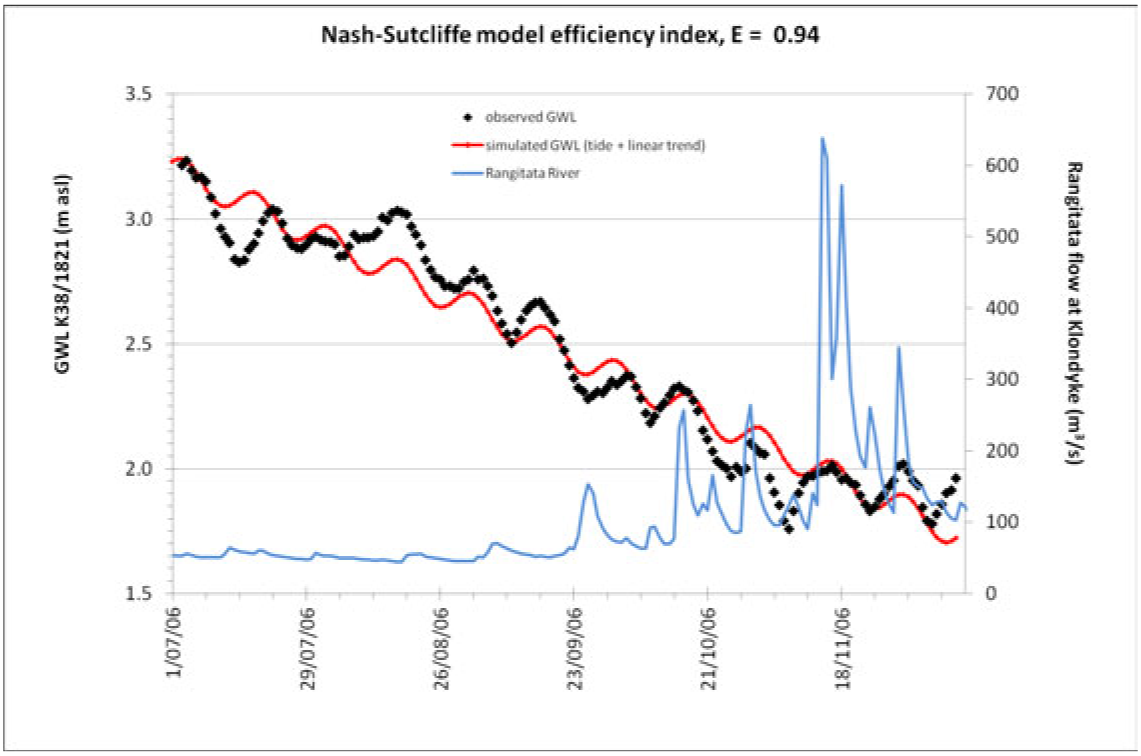


Figure F-7: **Processed tidal signal of piezometric levels monitored in 20 m deep well K38/1821**

Appendix G: Major ion water chemistry

The data catalogued here were sourced from Environment Canterbury's SQUALARC database on 31/10/2011. Values represent the average recorded concentration of samples for which the complete suite of major ions was analysed. Any major ion dataset with a reported ion balance >5% were disregarded. These data were processed into meq/L units and used in the assessment of the water-type and in the generation of the Stiff diagrams plot in Figure 5-1.

Shallow wells

well ID	easting	northing	depth (m)	Alkalinity (mg HCO_3/L)	Calcium (mg Ca/L)	Chloride (mg Cl/L)	Magnesium (mg Mg/L)	Potassium (mg K/L)	Sodium (mg Na/L)	Sulphate (mg SO_4/L)	Water-Type
J37/0012	2369294	5690027	6.7	44.3	13.1	7.1	3.4	1.0	7.1	8.1	Ca-HCO3
J37/0225	2368967	5690277	15.6	63.0	14.5	9.7	5.8	1.1	8.3	6.8	Ca-Mg-HCO3
K37/0038	2391530	5686260	9.1	27.0	11.0	3.8	3.7	0.8	6.1	11.0	Ca-Mg-HCO3
K37/0044	2386216	5681070	18.6	64.0	18.0	4.7	5.4	1.3	9.7	12.0	Ca-Na-HCO3
K37/0089	2379762	5694277	30.0	56.0	15.0	3.4	5.6	0.9	7.1	13.0	Ca-Mg-HCO3
K37/0096	2383201	5684049	27.7	64.0	16.0	4.4	6.0	1.2	8.8	11.0	Ca-Mg-HCO3
K37/0102	2379229	5698131	28.4	45.0	12.0	5.8	4.2	0.9	6.5	8.4	Ca-Mg-HCO3
K37/0130	2374017	5684048	15.9	37.8	11.9	6.5	3.5	0.9	8.0	7.0	Ca-Na-HCO3
K37/0232	2388159	5683226	8.9	34.4	12.2	3.7	4.0	0.9	6.7	11.3	Ca-Mg-HCO3
K37/0234	2385155	5684134	15.6	60.8	19.0	5.5	6.2	1.2	9.7	13.6	Ca-Mg-HCO3
K37/0243	2389758	5687962	21.3	59.9	14.8	5.1	5.3	1.0	10.2	6.8	Ca-Na-HCO3
K37/0245	2384890	5686732	19.8	47.3	18.7	6.5	5.6	1.1	9.0	14.6	Ca-HCO3
K37/0260	2382159	5692573	25.3	71.2	18.2	4.8	6.6	1.2	10.5	10.6	Ca-Mg-HCO3
K37/0268	2373714	5693882	13.1	47.0	15.0	5.8	4.3	1.7	8.1	12.0	Ca-Na-HCO3
K37/0339	2384300	5683200	13.5	59.0	17.0	5.1	5.4	1.1	9.4	11.0	Ca-Mg-HCO3
K37/0465	2370449	5693176	5.8	40.4	9.9	4.9	2.8	0.9	6.6	4.4	Ca-Na-HCO3
K37/0562	2390152	5684941	9.1	28.2	13.0	6.1	4.6	0.8	7.1	11.3	Ca-Mg-HCO3
K37/0595	2382054	5691690	26.0	60.0	18.0	4.4	6.3	1.1	9.5	15.0	Ca-Mg-HCO3
K37/0664	2386200	5686200	18.0	43.0	15.0	5.3	5.5	1.3	8.5	13.0	Ca-Mg-HCO3
K37/0671	2370793	5683098	7.6	37.8	9.3	2.5	1.9	0.5	4.0	3.9	Ca-HCO3
K37/0684	2370161	5687957	8.0	36.0	8.2	1.1	1.7	0.6	3.8	1.8	Ca-HCO3
K37/0717	2393589	5681905	10.0	33.0	16.0	9.2	5.8	1.2	8.8	15.0	Ca-Mg-HCO3-Cl
K37/0801	2370510	5687720	n/a	42.0	9.4	1.3	2.0	1.1	3.9	2.6	Ca-HCO3
K37/0871	2371358	5688424	9.0	42.0	12.0	7.3	3.3	1.0	7.2	6.2	Ca-Na-HCO3
K37/1117	2392714	5680400	8.0	29.6	13.9	8.8	4.8	1.1	8.9	15.7	Ca-Na-HCO3-Cl
K37/1118	2393000	5680800	7.0	30.0	9.8	3.9	3.7	0.7	6.4	10.0	Ca-Mg-HCO3
K37/1134	2389300	5684500	11.9	28.0	8.1	2.0	2.8	0.7	5.3	10.0	Ca-Na-HCO3
K37/1336	2383360	5680060	10.0	55.0	23.0	5.5	3.5	1.8	5.8	12.0	Ca-HCO3
K37/1381	2380339	5681874	10.0	34.0	11.0	1.4	1.2	0.7	2.7	4.7	Ca-HCO3
K37/1640	2372087	5689412	9.7	38.0	12.0	5.7	3.5	0.8	7.1	6.3	Ca-Na-HCO3
K37/1786	2386153	5691277	23.0	36.0	10.0	3.1	3.5	1.2	6.9	13.0	Ca-Na-HCO3
K38/0006	2391768	5672485	10.1	47.0	12.0	4.0	3.5	0.8	8.3	9.8	Ca-Na-HCO3
K38/0015	2382200	5670939	10.6	49.0	26.0	16.0	7.7	1.3	15.0	14.0	Ca-Na-HCO3
K38/0066	2387050	5666187	15.9	66.0	12.0	4.5	3.6	0.8	7.5	2.9	Ca-Na-HCO3
K38/0102	2388929	5679667	12.3	43.0	14.0	4.6	4.7	1.0	8.7	10.0	Ca-Na-HCO3
K38/0105	2382170	5662569	8.0	87.6	17.7	11.7	6.2	1.0	11.7	10.5	Ca-Na-HCO3
K38/0106	2386030	5665630	12.0	49.0	18.3	15.9	5.5	1.3	14.1	24.0	Ca-Na-HCO3-Cl
K38/0108	2385030	5666470	6.1	209.6	27.0	93.0	20.3	2.7	53.3	15.3	Na-Mg-HCO3
K38/0120	2379367	5666165	6.4	48.0	18.0	9.6	4.5	1.8	8.3	16.0	Ca-HCO3
K38/0127	2383200	5671090	10.0	42.5	17.5	15.9	5.7	1.1	14.6	7.9	Ca-Na-HCO3
K38/0144	2380481	5675837	7.6	42.1	18.2	12.3	5.3	1.1	10.8	10.7	Ca-Na-HCO3
K38/0148	2381239	5679037	9.1	43.3	15.7	5.4	2.4	1.0	5.1	9.2	Ca-HCO3
K38/0158	2373134	5679619	8.7	36.0	7.2	1.5	1.5	0.4	3.2	2.3	Ca-HCO3
K38/0252	2398650	5674100	8.2	57.3	26.3	29.7	9.3	1.1	19.0	24.7	Ca-Na-HCO3-Cl
K38/0255	2380725	5665462	8.4	44.0	21.0	14.0	6.1	1.6	12.0	27.0	Ca-Na-HCO3-Cl
K38/0356	2381982	5667409	9.1	37.8	18.2	22.2	6.0	1.3	23.8	10.1	Na-Mg-Cl-HCO3
K38/0371	2384128	5664001	7.9	107.5	31.5	51.0	11.5	2.4	51.5	32.0	Na-Mg-HCO3-Cl
K38/0404	2380006	5669242	7.3	48.5	20.1	12.6	6.5	1.5	11.9	15.0	Ca-Na-HCO3
K38/0409	2382000	5667089	7.0	53.0	15.2	17.3	5.7	1.2	10.5	8.6	Ca-Na-HCO3
K38/0410	2378800	5673580	7.5	47.4	13.1	8.8	4.0	1.0	9.3	5.8	Ca-Na-HCO3
K38/0412	2395518	5675989	5.2	45.8	18.2	10.5	5.6	1.5	10.9	15.7	Ca-Na-HCO3
K38/0473	2384078	5664042	21.5	61.0	28.0	13.4	6.7	0.7	8.0	1.8	Ca-HCO3
K38/0517	2389931	5675028	6.0	30.0	6.9	1.1	1.4	0.6	3.9	4.5	Ca-HCO3
K38/0615	2392234	5675566	9.5	39.0	15.0	6.8	5.0	1.1	9.5	14.0	Ca-Na-HCO3
K38/0637	2384310	5666020	8.0	191.2	36.0	100.5	22.2	4.5	73.7	32.2	Na-Mg-HCO3-Cl
K38/0659	2375532	5675248	10.0	44.0	12.0	4.5	2.8	0.8	5.0	6.5	Ca-HCO3
K38/0675	2392220	5679000	8.0	36.0	20.0	10.0	6.9	1.2	9.8	17.0	Ca-Mg-HCO3-Cl
K38/0680	2385960	5672760	11.5	40.0	13.0	3.0	1.8	1.3	5.8	3.7	Ca-HCO3
K38/0684	2378260	5671543	16.0	39.0	19.0	11.0	5.3	1.1	9.9	16.0	Ca-HCO3-Cl
K38/0747	2381215	5665006	6.7	41.0	18.0	18.1	4.7	1.7	20.3	17.0	Na-Mg-HCO3-Cl
K38/0754	2396227	5678062	10.0	31.0	17.0	10.0	6.2	1.1	10.0	19.0	Ca-Mg-HCO3-Cl
K38/0760	2381050	5664740	10.5	102.0	25.0	17.0	8.2	1.3	14.0	10.0	Ca-Mg-HCO3
K38/0852	2377110	5675720	11.8	42.0	14.0	6.7	3.6	1.0	7.7	8.9	Ca-HCO3
K38/0861	2383300	5675420	12.5	42.0	15.0	4.4	2.5	1.1	5.4	9.8	Ca-HCO3
K38/0974	2394392	5679608	10.0	31.0	12.0	5.4	4.5	0.8	7.3	13.0	Ca-Mg-HCO3
K38/0979	2388355	5672002	9.6	38.0	20.0	11.0	3.2	2.9	7.1	6.9	Ca-HCO3
K38/1017	2384158	5672289	12.0	45.7	20.3	10.8	4.6	1.4	9.3	14.6	Ca-HCO3
K38/1032	2391695	5677473	7.9	40.0	15.0	6.5	5.2	1.0	9.4	14.0	Ca-Na-HCO3
K38/1050	2391814	5669698	6.3	35.0	11.0	2.6	2.3	0.7	4.2	9.4	Ca-HCO3
K38/1078	2380610	5665290	30.0	47.2	21.0	12.8	5.4	1.2	11.6	24.4	Ca-HCO3-Cl
K38/1079	2382300	5666760	6.0	60.8	28.9	31.3	10.8	1.7	19.2	14.0	Ca-Mg-HCO3-Cl
K38/1081	2381353	5670211	13.4	57.2	23.0	10.4	4.4	1.1	11.4	8.1	Ca-HCO3
K38/1092	2378350	5679790	17.0	62.0	24.0	11.0	6.4	1.4	11.0	11.0	Ca-HCO3
K38/1171	2381170	5665610	2.0	56.0	14.0	14.0	3.8	2.3	18.5	7.9	Na-Mg-HCO3
K38/1181	2388575	5673390	n/a	64.0	27.0	9.6	4.8	2.7	8.7	18.0	Ca-HCO3

Shallow wells (continued)

well ID	easting	northing	depth (m)	Alkalinity (mg HCO$_3$/L)	Calcium (mg Ca/L)	Chloride (mg Cl/L)	Magnesium (mg Mg/L)	Potassium (mg K/L)	Sodium (mg Na/L)	Sulphate (mg SO$_4$/L)	Water-Type
K38/1298	2378678	5672636	7.0	47.0	16.0	10.0	5.0	1.3	10.0	10.0	Ca-Na-HCO3
K38/1314	2387447	5668882	8.0	51.0	24.0	10.0	3.6	1.3	8.1	19.0	Ca-HCO3
K38/1357	2389030	5667470	6.0	48.0	22.0	13.0	3.8	1.7	9.0	16.0	Ca-HCO3
K38/1358	2386660	5675800	10.0	40.0	14.0	4.0	1.9	1.1	4.7	6.3	Ca-HCO3
K38/1381	2383680	5679370	22.5	58.0	20.0	5.8	3.9	1.3	5.8	14.0	Ca-HCO3
K38/1443	2386500	5674150	11.8	47.0	19.0	4.2	2.4	1.2	5.6	9.4	Ca-HCO3
K38/1540	2384924	5664799	6.0	58.0	11.0	6.5	3.4	0.8	7.8	2.5	Ca-Na-HCO3
K38/1704	2386036	5665617	29.3	63.0	11.0	5.7	3.6	0.8	7.8	2.4	Ca-Na-HCO3
K38/1800	2385599	5668379	12.4	50.0	18.0	11.0	4.8	1.5	10.0	12.0	Ca-HCO3
K38/1801	2385159	5667741	12.5	68.0	30.0	20.0	9.2	1.7	17.0	21.0	Ca-Na-HCO3
K38/1802	2382874	5671368	16.0	57.0	29.0	17.0	9.3	1.5	17.0	17.0	Ca-Na-HCO3
K38/1821	2389390	5667312	19.4	66.0	20.0	8.2	4.5	1.1	9.8	7.8	Ca-HCO3
K38/1869	2385853	5673492	11.0	45.0	18.0	4.1	2.2	1.1	5.5	8.7	Ca-HCO3
K38/1892	2394257	5674299	4.6	38.0	14.0	6.6	4.7	1.0	9.9	14.0	Ca-Na-HCO3
K38/1894	2395294	5672876	9.1	59.0	17.0	9.8	5.4	1.0	12.0	14.0	Ca-Na-HCO3
K38/1933	2396490	5673990	7.0	61.0	20.0	16.0	6.9	1.2	17.0	23.0	Ca-Na-HCO3
K38/1934	2393560	5671390	6.0	54.0	19.0	9.0	7.0	1.5	12.0	18.0	Ca-Mg-HCO3
K38/2096	2381598	5664448	7.0	41.0	18.0	17.5	5.0	1.5	20.8	19.0	Na-Mg-HCO3-Cl
K38/2111	2383690	5671990	8.6	38.0	21.0	13.0	6.4	1.3	12.0	15.0	Ca-Na-HCO3-Cl
K38/2200	2398896	5674183	6.0	60.1	21.3	32.0	8.8	2.4	26.1	26.1	Na-Mg-HCO3-Cl
K38/2273	2376445	5675335	n/a	40.0	16.0	8.0	3.7	1.0	6.9	11.0	Ca-HCO3
K38/2274	2382354	5663035	9.5	86.0	19.0	16.0	6.7	1.0	11.0	8.4	Ca-Mg-HCO3

Deep wells

well ID	easting	northing	depth (m)	Alkalinity (mg HCO$_3$/L)	Calcium (mg Ca/L)	Chloride (mg Cl/L)	Magnesium (mg Mg/L)	Potassium (mg K/L)	Sodium (mg Na/L)	Sulphate (mg SO$_4$/L)	Water-Type
K36/0973	2370288	5711165	58.5	67.0	16.0	4.9	2.4	0.9	6.9	2.5	Ca-HCO3
K37/0083	2380346	5697656	41.0	73.1	20.0	6.6	7.2	1.2	10.1	11.4	Ca-Mg-HCO3
K37/0103	2378393	5695847	46.0	62.0	13.0	3.4	5.5	1.0	7.7	7.4	Ca-Mg-HCO3
K37/0269	2376214	5696104	45.0	37.0	9.4	3.1	3.4	0.8	4.4	5.1	Ca-Mg-HCO3
K37/0356	2378103	5692847	48.0	59.0	13.0	4.3	5.9	0.9	7.5	5.6	Ca-Mg-HCO3
K37/0493	2374995	5692491	36.0	46.4	10.3	2.6	3.5	0.9	6.4	5.3	Ca-Na-HCO3
K37/0813	2375949	5689765	39.8	57.0	12.0	2.4	4.6	1.0	6.4	5.8	Ca-Mg-HCO3
K37/0944	2385145	5694190	35.9	63.0	16.0	4.3	5.1	1.0	8.4	4.1	Ca-Mg-HCO3
K37/1312	2379710	5681440	78.0	65.0	15.0	4.8	5.1	0.9	8.0	3.8	Ca-Mg-HCO3
K37/1531	2381291	5694811	101.3	64.0	17.0	4.9	4.8	1.0	8.3	3.8	Ca-HCO3
K37/1532	2380706	5694432	154.0	64.0	17.0	5.0	3.8	0.9	7.4	3.8	Ca-HCO3
K37/1563	2377898	5699518	48.4	64.3	15.8	4.9	6.1	1.1	8.6	4.0	Ca-Mg-HCO3
K37/1668	2384670	5691935	58.4	61.0	17.0	4.8	4.8	1.0	8.3	3.2	Ca-HCO3
K37/1793	2383831	5693275	125.6	62.0	17.0	4.7	5.2	1.1	8.8	5.4	Ca-HCO3
K37/1999	2384768	5692867	61.5	61.0	17.0	4.9	5.5	1.0	9.5	6.8	Ca-Mg-HCO3
K37/2130	2378795	5699625	76.6	55.5	16.0	6.1	6.1	1.1	8.2	2.7	Ca-Mg-HCO3
K37/2430	2372410	5690770	45.7	43.0	14.0	7.6	4.9	1.2	9.0	6.4	Ca-Na-HCO3
K37/2438	2381090	5699680	94.9	62.3	17.3	7.8	7.6	1.2	9.3	8.6	Ca-Mg-HCO3
K37/2468	2390477	5682200	78.1	62.0	16.0	6.5	3.6	1.5	8.5	1.8	Ca-HCO3
K37/2479	2374649	5704411	51.0	67.7	17.3	5.3	6.9	1.1	7.4	9.2	Ca-Mg-HCO3
K37/2543	2384024	5689116	39.5	32.0	12.0	3.3	3.8	0.9	6.1	13.0	Ca-Mg-HCO3
K37/2551	2377929	5699476	65.9	64.4	17.8	5.2	4.4	1.0	7.9	1.4	Ca-HCO3
K37/2591	2385200	5683650	113.2	65.0	21.0	6.8	6.6	1.1	9.4	13.0	Ca-HCO3
K37/2766	2393459	5681374	53.5	52.0	13.0	7.2	4.2	1.1	8.6	2.6	Ca-Na-HCO3
K37/3190	2374675	5706314	50.0	76.0	12.0	4.5	4.4	0.8	9.3	3.0	Ca-Na-HCO3
K38/0044	2384600	5671600	90.3	64.0	14.0	5.2	5.1	0.9	8.0	2.9	Ca-Mg-HCO3
K38/0264	2383332	5662559	41.3	63.0	11.0	5.8	3.5	0.7	8.3	1.7	Ca-Na-HCO3
K38/0459	2380933	5669890	66.2	53.9	13.2	7.6	3.9	0.8	7.8	2.3	Ca-Na-HCO3
K38/0604	2382565	5674844	65.5	50.0	14.0	6.8	4.0	1.0	8.0	4.9	Ca-Na-HCO3
K38/0690	2382475	5663456	43.7	63.3	11.9	6.1	3.7	0.8	8.4	1.7	Ca-Na-HCO3
K38/0715	2381386	5671996	85.9	61.0	12.0	5.2	3.6	0.8	7.4	2.0	Ca-Na-HCO3
K38/1020	2390788	5675673	84.4	63.0	13.0	7.4	3.5	1.0	9.4	1.7	Ca-Na-HCO3
K38/1097	2386240	5673750	81.9	64.0	14.0	4.6	4.3	0.9	8.5	2.9	Ca-Na-HCO3
K38/1316	2387320	5667700	119.4	65.5	12.0	4.3	3.6	0.8	8.3	2.6	Ca-Na-HCO3
K38/1354	2376008	5676139	71.4	56.0	13.0	3.9	3.2	0.7	6.6	1.4	Ca-HCO3
K38/1366	2379806	5670901	63.9	58.0	14.0	7.5	3.8	0.8	8.0	2.3	Ca-HCO3
K38/1379	2383680	5679370	131.0	87.0	31.0	6.6	3.5	1.4	6.0	16.0	Ca-HCO3
K38/1380	2383680	5679370	131.0	59.0	21.0	6.4	3.6	1.4	5.8	16.0	Ca-HCO3
K38/1402	2375461	5675455	68.0	54.0	13.0	4.3	3.4	0.9	5.4	5.7	Ca-HCO3
K38/1433	2378639	5673595	65.0	56.0	16.0	6.6	3.3	0.8	7.5	2.1	Ca-HCO3
K38/1512	2382124	5679669	186.1	72.0	14.0	5.0	4.9	0.9	9.1	2.2	Ca-Na-HCO3
K38/1691	2387260	5666500	85.3	67.0	14.0	4.8	4.9	0.9	8.3	2.5	Ca-Mg-HCO3
K38/1705	2389390	5667312	100.0	64.0	13.0	4.1	3.4	0.8	8.1	2.4	Ca-Na-HCO3
K38/1706	2389390	5667312	100.0	68.0	14.0	4.2	3.4	0.7	8.0	2.6	Ca-HCO3
K38/1707	2389390	5667312	100.0	89.0	24.0	3.9	2.8	0.9	8.3	3.0	Ca-HCO3
K38/1774	2392415	5674509	65.0	57.3	15.1	8.9	4.6	1.1	9.6	7.5	Ca-Na-HCO3
K38/1777	2387790	5667867	83.8	65.0	11.0	4.0	3.7	0.8	7.7	3.6	Ca-Na-HCO3
K38/1807	2397003	5675283	82.2	70.0	15.5	8.3	4.5	1.1	9.6	5.7	Ca-Na-HCO3
K38/1843	2394417	5679463	41.6	47.0	15.0	7.5	4.8	1.1	8.6	9.4	Ca-Na-HCO3

Surface water

site ID	description	easting	northing	Alkalinity (mg HCO$_3$/L)	Calcium (mg Ca/L)	Chloride (mg Cl/L)	Magnesium (mg Mg/L)	Potassium (mg K/L)	Sodium (mg Na/L)	Sulphate (mg SO$_4$/L)	Water-Type
SQ20177	Rangitata, Arundel	2373658	5691086	30.0	8.5	0.4	0.7	0.5	1.9	4.1	Ca-HCO3
SQ20176	Rangitata, SH1	2381961	5682866	51.0	8.2	2.0	5.2	0.9	6.3	6.55	Mg-Ca-HCO3
SQ20201	Orari, SH1	2374600	5674000	42.0	10.0	2.1	2.4	0.6	4.3	4.2	Ca-HCO3

Appendix H: General hydrochemistry

These data are from the same source as those in Appendix F. Values represent the average recorded concentration. The Ca/Mg ratio is the average ratio (not the averaged Ca concentration over the averaged Mg concentration). Silica concentrations in groundwater represent dissolved silica, whereas silica in surface water samples reflects reactive silica and is reported in units of SiO_2/L. In the map of measured silica concentrations (Figure 5-4) surface water data were converted to mg Si/L units (i.e. half the value of silica concentrations listed here). n/a denotes not analysed, or not applicable. Censored nitrate data, reported below method detection limits have been processed using the probability plotting procedure described by Helsel and Cohn (1988).

Shallow wells

well ID	easting	northing	depth (m)	conductivity (field) (mS/m)	dissolved oxygen (field) (mg O_2/L)	temperature (field) (°C)	iron (II) (mg Fe/L)	manganese (II) (mg Mn/L)	$\delta^{18}O$ (‰)	pH (field)	potassium (mg K/L)	silica (mg Si/L)	sulphate (mg SO_4/L)	nitrate (mg N/L)	Ca/Mg ratio (mg Ca/L / mg Mg/L)	water-type
J37/0012	2369294	5690027	6.7	14.3	9.1	11.0	0.067	0.500	-9.3	6.0	1.0	14.3	8.0	3.7	3.9	Ca-HCO3
J37/0027	2369420	5698600	13.0	n/a	n/a	n/a	0.050	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
J37/0225	2368967	5690277	15.6	17.7	4.2	12.7	0.035	0.085	n/a	6.5	1.2	16.3	6.8	3.9	2.5	Ca-Mg-HCO3
K37/0038	2391530	5686260	9.1	12.6	9.9	14.1	0.060	0.005	-9.1	n/a	0.8	12.0	11.0	5.3	3.0	Ca-Mg-HCO3
K37/0044	2386216	5681070	18.6	19.4	8.3	12.5	0.015	0.005	-9.1	n/a	1.3	18.0	12.0	6.3	3.3	Ca-Na-HCO3
K37/0089	2379762	5694277	30.0	17.1	7.4	12.5	0.015	0.005	-8.7	6.6	0.9	19.0	13.0	4.8	2.7	Ca-Mg-HCO3
K37/0096	2383201	5684049	27.7	18.4	7.4	12.8	0.040	0.005	-9.3	n/a	1.2	18.0	11.0	5.4	2.7	Ca-Mg-HCO3
K37/0102	2379229	5698131	28.4	14.0	8.3	12.4	0.015	0.005	-9.7	6.1	0.9	18.0	8.4	4.2	2.9	Ca-Mg-HCO3
K37/0130	2374017	5684048	15.9	14.1	16.7	12.2	0.124	0.006	-8.3	6.3	0.9	15.3	7.0	4.6	3.3	Ca-Na-HCO3
K37/0231	2389918	5684915	9.7	n/a	n/a	n/a	0.050	0.010	n/a	n/a	0.8	n/a	8.1	4.3	2.5	n/a
K37/0232	2388159	5683226	8.9	13.6	n/a	13.1	0.015	0.005	-8.9	6.5	0.9	n/a	11.3	5.3	3.1	Ca-Mg-HCO3
K37/0234	2385155	5684134	15.6	25.1	8.2	12.7	0.097	0.030	-9.1	6.5	1.2	18.4	13.5	7.5	3.1	Ca-Mg-HCO3
K37/0243	2389758	5687962	21.3	17.8	6.2	12.8	0.040	0.005	-9.2	6.5	1.0	16.7	6.8	6.4	2.8	Ca-Na-HCO3
K37/0245	2384890	5686732	19.8	20.7	8.1	12.6	0.110	0.007	-9.2	6.2	1.1	17.9	14.6	8.3	3.3	Ca-HCO3
K37/0260	2382159	5692573	25.3	20.6	6.9	12.7	0.459	0.050	-9.2	6.8	1.2	19.0	10.6	6.5	2.8	Ca-Mg-HCO3
K37/0268	2373714	5693882	13.1	0.2	n/a	12.2	0.030	0.005	-8.8	6.3	1.7	17.0	12.0	5.0	3.5	Ca-Na-HCO3
K37/0339	2384300	5683200	13.5	19.0	9.4	12.8	0.015	0.005	-9.1	n/a	1.1	19.0	11.0	6.8	3.1	Ca-Mg-HCO3
K37/0413	2385100	5694300	9.0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	4.0	2.5	3.2	n/a
K37/0465	2370449	5693176	5.8	11.4	9.3	11.2	1.370	0.005	-8.0	6.1	1.0	15.9	4.5	2.7	3.6	Ca-Na-HCO3
K37/0499	2380050	5683220	6.6	6.0	5.1	14.5	1.500	0.030	n/a	7.2	0.7	6.8	1.4	0.1	10.9	n/a
K37/0500	2379141	5684048	7.3	5.6	5.0	13.9	6.600	0.190	n/a	7.2	0.7	6.2	1.7	0.0	10.7	n/a
K37/0562	2390152	5684941	9.1	16.4	8.1	12.7	0.045	0.005	-9.1	6.0	0.8	13.0	11.5	7.3	2.8	Ca-Mg-HCO3
K37/0595	2382054	5691690	26.0	20.4	8.3	12.5	0.030	0.005	-8.9	6.2	1.1	19.0	15.0	7.1	2.9	Ca-Mg-HCO3
K37/0664	2386200	5686200	18.0	18.3	8.9	13.6	0.015	0.005	-9.1	n/a	1.3	18.0	13.0	7.9	2.7	Ca-Mg-HCO3
K37/0671	2370793	5683098	7.6	8.3	7.6	11.6	0.015	n/a	-10.3	6.6	0.5	11.4	3.9	1.1	5.0	Ca-HCO3
K37/0684	2370161	5687957	8.0	n/a	n/a	n/a	0.011	0.001	-11.1	n/a	0.6	11.0	1.8	0.1	4.8	Ca-HCO3
K37/0717	2393589	5681905	10.0	20.0	5.7	15.7	0.015	0.005	-9.3	5.5	1.2	13.0	15.0	10.0	2.8	Ca-Mg-HCO3-Cl
K37/0801	2370510	5687720	n/a	n/a	8.0	n/a	0.240	0.011	-10.4	n/a	1.1	7.3	2.6	0.1	4.7	Ca-HCO3
K37/0871	2371358	5688424	9.0	13.2	6.9	10.1	0.015	n/a	-9.0	6.5	1.0	12.0	6.2	3.8	3.6	Ca-Na-HCO3
K37/1117	2392714	5680400	8.0	11.0	n/a	12.6	0.060	0.005	-9.4	6.2	1.1	n/a	15.7	6.6	2.9	Ca-Na-HCO3-Cl
K37/1118	2393000	5680800	7.0	18.3	7.4	15.0	0.015	0.005	-9.2	7.0	0.7	13.0	10.0	4.4	2.6	Ca-Mg-HCO3
K37/1134	2389300	5684500	11.9	9.7	9.5	13.4	0.030	0.005	-9.3	n/a	0.7	13.0	10.0	2.3	2.9	Ca-Na-HCO3
K37/1335	2382480	5681140	12.5	6.1	6.2	13.5	0.090	0.005	n/a	7.1	0.8	8.2	1.4	0.3	8.7	n/a
K37/1336	2383360	5680060	10.0	n/a	9.6	12.8	0.032	0.004	-9.3	n/a	1.8	10.0	12.0	4.3	6.6	Ca-HCO3
K37/1381	2380339	5681874	10.0	n/a	7.9	12.9	0.069	0.001	-10.0	n/a	0.7	7.2	4.7	0.5	9.2	Ca-HCO3
K37/1640	2372087	5689412	9.7	n/a	9.2	12.5	0.009	0.001	-8.4	n/a	0.8	15.0	6.3	2.7	3.4	Ca-Na-HCO3
K37/1786	2386153	5691277	23.0	12.5	6.8	13.4	0.160	0.005	-9.1	n/a	1.2	15.0	13.0	2.6	2.9	Ca-Na-HCO3
K37/2896	2370072	5687591	9.2	5.9	4.6	7.9	0.030	n/a	-10.9	6.8	0.3	9.3	1.7	0.1	4.6	n/a
K38/0006	2391768	5672485	10.1	140.9	n/a	12.7	0.015	0.005	-8.9	6.5	0.8	15.0	9.8	3.2	3.4	Ca-Na-HCO3
K38/0015	2382200	5670939	10.6	30.1	4.8	12.3	0.015	0.005	-9.0	6.3	1.3	15.0	14.0	16.8	3.4	Ca-Na-HCO3
K38/0037	2384600	5670500	10.1	21.4	8.7	11.7	0.015	0.005	-9.2	6.1	1.3	14.0	14.0	7.7	4.1	n/a
K38/0066	2387050	5666187	15.9	13.0	4.8	12.8	0.015	0.005	-8.3	7.0	0.8	17.0	2.9	0.7	3.3	Ca-Na-HCO3
K38/0102	2388929	5679667	12.3	16.5	9.0	12.6	0.015	0.005	-9.1	7.0	1.0	17.0	10.0	6.6	3.0	Ca-Na-HCO3
K38/0105	2382170	5662569	8.0	19.7	1.8	11.9	0.212	0.010	-8.6	6.8	1.0	17.8	10.0	0.1	2.9	Ca-Na-HCO3
K38/0106	2386030	5665630	12.0	30.7	9.0	12.1	0.550	0.005	-8.3	6.2	1.3	15.0	24.0	9.2	3.1	Ca-Na-HCO3-Cl
K38/0108	2385030	5666470	6.1	48.1	0.1	12.4	14.204	1.100	-7.8	6.2	2.7	18.0	15.3	4.4	2.8	Na-Mg-HCO3
K38/0111	2380200	5664500	n/a	n/a	7.0	12.1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	1.8	3.1	n/a
K38/0120	2379367	5666165	6.4	19.8	1.1	14.5	0.015	0.005	-9.2	5.8	1.8	15.0	16.0	5.6	4.0	Ca-HCO3
K38/0127	2383200	5671090	10.0	21.9	9.7	11.3	0.060	0.020	n/a	6.2	1.1	14.8	8.0	10.2	3.0	Ca-Na-HCO3
K38/0135	2385190	5677150	n/a	7.9	5.9	12.9	0.040	0.005	n/a	6.6	0.8	9.3	2.2	0.7	8.5	n/a
K38/0144	2380481	5675837	7.6	20.6	9.8	12.3	0.015	0.001	-8.9	6.3	1.1	14.1	10.6	8.8	3.4	Ca-Na-HCO3
K38/0148	2381239	5679037	9.1	13.8	8.8	11.8	0.138	0.020	-9.7	6.2	1.0	11.0	8.9	3.1	6.5	Ca-HCO3
K38/0153	2377400	5677500	7.8	16.1	10.5	13.4	0.015	0.005	-8.1	6.3	1.0	17.0	7.2	6.2	3.2	n/a
K38/0158	2373134	5679619	8.7	6.4	7.4	10.3	0.015	n/a	-10.9	6.9	0.4	10.0	2.3	0.2	4.8	Ca-HCO3
K38/0231	2382600	5663000	9.0	n/a	n/a	12.3	5.175	n/a	n/a	n/a	1.0	n/a	5.7	0.3	n/a	n/a
K38/0252	2398650	5674100	8.2	14.9	5.3	12.6	0.040	0.005	-8.6	6.1	1.1	15.3	24.7	10.9	2.9	Ca-Na-HCO3-Cl
K38/0253	2381700	5664200	15.0	n/a	n/a	12.1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	2.7	n/a	n/a
K38/0254	2379700	5667400	6.0	n/a	n/a	11.7	7.987	n/a	n/a	n/a	1.2	n/a	17.4	3.5	n/a	n/a
K38/0255	2380725	5665462	8.4	24.5	0.9	13.7	0.015	0.100	-8.7	6.1	1.6	14.0	27.0	6.8	3.4	Ca-Na-HCO3-Cl
K38/0356	2381982	5667409	9.1	39.1	8.6	12.1	0.503	0.005	-8.3	6.2	1.3	16.0	10.1	9.0	2.9	Na-Mg-Cl-HCO3
K38/0360	2385540	5673340	18.0	12.4	4.3	7.4	0.340	0.005	n/a	6.6	1.4	12.0	3.6	2.0	7.2	n/a
K38/0367	2379657	5668351	7.0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	11.2	n/a	n/a
K38/0371	2384128	5664001	7.9	50.1	3.3	13.5	0.030	0.005	-8.4	5.8	2.4	16.0	32.0	19.6	2.7	Na-Mg-HCO3-Cl
K38/0404	2380006	5669242	7.3	23.5	9.2	11.7	0.045	0.010	-8.5	6.2	1.5	16.4	14.4	9.6	3.1	Ca-Na-HCO3
K38/0409	2382000	5667089	7.0	25.4	7.9	14.0	0.400	0.005	-8.9	6.3	1.2	15.0	8.6	8.5	2.7	Ca-Na-HCO3
K38/0410	2378800	5673580	7.5	14.5	9.2	11.9	0.160	0.005	n/a	6.5	1.0	17.1	5.8	5.7	3.3	Ca-Na-HCO3
K38/0412	2395518	5675989	5.2	19.1	4.9	12.1	0.233	0.020	-9.0	6.1	1.5	14.3	15.5	7.6	3.3	Ca-Na-HCO3
K38/0473	2384078	5664042	21.5	n/a	4.8	11.9	0.315	n/a	n/a	n/a	0.7	n/a	1.8	1.5	2.6	Ca-HCO3
K38/0517	2389931	5675028	6.0	0.1	n/a	12.3	0.015	0.005	-9.8	6.4	0.6	8.4	4.5	0.5	4.9	Ca-HCO3
K38/0615	2392234	5675566	9.5	18.2	8.9	13.6	0.015	0.005	-9.0	7.1	1.1	16.0	14.0	7.2	3.0	Ca-Na-HCO3
K38/0637	2384310	5666020	8.0	67.0	1.8	12.3	15.548	0.050	-8.2	6.0	4.5	17.0	32.2	6.0	2.6	Na-Mg-HCO3-Cl
K38/0659	2375532	5675248	10.0	11.8	7.8	12.9	0.030	n/a	-10.0	6.6	0.8	12.0	6.5	2.4	4.3	Ca-HCO3
K38/0675	2392220	5679000	8.0	23.6	7.9	14.1	0.015	0.005	-9.0	7.0	1.2	16.0	17.0	12.3	2.9	Ca-Mg-HCO3-Cl
K38/0680	2385960	5672760	11.5	12.5	5.0	10.3	0.630	0.005	n/a	6.1	1.3	12.0	3.7	1.9	7.2	Ca-HCO3
K38/0683	2388190	5672870	6.0	12.8	5.9	7.0	1.600	0.005	n/a	6.1	1.4	11.0	4.9	2.1	7.4	n/a
K38/0684	2378260	5671543	16.0	20.5	10.2	11.2	0.050	n/a	-8.7	6.5	1.1	15.0	16.0	8.5	3.6	Ca-HCO3-Cl

Shallow wells (continued)

well ID	easting	northing	depth (m)	conductivity (field) (mS/m)	dissolved oxygen (field) (mg O_2/L)	temperature (field) (^oC)	iron (II) (mg Fe/L)	manganese (II) (mg Mn/L)	$\delta^{18}O$ ($^o/_{oo}$)	pH (field)	potassium (mg K/L)	silica (mg Si/L)	sulphate (mg SO_4/L)	nitrate (mg N/L)	Ca/Mg ratio (mg Ca/L / mg Mg/L)	water-type
K38/0698	2384924	5664799	6.0	n/a	n/a	11.1	5.416	n/a	n/a	n/a	n/a	n/a	n/a	9.6	n/a	n/a
K38/0747	2381215	5665006	6.7	23.6	4.2	12.7	0.015	0.005	-8.8	6.1	1.7	15.0	17.0	11.6	3.8	Na-Mg-HCO3-Cl
K38/0754	2396227	5678062	10.0	20.9	5.5	14.2	0.015	0.005	-9.1	5.4	1.1	14.0	19.0	8.9	2.7	Ca-Mg-HCO3-Cl
K38/0760	2381050	5664740	10.5	26.3	0.1	11.7	0.015	0.020	-8.6	6.8	1.3	17.0	10.0	4.1	3.0	Ca-Mg-HCO3
K38/0852	2377110	5675720	11.8	15.5	n/a	13.0	0.015	0.005	-8.8	6.0	1.0	15.0	8.9	4.8	3.9	Ca-HCO3
K38/0861	2383300	5675420	12.5	14.1	9.5	15.4	0.015	0.005	-9.9	6.1	1.1	12.0	9.8	3.0	6.0	Ca-HCO3
K38/0957	2380680	5668000	8.0	n/a	n/a	12.0	0.850	n/a	n/a	n/a	1.2	n/a	9.2	8.0	n/a	n/a
K38/0974	2394392	5679608	10.0	10.5	8.2	12.9	0.030	0.005	-9.1	6.3	0.8	13.0	13.0	5.9	2.7	Ca-Mg-HCO3
K38/0979	2388355	5672002	9.6	16.2	5.0	13.1	0.015	0.005	n/a	5.9	2.9	12.0	6.9	7.2	6.3	Ca-HCO3
K38/1017	2384158	5672289	12.0	20.8	7.9	11.7	0.024	0.005	-9.2	6.1	1.4	13.4	14.6	7.6	4.5	Ca-HCO3
K38/1032	2391695	5677473	7.9	18.8	8.7	15.3	0.015	0.005	-8.9	6.9	1.0	16.0	14.0	7.6	2.9	Ca-Na-HCO3
K38/1050	2391814	5669698	6.3	0.1	n/a	11.8	0.110	0.005	-9.5	6.3	0.7	8.2	9.4	1.4	4.8	Ca-HCO3
K38/1075	2381320	5670320	10.0	n/a	n/a	12.5	0.170	n/a	n/a	n/a	1.1	n/a	7.2	9.1	n/a	n/a
K38/1077	2382964	5669956	8.0	n/a	n/a	12.1	0.330	n/a	n/a	n/a	0.9	n/a	1.7	5.6	n/a	n/a
K38/1078	2380610	5665290	30.0	24.0	2.4	12.6	0.425	0.020	-8.8	6.2	1.2	14.0	24.4	4.8	3.4	Ca-HCO3-Cl
K38/1079	2382300	5666760	6.0	33.1	7.6	11.8	0.175	0.003	-8.5	6.2	1.7	14.0	14.0	12.3	2.7	Ca-Mg-HCO3-Cl
K38/1081	2381353	5670211	13.4	26.7	5.5	12.3	4.692	0.005	-8.6	6.5	1.1	15.0	8.1	1.7	2.9	Ca-HCO3
K38/1092	2378350	5679790	17.0	n/a	9.2	15.4	0.001	0.002	-8.8	n/a	1.4	15.0	11.0	7.7	3.8	Ca-HCO3
K38/1171	2381170	5665610	2.0	n/a	n/a	19.6	0.365	0.009	n/a	n/a	2.3	n/a	7.9	6.6	3.7	Na-Mg-HCO3
K38/1181	2388575	5673390	n/a	n/a	8.6	14.5	0.017	0.004	-9.1	n/a	2.7	9.7	18.0	5.4	5.6	Ca-HCO3
K38/1298	2378678	5672636	7.0	19.8	7.8	12.7	0.015	0.005	-8.8	6.0	1.3	17.0	10.0	7.6	3.2	Ca-Na-HCO3
K38/1301	2384830	5674650	6.0	8.3	5.0	13.5	0.015	0.005	n/a	7.0	0.9	11.0	1.8	0.7	7.9	n/a
K38/1302	2384930	5677340	12.1	10.6	6.1	7.9	0.015	0.005	n/a	6.1	0.9	11.0	2.1	2.3	6.0	n/a
K38/1314	2387447	5668882	8.0	22.3	9.7	12.9	0.015	0.005	-9.6	6.1	1.3	13.0	19.0	7.0	6.7	Ca-HCO3
K38/1357	2389030	5667470	6.0	14.1	6.1	13.9	0.100	0.005	n/a	6.9	1.7	12.0	16.0	6.9	5.8	Ca-HCO3
K38/1358	2386660	5675800	10.0	16.2	5.3	13.0	0.040	0.005	n/a	6.5	1.1	11.0	6.3	4.0	7.4	Ca-HCO3
K38/1372	2385223	5666882	6.7	n/a	9.7	12.0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	9.3	2.9	n/a
K38/1381	2383680	5679370	22.5	n/a	n/a	n/a	0.500	0.020	-9.4	n/a	1.3	13.0	14.0	3.7	5.1	Ca-HCO3
K38/1443	2386500	5674150	11.8	n/a	8.6	n/a	0.026	0.001	-9.3	n/a	1.2	10.0	9.4	3.0	7.9	Ca-HCO3
K38/1540	2384924	5664799	29.7	12.2	5.1	12.3	0.015	0.005	-8.8	7.6	0.8	17.0	2.5	0.5	3.2	Ca-Na-HCO3
K38/1704	2386036	5665617	29.3	13.1	5.7	12.6	0.015	0.005	-9.0	7.7	0.8	18.0	2.4	1.1	3.1	Ca-Na-HCO3
K38/1800	2385599	5668379	12.4	16.3	4.0	14.0	0.050	0.005	-9.1	6.1	1.5	13.0	12.0	7.0	3.8	Ca-HCO3
K38/1801	2385159	5667741	12.5	33.6	4.7	13.2	0.015	0.005	-8.2	6.3	1.7	16.0	21.0	14.2	3.3	Ca-Na-HCO3
K38/1802	2382874	5671368	16.0	33.1	7.7	12.3	0.015	0.005	-8.3	6.4	1.5	16.0	17.0	18.0	3.1	Ca-Na-HCO3
K38/1821	2389390	5667312	19.4	17.5	5.7	12.5	0.015	0.001	-9.3	6.7	1.1	17.0	7.8	2.9	4.4	Ca-HCO3
K38/1869	2385853	5673492	11.0	n/a	7.2	13.8	0.003	0.001	-9.3	n/a	1.1	10.0	8.7	2.7	8.2	Ca-HCO3
K38/1892	2394257	5674299	4.6	0.1	n/a	13.2	0.015	0.005	-8.9	5.9	1.0	16.0	14.0	6.5	3.0	Ca-Na-HCO3
K38/1894	2395294	5672876	9.1	0.1	n/a	11.7	0.040	0.005	-8.7	6.3	1.0	17.0	14.0	4.8	3.1	Ca-Na-HCO3
K38/1933	2396490	5673990	7.0	0.3	n/a	14.5	0.060	0.005	-8.5	5.8	1.2	17.0	23.0	6.6	2.9	Ca-Na-HCO3
K38/1934	2393560	5671390	6.0	0.2	n/a	12.5	0.050	0.005	-8.8	6.1	1.5	17.0	18.0	8.4	2.7	Ca-Mg-HCO3
K38/2096	2381598	5664448	7.0	24.1	2.6	12.7	0.015	0.005	-8.2	6.1	1.5	15.0	19.0	12.2	3.6	Na-Mg-HCO3-Cl
K38/2111	2383690	5671990	8.6	n/a	8.5	13.8	0.050	0.003	-9.3	n/a	1.3	12.0	15.0	11.2	3.3	Ca-Na-HCO3-Cl
K38/2200	2398896	5674183	6.0	33.2	1.0	12.9	0.103	0.093	-8.3	5.9	2.4	15.8	26.1	8.4	2.5	Na-Mg-HCO3-Cl
K38/2273	2376445	5675335	n/a	16.6	n/a	13.4	0.015	0.005	-9.3	6.1	1.0	14.0	11.0	5.4	4.3	Ca-HCO3
K38/2274	2382354	5663035	9.5	22.0	0.3	12.8	0.015	0.005	-8.4	6.9	1.0	17.0	8.4	1.2	2.8	Ca-Mg-HCO3

Deep wells

well ID	easting	northing	depth (m)	conductivity (field) (mS/m)	dissolved oxygen (field) (mg O_2/L)	temperature (field) (^oC)	iron (II) (mg Fe/L)	manganese (II) (mg Mn/L)	$\delta^{18}O$ ($^o/_{oo}$)	pH (field)	potassium (mg K/L)	silica (mg Si/L)	sulphate (mg SO_4/L)	nitrate (mg N/L)	Ca/Mg ratio (mg Ca/L / mg Mg/L)	water-type
K36/0973	2370288	5711165	58.5	14.7	8.0	16.3	0.005	0.005	-9.0	8.0	0.9	14.0	2.5	2.1	6.7	Ca-HCO3
K37/0083	2380346	5697656	41.0	19.7	8.9	12.2	0.068	0.005	-9.1	6.8	1.2	19.5	11.4	7.0	2.8	Ca-Mg-HCO3
K37/0103	2378393	5695847	46.0	16.1	6.3	12.5	0.050	0.005	-8.8	7.0	1.0	17.0	7.4	4.0	2.4	Ca-Mg-HCO3
K37/0262	2376650	5692418	32.6	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	6.0	1.6	n/a	n/a
K37/0269	2376214	5696104	45.0	11.4	7.6	12.5	0.040	0.005	-9.1	6.0	0.8	12.0	5.1	2.7	2.8	Ca-Mg-HCO3
K37/0356	2378103	5692847	48.0	16.2	8.1	13.0	0.015	0.005	-8.8	7.3	0.9	17.0	5.6	4.8	2.2	Ca-Mg-HCO3
K37/0493	2374995	5692491	36.0	12.0	9.6	12.2	0.050	0.020	-9.7	6.8	0.9	16.2	5.4	2.6	2.9	Ca-Na-HCO3
K37/0765	2374995	5692491	36.0	n/a	n/a	n/a	n/a	n/a	-9.1	n/a	n/a	n/a	n/a	n/a	n/a	n/a
K37/0813	2375949	5689765	39.8	13.1	8.2	12.3	0.015	0.005	-9.5	n/a	1.0	16.0	5.8	2.5	2.6	Ca-Mg-HCO3
K37/0944	2385145	5694190	35.9	17.5	5.4	12.9	0.015	0.005	-8.8	7.1	1.0	17.0	4.1	5.8	3.1	Ca-Mg-HCO3
K37/1311	2385145	5694190	35.9	8.2	6.1	13.6	5.600	0.110	-9.8	7.5	0.7	2.1	1.2	0.5	5.2	n/a
K37/1312	2379710	5681440	78.0	n/a	8.6	12.9	0.007	0.001	-9.2	n/a	0.9	16.0	3.8	2.0	2.9	Ca-Mg-HCO3
K37/1531	2381291	5694811	101.3	17.0	9.8	12.3	0.015	0.005	-9.2	7.2	1.0	17.0	3.8	4.7	3.5	Ca-HCO3
K37/1532	2380706	5694432	154.0	16.3	7.4	12.3	0.015	0.005	-9.3	7.3	0.9	17.0	3.8	4.9	4.5	Ca-HCO3
K37/1563	2377898	5699518	48.4	11.4	n/a	11.8	0.173	0.010	-9.1	7.2	1.1	n/a	4.0	6.0	2.6	Ca-Mg-HCO3
K37/1668	2384670	5691935	58.4	17.2	8.8	12.7	0.015	0.005	-9.3	7.0	1.0	17.0	3.2	4.9	3.5	Ca-HCO3
K37/1686	2384670	5691935	58.4	17.2	9.0	11.9	0.015	0.005	-9.1	7.0	0.9	18.0	3.3	6.7	2.9	n/a
K37/1793	2383831	5693275	125.6	17.7	9.0	12.3	0.015	0.005	-9.3	7.0	1.1	17.0	5.4	5.1	3.3	Ca-HCO3
K37/1951	2373757	5681013	118.5	11.1	3.4	13.1	0.015	n/a	-9.0	7.4	0.7	17.0	2.0	0.8	3.9	n/a
K37/1999	2384768	5692867	61.5	18.2	9.0	12.6	0.015	0.005	-9.3	6.7	1.0	18.0	6.8	5.5	3.1	Ca-Mg-HCO3
K37/2130	2378795	5699625	76.6	16.0	7.2	14.9	0.270	0.005	-8.5	7.2	1.1	17.5	2.7	8.8	2.6	Ca-Mg-HCO3
K37/2430	2372410	5690770	45.7	n/a	9.6	n/a	0.024	0.001	-8.0	n/a	1.2	17.0	6.4	4.9	2.9	Ca-Na-HCO3
K37/2438	2381090	5699680	94.9	18.5	7.3	12.6	0.015	0.002	-9.0	6.9	1.2	18.0	8.6	8.9	2.3	Ca-Mg-HCO3
K37/2468	2390477	5682200	78.1	12.1	9.5	14.0	0.050	0.005	-8.9	n/a	1.5	18.0	1.8	4.5	4.4	Ca-HCO3
K37/2479	2374649	5704411	51.0	19.7	10.2	11.3	0.030	0.005	-9.2	6.5	1.1	15.0	9.2	6.6	2.5	Ca-Mg-HCO3
K37/2543	2384024	5689116	39.5	13.0	9.1	13.3	0.015	0.005	-9.1	n/a	0.9	15.0	13.0	4.3	3.2	Ca-Mg-HCO3
K37/2551	2377929	5699476	65.9	13.6	11.0	11.6	0.060	0.005	-8.9	7.4	1.0	16.5	1.4	6.3	4.1	Ca-HCO3
K37/2591	2385200	5683650	113.2	n/a	n/a	n/a	0.015	0.005	n/a	n/a	1.1	17.0	13.0	9.6	3.2	Ca-HCO3
K37/2766	2393459	5681374	53.5	15.7	6.4	12.8	0.015	0.005	-9.0	7.1	1.1	16.0	2.6	5.7	3.1	Ca-Na-HCO3
K37/3190	2374675	5706314	50.0	13.8	2.8	12.8	0.150	0.005	-9.2	6.7	0.8	18.0	3.0	0.5	2.7	Ca-Na-HCO3
K38/0042	2382100	5670480	83.0	n/a	n/a	n/a	0.130	0.010	n/a	n/a	1.0	18.0	4.3	3.2	3.3	n/a
K38/0044	2384600	5671600	90.3	n/a	9.4	12.9	0.001	0.001	-9.5	n/a	0.9	17.0	2.9	1.6	2.7	Ca-Mg-HCO3
K38/0264	2383332	5662559	41.3	13.0	6.0	10.5	0.730	0.050	n/a	8.0	0.8	18.3	1.7	0.5	3.2	Ca-Na-HCO3
K38/0383	2380693	5665307	36.0	n/a	4.2	12.3	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.4	3.3	n/a
K38/0459	2380933	5669890	66.2	13.9	7.9	12.7	0.053	0.005	-8.7	6.9	0.8	15.9	2.3	3.2	3.4	Ca-Na-HCO3
K38/0604	2382565	5674844	65.5	15.8	7.3	13.2	0.015	0.005	-9.4	6.7	1.0	16.0	4.9	4.4	3.5	Ca-Na-HCO3
K38/0690	2382475	5663456	43.7	13.1	5.8	13.0	0.065	0.005	-8.6	7.5	0.8	18.1	2.8	1.1	3.1	Ca-Na-HCO3
K38/0715	2381386	5671996	85.9	13.3	6.5	13.3	0.015	0.005	-9.2	7.7	0.8	18.0	2.0	1.3	3.3	Ca-Na-HCO3
K38/1020	2390788	5675673	84.4	14.0	7.4	13.0	0.015	0.005	-8.9	7.2	1.0	18.0	1.7	2.1	3.7	Ca-Na-HCO3
K38/1097	2386240	5673750	81.9	n/a	8.1	13.6	0.008	0.001	-9.0	n/a	0.9	17.0	2.9	0.9	3.3	Ca-Na-HCO3
K38/1316	2387320	5667700	119.4	12.1	8.0	13.6	0.002	0.005	-9.4	7.7	0.8	19.5	2.6	0.3	3.3	Ca-Na-HCO3
K38/1354	2376008	5676139	71.4	12.3	9.2	12.7	0.001	0.001	-9.1	7.3	0.7	16.0	1.4	2.5	4.1	Ca-HCO3
K38/1366	2379806	5670901	63.9	15.2	5.1	12.7	0.015	0.005	-8.3	7.4	0.8	16.0	2.3	3.4	3.7	Ca-HCO3
K38/1379	2383680	5679370	131.0	n/a	n/a	n/a	0.950	0.040	-9.4	n/a	1.4	19.0	16.0	3.6	8.9	Ca-HCO3
K38/1380	2383680	5679370	75.0	n/a	n/a	n/a	0.720	0.040	-9.4	n/a	1.4	12.0	16.0	3.8	5.8	Ca-HCO3
K38/1402	2375461	5675455	68.0	10.8	7.6	12.6	0.015	n/a	-9.9	6.3	0.9	14.0	5.7	2.4	3.8	Ca-HCO3
K38/1433	2378639	5673595	65.0	15.3	2.4	12.7	0.015	0.005	-8.3	7.3	0.8	16.0	2.1	3.8	4.8	Ca-HCO3
K38/1512	2382124	5679669	186.1	n/a	9.4	13.9	0.001	0.001	-8.9	n/a	0.9	17.0	2.2	1.0	2.9	Ca-Na-HCO3
K38/1691	2387260	5666500	85.3	n/a	8.8	13.7	0.006	0.001	-9.4	n/a	0.9	18.0	2.5	0.9	2.9	Ca-Mg-HCO3
K38/1705	2389390	5667312	100.0	12.4	9.1	13.2	0.015	0.005	-9.2	7.9	0.8	20.0	2.4	0.1	3.8	Ca-Na-HCO3
K38/1706	2389390	5667312	72.5	12.9	7.9	13.2	0.015	0.005	-9.2	8.5	0.7	20.0	2.6	0.2	4.1	Ca-HCO3
K38/1707	2389390	5667312	34.0	16.0	6.8	12.7	0.015	0.005	-9.2	10.0	0.9	18.0	3.0	0.3	8.6	Ca-HCO3
K38/1774	2392415	5674509	65.0	15.0	7.2	12.7	0.075	0.005	-8.9	6.6	1.1	15.3	7.4	4.8	3.4	Ca-Na-HCO3
K38/1777	2387790	5667867	83.8	12.5	6.2	12.7	0.015	0.005	-9.4	7.3	0.8	18.0	3.6	0.7	3.0	Ca-Na-HCO3
K38/1807	2397003	5675283	82.2	15.3	5.7	12.9	0.040	0.001	-9.0	6.6	1.1	15.3	5.8	2.8	3.5	Ca-Na-HCO3
K38/1843	2394417	5679463	41.6	n/a	n/a	n/a	0.040	0.005	-9.1	n/a	1.1	15.0	9.4	6.2	3.1	Ca-Na-HCO3

Surface water

SITE ID	easting	northing	source	conductivity (field)	dissolved oxygen (field)	temperature (field)	iron (II)	manganese (II)	$\delta^{18}O$	pH (field)	potassium	(reactive) silica	sulphate	nitrate	Ca/Mg ratio	water-type
				(mS/m)	(mg O_2/L)	(^oC)	(mg Fe/L)	(mg Mn/L)	($^o/_{oo}$)		(mg K/L)	(mg SiO_2/L)	(mg SO_4/L)	(mg N/L)	(mg Ca/L / mg Mg/L)	
SQ20166	2369622	5687318	ORARI RIVER	n/a	9.5	11.5	0.0	0.0	n/a	n/a	n/a	n/a	2.0	0.1	4.7	n/a
SQ20166	2369622	5687318	ORARI RIVER	0.1	10.2	11.8	0.0	0.0	-9.6	7.9	n/a	5.8	4.3	0.3	9.2	n/a
SQ20175	2390916	5667967	RANGITATA RIVER	0.1	10.2	11.4	0.0	0.0	-9.8	7.9	0.9	8.4	6.6	0.6	6.7	n/a
SQ20176	2381961	5682866	RANGITATA RIVER	0.1	10.6	10.5	0.0	0.0	-10.2	8.0	0.5	5.4	4.1	0.1	11.8	Mg-Ca-HCO3
SQ20177	2373658	5691086	RANGITATA RIVER	n/a	11.9	8.0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.0	n/a	Ca-HCO3
SQ20178	2370000	5709900	RANGITATA RIVER	n/a	10.5	11.5	n/a	n/a	-11.1	n/a	0.6	11.0	4.2	0.5	4.2	n/a
SQ20201	2374600	5674000	ORARI RIVER	n/a	11.4	7.7	n/a	n/a	-10.1	n/a	n/a	n/a	n/a	0.0	n/a	Ca-HCO3
SQ20284	2388600	5671700	F W WALLACE	n/a	7.4	11.6	n/a	n/a	n/a	n/a	n/a	n/a	n/a	1.0	n/a	n/a
SQ20306	2376000	5674400	TAUMATAKAHU STREAM	n/a	9.1	12.5	n/a	n/a	n/a	n/a	n/a	n/a	n/a	5.6	n/a	n/a
SQ20513	2389300	5670100	SALMON FARM	n/a	9.9	10.7	n/a	n/a	n/a	n/a	n/a	n/a	n/a	4.2	n/a	n/a
SQ20540	2378710	5666930	FITZGERALD DRAIN	n/a	8.4	11.4	n/a	n/a	n/a	n/a	n/a	n/a	n/a	5.1	n/a	n/a
SQ20541	2380506	5665336	PETRIES DRAIN	n/a	8.0	10.8	n/a	n/a	n/a	n/a	n/a	n/a	n/a	4.3	n/a	n/a
SQ20542	2380100	5664630	PETRIES DRAIN	n/a	8.1	10.8	n/a	n/a	n/a	n/a	n/a	n/a	n/a	3.7	n/a	n/a
SQ20543	2380660	5664110	SETTLEMENT ROAD DRAIN	n/a	9.0	12.2	n/a	n/a	n/a	n/a	n/a	n/a	n/a	6.7	n/a	n/a
SQ20544	2382767	5661704	OLD ORARI LAGOON OUTFA	n/a	9.4	12.0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	8.6	n/a	n/a
SQ20545	2382736	5663326	RHODES STREAM	n/a	10.1	11.2	n/a	n/a	n/a	n/a	n/a	n/a	n/a	5.8	n/a	n/a
SQ20546	2382000	5664000	RHODES STREAM	n/a	7.1	11.4	n/a	n/a	n/a	n/a	n/a	n/a	n/a	8.3	n/a	n/a
SQ20547	2383360	5663610	ROSS DRAIN	n/a	7.2	11.6	n/a	n/a	n/a	n/a	n/a	n/a	n/a	11.0	n/a	n/a
SQ20548	2384210	5664070	YOUNGMANS DRAIN	n/a	11.8	11.7	n/a	n/a	n/a	n/a	n/a	n/a	n/a	7.8	n/a	n/a
SQ20597	2380800	5665700	ANCHOR PRODUCTS LTD	n/a	9.8	n/a	n/a	n/a	n/a	n/a	n/a	n/a	14.0	n/a	n/a	n/a
SQ20615	2382200	5662700	PARKE RD	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	75.0	n/a	n/a	n/a
SQ20681	2383400	5663600	ALPINE DAIRY PRODUCTS	n/a	7.1	13.5	n/a	n/a	n/a	n/a	n/a	n/a	n/a	9.4	n/a	n/a
SQ20694	2382300	5662800	ALPINE DAIRY PRODUCTS	n/a	8.6	11.3	n/a	n/a	n/a	n/a	n/a	n/a	n/a	2.8	n/a	n/a
SQ20703	2385250	5665550	ALPINE DAIRY PRODUCTS	n/a	9.9	14.0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.1	n/a	n/a
SQ20706	2385000	5667150	ALPINE DAIRY PRODUCTS	n/a	8.5	11.0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	2.5	n/a	n/a
SQ21056	2386100	5665700	ORARI RIVER	n/a	6.1	12.9	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.1	n/a	n/a
SQ21058	2377690	5667920	ORARI RIVER	n/a	6.3	11.1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.6	n/a	n/a
SQ21303	2380600	5665400	CANAL ROAD DRAIN/STREA	n/a	9.9	11.4	n/a	n/a	n/a	n/a	n/a	n/a	n/a	1.0	n/a	n/a
SQ21311	2378800	5667000	COOPERS CREEK	n/a	n/a	10.8	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.9	n/a	n/a
SQ22005	2381700	5664700	RHODES CREEK	n/a	8.4	13.6	0.0	0.0	n/a	n/a	n/a	n/a	6.5	1.8	4.5	n/a
SQ22031	2377736	5667965	ORARI RIVER	n/a	3.7	15.3	0.5	n/a	n/a	n/a	n/a	n/a	n/a	0.2	n/a	n/a
SQ25053	2380600	5664100	GROUNDWATER WELL	n/a	8.3	12.1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	8.1	n/a	n/a
SQ25054	2382300	5666500	ADP GROUNDWATER	n/a	10.0	15.8	n/a	n/a	n/a	n/a	n/a	n/a	n/a	5.0	n/a	n/a
SQ25058	2383200	5666400	ADP GROUNDWATER	n/a	n/a	16.0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.1	n/a	n/a
SQ25063	2381700	5663200	GROUNDWATER WELL	n/a	9.0	13.5	n/a	n/a	n/a	n/a	n/a	n/a	n/a	6.9	n/a	n/a
SQ25064	2382400	5666400	GROUNDWATER WELL	n/a	7.2	12.1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	1.5	n/a	n/a
SQ25066	2382200	5662900	ADP GROUNDWATER	n/a	n/a	13.0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	4.0	n/a	n/a
SQ25116	2393200	5674800	RANG - HINDS GROUNDWAT	n/a	n/a	13.7	n/a	n/a	n/a	n/a	n/a	n/a	n/a	2.2	n/a	n/a
SQ25121	2390000	5684900	RANG - HINDS GROUNDWAT	n/a	n/a	14.0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	3.8	n/a	n/a
SQ25122	2389800	5687900	RANG - HINDS GROUNDWAT	n/a	n/a	14.8	n/a	n/a	n/a	n/a	n/a	n/a	n/a	1.1	n/a	n/a
SQ25127	2385200	5694400	RANG - HINDS GROUNDWAT	n/a	n/a	15.3	n/a	n/a	n/a	n/a	n/a	n/a	n/a	3.2	n/a	n/a
SQ25162	2376100	5692200	WATER WELL	n/a	n/a	10.3	n/a	n/a	n/a	n/a	n/a	n/a	n/a	2.6	n/a	n/a
SQ25338	2392250	5683950	WHYTE WELL - FRISBYS RO	n/a	9.3	12.0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	6.0	n/a	n/a
SQ26064	2399293	5674641	TWENTY-ONE DRAIN	n/a	9.3	12.5	n/a	n/a	n/a	n/a	n/a	n/a	n/a	4.9	n/a	n/a
SQ26065	2398940	5674120	PYES DRAIN	n/a	9.1	13.1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	4.7	n/a	n/a
SQ26066	2398530	5673930	MADDISON DRAIN	n/a	9.4	11.8	n/a	n/a	n/a	n/a	n/a	n/a	n/a	4.3	n/a	n/a
SQ26067	2398229	5673793	GREENROCK RACE	n/a	10.2	12.6	n/a	n/a	n/a	n/a	n/a	n/a	n/a	5.4	n/a	n/a
SQ26068	2397620	5673370	STORMY DRAIN	n/a	8.7	13.0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	5.7	n/a	n/a
SQ26069	2397270	5672920	MCKEAGES DRAIN	n/a	9.0	12.7	n/a	n/a	n/a	n/a	n/a	n/a	n/a	5.7	n/a	n/a
SQ26070	2395980	5672230	CROWES DRAIN	n/a	8.5	12.7	n/a	n/a	n/a	n/a	n/a	n/a	n/a	5.3	n/a	n/a
SQ26071	2395400	5671740	YEATMANS DRAIN	n/a	9.1	12.8	n/a	n/a	n/a	n/a	n/a	n/a	n/a	5.4	n/a	n/a
SQ26072	2394360	5670770	TERRACE RACE	n/a	7.9	13.2	n/a	n/a	n/a	n/a	n/a	n/a	n/a	6.0	n/a	n/a
SQ26073	2392720	5671680	OAKDALE DRAIN	n/a	0.7	10.4	n/a	n/a	n/a	n/a	8.1	n/a	n/a	0.0	n/a	n/a
SQ26133	2384550	5665950	ANCHOR PRODUCTS LTD	n/a	n/a	n/a	n/a	n/a	n/a	n/a	2.0	n/a	n/a	5.4	n/a	n/a
SQ26134	2385200	5667100	ANCHOR PRODUCTS	n/a	6.8	10.4	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.9	n/a	n/a
SQ26144	2384010	5666090	ANCHOR PRODUCTS LTD	n/a	3.2	10.6	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.0	n/a	n/a
SQ26145	2385320	5665600	ANCHOR PRODUCTS LTD	n/a	14.4	14.2	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.0	n/a	n/a
SQ26146	2385230	5664820	ANCHOR PRODUCTS LTD	n/a	15.6	11.1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	3.5	n/a	n/a
SQ26147	2385690	5665570	KAPUNATIKI CREEK	n/a	12.4	14.4	n/a	n/a	n/a	n/a	n/a	n/a	n/a	6.3	n/a	n/a
SQ26148	2384720	5668700	KAPUNATIKI CREEK	n/a	n/a	n/a	n/a	n/a	n/a	n/a	130.0	n/a	12.0	7.0	6.0	n/a
SQ26217	2368594	5689160	ORARI RIVER	n/a	8.3	12.0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	4.8	n/a	n/a
SQ26221	2388439	5671713	MCKINNONS STREAM	n/a	8.0	11.5	n/a	n/a	n/a	n/a	n/a	n/a	n/a	3.9	n/a	n/a
SQ26222	2389200	5670420	MCKINNONS STREAM	n/a	7.0	10.5	n/a	n/a	n/a	n/a	n/a	n/a	n/a	3.9	n/a	n/a
SQ26346	2379100	5686110	EALING SPRINGS	n/a	7.3	10.8	n/a	n/a	n/a	n/a	n/a	n/a	n/a	2.1	n/a	n/a
SQ26347	2381030	5684490	EALING SPRINGS	n/a	7.7	10.3	n/a	n/a	n/a	n/a	n/a	n/a	n/a	1.5	n/a	n/a
SQ26348	2380250	5684970	EALING SPRINGS	n/a	8.3	10.0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	5.5	n/a	n/a
SQ26349	2382020	5683250	EALING SPRINGS	n/a	8.3	10.2	n/a	n/a	n/a	n/a	n/a	n/a	n/a	5.1	n/a	n/a
SQ26367	2382330	5683080	EALING SPRINGS	5.7	11.4	10.7	0.0	n/a	-10.7	7.6	n/a	8.7	1.6	0.1	4.8	n/a
SQ26862	2368560	5689190	ORARI RIVER	7.6	10.3	11.6	0.0	n/a	-10.2	7.0	n/a	11.0	6.7	1.9	4.4	n/a
SQ26863	2376800	5670280	ORARI RIVER	7.7	9.4	11.1	0.0	n/a	-10.7	6.7	n/a	9.9	5.1	0.9	4.9	n/a
SQ26866	2370850	5687310	COOPERS CREEK	22.1	12.9	13.6	0.0	n/a	-9.2	7.2	n/a	11.0	20.0	7.5	4.0	n/a
SQ26867	2378080	5667900	COOPERS CREEK	5.6	12.8	10.7	0.0	n/a	-10.9	8.1	n/a	7.7	1.9	0.1	4.5	n/a
SQ26876	2371990	5679960	DOBIES STREAM	7.3	7.3	9.7	0.0	n/a	-10.7	7.0	n/a	8.4	3.4	0.3	4.5	n/a
SQ26879	2373650	5675930	TE AO STREAM	24.2	12.2	14.9	0.0	0.0	-8.8	7.3	n/a	9.1	21.0	8.8	3.9	n/a
SQ26880	2380892	5665359	RHODES STREAM	n/a	9.5	10.8	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.0	n/a	n/a
SQ26928	2360696	5716990	RANGITATA RIVER	n/a	11.0	8.6	n/a	n/a	n/a	n/a	n/a	n/a	n/a	1.3	n/a	n/a
SQ26939	2370841	5690931	COOPERS CREEK	n/a	8.9	12.5	n/a	n/a	n/a	n/a	n/a	n/a	n/a	1.0	n/a	n/a
SQ26940	2370472	5692792	COOPERS CREEK	n/a	9.4	12.4	n/a	n/a	n/a	n/a	n/a	n/a	n/a	1.2	n/a	n/a
SQ26942	2370454	5697113	COOPERS CREEK	n/a	10.6	11.0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	1.3	n/a	n/a
SQ26943	2369226	5696752	KOWHAI STREAM	n/a	10.2	6.8	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.2	n/a	n/a
SQ26944	2368223	5696333	SCOTSBURN STREAM	n/a	10.2	12.3	n/a	n/a	n/a	n/a	n/a	n/a	n/a	1.1	n/a	n/a
SQ26945	2370304	5695174	EAST BRANCH COOPERS C	n/a	8.6	10.5	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.1	n/a	n/a
SQ26947	2368177	5699039	KOWHAI STREAM	n/a	9.3	11.5	n/a	n/a	n/a	n/a	n/a	n/a	n/a	1.0	n/a	n/a
SQ26948	2369967	5695676	KOWHAI STREAM	n/a	n/a	13.5	n/a	n/a	n/a	n/a	n/a	0.2	n/a	0.003	n/a	n/a

Appendix I: Hydrochemical transects

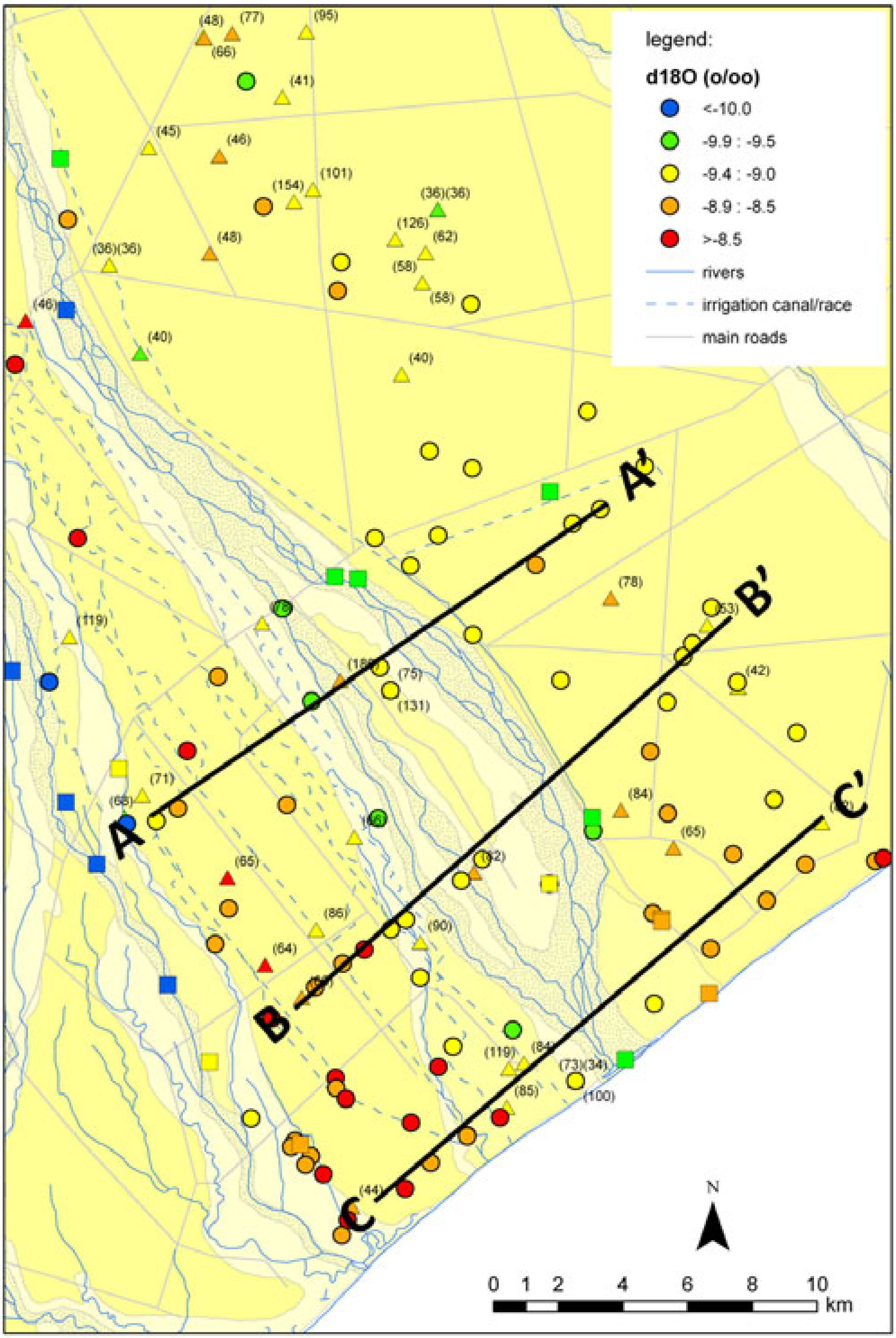


Figure I-1: Map showing hydrochemical transects plot in Figure 5-7. A-A' = SH1 transect; B-B' = Rangitata Island transect; C-C' = coastal transect

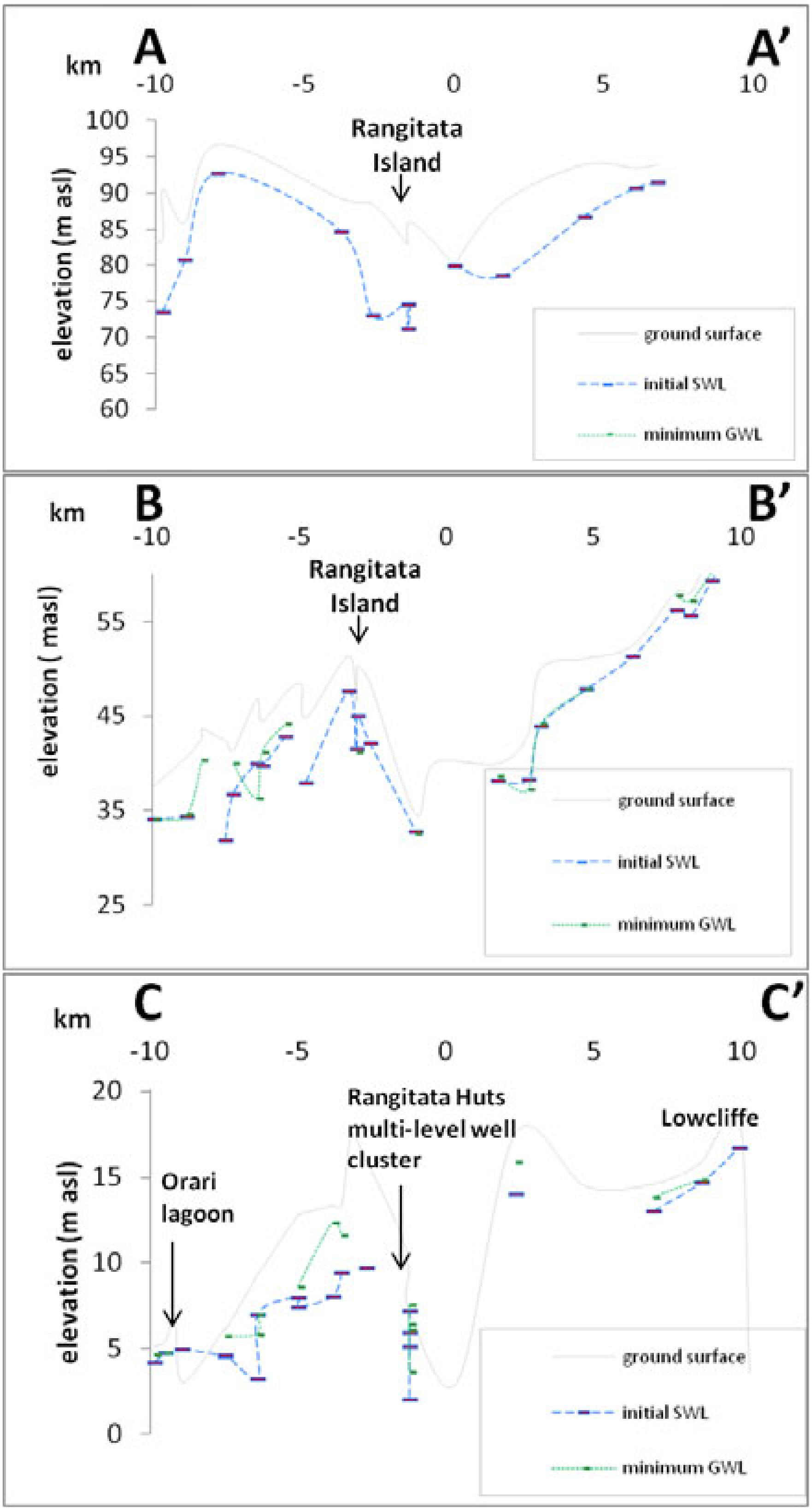


Figure I-2: Groundwater levels reported for wells featured in hydrochemical transects. Initial static water level (SWL) and minimum groundwater level (GWL) information extracted from wells database