Environment Canterbury Regional Council
Kaunihera Taiao ki Waitaha

TECHNICAL REPORT Science Group

# Coastal groundwater discharge in the Waimakariri zone

Report No. R19/79
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Zeb Etheridge

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Environment Canterbury
Regional Council
*Kaunihera Taiao ki Waitaha*

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# Summary


**Background**

This report investigates how much groundwater discharges to sea from the Waimakariri Canterbury Water Management Strategy (CWMS) zone, which stretches from the Waimakariri River mouth in the south to approximately 3.5 km north of the Ashley River/Rakahuri mouth in the north. The investigation helps to provide a firm foundation of hydrological knowledge to support the sub-region planning process.

**The problem**

Previous estimates of coastal discharge rates cover a broad range, from 3 to 10 m³/s. Understanding the rate of coastal discharge is important for both groundwater allocation and nutrient load limit setting. A high offshore flow rate could mean that some of the nutrient losses from the inland plains are likely to be transported offshore without affecting the water quality in lowland streams. Conversely, a low rate of offshore flow would suggest that higher groundwater allocation is more likely to have an impact on spring-fed streams, and that a greater proportion of nutrient losses from the inland plains will probably discharge to the lowland stream system.

**What I did**

I began by looking at a previously developed conceptual model of the coastal aquifer system, and then explored a range of hydrogeological data to see if the model is still valid.

I reviewed stratigraphy information from an offshore geophysical survey undertaken after the 2010-2011 Canterbury earthquakes. I analysed groundwater level data to establish whether the piezometric surface slopes towards the coast, and to estimate the gradient of this slope. I reviewed and re-analysed the pumping test data held in Environment Canterbury databases to estimate the transmissivity of the coastal zone aquifers and supplemented these data with transmissivity estimates derived from analysis of groundwater response to ocean tide fluctuations in several coastal wells. I also analysed groundwater quality data and reviewed previous groundwater age tracer data interpretations to see what insights this dataset provided into offshore groundwater flow.

After refining my conceptual understanding of the coastal aquifer system, I collated the hydraulic gradient and transmissivity data into likely upper and lower values and used some simple Darcy's Law calculations to provide estimates of the offshore flow rate.

**What I found**

I found that the offshore groundwater discharge rate is likely to be between 1.5 and 5.4 m³/s, with a median estimate of 2.5 m³/s. This is lower than most previous estimates. Offshore groundwater flow rates from the coastline between the Waimakariri River mouth and Pegasus Town are likely to be very low, less than 0.3 m³/s. Higher discharge rates are likely north of Pegasus Town. My analysis suggests that this may be because the seabed aquifers have a thinner capping layer of low permeability marine deposits in this northern part of Pegasus Bay. This allows more groundwater to seep out through the seabed. The lower outflow rate and density of spring-fed streams in the northern coastal zone could also play a role.

**What does it mean?**

Low offshore flow rates from the southern coastline section mean that nutrient loads from the inland plains are more likely to discharge to surface water bodies and groundwater abstractions than offshore. The higher offshore discharge rates along the northern coastline suggest that some nutrients are likely to be transported offshore there.

The Waimakariri Zone water budget needs to be reconsidered in light of these findings because it does not balance if previous estimates are substituted with the lower offshore discharge rate estimated here. Part of the difference may be accounted for by ungauged surface water flows in the lowland streams, principally the tidal reaches that cannot easily be measured. These findings were used in the development of our groundwater model for the zone.

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# 1 Introduction

## 1.1 Background

Environment Canterbury is working with the Waimakariri Water Zone Committee and local community as part of the Canterbury Water Management Strategy (CWMS) Waimakariri sub-regional plan development. One of the main purposes of the sub-regional plan is to set nutrient load and flow limits for the Waimakariri CWMS zone. Nutrient limits are a way of managing diffuse sources of nitrogen loss in the catchment; flow limits are used to help maintain flows in rivers and streams in order to protect ecological, recreational and aesthetic values.

Prior to the start of the limit setting process we undertook a gap analysis study, the main findings of which are presented in Dodson (2015). The aim of the study was to determine which components of the Waimakariri CWMS Zone hydrological system were both uncertain and critical to the outcomes of the planning process. One of the key components identified as needing further investigation was offshore groundwater discharge rates.

This report investigates offshore groundwater flow rates in the Waimakariri CWMS Zone; the outcomes will be used in later modelling of groundwater flow including potential impacts to lowland streams and nutrient transport to support the limit setting process.

My study area is the Waimakariri coastal area, stretching from the Waimakariri River mouth in the south to Ashworth Beach Road (approximately 3.5 km north of the Ashley River/Rakahuri mouth) in the north. The area is characterised by the Kaiapoi River and its spring-fed tributaries in the south and the Ashley River/Rakahuri and its coastal lagoon in the north (see Figure 1-1).

## 1.2 Previous studies

Dodson *et. al.* (2012) estimated offshore flow based on the residual of a water budget assessment for the Ashley – Waimakariri area. The mean recharge to groundwater was estimated to be ~17 cubic metres per second ($m^3/s$), with 1.7 $m^3/s$ of abstraction and 7 $m^3/s$ of discharge to the lowland streams and spring system. The balance of 8.2 $m^3/s$ (approximately 50% of the total outflow budget) was assumed to discharge offshore. This estimate for offshore discharge was slightly lower than the 10 $m^3/s$ estimate provided in Talbot (1980). The latter was based on a numerical modelling study, but much less data were available at that time to constrain the model parameters.

Brown and Weeber (2002) summarise water budget estimates developed by PDP (1993) for the area between the Waimakariri and Ashley Rivers. Offshore leakage was estimated at 2.9 – 3.5 $m^3/s$ based on a water balance analysis. Sanders (1997) assumed that groundwater in aquifers near the coast continues to flow underground beneath the coastline, and noted that if either the PDP (1993) or Talbot (1980) estimates were true, the annual outflow would be at least double the magnitude of groundwater abstractions estimated at that time (~1.2 $m^3/s$).

An unpublished Environment Canterbury draft report (Sanders, 2004) on development of a steady state groundwater model for the Ashely-Waimakariri plains states that: *Initial steady state model runs indicate that in an average year about 80% of the losses from groundwater are to springfed drains and streams, while the remainder is split almost evenly between pumping by wells and off-shore leakage*. The model was optimised to achieve a reasonable match between observed and model groundwater levels. Although the groundwater model water budget is not documented, the model total target flow rate in spring-fed streams was 7.5 $m^3/s$. This suggests that the total water budget for the zone was around 9.4 $m^3/s$ and the model offshore flow rate was approximately 1 $m^3/s$.

Dodson (2015) interviewed various groundwater practitioners with experience in the Waimakariri CWMS Zone regarding offshore groundwater discharge. Based on the responses, there appears to be a wide variation in opinion regarding the basic question of whether or not offshore groundwater discharge is occurring, as well as the possible discharge mechanisms and the quantum of flow if discharge is occurring. Similar lines of evidence were cited by the interviewees to support the different hypotheses. Dodson noted that the connection between the groundwater system and the ocean is particularly important if the aim is to determine the likely effects of abstraction on lowland streams. He recommended undertaking an investigation to refine our understanding of offshore groundwater discharge.

Golder (2013) reports that published literature is unanimous in estimating that the amount of groundwater flowing offshore within the upper aquifer from the Christchurch aquifer system (immediately south of the Waimakariri River) is small in relation to other contributors to the budget, perhaps less than 1 $m^3/s$ (Scott, 2010). This is somewhat at odds with some of the Waimakariri Zone estimates above, given that the Christchurch coast length (~19 km) is similar the Waimakariri Zone coast length (~16 km), and the depositional environments are broadly similar. Possible explanations include differences in groundwater discharge to surface water, upgradient recharge, hydraulic gradients and geological controls.

## 1.3 Report structure

In this report I take an existing conceptual model of the coastal aquifer system in Pegasus Bay as the starting point for my offshore flow analysis, and then interrogate a range of more recent hydrogeological data to see whether the model holds true, and if so what flow parameters can be applied to it. In the final part of the report I draw together the evidence from a range of datasets to provide an estimate of the rate of offshore groundwater discharge.

I discuss the existing conceptual model in Section 2, and then go on (Section 3) to review the geological data that have been collected since the conceptual model was developed.

In Section 4 I discuss how the coastal aquifer system has previously been conceptualised as a series of aquifers and aquitards, provide some estimates of the depths of glacial and interglacial period strata and review the vertical connectivity of the aquifer system.

Because offshore groundwater flow cannot happen in the absence of a hydraulic gradient, I explore available groundwater level data in Section 5 and discuss whether there is any evidence of an easterly slope in groundwater elevations from wells at various depths in the aquifer.

We know from Darcy's Law that the groundwater flow rate is a function of hydraulic gradient and aquifer transmissivity, so in Section 6 I collate and analyse aquifer test data from the Waimakariri CWMS Zone and adjacent Christchurch – West Melton Zone.

In Section 7 I investigate how coastal groundwater level response to ocean tide cycles can be used to provide further insights into the hydrogeology and parameterisation of the coastal zone aquifers.

In Section 8 I review the three main studies regarding isotope data analysis and the use of nitrate as a tracer in groundwater based on water quality data held in our database, to see if this information provides any insights into offshore groundwater flow from the Waimakariri CWMS zone.

In Section 9 I bring all of the above together to provide an estimate of the rate of offshore groundwater flow from the Waimakariri CWMS zone.

I provide an updated conceptual model of the coastal aquifer system in Section 10, followed by a summary of the main conclusions of the study and some recommendations for possible future work in Section 11.

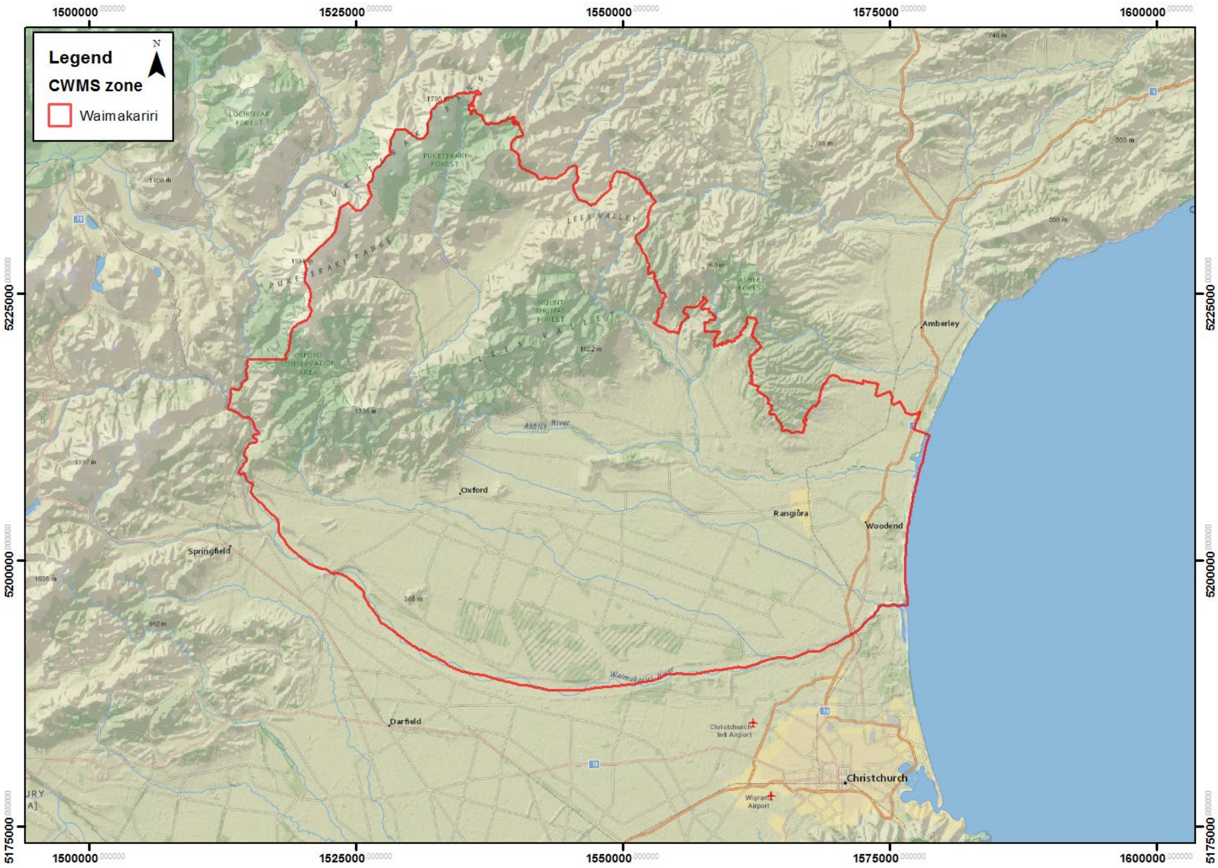


**Figure 1-1: Study area**

# 2 Current conceptualisation

Brown and Weeber (1992) provide a conceptual cross section of the hydrostratigraphy of the aquifer system near Christchurch (Figure 2-1). The model suggests that the Riccarton Gravel (Q2/Q4 strata) extends approximately 40 km offshore, outcropping in the seabed at around 50 m depth below sea level. Relatively unimpeded ocean discharge is possible through the Q2/Q4 strata seafloor outcrop under this conceptualisation. The underlying gravel units are considered to pinch-out offshore, with vertical leakage being the predominant means for any ocean discharge.

This cross section is based purely on a conceptual evaluation of the depositional environment, and does not incorporate the insights into Quaternary stratigraphy provided by offshore geophysical surveys. The rationale for the underlying gravel units pinching-out eastward is simply related to the decreasing flow velocity of river water with distance across a land surface with diminishing gradient. The decrease in velocity could potentially result in the grain size becoming progressively finer eastward, moving away from the sediment source (Southern Alps and foothills) [John Weeber, pers. comms.]. However it is not clear that this would necessarily be the case: coarse sediment could still have been transported significant distances by the Waimakariri during high flow periods.

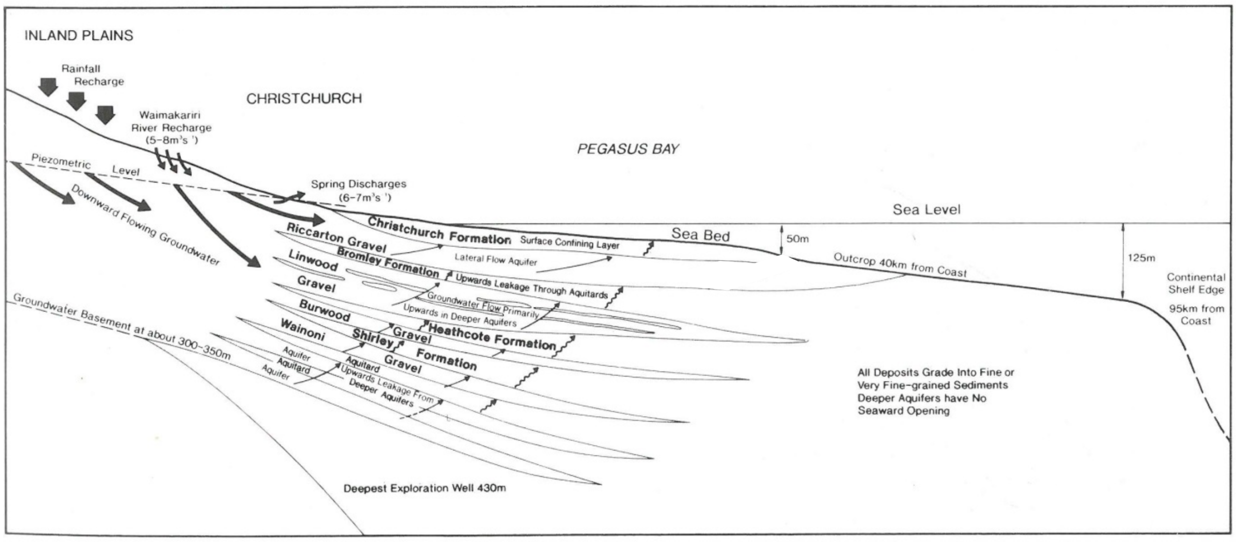


**Figure 2-1: Cross section of Pleistocene stratigraphy beneath northern Canterbury plains near Christchurch (NCCB 1986 modified by Brown and Weeber, 1992)**

In this report I use the term aquifer to refer to the generally more permeable sedimentary strata that were deposited in glacial periods in the coastal zone. Although these strata may comprise a series of discrete gravel lenses with limited lateral extent, within a broader matrix of finer material, they are as a whole believed to be more transmissive than the interglacial/marine deposits in the coastal zone, which I refer to as aquitards.

I generally use the QMap (Forsyth *et. al.,* 2008) naming convention in this report, but some diagrams use the local stratigraphic names. I have summarised the stratigraphic sequence under both naming conventions below for clarity.

**Table 2-1: Stratigraphic nomenclature**

| OIS | QMAP unit | Climate | Base Age (ka) | Climate Stage Name | Customary name | | |
|---|---|---|---|---|---|---|---|
| | | | | | Inland | Near coast | Offshore |
| 1 | Q1 | Warm | 10-14 | Holocene - Aranui | Springston Fm. | Christchurch Fm. | Pegasus Bay Fm. |
| 2<br>3<br>4 | Q2/ Q4 | Cold | 24<br>59<br>71 | Otira Glacial | Burnham Fm. | Riccarton Gravel | Canterbury Bight Fm. (Upper) |
| 5 | Q5 | Warm | 125 | Kaihunui Interglacial | - | Bromley Fm. | Canterbury Bight Fm. (Lower) |
| 6 | Q6 | Cold | 185-195 | Waimea Glacial | Woodlands Fm. | Linwood Gravel | |
| 7 | Q7 | Warm | 245 | Karoro Interglacial | - | Heathcote Fm. | |
| 8 | Q8 | Cold | 303 | Waimaunga Glacial | Hororata Fm. | Burwood Gravel | |
| 9 | Q9 | Warm | 339 | Brunswick Interglacial | - | Shirley Fm. | |
| 10 | Q10 | Cold | 362 | Nemona Glacial | Wainoni Gravel | | |

In this report I refer to groundwater at, or shallower than, 45-50 m depth, which is generally in the Q1 and Q2/Q4 strata, as *shallow* groundwater and to these strata as the *shallow aquifers*. Groundwater in the deeper material is referred to *deep groundwater* and the strata below 45-50 m depth as the *deep* or *deeper aquifers*. These terms are for descriptive convenience, and do not imply that we conceptualise the aquifer as hydraulically separate systems.

# 3 Geological data

## 3.1 Data sources

I have collected and reviewed geological information for the Waimakariri coastal zone in order to understand the potential for stratigraphic controls on groundwater flow, and how these vary within the study area. The main sources of geological data I reviewed to enhance my understanding of the study area geology were:

- A 1998 MSc thesis entitled: *A hydrogeological model for the Kaiapoi Aquifer system*
- A series of hand drawn cross sections drawn by former Environment Canterbury personnel in the late 1990s
- A 3D geological model developed by Environment Canterbury in 2011
- Two NIWA reports on interpretation of offshore geophysical data

Relevant information from these sources is summarised in the following report sections.

## 3.2 Lovell (1998) MSc thesis

Lovell (1998) developed a conceptual hydrogeological model of the Kaiapoi artesian aquifer system as part of his University of Canterbury MSc thesis. The study presents six geological sections of the Kaiapoi area based on well logs held in the Environment Canterbury database, and a fence diagram and three-dimensional (3D) hydrogeological model. Materials recorded on well logs were classified either as aquifers (defined as any material containing gravel) and aquitards (defined as any material not containing gravel) for the fence diagram and 3D model. The author notes that coarse sand deposits can behave as aquifers and gravels within a silt or clay matrix as aquitards. Whilst this simplistic classification limits the applicability of the fence diagram and hydrogeological model for this current study, the thesis contains a range of useful information on the local geology. I have summarised some of this in the following paragraphs.

### 3.2.1 Q1 deposits

Coastal fine sediments which have been deposited since the end of the Otiran (most recent) Glaciation 14,000 years ago are referred to as Christchurch Formation, or Q1 deposits. This formation principally comprises beach, inter-dune and swamp deposits in the coastal zone, consisting of sand, peat, silt and clay. An abundance of peat and fine sediment over the entirety of the former Kaiapoi Island (between the former north and south branches of the Waimakariri River) indicate that the area was covered in swamp and estuarine lagoon for much of the period since sea level stabilised c. 6,500 years ago.

Mapping the most westerly extent of marine shells present in the Q1 material (Christchurch Formation), along a line roughly between Kaiapoi and Woodend (approximately 6 km west of the present coastline), provides an indication of the inland limit of the shoreline prior to commencement of recent (post-glaciation) recession. The relatively fine Christchurch Formation sediments generally have orders of magnitude lower permeability than those of the underlying Q2/Q4 gravel, and because of this the Q1 material in the coastal zone are often referred to as the *coastal confining layer*. River erosion has removed these deposits in various places, however, replacing them with river gravels which provide enhanced connectivity between the ground surface and the deeper Q2/Q4 deposits.

The Christchurch formation reaches a thickness of up to 35 m at the coast, diminishing effectively to zero approximately 16 km inland. The thickness of the coastal fine sediments (clay/silt/peat/sand) decreases in a northerly direction along the Waimakariri CWMS zone coastal zone. The implication of this is an increase in the degree of connectedness between the deeper Q2/Q4 deposits (alluvial gravels) and near surface deposits to the north. This is an important transition that will change the nature of the offshore flow along the coast northwards.

### 3.2.2 Q2/Q4 and Q5 deposits

Known locally as the Riccarton Gravel, the Q2/Q4 strata comprise gravel-dominated sediments which were deposited during the most recent (Otiran) glaciation and generally vary between 20 and 40 m thickness in the Kaiapoi area. Lovell notes that a prominent laterally discontinuous blue peat horizon is present between 20 and 30 m depth here.

Lovell (1998) considers that the presence of sandy gravel in many of the well log sections classified as Bromley Formation (Q5) indicate that significant amounts of alluvial gravel were being laid down synchronously with deposition of sands and silts along the coast. The Bromley Formation strata present at the coast to the north of the study area display inter-layering of thin gravels and fine sand, whereas the Bromley Formation strata to the south show thicker layers of the alluvial and coastal deposits.

### 3.2.3 Q6 deposits

The Q6 deposits (Linwood Gravel) are the thickest alluvial deposits penetrated by wells in the area, being around 50 m thick in most wells. The Linwood Gravels and are generally logged as clean gravels, containing varying amounts of clay and sand matrix in some locations. In the Kaiapoi area two distinct peat/clay/silt beds represent breaks in gravel deposition.

### 3.2.4 Deeper strata

The Q7 (Heathcote Formation in Christchurch) is described as estuarine and marine beds underlying the Linwood Gravel (Brown and Wilson 1988). Lovell found that because few wells penetrate these strata in the Kaiapoi area, and fine sediments occur in well logs at varying depths, it was difficult to establish lateral continuity and correlation of the Heathcote layers on cross sections. This issue becomes more prevalent with depth in the Quaternary sequence, with a reducing number of well logs with depth and lateral variability in the material descriptions for those few logs that do penetrate the deeper strata. This means that generalised descriptions of sediment texture (and any associated inferences about transmissivity) are difficult and unreliable for the deeper parts of the Quaternary strata.

## 3.3 Hand-drawn cross sections

A series of hand-drawn geological cross sections through the Waimakariri zone created by John Weeber and John Hughey in the mid to late 1990s are held within our archives. The locations of the sections are shown on Figure 3-1 below and some of the cross sections are provided in Appendix 1. Of note for this project is the high sand content in the Q1 material shown on cross section M35:863-700. Although the permeability of medium to fine sand is one or more orders of magnitude less than that of gravel, meaning that groundwater discharge rates through this material are expected to be relatively low, the potential for diffuse upward seepage into this material from the underlying Q2/Q4 strata is potentially significant. The Q1 strata also include gravels and gravelly sand river channel deposits in some areas, associated with former courses of the Waimakariri River.

## 3.4 3D geological model

Dodson *et. al.* (2012) provide summary information on a geological model of the coastal confined aquifer system developed in Leapfrog Hydro by Durney *et al., (*2011), to visualise the coastal confined aquifer system and to examine whether there were geological barriers that would prevent seepage from the Waimakariri River flowing north. Durney *et al.* (2011) constructed the model in three steps:

1. Import a collar file of the bore logs. This file included all the relevant information (i.e. bore depth, strata and screen details etc.) used to construct the model
2. Classify strata-coded bore logs into units (either aquifer or aquitard) using Wilson's (1989) stratigraphic classification for the aquifer nomenclature
3. Construct a layer-cake model based on the grouped strata-coded bore logs.

The model boundaries were constrained to the inland extent of the confining layers and the base of the Quaternary deposits. Aquifer units were pinched out to the north. Jongens' (2011) data for the depth of Quaternary deposits were used to define the maximum possible depths of the units. But the model depth was also limited to the maximum depth of the bore log data in areas of deep Quaternary cover, to avoid interpolation errors. The locations of a series of cross sections extracted from the model are shown on Figure 3-1 below.

The model only defines the top and base of the glacial and interglacial strata, and does not provide information on the composition (grain size) of the material within each model layer. Information provided in Section 3.2 above indicates that the composition of the interglacial material is variable, with finer grained marine sediments being intersected by alluvial channel deposits. This means that modelling the coastal groundwater system as a series of laterally consistent aquifers (glacial stage deposits) and aquitards (interglacial stage deposits) could give misleading results. Furthermore, Lovell (1998) notes that because the Ashley River sediment source is foothills (rather than alpine as per the Waimakariri), the compositional contrast between glacial and interglacial period deposits may be lower. I discuss the implications of this for modelling the coastal zone groundwater system in Section 10.

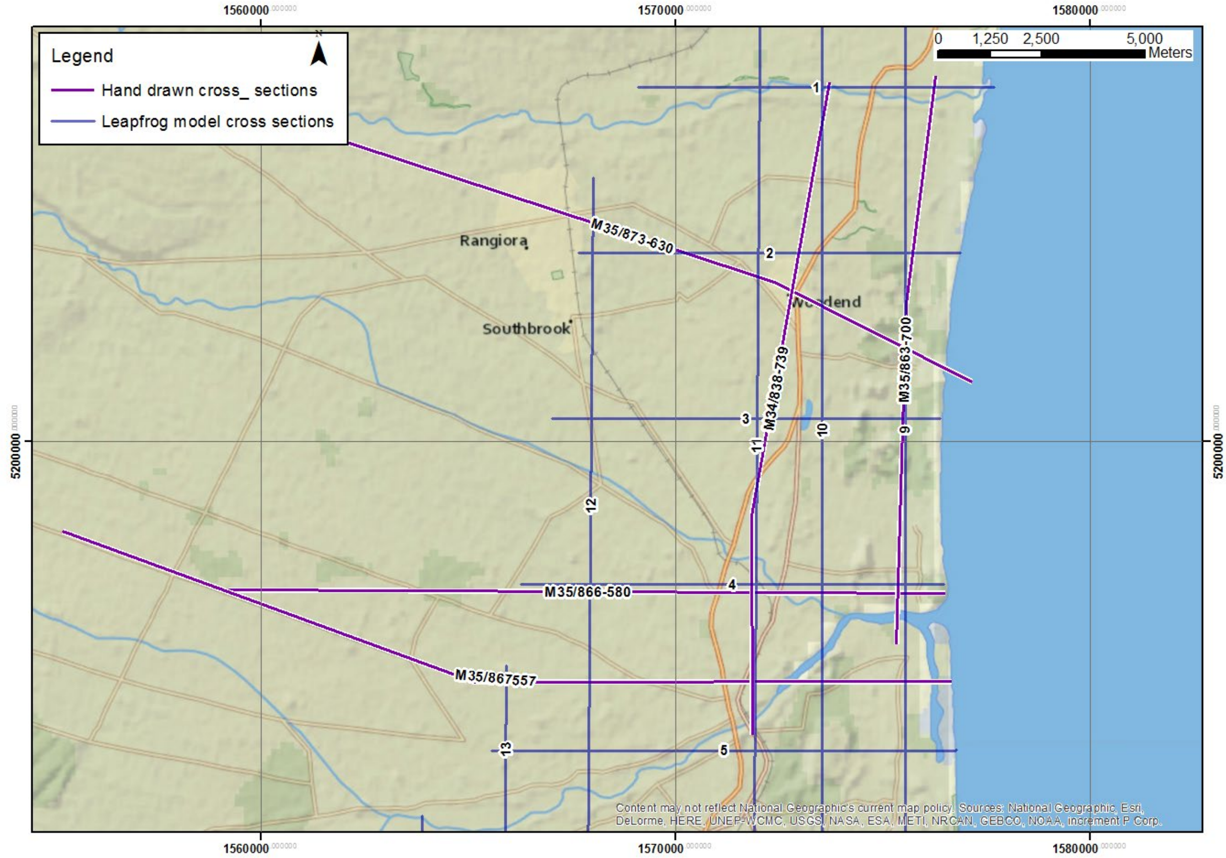


**Figure 3-1: Geological cross section locations**

## 3.5 Offshore geophysical surveys

The need to improve understanding of fault systems in Pegasus Bay since the 2010/2011 Christchurch earthquakes has driven various investigations of the seabed geology off the coast of the Waimakariri CWMS zone. Barnes *et.al*. (2011) interpreted geophysical data from surveys undertaken by NIWA in 2011 to contribute to understanding the wider crustal faulting and geological context of the 2010-2011 Canterbury earthquakes, and to determine whether or not active submarine faults capable of producing large earthquakes exist beneath Pegasus Bay.

Figure 3-2 below shows the fault structure presented in Barnes *et.al*. (2011). The locations of interpreted seismic stratigraphic sections marked in grey refer to figure numbers in the Barnes *et.al.* (2011). Although the fault structure shown below terminates at the shoreline because this is the termination of the survey, some of the faulting and folding is likely to continue eastwards. Davey *et. al.* (2012) interpreted a gravity anomaly lineament immediately east of the Pegasus Bay Fault, which may depict the fault alignment below the land surface.

The offshore geophysical surveys contain useful and potentially significant information on the offshore stratigraphic structure, but these data had not previously been processed to unlock this information. The focus of previous data interpretation was on understanding the fault system. Environment Canterbury therefore commissioned NIWA (Barnes, 2015) to undertake an exploratory re-interpretation of the data, to help us to understand what insights can be gained into the offshore aquifer structure from interpretation of the geophysical data.

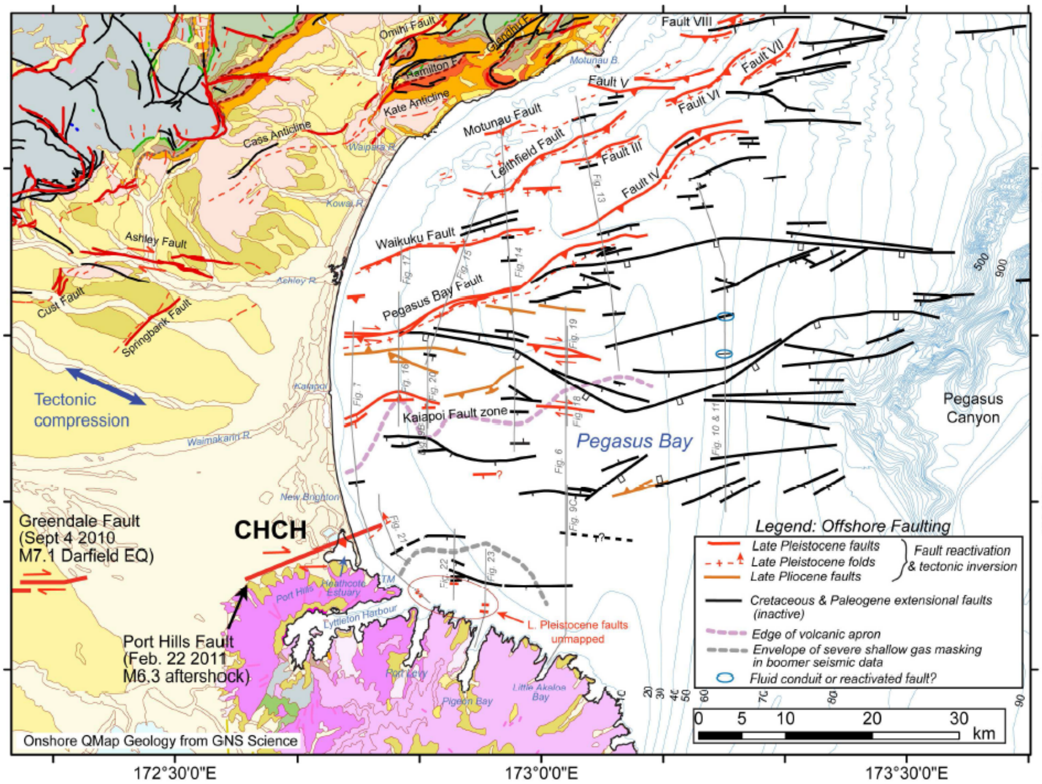


**Figure 3-2: Map of Pegasus Bay fault structure (from Barnes *et. al.,* 2011)**

Barnes (2015) reviewed three seismic reflection profiles acquired in Pegasus Bay in 2011, to evaluate the potential of such data for constraining the distribution of submarine aquifers and aquitards beneath Pegasus Bay. In particular, the study focussed on recognition of the Q2/Q4 (Riccarton Gravel and Linwood Gravel formations). Much of the information in Sections 3.5.1 and 3.5.2 are direct extracts from the Barnes report, which uses the Riccarton Gravel (Q2/Q4) and Linwood Gravel (Q6) terminology.

Barnes notes that the seismic profiles do not contain direct information on sediment grain size/layering characteristics. Reflection strength is a function of the impedance contrasts across the medium, which relate to physical properties such as velocity and density. However, the stratigraphic architecture provides some useful insights. For example, the fine grained marine sediments of the post-glacial sequence exhibit generally weak reflectivity with discontinuous but planar internal reflections, whereas localised channel-like irregular reflections within the Riccarton Gravel and Linwood Gravel formations would be consistent with (but not unique to) a fluvial or coastal environment.

Barnes (2015) provides a schematic model of marine sediment transport taken from Nokes (2014), which I have reproduced as Figure 3-3 below. The model indicates that fluvial deposition in Pegasus Bay during the Otiran (Q2/Q4) glaciation was accompanied by longshore drift associated with the Southland Current (see Gibbs and Adams, 1982), which is likely to have transported the finer-grained deposits northwards, preferentially leaving coarser grained alluvial deposits at the coastal margin. A circulatory current is shown to develop in the southern half of the bay during the postglacial marine transgression, forming a depositional bar or spit which extends approximately 40 km north east of Banks Peninsula and is evident in the Pegasus Bay bathymetry (see Figure 3-2). Northerly longshore drift prevails at the northern end of the Waimakariri CWMS zone in the current postglacial period. The nearshore ocean currents in the southern part of Pegasus Bay have deposited a thicker sequence of fine-grained marine sediment over the Q2/Q4 deposits here, reducing the potential for seabed groundwater discharge via upward seepage. Continued northerly sediment transport in the northern part of Pegasus Bay limited such capping of the glacial period alluvial deposits. This means that the potential for offshore flow via vertical seepage through these strata is greater here. I discuss this in more detail later in this report.

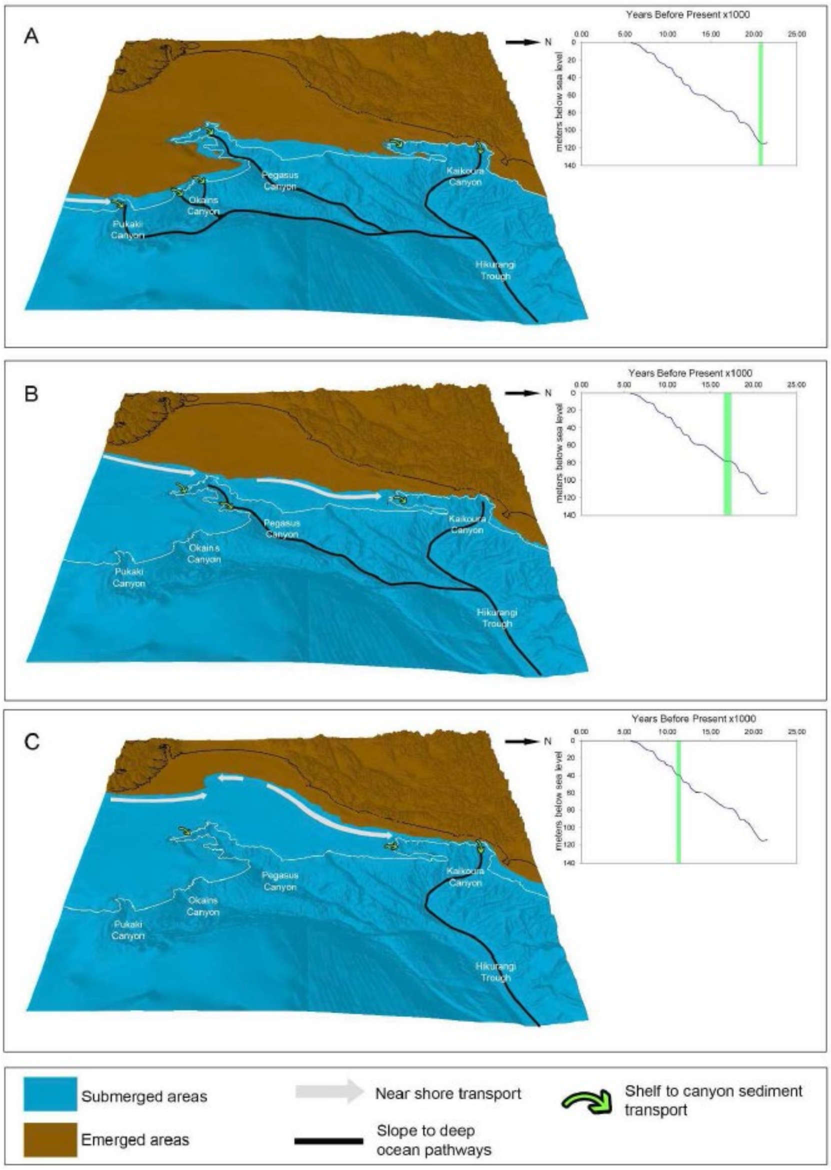


**Figure 3-3: Schematic model of North Canterbury margin sediment transport at three stages from last glacial maximum (A) to 12 ka (C), from Nokes (2014)[1]**

[1] (A) Last glacial maximum (20 ka) sea level lowstand (~-120 m), exposing coastal plain to shelf break and canyon heads. Small arrows indicate sediment transport routes. (B) Sedimentation transport during early transgressive sea level stage at about 18 ka (-80 m). (C) Sedimentation transport during mid transgressive sea level stage at about 12 ka (-40 m).

### 3.5.1 East – west survey profiles

Boomer profile KAH-10 presented in Barnes (2015) extends E-W from New Brighton Beach for about 46 km (see Figure 3-4), crossing the axis of a sandy submarine spit northeast of Banks Peninsula. The profile terminates on the shelf in about 60 m water depth, some 12 km west of the Pegasus Canyon. Reflections are generally stronger (i.e. of high amplitude) across the inner 20-25 km of the profile (see Figure 3-5), and weaker further east beneath the sandy spit. This is consistent with my discussion of coastal margin sediment transport above.

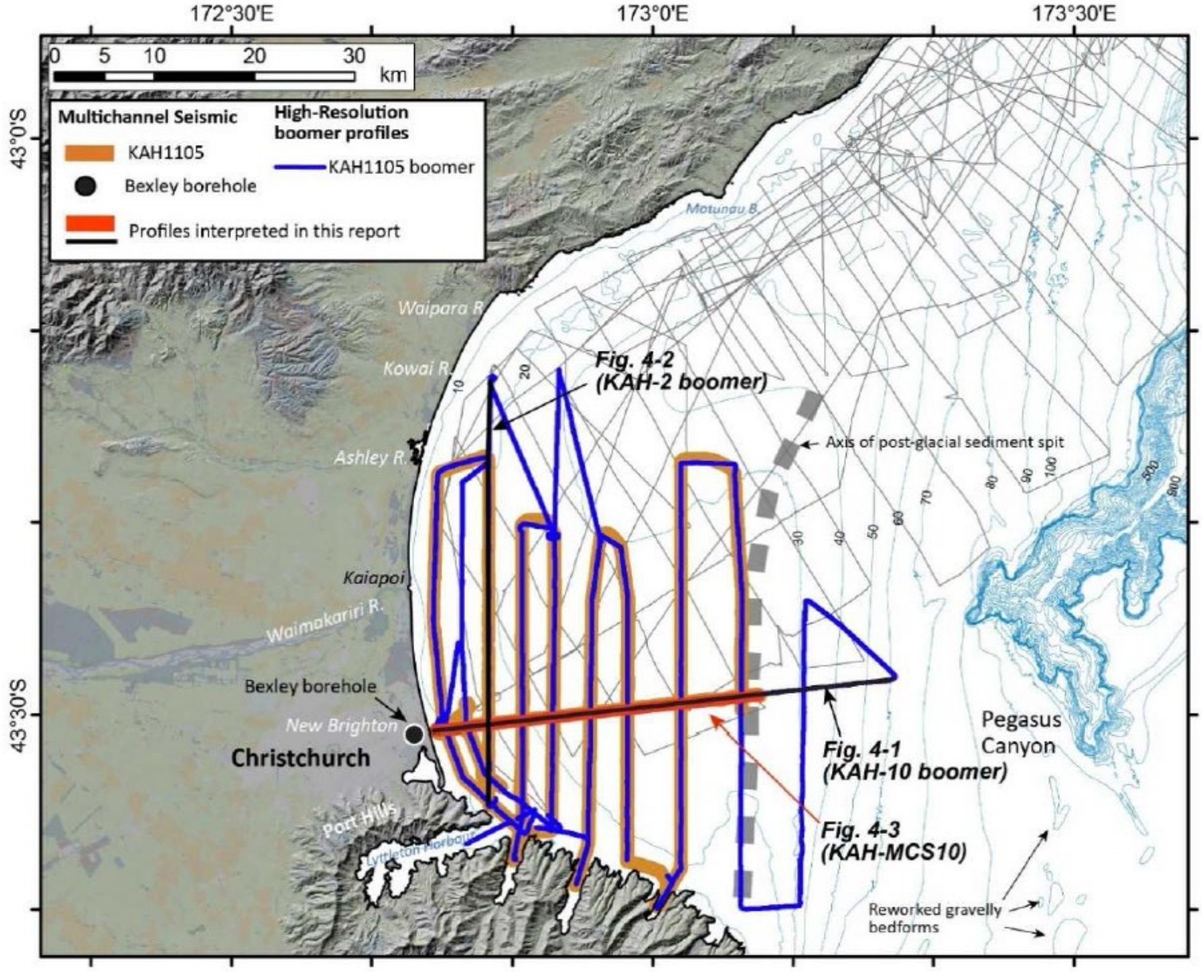


**Figure 3-4: Distribution of marine seismic reflection profiles (from Barnes, 2015[2])**

On Figure 3-5 A and Figure 3-5 B, intervals with relatively stronger reflectivity are shaded in grey, whilst irregular, non-planar reflections within these intervals are highlighted in black. This approach was used by Barnes to interpret features that might be indicative of formation boundaries and changes in sedimentary environment.

Close to shore, below ~35 m depth[3] the sequence is relatively strongly reflective to a depth of at least 70 m. Beyond a few kilometres from shore this interval of stronger reflections forks into two separate units with relatively strong reflections that deepen gently (0.05°) to the east. The top of the upper reflective package correlates well with the top of the Riccarton Gravel in the Bexley Bore (36 m below sea level), whilst the top of the lower reflection package appears to correlate approximately with the top of the Linwood Gravel Formation (~70 m). Regional seismic correlations indicate that the top of the Riccarton Gravel coincides with an erosional unconformity (labelled PGS2/1).

[2] Figure numbers refer to figures in Barnes (2015)

[3] Note that depths are estimated from two way travel times, and are approximate only. See Barnes (2015) for further details

The Riccarton Gravel may reach a thickness of up to 23 m about 20 km from shore. It exhibits generally more discontinuous, wavy-like reflections closer to shore, and more planar reflections offshore beyond about 15 km from the coast. There are some isolated irregular, non-planar reflections within the unit that are visible to at least 30 km from the coast, beneath the post-glacial sand spit. The lower part of the Riccarton Gravel appears to be associated with the strongest reflections.

Marine sediments of the Christchurch – Pegasus Bay formation are generally weakly reflective, with a few semi-continuous planar internal reflections. They downlap onto the top of the Riccarton Gravel formation beneath the outer end of the profile.

The interval between the Riccarton Gravel and Linwood Gravel formations is weakly reflective, and is inferred to be marine sediments of the Bromley Formation (Q5, equivalent to the Lower Member of the Canterbury Bight Formation, of Herzer, 1981). Near the coast, this unit is not easily identified within the strongly reflective composite sequence.

Information provided in Barnes (2015) shows that strong seismic reflections corresponding to the Riccarton Gravel and Linwood Gravel formations extend at least 33 km offshore, to beyond the end of line KAH-MCS10 (Figure 3-4). The author noted that after considering the work by Herzer (1981), Carter and Herzer (1986) and Nokes (2014), the outer part of the Riccarton Gravel formation may be covered by a veneer and/or bedforms comprising reworked sandy and gravelly transgressive sediments.

The reflectivity of the Riccarton Gravel and Linwood Gravel deposits generally reduces eastwards along line KAH-MCS10. This could potentially reflect a reduction in the frequency of gravel bands within the sequence, although there are alternative explanations.

The E-W trending GI gun multichannel profile KAH-MCS10 largely repeats the location of boomer profile KAH-10, but extends for only 33 km offshore to about the mid-shelf between New Brighton and Pegasus Canyon. The Linwood Gravel Formation can be traced to about 115 m depth beneath the eastern end of the profile. Notably, channelized seismic architecture associated with dipping reflections that possibly represent migrating point bars is imaged within the Linwood Gravel Formation about 25 km offshore (Figure 3-5 C, enlargement at lower vertical exaggeration).

*Summary*

The key findings from interpretation of the east- west survey profiles for this report are that:

- Strong seismic reflections corresponding to the Riccarton Gravel and Linwood Gravel formations extend at least 33 km offshore, and hence these transmissive units are likely to extend for a significant distance beneath the seabed; and
- Marine sediments of the Christchurch – Pegasus Bay formation downlap onto the top of the Riccarton Gravel formation beneath the outer end of the profile (~33 km offshore), suggesting that any seabed outcrop of Q2/Q4 deposits is more than 30 km east of the coastline.

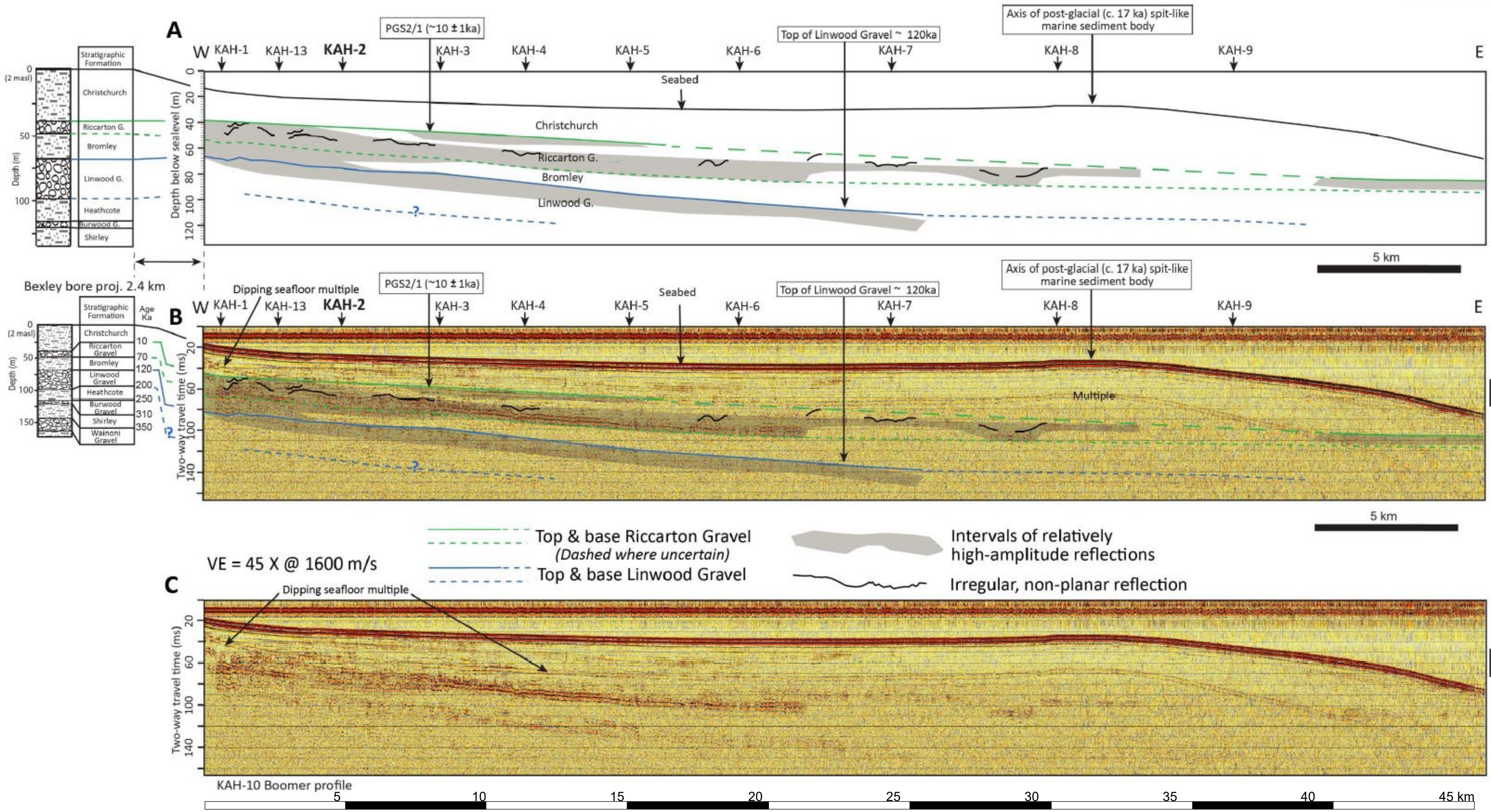


**Figure 3-5: Interpretation of profile KAH-10 (from Barnes, 2015)**

### 3.5.2 North – south survey profile

Boomer profile KAH-2 extends N-S from Lyttleton Heads to east of the Kowai River (Figure 3-4). The profile lies in about 20 m water depth, about 3-7 km from shore, and crosses the active Pegasus Bay Fault and Waikuku Anticline north of the Waimakariri and Ashley river mouths, respectively (Figure 3-6).

The general stratigraphy on the KAH-2 profile correlates well with profile KAH-10. It includes two separate strongly reflective intervals that appear to correlate reasonably well to the Riccarton Gravel and Linwood Gravel formations, each overlain by weakly reflective intervals. The upper weakly reflective unit comprises marine sediments of the post-glacial sequence (Christchurch – Pegasus Bay formations), and is characterised by patches of gas masking in the south. The base of this unit (top of Riccarton Gravel) is marked by the erosional transgressive surface labelled PGS2/1. The position of this surface is obvious over the growing tectonic faults but is not obvious south of the Waimakariri River mouth where it appears to project above particularly strong reflections within the Riccarton Gravel. The lower of the two weakly reflective intervals is inferred to represent marine sediments of the Bromley Formation. The contact with overlying Riccarton Gravel is not precise, notably in the north.

We can see from Figure 3-6 that the thickness of the Riccarton Gravel is greatest immediately north of the Pegasus Bay Fault, where around 21 m of these highly reflective deposits are seen. These glacial period deposits pinch out around the Waikuku anticline, and appear to be approximately 14 m thick on south side of the fault (i.e. 50% thinner than immediately north of the fault).

In the southern half of the profile the lower 10-15 m of the Riccarton Gravel is characterised by particularly strong reflections, and there are several strongly irregular reflections, perhaps coinciding with buried channels, within the unit. These features are particularly well imaged SE of the present Waimakariri River mouth, and include strong reflections that terminate laterally very abruptly (Figure 3-6). The vertical and lateral variability in the reflections, and the abrupt terminations of some strong reflections seen particularly in profile KAH-2 would be consistent with the expected stratigraphic complexities within these predominantly fluvial formations.

Identification of the Linwood Gravel Formation is inferred from its tie onto line KAH-10, and subsequent correlation to the Bexley Bore. The units thickness may be of the order of 20-25 m, however it’s base is imprecisely identified. Generally, the stronger reflections within this unit are in the northern half of the profile. There are some dipping reflections within the unit, possibly representing migrating point bars, notably off the Ashley River mouth. The thickness of this formation does not appear to be significantly greater on the northern side of Pegasus Bay Fault, but may be greater around the Waikuku anticline.

Structural contours of the base of the Quaternary sediments interpreted by Jongens (2011) show a trough-like structure centred on Woodend Beach, extending to a maximum depth of 400 m below sea level. Although the seismic reflection profiles provided in Barnes (2015) do not interpret data to the base of the Quaternary, the location of the trough does roughly correspond with the syncline located to the north of the Pegasus Bay Fault shown in Figure 3-6.

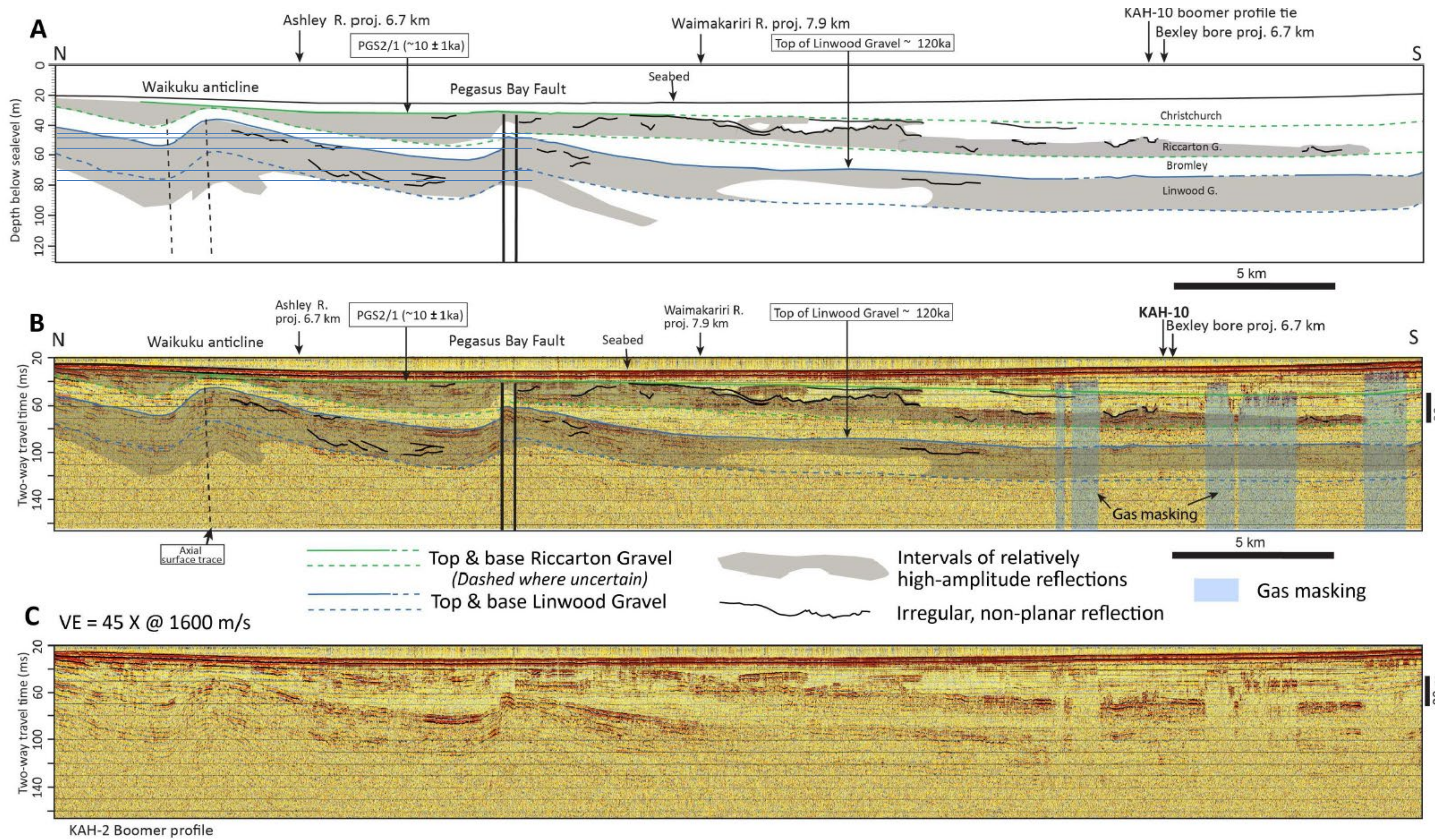


**Figure 3-6: Interpretation of profile KAH-2 (from Barnes, 2015)**

# 4 Hydrostratigraphy

Although the coastal aquifer system comprises a complex and heterogeneous mixture of fine and coarse grained deposits, previous studies (e.g. Sanders, 2004; Dodson *et. al.,* 2012) have conceptualised the coastal aquifer as a sequence of aquifers and aquitards. The inferred aquifers comprise the generally more transmissive material deposited in the coastal zone during glacial periods; the aquitards comprise the generally less transmissive material deposited during interglacial periods.

The purpose of this report section is to summarise information on the coastal zone hydrostratigraphy to provide a framework for analysis of hydrogeological data in the second half of this report.

## 4.1 Inferred depths of glacial and interglacial period strata

I have estimated the depths of the glacial and interglacial strata at the coastline in Table 4-1 below based on NIWA (2015), Sanders (2004) and the hand-drawn cross sections in Appendix 1. I have included data from Christchurch for reference. Figure 3-6 shows that the elevations and thickness of strata on the north side of the Pegasus Bay is much more variable, and hence the estimated depths Table 4-1 are rough averages for this section of the coast.

**Table 4-1: Inferred depths of glacial and interglacial period strata**

| Coastal section | QMap Unit | Climate | Depth to top (m) | Thickness (m) |
|---|---|---|---|---|
| Christchurch (based on Bexley Well M35/6038) | Q1 | Interglacial | 0 | 40 |
| | Q2/Q4 | Glacial | 40 | 10 |
| | Q5 | Interglacial | 50 | 20 |
| | Q6 | Glacial | 70 | 30 |
| | Q7 | Interglacial | 100 | 15 |
| | Q8 | Glacial | 115 | 5 |
| | Q9 | Interglacial | 120 | 30 |
| | Q10 | Glacial | 150 | ? |
| South of Pegasus Bay Fault/Pegasus Town | Q1 | Interglacial | 0 | 20 |
| | Q2/Q4 | Glacial | 20 | 30 |
| | Q5 | Interglacial | 50 | 10 |
| | Q6 | Glacial | 60 | 30 |
| | Q7 | Interglacial | 90 | 10 |
| | Q8 | Glacial | 100 | 20 |
| | Q9 | Interglacial | 120 | 10 |
| | Q10 | Glacial | 130 | 15 |
| North of Pegasus Bay Fault/Pegasus Town | Q1 | Interglacial | 0 | 10 |
| | Q2/Q4 | Glacial | 10 | 35 |
| | Q5 | Interglacial | 45 | 10 |
| | Q6 | Glacial | 55 | 35 |
| | Q7 | Interglacial | 90 | 10 |
| | Q8 | Glacial | 100 | 20 |
| | Q9 | Interglacial | 120 | 10 |
| | Q10 | Glacial | 130 | 15 |

## 4.2 Vertical connectivity of aquifer system

Significant vertical flow (leakage) between adjacent aquifers is expected to occur in some areas, particularly where the interglacial deposits are dissected by river channel deposits associated with migration of the Waimakariri and Ashley/Rakahuri rivers across the alluvial plain.

The Christchurch Formation sediments, which are generally estuarine and coastal swamp deposits, generally have orders of magnitude lower permeability than those of the underlying Q2/Q4 gravel. Because of this the Q1 material in the coastal zone are often referred to as the *coastal confining layer*. River erosion has removed the fine deposits in various places, however, replacing them with river channel deposits which provide enhanced connectivity between the ground surface and the deeper Q2/Q4 deposits. Evidence of this was seen in our 2010 and 2011 piezometric survey contours (see Calder-Steele, 2015), with a localised groundwater mound evident in well M35/8397. The fine-grained Christchurch Formation deposits are very thin in this area (probably due to erosion by the Waimakariri River following a former more northerly channel), promoting the upward passage of water from the deeper part of the system, where groundwater levels are artesian.

PDP (2003) provides information on the hydrogeology of the shallow aquifer system east of Kaiapoi in association with consenting of the sewage treatment plant (STP). A number of monitoring wells were installed in the vicinity of the STP, to a maximum depth of 19 m. The investigation results showed that the local geology comprises fine to coarse-grained sand with occasional traces of clay or silt in the near surface deposits. Shell fragments become gradationally more prolific with depth to approximately 16 m, where a layer of gravel >2.5 m thick was encountered. Minor gravel bands were also recorded at shallower depths in some wells. The shallow (Q1) deposits in this area are therefore relatively coarse, and probably quite transmissive.

Lovell (1998) concludes that the Kaiapoi groundwater system displays a greater degree of connectivity between individual glacial stage deposits due to a thinning of the generally finer-grained interglacial stage material northwards of Banks Peninsula. Thicknesses of up to 20 m of interglacial coastal sediment are typical for the Christchurch area whereas 5 m is typical beneath the southern part of the Waimakariri coastal zone. The author suggests that this is likely to be attributable to the greater protection from erosive southerly storm events that Banks Peninsula provides to the southern part of the Pegasus Bay coastline, allowing for greater accumulation of marine sediments and progradation of the shoreline here. An alternative explanation of increased reworking and erosion of the interglacial deposits by the Waimakariri and Ashley/Rakahuri rivers is also put forward. The net results of one or both of these processes is that leakage rates between vertically separated transmissive deposits within the coastal region is expected to increase with distance north of Christchurch, and in particular Woodend.

## 4.3 Summary

The main points of note regarding coastal zone hydrostratigraphy in the study area are:

- The shallow Q1 deposits have previously been referred to as the coastal confining layer. This nomenclature is based on the broad contrast between the moderate hydraulic conductivity of these deposits and the high conductivity of the underlying Q2/Q4 material. It does not necessarily mean that groundwater recharge, discharge and flow are negligible in the Q1 material.
- Inter-fingering of finer grained marine and coastal zone interglacial material with coarse river channel deposits allows for locally significant vertical and lateral groundwater flow within these so called aquitards.
- The permeability contrast between interglacial and glacial period deposits is expected to reduce northwards in the study area, particularly north of Woodend.

# 5 Groundwater level data

Because offshore groundwater discharge cannot occur in the absence of a coastward, or upwards offshore hydraulic gradient, analysis of groundwater level data from the coastal zone is a key component of this study. The presence or absence of vertical hydraulic gradients can also provide insights into the anisotropy of the groundwater system and the presence of flow impediments. The main water level data sources I have used in this study are:

- Groundwater contours interpreted from piezometric surveys of shallow wells in May 1985, June 2010 and May 2011
- Groundwater contours from May and September 1979 piezometric surveys
- Groundwater level readings held on our Wells and Records Manager databases for coastal zone wells

- A piezometric survey of approximately 20 wells installed in the deeper part of the aquifer system (>40 m depth) in the coastal zone undertaken on 12 February 2016

## 5.1 Vertical hydraulic gradient

I evaluated the vertical hydraulic gradient between the deeper and shallower parts of the lower Waimakariri plains aquifer system using all available water level data, the results of which are summarised in Figure 5-1 below. Details of the data used to derive these estimates are provided in Appendix 2.

The data show a strong upward hydraulic gradient in the south eastern corner of the zone, which dissipates somewhere around Pegasus Town in the north and the confluence of the Eyre River diversion and Waimakariri River in the west. I present a conceptual model which encapsulates this information in Section 10. Outside of the Silverstream area there is no clear correlation between the inferred location of the upward coastal zone hydraulic gradient and spring locations. This may be because there are multiple drivers for spring locations, such as surface topography and groundwater recharge from rivers.

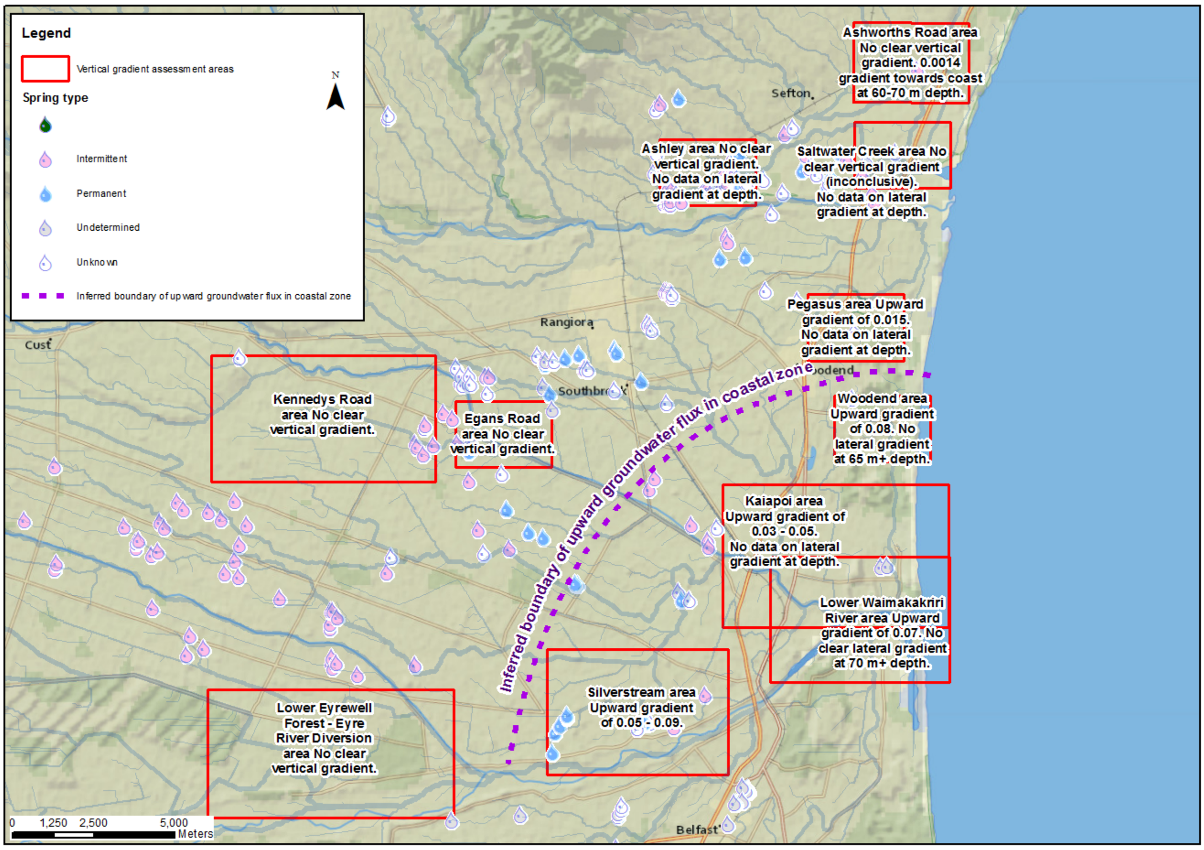


**Figure 5-1: Hydraulic gradient interpretation summary**

The most reliable estimates of vertical hydraulic gradients are available from Woodend Beach, where Environment Canterbury record groundwater levels at three different depths. This was originally done in a multi-piezometer well (M35/7024/7078/7079), but this was damaged in the 2010-2011 earthquakes and subsequently replaced by individual wells (BW24/0037-0039) at slightly different depths, but likely within the same hydrostratigraphic unit. An upward gradient of ~4.0E-02 is evident in data from piezometers M35/7078 (screened at 44 – 54 m depth, likely Q6 deposits) and M35/7079 (screened at 25.5 – 27.5 m depth, likely Q2/Q4 deposits). An upward gradient of 8.6E-02 is seen between wells BW24/0038 (67 – 68.5 m, likely Q6 deposits) and BW24/0037 (25 – 26.5 m, likely Q2/Q4 deposits). The gradient between BW24/0039 (125.5 – 127.5), likely screened in Q10 material and BW24/0037 (Q2/Q4 material) is 7.9E-02.

The upward gradient is likely to be driven by a combination of the high anisotropy ratio (horizontal to vertical hydraulic conductivity) of the coastal zone Quaternary deposits and the propagation of groundwater pressure from higher ground away inland of the coastal zone. The presence of some form of offshore groundwater flow impediment could also contribute to the vertical hydraulic gradient. I have estimated the anisotropy ratio as follows:

- The geometric mean transmissivity is 500 m²/d for the ~200 Waimakariri CWMS zone wells in our Aquifer Test database with T values. If we assume a mean effective thickness of 5-20 m[4] for the aquifer intervals that were tested, this gives a hydraulic conductivity of 25 – 100 m/d. PDP (2016) summarised transmissivity and hydraulic conductivity estimates derived from constant rate pumping tests undertaken on 44 wells in the zone. The geometric means for these data are 1,100 m²/d and 110 m/d for transmissivity and hydraulic conductivity respectively.
- The geometric mean vertical hydraulic conductivity (Kv)[5] from the 18 wells in our database with interpreted leakage values is 5.0E-02 m/d. Data provided in PDP (2016) give a geometric mean Kv of 1.7E-02 m/d
- The mean anisotropy ratio from 24 wells analysed using a leaky aquifer analytical solution is around 300 (with a wide range of values around this mean).

The upward gradient reduces significantly over the 2 km distance between Woodend Beach and Pegasus Town (see Appendix 2 and Figure 5-1) and disappears completely somewhere north of the town. Information provided in Section 3 (e.g. Figure 3-2) shows that this coincides with the location of the Pegasus Bay Fault, which has been mapped offshore by Barnes *et. al.* (2013). The work of Davy *et. al.* (2012) shows a gravity anomaly in the Woodend Beach area extending westwards, which may signify the landward extension of the Pegasus Bay Fault. The coincidence of the fault location with dissipation of the vertical hydraulic gradient suggests a possible structural influence on local groundwater flow. The information I provided in Section 3 shows that nearshore ocean sediment transport and deposition patterns and/or erosion of the interglacial deposits have also resulted in a lower thickness of the postglacial low permeability marine deposits in the northern part of Pegasus Bay. There are several scenarios which would explain the dissipation of the vertical gradient north of the fault. I consider the most likely of these to be:

1. The offshore deposits are more transmissive on the north side of the fault, allowing for more flow at depth and less impetus for upward discharge to the shallower aquifer system; and/or
2. The reducing thickness of low permeability interglacial and postglacial capping deposits in the northern part of Pegasus Bay, together with the inferred northwards reduction in permeability contrast between glacial and interglacial strata, allow for more vertical seepage through the seabed sediments here.

Although the thickness of the Q2/Q4 deposits is 50% greater on the northerly (down-throw) side of the Pegasus Bay Fault as discussed in Section 3.5.2, these strata appear to pinch out around the Waikuku anticline (see Figure 3-6). The thickness of the Q6 strata may increase around the anticline, and on this basis Scenario 1 above could at least partly explain the dissipation of vertical gradients. However the absence of distinct confining layers to the north, perhaps coupled with the lower density of spring-fed streams (draining the aquifer)[6] is likely to be the main driver for the change in vertical gradient.

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[4] 5 m is probably close to the minimum thickness tested, assuming an average screen length of 3 m and vertical flow from only 1 m of material above and below the screen. 20 m is likely to be somewhere close to the upper limit for the average continuous vertical thickness of high transmissivity deposits in the Waimakariri CWMS zone.

[5] Based on geometric mean K'/B' of 0.002 and an assumed B' of 50 m, K' being vertical hydraulic conductivity and B' being vertical thickness interval.

[6] The lower drainage density may itself be a function of the lower degree of confinement, which means that groundwater levels are deeper due to offshore flow.

## 5.2 Horizontal hydraulic gradient in the shallow aquifer system

The 1979 and 1985 piezometric contours presented in NCCB_c (1982) and NCCB_a (1986) respectively are included in Appendix 2, along with contours interpolated for this study from a piezometric survey undertaken in April 1986 (Calder-Steele, 2016). Both of these surveys included wells only in the upper part of the aquifer system (typically wells <50 m depth).

The 2010 and 2011 surveys included only shallow wells less than 50 m deep, with the vast majority being less than 30 m deep and therefore likely screened in Q1 and Q2/Q4 period deposits. The data from these surveys were recently re-interpreted using a more robust interpolation procedure (see Calder-Steele, 2015), to provide a more reliable dataset upon which to base the offshore discharge assessment. Three sets of contours were produced for each survey: one set used groundwater level measurements from the survey wells only, a second set also used Ashley and Waimakariri River stage elevations estimated from Lidar data[7] (referred to here as the *wells + rivers* contours), and the third set added sea level along the coast as an additional set of data points for the interpolation (the *wells + rivers + coast* contours). The third set of contours therefore assumed that the shallow aquifer is unconfined at the coast. These are plotted in Figure 5-2 and Figure 5-3 below. Contours based on well data only and well data plus inferred river stage data terminate several kilometres from the coast[8].

Contours interpreted from the 2010 and 2011 piezometric surveys broadly show an east-south-easterly hydraulic gradient between Woodend and the Ashley River, and convergence of groundwater flow towards Kaiapoi and the lower Cam River/Ruataniwha south of Woodend. This same pattern is seen in the 1979 and 1985 groundwater contours, and mirrors the surface topography

I used all of the available groundwater contours to provide estimates of the shallow aquifer hydraulic gradient in the coastal zone (Table 5-1) at five locations (see Figure 5-2). Gradients range between 3.1E-04 and 3.8E-03 south of the Ashley River/Rakahuri and 5.6 – 6.3E-03 north of the Rakahuri. With regards to the 2010 and 2011 contour sets, the gradients estimated from the wells + rivers + coast contours are shallower than that interpreted from the wells only or wells + rivers contours in most instances. Hydraulic gradients estimated from the latter two contours sets are for points further inland, where the contours terminate.

**Table 5-1: Hydraulic gradients inferred from contour data**

| Contour set | Kaiapoi to coast | Woodend/ Woodend Beach | Pegasus Town | Waikuku/ Waikuku Beach | North of Ashley |
|---|---|---|---|---|---|
| May 1979 (NCCB_c)[9,11] | 3.8E-04 | 1.6E-03 | 1.8E-03 | 1.9E-03 | 5.6E-03 |
| Sept 1979 (NCCB_c)[9,11] | 6.5E-04 | 1.5E-03 | 2.2E-03 | 1.9E-03 | 5.6E-03 |
| 1985 (NCCB_a)[10,11] | 2.9E-04 | 1.2E-03 | 2.2E-03 | 2.5E-03 | N/A |
| April 1986[11] | 6.8E-04 | 2.3E-03 | 3.6E-03 | 2.3E-03 | 6.3E-03 |
| 2010 | 3.3E-04 | 1.1E-03 - 3.8E-03 | 1.8-03 - 3.2E-03 | 1.1E-03 – 2.5E-03 | N/A |
| 2011 | 3.3E-04 | 9.0E-04 - 2.5E-03 | 1.4E-03 - 2.5E-03 | 2.2E-03 - 2.5E-03 | N/A |

[7] For those reaches of the rivers with permanent flow and good connectivity with shallow groundwater.

[8] Due to a lack of suitable wells to measure closer to the coast

[9] The NCCB_c report states that the six monthly groundwater level surveys being undertaken at that time included wells in the “uppermost artesian aquifer”

[10] The NCCB_a report notes that May 1985 is the period of lowest recorded levels since the early 1970s, and that groundwater levels near the coast are for the uppermost aquifer.

[11] Assumes groundwater elevation at coast = 0 m above sea level (asl)

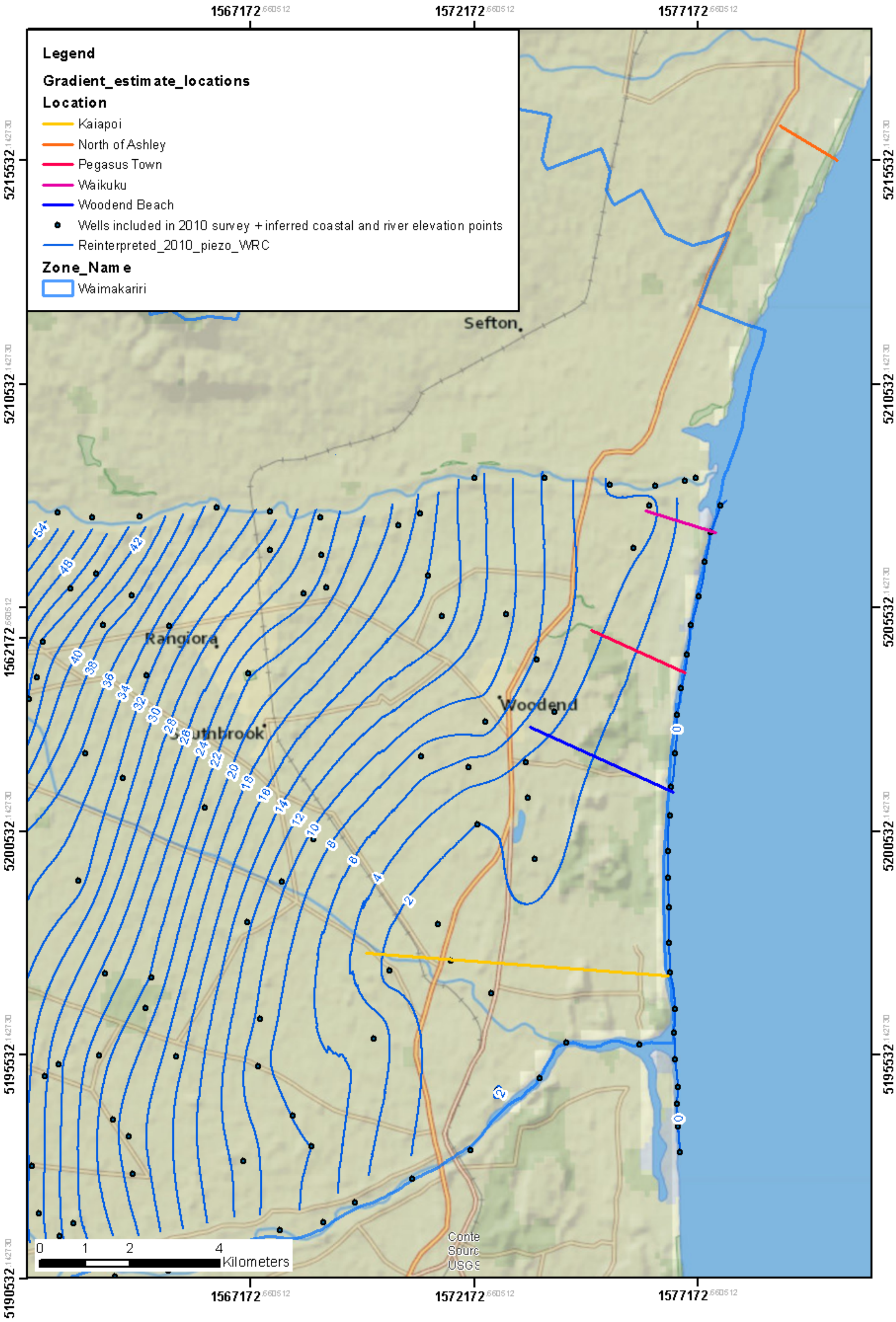



Figure 5-2: Re-interpreted 2010 survey piezometric contours

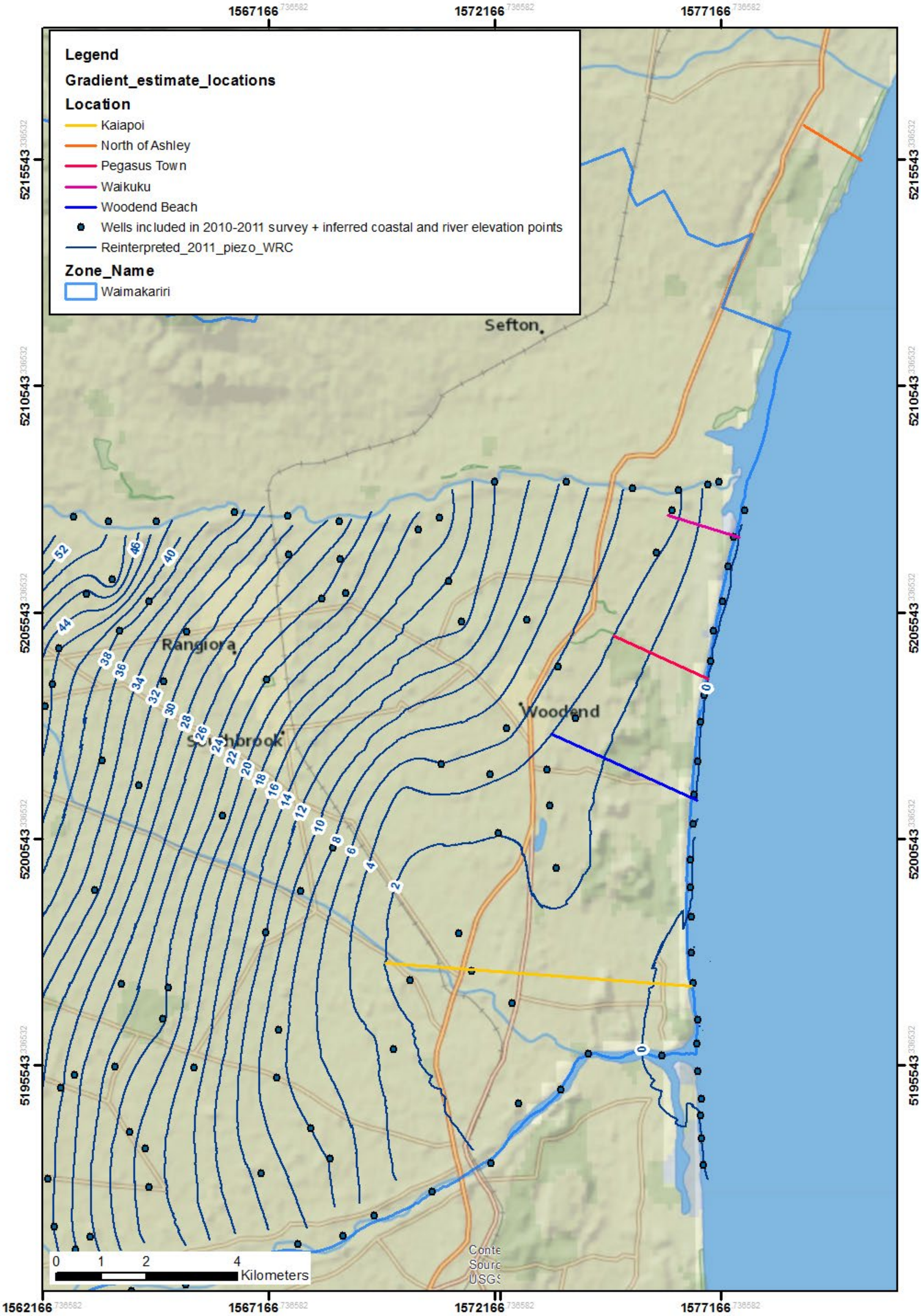



**Figure 5-3: Re-interpreted 2011 survey piezometric contours**

Previous groundwater level monitoring data from 12 wells installed between 20 and 30 m depth in Pegasus Town were provided to us by BECA Ltd. My analysis of these data indicates an easterly hydraulic gradient of between 2E-03 and 3E-03. The hydraulic gradient between the western edge of Pegasus Town and the coast is likely to reduce in association with groundwater discharge to Waikuku Stream[12], and could therefore be lower than these values.

Groundwater level data are available in our Wells database for a number of shallow wells in the Woodend Beach and Ashley River areas. My analysis of these data (see Appendix 2) indicates a hydraulic gradient of 2.1E-03 – 2.5E-03 towards the coast. Although the elevation datum for some of these wells are less reliable than the piezometric survey wells (for which well head elevations were surveyed), I have checked the datum values in our database against Lidar data and found no significant discrepancies, and a general agreement with local topographic features. Because these are consistent with the piezometric contour data discussed above, it appears that discharge to Waikuku Stream may not have a significant effect on the hydraulic gradient around Pegasus Town.

PDP (2003) provides information on investigation of the hydrogeology of the shallow aquifer system east of Kaiapoi, as discussed in Section 4.2. The data gathered for this study showed no evidence of a vertical hydraulic gradient between 0.5 and 19 m depth. A piezometric contour map provided in the PDP (2003) report shows a hydraulic gradient of around 2.3 E-04 to the east. Water level readings from wells BW24/0109 and BW24/0110 recorded in March 2013 show a similar gradient. Both of these values are similar to those in Table 5-1 above.

My interpretation of the shallow groundwater level data can be summarised as follows:

- A relatively steep hydraulic gradient in the order of 5E-03 is apparent north of the Ashley River,
- Between Pegasus Town and Waikuku Beach/the Ashley River the hydraulic gradient is between 1.5E-03 and 3.5E-03 towards the coast.
- South of Pegasus Town, groundwater outflow to the Cam River/Ruataniwha and Kaiapoi River and tributaries results in a lower hydraulic gradient on the eastern side of Kaiapoi. The coastward hydraulic gradient in the shallower aquifers here appears to be in the order of 2E-04 to 7E-04.

## 5.3 Horizontal hydraulic gradient in the deeper aquifer system

### 5.3.1 Hydraulic gradients in coastal zone

I used groundwater level data from our Wells database to estimate hydraulic gradients in the deeper aquifer system. These data comprise a mixture of regular water level readings from Environment Canterbury monitoring wells, regular or intermittent readings from private wells (often from monitoring associated with resource consents) and one-off readings recorded when wells were first installed.

Groundwater level data from Q6 deposits in the Woodend area (see Appendix 2) show no lateral gradient at depth.

I have analysed groundwater levels and well head elevations recorded during the February 2016 piezometric survey using simple triangulation with linear interpolation. Results (Table 5-2) suggest that a relatively steep gradient is present in the Waikuku area; the hydraulic gradient north of the Ashley River is very shallow.

[12] The mean flow of the Waikuku Stream at Waikuku Beach Road was reported as 0.5 m³/s in Smith (2012)

**Table 5-2: Hydraulic gradients interpolated from 12/02/2016 piezometric survey**

| Area | Wells monitored | Depths | Interpolated gradient |
|---|---|---|---|
| Waikuku | M35/8596, M35/18159, BW24/0115 and M35/10553 | 60 – 70 m | 3.5E-03 to the south east |
| Saltwater Creek | M34/0580, M34/5640, M34/5803 | 40 – 50 m | 4.5E-04 to north east |
| Leithfield | M34/0158, M34/0340, M34/5604, M34/5684 | 85 – 135 m | 1.5E-04 to south east |

Groundwater level data recorded on a regular basis between 2007 and 2008 in the Ashworths Road area (see Appendix 2) show a coastward gradient of 0.0014 at 60-70 m depth.

## 5.4 Hydraulic gradient summary

### 5.4.1 Waimakariri River to Pegasus Town

This area is characterised by a shallow lateral gradient in the Q1 and Q2/Q4 deposits, probably around 2E-04 but possibly as high as 7.0E-04. The lateral gradient in the shallow Q1 and Q2/Q4 strata inland of here is much steeper, in the order of 5E-03, but reduces significantly towards the coast. This almost certainly relates to groundwater discharge to surface watercourses such as the Kaiapoi River and Ohoka Stream and their various spring-fed tributaries. As noted above, there is no discernible hydraulic gradient in the Q6 strata in the Woodend area.

The very low lateral gradient in the Q6 and deeper strata aligns with the high radiocarbon ages (>1,000 years) interpreted from the three deep well (>100 m) water samples taken from this area (see Section 8.1). Our water level data from wells M35/0541 and BW24/0038 at Woodend Beach do not show any evidence of a lateral gradient in the 60 - 70 m (Q6) depth range. The elevations of these wellheads have not been surveyed, however, and were interpolated from a digital terrain model (DTM) based on Lidar survey data. This means that the elevation accuracy is expected to be low, and any error could potentially mask a small hydraulic gradient. The two wells are located 2,100 m apart in an east-west orientation, so if the coastward well water level was 25 cm lower than the landward well, for instance, without this being evident in the data due to wellhead elevation errors, an easterly gradient of 1E-04 could be present. Information provided later in this report (Section 8.1) show that this gradient would still be consistent with the radiocarbon age results from the deep coastal zone wells. A low hydraulic gradient in these deeper strata is also consistent with the inferred presence of a low permeability capping layer over the offshore glacial period deposits, as discussed later in Section 9.4.

### 5.4.2 Pegasus Town to Ashley River

The upward hydraulic gradient found along the Waimakariri River to Pegasus Town coastline dissipates around Pegasus Town, and does not seem to be present further north. The 2010 and 2011 piezometric survey data suggest that the lateral hydraulic gradient in the shallower strata (Q1 and Q2/Q4 deposits) becomes steeper north of Woodend Beach, in the order of 1.5 – 3.5E-03 towards the coast for the Pegasus Town to Ashley River section. This steeper gradient is likely to relate to a combination of topography, losses from the Ashley River and lower groundwater outflows to surface watercourses along this stretch of the coastal zone.

Information presented in Section 5.3.1 indicates that the hydraulic gradient in the deeper strata is likely to be in the order of 3.5E-03 to the south east, and slightly less than this towards the coast (which is orientated roughly east-south-east).

### 5.4.3 Ashley River to northern zone boundary

Groundwater contour data suggest a reasonably steep lateral hydraulic gradient of around 5E-03 in the shallow strata (Q1 + Q2/Q4) north of the Ashley River/Rakahuri.

The information I provided in Section 5.3 shows that an offshore gradient of 1.4E-03 is evident at 60-70 m depth in the Ashworths Road area. Data collected during the February 2016 coastal piezometric survey (from around Leithfield Beach, see Section 5.3.1) suggest a shallower lateral gradient in the deeper strata, in the order of 3E-04 on average for this part of the coastline. The difference between these two values may relate to differences in transmissivity, with the lower transmissivity around the

Ashworths Road area and more transmissive deposits around Leithfield. I have used the geometric mean of these two values (6.5E-04) for the offshore flow rates estimates later in this report.

# 6 Aquifer test data

## 6.1 Aquifer properties

The rate of offshore flow through the coastal aquifer system is partially controlled by the transmissivity of the aquifer. In this section I review the transmissivity of the sedimentary deposits in the Waimakariri coastal zone. I use these data in Section 9 as inputs to my offshore flow rate calculations.

### 6.1.1 Shallow deposits

Transmissivity estimates are recorded in our database from 20 wells <35 m deep at nine separate sites in the coastal zone, with a geometric mean transmissivity value of 700 m²/d (Table 6-1). Although there is no well log for M35/4700, it is probably screened in Q1 deposits based on the recorded well depth. The remainder of the wells are likely to be screened in Q2/Q4 material.

**Table 6-1: Coastal zone shallow well aquifer test data**

| Well No | Observation wells | Pumping well depth (m) | Screen length (m) | T (m²/d) |
|---|---|---|---|---|
| M35/4700 | Listed as M35/0864, but this is probably incorrect[13] | 12.2 | ? | 1,580 |
| M35/6760 | None | 18 | ? | 350 |
| M35/3487 | M35/1825 (distance = 220 m, screen = 13 – 16 m)<br>M35/7106 (d = 215 m, screen = 21 - 22 m)<br>M35/7186 (d = 130 m, screen = 19 - 21 m) | 21 | ? | 875 |
| M35/0470 | M35/0530 (distance = 190 m, depth = 29 m)<br>M35/0560 (distance = 250 m, depth = 26 m)<br>M35/0564 (distance = 160 m, depth = 21 m)<br>M35/0565 (distance = 335 m, depth = 18 m) | 30.2 | 5.9 | 360 |
| M35/4897 | M35/0410 (distance = 320 m, depth = 20 m)<br>M35/4140 (distance = 20 m, depth = 19 m) | 22.3 | 3 | 777 |
| M35/0527[14] | Piezometers at 10 m, 20 m, 30 m, 50 m, 80 m distance, all 23 m deep<br>M35/0167 (distance = 415 , depth = 33 m) | 23.4 | 3 | 2,100 |
| M35/11591 | M35/11478 (distance = 1400 , depth = 30 m) | 25.5 | 3 | 3,000 |
| M35/11592 | None | 26.3 | 3 | 1,800 |
| M35/18107 | None | 28.5 | 3 | 420 |
| BW24/0037 | None | 26.5 | 1.5 | 45 |
| ***Geometric mean*** | | | | 700 |

I re-interpreted the pumping test data from well M35/0527 to explore how the effects of partial penetration of the aquifer and conceptualisation of the aquifer system at this location as an unconfined rather than leaky confined unit affect the transmissivity value. This is important because I use transmissivity data later in this report to estimate offshore flow rates. My analysis, which is presented in Appendix 3, shows that analysing the data using an unconfined aquifer analytical solution with partially penetrating wells yields a geometric mean T value of 5,900 m²/d – nearly three times greater than the leaky aquifer interpretation value. Ignoring the effects of partial penetration results in a 25-30% underestimation of the T value at this location. I discuss partial penetration further below. If we based

[13] M35/0864 is located > 5km away

[14] See re-analysis of pumping test data in Appendix 3

coastal discharge estimates on the original interpretation it could translate to a significant underestimate of offshore flow rates. I explore the likely average transmissivity of the coastal aquifer system further in Section 9.

### 6.1.2 Deep (>35 m) deposits

I have summarised the aquifer test data from the 12 coastal zone wells >35 m deep in Table 6-2.

**Table 6-2: Coastal zone deep well aquifer test data**

| Well No | Observation wells | Pumping well depth (m) | Screen length (m) | T ($m^2/d$) | QMap Unit |
|---|---|---|---|---|---|
| BW24/0038 | None | 68.5 | 1.5 | 240 | Q6 |
| M35/10385 | None | 90 | 2 | 100 | Q6 |
| M35/0847 | M35/0872, M35/1438 | 98 | 6.2 | 3,000 | Q8 |
| BW24/0039 | None | 126 | 2 | 990 | Q10 |
| M35/10908 | M35/10910 | 146 | 3 | 166 | Q10 |
| M35/11199 | None | 154 | 2 | 3,916 | Q10 |
| M35/11908 | M35/0788, M35/0834, M35/0847, M35/11199, M35/3529, M35/8211, M35/8212 | 156 | 3 | 1,660 | Q10 |
| M35/7542 | None | 206 | 4 | 930 | >Q10 |
| ***Geometric mean*** | | | | ***150*** | ***Q6*** |
| | | | | ***3,000*** | ***Q8*** |
| | | | | ***1,000*** | ***Q10*** |
| | | | | ***1,000*** | ***>Q10*** |
| **Total** | | | | **5,100** | **Q6+** |

### 6.1.3 Partial penetration effects

A review of cross section M35/863-700 in Appendix 1 together with local well logs (e.g. M35/0527) shows that the shallow Q2/Q4 deposits generally comprise 20 m of gravel and sand. The deeper Q6 period deposits generally comprise approximately 40 m of sand and gravel, although there is significant local variability on both thickness and composition. Well screen lengths are typically 1-3 m, meaning that very few (if any) wells fully penetrate the aquifer. We generally interpret aquifer properties based on data collected from observation wells located some distance from the pumping well. If the observation well is a long way away from the pumping well the effects of partial penetration may not be significant. The distance beyond which well partial penetration adjustments are negligible is defined by the following equation (Hantush, 1964):

$$r_{pp} = 2b(\frac{K_h}{K_v})^{0.5}$$

Where: $r_{pp}$ is the distance beyond which the effects of partial penetration are negligible, b is the aquifer thickness, $K_h$ is the aquifer horizontal hydraulic conductivity and $K_v$ is the aquifer vertical hydraulic conductivity (Walton, 2007).

Anisotropy ratios ($K_h/K_v$) of 2 to 20 are reported in Walton (2007) for sand and gravel deposits; this equates to a maximum distance of ~100 m within which well partial penetration adjustments are required. Some bore logs (e.g. M35/7024) record the presence of clay-bound gravel layers within the Riccarton Gravel in the study area, and this interlayering of low permeability material is likely to increase the anisotropy ratio significantly. Walton (2007) reports a $K_h/K_v$ ratio of 50 for sand with gravel and clay, and as shown in Section 5.1, ratios of 500 to 1000 are possible when considering a broader depth range (e.g. > 20 m vertical separation between pumping and observation well) in Canterbury. The examples plotted in Figure 6-1 show that for a $K_h/K_v$ ratio of 1000 and an aquifer thickness of 30 m, partial penetration effects would be significant at up to ~2 km from the pumped well. Effects would be significant up to ~1.5 km for a $K_h/K_v$ of 500. This suggests that some of the pumping test data held in our database which have not been analysed as a leaky aquifer system and where there is vertical separation between the pumping and observation well(s) could be affected by partial penetration, without this having been included in the analysis.

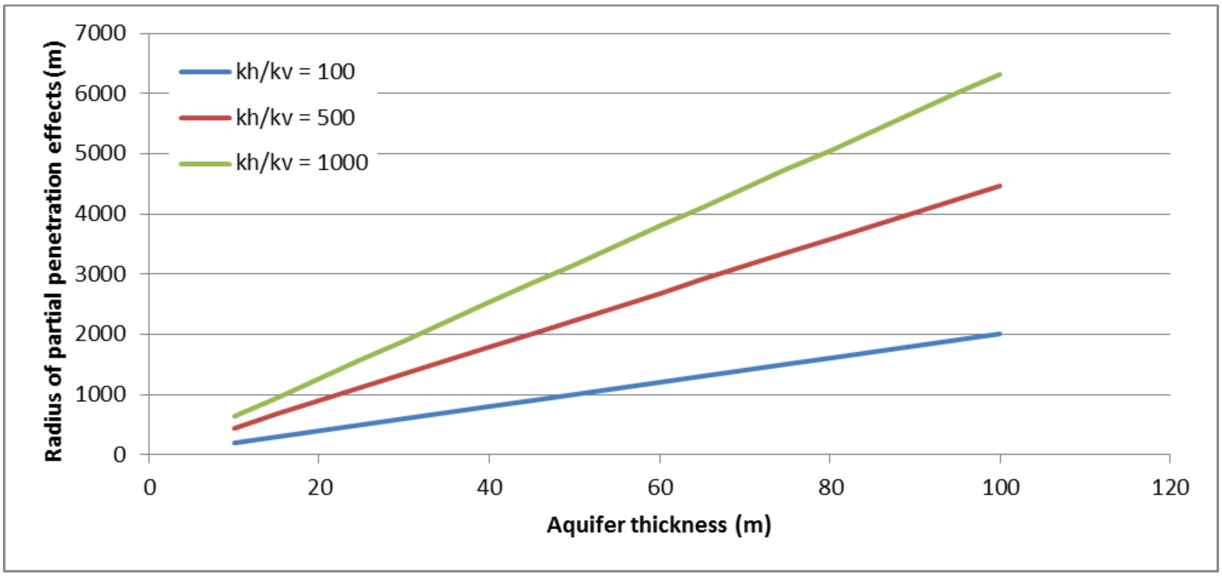



**Figure 6-1: Radial extent of partial penetration effects**

Partial penetration effects can be negative or positive depending on well geometry. If the pumped well and observation well are both screened at either the top or the bottom of the aquifer, the drawdown in an observation well is greater than it would be with fully penetrating wells. If the pumped well is screened at the top of the aquifer and the observation well screened at the bottom of the aquifer (or vice-versa), the drawdown in the observation well is less than for fully penetrating conditions (Reed, 1980 cited in Walton, 2007). My analysis in Appendix 3 shows that ignoring the effects of partial penetration can underestimate transmissivity by 30% in some instances. This highlights one of the uncertainties in pumping test interpretation and the need to consider the feasible range of conceptual models when selecting an analytical method for pumping test data interpretation. Further work should be undertaken to assess the effects of partial penetration on aquifer test interpretation in Canterbury.

I have highlighted those intervals of the coastal wells on hand-drawn cross section M35:863-700 (see Figure 3-1) described as sand or sand and coarser material in Appendix 1. This shows that on average, 75% of the Q1 interval is described as sand-size or coarser textured material. Taking a hydraulic conductivity range of 10E-05 to 10E-03 m/s for sand (Freeze & Cherry, 1979) and a 20 m saturated thickness gives a potential transmissivity of between 170 and 17,000 $m^2/d$. We only have one pumping test T value for the Q1 strata: 1,600 $m^2/d$ from well M35/4700, located west of Kaiapoi.

## 6.2 Evidence of boundary conditions in Pegasus Bay Fault zone

Because the location of the Pegasus Bay Fault seems to coincide with a significant change in the vertical hydraulic gradient and a transition from strongly artesian conditions to sub-artesian groundwater levels in the coastal aquifer system, I have undertaken a brief review of pumping test records to see if there is any evidence of a hydraulic boundary. The presence of a hydraulic boundary could have implications for offshore flow rates.

The results of my preliminary analysis indicate that there are some possible suggestions of a hydraulic boundary condition around the Pegasus Bay Fault or a change in aquifer properties in the proximity of the fault. The data, which are summarised below, are not conclusive however.

### 6.2.1 Well M35/7543

A file note held on our database (reference C14C/62420) discusses a series of pumping tests undertaken on well M35/7542 by Environment Canterbury in 1998. The well is located east of Woodend and immediately south of Pegasus Town and was initially drilled to and pump tested at 110 m depth, before being deepened to 206 m to improve yield and water quality. The file note indicates that during an eight hour constant rate test the slope of the drawdown curve was consistent from 7 minutes to 40 minutes into the test, and a Jacob straight-line analysis of the pumped well data suggested a transmissivity value of 730 m²/d over this period. A steepening of the drawdown curve was interpreted as a reduction in transmissivity to 510 m²/d from about 50 minutes onwards, and this was attributed to a low permeability hydraulic boundary at about 200 m from the pumping bore (assuming a storativity value of 1E-03). Considering the geological information provided in Section 3 and the groundwater level data in Section 5 (in particular the significant reduction in vertical gradient between Woodend Beach and Pegasus Town 2 km north), the most likely location for a hydraulic boundary is the Pegasus Bay Fault. However, groundwater levels are likely to have been affected by tidal fluctuations at this location, and it is not clear whether part or all of the apparent boundary effect relates to tidal variability.

### 6.2.2 Pegasus Town well M35/18017

Pegasus Town well M35/18017 is located approximately 2 km north of the Pegasus Bay Fault location mapped in Barnes *et. al*. (2011), and was test pumped for three days in 2010 as part of the consenting process for the town water supply. The pumping test interpretation report (URS, 2010) found that the early time drawdown data from the pumped well were consistent with a transmissivity of ~160 m²/d whilst the late time data (after 200 minutes) yielded a transmissivity estimate of ~800 m²/day. The report concluded that the pumped well response was indicative of a recharge/transmissive boundary and/or delayed yield (i.e. leakage).

The monitoring well data from this pumping test are affected by background noise associated with pumping in a nearby well as well as tidal fluctuations and barometric pressure shifts. Although extensive data processing would be required to remove this noise before the data could be conclusively analysed for the presence of boundary conditions, there are no obvious boundary effects in the data in its current form. Leaky aquifer analysis of the observation well data provided in the pumping test report suggests that vertical leakage rates in this area are likely to be very low, with a K'/B' value of 1E-7 interpreted. The drawdown followed a typical confined aquifer response.

### 6.2.3 Well M35/10908

Pumping test drawdown data from well M35/10908 (146 m deep) on the western edge of Pegasus town followed a typical leaky aquifer response, with no obvious horizontal boundary effects. A K'/B' value of 3.7E-4 was interpreted from the data.

# 7 Groundwater tidal response data

## 7.1 Summary

In this section of the report I obtain information on the hydraulic properties of the coastal aquifer system by analysing the response of groundwater levels to tidal cycles. The main components of my analysis are:

- Discussion of the analytical equations that can be used to analyse tidal response data; depending on the structure (or conceptual model) of the coastal aquifer
- Interpretation of a conceptual model of the Waimakariri coastal aquifer; and
- Derivation of inputs for and calculation of coastal aquifer properties

My main findings are as follows:

- Although none of the analytical solutions align perfectly with my conceptual model of the Waimakariri zone coastal aquifer, the Li and Jiao (2001a) equation is suitable for the purposes of this study

- My analysis of tidal response data yielded the following transmissivity (T) estimates:
  - Q2/Q4 strata T = 2,500 $m^2/d$
  - Q6 strata T = 4,500 $m^2/d$
  - Q8 strata T = 13,800 $m^2/d$
- These T estimates can be used in combination with pumping test-based values to estimate offshore coastal discharge

## 7.2 Introduction

Groundwater levels in coastal zone wells often vary in response to ocean tide cycles because the diurnal rise and fall of sea levels applies a varying pressure load to aquifers beneath the seabed. As these periodic pressure fluctuations propagate inland, their amplitudes are attenuated and the cycle phase shifts. Various researchers (Jacob, 1950; Ferris, 1951; Jiao and Tang, 1999) have shown that the inland propagation of the tidal pressure wave in seabed aquifers is a function of hydraulic diffusivity (transmissivity/storativity), and leakage between the ocean and the aquifer in the case of leaky confined systems.

Because the storativity of unconfined aquifers is much higher than confined aquifers, a typical damping distance for an unconfined aquifer is less than several hundred metres. The tidal influence of a confined aquifer can extend landward by several thousand meters (Lanyon *et. al.,* 1982, referenced in Wang *et. al.,* 2012).

Although tidal response analysis provides estimates of hydraulic diffusivity rather than transmissivity,[15] we can translate diffusivity values into transmissivity estimates by making assumptions about storativity of determining storativity from other methods (e.g. barometric efficiency analysis, discussed later in this section). The long inland propagation distances of tidal response in confined aquifers means that tidal response data can potentially be collected from a large number of wells in the coastal zone, making this a valuable source of aquifer property information.

## 7.3 Analytical solutions

Analytical solutions of tidal pressure propagation to inland monitoring wells have been developed for a range of aquifer configurations. Wang et. al. (2012) provide a summary of some of these solutions, which include:

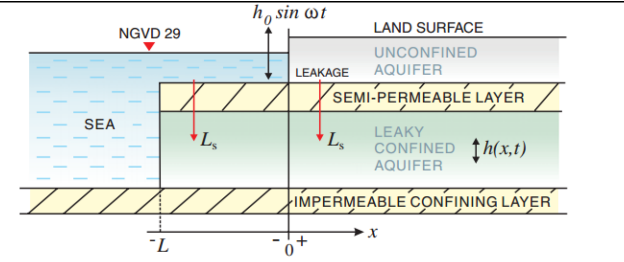
- Single confined aquifer: e.g. Jacob (1950), Van der Kamp (1972)
- Unconfined aquifer: e.g. Nielson (1990), Yeh *et. al.* (2010)
- Multi-layered aquifer: e.g. Jiao and Tang (1999), Li and Jiao (2001)

Because the Quaternary sequence beneath the Pegasus Bay seafloor is probably best considered as a succession of possibly leaky confined aquifers becoming increasingly more confined with depth, the multi-layer aquifer analytical solutions are likely to provide the best representation of the coastal aquifer system. However, despite an extensive literature review, I have not found an analytical solution which describes tidal head propagation in a multi-layered leaky confined system extending under the sea. Most of the leaky aquifer tidal response models consider an unconfined aquifer underlain by a leaky confined unit, with both units terminating at the coast, or an unconfined aquifer which terminates at the coast underlain by a leaky confined unit extending under the seabed. The latter configuration exhibits the closest resemblance to our understanding of the coastal aquifer system in the study area.

Li and Jiao (2001a) developed an analytical solution of groundwater response to tidal fluctuation in a coastal multilayer aquifer system. Their conceptual model comprised an unconfined aquifer terminating at the coast underlain by a semipermeable confining layer and leaky confined aquifer extending under

[15] We need transmissivity rather than diffusivity data for offshore coastal discharge estimation

the seafloor (Figure 7-1). The solution assumes that tidal response in the unconfined aquifer is negligible due to a high specific yield and that elastic storage in the in the semi confining layer is also negligible.




h = head

$L_s$ = vertical leakage rate (K'/B')

L = aquitard roof length

X = distance of well from coast

Ω = frequency of harmonic oscillation [tidal frequency]

**Figure 7-1: Conceptual model of Li and Jiao (2001a) – leaky confined aquifer extending under the sea**

Li and Jiao (2001b, 2002) presented complete analytical solutions describing tidal groundwater wave propagation in coastal two-aquifer systems. The previous analytical solutions which either ignored the water table variation or the storativity of the leaky layers were improved and generalised by taking into account both the leakage and the storativity of the leaky layer, as well as the water level variations in the upper and lower aquifers. Their research found that the leaky layer's storativity behaves as a buffer to the tidal wave interference between the two aquifers. The buffer capacity increases with the leaky layer's thickness and specific storage and decreases with the leaky layer's vertical permeability. High buffer capacity can result in negligible tidal wave interference between the upper and lower aquifers, hence the solution can be simplified significantly. The analytical solution indicates that both storativity and leakage of the semi-permeable layer play an important role in the groundwater head fluctuation in the confined aquifer (Li and Jiao, 2010).

In the Waimakariri coastal zone the generally lower permeability interglacial deposits (aquitards) separating the more permeable glacial deposits (aquifers) are expected to be dominated by finer, more compressible and higher storativity deposits, but not as high as an unconfined aquifer. Because of this I believe that in areas where interglacial deposits have not been dissected by river channel deposits there is likely to be significant buffering of interference between tidal responses in the different transmissive layers. I have therefore assumed that there is no interference between the tidal response in these different layers. This should be investigated further in future.

Wang *et. al.* (2012) note that water table fluctuation in response to tidal cycles results in considerable variation in the weight of pore water, which has loading effects on groundwater flow in the underlying confined aquifer considered in their study. Their analytical solution, which accounts for this pressure loading, shows that it tends to enhance the amplitude and reduce the phase shift of the tide induced head fluctuation. These effects become considerable when the tidal loading coefficient is large, the aquifer's offshore extending length is long, and the unconfined aquifer has large values of hydraulic conductivity and specific yield. They derived a relative tidal propagation function for the aquifer system, incorporating the storativity (S) and transmissivity (T) of the confined aquifer, the vertical hydraulic conductivity (Kv) of the confining layer and the thickness (D) and specific yield (Sy) of the unconfined aquifer. They found that when the relative tidal propagation function exceeded $11\sqrt{S_y}$, their solution became equivalent to that of Van der Kamp (1972), i.e. water table loading has no effect on the confined aquifer.

After calculating the relative tidal propagation function using the range of possible aquifer parameters for Canterbury aquifers, I found that water table loading is very unlikely to affect the tidal response in confined aquifers in the study area. The transmissivity of the confined aquifer would need to be very low and the aquitard vertical hydraulic conductivity and unconfined aquifer thickness very large before water table loading became significant.

Based on the discussion above, I have assumed for this assessment that there is no interference in tidal responses between the different aquifer layers. This means that the Li and Jiao (2001a) can be used to evaluate tidal response data from our coastal aquifer wells, noting that the aquifer system conceptualisation presented in their solution does not align perfectly with the Pegasus Bay coastal aquifer. This is discussed in my recommendations for further work in Section 11.2.

## 7.4 Waimakariri zone coastal aquifer conceptualisation

As discussed in Section 4, the Waimakariri zone coastal aquifer is a multilayer system which could be conceptualised as either an unconfined (Q1 or Q1+Q2/Q4) aquifer underlain by a sequence of aquitards and leaky confined aquifers; or a leaky confined (Q2/Q4) aquifer underlain by a sequence of confined or leaky confined aquifers. It is important to understand which of these conceptualisations best describes the aquifer system before analysing tidal response data. In the next few paragraphs I analyse our groundwater level data to see what insights can be gained into how best to conceptualise the Waimakariri Zone coastal aquifer system.

We installed groundwater level loggers in eight coastal wells in the Waimakariri zone to supplement the three existing logged wells in the Woodend beach area. We also have groundwater level logger data in our archives from a multi-level piezometer well that was damaged in the 2010-2011 Canterbury earthquakes, giving us 14 coastal wells with logger data in total. The locations of the loggers are shown in Figure 7-2.

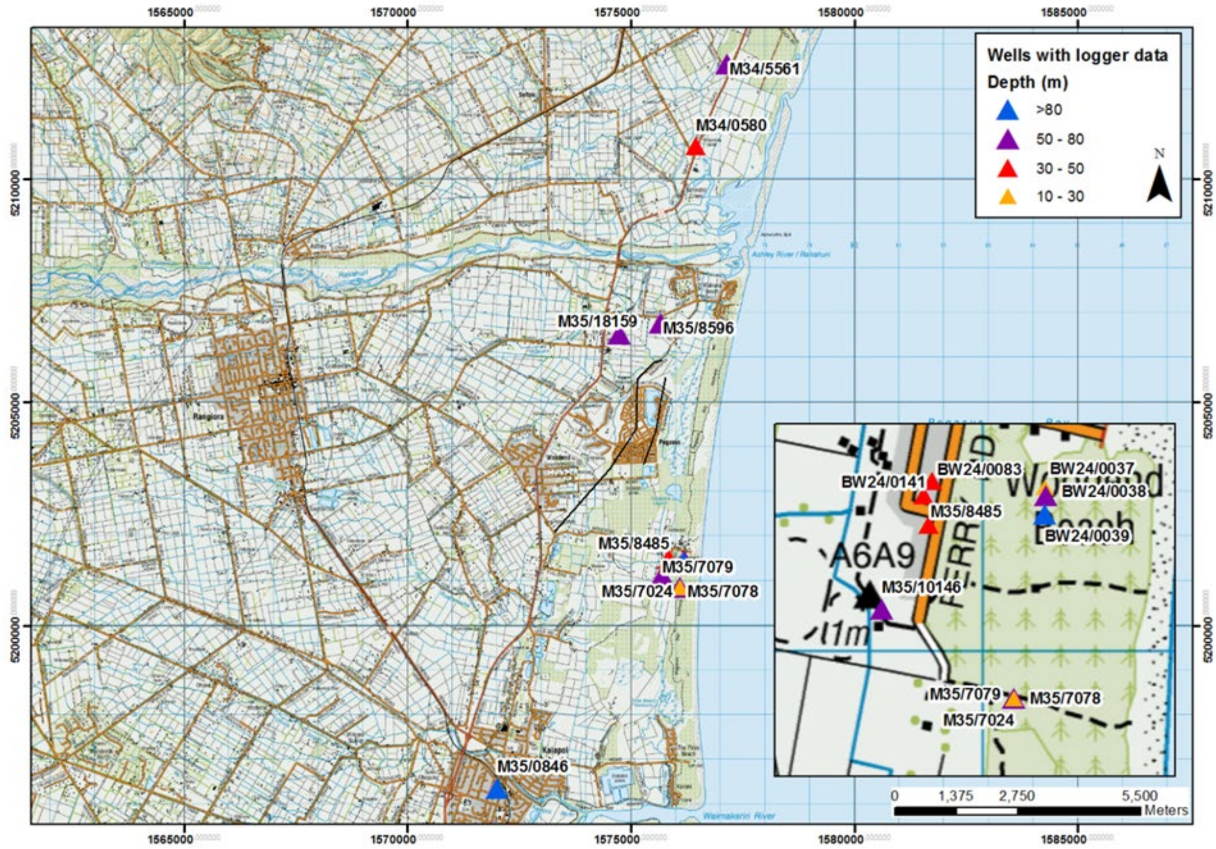



**Figure 7-2: Coastal well logger locations**

Data from well M35/10146 were affected by pumping and could not be used in the tidal response analysis. Ocean level data are logged at Sumner Head (approximately 20 km south of the Waimakariri River mouth) at one-minute intervals. I have summarised the logger data in Table 7-1 below and plotted six days (from various times, according to data availability) of data in Figure 7-4.

The ratio between the ocean tide cycle amplitude and the response in coastal wells is referred to as the amplitude ratio. I have calculated this for each well and provided the results in Table 7-1, and discuss the relative values further below.

**Table 7-1: Coastal well logger data summary**

| Well No | Depth/screen interval (m bgl) | Distance from coast (m) | Data start date | Data end date | Amplitude ratio | Notes |
|---|---|---|---|---|---|---|
| M35/7079 | 25.5 – 27.5 | 500 | 25/8/1994 | 26/10/2010 | 0.13 | Multi-piezo monitoring well |
| M35/7078 | 44 – 54 m | 500 | 25/8/1994 | 26/10/2010 | 0.19 | Multi-piezo monitoring well |
| M35/7024 | 72 – 77 m | 500 | 25/8/1994 | 26/10/2010 | 0.13 | Multi-piezo monitoring well |
| M35/0846 | 87.5 | 4600 | 27/3/1994 | Current | N/A | Monitoring well |
| BW24/0037 | 25 – 26.5 | 550 | 27/3/13 | Current | 0.005 | Monitoring well, |
| BW24/0038 | 67 – 68.5 | 550 | 27/3/13 | Current | 0.17 | Monitoring well |
| BW24/0039 | 125 – 127.5 | 550 | 3/7/13 | Current | 0.27 | Monitoring well |
| BW24/0083 | 45 | 850 | 4/9/15 | Nov 2015 | 0.09 | Domestic supply |
| M35/8485 | 34 | 825 | 14/9/15 | Nov 2015 | 0.14 | Domestic supply |
| BW24/0141 | 48 | 875 | 15/9/15 | Nov 2015 | 0.12 | Domestic supply |
| M35/10146 | 48 - 51 | 100 | 4/9/15 | Nov 2015 | 0.06 | Small community supply |
| M34/0580 | 38 | 1,600 | 21/1/16 | 26/2/16 | 0.031 | Domestic supply |
| M34/5561 | 64 | 1,600 | 21/1/16 | 26/2/16 | -0.003 | Domestic supply |
| M35/8596 | 47 - 56 | 1,600 | 21/1/16 | 26/2/16 | 0.009 | Domestic supply |
| M35/18159 | 55.5 – 57.5 | 2,600 | 21/1/16 | 26/2/16 | -0.008 | Domestic supply |

Under the Li and Jiao (2001a) conceptualisation, the relatively high storativity of the unconfined aquifer rapidly dampens aquifer tidal response. The amplitude ratio for wells in an unconfined aquifer is therefore much lower than that in a confined or leaky confined aquifer well at the same distance from the coast.

Water level data from wells M35/7079 and BW24/0037 give the Q2/Q4 aquifer response to ocean tide cycles at a similar distance from the coast. BW24/0037 is located approximately 550 m north of M35/7079, with both wells screened at the same depth. Whilst the amplitude ratio in well M35/7079 (0.13) is similar to that in the deeper parts of the aquifer system here, the tidal response in well BW24/0037 is almost completely dampened: the amplitude ratio is 0.005. The most likely explanation for this is locally variable confinement of the Q2/Q4 deposits, with unconfined conditions prevailing at BW24/0037 and leaky confined conditions at M35/7079. This explanation is compatible with the Q2/Q4 storativity values in Table A3-1 in Appendix 3, which range from 2 E-02 to 2 E-04 at different locations in the coastal zone under the Neuman (1974) solution interpretation, and suggest that the Q2/Q4 strata could be conceptualised as either an unconfined aquifer or a leaky confined aquifer, depending on the location. The inter-fingering of river channel deposits within the Q1 marine strata discussed in Section 3.2.1 offers an explanation for this variability.

Plotting amplitude ratio vs. depth for wells M35/7079, M35/7078, M35/7024, BW24/0037, BW24/0038 and BW24/0039 (all of which are located approximately 500 m from the coast) on Figure 7-3 shows a moderate positive correlation. This correlation is consistent with conceptualisation of the groundwater system as a series of leaky confined strata, with increasing confinement (reducing leakage) with depth and an associated reduction in tidal response dampening. Deviations from the best fit line could be explained by the variable effects of leakage on tidal dampening discussed in Li and Jiao (2001a).

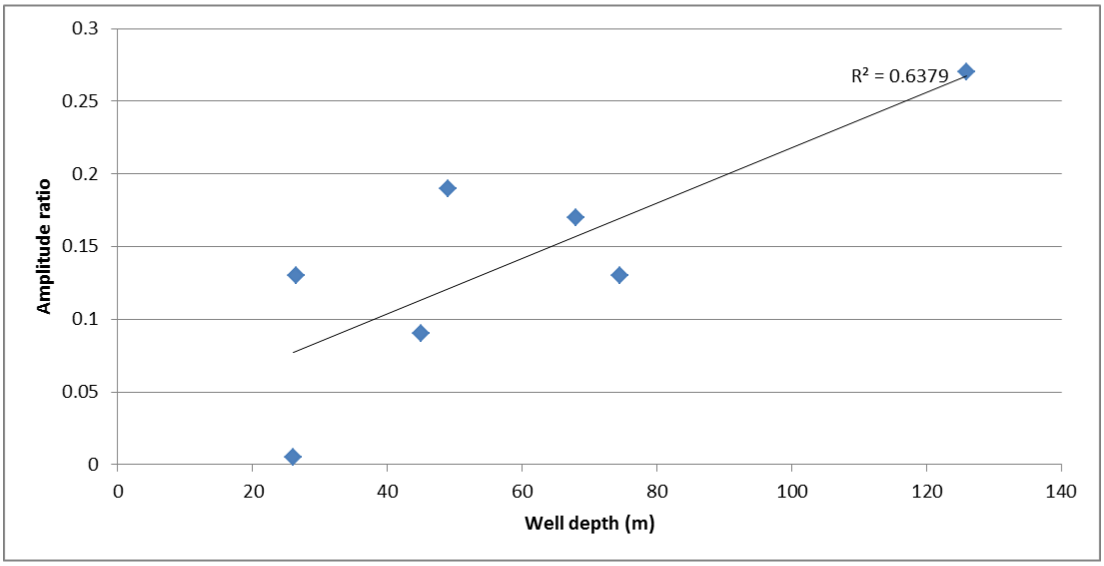



**Figure 7-3: Tidal response amplitude ratio vs. well depth for selected wells**

Based on the analysis above I concluded that the Li and Jiao (2001a) analytical solution for an unconfined aquifer overlying a leaky confined aquifer system could reasonably be used to parameterise the Waimakariri coastal zone aquifers.

## 7.5 Derivation of input values for tidal response analysis

Tidal response analysis considers aquifer compressibility, storativity, transmissivity, vertical hydraulic conductivity, thickness, porosity, roof length and, in the case of Wang *et. al.* (2012), specific yield. Because it is possible to fit model groundwater tidal response to measured data using a range of non-unique combinations of these parameters, defining as many of them as possible (or limiting their possible range) is helpful prior to undertaking the tidal data analysis. I explore possible ranges for those parameters which are subject to the greatest range of natural variability, and are most critical in the tidal data analysis, below.

### 7.5.1 Aquifer compressibility, storativity and porosity

Jacob (1940) derived the following relationship between open well barometric efficiency and aquifer compressibility:

$$B_e = \frac{\theta\beta}{\alpha+\theta\beta}$$

Where: $B_e$ = barometric efficiency, $\theta$ = porosity $\beta$ = water compressibility and $\alpha$ = aquifer compressibility.

We[16] analysed the barometric efficiency (BE) of eight wells in the Waimakariri zone using our groundwater level and barometric pressure logger data and converted these into compressibility estimates based on the equation above. Interpreted BE values ranged from 0.08 to 0.45, with an average of 0.26.

I translated the aquifer compressibility estimates into storativity values by using literature values for porosity[17] and estimates of the aquifer thickness based on screen length and material descriptions above and below the screen. Results (see Table 7-2) show compressibility values within the literature range for gravels, which is as expected.

[16] Much of the analysis was undertaken by Nicole Calder-Steele, Environment Canterbury.
[17] Based on well log material descriptions across and immediately adjacent to the well screen interval

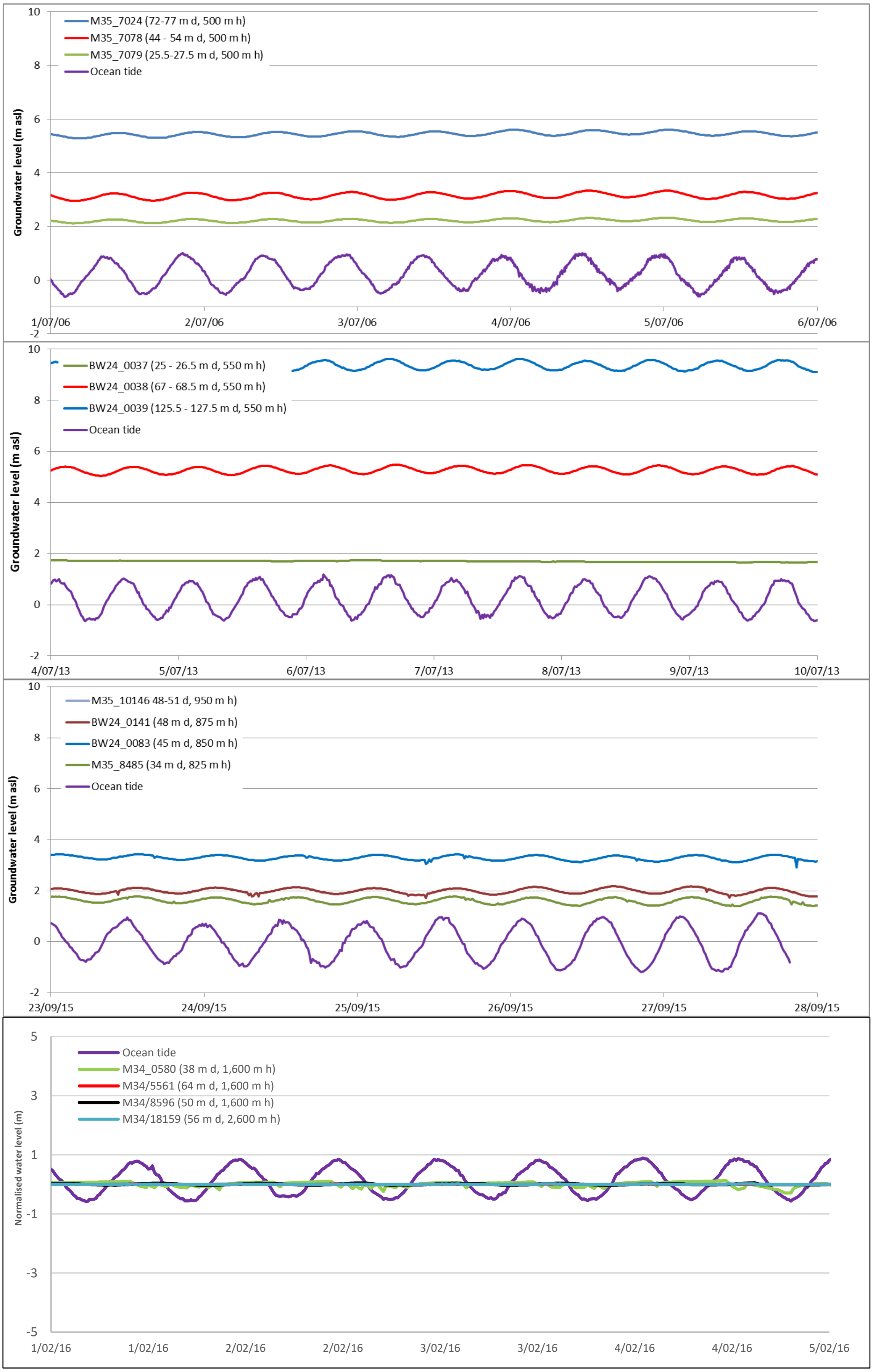



**Figure 7-4: Groundwater level data from coastal wells**

Based on this analysis, I used a compressibility range of 1E-10 to 1E-09 m²/N and a storativity range of 3E-05 to 1E-02 for the tidal response analysis. For shallower wells, which are screened in Q2/Q4 material and seem to be overlain by predominantly sandy deposits, I used lower compressibility and higher storativity values. The input values for the analysis are summarised in Appendix 4.

Aquifer porosity values are used in tidal response analysis to estimate the loading efficiency of the aquifer. The loading efficiency defines the proportion of the tidal pressure load that is transferred to aquifer formation pore water pressure. Literature porosity values for Waimakariri well log material descriptions range from 0.17 to 0.47, with a mean of 0.29. I used a best estimate porosity of 0.25 – 0.3.

**Table 7-2: Aquifer compressibility and storativity**

| Data source | | Screen interval or well depth (m) | Compressibility ($m^2/N$ or $Pa^{-1}$) | | | Storativity | | |
|---|---|---|---|---|---|---|---|---|
| | | | Lower estimate | Best estimate | Upper estimate | Lower estimate | Best estimate | Upper estimate |
| Literature[18] | Clay | N/A | 10 E-08 | - | 10 E-06 | 5.00E-03 | - | 5.0E-05 |
| | Sand | N/A | 10 E-09 | - | 10 E-07 | | | |
| | Gravel | N/A | 10 E-10 | - | 10 E-08 | | | |
| Barometric efficiency analysis on Waimakariri zone wells | BW24/0038 | 67-68.5 | 2.40E-10 | 2.12E-10 | 3.20E-10 | 6.10E-05 | 4.9E-05 | 5.4E-05 |
| | L35/0686 | 180-186.5 | 2.40E-10 | 2.30E-10 | 2.62E-10 | 5.50E-05 | 4.9E-05 | 4.8E-05 |
| | BW23/0133 | 117-120 | 3.58E-10 | 2.36E-10 | 1.87E-10 | 1.50E-04 | 1.1E-04 | 8.5E-05 |
| | L35/0882 | 53-56 & 58-76.5 | 2.41E-10 | 2.46E-10 | 2.45E-10 | 8.70E-05 | 8.3E-05 | 7.7E-05 |
| | BW24/0039 | 125.6-127.6 | 6.71E-10 | 4.87E-10 | 5.74E-10 | 4.40E-05 | 3.2E-05 | 3.3E-05 |
| | BW23/0134 | 81-84 | 6.14E-10 | 7.21E-10 | 9.07E-10 | 2.30E-04 | 2.5E-04 | 3.0E-04 |
| | M35/7078 | 44-45.5 & 52.5-54 | 3.58E-10 | 8.60E-10 | 9.93E-10 | 2.70E-05 | 5.0E-05 | 5.4E-05 |
| | M35/0846 | 67-68.5 | 1.09E-09 | 1.37E-09 | 1.27E-09 | 1.30E-04 | 1.5E-04 | 1.4E-04 |
| ***Geometric mean of wells data*** | | | ***-*** | ***4.3E-10*** | ***-*** | ***-*** | ***7.8E-05*** | ***-*** |

## 7.5.2 Transmissivity and vertical hydraulic conductivity

The information I provided in Section 6.1 show that interpreted Q2/Q4 transmissivity values recorded in our Aquifer Test database range from 45 – 3,000 m²/d. My analysis suggests that the transmissivity of the combined Q1 and Q2/Q4 material could be significantly higher than the database values suggest in some areas, possibly in excess of 10,000 m²/d. This is because the effects of partial penetration are usually ignored, which may cause T values to be underestimated by ~30% in some instances. Some of the test data may have also been analysed using leaky aquifer solutions when an unconfined aquifer solution would be more appropriate. I assumed a possible T range of 300 to 25,000 m²/d as a parameter constraint for the tidal data analysis.

Pumping test-based T values for the Q6+ strata range from 100 to 3,900 m²/d for the Waimakariri coastal zone, but it is not clear what thickness of aquifer has been evaluated during each test. Again I allowed a wide range of 300 to 25,000 m²/d for this analysis, allowing for some underestimation of parameters due to partial penetration.

Noting the expected eastward sedimentary fining discussed in Section 3, the transmissivity of the seabed aquifer units is likely to be generally lower than their landward counterparts. We do not have enough data to quantify this effect however, and the reduction in transmissivity may be sufficiently low to be insignificant for the tidal response analysis. I therefore excluded this matter from my analysis.

Data in Table A3-1 (APPENDIX 3) give a $K_v$ range of 0.05 – 1.5 m/d for the shallow coastal aquifer system, with a geometric mean of 0.74 m/d. Our Aquifer Test database gives a K'/B' range of 5E-05 to 0.4 $day^{-1}$ and a geometric mean of 1.7E-03 $day^{-1}$ for all leaky aquifer analysis within the Waimakariri

[18] For confined aquifers, taken from Freeze and Cherry, 1979.

zone. Assuming an average B' of 50 m gives a vertical hydraulic conductivity range of 2.5E-03 to 3 m/d, with a geometric mean of 9E-02 m/d. I assumed a broader range of 1E-06 to 5 m/d for the tidal data analysis.

## 7.6 Leaky confined aquifer tidal response analysis

We[19] implemented the Li and Jiao (2001a) analytical solution in an Excel spreadsheet and used the in-built solver with the information above (summarised in Appendix 4, together with a discussion of some of the model inputs and analysis considerations) as parameter constraints to determine the aquifer parameter combination with the minimum objective function. For the latter we used a simple sum of squared residuals ($R^2$) as follows:

$$\sum_{t=0}^{t=n}(H_m - H_o)^2$$

Where t = time since start of observation period (days), $H_m$ = model head (m), $H_o$ = observed head (m). For most of the wells I used approximately one week of data for the optimisation.

I have included plots of model and measured coastal aquifer tidal for one parameter optimisation in Appendix 5, and full results in Appendix 6.

During the data analysis I found that application of tidal response analytical solutions to logger data from the coastal monitoring wells yielded non-unique solutions – i.e. different combinations of parameters yielded the same objective function value. This is shown in Figure 7-5 below, which plots transmissivity versus storativity for all of the wells I analysed. Because the solution is non-unique it is not possible to infer a single transmissivity value (or any other parameter value) for each well. But by making some assumptions about the likely range of storativity values for each well we can still obtain a useful estimate of the probable transmissivity range. I have done this in Table 7-3 below.

I have assumed for my analysis that the vertical hydraulic conductivity of and separation between the Quaternary deposits are sufficiently low and large respectively for the glacial period deposits to behave as separate aquifers. I have also assumed that the transmissivity of the interglacial period deposits is negligible. Under this assumption the transmissivity of the full thickness of Quaternary material is equal to the sum of the transmissivity estimates for each of the glacial period strata. The geometric mean aquifer parameters for the glacial period strata are shown at the bottom of Table 7-3.

[19] Much of the analysis work was undertaken by Sunsoo Koh, Environment Canterbury.

**Table 7-3: Tidal response analysis parameter results**

| Well | Screen/well depth (m bgl) | Strata | S range | T range ($m^2/d$) | K'/B'[20] range (m/d) |
|---|---|---|---|---|---|
| M35/7079 | 25.5 – 27.5 | Q2/Q4 | 4E-04 - 1E-03 | 2,000 - 4,300 | 6.0E-03 - 1.0E-02 |
| M35/7078 | 44 – 54 m | Q2/Q4 | 1E04 - 4E-04 | 4,900 - 10,500 | 1.8E-03 - 4.4E-03 |
| M35/7024 | 72 – 77 m | Q6 | 1E-04 - 6E-04 | 300 - 5,200 | 0 - 5.0E-03 |
| BW24/0037 | 25 – 26.5 | Q2/Q4 | 1E-03 - 1.5E-02 | 300 - 2,500 | 2.0E-02 - 8.0E-02 |
| BW24/0038 | 67 – 68.5 | Q6 | 9E-05 - 6E-04 | 800 - 6,300 | 2.0E-04 - 4.0E-03 |
| BW24/0039 | 125 – 127.5 | Q8 | 6E-05 - 1E-04 | 11,000 - 17,400 | 3.0E-03 - 7.0E-03 |
| BW24/0083 | 45 | Q2/Q4 | 2E-04 - 8E-04 | 1,700 - 3,600 | 1.4E-03 - 5.0E-03 |
| M35/8485 | 34 | Q2/Q4 | 1E-04 - 5E-04 | 2,200 - 4,400 | 0 - 1.8E-03 |
| BW24/0141 | 48 | Q2/Q4 | 1E-04 - 5E-04 | 1,500 - 2,600 | 0 - 8.0E-04 |
| M34/5561 | 64 | Q6 | 1E-04 - 5E-04 | 9,000 | 5.0E-02 |
| M35/8596 | 47 - 56 | Q6 | 5E-04 - 9E-04 | 3,600 – 5,900 | 1.2E-02 |
| M35/18159 | 55.5 – 57.5 | Q6 | 1E-04 - 5E-04 | 17,000 | 4.0E-02 |
| ***Geometric mean*** | | ***Q2/Q4*** | ***2.1E-04*** | ***2,500*** | ***3.9E-03*** |
| | | ***Q6*** | ***1.4E-05*** | ***4,500*** | ***1.0E-02*** |
| | | ***Q8*** | ***6.0E-05*** | ***13,800*** | ***4.6E-03*** |

The Q8 transmissivity interpreted from well BW24/0039 is significantly higher than the other wells, and may not be representative of the average value for these deposits. For instance Little (1997) summarises transmissivity values interpreted from pumping tests on nine different wells in the Q8 deposits with a range of 600 – 8,000 $m^2/d$ and a geometric mean of 2,700 $m^2/d$. If we assume that the mean T value for the Q8 coastal zone strata is 3,000 $m^2/d$ and that the Q6 strata are similarly transmissive, the combined transmissivity of the combined Q2 – Q8 sequence based on the tidal response analysis only would be ~12,000 $m^2/d$. I discuss this further below.

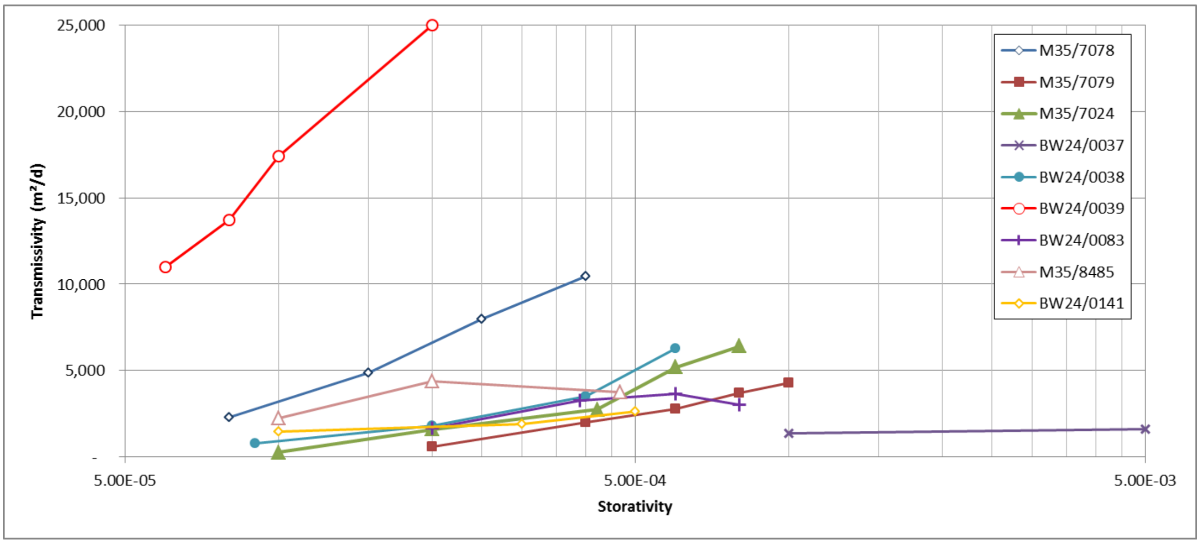



**Figure 7-5: Tidal response analysis T vs. S results**

My analysis also suggests that the analytical solution is fairly insensitive to leakage values for some wells, as shown in Figure 7-6 below. K' values of 1E-04 to 0.7 m/d can be coupled with T values between 2,500 and 4,200 $m^2/d$ to achieve the same $R^2$ value for the data shown. Because of this the leakage values estimated from the tidal response analysis for several of the wells in this report are not considered

[20] An aquitard thickness of 50 m was assumed during the tidal response analysis.

to be reliable. Further work could be undertaken to determine which data sets are likely to generate unique and therefore more reliable estimates of vertical hydraulic conductivity.

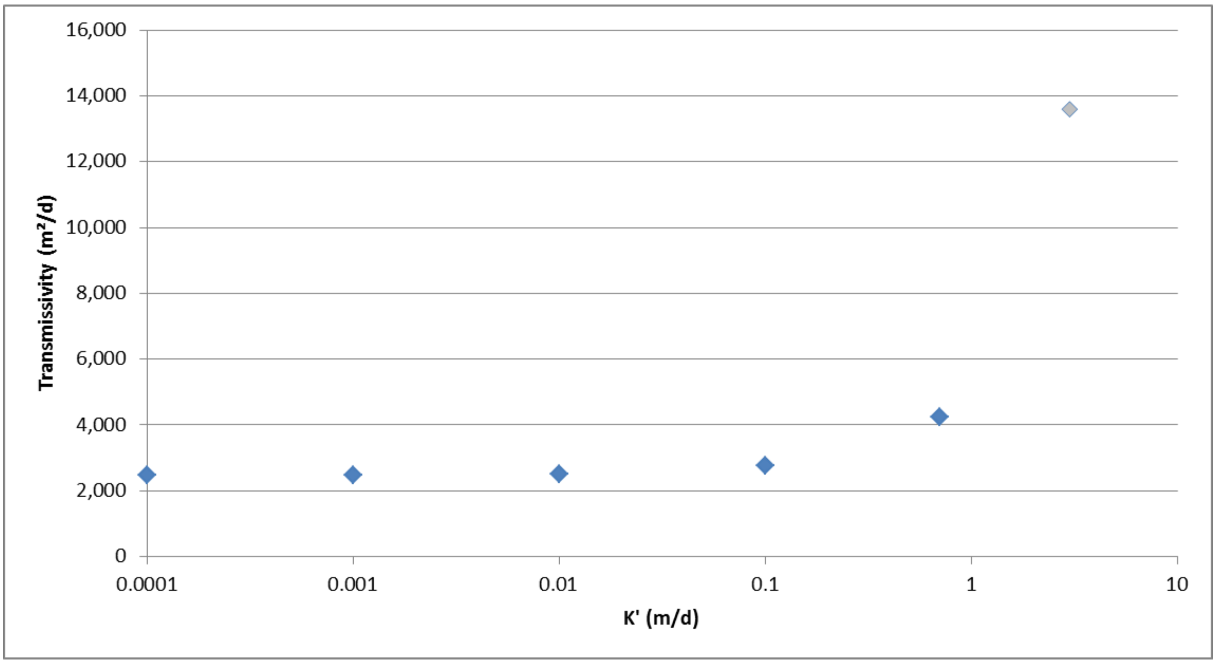



**Figure 7-6: Transmissivity versus vertical hydraulic conductivity for well M35/7079**

# 8 Water chemistry data

## 8.1 Isotope data

The age of groundwater in coastal Waimakariri zone wells have been investigated in three main studies: Taylor *et al.* (1989), Stewart *et al*. (2002) and Van der Raaij (2011). I have reviewed the age interpretations in each of these reports, and considered the findings in the context of the broader hydrogeological information presented in previous sections of this report. I have probed the interpretations provided in the latter two reports to ascertain whether alternative interpretations are also consistent with the data.

Taylor *et al.* (1989) found that in the coastal confined system on the eastern outskirts of Kaiapoi, the oxygen-18 isotope ratios ($\delta_{18}O$) from shallow and deep wells both indicated groundwater sourced from the Waimakariri River. However, low tritium values (a sign of older water) in shallow and deep wells suggest upflow of old, deep water into the upper confined aquifer, rather than direct groundwater connection to the Waimakariri River near its present channelled outlet. This fits with the upward hydraulic gradient discussed in Section 5.1 of this report, but yields no further insights into the rate of offshore flow. The Waimakariri River signature in the isotope data may relate to historic aquifer recharge from the river, before the Wrights Cut diversion was completed in 1930. The purpose of this channelisation and straightening was to allow the river to carry shingle and sand more efficiently, and therefore reduce the flood risk to Christchurch. These engineering works, in combination with aggregate extraction from the lower reaches of the river, are likely to have lowered the river elevation (this being the purpose of the works – to reduce flood risk), and will therefore have changed the groundwater-surface water interaction here. It is possible that the lower reach of the river has changed from a losing section to a gaining section. White *et. al.* (2012) show that the Wrights Cut to Old State Highway Bridge reach of the river gains somewhere in the order of 0.6 m³/s from the local groundwater system.

Stewart *et al*.'s (2002) report on the age and source of Canterbury Plains Groundwater concluded that very little offshore flow is likely in the deep aquifers near Kaiapoi, with very old (zero-tritium) groundwater found at Pegasus and Woodend Beach. The authors considered that young ages near the coast in the

Ashley River/Rakahuri area suggest active offshore flow in the uppermost confined aquifer near Waikuku, but that offshore flow is not likely further south. In my view the very low tritium concentration reported for well M35/6662 (screened from 54 to 61 m) at Kairaki Beach and zero concentration in well M35/7024 (screened from 72 to 77 m) at Woodend Beach do suggest that groundwater velocities are low in the deeper aquifer system. But zero tritium was also recorded in some wells further inland, e.g. wells M35/8381 (screened 86.5 – 88 m) and M35/3289 (77 m deep), and some easterly groundwater flow is likely in these locations. Furthermore, a simple groundwater velocity model based on the land surface recharge rate, aquifer thickness and effective porosity presented in Appelo and Postma (1996) yields a mean residence time of 80 years for a well penetrating 80 m into a 200 m thick aquifer[21]. Because of this the low or zero tritium concentrations do not necessarily indicate an absence of offshore flow for wells in this depth range – they may just be a function of the well depth. A low or zero tritium concentration in a shallow well would provide much more compelling evidence of a low flow rate. The authors noted that carbon-14 sampling would be useful to confirm the suspected low offshore flow rates.

Van der Raaij (2011) reviewed and remodelled isotope data from the zone and concluded that ages in the confined aquifer system near the coast were mostly greater than 80 years minimum age, the oldest groundwater having a radiocarbon age of around 10,000 years[22]. The radiocarbon age interpretation came from well M35/10908, which is screened at 143 – 146 m depth and located in Pegasus Town, north of the inferred position of the Pegasus Bay Fault discussed in Section 3.5.2. The transmissivity of the aquifer here is low, with a T value of 170 m²/d interpreted from pumping test data. Very old water, aged at 3,800 and 1,350 years was also interpreted for samples from wells M35/7542 (screened 202 – 206 m depth) and M35/0737 (screened from 128 – 132 m). Well M35/7542 is located east of Woodend approximately 2 km from the coast and is screened in a more transmissive part of the aquifer, with an interpreted T value of 900 m²/d. Well M35/0737 is located on the northern outskirts of Kaiapoi, approximately 2.5 km from the coast. The specific capacity of this well suggests the transmissivity is likely to be similar to well M35/7542, in the order of 1,000 m²/d.

The Van der Raaij study found that shallow groundwater from wells such as M35/7079 (27.5 m deep, located at Woodend Beach) is old, with a tritium data-interpreted mean residence time of 41 – 100 years, and concluded overall that there is almost no offshore flow from the aquifer here. This is perhaps not the only explanation that fits with the M35/7079 tritium data: the strong upward gradient present at this location (see Section 5) shows that the shallow aquifer is being fed by recharge from the deeper system, and hence the high mean residence time in well M35/7079 can be explained by upward flow, which may mix with more recent recharge in the shallow aquifer and flow offshore. Nevertheless, as noted above the low tritium concentrations in this shallow well provide a more compelling indication of a low offshore flow rate.

Although the radiocarbon data provide a more robust indication that flow rates in the deeper part of the aquifer in the coastal zone might be low, we do not yet know how low. Given that an upward hydraulic gradient is evident in the coastal zone, extending approximately 12 km inland, the recharge source for the >100 m deep radiocarbon samples must have been more than 12 km from the coast. If we assume that the recharge source for the radiocarbon water samples was land surface recharge on the Waimakariri plains 14 km from the coast[23], and take the geometric mean radiocarbon age of the three deep well water samples of 3,700 years (noting that the radiocarbon ages are likely to overstate mean residence time to some extent) the mean particle velocity along the flow path would be 3.8 m/year. Taking this velocity with an assumed effective porosity of 0.1 gives a groundwater flow rate of 0.4 m/year, equivalent to 0.1 m³/s of offshore discharge through a 300 m aquifer thickness over the 16 km Waimakariri coastline. On this basis the radiocarbon data do suggest that offshore flow rates are probably much lower than some of the previous estimates, at least along the Kaiapoi to Pegasus Town coastline.

Age interpretations provided in Van der Raaij (2011) for wells in the Waikuku Beach area give young groundwater ages, less than 6 years. These wells are generally shallow, three being between 20 and 25 m deep and one being screened between 52 and 58 m depth. The young ages suggest higher

[21] Assumes effective porosity = 0.2 and an average land surface recharge rate of 0.25 m/year

[22] It should be noted that the radiocarbon ages are likely to overstate mean residence time according to Van der Raaij (2011)

[23] In reality it was probably much further than this

groundwater flow velocities, consistent with an absence of upflow from the deeper aquifer and higher rates of offshore groundwater flow in the coastal zone here.

## 8.2 Water quality data

### 8.2.1 Nitrate as a tracer

Nitrates occur naturally in groundwater, but generally at concentrations less than about 1 to 3 mg/L nitrate-N (Close and Smith, 2001; Chapelle, 1993; Madison and Brunett, 1985 referenced in Hanson, 2002). More recent analysis carried out by Morgenstern and Daughney (2012) shows that natural concentrations of nitrate-N in New Zealand groundwater are likely to be below 0.25 mg/L. The authors identify two step changes in groundwater nitrate concentrations: one in the 1880s, when groundwater nitrate increased from pristine/background concentrations (<0.25 mg/L) up to 2.5 mg/L in response to the advent of low intensity agriculture in New Zealand. The second occurred in the 1950s, when the effects of high intensity land use were reflected in nitrate concentrations >2.5 mg/L. Nitrate can therefore potentially be used as a tracer in areas of oxic groundwater, where no denitrification occurs, and where agricultural soil drainage nitrate concentrations are not diluted by cleaner water sources (e.g. river recharge to aquifers).

Low concentrations of dissolved oxygen and elevated iron, manganese and arsenic indicate that reducing conditions are present in some parts of the coastal zone aquifer (see Dodson *et. al.,* 2012). This means that some denitrification is likely to occur in the aquifer in the Waimakariri coastal zone. Because some denitrification is expected to occur in this coastal zone, an absence of nitrate does not necessarily signal groundwater of pre-agricultural origin. High nitrate concentrations in deeper coastal zone wells probably would signal significant groundwater flow rates, however. I have plotted nitrate concentrations from coastal wells in the Waimakariri zone in Figure 8-1 below. Nitrate concentrations are low in the deeper wells, often below the detection limit (0.05 – 0.1 mg/L[24]). Low concentrations are also seen in the shallow wells at Waikuku Beach, and this probably reflects dilution of nitrate concentrations from agricultural land with low nitrate Ashley River/Rakahuri water. Nitrate concentrations are above the limit of detection in well BW24/0039 (126 m deep) at Woodend Beach, despite zero detections in the shallower wells at this location. This could be due to groundwater flow and transport of nitrate from inland plains agricultural land to the deeper part of the aquifer system at this location, but it could also be derived from natural sources (e.g. bedrock nitrogen and nitrogen leached from natural soils). The nitrate data therefore do not provide any clear insights into offshore groundwater flow from the Waimakariri zone.

[24] Recent samples generally have a limit of detection of 0.05 mg/L, older samples have a limit of 0.1 mg/L.

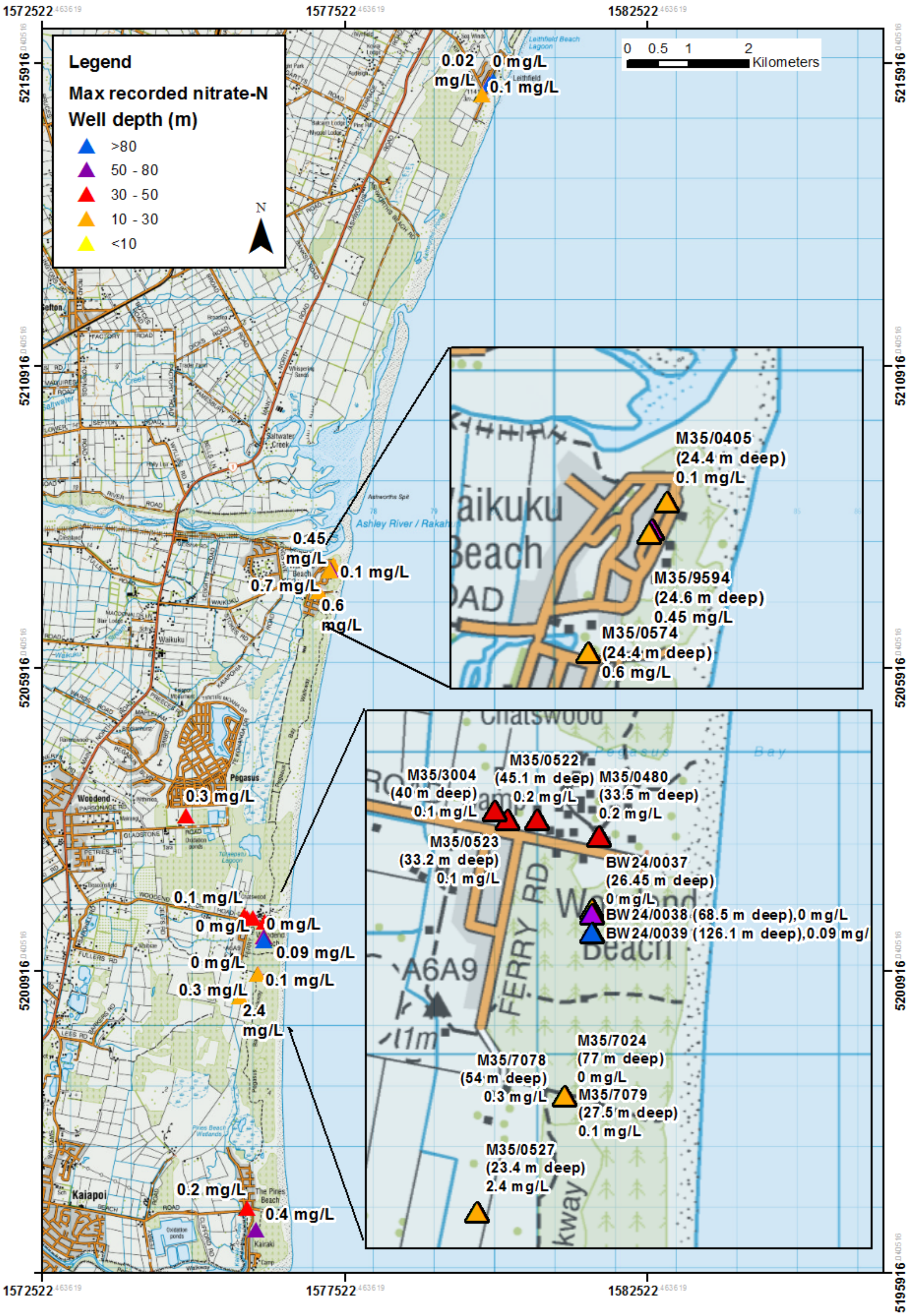



**Figure 8-1: Coastal well nitrate concentrations**

# 9 Offshore groundwater flow rates

## 9.1 Overview

In this section of the report I firstly explore the potential for offshore flow through the possible seabed outcrop of Q2/Q4 and Q6 period strata. I then go on to estimate the total offshore discharge through the Waimakariri zone coastal aquifer using some simple Darcy's Law calculations. I have broken the coastline down into three sections for the calculations: Waimakariri River to Pegasus Town, Pegasus Town to Ashley River and Ashley River to Ashworths Beach Road (the approximate location of the northern boundary of the Waimakariri Zone). It should be noted that the boundary between the Waimakariri/Pegasus Zone and the Pegasus/Ashley Zone is a "fuzzy" one, not based on any solid geological evidence. It is likely that there are onshore structural features yet to be discovered that may explain the reduction in vertical hydraulic gradients. Any such features would provide a stronger basis for zonation of the coastal hydrogeology.

## 9.2 Transmissivity summary

### 9.2.1 Combined pumping test and tidal response analysis data

I have summarised the transmissivity values interpreted from the pumping test and tidal response analysis in Table 9-1 below.

**Table 9-1: Transmissivity summary**

| Well | Data source | Strata | T min m²/d | T max m²/d | T med m²/d |
|---|---|---|---|---|---|
| M35/4700 | Pumping | Q1 | 160 | 3,200 | 1,600 |
| M35/7079 | Tidal | Q2/Q4 | 2,000 | 4,300 | 3,150 |
| M35/7078 | Tidal | Q2/Q4 | 4,900 | 10,500 | 7,700 |
| BW24/0037 | Tidal | Q2/Q4 | 300 | 2,500 | 1,400 |
| BW24/0083 | Tidal | Q2/Q4 | 1,700 | 3,600 | 2,650 |
| M35/8485 | Tidal | Q2/Q4 | 2,200 | 4,400 | 3,300 |
| BW24/0141 | Tidal | Q2/Q4 | 1,500 | 2,600 | 2,050 |
| M35/6760 | Pumping | Q2/Q4 | 245 | 455 | 350 |
| M35/3487 | Pumping | Q2/Q4 | 613 | 1,138 | 875 |
| M35/0470 | Pumping | Q2/Q4 | 252 | 468 | 360 |
| M35/4897 | Pumping | Q2/Q4 | 544 | 1,010 | 777 |
| M35/0527 | Pumping | Q2/Q4 | 1,470 | 2,730 | 2,100 |
| M35/11591 | Pumping | Q2/Q4 | 2,100 | 3,900 | 3,000 |
| M35/11592 | Pumping | Q2/Q4 | 1,260 | 2,340 | 1,800 |
| M35/18107 | Pumping | Q2/Q4 | 294 | 546 | 420 |
| BW24/0037 | Pumping | Q2/Q4 | 32 | 59 | 45 |
| M35/7024 | Tidal | Q6 | 300 | 5,200 | 2,750 |
| BW24/0038 | Tidal | Q6 | 800 | 6,300 | 3,550 |
| M34/5561 | Tidal | Q6 | 6,300 | 11,700 | 9,000 |
| M35/8596 | Tidal | Q6 | 3,600 | 5,900 | 4,750 |
| M35/18159 | Tidal | Q6 | 11,900 | 22,100 | 17,000 |
| BW24/0038 | Pumping | Q6 | 168 | 480 | 240 |

| Well | Data source | Strata | T min m²/d | T max m²/d | T med m²/d |
|---|---|---|---|---|---|
| M35/10385 | Pumping | Q6 | 70 | 1,200 | 100 |
| M35/0847 | Pumping | Q8 | 300 | 6,000 | 3,000 |
| BW24/0039 | Tidal | Q8 | 11,000 | 17,400 | 14,200 |
| BW24/0039 | Pumping | Q10 | 693 | 1,287 | 990 |
| M35/10908 | Pumping | Q10 | 116 | 216 | 166 |
| M35/11199 | Pumping | Q10 | 2,741 | 5,091 | 3,916 |
| M35/11908 | Pumping | Q10 | 1,162 | 2,158 | 1,660 |
| M35/7542 | Pumping | >Q10 | 93 | 1,860 | 930 |
| **Geometric means** | | Q1 | **160** | **3,200** | **1,600** |
| | | *Q2/Q4* | **746** | **1,574** | **1,175** |
| | | *Q6* | **962** | **4,335** | **2,083** |
| | | *Q8* | **1,817** | **10,218** | **3,000** |
| | | Q10 | **712** | **1,322** | **1,017** |
| | | >Q10 | **93** | **1,860** | **930** |

**Notes**[25]: Because the pumping test analyses-based T values do not include uncertainty analysis I have assumed a range of 10% - 200% of the estimated T value for strata with ≤2 T values (i.e. n ≤2) and a range of 70% to 130% where n>2 to derive the T min and T max values above.

### 9.2.2 Shallow aquifer deposits (Q1 and Q2/Q4 material)

If we take a T range of **200** to **3,000** m²/d for the Q1 strata (thereby using a broader range to account for the uncertainty associated with the single T estimate for this material) and **1,500** to **4,000** for the Q2/Q4 strata (roughly based on the range of geometric means in Table 9-1), the combined transmissivity of the full thickness of both units would be **1,700** – **7,000** m²/d. Note that as with all of the transmissivity values discussed in this section of the report, this does not represent the full range of possible T values at any one location, but a possible range for the average transmissivity along the whole Waimakariri coastline.

### 9.2.3 Deeper aquifer deposits (Q6 – Q8 material)

The geometric mean T value for the two pumping tests undertaken within the assumed Q6 strata depth range is 150 m²/d. Given that some of the interglacial deposits are also transmissive, and noting that the vast majority of wells only penetrate a small proportion of a single glacial period layer, the combined transmissivity of the Q6 strata may be much higher.

Tidal response data for Q6 depth range wells yield T estimates of 1,200 – 17,000 m²/d and a geometric mean of 4,600 m²/d. The geometric mean T for the combined pumping test and tidal response analysis data set is 1,700 m²/d. I have assumed a possible range of **1,000** to **4,000** m²/d based on the data in Table 9-1.

I have assumed a possible range **of 2,000 – 4,000** m²/d. for the Q8 strata. This is lower than the geometric mean shown in Table 9-1 because the very high T max value interpreted from the tidal response data skews the data upwards.

The geometric mean T value for the five wells with pumping test data within the assumed Q10 depth range is 1,000 m²/d with a range of 200 – 3,900 m²/d. Only one T value (900 m²/d) is available for wells installed below the assumed Q10 depth range. I have again assumed a possible range of **2,000 – 6,000** m²/d for the Q10+ depth material, allowing for some possible additional transmissivity below the Q10 strata.

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[25] Internal data source: P:\Groundwater\Waimakariri\Groundwater\Groundwater Quantity\Spreadhseets\CoastalZoneTSummary.xlsx

### 9.2.4 Combined Quaternary deposits transmissivity

Taking the values above gives us a combined transmissivity for the Q1 – Q10+ strata of **6,700 – 21,000** with a geometric mean of **10,000** m²/d (the latter being taken directly from the summed T med value for the Q1-Q10+ strata in Table 9-1).

## 9.3 Offshore flow rate estimates

Darcy's Law states that Q = Aki or Q = wTi, where Q = flow rate, A = cross sectional area, k = hydraulic conductivity, i = hydraulic gradient, w = aquifer width and T = transmissivity.

The length of the Waimakariri River to Pegasus Town coastline is 8 km; the Pegasus Town to Ashley River section is 4 km long and the Ashley River to northern zone boundary section is also 4 km.

I have calculated offshore flow rates between the Waimakariri River mouth and Pegasus Town and from Pegasus Town to the top of the Waimakariri Zone at Ashworths Beach road using Darcy's Law based on the above coastline lengths, the hydraulic gradient data in Section 5.4 and the transmissivity data summarised in Section 9.2.

Results (Table 9-2) suggest that offshore flow rates through the stretch between Pegasus Town and the Waimakariri River are very low, probably less than 0.3 m³/s. Coastal discharge rates appear to be much higher north of Pegasus Town, up to 5 m³/s.

**Table 9-2: Offshore groundwater discharge rate estimates**

| Area | Depth interval (m) | Length (km) | Gradient | T min (m²/d) | T max (m²/d) | Flow min (m³/s) | Flow max (m³/s) |
|---|---|---|---|---|---|---|---|
| Waimakariri River to Pegasus Town | Q1 to Q2/Q4 | 8.0 | 2E-04 | 1,700 | 7,000 | 0.03 | 0.13 |
| | Q6+ | | 1E-04 | 5,000 | 14,000 | 0.05 | 0.13 |
| ***Sub total*** | | | | | | ***0.07*** | ***0.26*** |
| Pegasus Town to Ashley River | Q1 to Q2/Q4 | 4 | 2.50E-03 | 1,700 | 7,000 | 0.2 | 0.81 |
| | Q6+ | | 3.50E-03 | 5,000 | 14,000 | 0.81 | 2.27 |
| ***Sub total*** | | | | | | ***1.0*** | ***3.08*** |
| Ashley River to zone N boundary | Q1 to Q2/Q4 | 4 | 5.00E-03 | 1,700 | 7,000 | 0.39 | 1.62 |
| | Q6+ | | 6.50E-04 | 5,000 | 14,000 | 0.15 | 0.42 |
| ***Sub total*** | | | | | | ***0.5*** | ***2.04*** |
| **Total** | | | | | | **1.5** | **5.4** |

Using the geometric mean T values from the pumping test and tidal response analysis data gives offshore flow rates of 0.2 m³/s south of Pegasus town, 1.5 m³/s between Pegasus Town and the Ashley River/Rakahuri, and 0.9 m³/s north of the river. This equates to a total offshore discharge of 2.5 m³/s.

Because aquifer transmissivity is spatially variable, it is difficult to make a reliable estimate of the mean value over an area as large as the Waimakariri zone coastline from a relatively small number of data points. The thickness of the Q2/Q4 deposits, and possibly the deeper strata, is greater immediately north of the Pegasus Bay Fault but thin considerably towards the Waikuku anticline (see Figure 3-6) for instance, and this will affect the transmissivity (all else being equal) and hence offshore flow rates for this part of the coast.

Increasing the assumed hydraulic gradient of the coastline aquifer between Pegasus Town and Ashley River to 6.0E-03, or the transmissivity of the Quaternary sediments to 40,000 $m^2/d$, is required in order to yield a total offshore flow rate of 8.2 $m^3/s$, as per the upper limit provided in Dodson *et. al.* (2012).

I recommend that a median estimate offshore flow rate of 2.5 $m^3/s$ should be used for water budget purposes until further work is done to refine this, and that groundwater modelling should use the 1.5 – 5.4 $m^3/s$ range above as a starting point for model parameter optimisation. I suggest that 5.4 $m^3/s$ should be taken as a likely ceiling for the offshore discharge rate until further work has been done to refine this estimate. These values are lower than the water balance residual of 8.2 $m^3/s$ presented in Dodson *et. al.* (2012) and suggest that revision may be required to one or more components of our current water budget estimate. Outflow to the lowland streams below our gauging sites is likely to explain part of the difference (but possibly only a small part). It may be possible to refine the offshore flow rate estimate for the coastline north of the Ashley River/Rakahuri on the basis of the water budget for this area: estimating land surface and river loss aquifer recharge for the area between the coastline and foothills to the west here may provide a further means of estimating offshore flow rates here, assuming that uncertainties associated with the other water budget components are sufficiently small.

## 9.4 Flow potential through seabed outcrop zone

The closest location at which the seaward part of the aquifer system could outcrop is at the edge of the continental shelf, located some 60 km east of the Waimakariri coastline. If coastal groundwater discharge could occur only at this outcrop area the groundwater pressure at outcrop would be 0 m asl. Assuming and average artesian head of 4 m asl for the southern Waimakariri coast (south of Pegasus Town) would give a hydraulic gradient of 4m/60km = 7E-5. This would equate to a flow rate of 0.12 $m^3/s$ for the southern part of the Waimakariri coast based on the maximum estimated T value of 21,000 $m^2/d$. Coastal groundwater levels are lower for the norther part of the Waimakariri coast, e.g. 2 m asl, giving a hydraulic gradient of 2m/60km = 3E-05 and a flow rate of 0.06 $m^3/s$. The total discharge rate at the closest possible aquifer outcrop location is around 0.2 $m^3/s$ using the maximum T estimate derived above. This represents a small fraction of the estimated offshore discharge rates; the dominant offshore discharge pathway must be upward seepage through the seabed sediments.

If significant upward seepage does occur, the point at which the groundwater elevation in the deeper sediments reaches zero m asl could be much closer than 40 km from the coast. Because significant offshore flow from the deeper strata is only likely to occur via upward seepage, I consider that the thickness and hydraulic conductivity of post-glacial marine deposits overlying the Quaternary strata is the main control offshore groundwater discharge rates in the Waimakariri coastal zone.

Figure 3-5 shows that the thickness of this capping material increases from around 25 m at the coast to 50 m around 30-35 km offshore in the southern part of the zone. I would expect a capping layer of this thickness to limit the rate of offshore discharge if the hydraulic conductivity of the material is very low. Although the capping material is likely to be fine-grained (being predominantly marine deposits), and therefore have a low vertical hydraulic conductivity, we do not have sufficient data to quantify this. We also do not have much information on the thickness of the capping layer in the northern part of the zone, but expect that this material will be much thinner here due to the depositional environment discussed in Section 3.5 (see Figure 3-3). It is therefore necessary to use information on the hydraulic gradient and transmissivity of the aquifer system in the coastal zone to estimate how much water is likely to discharge from the deeper aquifer system via vertical offshore seepage to the seabed. I consider this to be a valid method because any upward seepage to the seabed from the underlying strata could only be supported by lateral flow into and through that underlying strata from the coastal aquifer system. The rate of lateral flow (and hence the rate of upward offshore seepage through the sea bed) is controlled by the lateral hydraulic gradient and conductivity. It is therefore not necessary to attempt to calculate vertical seepage rates[26] in order to approximately estimate offshore flow: estimate of lateral flow rates is sufficient.

[26] Which in any case would be very uncertain given the lack of data on the vertical hydraulic conductivity of the sea bed material.

# 10 Revised conceptual model of the coastal zone

## 10.1 Conceptual model

I have used the information presented in this report to revise our conceptual model of the Waimakariri coastal aquifer system. The model is presented as schematic cross sections for the coastal aquifer system at Kaiapoi (southern part of Waimakariri zone, Figure 10-1) and at the Ashley River/Rakahuri mouth (northern part of Waimakariri zone, Figure 10-2). The main features of my conceptual model are summarised in the following paragraphs.

The inland extent of coastal sediments is shown at approximately the same distance inland of the current coastline for each interglacial sedimentary sequence, based on information presented in NCCB_b (1986). The NCCB_b report analysed all available well logs for the Christchurch area and found that the presence and thickness of fine-grained estuarine and marine deposits diminished westwards from the coast, with the inland limit of this material being at approximately the same distance from the present-day coastline for each interglacial sedimentary interval. Lovell (1998) offered a number of possible explanations for this. One possibility is that steady down-warping of the Canterbury Plains through tectonic convergence could have maintained coastal land elevations, so that the inland extent of each marine transgression did not reduce with the increasing thickness of sediment deposited during successive glacial cycles. An alternative explanation is that coastal sediments did extend further inland, but subsequent erosion associated with receding sea levels at the onset of each glaciation removed this material inland, where they were at their thinnest.

The inland extent of interglacial marine and estuarine deposits reduces northwards in the Waimakariri zone due to tectonic uplift north of the Ashley, and possibly erosion of interglacial material by the Ashley River/Rakahuri. Furthermore, the thickness of interglacial coastal deposits reduces northwards along the Waimakariri zone coastline, and the contrast between glacial and interglacial deposits is believed to reduce towards the Ashley River/Rakahuri mouth as discussed in Section 4.2. This is likely to equate to a reduction in aquifer confinement in the northern part of the zone.

Finer grained marine/interglacial deposits in the coastal zone are laterally inter-fingered with more permeable alluvial deposits, where former Waimakariri River channels have replaced this material with coarse-grained strata.

In Section 9.4 I showed that groundwater discharge at the point of aquifer seabed outcrop in the southern part of the zone is likely to be negligible, regardless of transmissivity, because the hydraulic gradient will be very low; vertical leakage through the seabed is likely to be the predominant method of offshore groundwater discharge here. The thickness of low permeability marine sediments overlying the Q2/Q4 deposits is therefore likely to be a key control on offshore groundwater discharge rates, along with the magnitude of the vertical hydraulic gradient.

The saltwater-freshwater is shown to be further offshore in the south because artesian groundwater is present at the coastline here (e.g. 6 m above ground level at 125 m depth at Woodened Beach). Groundwater levels in the northern zone area are sub-artesian.

Longshore ocean currents in the northern half of the zone have reduced the deposition of fine-grained marine sediments here. This means that the low permeability capping layer over and between the transmissive glacial period alluvial strata is thinner in this area, allowing for more groundwater discharge through vertical seepage. Conversely, a sedimentary bar (now underwater) was deposited northwards from the Banks Peninsula in the early stages of the current interglacial, and a greater thickness of marine sediments have been deposited around this bar. The bar transitions to a flatter bathymetry[27] approximately 35 km east of Pegasus Town, a few km south of the Pegasus Bay Fault. This low permeability material limits the rate of vertical groundwater seepage through the seabed in the southern part of the Waimakariri coastal zone, and also along the Christchurch coastal zone.

[27] Flatter in the east-west direction

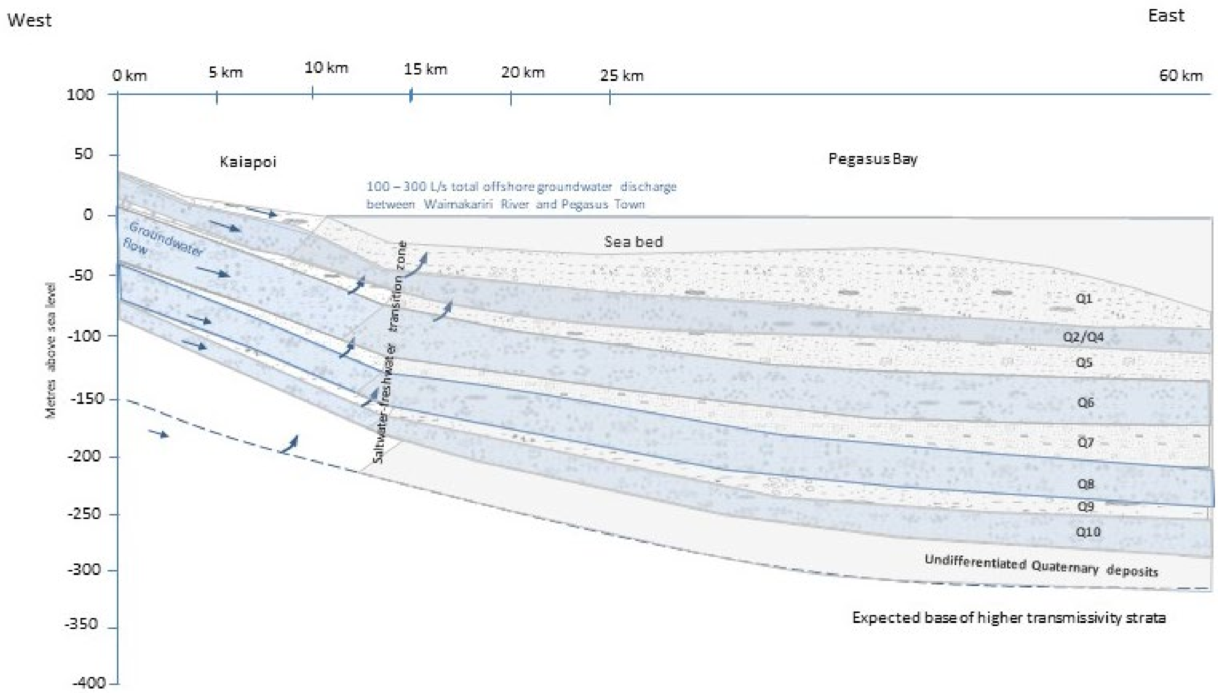


**Figure 10-1: Schematic cross section of the Waimakariri coastal aquifer system – south**

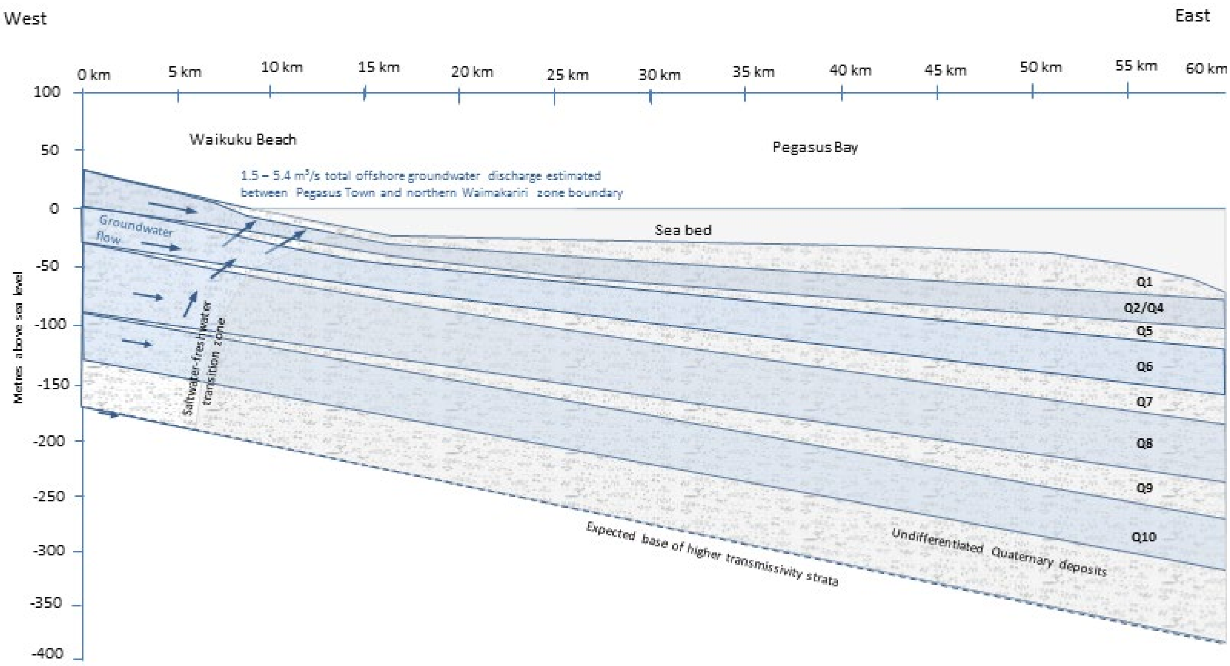


**Figure 10-2: Schematic cross section of the Waimakariri coastal aquifer system – north**

## 10.2 Implications for nutrient management

Considering a simple model of water particle (or contaminant) transport through a homogeneous aquifer system, nitrate draining from the inland Waimakariri Plains is expected to move deeper into the aquifer with increasing distance from the recharge location. If offshore groundwater flow is limited, the inland plain nitrate will be transported upwards in the coastal zone and may discharge into surface water bodies (minus any denitrification losses). In areas where offshore groundwater flow is significant, the inland plains nitrogen load is likely to be transported offshore without impacting on surface water quality. This means that land use intensification in the inland plains of the northern Waimakariri Zone[28] is less likely to impact on lowland streams than intensification in the southern part of the zone (see Figure 10-3). This should be taken into consideration when a nutrient management strategy is developed for the Waimakariri Zone.

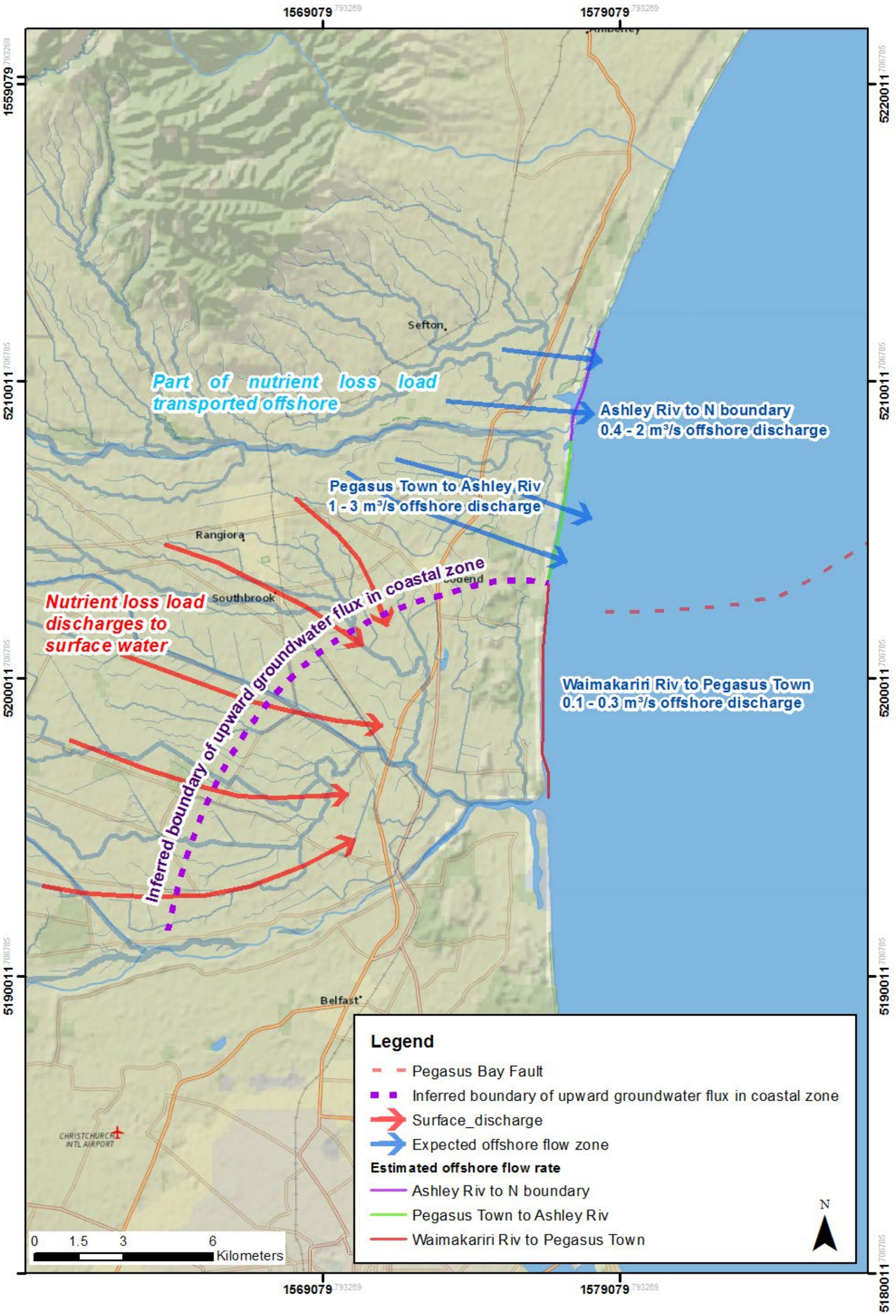


**Figure 10-3: Offshore flow summary**

[28] Although the likely groundwater flow paths shown in Figure 10-3 means that the inland plains catchment of for the northern Waimakariri coastline is very limited

# 11 Conclusions and recommendations

## 11.1 Conclusions

The coastal hydrogeology conceptual model discussed in Section 2 of this report still appears to be a reasonable representation of the aquifer system on the south side of the Pegasus Bay Fault, but I have made some modifications to incorporate the new information presented in this report.

I estimated the hydraulic gradient for the coastal aquifer system using re-interpreted contours from previous piezometric surveys, together with a mixture of long term and sporadic water level records from coastal wells and a small piezometric survey undertaken for this study in February 2016. The data suggest a generally shallow hydraulic gradient in the aquifer east of Kaiapoi between the Waimakariri River and Pegasus Town, and steeper gradients north of here.

I analysed our water quality data, using nitrate as a tracer to see if this provided useful insights into offshore flow, but this was inconclusive. I also reviewed previous age tracer interpretation reports, and found that the very old (>1,000 year) radiocarbon aging results for some deep coastal zone wells is compatible with a low hydraulic gradient in these strata.

I collated and reviewed pumping test data from coastal zone wells to provide some initial estimates of the likely transmissivity range of the various glacial period strata. I reanalysed some of the data using an alternative hydrogeological conceptualisation of the shallow aquifer as an unconfined system, and accounted for the effects of partial penetration of the aquifer by the pumping well and monitoring wells. I also highlighted the uncertainties associated with pumping test-derived transmissivity estimates.

I extended the transmissivity estimates available from pumping test data by analysing the groundwater level response to ocean tide cycles in 12 coastal wells. My interpreted values were generally of the same order as the pumping test values and provided a broader dataset from which to estimate the mean transmissivity of the coastal aquifer.

I broke the coastline down into three sections based on my conceptualisation of the system and estimated offshore flow rates at two depth intervals for each using Darcy's Law. My results indicate very low offshore discharge rates, less than 0.3 $m^3/s$ from the southern half of the Waimakariri coastline, between the Waimakariri River mouth and Pegasus Town. Higher flow rates in the order of 1.5 – 5.4 $m^3/s$ are likely north of Pegasus Town. My median estimate of the total groundwater discharge from the Waimakariri coastal zone is 2.5 $m^3/s$. These differences can be explained by the thinner capping layer of postglacial marine sediment over the northern Waimakariri coastline seabed aquifer and likely northward thinning of the interglacial deposits, both of which mean that there is less resistance to seabed seepage here.

## 11.2 Recommendations

A revised water budget should be developed as part of the groundwater modelling work being undertaken to support the Waimakariri zone sub-region planning process, to account for the lower coastal groundwater discharge rate estimated in this study.

# 12 Acknowledgments

I am very grateful to Sungsoo Koh for his work building an aquifer parameter optimisation algorithm for the tidal response data, and associated processing of the observation input data, and to Nicole Calder-Steele for her barometric efficiency analysis and re-interpretation of the 2010 and 2011 piezo survey data. Peter Callander, John Weeber, Maureen Whalen, Philippa Aitcheson-Earl, Matt Dodson and Carl Hanson provided useful review comments, which helped to shape this report. I am also grateful to Fouad Alkhaier and Nicola Wilson for reviewing my spreadsheet implementations of some of the analytical solutions.

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# APPENDIX 1 Geological cross sections

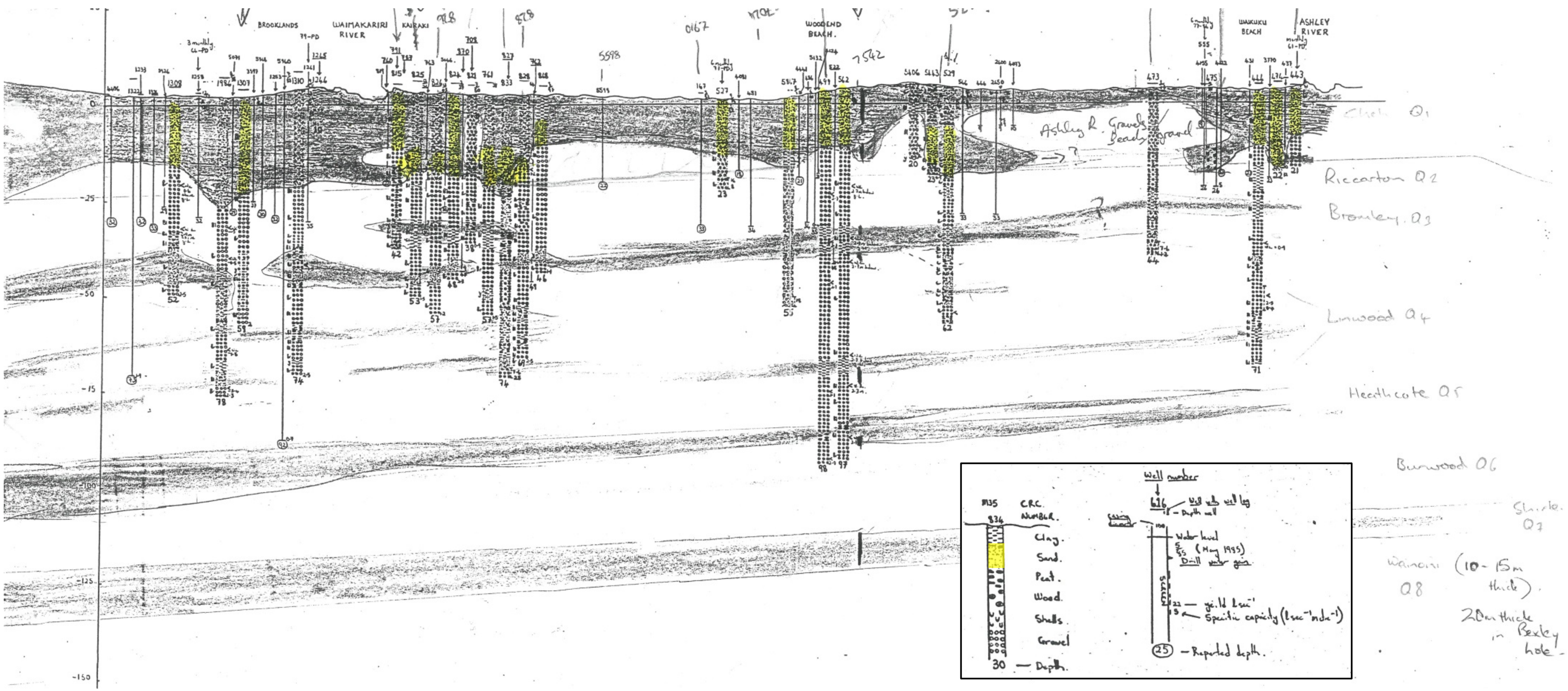



Figure A1-1: Section M35:863-700

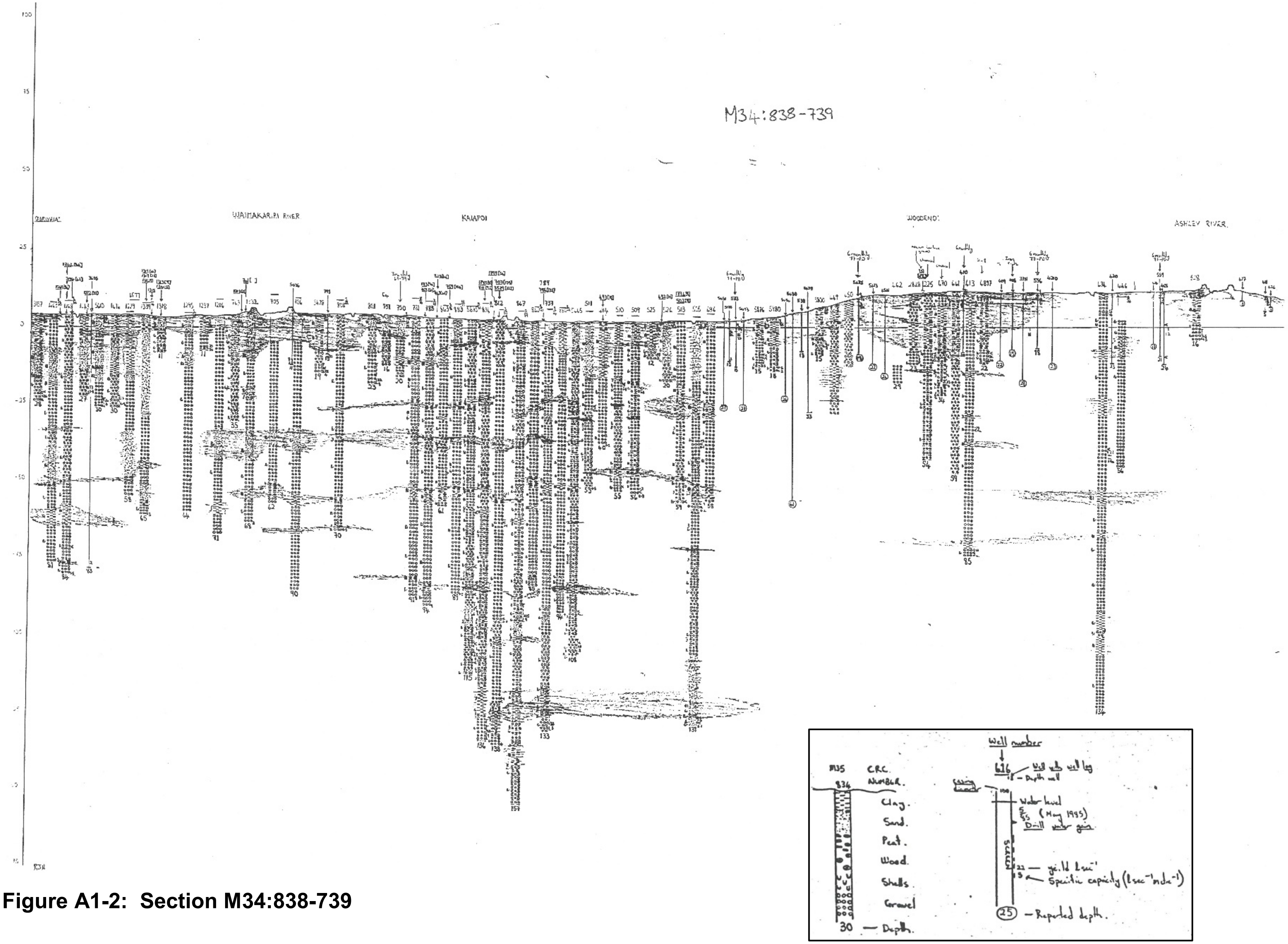



Figure A1-2: Section M34:838-739

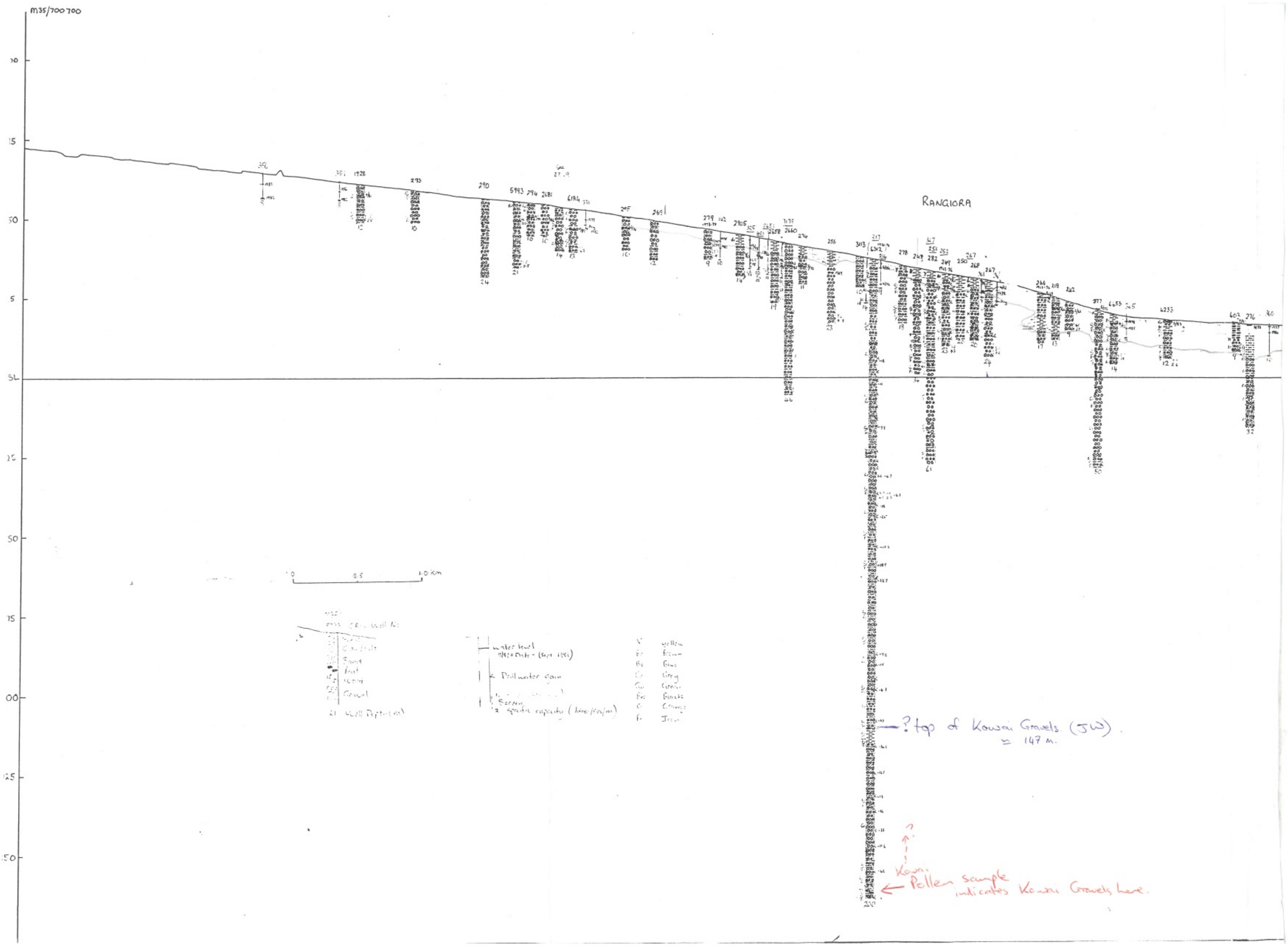



Figure A1-3: Section M35:873-630 – west

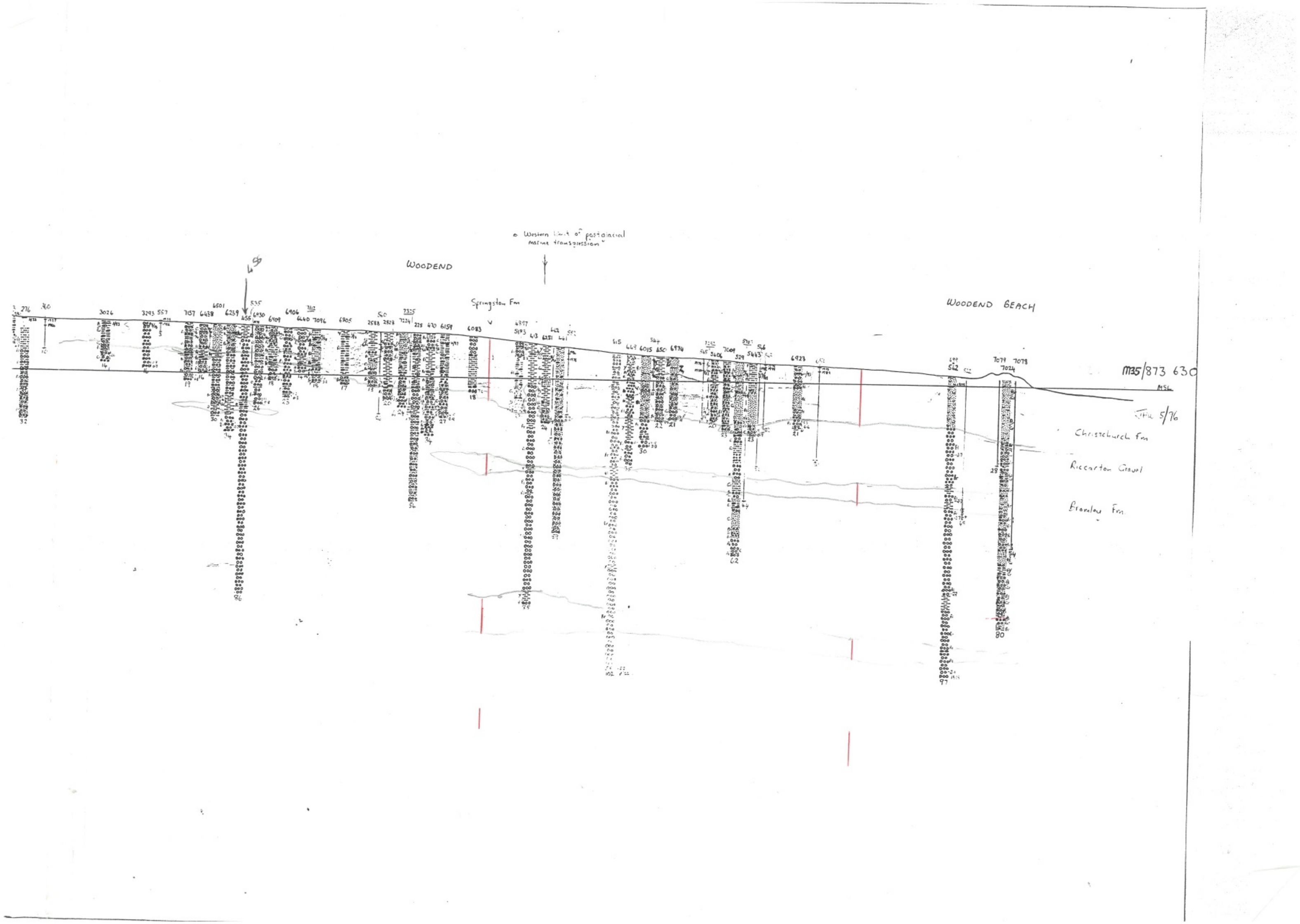



Figure A1-4: Section M35:873-630 – east

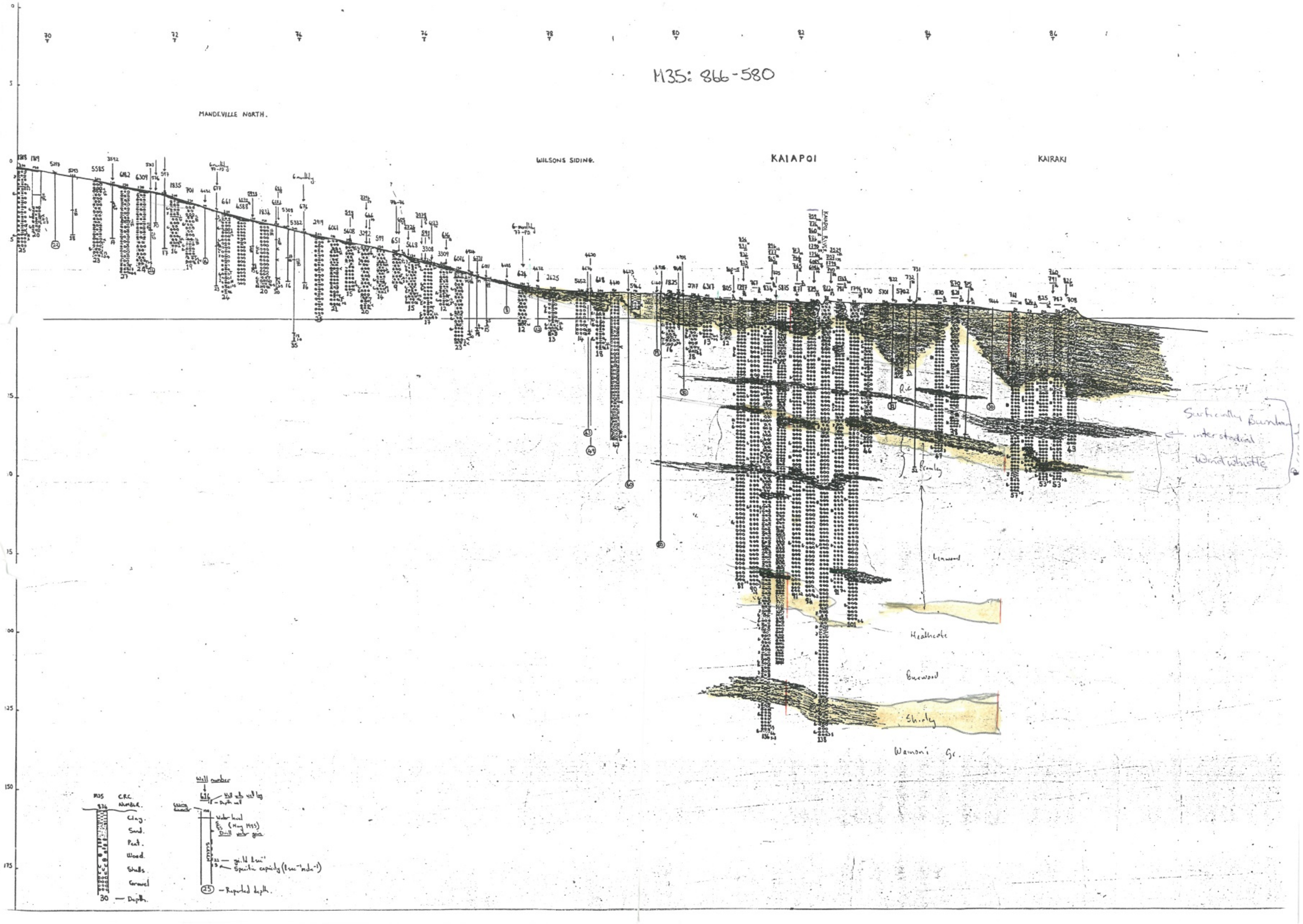



Figure A1-5: Section M35:866-580

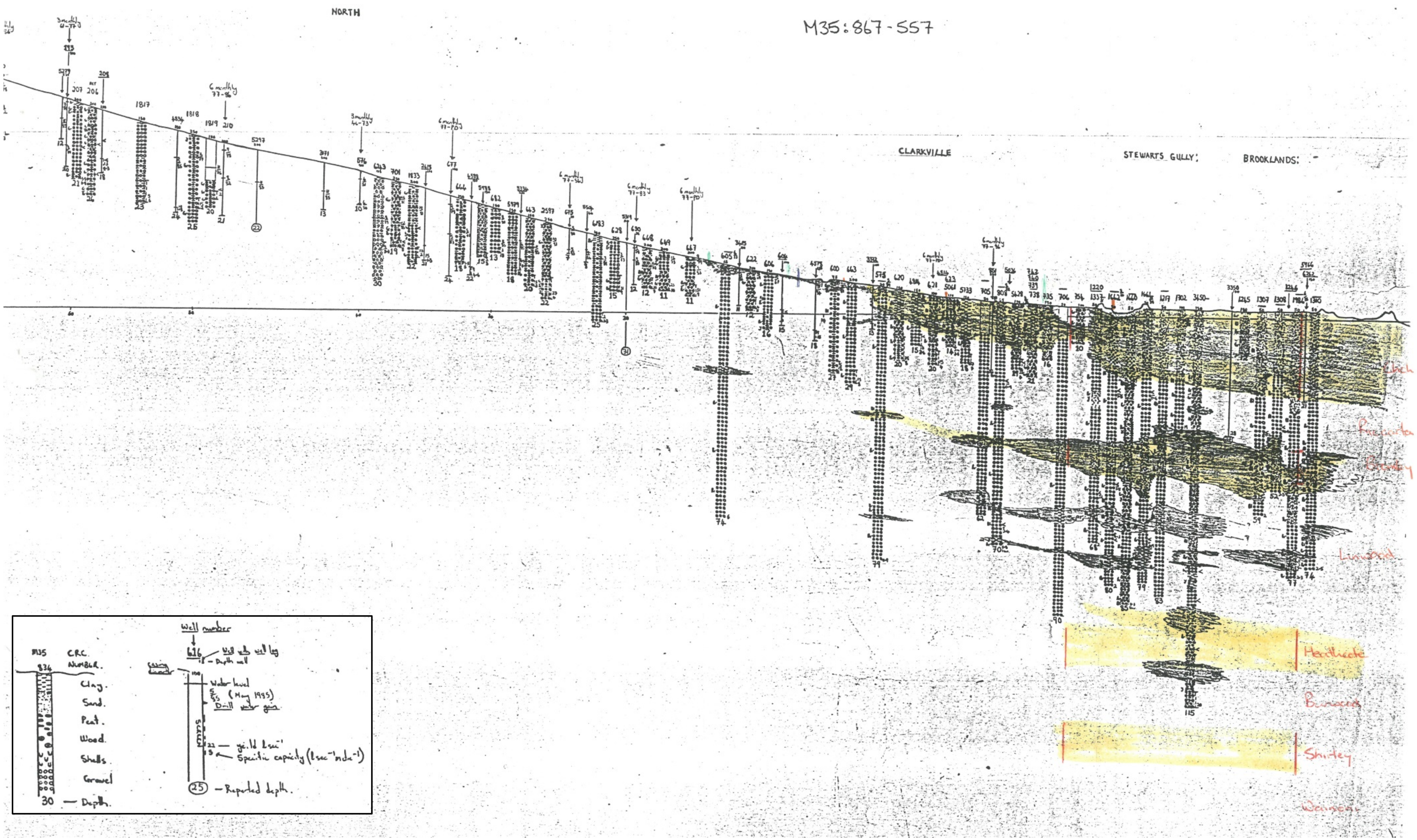



Figure A1-6: Section M35:867-557

# APPENDIX 2 Hydraulic gradient data

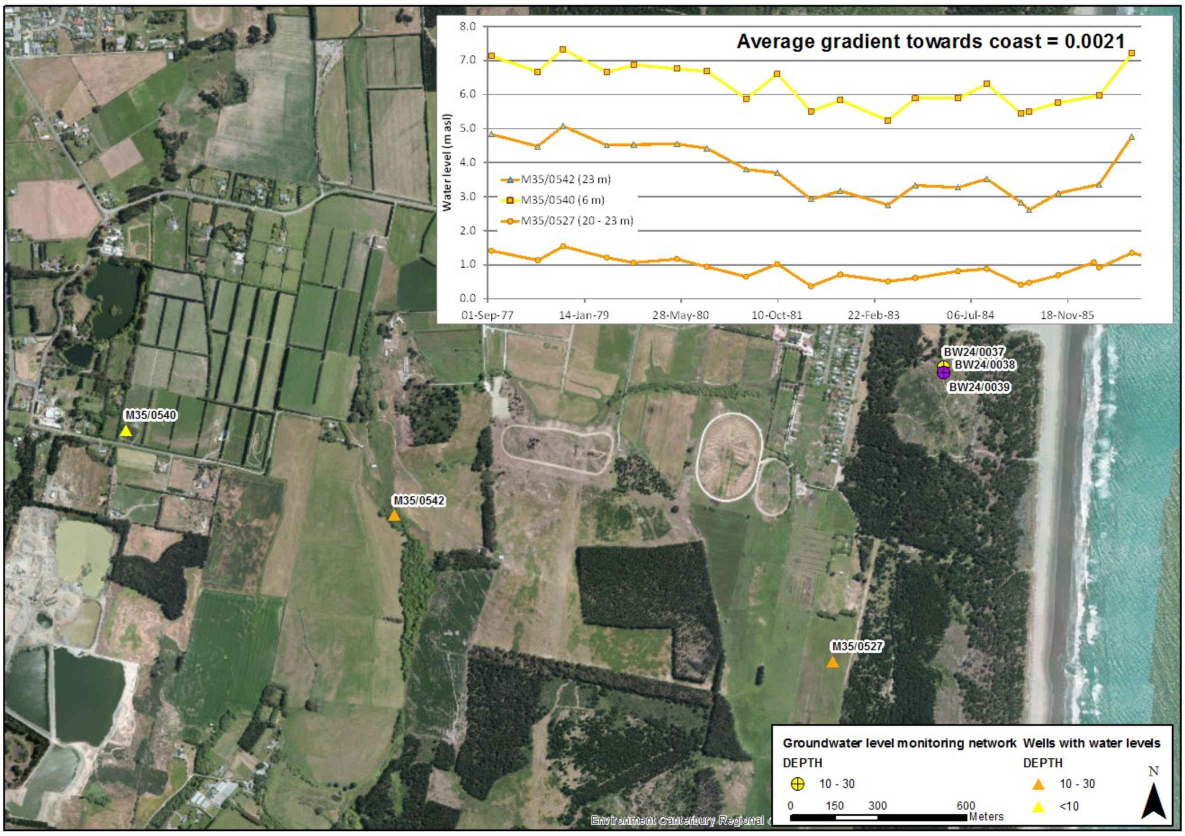



**Figure A2- 1: Shallow aquifer - Woodend Beach area**[29]

[29] See Figure 5-1 for location plan

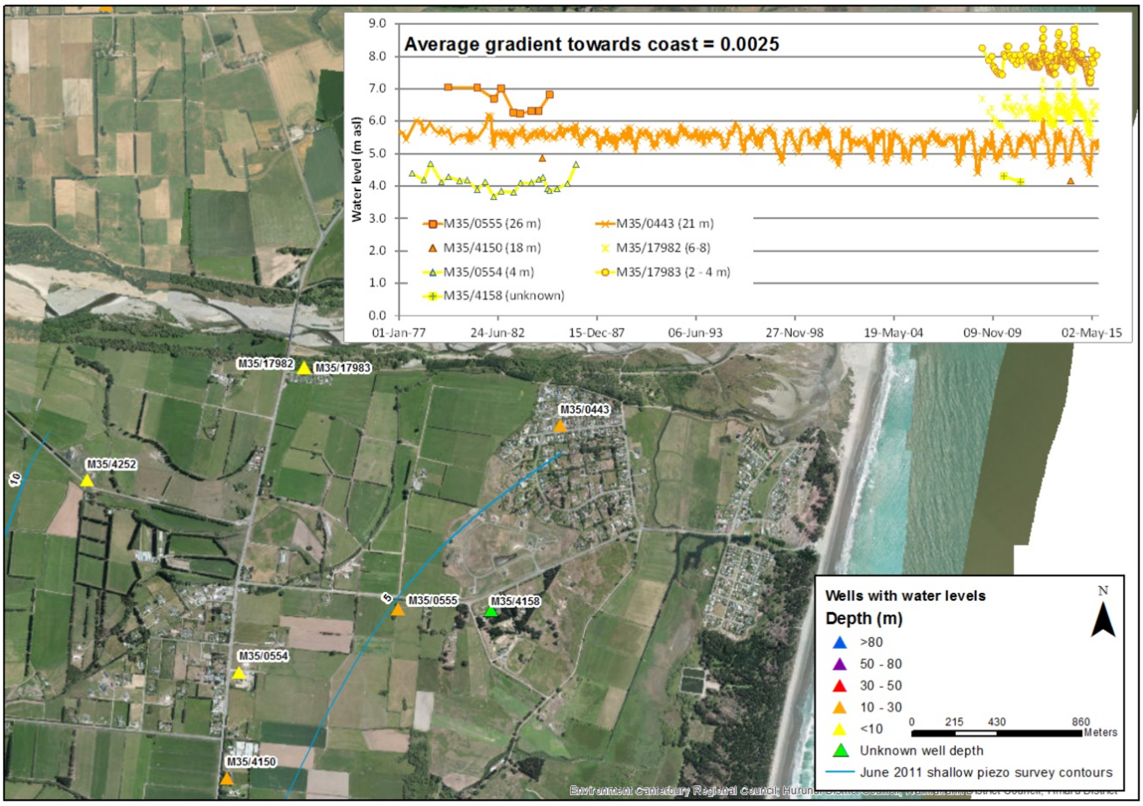



**Figure A2- 2: Shallow aquifer - Ashley River area**[29]

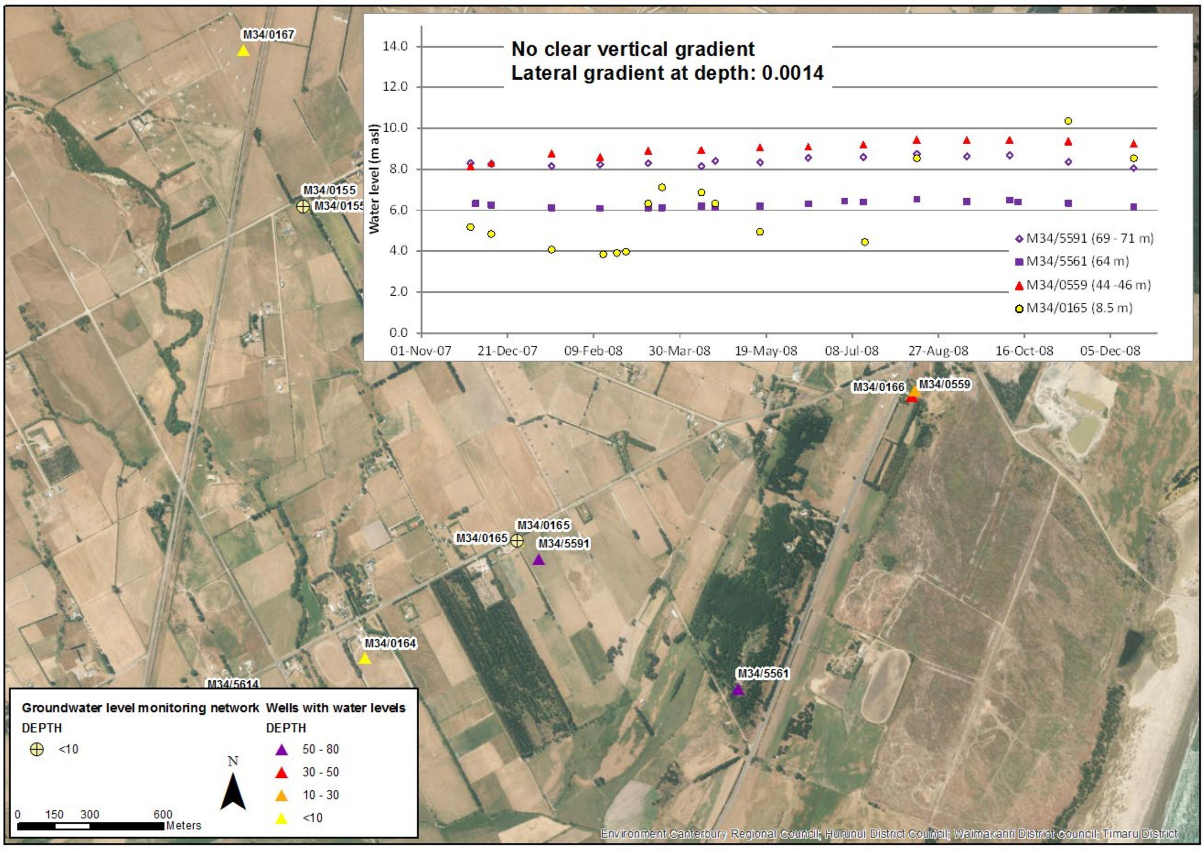



**Figure A2-3: Ashworths Road area**[29]

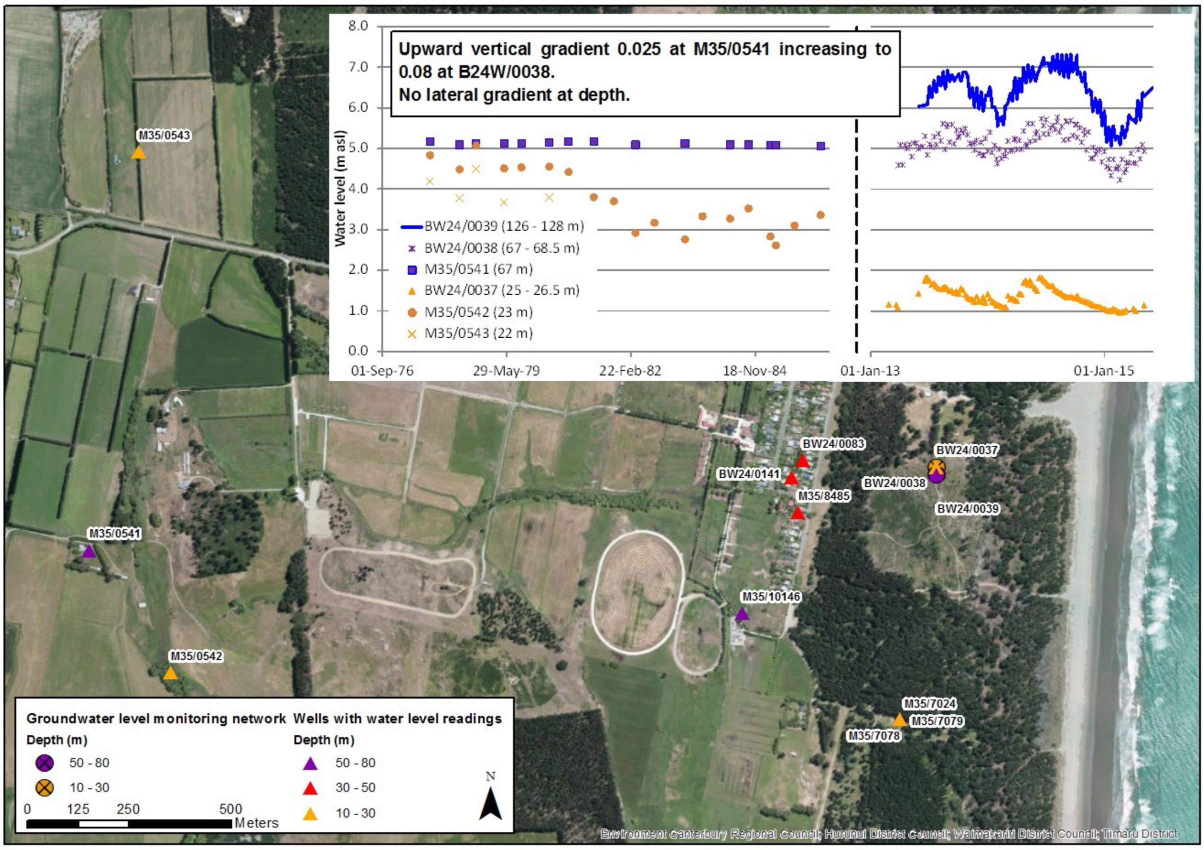



**Figure A2-4: Deep aquifer – Woodend Beach[29]**

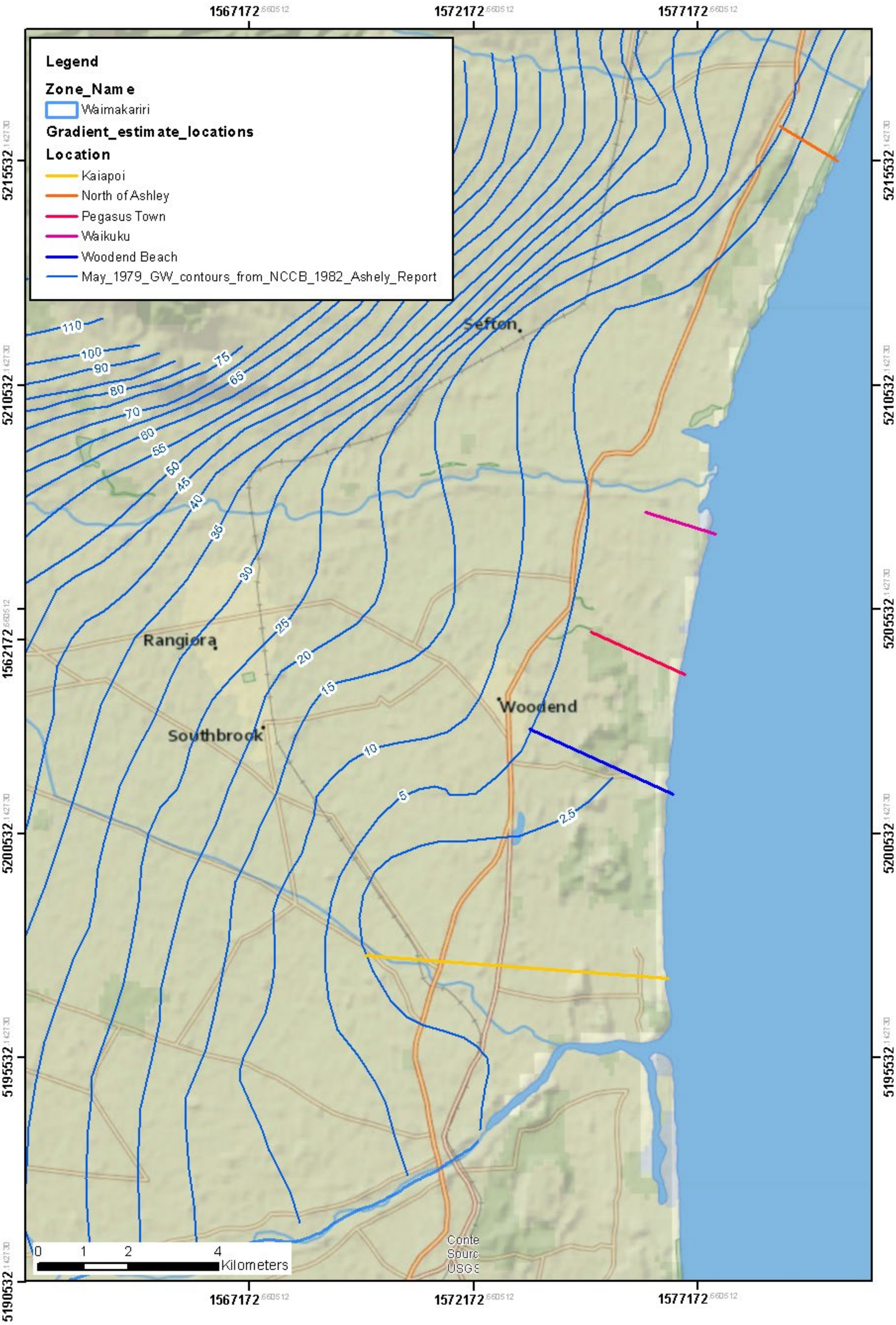



Figure A2-5: May 1979 piezometric contours (from NCCB_c, 1982)

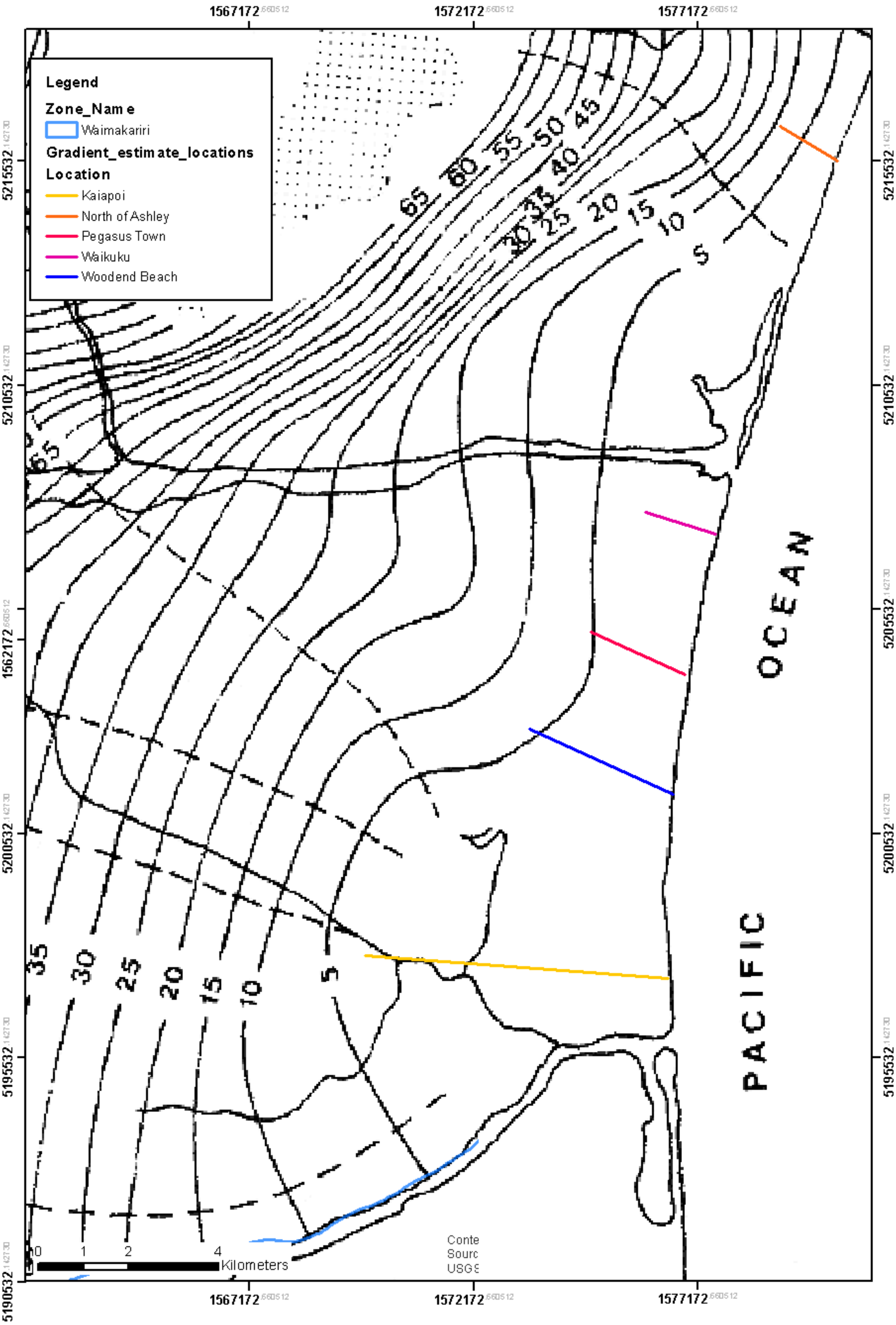



**Figure A2-6: September 1979 piezometric contours (from NCCB_c, 1982)**

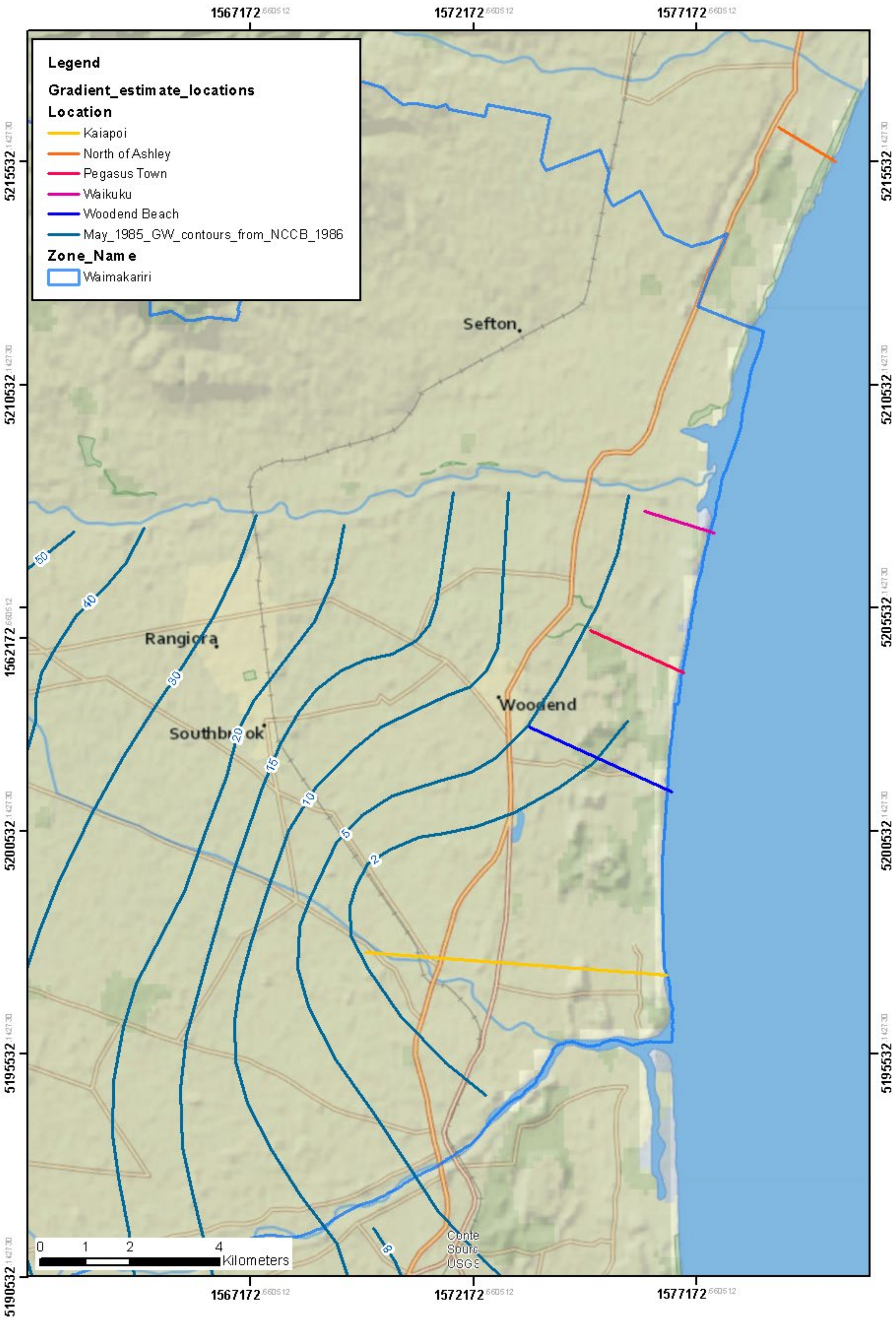



Figure A2-7: May 1985 piezometric contours (from NCCB_a, 1986)

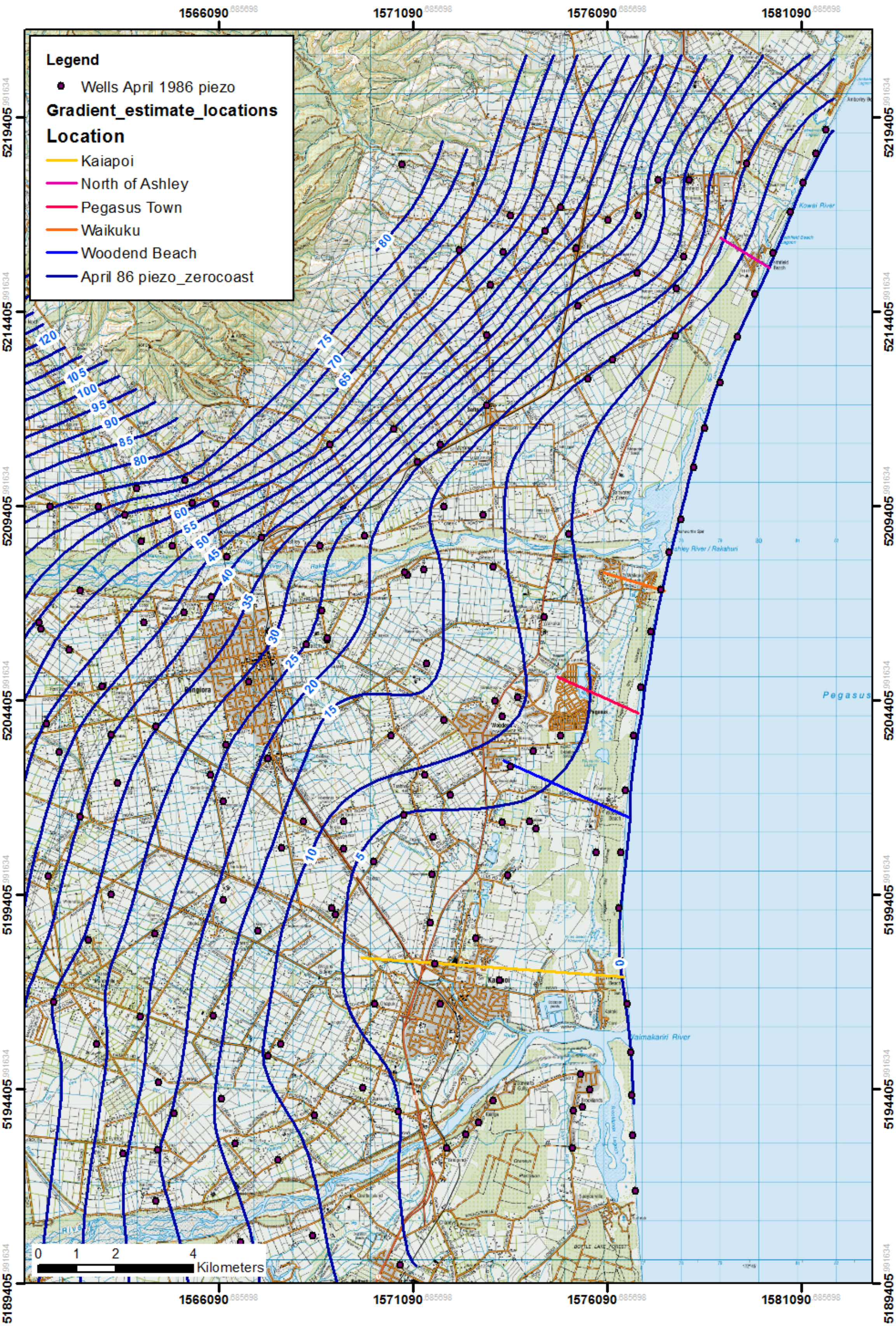



**Figure A2-8: April 1986 piezometric contours**

# APPENDIX 3 Aquifer test re-interpretation for well M35/0527

Pumping test data from a constant rate test on well M35/0527 at Woodend Beach in 1982 were re-analysed by Sanders in 1997 (Trim file reference C14C/62316). The analysis conceptualised the Q2/Q4 material (Riccarton Gravel) as a leaky confined aquifer with fully penetrating wells, and used the Hantush – Jacob leaky aquifer solution to derive transmissivity estimates varying between 1,100 and 7,900 m²/d for the six observation wells used in the pumping test. The geometric mean T value was 2,000 m²/d and leakage estimates ranged from 72 to 1800 m, with K'/B' results (aquitard $K_v$/aquitard thickness) ranging from 3E-5 to 1E-4. Storativity values between 1.9 E-04 and 2.9 E-03 were interpreted. If the aquifer system is conceptualised as a leaky (Riccarton Gravel) aquifer overlain by an unconfined (Christchurch Formation) aquifer with a 5 m (B') aquitard separating the two, the interpreted aquitard vertical hydraulic conductivity (K') ranges from 1E-4 to 4E-4 m/d.

Given that the composition of the Q1 (Christchurch Formation) in this area is dominated by sand deposits according to local well logs, the aquifer system could alternatively be conceptualised as an unconfined unit with partially penetrating wells. Re-analysis of the data using the Neuman (1974) solution for unsteady flow to a fully or partially penetrating well in a homogeneous, anisotropic unconfined aquifer with delayed gravity response yields a different set of parameter estimates. I assumed for this re-analysis that the Christchurch Formation and Riccarton Gravel act as a single unconfined aquifer (with 40 m saturated thickness) and with the pumped well and observation wells partially penetrating the aquifer. The $K_v$ parameter under this conceptualisation represents the vertical hydraulic conductivity of the Riccarton Gravel and Christchurch Formation together, whilst $K_v$ represents the vertical hydraulic conductivity of an aquitard separating these two units under the previous (Hantush-Jacob) leaky aquifer interpretation.

Because the previous leaky aquifer analysis assumes that all wells fully penetrate the aquifer (or that the effects of partial penetration on the drawdown response are negligible), the interpreted T results do not necessarily represent the transmissivity of the full aquifer thickness.

If we assume that flow to the pumped well was horizontal only, the effective aquifer thickness would be 3 m (i.e. the well screen interval). Based on a 20 m homogeneous aquifer thickness, the geometric mean Hantush –Jacob T estimate would equate to a transmissivity of ~13,700 m²/d when factored up to the full thickness of Riccarton Gravel. Interestingly, the Hantush - Jacob derived T estimate for well M35/0167 (which is probably located sufficiently far from the pumped well for partial penetration effects to be negligible) is much higher than values interpreted from the closer piezometers. This aligns with the explanation above, where the effects of partial penetration are positive (increase drawdown) when the pumped and observation wells both penetrate the same part of the aquifer. A higher drawdown could equate to a lower T value in aquifer test interpretation when partial penetration effects are ignored.

**Table A3-1: Aquifer test interpretation results from well M35/0527**

| Well No | T (m²/d) | | S | | $K_v$ (m/d) | |
|---|---|---|---|---|---|---|
| | Hantush – Jacob | Neuman (1974) | Hantush – Jacob | Neuman (1974) | Hantush – Jacob | Neuman (1974) |
| M35/0167 (at 415 m) | 7,900 | 11,600 | 1.90E-04 | 2.00E-04 | 1.48E-04 | 0.05 |
| Piezometer at 80 m | 1,900 | 2,750 | 5.90E-04 | 1.90E-03 | 5.04E-04 | 0.63 |
| Piezometer at 50 m | 1,700 | 4,700 | 1.40E-03 | 7.00E-03 | 3.18E-04 | 0.81 |
| Piezometer at 30 m | 1,700 | 6,300 | 7.20E-04 | 8.00E-03 | 3.82E-04 | 0.70 |
| Piezometer at 20 m | 1,500 | 11,600 | 1.80E-03 | 2.00E-02 | 3.08E-04 | 0.33 |
| Piezometer at 10 m | 1,150 | 7,500 | 2.90E-03 | 3.00E-02 | 2.77E-04 | 1.49 |
| ***Geometric mean*** | ***2,050*** | ***5,900*** | ***1.25E-03*** | ***9.14E-03*** | ***3.50E-04*** | ***0.74*** |

I also analysed the data from monitoring well M35/0167 under the standard assumption that it fully penetrates the aquifer. The interpreted T value was 8,600 m²/d, approximately 25% lower than the interpreted value for a partially penetrating well. The full penetration Neuman (1974) T value for the piezometer at 80 m distance is 1,900 m²/d, approximately 30% lower than the partial penetration interpretation.

Although my re-interpreted T values are much higher than any recorded in the Waimakariri zone at this depth, very high T values have been interpreted from shallow wells in the Christchurch – West Melton Zone. Pumping test data from well M36/0175 were interpreted with T values between 15,000 and 20,000 m²/d based on six observation wells at varying distances and depths.

My re-analysis of the M35/0527 pumping test data highlight the significant effects of aquifer system conceptualisation and assumptions over aquifer penetration on transmissivity estimates. A review of borelogs in this area also shows that the Christchurch Formation is dominated by sand-size material here (see cross section M35:863-700 in Appendix 1), meaning that although we do not have any pumping test data for wells screened in this formation in the coastal zone, its transmissivity could be significant when considering coastal discharge rates.

# APPENDIX 4 Tidal response analysis model assumptions and parameter constraints

Li and Jiao (2001a) showed that when roof length (see Figure 7-1) is greater than a certain threshold value, the tidal response will behave as if it is infinite. This is relevant because the location at which the transmissive parts of the aquifer system outcrop on the seabed (if they do indeed outcrop) is not well known. My analysis suggests a threshold in the order of 3 km is likely for the Waimakariri coastline. Given the coastal bathymetry, any outcrop of the transmissive material is likely to be much more than 3 km offshore, and hence the effects of roof length uncertainty on the model results can be ignored.

Li and Jiao (2001a) also demonstrated that leakage is an important dampening factor when the ratio of leakage to storativity (termed *dimensionless leakage*, u) is great (e.g. >10) and where roof length is short (dimensionless roof length (aL) <1). Assuming a storativity of 1E-4 and a K' of 1 m/d gives a dimensionless leakage of 16.5, so high u values are possible for the aquifer system in our study area, particularly the Q2/Q4 and to a lesser extent Q6 deposits. I would expect dimensionless leakage to generally reduce with depth, as the cumulative thickness of generally lower permeability interglacial period marine deposits (i.e. the aquitard in Figure 7-1) between the seafloor and the successive transmissive horizons increases. Assuming a roof length of 5 km, a storativity of 1E-04 and a transmissivity of 3,000 m²/d gives an aL value of ~2. This is likely to be the minimum aL value for the Waimakariri zone coastal aquifer system; the roof length cannot be considered short, and an aL value in excess of 5 is more likely. This means that leakage is not necessarily a major dampening factor. For long roof lengths (e.g. aL = 5) high leakage rates (u ≥15) equate to lower amplitude ratios, but in the range u ≥ 0 ≤5 the effects of leakage rates are variable (Li and Jiao, 2001a). So because a range of dimensionless leakage values are feasible for the Waimakariri coastal zone aquifer system, the likely effects of leakage on tidal response cannot be readily predicted.

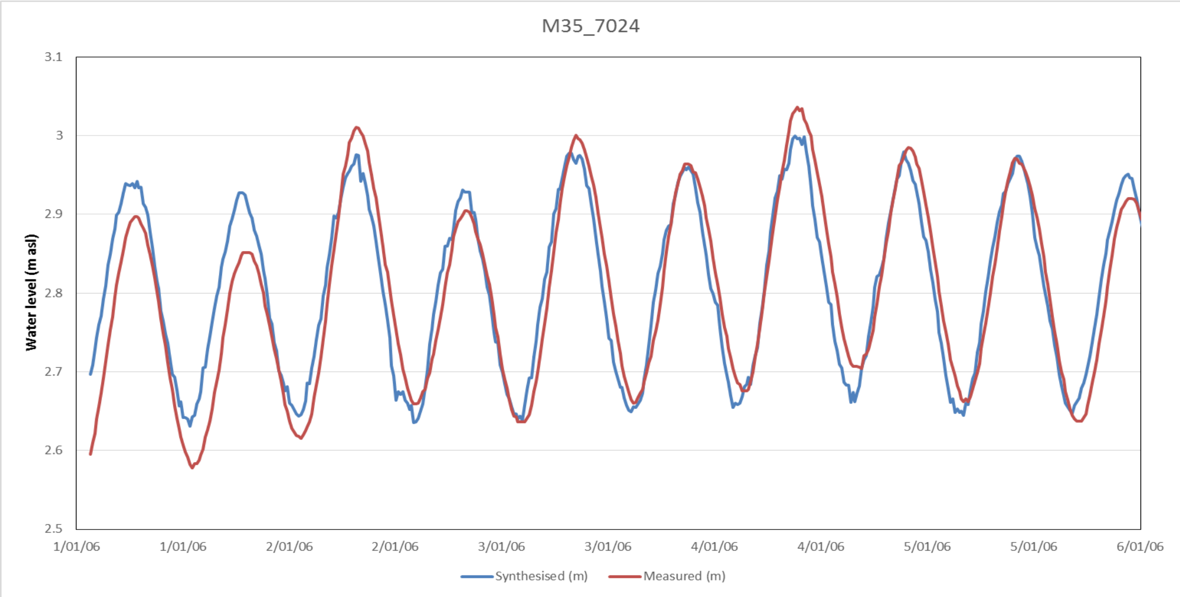
**Table A4- 1: Parameter constraints**

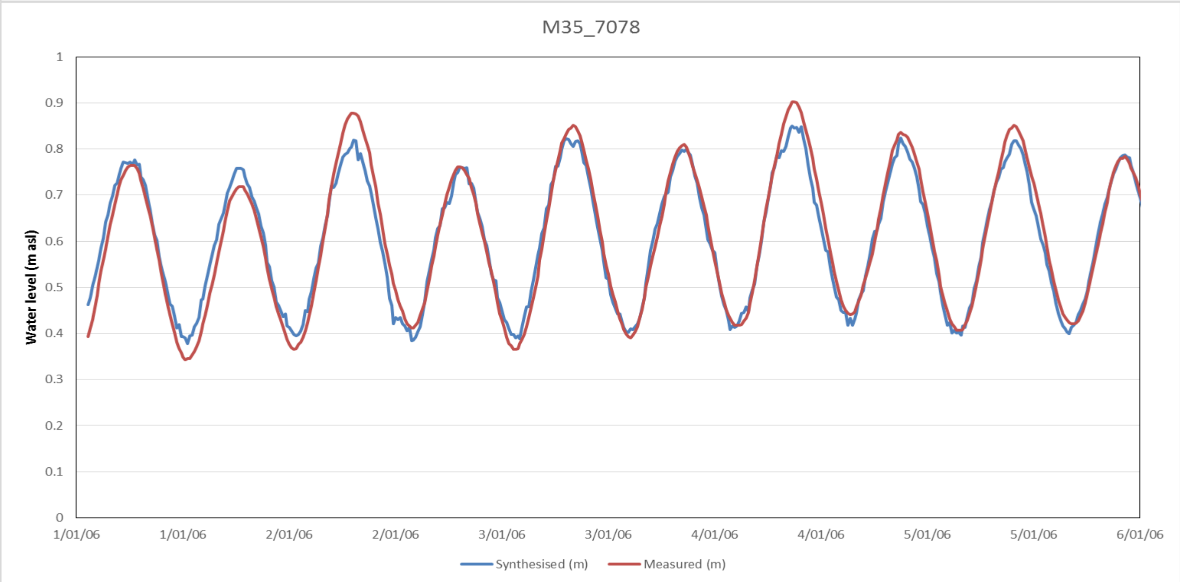
| Well (depth/screened interval, distance from coast) | S min | S best est | S max | α min | α best est | α max |
|---|---|---|---|---|---|---|
| M35_7079 (25.5-27.5 m d, 500 m w) | 1.00E-04 | 3.00E-04 | 1.00E-02 | 1.00E-10 | 1.00E-10 | 1.00E-09 |
| M35_7078 (44 - 54 m d, 500 m w) | 5.40E-05 | 5.00E-05 | 2.70E-05 | 3.58E-10 | 8.60E-10 | 9.93E-10 |
| M35_7024 (72-77 m d, 500 m w) | 3.00E-05 | 5.00E-05 | 3.00E-04 | 1.00E-10 | 5.00E-10 | 1.00E-09 |
| BW24_0083 (45 m d, 850 m w) | 3.00E-05 | 1.00E-04 | 5.00E-04 | 1.00E-10 | 3.00E-10 | 1.00E-09 |
| M35_8485 (34 m d, 825 m) | 1.00E-04 | 5.00E-04 | 1.00E-03 | 1.00E-10 | 3.00E-10 | 1.00E-09 |
| BW24_0141 (48 m d, 875 m w) | 3.00E-05 | 1.00E-04 | 5.00E-04 | 1.00E-10 | 3.00E-10 | 1.00E-09 |
| M35_10146 (48-51 d, 100 m w) | 3.00E-05 | 1.00E-04 | 5.00E-04 | 1.00E-10 | 3.00E-10 | 1.00E-09 |
| BW24_0037 (25 - 26.5 m d, 550 m w) | 1.00E-04 | 5.00E-04 | 1.00E-02 | 5.00E-10 | 2.00E-10 | 1.00E-09 |
| BW24_0038 (67 - 68.5 m d, 550 m w) | 5.40E-05 | 4.90E-05 | 1.00E-04 | 2.40E-10 | 2.12E-10 | 3.20E-10 |
| BW24_0039 (125.5 - 127.5 m d, 550 m w) | 3.30E-05 | 3.20E-05 | 1.00E-04 | 6.71E-10 | 4.87E-10 | 5.74E-10 |

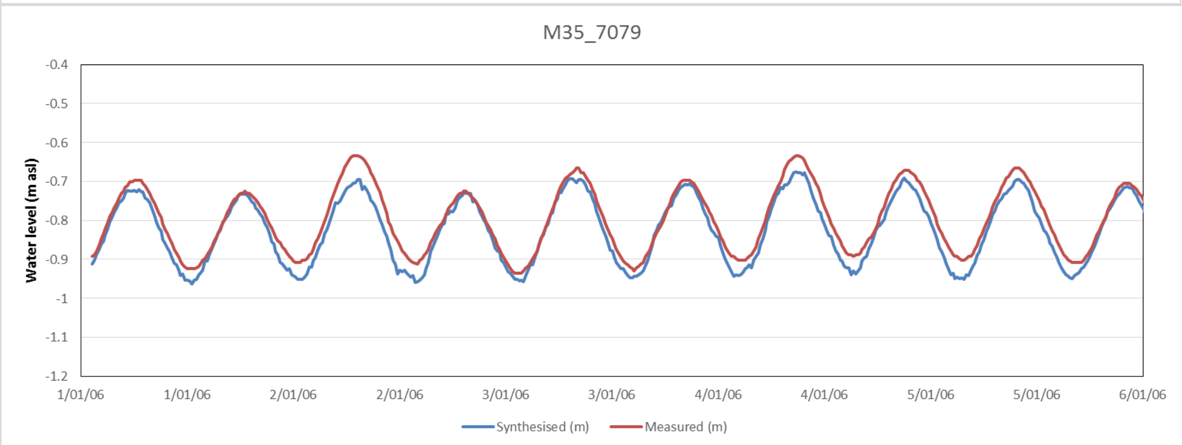
| Well | T min | T max | K' min | K' max | η min | η best est | η max |
|---|---|---|---|---|---|---|---|
| M35_7079 | 300 | 25000 | 1.00E-06 | 5 | 1.50E-01 | 3.00E-01 | 4.00E-01 |
| M35_7078 | 300 | 25000 | 1.00E-06 | 0.5 | 1.50E-01 | 2.50E-01 | 4.00E-01 |
| M35_7024 | 300 | 25000 | 1.00E-06 | 0.5 | 1.50E-01 | 2.50E-01 | 4.00E-01 |
| BW24_0083 | 300 | 25000 | 1.00E-06 | 0.5 | 1.50E-01 | 2.50E-01 | 4.00E-01 |
| M35_8485 | 300 | 25000 | 1.00E-06 | 5 | 1.50E-01 | 2.50E-01 | 4.00E-01 |
| BW24_0141 | 300 | 25000 | 1.00E-06 | 0.5 | 1.50E-01 | 2.50E-01 | 4.00E-01 |
| M35_10146 | 300 | 25000 | 1.00E-06 | 0.5 | 1.50E-01 | 2.50E-01 | 4.00E-01 |
| BW24_0037 | 300 | 25000 | 1.00E-06 | 5 | 1.50E-01 | 2.50E-01 | 4.00E-01 |
| BW24_0038 | 300 | 25000 | 1.00E-06 | 0.5 | 1.50E-01 | 2.50E-01 | 4.00E-01 |
| BW24_0039 | 300 | 25000 | 1.00E-06 | 0.5 | 1.50E-01 | 2.50E-01 | 4.00E-01 |

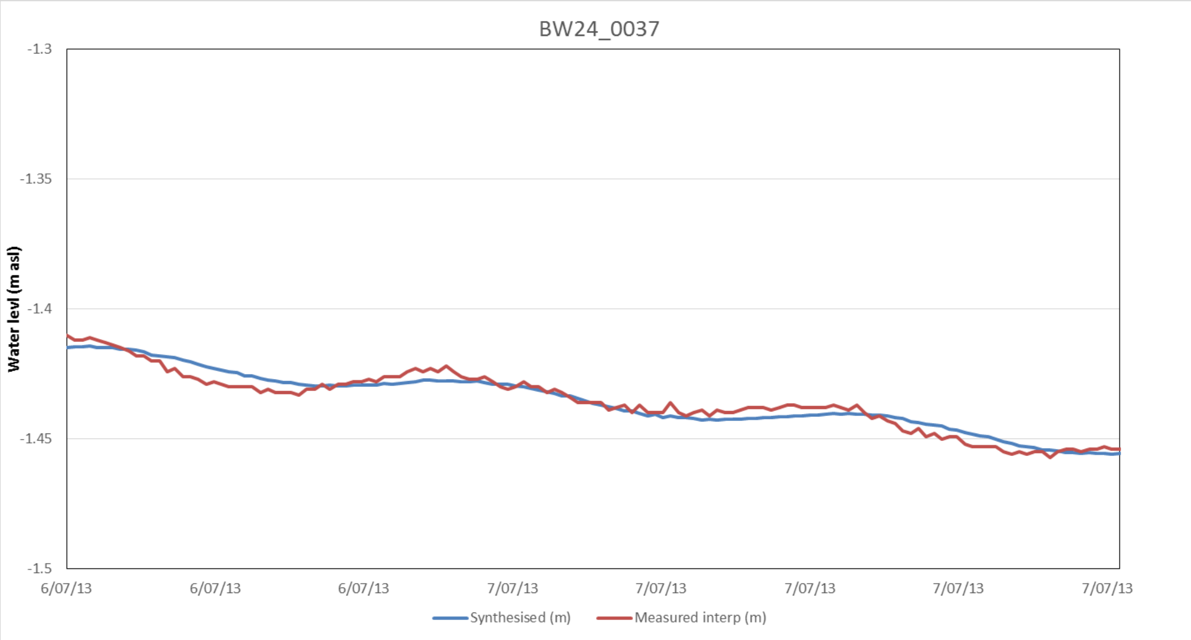
S= storativity, α = aquifer compressibility (m²/N), T = transmissivity (m²/d), K' = vertical hydraulic conductivity (m/d), η = porosity

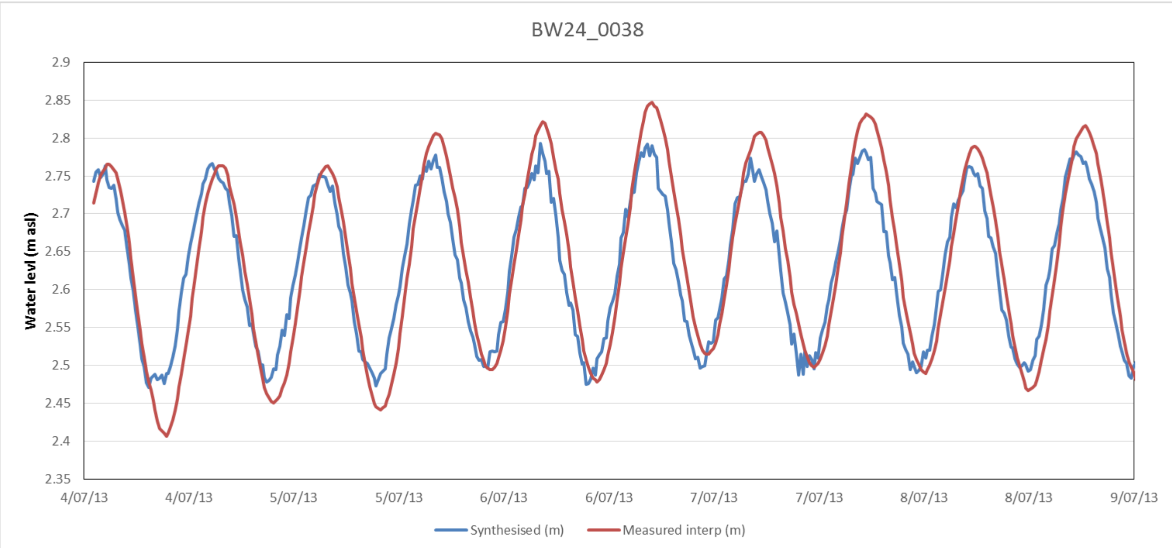
# APPENDIX 5 Tidal response analysis model and measured groundwater level plots

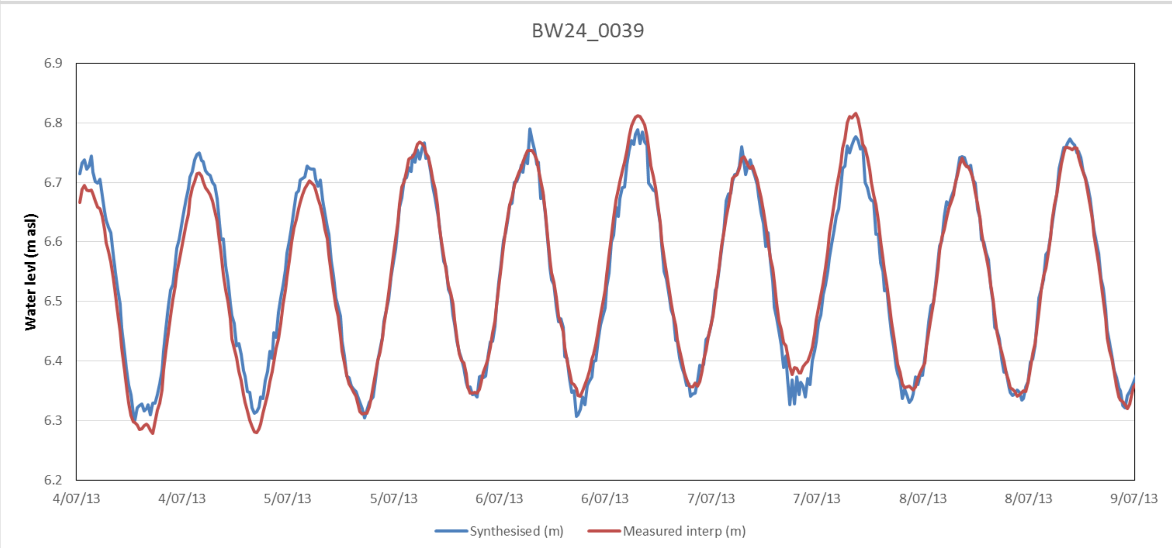


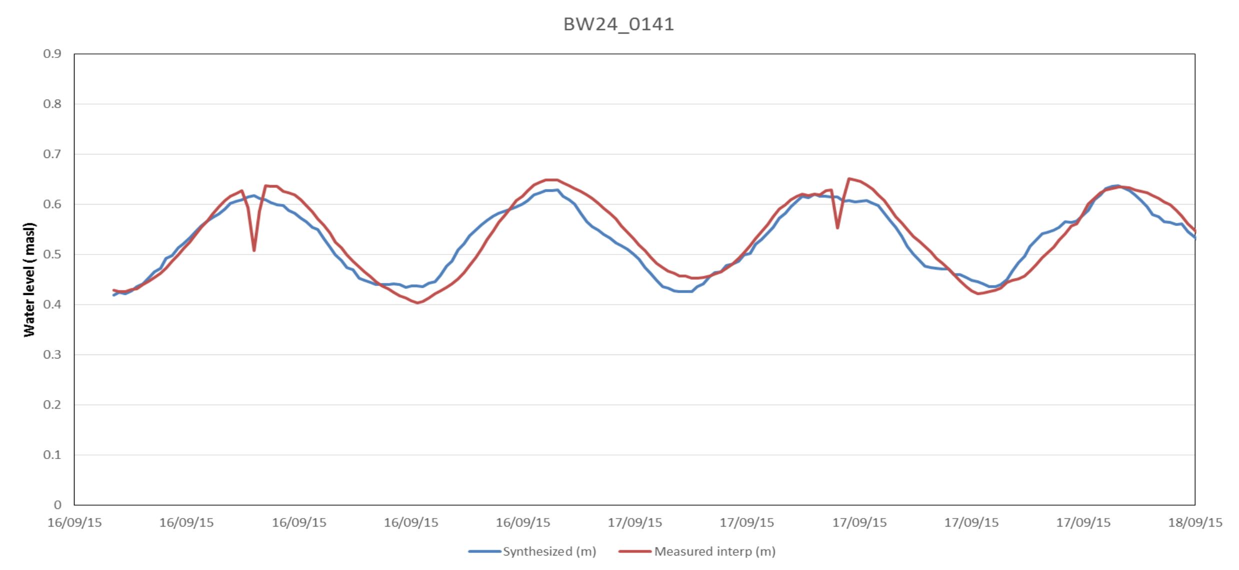



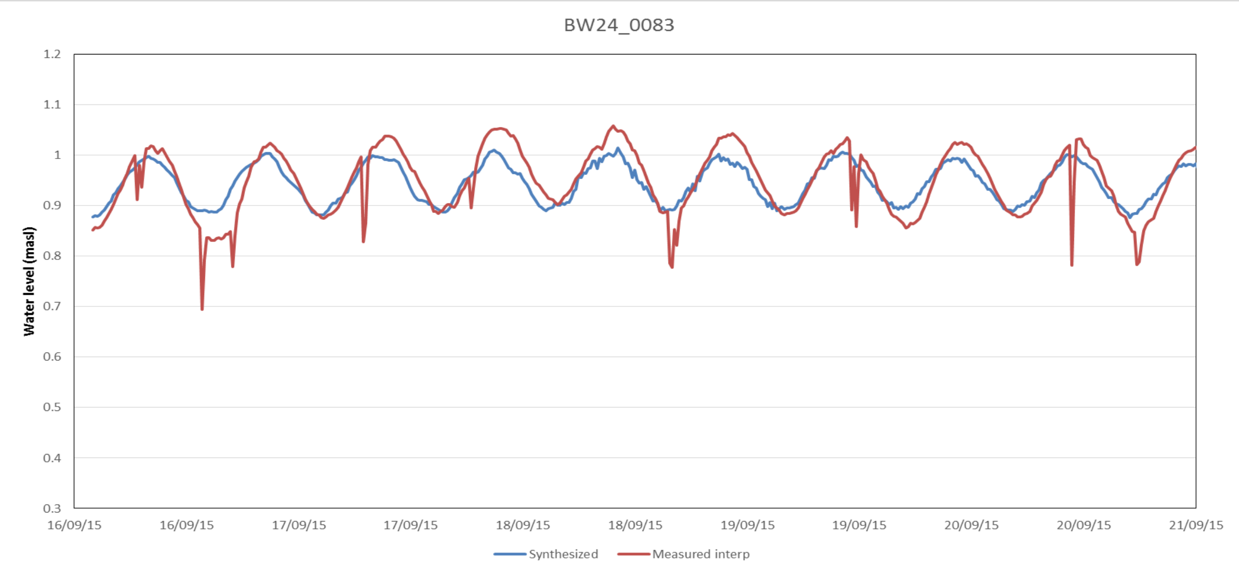



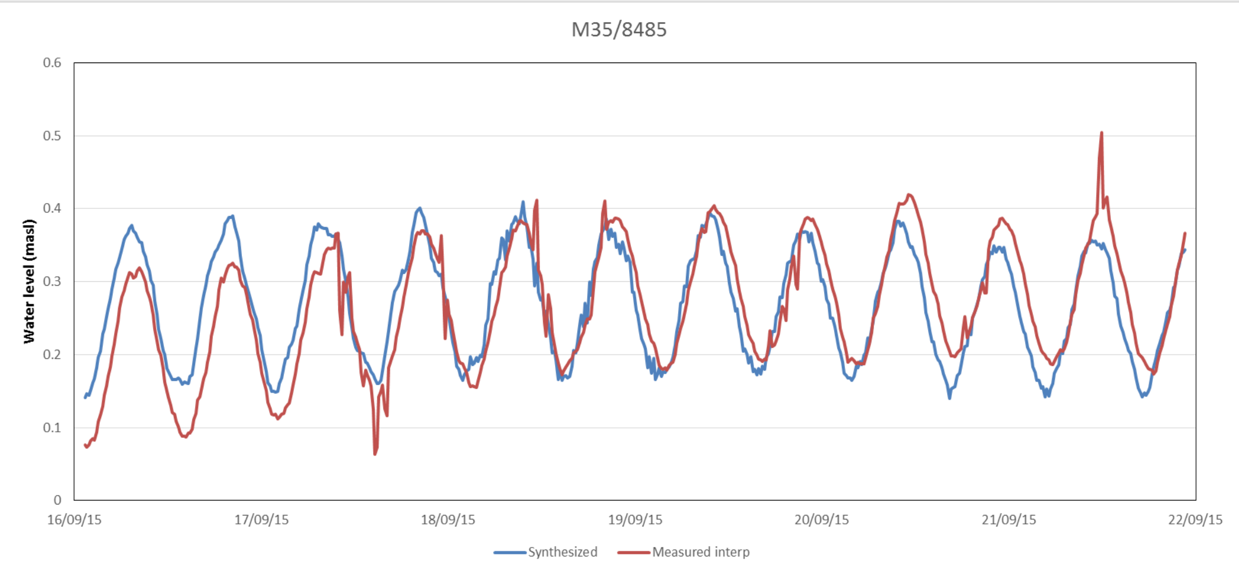

BW24_0037
Water levl (m asl)
-1.3
-1.35
-1.4
-1.45
-1.5
6/07/13
6/07/13
6/07/13
7/07/13
7/07/13
7/07/13
7/07/13
7/07/13
Synthesised (m)
Measured interp (m)


BW24_0038
Water levl (m asl)
2.9
2.85
2.8
2.75
2.7
2.65
2.6
2.55
2.5
2.45
2.4
2.35
4/07/13
4/07/13
5/07/13
5/07/13
6/07/13
6/07/13
7/07/13
7/07/13
8/07/13
8/07/13
9/07/13
Synthesised (m)
Measured interp (m)


BW24_0039
Water levl (m asl)
6.9
6.8
6.7
6.6
6.5
6.4
6.3
6.2
4/07/13
4/07/13
5/07/13
5/07/13
6/07/13
6/07/13
7/07/13
7/07/13
8/07/13
8/07/13
9/07/13
Synthesised (m)
Measured interp (m)


BW24_0141
Water level ( masl)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
16/09/15
16/09/15
16/09/15
16/09/15
16/09/15
17/09/15
17/09/15
17/09/15
17/09/15
17/09/15
18/09/15
Synthesized (m)
Measured interp (m)


BW24_0083
Water level (masl)
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
16/09/15
16/09/15
17/09/15
17/09/15
18/09/15
18/09/15
19/09/15
19/09/15
20/09/15
20/09/15
21/09/15
Synthesized
Measured interp


M35/8485
Water level (masl)
0.6
0.5
0.4
0.3
0.2
0.1
0
16/09/15
17/09/15
18/09/15
19/09/15
20/09/15
21/09/15
22/09/15
Synthesized
Measured interp

# APPENDIX 6 Tidal response analysis parameter results

Results for all wells for porosity = 0.25 and B' = 50.
Greyed-out results = either higher $R^2$ or unable to solve within parameter constraints.

M35/7079

| S | T m²/d | K' (m/d) | a | R² |
|---|---|---|---|---|
| 1.00E-03 | 4,300 | 5.00E-01 | 4.00E-10 | 0.36 |
| 8.00E-04 | 3,700 | 5.00E-01 | 4.00E-10 | 0.39 |
| 6.00E-04 | 2,800 | 0.37 | 4.00E-10 | 0.38 |
| 4.00E-04 | 2,000 | 0.28 | 4.00E-10 | 0.43 |
| 2.00E-04 | 600 | 0.01 | 4.00E-10 | 0.39 |
| *Geomean* | *3,072* | | | |

M35/7024

| S | T | K1 | a | R² |
|---|---|---|---|---|
| 8.00E-04 | 6,418 | 0.33 | 1.00E-10 | 1.12 |
| 6.00E-04 | 5,214 | 0.25 | 1.00E-10 | 1.12 |
| 4.22E-04 | 2,760 | 0.18 | 1.0E-10 | 1.16 |
| 2.00E-04 | 1,620 | 0.083 | 1.00E-10 | 1.12 |
| 1.00E-04 | 278 | 0 | 5.20E-10 | 1.02 |
| *Geomean* | *1,595* | | | |

BW24/0038

| S | T | K1 | a | R² |
|---|---|---|---|---|
| 6.00E-04 | 6,300 | 0.2 | 4.00E-10 | 1.19 |
| 4.00E-04 | 3,500 | 0.08 | 4.00E-10 | 1.18 |
| 2.00E-04 | 1,800 | 0.025 | 4.00E-10 | 1.19 |
| 9.00E-05 | 800 | 0.01 | 4.00E-10 | 1.18 |
| 3.85E-04 | 4,514 | 0.14 | 2.4E-10 | 1.16 |
| *Geomean* | *2,374* | | | |

BW24/0083

| S | T | K1 | a | R² |
|---|---|---|---|---|
| 2.00E-04 | 1,669 | 0.068 | 1.00E-10 | 0.62 |
| 3.90E-04 | 3,253 | 0.13 | 1.0E-10 | 0.63 |
| 6.00E-04 | 3,643 | 0.26 | 2.20E-10 | 0.74 |
| 8.00E-04 | 3,013 | 0.21 | 5.50E-10 | 0.68 |
| *Geomean* | *2,778* | | | |

BW24/0141

| S | T | K1 | a | R² |
|---|---|---|---|---|
| 1.00E-04 | 1,494 | 0.039 | 1.00E-10 | 0.15 |
| 3.00E-04 | 1,914 | 0.0068 | 4.80E-10 | 0.12 |
| 5.00E-04 | 2,629 | - | 5.9E-10 | 0.11 |
| *Geomean* | *1,959* | | | |

M35/7078

| S | T | K1 | a | R² |
|---|---|---|---|---|
| 4.00E-04 | 10,448 | 0.22 | 1.00E-10 | 0.52 |
| 2.50E-04 | 7,970 | 0.13 | 1.00E-10 | 0.52 |
| 1.50E-04 | 4,857 | 0.085 | 1.00E-10 | 0.53 |
| 8.00E-05 | 2,284 | 0.044 | 1.00E-10 | 0.53 |
| 5.00E-05 | 8,572 | | | 1.01 |
| *Geomean* | *5,513* | | | |

BW24/0037

| S | T | K1 | a | R² |
|---|---|---|---|---|
| 1.00E-03 | 1,400 | 4 | 4.00E-10 | 0.0016 |
| 5.00E-03 | 1,600 | 4.00 | 4.00E-10 | 0.0016 |
| 8.00E-03 | 1,800 | 4 | 4.00E-10 | 0.0016 |
| 1.50E-02 | 2,500 | 4 | 4.00E-10 | 0.0016 |
| 1.00E-03 | 300 | 1 | 4.00E-10 | 0.0016 |
| 5.00E-03 | 800 | 1 | 4.00E-10 | 0.0016 |
| 8.00E-03 | 1,100 | 1 | 4.00E-10 | 0.0016 |
| 1.50E-02 | 2,000 | 1 | 4.00E-10 | 0.0016 |
| *Geomean* | *1,232* | | | |

BW24/0039

| S | T | K1 | a | R² |
|---|---|---|---|---|
| 6.00E-05 | 11,004 | 0.15 | 5.70E-10 | 0.33 |
| 8.00E-05 | 13,695 | 0.19 | 6.40E-10 | 0.33 |
| 1.00E-04 | 17,421 | 0.23 | 6.4E-10 | 0.33 |
| 2.00E-04 | 25,000 | 0.35 | 4.80E-10 | 0.34 |
| *Geomean* | *13,795* | | | |

M35/8485

| S | T | K1 | a | R² |
|---|---|---|---|---|
| 7.00E-04 | 5,965 | 0.17 | 9.90E-10 | 1.14 |
| 4.67E-04 | 3,745 | - | 4.5E-10 | 0.95 |
| 2.00E-04 | 4,403 | 0.085 | 1.00E-10 | 0.96 |
| 1.00E-04 | 2,237 | 0.042 | 1.00E-10 | 0.96 |
| *Geomean* | *3,329* | | | |

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