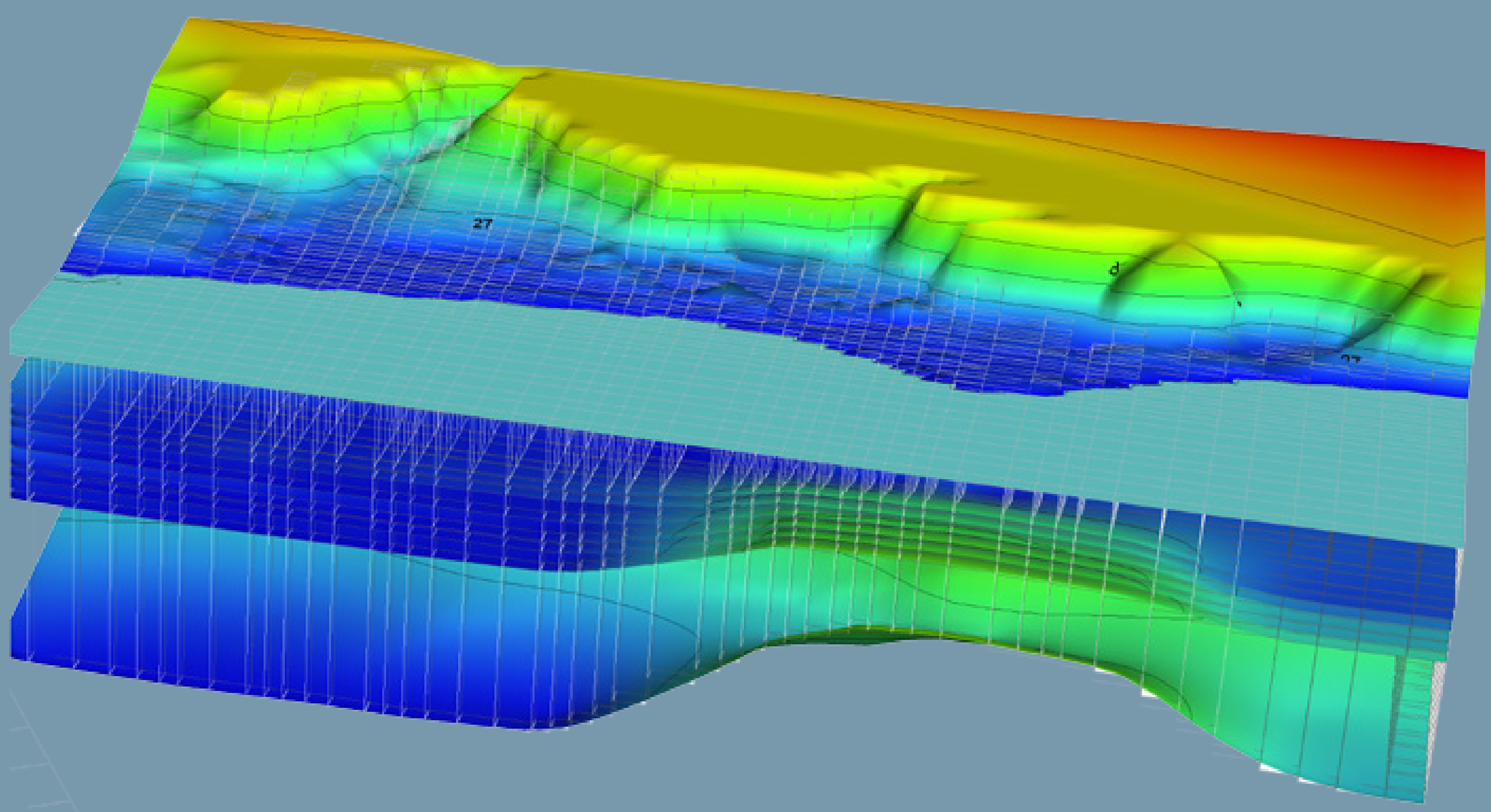
Kapiti Coast groundwater resource investigation

Catchment hydrogeology and modelling report

greater WELLINGTON
REGIONAL COUNCIL
Te Pane Matua Taiao



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Contents

1. Introduction

1.1 Background: Proposed regional water allocation framework

In May 2011 Greater Wellington Regional Council (GWRC) published a technical report (Hughes and Gyopari, 2010) detailing a proposed methodology for the conjunctive management of groundwater and surface water abstraction in the Wairarapa Valley. The methodology proposed significant modifications to the existing GWRC Regional Freshwater Plan (RFP)[1] in the way that the region's freshwater resources are allocated to ensure that they are sustainable.

The new framework proposes a more holistic approach to water resource management and is built on the concept that groundwater and surface water are a single connected resource and must therefore be managed conjunctively. The integration of groundwater and surface water allocation ensures that the cumulative effects of water abstraction remain within sustainable limits as defined by environmental flows in rivers, streams and wetlands.

The framework makes provision for the regulation of groundwater pumping in order to mitigate immediate effects on freshwater ecosystems (streams, rivers, springs and wetlands). It also considers the longer-term cumulative effects of groundwater abstraction on the surface water environment on a catchment-wide scale to establish sustainable groundwater allocation limits.

1.2 Study objectives

This report details the investigations undertaken to apply the framework for conjunctive water management methodology to the Kapiti Coast.

The objectives of investigation are to:

- Review and revise the conceptual hydrogeology of the Kapiti Coast;
- Characterise and quantify the flow dynamics and waters balances of the various aquifers;
- Characterise groundwater and surface water connectivity;
- Quantify of groundwater abstraction effects on surface water ecosystems;
- Review and revise groundwater management zones;
- Estimate the sustainable allocation limits for each zone based upon criteria such as surface water depletion effects and saline intrusion risk;
- Apply the conjunctive water management framework. (*Kapiti Coast groundwater investigation: Proposed framework for conjunctive water management.* Greater Wellington Regional Council, GW/ESCI-T-14/103)

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[1] WRC (1999)

1.3 Report structure

This report comprises the following sections:

Chapters 2-6 – The Hydrogeology of the Kapiti Coast: Documentation of a revised conceptual hydrogeological model for the Kapiti Coast.

Chapter 7 – Numerical Model Development: Details of numerical modelling undertaken to determine potential groundwater allocation limits for the Kapiti Coast.

Chapter 8 – Numerical model calibration and parameter sensitivity analysis

2. Hydrogeology of the Kapiti Coast

Characterisation and conceptualisation of the hydrogeology of the Kapiti Coast has drawn upon previous groundwater investigations (e.g. Kampman and Caldwell 1983, WRC 1994, and URS 2004) and an analysis of subsequently available hydrogeological information. The primary objectives of developing a conceptual hydrogeological model for the Kapiti Coast are:

- To provide a physical basis for the construction of the regional-scale numerical groundwater model described in the following section; and,
- To assist implementation of the proposed conjunctive water management framework to the groundwater resources.

2.1 Geology

The sedimentary sequence underlying the Kapiti Coast comprises a complex assemblage of fluvial and coastal sediments accumulated as a result of geological processes occurring along the western coast of the lower North Island over the past 400,000 years. These processes include significant variations in sedimentation rates and relative sea levels accompanying cyclic variations in climate between cold glacial and temperate interglacial conditions, structural deformation resulting in active uplift in the Tararua Range and development of a large sedimentary basin to the west, as well as altered sediment supply resulting from episodic volcanic eruptions in the central North Island.

2.1.1 Tectonic setting

The convergent tectonic setting of New Zealand has lead to the development of a series of anticlines and troughs resulting from the folding and faulting of greywacke basement in the south-west North Island. The Kapiti Coast lies along the south-western margin of the South Wanganui Basin (SWB), an extensive sedimentary basin which has formed adjacent to the convergent boundary which runs across the North Island where the Australian Plate to the west is being under-thrust by the Pacific Plate to the east. This boundary is marked by active volcanism across the central North Island and the formation of large axial ranges[2] to the south as the relative motion between the plates becomes increasingly oblique.

West of this boundary, subduction of the Pacific Plate has resulted in downwarping of the Australian Plate over the past 5 million years forming the extensive SWB which extends between the Marlborough Sounds and the Central Volcanic Region and from the North Island axial ranges to the South Taranaki Basin (Hughes, 2005). Subsidence within the SWB has resulted in the accumulation of 4 to 5 kilometres of mostly shallow marine sediments in the central basin area. Gradual emergence of the basin to the north during the Pleistocene (~last 2 million years) has resulted in a 4 to 6^{o} southward tilt of the strata infilling the basin.

[2] Including the Tararua, Ruahine, Kaweka, Kaimanawa and Raukumara Ranges

The Tararua Range forms the southern segment of the North Island axial range which formed as a result of north-west tilting of blocks of basement greywacke along the margin of the subducting Pacific Plate. Uplift rates within the Tararua Range are estimated to locally vary between 1.3 mm/year to 6.5 mm/year. Along the western margin of the Tararua Range, Hughes (2005) estimated uplift of approximately 0.3 mm/year in the Horowhenua District associated with the active formation of anticline features near Levin and Shannon.

Figure 1 illustrates the tectonic setting of the lower section of the North Island and shows the formation of the SWB along the western margin of the Tararua Range.

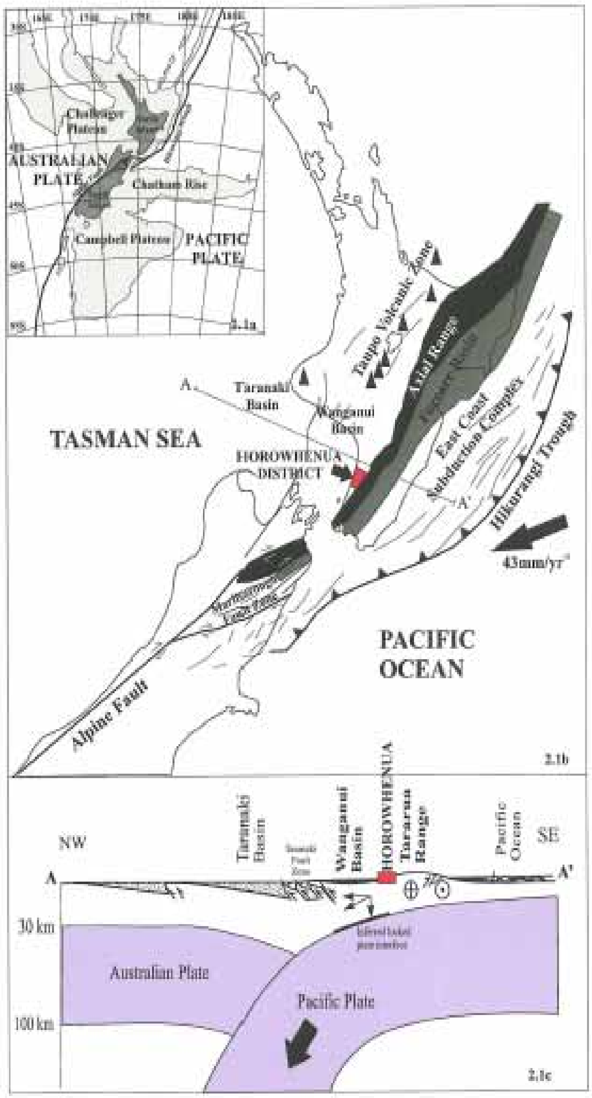

Figure 1: Tectonic setting of the North Island of New Zealand showing the position of New Zealand relative to the Pacific-Australian plate boundary and a cross sectional view illustrating the relationship between the South Wanganui Basin and the Tararua Range (from Hughes, 2005)

Ewig (2009) documented extensive deformation of the greywacke basement underlying the Kapiti Coast associated with ongoing deformation within the

South Wanganui Basin. As detailed in the following sections, this deformation potentially exerts a significant influence on both subsurface geology and hydrogeology across the Kapiti Coast, particularly in the Waikanae area.

2.1.2 Geological history

The geology of the narrow coastal plain which extends along the Kapiti Coast from Paekakariki in the south to the northern boundary of the Wellington Region near Manakau comprises an assemblage of late Quaternary glacial and interglacial deposits comprising an alternating sequence of sand and gravel deposits deposited during late Quaternary interglacial and glacial cycles.

During the Waimea (penultimate) glacial period which extended from approximately 200,000 to 120,000 years ago[3], severe erosion in the Tararua Range resulted in the deposition of extensive alluvial fans extending westwards from the foothills. This event was followed by an interglacial period (Oturi) between about 130 and 70 ka when sea levels rose to approximately 4 to 6 metres above current levels. During this event the coastline retreated to the coastal hills forming the prominent cliff line that marks the eastern margin of the coastal plain across the southern section of the Kapiti Coast (Jones and Gyopari, 2005).

Approximately 70 ka commencement of the last (Otiran) glaciation was accompanied by a drop in sea levels and increased erosion from the Tararua Range which resulted in the deposition of an extensive sequence of fluvioglacial outwash gravels over the remnants of the sediments accumulated during the earlier Waimea glaciation and subsequent interglacial period. During the Otiran glaciation broad alluvial fans were formed around the major river systems draining the Tararua Range.

Following the end of the Otiran glaciation (approximately 10 ka), sea levels gradually rose, stabilising close to present day levels at approximately 6.5 ka. This rise in sea level was accompanied by the inland migration of the coastline to the prominent marine terrace which can be traced across the coastal plain from Waikanae through to Otaki, approximately 3 kilometres inland from the present-day shoreline. Subsequent to this sea level maximum, accumulation of extensive coastal sand deposits resulted in the gradual retreat of the coastline to its current position. This Holocene coastal progradation was enhanced by longshore transport of increased sediment loadings in major river systems (such as the Wanganui and Rangitikei Rivers) associated with late Quaternary volcanic eruptions in the central North Island.

As the landscape evolved to its current form during the current (Aranuian) interglacial period, the main rivers systems draining the Tararua Range entrenched into the older glacial outwash and coastal sediments forming narrow elongate deposits of reworked alluvial gravels along the margins of the Otaki River, Waikanae River and Waitohu Stream.

As described in the previous section, the structure of the greywacke basement underlying the accumulating glacial and interglacial sediments continued to

[3] The notation ka is used in the remainder of the report to denote geological age in years before present

evolve during the late Quaternary Period due to structural deformation (faulting, tilting and warping) associated with the tectonic setting of the Lower North Island. This deformation resulted in the formation of a relatively complex geometry consisting of localised sedimentary basins and ridges (within the larger SWB structure) which are mantled by the Late Quaternary sedimentary deposits.

Figure 2 provides a schematic overview of the geological and geomorphological processes influencing the geological setting of the Kapiti Coast over the late Quaternary Period. During glacial periods sea levels declined and the rate of erosion in the Tararua Range accelerated resulting in the accumulation of extensive alluvial fans associated with the Waikanae and Otaki Rivers. During periods of sea level lowstand these alluvial fans would have extended a significant distance (perhaps of the order of tens of kilometres) west of the present-day coastline.

As the climate warmed during subsequent interglacial periods, rising sea levels resulted in the progressive landward retreat of the shoreline. This transgression resulted in the partial erosion and reworking of the older glacial outwash materials which were redeposited as marine gravel and sand following the prevailing southward longshore drift. This accumulation of sediment by longshore transport was augmented by large volumes of sediment transported down the major river systems (particularly the Rangatiki and Manawatu Rivers) following large-scale volcanic eruptions in the central North Island. As the climate warmed sediment supply in rivers draining the Tararua Range also declined resulting in the entrenchment of the river systems into underlying glacial materials producing relatively thin accumulations of well sorted, high permeable alluvium.

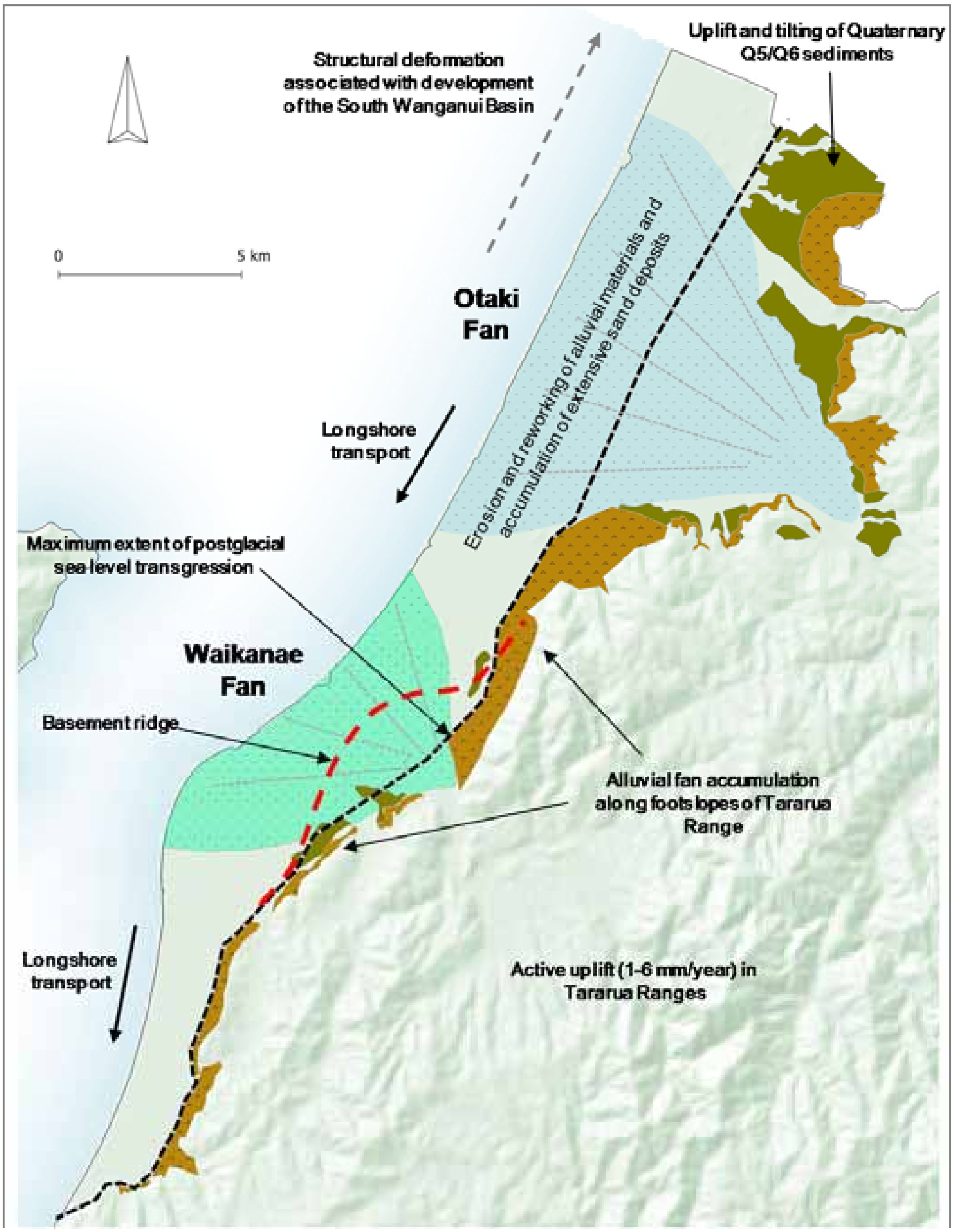

Figure 2: Schematic illustration of the geological and geomorphological processes influencing the geological history of the Kapiti Coast over the late Quaternary Period

As climate stabilised near the thermal maximum, progressive accumulation of longshore sediment resulted in the progradation of the coastline and deposition of terrestrial sediment (generally aeolian dunes and associated organic materials with associated alluvial gravels near the major rivers).

The cyclical pattern of sedimentation during successive Quaternary glacial and interglacial cycles resulted in the deposition of a repetitive sequence of sedimentary units (termed cyclothems) which can be recognised across the Kapiti Coast and the wider SWB.

Figure 3 illustrates an idealised sedimentary sequence deposited during a single glacial/interglacial cycle. The figure shows a characteristic transition in sediment type from shallow marine sand and gravel deposited during the initial glacial sea level lowstand followed by a transition to deeper fine-grained marine sediments during the subsequent interglacial period which are then overlain by progressively coarser marine and finally terrestrial sediments during the transition to the next glacial period.

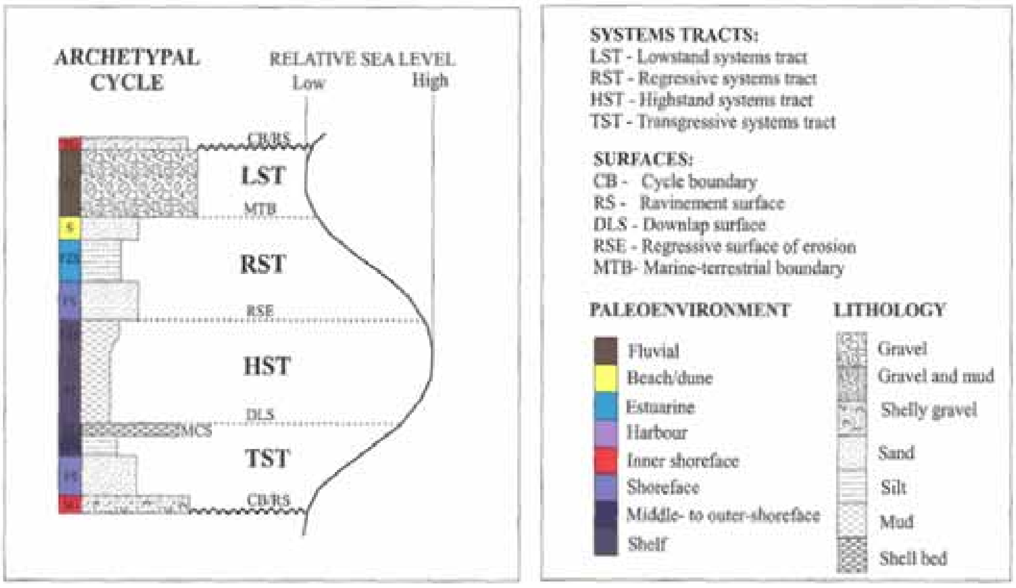

Figure 3: Idealised sedimentary sequence deposited during once symmetrical glacial-interglacial climate cycle (after Mitchell (2001), reproduced from Hughes (2005)

Detailed analysis of bore logs in the Waikanae area undertaken during investigations for the installation of the KCDC Waikanae borefield (Stratigraphic Solutions, 2003) recognised up to six separate stratigraphic units within the stratigraphic sequence down to depths of approximately 120 metres in the Waikanae area. Similar sedimentary transitions are also recognised across the wider SWB area (Hughes, 2005).

However, due to the difficulty correlating stratigraphic units between individual boreholes, it is not possible to identify sediments associated with a particular cyclothem over any significant distance. This is likely to reflect both the relatively coarse nature of available geological logs as well as the inherently heterogeneous nature of sedimentation in an environment as dynamic as the Kapiti Coast. As a consequence, the regional stratigraphy adopted for this report follows that proposed by Begg and Johnston (2000). As illustrated in Figure 4, the stratigraphic succession for the Kapiti Coast comprises five major units:

- Q1 – alluvial, aeolian and beach deposits associated with deposition over the current (Aranuian) interglacial period which commenced approximately 14 ka. On the Kapiti Coast Q1 alluvial deposits are generally restricted to the relatively well-defined floodplains of the Otaki and Waikanae rivers and Waitohu Stream where they have entrenched into older gravel deposits. Q1 sand and beach deposits occur on the western side of the prominent marine terrace that marks the maximum extent of the postglacial marine transgression (approximately 6.5 ka) which can be traced from the Otaki River to Waikanae.

- Q2 – extensive highly heterogeneous glacial outwash deposits typically comprising poorly sorted gravel with sand and silt accumulated on the Otaki and Waikanae river alluvial fans during the last (Otiran) glacial period (approximately 70 to 14 ka). These deposits form the relatively extensive Hautere Plain south of the Otaki River, occur as terrace remnants toward the base of the Tararua foothills near Waikanae and along the northern margin of the Otaki River valley and extend to the present day coastline under the Holocene (Q1) sand deposits.

- Q3: fine grained sediments which grade from silt-bound gravels near the (present day) coast to fine-grained (typically silt dominated) organic-rich materials further inland. The deposits accumulated during an interstadial[4] period during the middle stages of the Otiran glacial period; and,

- Q4: poorly sorted alluvial gravel, sand and silt (similar to the Q2 materials) deposited during the early stages of the Otiran glacial period.

- Q5 – beach deposits largely comprising marine gravel and sand accumulated in a shallow coastal environment during the last (Kaihinuan) interglacial period which extended between 125 to 75 ka. Surface exposure of the Q5 sediments is limited to isolated terrace remnants in the Waikanae and Hautere Plain area, with more extensive outcrop occurring to the north of Otaki forming the southern extent of the Tokomaru marine surface which extends across much of the southern Horowhenua District. Along the coastal margin between Otaki and Raumati, Q5 sediments are typically recorded at depths of between 60 to 100 metres bgl. The extent of surface exposure is therefore interpreted to reflect partial erosion of the these materials during the subsequent Otiran glaciation combined with uplift within the southern section of the South Wanganui Basin;

- Q6+ – weathered, poorly moderately sorted gravel accumulated during the penultimate (Waimean) glacial period between 180 to 125 ka. Although Q6 gravels are likely to be present at depth across much of the Kapiti Coast surface exposure is limited to higher remnant alluvial terraces along the eastern margin of the Hautere Plain and along the northern side of the Otaki River valley.

- Greywacke Basement: greywacke rocks of the Rakaia Terrane form the geological basement across the Kapiti Coast. These sediments have been extensively uplifted along the North Island axial range to form the foothills and mountains of the Tararua Range. Available bore log and geophysical data suggest relatively complex structural deformation of the greywacke basement associated with displacement along a series of NE-SW trending normal and reverse (thrust) faults underlying the coastal plain, particularly

[4] Interstadial refers to a period (typically relatively short ~10,000 years) of warmer temperatures during a glacial period

in the vicinity of Waikanae. This displacement appears to have resulted in the formation of horst and graben-type structures over which the Quaternary alluvial and marine sediments have been deposited.

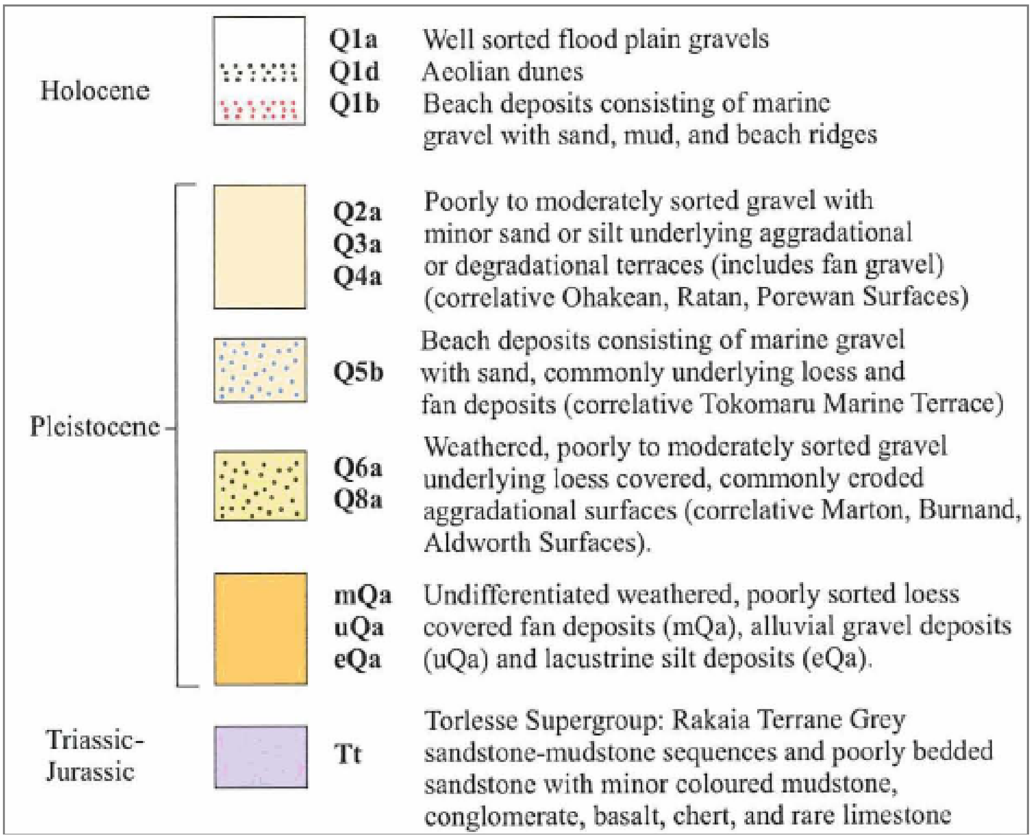

Figure 4: Stratigraphic succession for the Kapiti Coast (Begg and Johnston, 2000)

Figure 5 shows a simplified geological map of the Kapiti Coast. The map shows the spatial extent of the Q1 sand deposits along the coastal margin, with Q1 alluvium primarily confined to the relatively narrow, elongate floodplains of the Otaki and Waikanae rivers and the Waitohu and Mangaone streams.

The geological map also shows the surface exposure of older Q5 to Q8 deposits along the margin of the Tararua foothills, primarily in the Otaki area. Exposure of these older deposits along the margins of the Tararua foothills is interpreted to reflect the significant reworking and re-deposition of glacial outwash materials during subsequent periods of marine transgression which eroded a significant proportion of the total thickness of these deposits across a majority of the coastal plain. The current-day analogy is erosion of the upper ~40 metres of the Q2 outwash surface to the west of the Holocene marine terrace and the deposition of Holocene (Q1) sand deposits to an almost equivalent depth as a result of coastal progradation over the late Holocene (i.e. the last 6,500 years).

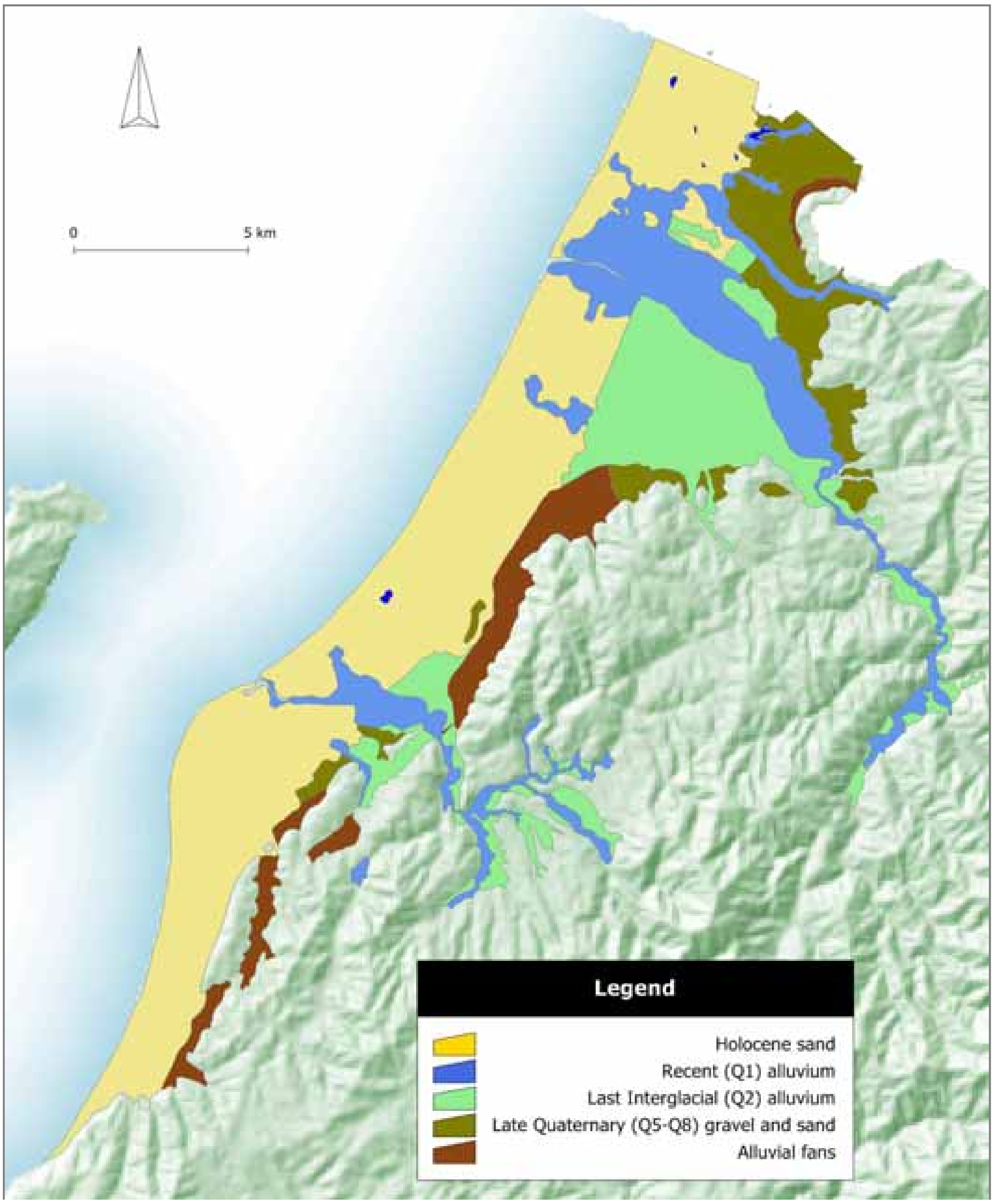

Figure 5: Simplified geological map of the Kapiti Coast (adapted from GNS Wellington QMap coverage)

2.2 Hydrostratigraphy

The Quaternary sediments forming the coastal plain host an extensive groundwater resource. Groundwater is found virtually throughout the entire sedimentary sequence, the major difference being the relative hydraulic conductivity which differentiates more permeable ‘aquifers’ from intervening lower hydraulic conductivity aquitard materials. As noted in URS (2004), although it is possible to identify discrete stratigraphic units corresponding to individual cyclothems within the geological succession, due both to the overall sediment texture and heterogeneous nature of these materials differentiation of individual hydraulic units requires subdivision at a coarser scale. For the purposes of this report, the five primary hydrostratigraphic units identified include:

- Shallow unconfined Holocene (Q1) sand and gravel aquifers along the seaward margin of the coastal plain. These sediments largely represent materials deposited along the coastal margin since the thermal maximum approximately 6,500 years ago;

- Shallow, moderate to highly permeable unconfined aquifers hosted in coarse, relatively well sorted recent (Q1) alluvium deposited adjacent to rivers and streams draining the Tararua Range; and

- A thick succession of moderate to low hydraulic conductivity Quaternary sand and gravel sediments forming a stratified aquifer system which becomes progressively confined with depth. This unit may comprise sediments associated with at least 4 cyclothems which individually grade from marine sand to regressional alluvium and finally terrestrial gravels and sand (often containing organic materials). Collectively these materials comprise sediments accumulated during Otiran, Kaihinuan and Waimean stages (Q2 to Q8) and generally comprise 3 layers of moderate to low hydraulic conductivity gravel materials (Q2, Q4 and Q6) separated by lower hydraulic conductivity layers of sand, silt and organic materials (Q3 and Q5);

- A relatively narrow band of locally derived slope and outwash materials accumulated along the foot slopes of the Tararua Range. These materials represent locally derived slope and outwash debris and interfinger with the outwash gravel and marine sediments on the coastal plain.

- Greywacke of the Murihiku Terrane. Although these materials max exhibit appreciable secondary porosity due to fracturing and jointing they are generally considered to form the groundwater basement for the Kapiti Coast area.

2.3 Groundwater management

For the purposes of resource management WRC (1994) divided the Kapiti Coast into the six groundwater management zones illustrated in Figure 6. These zones group areas of similar hydrogeological characteristics on the basis of landform, subsurface geology, hydraulic properties, and aquifer chemistry and are currently used as the primary unit for groundwater allocation in the Regional Freshwater Plan (RFP).

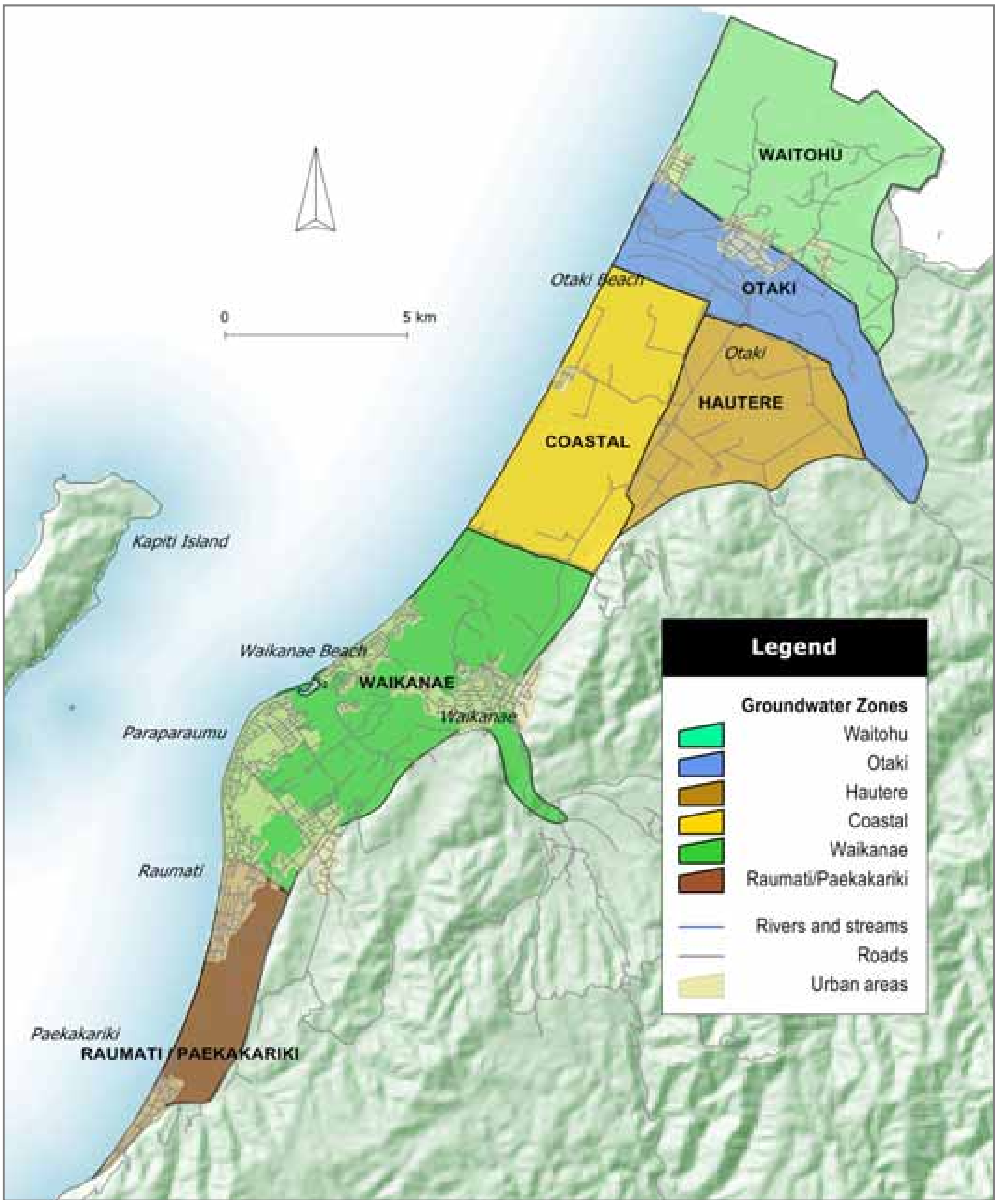

Figure 6: Existing groundwater management zones for the Kapiti Coast defined in the Regional Freshwater Plan

Refinement of the regional conceptual hydrogeological model for this report identified several areas where the boundaries of the current groundwater management zones appear to be relatively arbitrary and do not necessarily reflect the spatial and depth distribution of individual hydrogeological environments. Re-analysis of the overall framework for groundwater allocation resulted in the rationalisation of the six existing groundwater management zones into the four revised zones illustrated in Figure 7. The proposed zones are described in the following sections.

2.3.1 Otaki groundwater zone

The proposed Otaki groundwater zone amalgamates the existing Otaki and Waitohu zones to better reflect the extent of Q1 gravels associated with the Otaki River and Waitohu Stream as well as the underlying geology where older Q5 and Q6 deposits are exposed at the ground surface due to the regional tilt of sediments infilling the South Wanganui Basin. The proposed zone boundary is also modified to better reflect the extent of Quaternary sediments along the Tararua foothills (following the extent of greywacke basement exposure defined on the Wellington QMap coverage).

2.3.2 Te Horo groundwater zone

This zone combines the existing Hautere and Coastal groundwater zones. This recognises the continuity of the Quaternary gravel deposits comprising the Hautere Plain under the Holocene (Q1) sand deposits along the coastal margin. The revised groundwater zone boundary along the eastern side of the Hautere Plain also follows the extent of greywacke basement defined on the QMap coverage;

2.3.3 Waikanae groundwater zone

Essentially the Waikanae zone remains the same as the existing zone with relatively minor adjustments to the zone boundaries. These adjustments include:

- A slight shift and re-alignment of the northern boundary to finish at the greywacke exposure on the northern side of Hadfield Road to reflect the approximate southerly extent of the Otaki fan and better align with assumed groundwater flow directions (e.g. Kampman and Caldwell, 1983) rather than Peka Peka Road;

- Truncation of the groundwater zone boundary near the start of the Reikorangi Valley to reflect the exposure of greywacke basement in the bed of the Waikanae River near this location; and,

- Re-alignment of the southern boundary to better reflect the southerly extent of the Waikanae River alluvial fan (based on bore logs) and the alignment of the flow divide between Wharemauku Stream and Mazengarb Drain indicated by piezometric contours (Jones and Gyopari, 2005);

2.3.4 Raumati groundwater zone

The proposed Raumati zone remains the same as the current Raumati-Paekakariki zone with the modifications to the northern boundary with the Waikanae zone as listed above and amendments to the eastern boundary to follow the QMap greywacke basement exposure.

The proposed (and existing) groundwater management zones do not denote hydraulically separate or physically isolated compartments of the regional groundwater system. They have ‘soft’ boundaries based on flow divides or mark key geological and/or hydrogeological changes in the water-bearing strata. As a consequence, the potential for localised cross boundary flows must be appreciated, especially under the influence of well abstractions.

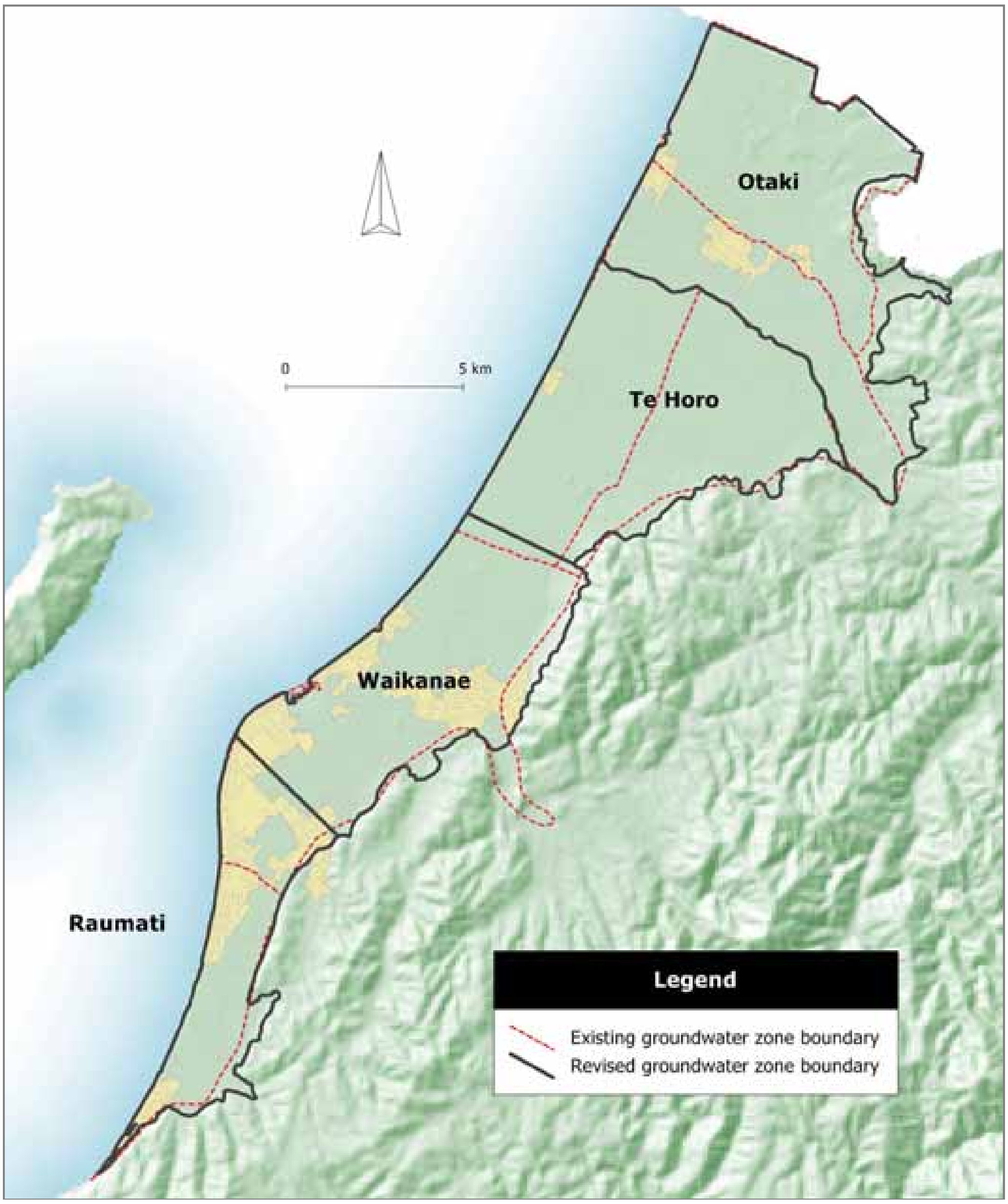

Figure 7: Proposed new groundwater zone boundaries

3. Raumati groundwater zone

The Raumati groundwater zone occupies the southernmost part of the Kapiti Coast, extending from the Paraparaumu Beach in the north to Paekakariki in the south. Figure 8 shows the spatial extent of the zone including primary surface water features (streams and wetlands), groundwater level monitoring and concurrent flow gauging sites and the locations of bores recorded on the GWRC Wells database.

The northern boundary runs NW-SE across the coastal plain and Paramaraumu Beach. This ‘boundary’ is really a transition zone approximating the southern extent of the Waikanae River fan. Laterally continuous gravel layers in the Waikanae area are replaced by a thick sequence of sand to the south. The boundary also corresponds with a flow divide between the Mazengarb and Wharemauku catchments - identified from piezometric surveying (Jones and Gyopari, 2005).

Approximately 630 bores are recorded on the GWRC Wells database in the Raumati groundwater zone. These tend to be are clustered in Paekakariki Beach, Raumati Beach and Raumati South with few bores located across the remaining area (Figure 8). The majority of bores are less than10 metres deep, although fewer than 20 have been drilled to depths in excess of 15 metres. The major use of groundwater is for domestic (garden) supply with some limited utilisation for other purposes such as irrigation, horticultural and domestic (potable) water supply.

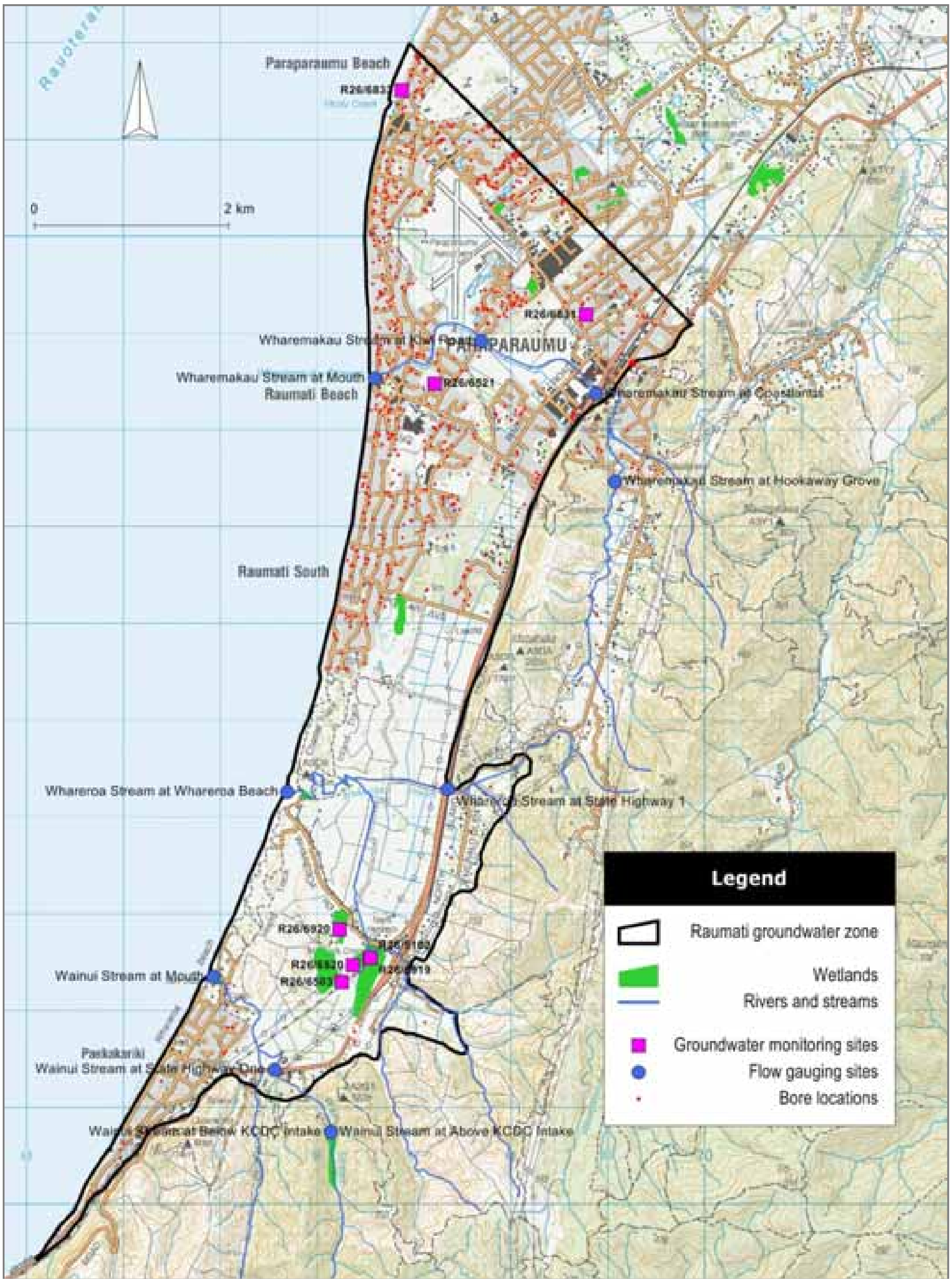

Figure 8: Raumati groundwater zone

3.1 Raumati zone geology

Relatively limited data is available to characterise subsurface geology in the Raumati groundwater zone with logs available from fewer than 10 bores in excess of 20 metres deep. Bore logs indicate medium to fine sand predominates in the upper 40 metres of the stratigraphic column with occasional, discontinuous layers of silt, peat and sandy gravel materials. Deeper bores in the Raumati area show a thick sequence of fine sand containing organic material and isolated gravel lenses extending to a depth of approximately 60 metres below ground. Further south, bore logs indicate greater textural variability with an increased frequency of gravel layers interbedded with fine sand and peat. Thicker, poorly sorted gravel sequences are also encountered close to the base of the Tararua foothills, suggesting the interfingering of locally derived alluvial fan materials with the coastal sand deposits.

The overall nature of the subsurface geology in the Raumati groundwater zone is likely to be highly variable, particularly toward the southern extent of the coastal plain.

Figure 9 illustrates the typical geological heterogeneity observed in the Raumati groundwater zone in the drillers log for a 61 metre deep bore installed at Queen Elizabeth Park. The log shows the characteristic sequence of medium to fine sand interspersed with layers of gravel and fine-grained organic materials (silt and peat) which are not be readily correlated with other nearby bore logs.

The primary geological units in the Raumati groundwater zone comprise locally derived alluvial fan materials along the base of the Tararua foothills and the medium to fine sand deposits forming the coastal plain. Although both coarser gravel and fine-grained organic materials are identified on bore logs, insufficient information is available to further differentiate these materials into laterally continuous geological or stratigraphic units.

The discontinuous nature of the subsurface geology is likely to reflect the mode of deposition with a majority of the sand material accumulated by longshore drift (and associated aeolian deposition along the coastal margin). The isolated gravel layers are likely to reflect alluvial deposition associated with historical channels of local streams draining the Tararua Foothills (including the Wharemauku, Whareroa and Wainui streams) and deposition of marine gravels during periods of sea level highstand. Lenses of silt and organic materials are likely to reflect accumulation of fine-grained materials associated with wetland areas within and landward of an active dune system along the coastal margin.

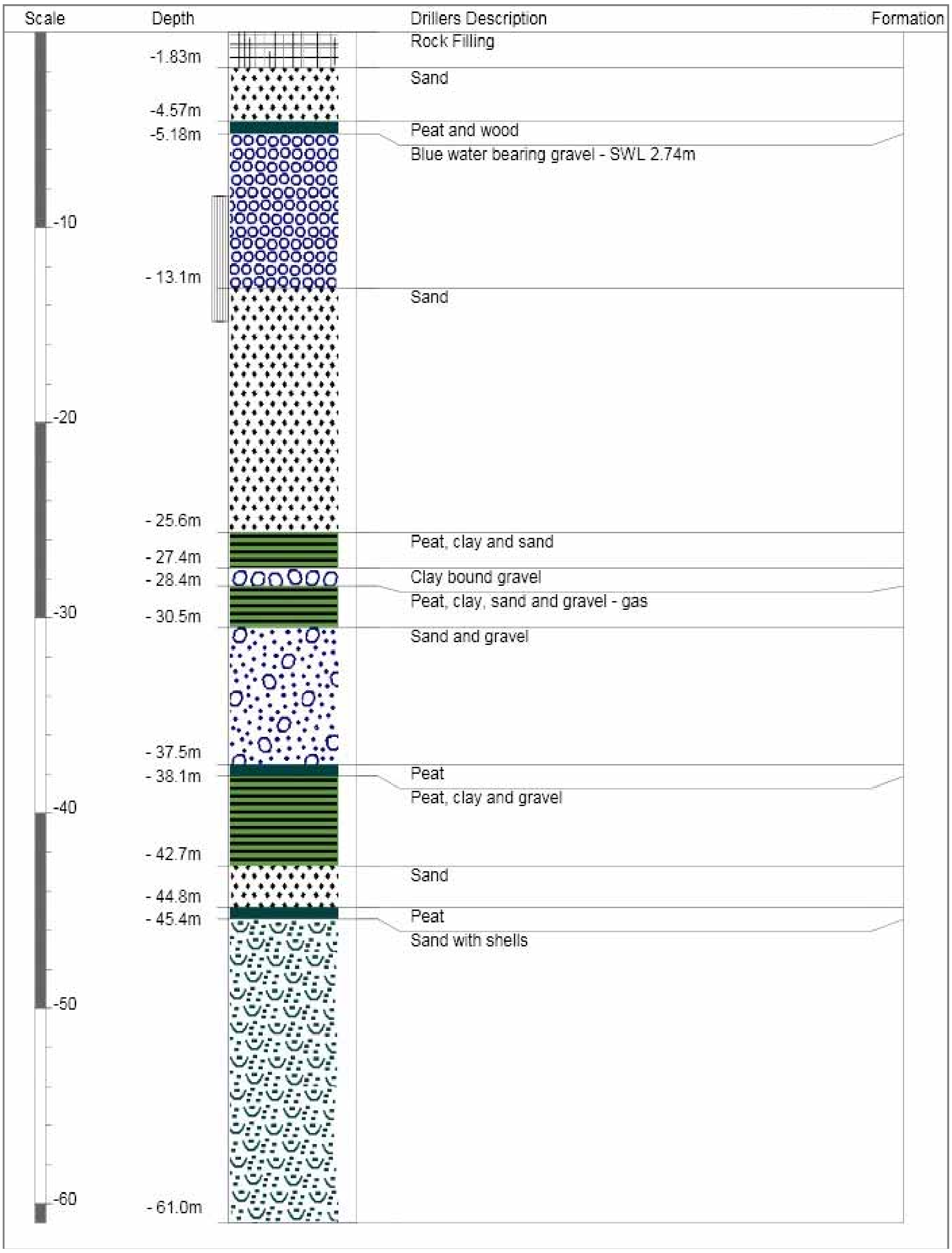

Figure 9: Representative bore log from the Raumati groundwater zone

3.2 Raumati zone hydrogeology

Bore logs indicate static groundwater levels typically occur within 4 metres of the land surface across the Raumati groundwater zone. No clear relationship is observed between reported bore depths and observed static water level, with appreciably different static water levels occurring in relatively closely spaced bores. Together with the observed subsurface geology, these results suggest the Raumati groundwater zone can be best characterised as a single stratified aquifer system containing multiple, discrete water-bearing sand and gravel intervals interspersed with lower hydraulic conductivity silt and organic/peat layers.

A thicker water-bearing gravel layer is noted in some bores at depths of between 40 to 60 metres but the lack of geological data makes identification of this water-bearing layer as a separate hydraulic unit relatively speculative.

3.2.1 Hydraulic properties

Bullock (2004) described a constant-rate aquifer test at QE Park in 1994 undertaken to determine the potential impact of abstraction on nearby wetland areas. The test involved abstraction from the QE Park supply bore at a rate of 22 L/s for a period of 36 hours with water levels monitored in three shallow piezometers and two nearby wetland areas during the test. Calculated aquifer parameters indicated a transmissivity of 2,400 m^2/day and a storage coefficient of $1x10^{-4}$ in a gravel layer between 7 to 15 metres below ground. Water level monitoring in one of the wetland areas indicated vertical leakage in response to pumping while levels in the other area appeared to be perched above the surrounding water table.

Results from this test are unlikely to be representative of the bulk hydraulic properties of the sand deposits. No reliable data is available to quantify the hydraulic conductivity of the sand materials. However, based on results of aquifer testing in similar deposits elsewhere on the Kapiti Coast a value of 1 to 2 m/day is considered to be representative of the bulk hydraulic conductivity of this material.

3.2.2 Groundwater/surface water interaction

The Raumati groundwater zone is drained by three primary surface water catchments. The Wharemauku Stream flows westward across the coastal plain reaching the sea at Raumati Beach, Whareroa Stream drains the middle section of the Raumati groundwater zone to the north of QE Park, while the Wainui Stream flows from the foothills to the coast immediately north of Paekakariki.

Concurrent gauging results from Wharemauku Stream show a relatively consistent increase in downstream discharge across the coastal plain indicating groundwater discharge of between 30 to 50 L/s between SH1 (Coastlands) and the coast during summer low flow conditions (Figure 10).

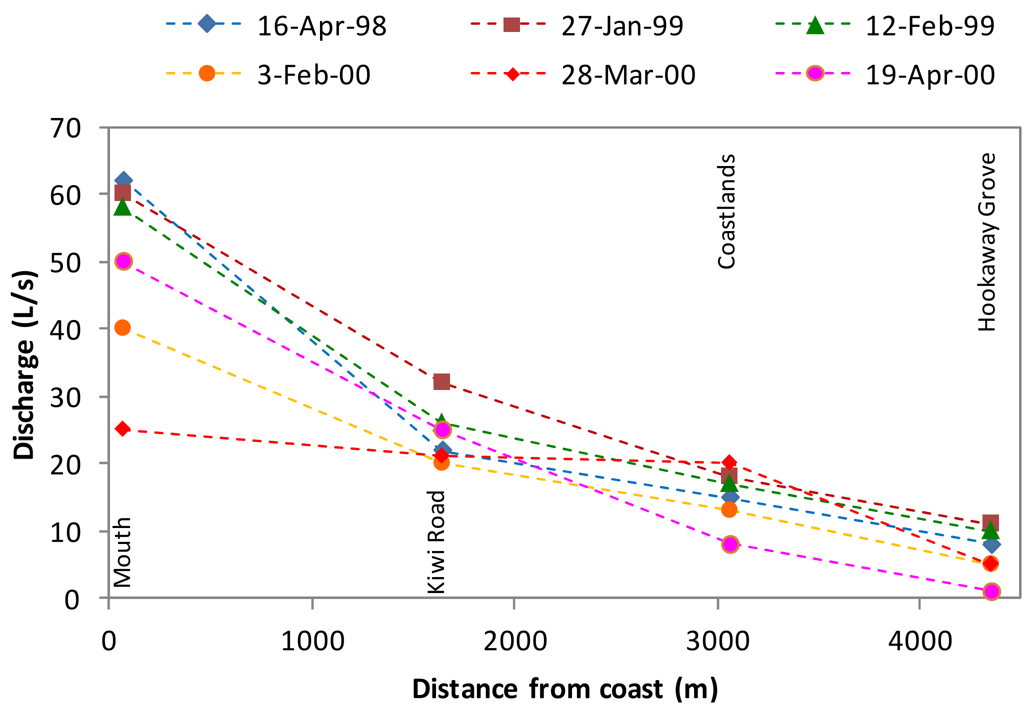

Figure 10: Concurrent gauging results from Wharemauku Stream

Figure 11 shows gauging results from Wainui Stream. These data indicate flow loss across the reach from the KCDC water supply intake to SH1 with flow gain of between 5 to 25 L/s occurring across the downstream of SH1 suggesting interaction between the stream and the surrounding unconfined aquifer.

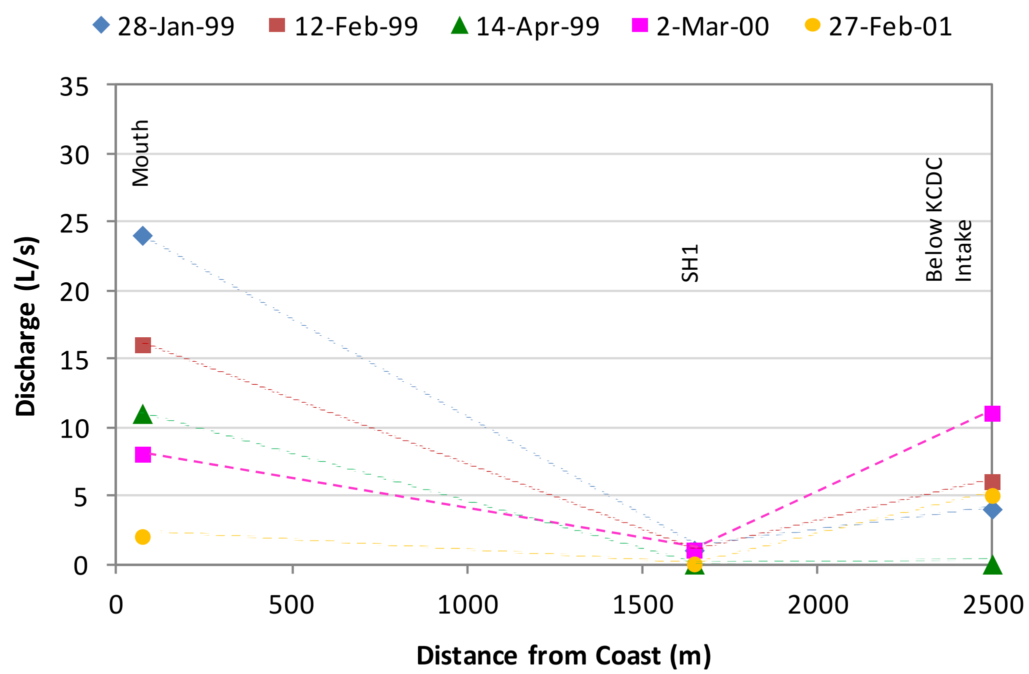

Figure 11: Concurrent gauging results from Wainui Stream

The limited gauging data available in the Whareroa catchment indicate a similar pattern to that observed in the Wainui catchment with a flow gain of approximately 20 L/s in the Whareroa Stream between SH1 and the coast. This flow gain is interpreted to reflect baseflow discharge from the shallow sand aquifer.

3.2.3 Groundwater levels

Figure 12 shows a plot of groundwater levels recorded in the Raumati groundwater zone since 1993. The hydrographs show a similar temporal response which appears to reflect both seasonal and longer-term variations in rainfall recharge.

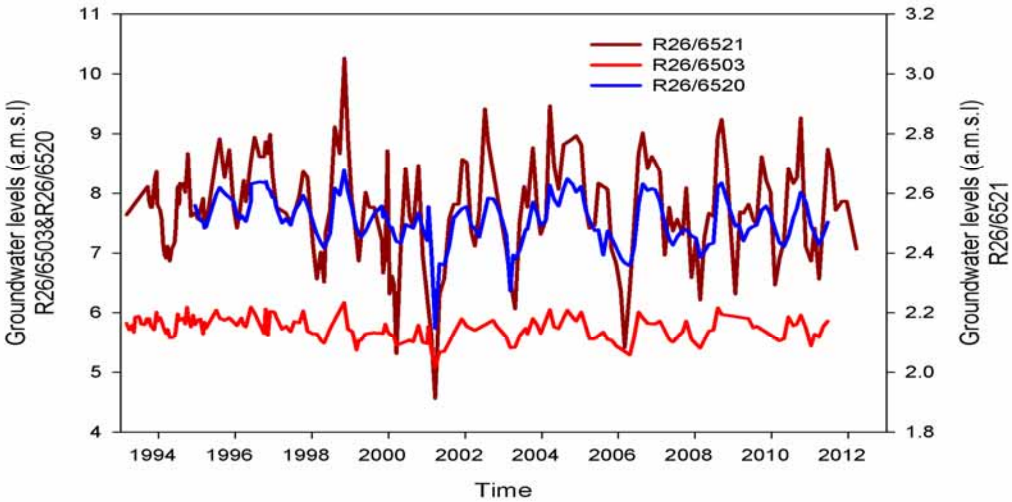

Figure 12: Groundwater levels in the Raumati/Paekakariki groundwater zone

3.3 Raumati zone conceptual hydrogeological model

Limited data is available to characterise the hydrogeology of the Raumati groundwater zone. The primary hydrostratigraphic units identified are an accumulation of locally derived coarse-grained, poorly sorted alluvial materials which form a relatively narrow alluvial fan along the base of the Tararua foothills. Along the eastern margin of the coastal plain these alluvial materials interfinger with a thick succession of medium to fine sand containing isolated lenses of gravel and fine-grained/organic materials.

Groundwater occurs throughout the stratigraphic succession in the Raumati groundwater zone. The sand materials form a relatively low-yielding aquifer system which likely becomes increasingly confined at depth. Higher yielding sediments occur in isolated gravel lenses which are likely to be associated with former channels of the main streams draining the Tararua foothills or accumulated in an active coastal environment.

The aquifer system is recharged by infiltration of rainfall on the coastal plain augmented by infiltration of runoff from the foothills to the east. Groundwater discharge occurs via baseflow to the main streams draining the coastal plain as well as from evapotranspiration in wetland areas where the water table intersects the land surface. Given the relatively limited baseflow discharge observed (~100 L/s) and the relatively modest rates of evapotranspiration, particularly in areas of urban or agricultural development, it is inferred that outflow to the coast may be a significant component of the overall aquifer water balance in the Raumati groundwater zone.

Table 1 summarises the hydraulic characteristics and spatial distribution of the primary hydrostratigraphic units in the Raumati groundwater zone while Table 2 summarises key components of the aquifer water balance. These data are combined on the schematic representation of the conceptual aquifer model shown in Figure 13.

Table 1: Summary of the hydraulic characteristics and spatial distribution of the primary hydrostratigraphic units in the Raumati groundwater zone

Hydrostratigraphic Unit	Description	Spatial/depth distribution
Coastal Sand (Q1 and possible older coastal sand deposits)	• Medium to fine sand with discontinuous layers (lenses) of gravel and silt/peat. Sand may become increasingly cemented at depth, particularly near the Tararua foothills • Relatively low bulk hydraulic conductivity (~2-5 m/day) which increases markedly in discrete coarse-grained water-bearing intervals (~5 - 100 m/day) • Forms a stratified aquifer system likely to become increasingly confined at depth	• Comprises coastal plain to a depth exceeding 60 metres • Interfinger with locally derived alluvial fan materials along eastern margin of coastal plain • Extends offshore an unknown distance
Alluvial Fans (Q1 and older)	• Poorly sorted sand, gravel and silt with layers of organic material • Moderate to low hydraulic conductivity (~2-10 m/day) but may contain higher hydraulic conductivity layers of reworked gravel	• Restricted to a relatively narrow strip along the eastern margin of the coastal plain

Table 2: Summary of key water balance components in the Raumati groundwater zone

Component	Description	Net Flux
Rainfall	• Infiltration of rainfall on coastal plain	• Not determined
Sideslope infiltration	• Infiltration of runoff on alluvial fans along the western margin of the Tararua foothills	• Not determined but may be significant given limited surface drainage from a majority of small catchments • Recharge augmented by vertical gradient developed upslope on alluvial fans
Baseflow/spring discharge	• Wharemauku Stream • Whareroa Stream • Wainui Stream	• Gain of +30 to 50 L/s between Coastlands and Raumati Beach • Gain of +20 L/s between SH1 and coast • Flow loss of 5-15 L/s between KCDC intake and SH1. Gain of 5 to 25 L/s between SH1 and mouth
Wetland areas	• Losses due to evapotranspiration and direct evaporation	• Not determined. Likely to be a relatively minor component of overall aquifer water balance
Offshore discharge	• Discharge offshore	• Not determined but may comprise a significant component of overall water balance based on available piezometric data

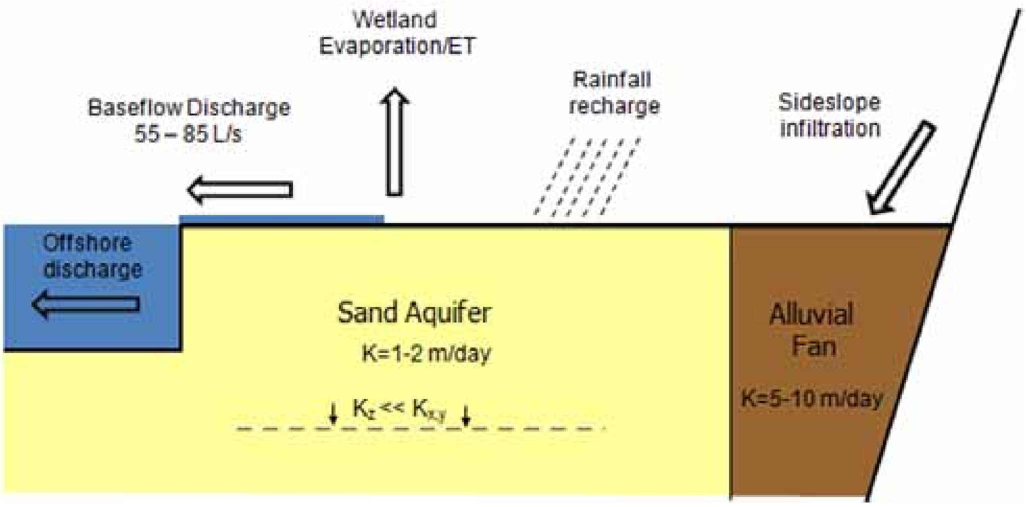

Figure 13: Schematic conceptual hydrogeological model of the Raumati groundwater zone

4. Waikanae groundwater zone

The Waikanae groundwater zone extends across the coastal plain from the Peka Peka Road in the north to Paraparaumu Beach in the south. Figure 14 shows the spatial extent of the proposed Waikanae groundwater zone including primary surface water features (streams and wetlands), groundwater level monitoring sites as well as the location of bores recorded on the GWRC Wells database.

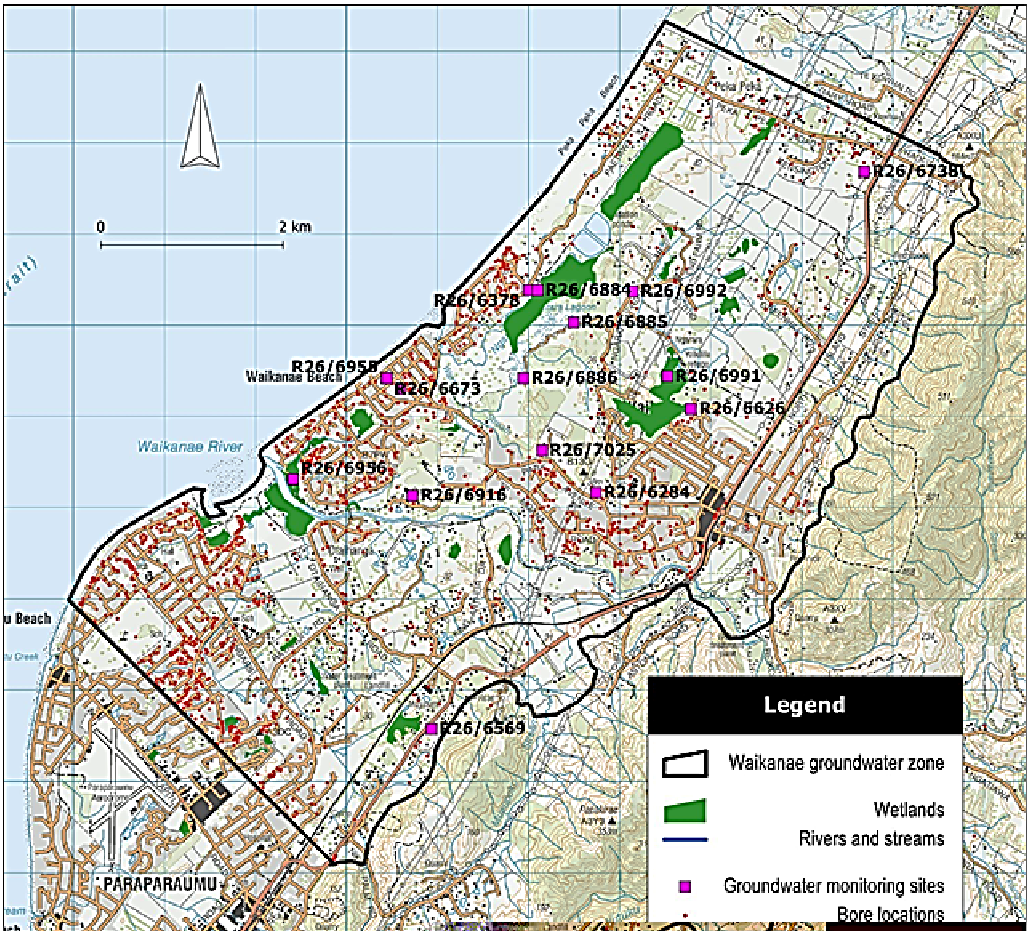

Figure 14: Waikanae groundwater zone

The spatial extent of the proposed Waikanae groundwater zone largely matches the boundaries of the existing Waikanae groundwater zone defined in the RWP with the following modifications:

- The northern boundary, representing the approximate transition between the Otaki and Waikanae river fans is shifted slightly to the north to extend from the large greywacke outcrop north of Hadfield Road toward the coast, parallel to the estimated groundwater flow direction (Kampman and Caldwell, 1983).

- The inland boundary is truncated at the start of the Waikanae River valley to reflect the outcrop of greywacke basement within the Waikanae River to the east of SH1; and

- The southern boundary is shifted approximately 2.5 kilometres to the north of the existing boundary. This boundary coincides with the southern margin of the Waikanae River fan where laterally continuous gravel layers in the Waikanae area are essentially replaced by sand. This is therefore a transitional boundary between fluvial deposition and longshore sediment transport. It also corresponds with a flow divide between the Mazengarb and Wharemauku catchments identified from piezometric surveying (Jones and Gyopari, 2005).

Both the northern and southern boundaries of the Waikanae groundwater zone therefore mark transitional changes in the geological and hydrogeological environment. They are also parallel to flow lines and as such are no-flow ‘soft’ boundaries and cross-boundaries could occur if local groundwater abstraction drawdowns propagate across them.

The Waikanae groundwater zone contains the most highly developed aquifers on the Kapiti Coast and approximately 1,400 bores recorded in the zone on the GWRC Wells database. A significant proportion of these bores are less than about 6m deep and used for domestic garden watering in the residential areas of Waikanae, Waikanae Beach and Paraparaumu. Deeper water bearing layers (15 to 50 metres) are also utilised for a range of horticultural and agricultural applications. The Kapiti Coast District Council (KCDC) also hold resource consents for large-scale abstraction (up to 23,000 m^3/day) from deeper (>70 metre) water bearing layers for supplementary municipal supply (these are rarely utilised however).

In recent years, several phases of drilling and hydrogeological investigation have been carried out in the Waikanae area as part of municipal water supply developments undertaken by the Kapiti Coast District Council (e.g. PDP 1999, URS 2004, Beca 2010, Beca 2012). In addition, various postgraduate research investigations have contributed to the hydrogeological characterisation of the Waikanae area. These include Welch (2004), Ewig (2009) and Allen (2010). As a result of these investigations, the Waikanae groundwater zone contains by far the best characterised groundwater resources on the Kapiti Coast.

4.1 Waikanae zone geology

The geology and geological history of the Waikanae groundwater zone has been described extensively in previous reports including WRC (1994), PDP (1996a), PDP (1996b), PDP (2003), URS (2003), URS (2004) and Jones and Gyopari (2005).

The subsurface geology of the coastal section of Waikanae groundwater zone at depths of less than 30 metres tends to be dominated by extensive sand deposits which contain isolated gravel lenses increasing in frequency with depth. This area represents the accumulation of marine and non-marine coastal sediments since the post glacial sea level highstand approximately 6.5 ka. At this time relative sea levels were between 4 to 6 metres higher than at the current time and older pre-existing fluvioglacial outwash deposits were eroded back to the low cliff line which can be traced along the coastal plain between Waikanae and the Otaki River. As sea levels fell over the subsequent period, deposition of extensive sand deposits (aided by increased sedimentation resulting from volcanic activity in the central North Island) resulted in deposition of these extensive sand deposits and accompanying progradation of the coastline to its present position approximately 3 kilometres seaward of the postglacial marine terrace.

To the east of the marine terrace, the near-surface geology largely comprises poorly sorted fluvioglacial outwash gravel (Q2) deposits accumulated during the last (Otiran) glaciation. These gravel materials interfinger with locally derived slope deposits at the base of the Tararua foothills.

A relatively thin, elongate sequence of postglacial alluvial gravels (Q1) mark the extent of postglacial entrancement and reworking of older sand and gravel materials on the Waikanae River floodplain. These recent river gravels also trace the course of the 'Waimea River', a channel of the Waikanae River which flowed in a north-west direction across the coastal plain from near the present-day Waikanae township before being diverted into the Waikanae River by channel works during the late 1890's (Welch, 2004).

The thick sequence of alluvial gravel and sand deposits which underlie the Holocene sediments reflect the relatively complex history of the Kapiti Coast. WRC (1994), PDP (1996a and b), PDP (2003) described these sediments in terms of three main stratigraphic units which in depth order are:

- 'Parata Gravels' (Q2-4) - poorly sorted fluvioglacial outwash gravels associated with the last glaciation;
- A layer of 'marine sand' comprising a sequence of peat, sand and silt up to 20 metres in thickness accumulated during the Kaihinu interglacial period (Q5); and
- 'Waimea Gravels' (Q6-8) - medium to poorly sorted blue/brown gravels containing varying amounts of sand and silt deposited during the penultimate Waimea glacial period.

Stratigraphic Solutions (2003) presented a refined conceptual geological model of the Waikanae groundwater zone based on detailed analysis of available bore logs for the KCDC Waikanae/Otaihanga Borefield project. The conceptual model comprised six stratigraphic units which include a repeating sequence of sedimentary deposits (cyclothems) grading from marine sediments (mostly coarse sand with isolated beach gravel) through non-marine sands, gravels, clay-bound gravels or dune sands ending with fine-grained non-marine beds (peat, silt and/or clay) dune sand or sandy gravel. Individual stratigraphic units were inferred to correspond to cyclical climate and sea level variations over the late Quaternary period essentially sub-dividing the previously identified stratigraphic units on the basis of sedimentation occurring during early and late-phase Otira glacial and Kaihinu interglacial periods.

A generalised conceptual model of the interpreted stratigraphic succession in the Waikanae area developed by Stratigraphic Solutions (2003) is shown in Figure 15. Based on an interpretation of available drill log information, Figure 16 shows schematic geological cross sections of the coastal plain in the

Waikanae groundwater zone showing the spatial distribution of the interpreted geological units.

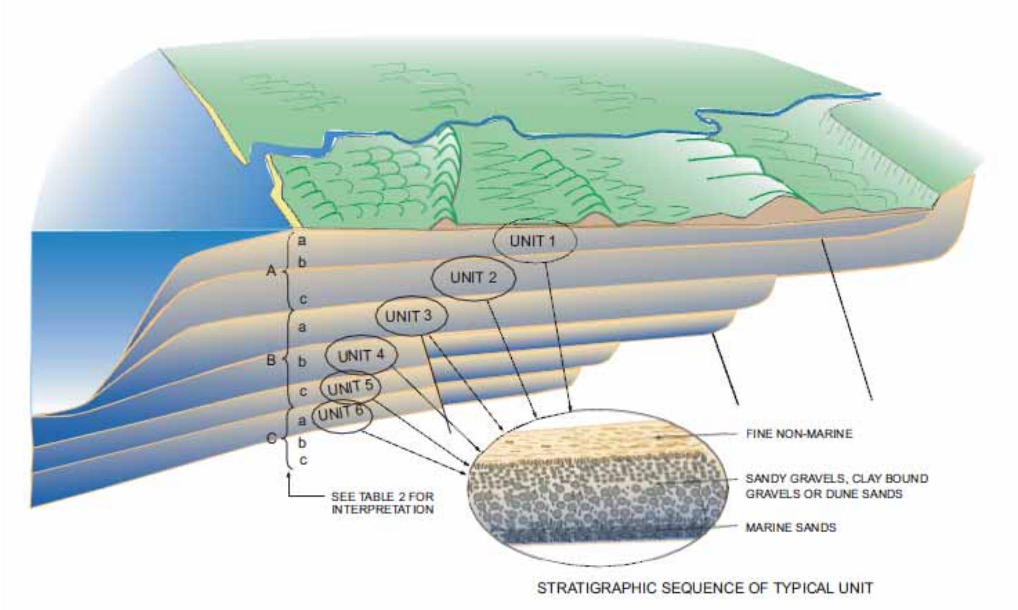

Figure 15: Generalised conceptual model of the late Quaternary stratigraphic succession in the Waikanae area (URS, 2004)

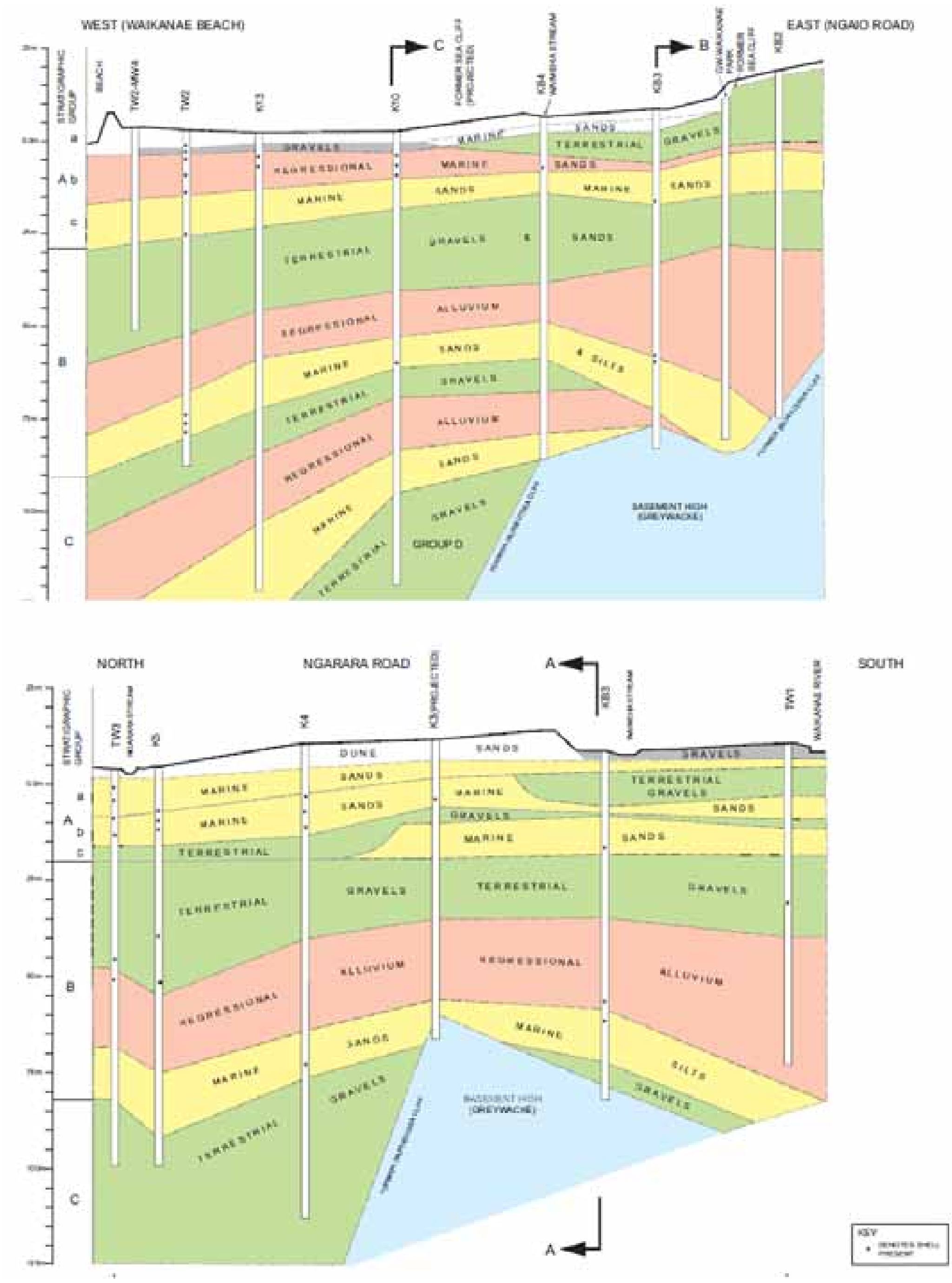

Figure 16: Schematic geological cross sections of the Waikanae groundwater zone orientated west-east (upper panel) and north-south (lower panel) from URS 2004

The heterogeneous nature of the sedimentary deposits and the lack of detailed lithological descriptions on a majority of bore logs renders application of this detailed geological model across the wider Waikanae area proved difficult. As a more practical alternative, and in accordance with the stratigraphic succession proposed by Begg and Johnston (2000), this study recognises the following five units:

- Q1 alluvium - thin, relatively coarse sand and gravel deposits associated with deposition on the active floodplain of the Waikanae River since the last glaciation. These deposits are typically less than 15 metres thick and occur along the riparian margins of the current channel of the Waikanae River and the alignment of the historical ‘Waimeha River’.

- Q1 sand - fine to medium sand containing silt and isolated gravel layers increasing in frequency toward the base of this unit. These deposits represent deposition along the prograding coastal margin over the past 6,500 years and occur west of the Holocene marine terrace increasing in thickness from around 15 metres in inland areas up to 40 metres near the coast. Discontinuous peat deposits are prevalent within this unit.

- Q2 to Q4 alluvium - poorly sorted, gravel and sand containing variable amounts of silt. These deposits are interpreted to result from active deposition on the Waikanae River floodplain during the last (Otiran) glaciation (~14 to 70 ka). These deposits form the higher surface to the east of the Holocene marine terrace and underlie the Holocene (Q1) deposits toward the coast (and offshore).

- Q5 sand - fine grained materials (sand, silt and organics) with isolated gravel layers accumulated during the last (Kaihinu) interglacial period (~approximately 70 to 120 ka). This unit generally acts as an aquitard, although it can locally provide good well yields.

- Q6-8 medium to poorly sorted blue gravels representing fluvioglacial outwash materials accumulated during the penultimate (Waimea) glacial period 125 to 185 ka.

In summary, the geology of the Waikanae groundwater zone comprises a sequence of relatively extensive Holocene sand and gravel deposits up to 40 metres thick (seaward of the Holocene marine terrace) underlain by a complex assemblage of late Quaternary glacial and interglacial deposits comprising an alternating sequence of sand and gravel deposits deposited during late Quaternary interglacial and glacial cycles. While stratigraphic succession can be subdivided in various ways to accurately reflect the overall geological history, a simple subdivision has been adopted in this report to reflect the overall grouping of sediment textures which ultimately establish the overall hydrogeological setting described in the following section.

In terms of the overall geological setting URS (2004) noted several observations regarding the geological conditions encountered during installation of the Waikanae borefield including:

- Lithification (hardening) was more pervasive in deeper layers than expected;

- The gravel beds encountered were consistently less well-sorted and more silt-rich than expected, particularly east of Ngarara Road; and,

- The alignment of the observed textural transition appears to correspond with the alignment of a sea cliff formed along a transcurrent fault which follows a north-northeast to south-southwest alignment from the southern extent of Ngarara Road.

The final geological factor influencing the hydrogeological setting in the Waikanae groundwater zone is the structure of the underlying greywacke basement. Greywacke is recorded on a number of bore logs in the vicinity of Waikanae indicating the presence of a basement high in this area (i.e. the 'sea cliff' identified in the URS 2004 report). As shown on Figure 17, the logs indicate depth to basement of around 50 metres bgl along the alignment of SH1, increasing to around 90 metres near the western side of Waikanae township. Greywacke is not intercepted in logs from bores to the west of an alignment approximately 2 kilometres west from the Tararua foothills suggesting basement in this area rises stepwise toward the east.

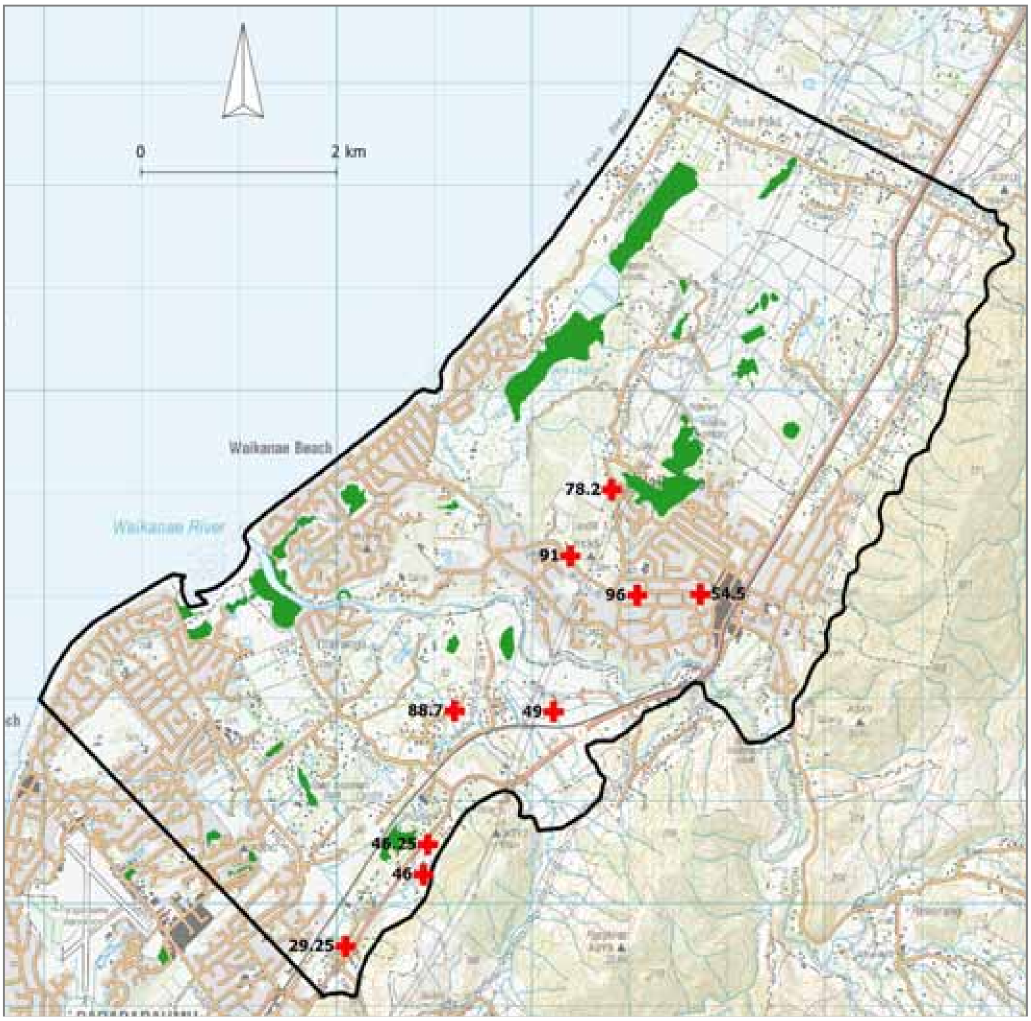

Figure 17: Depth to greywacke basement recorded in bores in the Waikanae groundwater zone

Residual gravity surveying undertaken by Ewig (2009) shows the presence of a NE-SW trending basement high immediately to the east of Waikanae consistent with available drilling logs (Figures 18 and 19). Interpretation of seismic refraction surveying undertaken along Peka Peka Road as part of the same investigation suggests the basement high occurs in the form of a horst structure in this area which merges with the broader basement 'shelf' in the

Waikanae area. The survey results were interpreted to reflect a ‘step-over’ feature between the large fault running along the base of the Tararua foothills to the north of Hadfield Road (mapped as the active Ohariu Fault on the GNS Qmap coverage) and a similar feature running along an alignment coincident with the horst feature along Peka Peka Road and the western margin of the Waikanae basement high.

Structural deformation associated with this ‘step over’ feature is inferred to have resulted in the formation of the Waikanae basement high and a corresponding pull-apart basin centered at the eastern end of Peka Peka Road extending southwards along the base of the Tararua foothills across for a distance of between 2 to 3 kilometres.

Ewig (2010) associated the series of large, north-south trending sand dunes in the Peke Peka area with deformation associated with the underlying horst structure. However, other effects, such as textural changes in the Quaternary sediments noted by URS (2004) and associated influences on aquifer hydrogeology, may also be associated (at least in part) with deformation of basement in the Waikanae area.

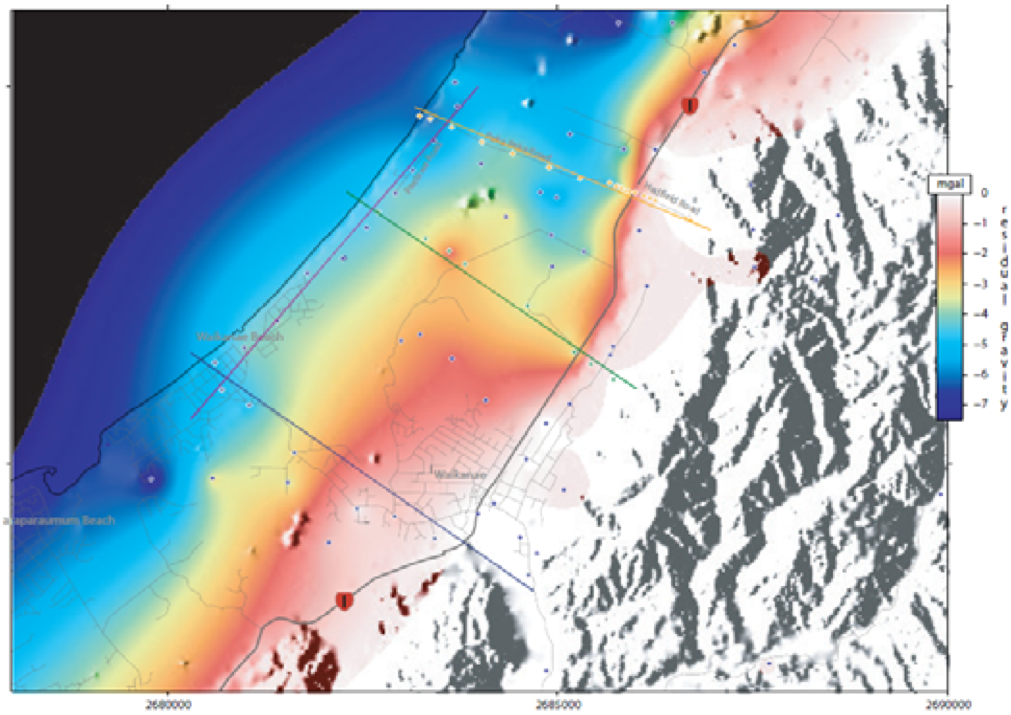

Figure 18: Residual gravity map of the greater Waikanae area

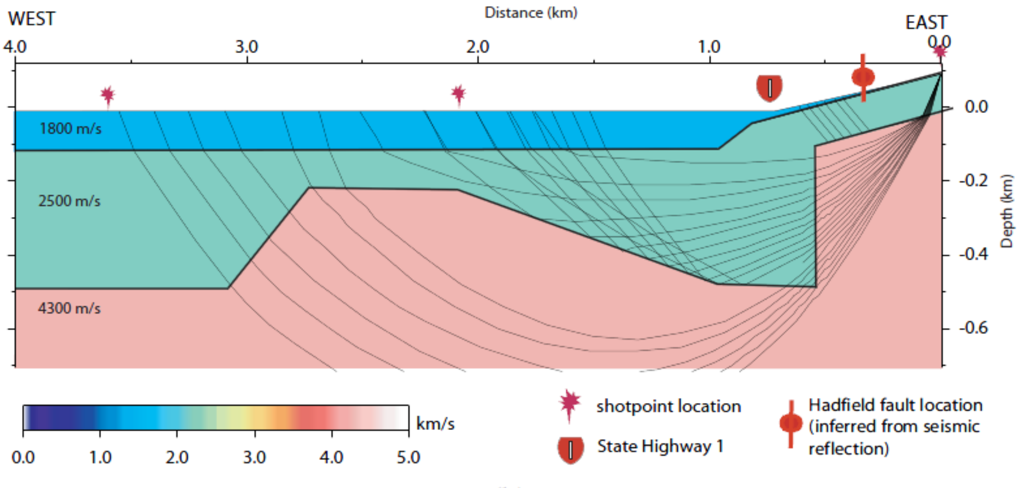

Figure 19: Seismic velocity model based on seismic refraction surveying along Peka Peka Road (Ewig, 2009)

4.2 Waikanae zone hydrogeology

The Waikanae groundwater zone consists of at least three discrete water-bearing layers within a complex geological environment.

The Holocene (Q1) sand and gravel deposits form an extensive unconfined aquifer system which is recharged by local rainfall as well as flow loss from the Waikanae River. Piezometric contours indicate groundwater flow is generally concordant with the gradual seaward slope of the coastal plain indicating discharge is likely to occur along the coastal margin (Jones and Gyopari, 2005). The aquifer system is also hydraulically connected to numerous wetlands and streams on the coastal plain.

Recent (Q1) alluvial gravels underlying the Waikanae River floodplain form a highly permeable riparian aquifer. Available gauging information (summarised in Section 4.2.3) indicates significant hydraulic connection between these deposits and the Waikanae River. The spring-fed Waimeha Stream is inferred to represent drainage of throughflow occurring within permeable gravels along the paleochannel of the ‘Waimea River’.

The late Quaternary (Q2 to Q6+) alluvial materials underlying the Holocene sand and gravel deposits host an extensive groundwater resource. These deposits exhibit a significant degree of heterogeneity reflecting the complex geological and geomorphological history of the area with deposition on the Waikanae River fan influenced by changes in erosion rates and relative sea level during successive glacial and interglacial cycles. Structural deformation associated with the basement shelf underlying Waikanae also appears to have influenced the depositional environments and the hydrogeology of the overlying sediments, particularly prior to the last glaciation.

Based on an interpretation of available geological, hydrogeological, aquifer test and bore construction information, three primary water-bearing intervals are identified within this sequence (nominally associated with the parent unit in the stratigraphic sequence):

- Q2-4 gravels form the terrace surface to the east of the Holocene marine terrace and extend under the Holocene (Q1) sand deposits to the coast. To the east these materials may interfinger with locally derived alluvium accumulated at the base of the Tararua foothills. However, across the majority of the coastal plain these materials appear to form a laterally continuous, unconfined/semi-confined aquifer extending between 30 to 40 metres below ground[5].

- A relatively poorly defined semi-confined aquifer system hosted in permeable gravel materials (Q4) accumulated during early stages of the Otira glacial period. These materials nominally occur between 50 to 60 metres below ground across the coastal plain; and

- A poorly defined layer of heterogenous sand and gravel (likely comprising Q6 and older materials) extending below 70 metres. This unit (previously referred to as the 'Waimea Gravels') appears to be highly heterogenous comprising channelized deposits of more permeable gravel materials separated by low hydraulic conductivity silts and sands. As a consequence, description of this layer as a single water-bearing unit may be a generalisation as significant variations in sediment texture and associated hydraulic properties are likely to occur both spatially and with depth.

The late Quaternary alluvial materials (certainly the Q2 and Q4 materials) lap onto the basement high underlying Waikanae. URS (2004) noted the influence of the basement high on the overall groundwater potential of the Waikanae groundwater zone marking a transition from a thinner (possibly lower hydraulic conductivity) sedimentary sequence in the east to a thicker, better sorted, laterally continuous geological sequence to the west.

At a regional-scale, the materials separating the primary water-bearing units (i.e. Q3 sand, silt and gravel and the Q5 sand and silt respectively) can be considered as forming aquitards. However, due to the overall heterogeneity of the alluvial materials, at a local scale these materials may exhibit significant variation in hydraulic properties. For example, in the Waikanae area, the basal part of the Q5 unit appears to locally form a viable aquifer. The aquifer system in the Waikanae Groundwater Zone is therefore best described as a heterogeneous stratified system comprising multiple, leaky water-bearing intervals which become increasingly confined at depth, rather than hosting discrete 'aquifers' in the conventional sense.

4.2.1 Hydraulic properties

As a result of hydrogeological investigations undertaken for the KCDC Waikanae/Otaihanga Borefield project and the more recent drilling and testing associated with the river augmentation project (Beca, 2012 in prep), a significant amount of aquifer test information is available in the Waikanae groundwater zone compared to other areas of the Kapiti Coast.

In general, aquifer transmissivity values are typically low (<50 m^2/day) in the Holocene (Q1) sand aquifer reflecting the fine-grained nature of these

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5 This unit essentially corresponds with the upper part of the 'Parata Gravels' referred to by WRC (1994) and PDP (1996 a and b)

sediments and the frequent occurrence of low hydraulic conductivity silt and peat intervals. For example, Welch (2004) and Jones and Gyopari (2005) report transmissivity values of between 20 to 50 m^2/day from falling head tests conducted in shallow piezometers screened in coastal sand deposits to north of the Waikanae River. Aquifer hydraulic conductivity increases appreciably in the recent alluvium adjacent to the Waikanae River due to their coarser texture and relatively well sorted nature. Jones and Gyopari (2005) reported aquifer transmissivity vales ranging from 90 to 6,600 m^2/day from shallow (<15 m deep) Q1 alluvial deposits with a mean value of 1,700 m^2/day.

WRC (1994) summarised results of pumping tests from bores screened between 20 to 25 metres below ground near the Waikanae River indicating transmissivity values of the order of 400 m^2/day with a storage coefficient of between $2x10^{-3}$ and $3x10^{-4}$ for Q1 alluvial gravels.

Aquifer testing undertaken on the KCDC TW2 investigation bore screened between 32 to 38 metres on Te Moana Road near Waikanae Beach (Q2 aquifer) indicated semi-confined conditions with a transmissivity value of 940 m^2/day and storage co-efficient of $8.5x10^{-5}$, with significant vertical leakage occurring in response to pumping. Analysis of aquifer testing undertaken at a depth of 71 to 74 metres bgl[6] on the GWRC investigation bore at Waikanae Christian Holiday Park (Q6 aquifer) yielded a moderate transmissivity of 680 m^2/day and little or no drawdown was observed in overlying water-bearing layers (indicating relatively well confined conditions at this location).

A considerable amount of pump test data is available for the KCDC borefield and also more recently for exploration wells drilled around Waikanae (north and south of the river) as part of the proposed KCDC river flow augmentation project.

Table 3 provides a summary of the hydraulic properties for the primary hydrostratigraphic units derived from these tests. This information shows that there is little distinction between the younger Q2-4 deposits and Q5 and Q6+ units in terms of the mean hydraulic conductivity values. The more recent testing (Beca 2012 in prep) also suggests the deposits of Q5 age and older have a significantly lower mean hydraulic conductivity to the east of the basement step (Figure 19) which seems to have strongly influence the Quaternary depositional environments prior to the last glaciation. Overall, the testing data suggest that a significantly 'leaky' and heterogeneous aquifer system underlies Waikanae area.

[6] Equivalent to the Waimea Aquifer (PDP 1996a,b) or URS (2003) stratigraphic unit 6

Table 3: Hydraulic properties for primary hydrostratigraphic units derived from KCDC wellfield bore testing and recent 2012 testing (Beca, in prep)

	Q2-4 ('Parata')	Q5 (Pleistocene sand)	Q6+('Waimea')
Hydraulic conductivity, K m/d			
Min	7	3	13
Max	46	76	30
Mean	23	24	21
GeoMean	18	21	20
Transmissivity, T m2/d			
Min	105	90	277
Max	1300	2272	910
Mean	461	646	596
GeoMean	321	507	572
Storage coefficient, S	-		
Min	4.3E-05	2.7E-06	2.3E-04
Max	6.3E-04	1.1E-03	9.0E-04
Mean	4.3E-04	3.4E-04	6.1E-04
GeoMean	2.9E-04	2.0E-04	5.2E-04
Specific storage, Ss m-1			
Min	2.9E-06	1.8E-07	7.5E-06
Max	4.2E-05	4.0E-05	2.9E-05
Mean	2.4E-05	1.5E-05	2.0E-05
GeoMean	1.6E-05	8.2E-06	1.7E-05
Vertical hydraulic conductivity (aquitards) m/d			
Min	4.20E-04		
Max	4.70E-04		
Mean	4.45E-04		
GeoMean	4.44E-04		
Leakage, K'/B' min-1			
Min	1.60E-08		
Max	2.20E-08		
Mean	1.90E-08		
GeoMean	1.88E-08		

4.2.2 Groundwater Levels

Groundwater levels are currently monitored in a number of bores in Waikanae groundwater zone. These show that static water levels tend to be relatively close to the ground surface but deepen inland. A slight upward gradient is observed in deeper water-bearing intervals near the coast.

Welch (2004) analysed the groundwater levels in six shallow piezometers in the vicinity of Waikanae township in response to rainfall and stage changes in the Waikanae River. Results of this study indicated a virtually instantaneous reaction in shallow groundwater immediately adjacent to the river to changes in river stage with increasing lag and a decreased magnitude of response observed in bores further from the river. Outside the (Q1) alluvial gravel deposits of the Waikanae River floodplain, groundwater levels responded primarily to rainfall events rather than changes in river stage. The study concluded that the observed groundwater level response was consistent with the propagation of a pressure wave through the moderate to high hydraulic conductivity alluvial gravel deposits in response to episodic changes in river stage.

Figure 20 shows the observed relationship between groundwater levels and river stage in the vicinity of the Waikanae River.

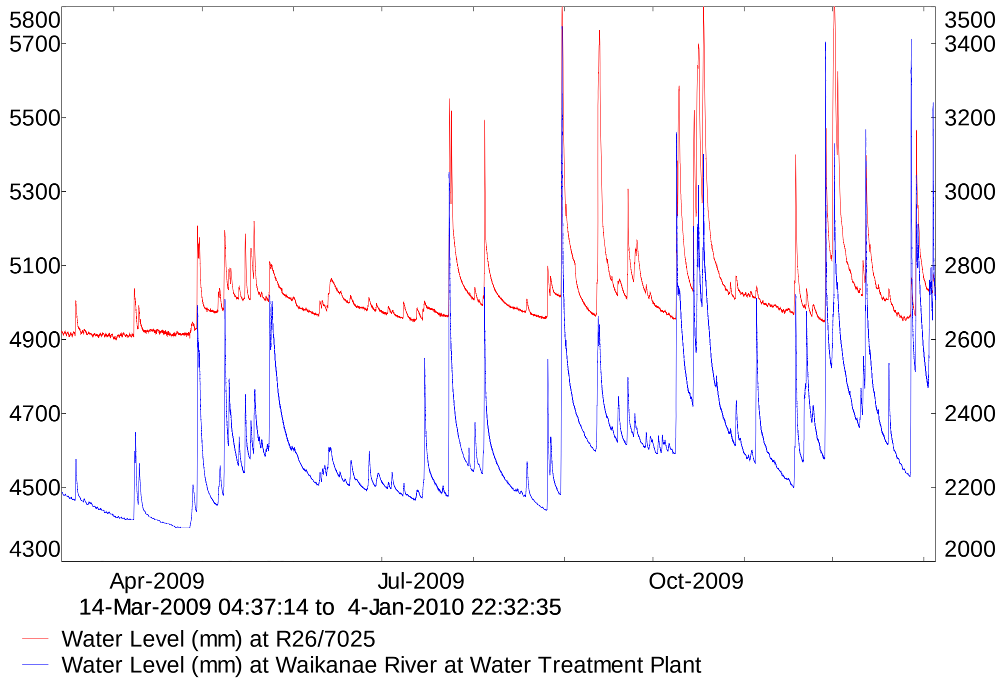


Figure 20: Relationship between Waikanae River stage and groundwater levels at R26/7025

Figure 21 shows a characteristic hydrograph for shallow bores screened in the Holocene sand aquifer in the Waikanae groundwater zone. Groundwater levels respond rapidly to recharge following individual rainfall events then recede slowly as water is progressively drained from the aquifem. The overall seasonal variation appears to track the frequency and magnitude of rainfall events with maximum levels generally occurring in late winter or spring and minimum levels in autumn.

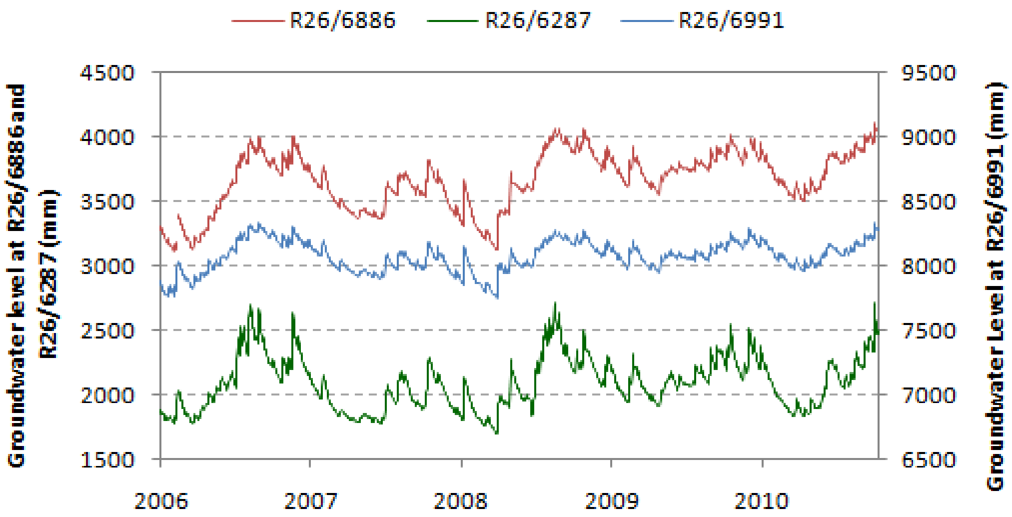


Figure 21: Temporal groundwater level response recorded in the Holocene sand aquifer, Waikanae groundwater zone

Figure 22 presents representative water level hydrographs for deeper bores (>70 metres) in the Waikanae groundwater zone. These show a relatively tight clustering of reduced water levels (~2 to 3 m asl) for bores located within 1,500 metres of the coast (R26/6378, R26/6566, R26/6673 and R26/6284). In contrast, levels recorded in R26/6284, a 90 metre deep bore at Waikanae Park approximately 2,600 metres from the coast, are appreciably higher at ~8.5. to 9.0 m asl (Figure 24). The coastal bores exhibit relatively limited seasonal variation with drawdown associated with abstraction from various KCDC production bores evident in R26/6594 and R26/6378. Again R26/6284 shows a markedly different response exhibiting seasonal variations of up to 1 metre which appear to track the overall seasonal pattern of rainfall recharge.

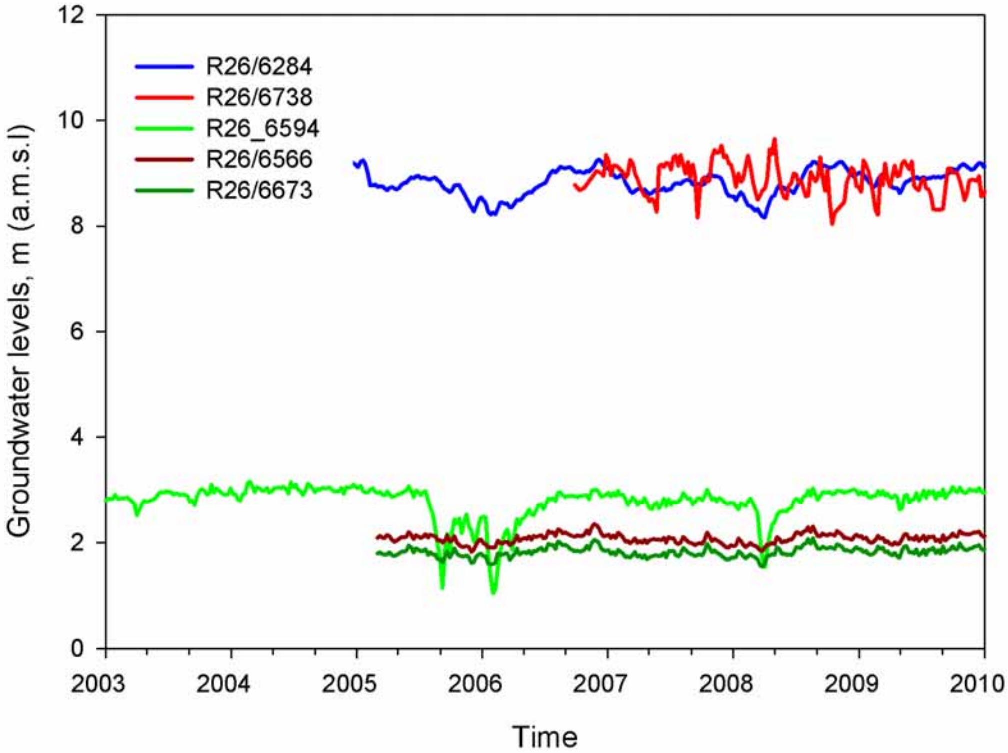


Figure 22: Mean daily groundwater levels in selected deeper (>70 metre) monitoring bores in the Waikanae groundwater zone, 2003 to 2010

Figure 23 shows that groundwater levels in R26/6284 (90m depth, 2.6km from the coast) closely follow those recorded in shallower bores on the eastern side of the coastal plain. The commonality of seasonal response in these bores, regardless of depth, suggests rainfall recharge is the primary driver of temporal groundwater level response in the groundwater system in this area which appears to respond as a single hydraulic unit. Possible explanations for the difference in groundwater levels response observed in R26/6284 compared to other deeper bores closer to the coast include:

- The presence of the basement high which may limit lateral hydraulic connectivity between deeper water-bearing intervals intercepted in R26/6284 and equivalent deposits further to the west. It is noted that bores both to the west and east of R26/6284 encountered basement at shallower depths than the screened interval in this bore, suggesting it may be located in a low point on the basement profile.

- Nearby bore logs suggest the Q5 deposits (primarily fine sand and silt) are irregular or absent to the east of the basement high, potentially increasing vertical hydraulic connectivity through the sedimentary sequence.

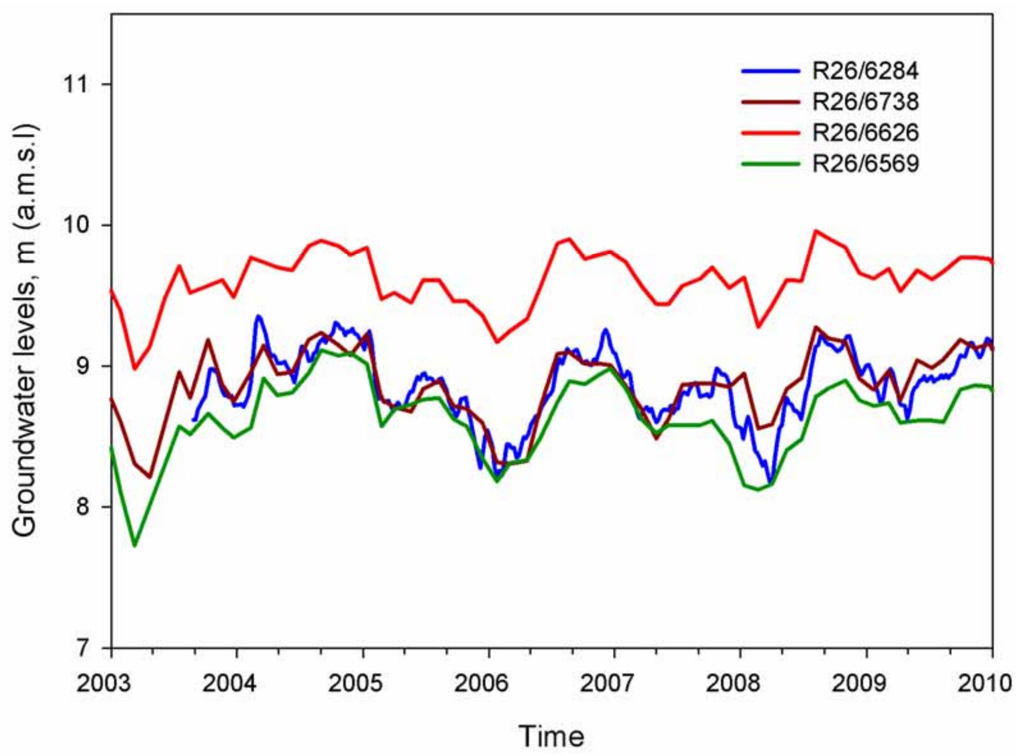


Figure 23: Groundwater levels recorded in bores on the eastern side of the coastal plain

Table 4 provides a listing of median reduced groundwater levels in monitoring bores in the Waikanae groundwater zone. These show the general decline in piezometric level to the west reflecting the overall piezometric gradient toward the coast. When plotted in terms of distance from the coast (Figure 24), the data exhibit two notable features:

- Limited vertical head difference is observed between median piezometric levels at varying depths within the stratigraphic sequence across the entire coastal plain. For example, along the coastal margin nested piezometers show negligable head difference between individual water-bearing layers between 30 and 70 metres below ground. Further inland, a limited upward gradient of ~0.5 metres is observed between bores screened at 19 metres (R26/6916) and 70 metres (R26/6594) at the Waikanae Christian Holiday Park (WCHP) approximately 1,400 metres from the coast; and,

- Piezometric levels appear to show a distinct break in slope which appears to correspond to the location of the western margin of the basement high. To the west the piezometric gradient is relatively flat (~0.0006) while to the east it roughly approximates the overall topographic gradient at least as far as the Holocene marine terrace (~0.005). Few data are available to quantify the slope of the piezometric toward the base of the Tararua foothills, the only monitoring bore being R26/5699, located adjacent to SH1 approximately 3 kilometres south of the Waikanae River.

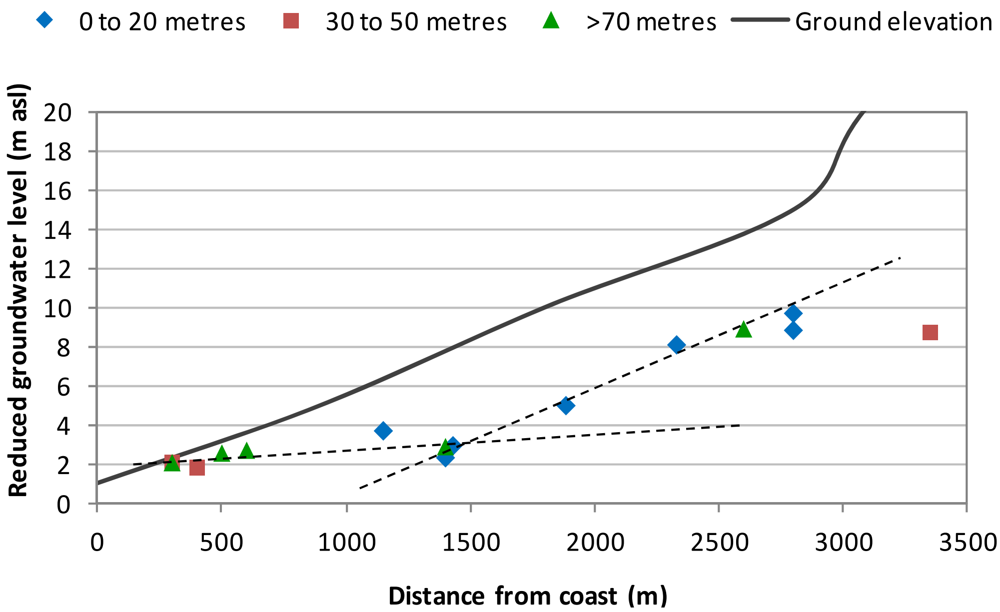


Figure 24: Relationship between reduced groundwater level and distance from the coast for monitoring bores in the Waikanae groundwater zone

Table 4: Median groundwater RL in monitoring bores in the Waikanae groundwater zone

Well Number	Site Name	Depth (m)	Distance to Coast (m)	Median Water Level (m asl)
R26/6956	Estuary shallow	52	300	2.08
R26/6566	Estuary deep	73	300	2.08
R26/6673	Tiata St shallow	33	400	1.82
R26/6955	Tiata St deep	45	400	1.81
R26/6377	Waikanae Golf Club	80	500	2.56
R26/6378	Rutherford Drive	110	600	2.7
R26/6886	Te Harakeke	6	1,150	3.70
R26/9616	WCHP Shallow	19	1,400	2.32
R26/6594	WCHP Deep	71	1,400	2.88
R26/6992	KCDC K6	4	1,430	2.93
R26/7025	KCDC W1	2	1,885	4.98
R26/6991	Nga Manu	2	2,330	8.08
R26/6284	Waikanae Park	87	2,600	8.89
R26/6626	McLauchlan	16	2,750	9.68
R26/6738	McCardle	20	2,800	8.82
R26/5699	Staff College	33	3,350	8.72

The equalisation of piezometric head between bores of varying depths suggests vertical hydraulic connection (i.e. leakage) between water-bearing intervals across a majority of the stratigraphic sequence. This is consistent with the observation of (limited) drawdown in shallow bores during aquifer testing undertaken on KCDC production bores screened in the Q6 layer (e.g. URS 2003, Beca 2010).

Figure 25 shows that the degree of interconnection between individual waterbearing layers can vary both spatially and with depth reflecting the overall hetereogeneity of the alluvial materials. This figure shows drawdown in response to abstraction from the Q6 aquifer during March 2008 of up to ~3 metres in R26/6378 (110 metres deep) reflecting localised pumping effects. During this period a drawdown (~1 metre) was observed in the WCHP deep observation bore (R26/6594, 76 metres) while limited response was observed in the shallow monitoring bore at the same site (R26/6916, 19 metres). In contrast, at the KCDC Estuary monitoring site approximately 0.4 metres drawdown was observed in the shallower piezometer (R26/6956, 52 metres) while drawdown was less than 0.1 metres in the deeper piezometer at the same site (R26/6566, 76 metres).

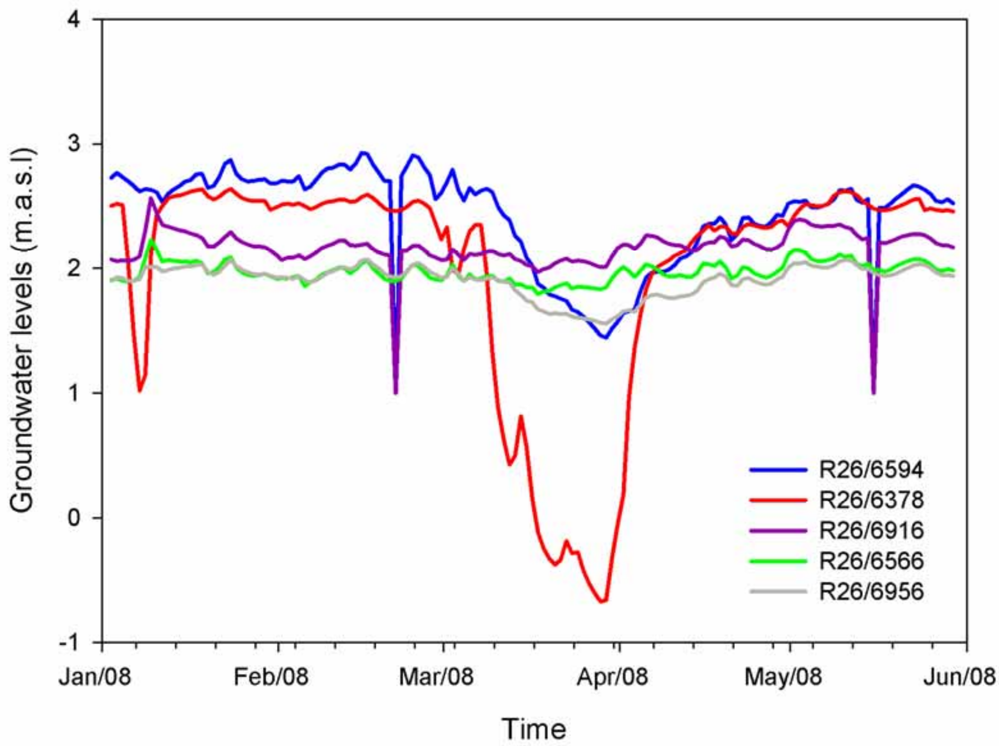


Figure 25: Drawdown in response to abstraction from the Q6 (Waimea) aquifer, Jan to May 2008

The piezometric gradient is therefore relatively flat toward the coastal margin (<0.001), steepening rapidly to around 0.005 toward the inland margin of the coastal plain. The aparent break in slope observed in the piezometric gradient appears to correspond with the western margin of the basement high underlying the Waikanae township. The reason for this relatively abrupt change in hydraulic gradient at this point is uncertain but could possibly be related to both a change in overall sediment texture (as noted in URS, 2004) and/or limited lateral continuity of individual water-bearing strata across this feature.

Limited vertical hydraulic gradient is observed between individual water-bearing layers throughout the entire stratigraphic sequence although both response to seasonal recharge and abstraction can vary both spatially and with depth reflecting the heterogeneity of the alluvial materials. Groundwater levels on the basement high (i.e. ~east of Ngarara Road) appear to respond in a very similar manner to seasonal recharge suggesting relatively good hydraulic connection across the entire sedimentary sequence, possibly due to the irrigular occurrence of the lower hydraulic conductivity Q5 sediments in this area and the geomentry of the basement 'ridge'. To the west, the deeper Q6 aquifer appears to be relatively well confined by the overlying Q5 sediments exhibiting different seasonal response to the overlying Q2 aquifer. However, in places the Q5 materials appear to exhibit sufficient hydraulic conductivity to allow appreciable vertical leakage in response to large-scale pumping induced drawdown in the Q6 aquifer.

Groundwater levels in the Holocene (Q1) sand respond to localised rainfall recharge exhibiting the characteristic short-term hydraograph response observed in these deposits along the entire coastal margin of the Kapiti Coast.

4.2.3 Groundwater/surface water interaction

The Waikanae River drains the western slopes of the Tararua Range and flows across the coastal plain in the vicinity of Waikanae Beach. Other streams draining the Waikanae groundwater zone include the Ngarara Stream which drains wetland areas on the coastal plain north of Waikanae, the spring-fed Waimeha Stream originating on the paleochannel of the 'Waimeha River', the Mazengarb Drain which drains the coastal plain south of the Waikanae River and the Wharemauku Stream which flows from the Tararua foothills reaching the coast at Raumati Beach.

Figure 26 shows the location of concurrent flow gauging sites in the Waikanae area

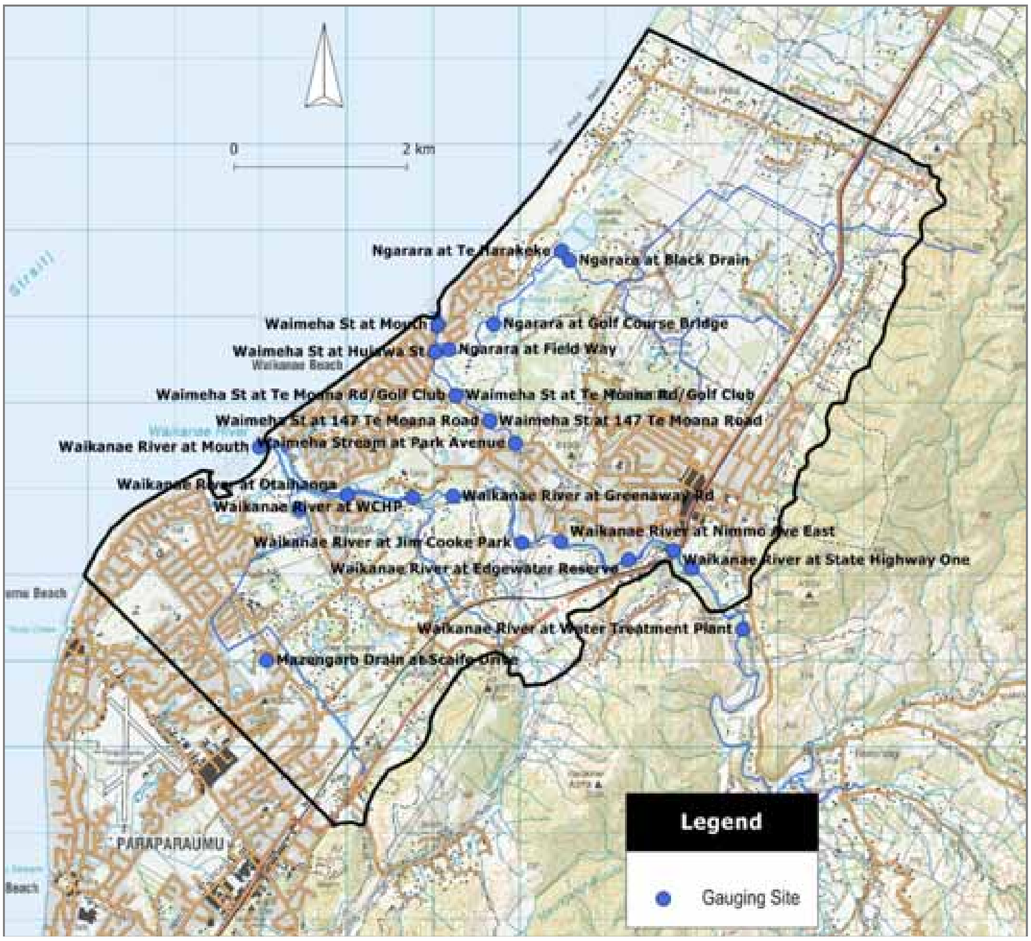


Figure 26: Concurrent gauging sites in the Waikanae groundwater zone

Gauging data indicate significant interaction between the Waikanae River and surrounding Q1 gravels. As illustrated in Figure 27, data indicate appreciable flow loss over the reach between Transmission Lines and Jim Cooke Memorial Park[7]. During periods of low flow gauged losses over this reach are generally of the order of 300 L/s (26,000 m^3/day) which may account for between 40 to 60 percent of the upstream flow. The few gauging data in the lower section of the river indicate an increase in flow reflecting baseflow discharge to lower reaches of the river from the surrounding unconfined aquifer.

[7] Both sites located downstream of KCDC water supply intake so observed flow variation not affected by abstraction

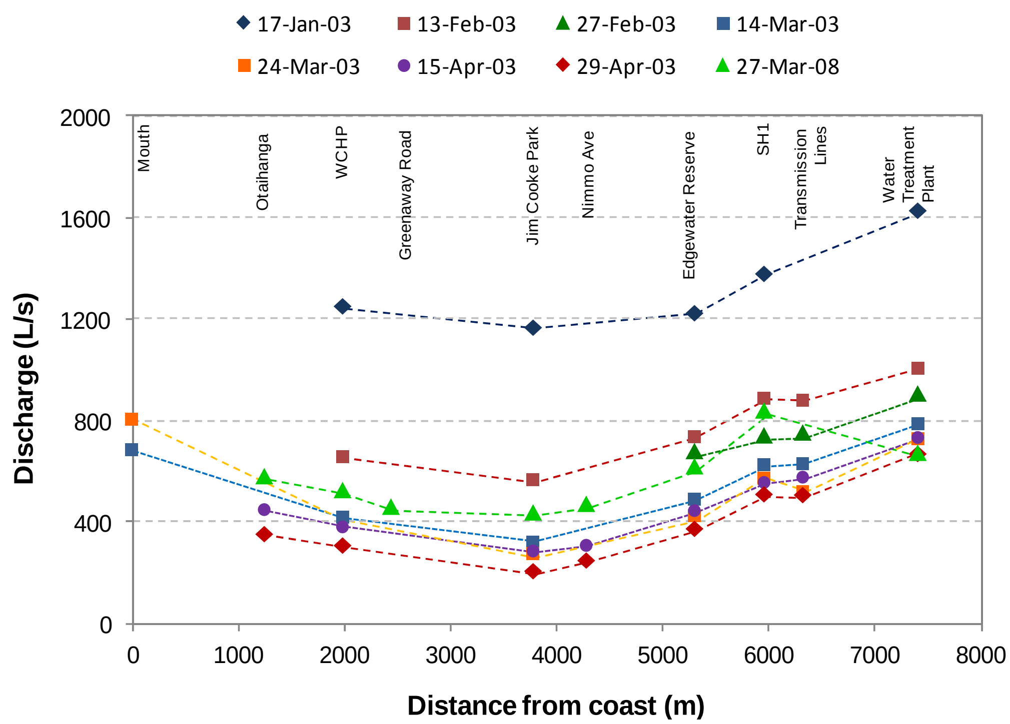


Figure 27: Concurrent gauging results from the Waikanae River

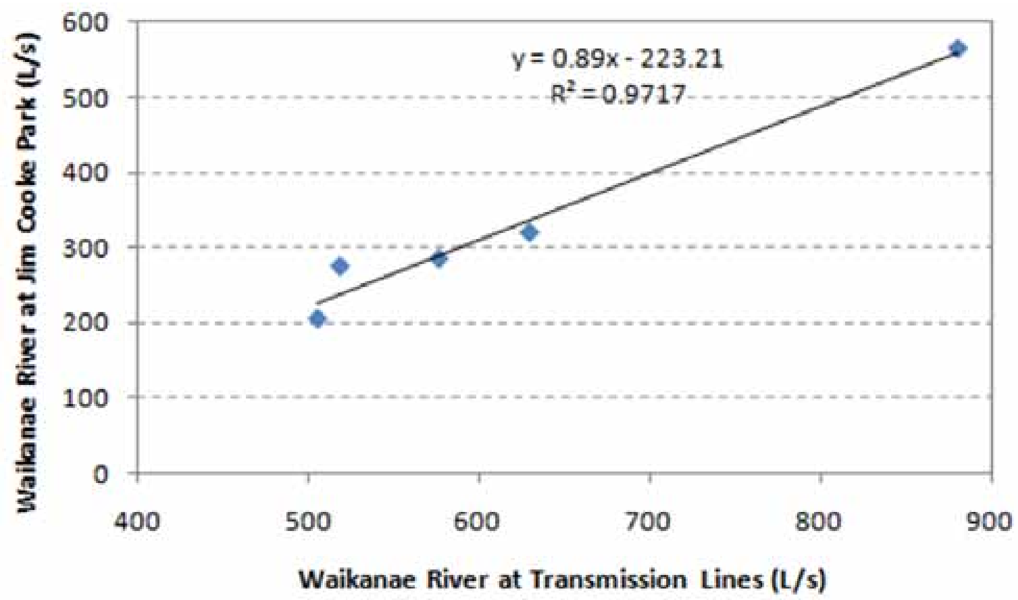


Figure 28: Correlation between measured discharge at Transmission Lines and Jim Cooke Park

Figure 28 shows the observed correlation between measured flow in the Waikanae River at Transmission Lines and Jim Cooke Park. Based on the observed relationship, the estimated flow loss over this reach ranges from approximately 550 L/s (~48,000 m^3/day) at median flow (3,000 L/s at the GWRC Waikanae River at Water Treatment Plant recorder site) to around 320 L/s (28,000 m^3/day) at MALF (845 L/s).

A proportion of the throughflow occurring in the Q1 gravel aquifer adjacent to the Waikanae River is interpreted to follow the paleochannel of the 'Waimeha

River' and discharge into (what is now) the Waimeha Stream. As illustrated in Figure 29**,** flow in the Waimeha Stream increases rapidly in its headwaters downstream of Park Avenue, with typical discharge of approximately 150 L/s at Te Moana Road indicating significant baseflow discharge over this reach.

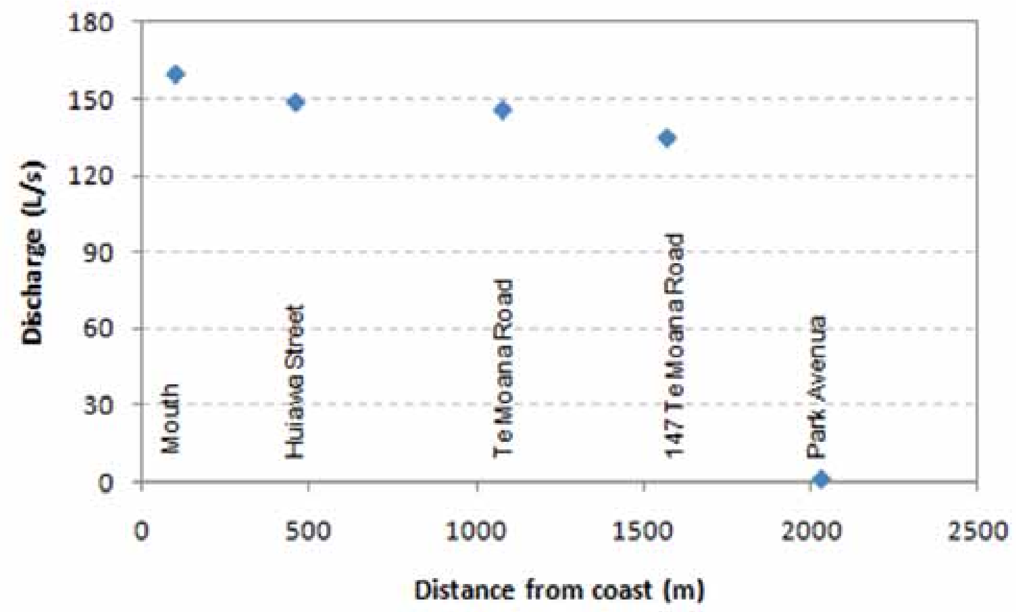


Figure 29: Concurrent gauging results from Waimeha Stream, 27 March 2008

The Ngarara Stream drains the Te Harakeke and Nga Manu wetlands which occur on the coastal plain north of Waikanae. Limited flow gaugings on the Ngarara Stream indicate that the flow upstream of the Waimeha Stream confluence ranges from 30 to 400 L/s. Due to the ephemeral nature of runoff to this stream (with a significant contribution from urban stormwater), it is assumed that the lower figure represents the likely magnitude of baseflow discharge from shallow groundwater during summer conditions.

The Mazengarb Drain is a similar stream which drains the coastal plain south of the Waikanae River. Jones and Gyopari (2005) suggested a groundwater contribution of the order to 50 L/s to the lower reaches of this stream.

Waikanae groundwater zone hosts a number of significant wetland areas on the coastal plain both north and south of the Waikanae River (Figure 15). Jones and Gyopari (2005) note that these ecosystems are largely sustained by groundwater inflow in areas where the water table in the Holocene (Q1) sand aquifer intersects (or lies close to) the land surface, particularly in interdunal depressions. In localised areas, evaporation from open water and evapotranspiration from wetland vegetation may comprise a relatively small component of the overall water budget in the unconfined aquifer which increases in significance during extended periods of low rainfall.

4.2.4 Recharge and discharge

The groundwater system in the Waikanae groundwater zone is recharged by a combination of rainfall infiltration on the coastal plain, flow loss from the Waikanae River and infiltration of local runoff from the Tararua foothills via the alluvial fans which extend along their western margin.

Rainfall infiltration and flow loss from the Waikanae River appear to dominate recharge to the Q1 sand and gravel aquifers on the coastal plain. The Q2 aquifer is likely be recharged by rainfall infiltration on the terrace surface to the east of Holocene marine terrace and also appears to be hydraulically connected to the overlying Q1 sand across the coastal plain, forming a largely unconfined aquifer system (which may be locally confined by accumulations of finer sediment).

Recharge to the deeper Q4 and Q6 intervals is less certain. Groundwater level response along the inland margin of the coastal plain suggests some degree of hydraulic connection across the entire stratigraphic sequence. This may reflect the heterogenous nature of the alluvial deposits in this area combined with a general coarsening of sediment textures on proximal areas of the Waikanae River fan, combined with vertical infiltration through the alluvial fan materials accumulated along the western margin of the Tararua foothills. Infiltration through these alluvial fan materials may be augmented by the overall geometry of these deposits which rise in excess of 40 metres above the coastal plain, significantly increasing the vertical hydraulic gradient.

Discharge from the Q1 sand and gravel deposits occurs to the lower reaches of the Waikanae River and the numerous lowland streams that originate toward the seaward margin of the coastal plain. Piezometric contours (e.g. Jones and Gypoari, 2006) also indicate discharge from the Q1 sand aquifer along the coastal margin. The flattening of the hydraulic gradient and the limited vertical head difference between water-bearing intervals at varying depths along the coastal margin suggests that diffuse (upward) leakage from the Q4 and Q6 aquifers may be a significant discharge mechanism for these deeper water-bearing layers. This leakage may also occur offshore in the area between the mainland and Kapiti Island.

4.3 Waikanae zone summary

The Waikanae groundwater zone hosts an extensive groundwater resource in a complex, relatively heterogeneous sequence of later Quaternary alluvial materials.

The Holocene (Q1) sand and gravel deposits form an extensive unconfined aquifer system which is recharged by local rainfall as well flow loss from the Waikanae River. The aquifer system is also hydraulically connected to numerous wetlands and streams on the coastal plain.

The underlying sequence of Q2 to Q6+ alluvial materials form a thick stratified aquifer system. Along the coastal margin these deposits can be separated into three distinct water-bearing units (the Q2, Q4 and Q6 aquifers respectively) which are separated by accumulations of predominantly fine-grained (sand and silt) materials. These units restrict the hydraulic connection between successive water bearing intervals resulting in progressively lower rates of groundwater flow circulation through the deeper aquifer system. However, the similarity in piezometric head observed throughout the stratigraphic sequence indicates sufficient vertical hydraulic conductivity exists to allow leakage to occur in response to fluctuations in the aquifer water budget (e.g. recharge or abstraction). East of the basement high which extends under the Waikanae township, differentiation of separate water-bearing units is more difficult with a similar response to seasonal recharge observed at all depths.

Table 5 provides a summary of the physical characteristics and spatial distribution of hydrostratigraphic units identified in the Otaki groundwater zone based on a review of geological, hydrogeological and groundwater level information.

Table 5: Physical properties and spatial distribution of hydrostratigraphic units in the Waikanae groundwater zone

Hydrostratigraphic Unit	Description	Spatial/depth distribution
Holocene (Q1) Sand	• Medium to fine sand with discontinuous layers (lenses) of gravel and silt/peat. • Relatively low bulk hydraulic conductivity (K~2-5 m/day) • Hosts a shallow unconfined aquifer system primarily recharged by local rainfall	• Extends from the Holocene marine terrace to the west of Waikanae township to the coast • Forms a wedge shaped deposit increasing in thickness from around 20 metres inland up to 40 metres near the coast.
Q1 gravel	• Coarse, heterogeneous deposits of sand and gravel • Hosts a highly permeable unconfined aquifer hydraulically connected to surface water • Highly permeable (K~50 -100 m/day)	• Underlies the recent floodplain of the Waikanae River and the former channel of the ‘Waimeha River’ • Forms a relatively narrow, elongate deposit generally between 10 to 15 metres thick
Q2 Gravel	• Moderately to poorly sorted alluvial gravel with varying amounts of silt and sand • Forms a low to moderate hydraulic conductivity unconfined/semi-confined aquifer (K~10-50 m/day) which is hydraulically connected to the overlying Q1 sand • Hydraulic conductivity may decrease toward the Tararua foothills, particularly in the area to the east of Ngarara Road	• Forms the higher terrace surface to the east of the Holocene marine terrace • Extends toward the coast (and further offshore) under the Holocene (Q1) sand
Q3 gravel, sand and silt	• Heterogenous deposits of sand, silt and gravel • Hydraulic conductivity sufficiently low to restrict hydraulic connection between the Q2 and Q4 sediments	• Typically 10 to 15 metres thick • May become coarser inland and virtually indistinguishable from Q2/Q4 deposits
Q4 Gravel	• Gravel and sand similar to Q2 deposits	• Thickness varies from <10 to 20 metres

	• Forms a moderately permeable semi-confined aquifer	
Q5 Sand and silt	• Medium to fine sand containing silt and organics (K 1-20 m/d) • Forms an aquitard separating water-bearing intervals in the Q2 and Q6 gravel deposits in most areas/ • May contain higher yielding relatively well graded medium to fine sand layers	• Occurs as a continuous layer to the west of the basement high. • May be discontinuous in the area overlying the basement high, or has a significantly different character (higher k).
Q6 and older gravel and sand	• Assigned to all alluvial materials interpreted to be Q6 (Waimean Stage - penultimate glacial) and older • Poorly sorted, weathered gravel in a silty, sandy matrix • Hosts a low to moderate yielding semi-confined to confined aquifer system • Typically low to moderate hydraulic conductivity (10-30 m/day) which may decrease inland due to increasing proportion of silt (both in terms of individual silt layers as well as in gravel matrix)	• Strata inferred to dip westward following profile of Waikanae fan (~1^{o})
Greywacke basement	• Well indurated siltstone and mudstone • May contain secondary hydraulic conductivity in joints and fractures but essentially considered to form the groundwater basement	• Form Tararua foothills to east of Waikanae groundwater zone • Large bedrock high underlying Waikanae township which appears to be associated with normal NE-SW trending normal faults extending along the Kapiti Coast • Basement surface appears relatively planar (~90 m bgl) between to west of SH1 but may step up toward the foothills

Iinformation indicates infiltration of rainfall and runoff from the Tararua foothills is a significant source of recharge to the Q1 sand aquifer. Streamflow gaugings also indicate a flow loss of approximately 550 L/s from the Waikanae River to the surrounding Q1 alluvium between Transmission Lines and Jim Cooke Park. A proportion of the flow loss from the Waikanae River appears to flow along the former channel of the ‘Waimeha River’ and emerge in headwater springs in the Waimeha Stream which carries a discharge of approximately 150 L/s. Appreciable baseflow discharge also occurs in the lower reaches of the Waikanae River (possibly of the order of 300 L/s) as well as the Mazengarb Drain (~50 L/s) and Ngarara Stream (30 L/s). An unknown component of groundwater throughflow is discharged offshore, although the observed reduction in piezometric gradient along the coastal margin may suggest that vertical leakage in this area may be a more important component of the water balance in the Q6 and Q2 aquifers.

Table 6 provides a summary of the key components of the overall water balance for the Otaki groundwater zone.

Table 6. Summary of key components of the water balance for the Waikanae groundwater zone

Component	Description	Comment
Rainfall	• Infiltration of rainfall on coastal plain • Infiltration of local runoff from Tararua foothills	• Not determined • Side-slope recharge through alluvial fan materials may make an appreciable contribution to water balance, possibly aided by significant vertical head developed on higher areas of alluvial fans
River Recharge	• Waikanae River	• Flow loss of ~300 L/s between Transmission Lanes and Jim Cooke Park during low flow (550 L/s at median flow)
Baseflow Discharge	• Waimeha Stream • Ngarara Stream • Mazengarb Drain • Otaki River	• ~150 L/s • ~30 L/s • ~50 L/s • Baseflow discharge to lower reaches may be of the order of 300 L/s
Wetland areas	• Losses due to evapotranspiration and direct evaporation	• Not determined. Large, regionally significant wetlands include Nga Manu and Te Harakeke Swamp. Likely to be a relatively minor component of overall aquifer water balance
Offshore discharge	• Discharge offshore	• Not determined but likely to be a major component of overall water balance in Q1 sand • Offshore discharge may occur via diffuse leakage from Q2/Q6 aquifers. However, flattening of piezometric gradient suggests this flux may be minor.

Figure 30 shows a schematic illustration of the conceptual hydrogeological model for the Waikanae groundwater zone.

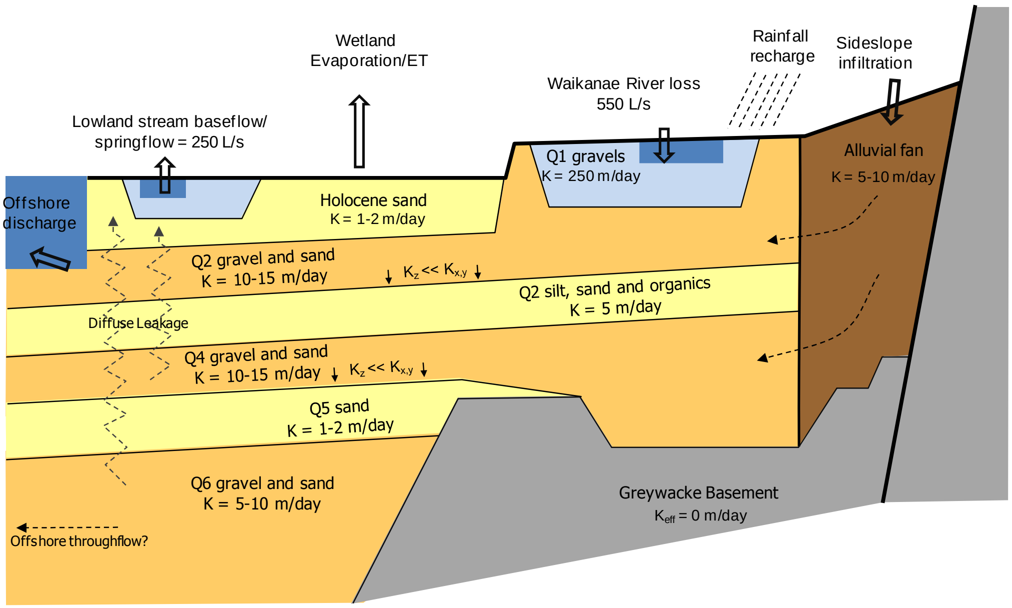


Figure 30: Schematic illustration of the conceptual hydrogeological model for the Waikanae groundwater zone

5. Te Horo groundwater zone

The Te Horo groundwater zone extends from the Otaki River in the north, to Peka Peka Road in the south and combines the existing Hautere and Coastal groundwater zones.

Figure 31 shows the spatial extent of the Te Horo groundwater zone including primary surface water features (streams and wetlands), groundwater level monitoring and concurrent flow gauging sites along with the location of bores recorded on the GWRC Wells database.

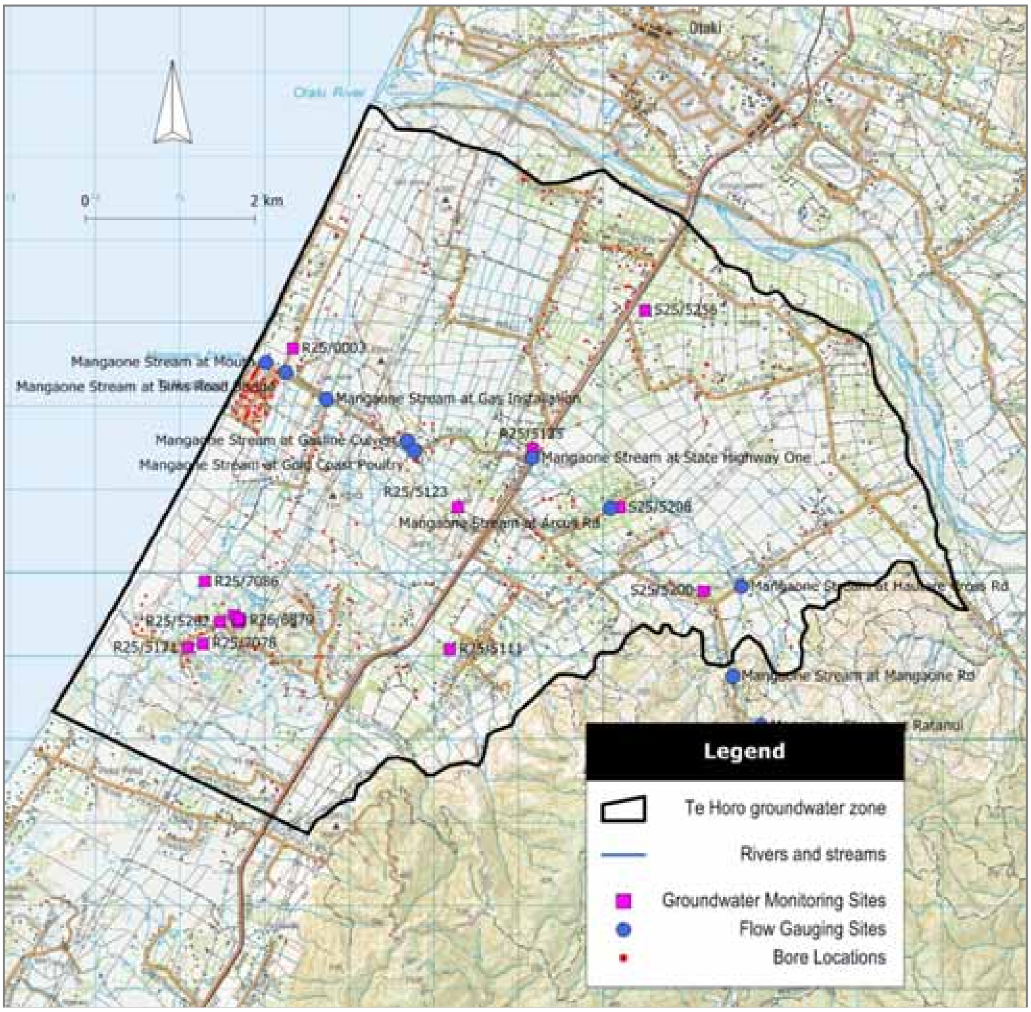


Figure 31: Te Horo groundwater zone

The southern boundary of the proposed Te Horo groundwater zone marks the approximate transition between the Otaki and Waikane river alluvial fans. This boundary is shifted slightly north of the existing Waikanae/Coastal zone boundary to extend from the large greywacke outcrop north of Hadfield Road toward the coast, parallel to the estimated groundwater flow direction (Kampman and Caldwell, 1983). The northern boundary is similarly modified from the existing Hautere/Otaki and Coastal/Otaki zone boundaries to more accurately reflect the geological transition to Q1 alluvium in the Otaki River valley. The eastern boundary largely follows the contact between greywacke basement and overlying Quaternary sediments[8].

5.1 Te Horo zone geology

The geology of the Te Horo groundwater zone comprises an alternating sequence of late Quaternary glacial and interglacial deposits similar to that observed in the Waikanae groundwater zone to the south. Detailed characterisation of the overall geological setting is complicated by the limited number of deep bores in the area.

Figure 32 contains a simplified stratigraphic section derived from detailed analysis of a deep investigation bore (R25/5152) drilled by the Manawatu Catchment Board at Te Horo Beach in the mid-1980's (Brown, 2003). As illustrated, the data show a vertical succession consisting of alternating interglacial (predominantly sand with some gravel) and glacial (silty, sandy gravel) deposits broadly correlated with the stratigraphic succession outlined by Begg and Johnston (2000)[9]. The primary geological units identified include:

Sand and gravel deposits (Q1) associated with postglacial coastal regression and subsequent progradation;

- A thick succession of poorly sorted alluvial gravel, sand and silt (Q2 and Q4) deposited during the last (Otira) glaciation. These deposits are separated by a thin sequence of organic material (Q3) deposited during an interstadial period (~40 to 50 ka). This layer is correlated with similar silt and peat deposits encountered in bores across the Hautere Plain and appears to thicken inland but may pinch-out to the north as it does not appear in bores along the southern margin of the Otaki River valley;

- A layer of beach and dune sand (Q5) accumulated during the last (Kaihinuan) interglacial period. These deposits are correlated with the Otaki Sandstone which forms the Tokomaru marine surface, a highly dissected terrace surface which across the inland areas of the southern Horowhenua District to the Pukehau area to the north of Otaki. The significant difference in elevation between the occurrence of these sediments at Te Horo Beach compared to surface outcrop further north is interpreted to reflect partial erosion of these materials to the south combined with tectonic uplift along the southern margin of the South Wanganui Basin;

- A layer of distinctive blue-grey gravel and sand (Q6) accumulated during the penultimate (Waimea) glacial period. These sediments appear to thicken and become increasingly gravel dominated inland, possibly reflecting deposition on proximal areas of the Otaki River fan. These deposits are correlated with gravel materials exposed in creek beds incised into the Tokoramu marine surface in the Pukehou area (Brown, 2003)

[8] As defined on the Wellington QMap coverage

[9] See section 2.1.2

- Deeper sediments comprising blue sand and silt with gravel and organic material are tentatively associated with older glacial and interglacial sequences including the Kaoroan Interglacial and the preceding Waimaunga glaciation.

Further inland, information pertaining to the deeper part of the stratigraphic succession is limited to three bores in excess of 100 metres deep on the Hautere Plain.

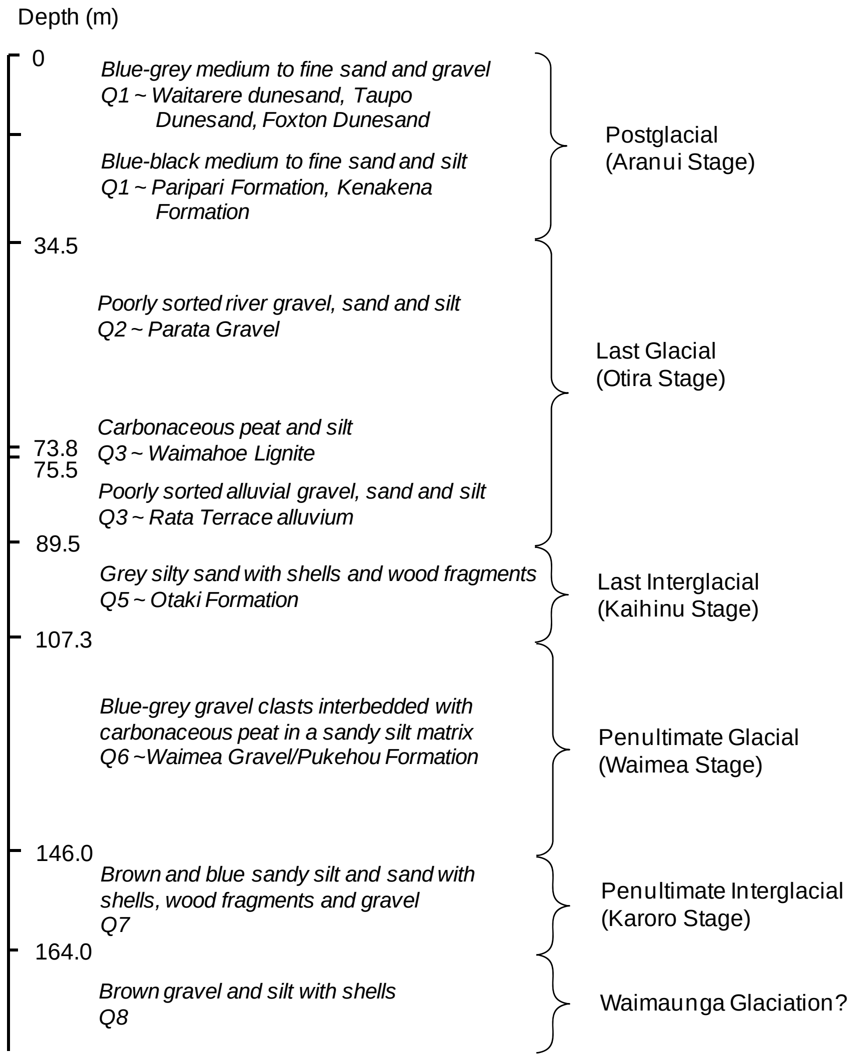


Figure 32: Simplified stratigraphic section from the Te Horo Beach investigation bore (R25/5152). Modified from Brown (2003)

West of the post-glacial marine terrace which runs sub-parallel to SH1, the surficial geology consists of Holocene sand and gravel deposits accumulated as a result of shoreline progradation over the past 6,500 years. These deposits increase in thickness from around 20 metres in the east to between 25 to 35 metres near the present-day coastline and generally tend to contain more frequent gravel layers at depth.

To the east, the Hautere Plain comprises a remnant of the extensive alluvial fan formed by the Otaki River during the last (Otiran) glaciation. These gravel deposits (Q2 and Q4) are interpreted to extend to a depth of between 60 to 70 metres across the central area of the Hautere Plain where they overlie Q5 and/or Q6 deposits. Small areas of these older Q5 and Q6 materials are mapped along the margins of the Mangaone Stream and at the base of the Tararua foothills. Surface outcrop of these deposits is interpreted to reflect the significant erosion of these materials across a majority of the coastal plain during subsequent glacial/interglacial cycles combined with possible uplift associated with vertical displacement on the high angle normal faults which are inferred to traverse the western margin of the foothills.

Figure 33 shows a schematic geological cross section of the Te Horo groundwater zone based on an interpretation of bore log information. It is noted the lateral correlation of all deposits older than Q3 is relatively tentative due to the relatively basic material descriptions on logs from the few deep bores in the Hautere Plain area.

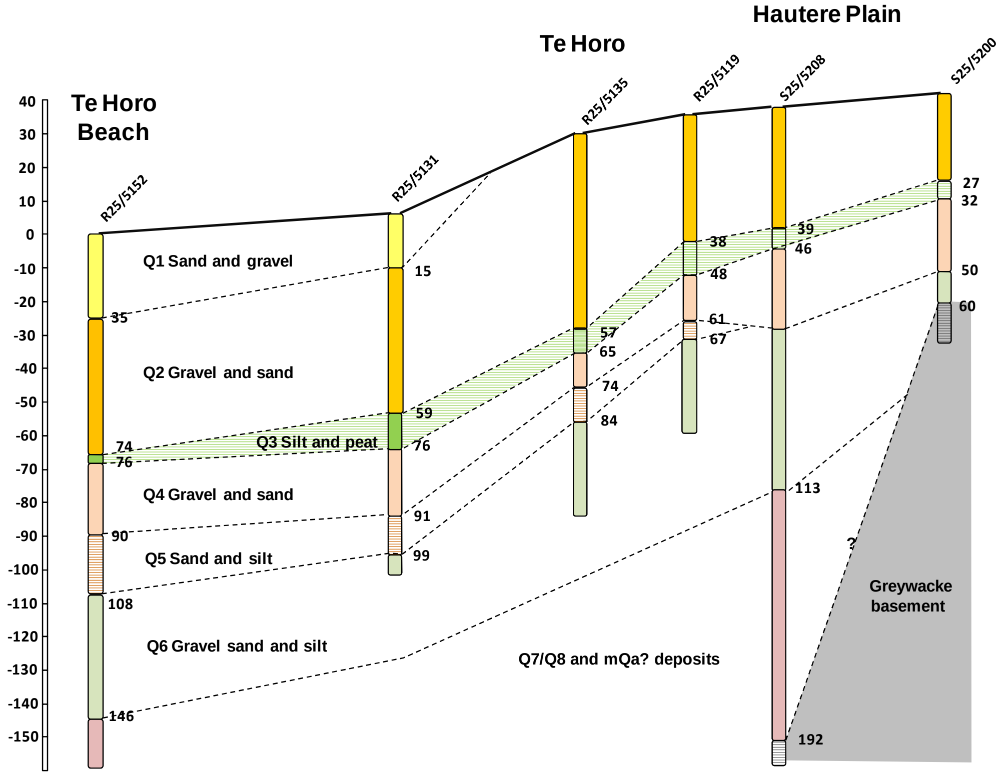


Figure 33. Schematic geological cross section of the Te Horo groundwater zone

Compared to lithologies recorded at on the Hautere Plain, the Q5 and Q6 deposits at Te Horo Beach appear to contain a significantly greater proportion of sand and fine sediment (silt, organics), possibly reflecting deposition on lower-energy, distal areas of the Otaki fan (or further offshore). Tentative correlation of the Q2 to Q6 deposits in the Te Horo Beach test bore with drillers logs from central areas of the Hautere Plain suggest a westerly gradient[10] of approximately 0.8[10].

[10] Approximately 50 metres difference in elevation over a distance of 3.5 kilometres

The structure of the greywacke basement underlying the Te Horo groundwater zone is largely unknown. The bore log from S25/5208 shows basement at a depth of approximately 190 metres in the central area of the Hautere Plain. However, closer to the Tararua foothills, basement is recorded at much shallower depth (e.g. 60 m bgl in S25/5200) suggesting the presence of a basement 'step' along the eastern margin of the Hautere Plain[11]. No bore logs intercept basement west of S25/5208, however mapping of residual gravity anomalies by Ewig (2009) suggest the NE-SW trending basement ridge observed along Peka Peka Road may continue northward under the western side of the Hautere Plain.

5.2 Te Horo zone hydrogeology

Groundwater is utilised for domestic supply in many parts of the Te Horo groundwater zone as well as for horticultural irrigation and commercial use in the vicinity of SH1. A total of 339 bores ranging in depth from 1 metre to 192 metres are recorded in this area on the GWRC Wells database.

WRC (1994) identified three primary aquifers underlying the Hautere Plain:

- A water-bearing gravel layer between 10 to 30 metres below ground exhibiting moderate hydraulic conductivity;
- A water-bearing gravel layer between 40 to 70 metres below ground exhibiting low to moderate hydraulic conductivity containing groundwater with elevated iron concentrations; and,
- A poorly defined sequence of low hydraulic conductivity water-bearing gravels between 90 and 150 metres below ground characterised as containing elevated boron levels.

Based on the geological assessment outlined in the previous section, these water-bearing strata are tentatively associated with better sorted (possibly reworked) gravel intervals within the Q2, Q4 and Q6 deposits respectively. These units appear to be relatively continuous toward the coast, corresponding to similar (although slightly deeper) units identified in the former Coastal groundwater zone (WRC, 1994). A review of bore construction information from the Te Horo groundwater zone confirms that a majority of bores have screens which correspond to these intervals although some variance is noted reflecting the overall heterogeneity of the alluvial materials. The few deeper logs in the Te Horo groundwater zone suggest a relatively thick sequence of Q7 (and possibly older) materials (sand silt and weathered gravels) underlying the Q6 deposits. The thickness and hydrogeological characteristics of this unit are not well defined, so for the purposes of this report these materials are been included within the Q6 (hydraulic) unit.

West of the Holocene marine terrace the upper portion of the Q2 alluvial has been removed as a result of postglacial sea level transgression and replaced by a layer of sand and gravel representing materials deposited by the prograding shoreline over the past 6,500 years. These materials form a low yielding

[11] Similar to that observed in the Waikanae groundwater zone

unconfined aquifer which is widely utilised for domestic and stock water supply. The aquifer increases in thickness from around 20 metres to the east to between 30 and 35 metres near the coast where it almost directly overlies the higher hydraulic conductivity layer within the Q2 deposits.

While the higher hydraulic conductivity gravel layers within the Q2, Q4 and Q6 deposits appear to be laterally continuous across a majority of the Te Horo groundwater, examination of individual bore logs indicate significant variability in geology, screen placement and yield, possibly reflecting a significant degree of heterogeneity within the gravel deposits. For example, examination of screen depths for individual bores also indicates a grouping of bores screened between 20 to 40 m bgl in the vicinity of SH1 north of Te Horo town while an increased number of deeper bores (40 to 70 metres) are located in the south-western section of the Hautere Plain. data also indicate relatively low yields are available from bores (regardless of depth) along the northern margin of the Hautere Plain, where a number of individual and communal water supply schemes pump water from bores screened in shallow Q1 alluvial gravels adjacent to the Otaki River for reticulation on the Hautere Plain[12].

5.2.1 Hydraulic properties

Limited data are available to characterise the hydraulic properties of the Te Horo groundwater zone. Overall the data suggest an overall decline in aquifer transmissivity closer to the coast, possibly reflecting a general decline in overall grain size on more distal parts of the Otaki River fan.

WRC (1994) summarised results from four aquifer tests on the Hautere Plain which yielded aquifer transmissivity values of the order of 70 to 230 m^2/day. Storage coefficients of 0.0005 calculated from two aquifer tests (undertaken on bores 19 and 75 metres deep) suggest semi-confined to confined conditions exist in deeper water-bearing layers across much of the Hautere Plain. The six aquifer tests in the (existing) Hautere groundwater zone recorded on the GWRC Wells database indicate transmissivity values of a similar order (i.e. between 10 to 200 m^2/day).

Hughes (1995c) reported the results of an aquifer test undertaken in a 73 metre deep bore located near the southern boundary of the Te Horo groundwater zone which indicated a transmissivity of 100 to 150 m^2/day and a storage coefficient of 0.0005 inferred to reflect relatively low-hydraulic conductivity confined conditions in the Q4 deposits at this location.

Jones (2002) analysed results of aquifer testing undertaken on two irrigation bores near Te Horo Beach both screened in the Q2 gravels at depths of approximately 50 metres. Analysis of test results indicated aquifer transmissivity values almost two orders of magnitude different (23 m^2/day vs 2,250 m^2/day) in the respective bores indicating significant spatial variability in

[12] This is consistent with the lower permeability observed in Q2/Q4 gravels in the Otaki groundwater zone, suggesting more limited reworking of alluvial materials on the northern sector of the Otaki River fan.

hydraulic properties[13]. A storage co-efficient of 0.002 was calculated from analysis of testing undertaken on the higher yielding bore, results of which also indicated appreciable leakage from the overlying (Q1) sand aquifer.

Limited aquifer test information is available from the Holocene (Q1) sand aquifer, in part due to the relatively low well yields obtainable which limit large-scale groundwater abstraction. However, given the overall similarity of these materials to those in the adjoining Waikanae groundwater zone, this aquifer is assumed to exhibit low hydraulic conductivity possibly of the order of 1 - 2 m/day.

Overall, aquifer test and specific capacity data indicate aquifers in the Te Horo groundwater exhibit hydraulic properties characteristic of a heterogeneous, relatively low hydraulic conductivity, stratified aquifer system which becomes increasingly confined with depth. Based on available data a majority of bores in the area screened in the Q2, Q4 and Q6 intervals are likely to exhibit transmissivity values in the range of 50 to 300 m^2/day, possibly reducing toward the coast. Aquifer transmissivity is also likely to be near or slightly below the bottom of this range in the Holocene (Q1) sand aquifer.

5.2.2 Groundwater levels

Figure 34 shows a plot of groundwater levels in the Holocene (Q1) sand aquifer between 2009 and 2010. This data indicate recharge to the shallow aquifer is largely event driven, with short-term increases in groundwater level following local rainfall events with the magnitude and timing of seasonal variation reflecting the overall decrease in the frequency and magnitude of rainfall recharge from late spring through to autumn resulting in a progressive decline in groundwater levels over this period.

Figure 35 shows a plot of groundwater levels recorded in 5 GWRC monitoring bores located on the Hautere Plain from 1993 to 2010.

[13] Results from the lower yielding bore were calculated from results of a single well test so reliability is uncertain, although the report notes an appreciable difference in yield between the two bores which is broadly consistent with the calculated transmissivity values

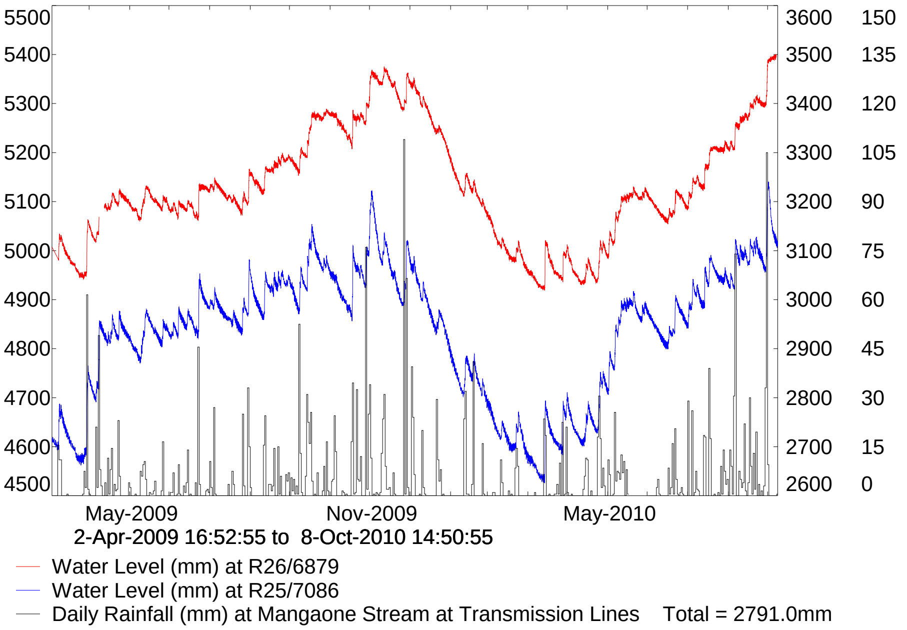


Figure 34: Groundwater levels in Holocene (Q1) sand aquifer, 2009 to 2010

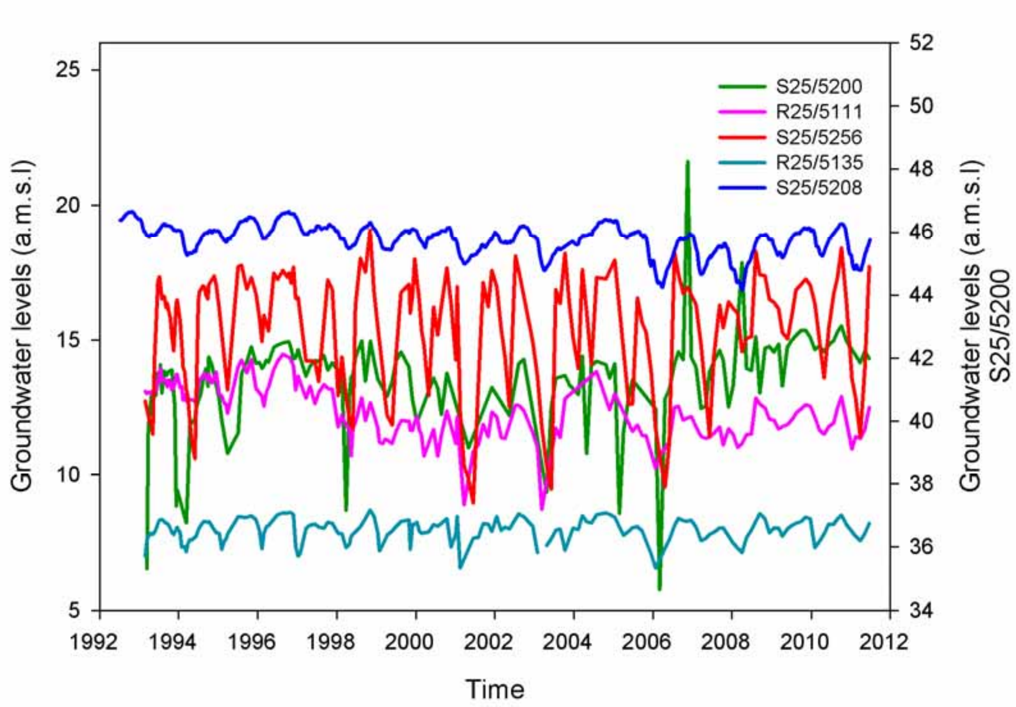


Figure 35: Groundwater levels on the Hautere Plain, 1993 to 2011

Well S25/5256, at 30 metre deep and located adjacent to SH1 toward the northern groundwater zone boundary, exhibits a large seasonal variation of up to 10 metres. The magnitude of this variation indicates significant flux through this water-bearing interval which is inferred to reflect a combination of:

- The significant contribution of recharge from rainfall and runoff from the Tararua foothills to the overall water balance of the Hautere Plain (given a majority of the area effectively has no surface drainage);

- The low to moderate hydraulic conductivity of this water-bearing layer (~150 to 250 m^2/day) which allows seasonal recharge to accumulate during the winter and spring and dissipate during the subsequent summer and autumn; and,

- The presence of a series of springs at the base of the Holocene marine terrace along Te Waka Road which provide an outlet for groundwater throughflow in the otherwise low to moderate hydraulic conductivity Q2 gravel and Q1 sand sediments

Water Levels in R25/5115, a 35 metre deep bore located approximately 2.5 kilometres south of Te Horo township exhibit a similar seasonal fluctuations and overall long-term trend to those observed in S25/5200, a 45 metre deep bore located along Te Horo Hautere Cross Road near the base of the foothills approximately 3 kilometres to the east. The similarity in water level variations suggests lateral continuity of water-bearing of the 40 to 60 metre water-bearing interval across the southern section of the Hautere Plain, with the appreciable head difference between the sites (~30 m) possibly reflecting the relatively low bulk hydraulic conductivity of the Q6 gravel deposits

The two deeper monitoring bores (R25/5135 ~85 metres and S25/5208 ~160 metres) exhibit a fluctuation consistent with rainfall recharge observed in shallower water-bearing layers. However, it is noted that while S25/5208 exhibits long-term variability similar to that observed in R25/5111 and S25/5200 (following long-term trends in rainfall variability), the shallower R25/5135 shows little or no long-term variation. Similarly, the significant difference in relative groundwater levels between R25/5135 and S25/5208 (~10 metres for bores 1,200 meters apart) suggests a degree of hydraulic separation between the respective water-bearing intervals;

Overall, water level data from the Hautere Plain area exhibit a pattern of seasonal and long-term variation consistent with rainfall recharge being the primary recharge mechanism. Comparison of temporal and spatial ground water levels indicates a stratified aquifer system with differing groundwater level response in individual, laterally continuous water-bearing layers which exhibit some degree of hydraulic connection.

Figure 36 shows a comparison in the groundwater levels recorded in S25/5208 on the Hautere Plain with those recorded in R25/5003, a 60 metre deep bore situated on Sims Road near Te Horo Beach. Both sites exhibit similar seasonal water level variations with the reduced magnitude of seasonal and temporal variation observed in R25/5003 possibly reflecting the location of this bore near the coastal margin which moderates overall variability. A similar relationship is observed between groundwater level in R25/5262 (a 90 metre bore located approximately 1 kilometre from the coast along Te Hapau Road) and deep bores located on the Hautere Plain and at Te Horo Beach.

While temporal water level variations observed in deeper water-bearing layers suggest a common recharge mechanism driven largely by seasonal rainfall recharge, relative groundwater levels indicate a degree of hydraulic connectivity between individual water-bearing layers. For example, groundwater levels recorded in the Sims Road observation bores indicate a 2 to 3 metre positive hydraulic gradient between water-bearing intervals intercepted at 160 and 60 metres below ground respectively at this site.

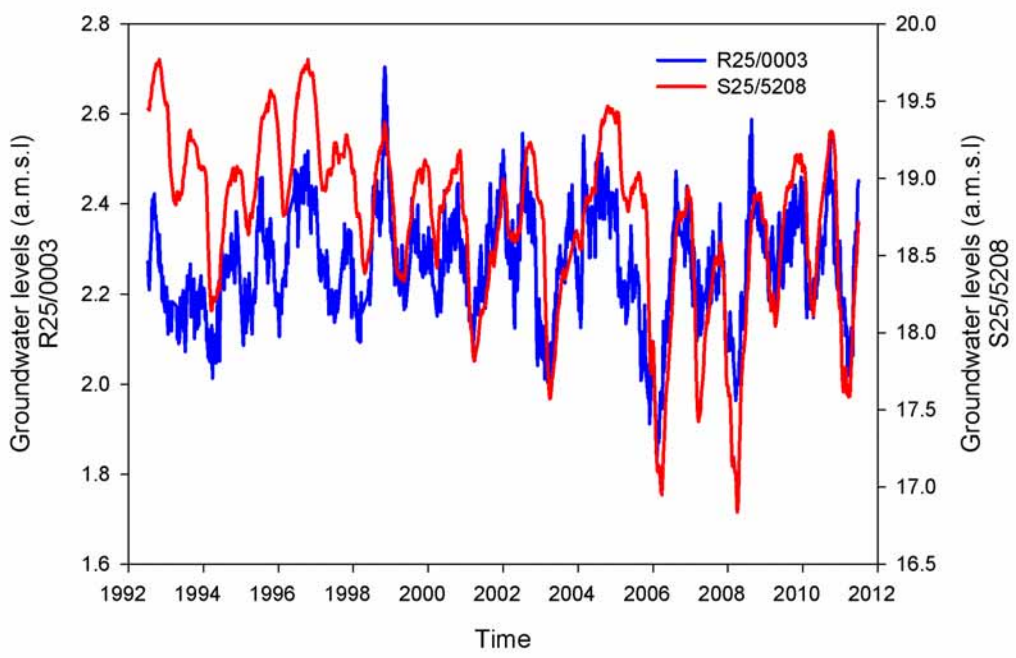


Figure 36: Groundwater levels recorded in S25/5208 (~160 m) on the Hautere Plain and R25/5003 (~60 m) at Te Horo Beach, 1992 to 2011

Piezometric survey data presented by Kampman and Caldwell (1985) indicate a relatively steep hydraulic gradient of the order of 0.007 across the Hautere Plain with groundwater flow in a predominantly north-west direction following the overall topographic gradient. West of the Holocene marine terrace, the hydraulic gradient reduces to approximately 0.0025 with groundwater flow in a north north-westerly direction perpendicular to the coast. The break in the slope of the piezometric surface is interpreted to reflect a combination of spring discharge along the base of the marine terrace and the reduction in aquifer hydraulic conductivity between the Q2 alluvium and Q1 sand deposits.

The available piezometric survey data also show a marked hydraulic divide (at least in shallow bores ~<40 metre deep) between the Hautere Plain and the Otaki River valley. The data also show the hydraulic gradient steepens appreciably as the coastal plain narrows south of the Te Horo township. This increased gradient may act to promote recharge to the groundwater system via the alluvial fan materials deposited along the western margin of the Tararua foothills.

5.2.3 Groundwater-surface water interaction

The Mangaone Stream traverses the Te Horo groundwater zone from headwaters in the Tararua foothills across the Hautere Plain to the coast at Te Horo Beach.

Figure 37 shows concurrent gauging results from the section of Mangaone Stream which crosses the Hautere Plain (essentially upstream of SH1). These data indicate a relatively consistent pattern of downstream flow loss suggesting progressive infiltration of water from the stream bed into the surrounding unconfined aquifer. Given available static water level data indicate that the water table occurs between 8 to 10 metres below ground in the area between Arcus Road and SH1 (no data is available from areas further upstream), it is likely that this section of Mangaone Stream is perched and not in direct hydraulic connection with the underlying aquifer. As a consequence, the rate of flow loss from the Mangaone Stream is unlikely to be influenced by variations in the underlying water table depth.

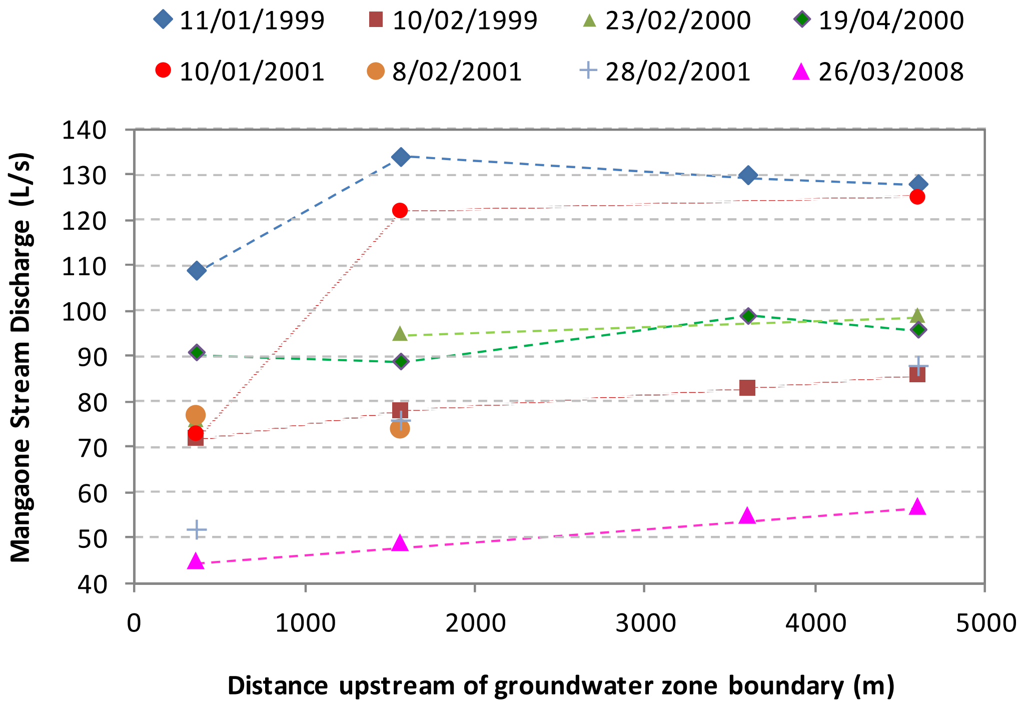


Figure 37: Concurrent gaugings from Mangaone Stream on the Hautere Plain

Figure 38 illustrates the observed correlation between Mangaone Stream flow at Mangaone Road and SH1. Assuming a median discharge of approximately 200 L/s at the GWRC Mangaone Stream at Ratanui flow site, the observed relationship suggests a flow loss of approximately 50 L/s (4,320 m^3/day) from the Mangaone Stream to the underlying Q2 aquifer.

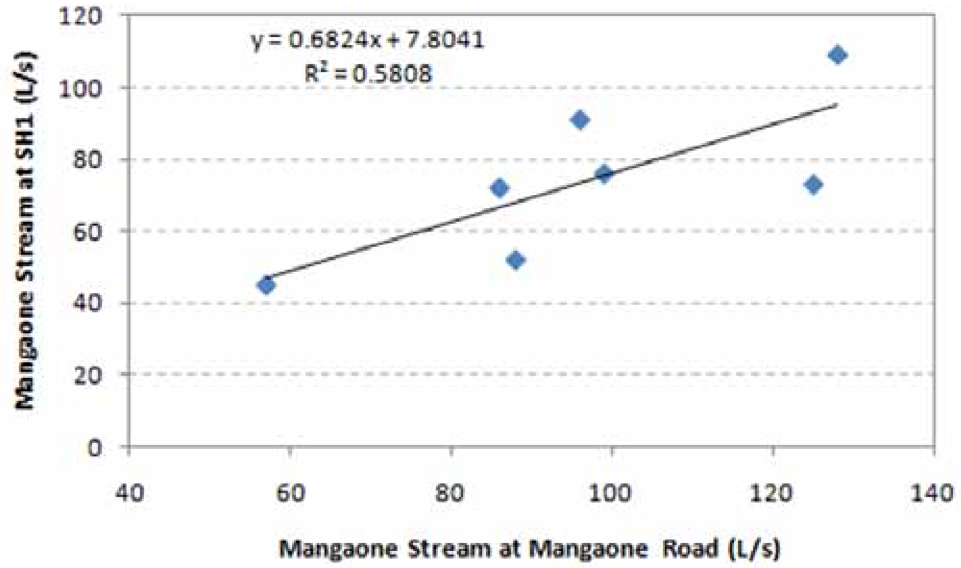


Figure 38: Correlation between flow in Mangaone Stream at Mangaone Road and SH1

Figure 39 shows the results of concurrent gauging undertaken in the lower reaches of the Mangaone Stream downstream of the Holocene marine terrace. The data from this reach show a consistent pattern of flow gain of between 100 to 250 L/s between SH1 and the coast. This flow gain is interpreted to reflect both direct groundwater seepage into the Mangaone Stream as well as drainage of groundwater from the shallow sand aquifer via the network of artificial drains which cover a significant percentage of the Coastal groundwater zone, particularly in the area to the north of Te Hapua Road. Discharge to this drainage network includes flow from a series of contact springs which occur at the base of the Holocene marine terrace.

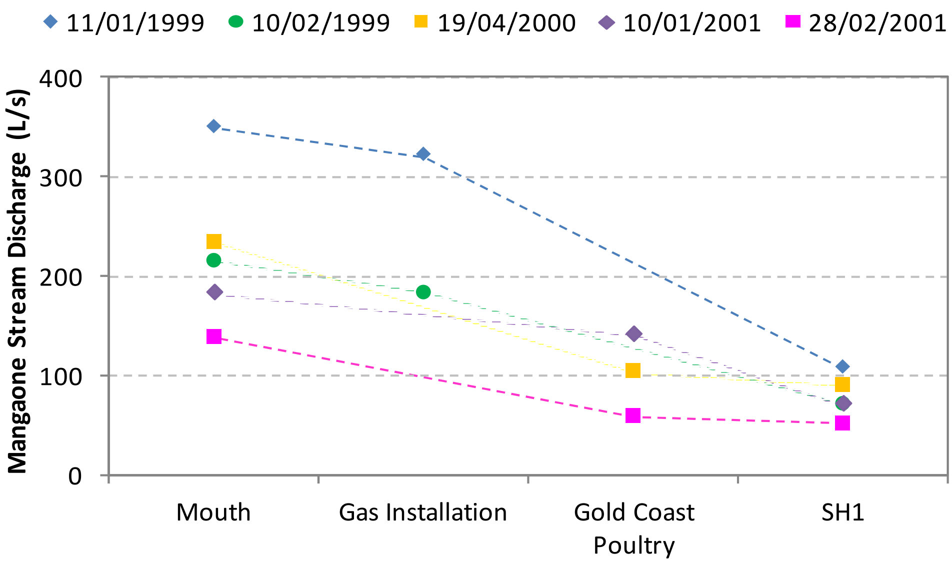


Figure 39: Concurrent gauging results from Mangaone Stream downstream of SH1

Allen (2010) investigated the hydrological characteristics of the Te Hapua wetland. Results of the study indicated the presence of two distinct wetland classes in the Te Hapua complex; fens were predominant in the area of larger dunes to toward the eastern margin while swamps were more prevalent toward the coastal margin. The study described the complex interaction between wetlands and the surrounding unconfined aquifer system and identified groundwater inflows/outflows as a key component of the water balance across the entire wetland complex. Both local and aquifer-scale groundwater abstraction was identified as having the potential to impact on the hydrology and overall ecology of wetland areas with the need for sufficiently detailed information to characterise potential impacts (including vertical leakage in response to pumping) identified as a priority to support future groundwater abstraction.

5.3 Summary

Overall, data indicate the Te Horo groundwater zone comprises a thick sequence of alluvial materials accumulated on the alluvial fan formed by the ancestral Otaki River during late Quaternary Period. The stratigraphic succession comprises at least three (possibly more at depth) units which represent active erosion and deposition during successive glacial and interglacial cycles. These materials host an extensive groundwater resource which comprises laterally extensive water-bearing layers (generally comprising moderately to well sorted gravels) separated by intervening layers of low hydraulic conductivity materials (fine sand, silt, and poorly sorted gravels) to form a stratified aquifer system which becomes increasingly confined with depth.

Table 7 provides a summary of the physical characteristics and spatial distribution of hydrostratigraphic units identified in the Te Horo groundwater zone based on a review of available geological, hydrogeological and groundwater level information.

Table 7: Summary of the physical characteristics and spatial extent of hydrostratigraphic units in the Te Horo groundwater zone

Hydrostratigraphic Unit	Description	Spatial/depth distribution
Holocene (Q1) Sand	• Medium to fine sand with discontinuous layers (lenses) of gravel and silt/peat. • Relatively low bulk hydraulic conductivity (~2-5 m/day) but may contain higher hydraulic conductivity materials in discrete gravel layers • Hosts a shallow unconfined aquifer system primarily recharged by local rainfall	• Occurs to the west of the prominent postglacial marine terrace which runs sub-parallel with SH1 • Forms a wedge shaped deposit increasing in thickness from around 20 metres inland to up to 35 metres near the coast
Q2 Gravel	• Poorly sorted alluvial gravel with varying amounts of silt and sand • Forms a stratified aquifer with layers of better sorted gravels forming the primary water-bearing intervals (K~10 - 20 m/day). Intervening silty	• Forms surface of Hautere Plan and continues westward under Holocene sand deposits past the present-day coastline. • Recorded between 35 and 90 metres in Te Horo test bore

Hydrostratigraphic Unit	Description	Spatial/depth distribution
	sandy gravels restrict vertical hydraulic conductivity resulting in progressive confinement at depth	• Correlated with alluvial materials extending from the ground surface to between 30 to 50 metres bgl across the Hautere Plain
Q5 Sand (Otaki Formation)	• Relatively well sorted medium to fine sand with silt and organic material. Correlated with layer of fine, organic-rich sediment observed across the Hautere Plain • Likely to form a laterally continuous relatively low hydraulic conductivity (K = 1-10 m/day) Aquitard in places.	• Recorded between 90-107 metres in Sims Road investigation bore • Surface exposure along base of Tararua foothills on eastern side of Hautere Plain • Strata dip westward following profile of Otaki fan but may be warped/uplifted toward eastern margin of Hautere Plain. Also inferred to dip to the south following the general ~2-4^{o} tilt of the South Wanganui Basin
Q6 and older gravel and sand	• Assigned to all alluvial materials interpreted to be Q6 (Waimean Stage - penultimate glacial) and older • Poorly sorted, weathered gravel in a silty, sandy matrix • Hosts a low yielding semi-confined to confined aquifer system • Typically low hydraulic conductivity (0K~5 to 20 m/day) and may become increasingly cemented at depth	• Recorded below 107 metres in Sims Road Investigation bore • Surface exposure of Q6 materials along base of Tararua foothills on eastern side of Hautere Plain • Strata dip westward following profile of Otaki fan but may be warped/uplifted toward eastern margin of Hautere Plain. Also inferred to the south following the general ~2-4^{o} tilt of the South Wanganui Basin
Alluvial fan materials	• Poorly sorted gravel, sand and silt locally deposited on footslopes of Tararua foothills • Likely to exhibit moderate to low hydraulic conductivity (k~2-10 m/day) but may contain better sorted, relatively permeable gravel layers	• Restricted to relatively narrow strip along western margin of the Tararua foothills
Greywacke basement	• Well indurated siltstone and mudstone • May contain secondary hydraulic conductivity in joints and fractures but essentially considered to form the groundwater basement	• Forms Tararua foothills to east of Te Horo groundwater zone • Bore logs suggest a basement 'step' along foothills margin 50 to 60 m blg • Intercepted at ~190 metres in central area of Hautere Plain

Hydrostratigraphic Unit	Description	Spatial/depth distribution
		• Residual gravity anomalies (Ewig, 2009) suggest a greywacke 'ridge' recorded in the Waikanae area may extend northward under the eastern margin of the Hautere Plain.

Water level information indicate infiltration of rainfall and runoff from the Tararua foothills is the primary source of recharge in the Te Horo groundwater zone. Streamflow gaugings also indicate a flow loss of approximately 50 L/s from the Mangaone Stream to the unconfined aquifer as it crosses the Hautere Plain. Downstream of the Holocene marine terrace the Mangaone Stream gains between 150 to 200 L/s from the surrounding Holocene (Q1) sand aquifer. This includes baseflow to the Mangaone Stream itself as well as discharge via a series of springs at the base of the marine terrace along Te Waka Road into an extensive artificial drainage network on the coastal plain. An unknown component of groundwater throughflow is discharged offshore.

Table 8 provides a brief summary of the key components of the overall water balance for the Te Horo groundwater zone.

Table 8: Summary of key components of the water balance of the Te Horo groundwater zone

Component	Description	Net Flux
Rainfall	Infiltration of rainfall on coastal plain	Not determined. Lack of surface runoff from Hautere Plain suggests soil moisture infiltration is a major component of overall water balance.
Sideslope infiltration	Infiltration of runoff on alluvial fans along the western margin of the Tararua foothills	Not determined but may be significant given limited surface drainage from a majority of small catchments Recharge augmented by vertical gradient developed upslope on alluvial fans
River recharge	Mangaone Stream	Flow loss of ~50 L/s across the Hautere Plan
Baseflow/spring discharge	Mangaone Stream	Springs at base of postglacial marine terrace may act as constant head for upper (20 to 30 metre) water-bearing interval on the Hautere Plain Baseflow discharge of ~150 to 250 L/s into Mangaone Stream belowmarine terrace (include discharge from drains across the Holocene sand)

Component	Description	Net Flux
Wetland areas	Losses due to evapotranspiration and direct evaporation	Not determined. Large, regionally significant wetland complex in Te Hapua area. Likely to be a relatively minor component of overall aquifer water balance
Offshore discharge	Discharge offshore	Not determined but may comprise a significant component of overall water balance based on available piezometric data

Figure 40 shows a schematic illustration of the conceptual hydrogeological model for the Te Horo groundwater zone.

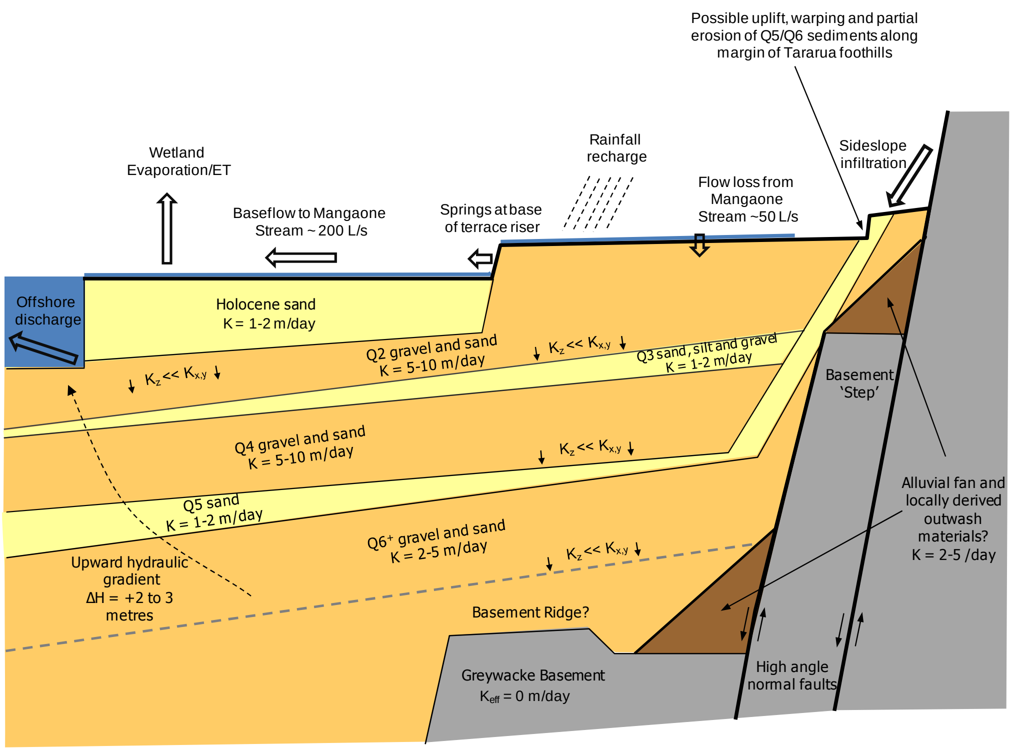


Figure 40: Conceptual hydrogeological model of the Te Horo groundwater zone

6. Otaki groundwater zone

The Otaki groundwater zone extends across the coastal plain from the southern margin of the Otaki River valley to the northern boundary of the Wellington Region. The new zone combines the previous Otaki and Waitohu groundwater zones.

The southern boundary of the Otaki groundwater zone follows the prominent river terrace to the east of Highway 1 that forms a hydraulic divide between the Q2 gravels of the Hautere Plain and the Q1 alluvium of the Otaki River floodplain. To the west of Highway 1 this boundary become less well defined, particularly near the coast where it is partially obscured by Holocene sand deposits. The eastern boundary traces the approximate contact between the Q5 and Q6 alluvial terraces (and associated alluvial fans) and the greywacke bedrock of the Tararua foothills.

Figure 41 shows the spatial extent of the Otaki groundwater zone including primary surface water features (streams and wetlands), groundwater level and concurrent flow gauging sites along with the location of bores recorded on the GWRC Wells database.

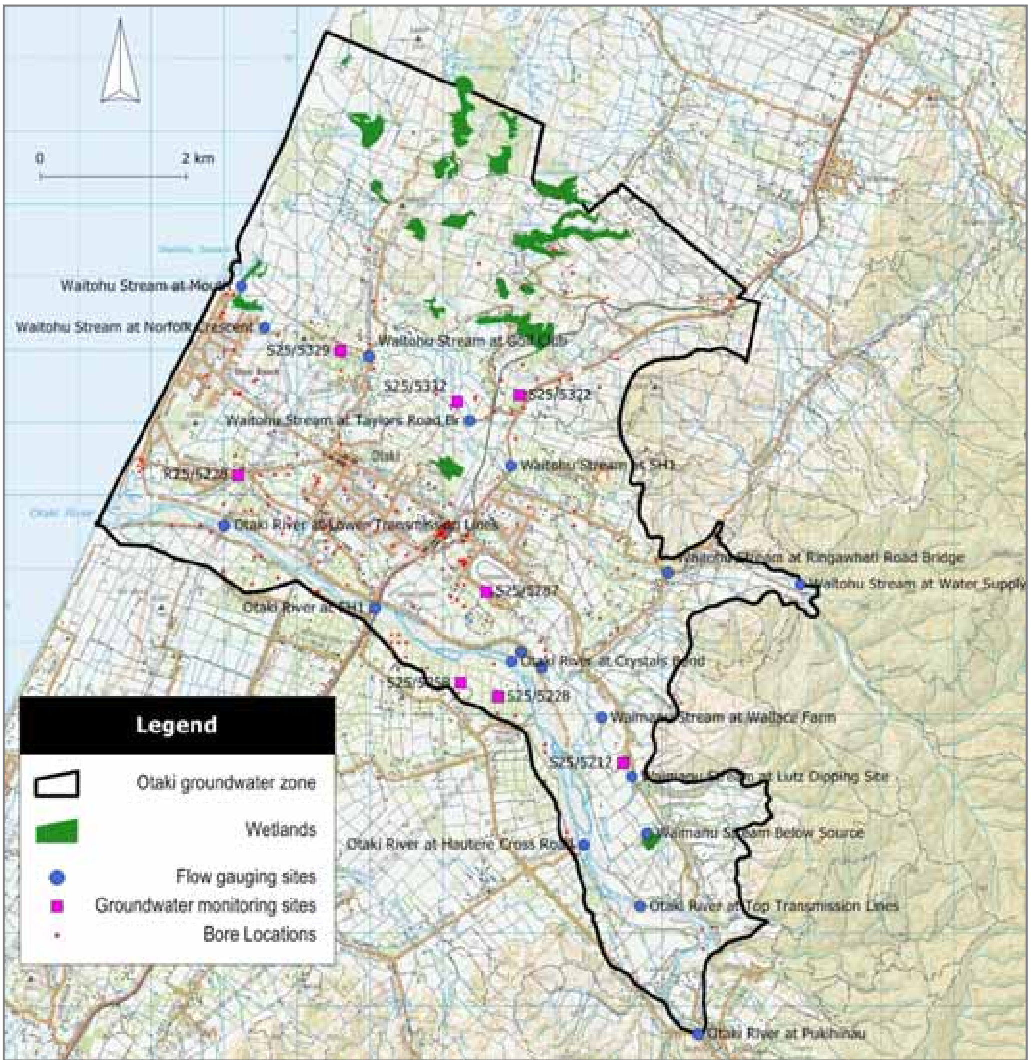


Figure 41: Otaki groundwater zone

6.1 Otaki zone geology

The subsurface geology of the Otaki groundwater zone comprises a thick sequence of late Quaternary glacial and interglacial deposits similar to that observed in the Te Horo and Waikanae groundwater zones to the south. The main distinction from the geological environment observed elsewhere on the coastal plain being the extent of postglacial river entrenchment along the Otaki River and Waitohu Stream, and the relatively extensive surface exposure of older Q5 sand deposits (termed the Otaki Formation) across the northern section of the Otaki groundwater zone as a result of the regional tilt of sediments infilling the South Wanganui Basin.

Figure 42 shows a simplified geological map of the Otaki groundwater zone. The map shows the extensive deposits of Holocene (Q1) sand along the coastal margin, the extent of postglacial river entrenchment and deposition of reworked Q1 alluvium along the Otaki River and Waitohu Stream as well as the extensive late Quaternary alluvial terrace remnants (Q2, Q5 and Q6) which extend out from the Tararua foothills along the margins of the main stream channels. Deposits of these alluvial materials sequentially underlie the Q1 sand and alluvial deposits toward the coastal margin.

North of the Waitohu Stream, Holocene (Q1) sand deposits extend approximately 3.5 kilometres inland from the present-day coastline indicating the extent of coastal progradation since sea levels stabilised in the Holocene thermal optimum approximately 6,500 ka. These deposits largely consist of fine sand with occasional gravel and organic layers reflecting shallow marine and aeolian deposition along the coastal margin. These deposits extend to a depth of between 20 to 40 metres below ground, possibly increasing in thickness to the north. Limited geological information is available from bores deeper than 40 metres in this area so the underlying sediments are inferred to comprise fine, partially cemented Q5 sand and moderately to poorly sorted silt-bound Q6 gravels.

Inland of the Holocene sand, surface exposure of Q5 deposits form a broad terrace which is extensively dissected along local rivers and streams. This terrace forms the southern extent of the Tokomaru marine surface which extends along the margin of the Tararua foothills across much of the southern Horowhenua District. Well logs in this area indicate a sequence of dense/cemented fine to medium sand with intermittent gravel up to 40 metres thick which are separated from an underlying sequence of silty, sandy gravels (interpreted as Q6) by a layer of fine-grained peat and organic materials. Further south, along the northern margin of the Waitohu Stream, coarse Q2 alluvium approximately 30 to 40 metres thick overlies a thin layer of dense/cemented sand (Q5) and underlying silty sand and gravel (Q6). In the Reikorangi area bore logs on the Q6 terrace surface indicate a heterogeneous sequence of highly weathered clay (silt), sand and gravel extending to a depth of at least 80 metres below ground. It is uncertain if this represents the thickness of the Q6 deposits in this area or whether the bore penetrates older Q7/Q8 deposits at depth.

Within the Otaki River valley, the active floodplain is covered by a thin (~10 metre) layer of coarse-grained Q1 alluvium which appears to thin toward the northern margin. West of Otaki township the Q1 alluvium associated with the Otaki River merges with similar deposits from the Waitohu Stream. The Q1 gravels are underlain by a sequence of Q2 and Q4 gravel and sand extending to a depth of approximately 25 to 35 metres[14]. In turn, the few deeper bore logs in this area indicate a sequence of fine sand and silt containing layers of gravel and organics extending to a depth of at least 80 metres. On the basis of the available data the boundary between the Q5 and Q6 deposits is tentatively assumed to occur at a depth of approximately between 40 to 50 metres, deepening both to the south and west following both the profile of the Otaki fan (approximate 1^{o} dip to the north-west) and regional dip of ~2 to 4^{o} to the south.

[14] Note the Q3 deposits recorded in the Te Horo groundwater zone appear to pinch out to the north in the vicinity of the Otaki River and it is difficult to distinguish Q2 and Q4 on the basis of available drillers logs

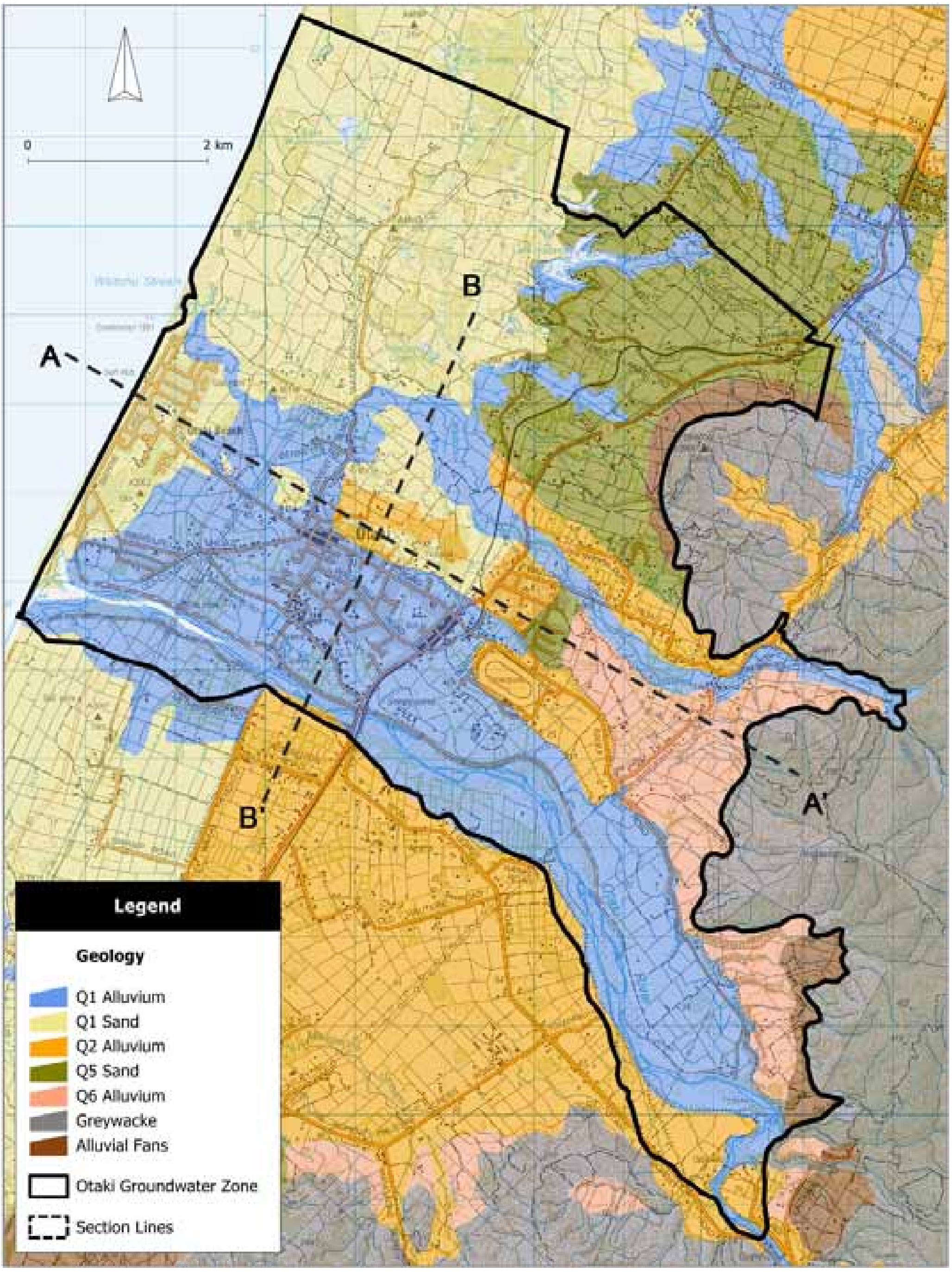


Figure 42: Simplified geology of the Otaki groundwater zone (based on GNS Wellington QMap coverage). Note: The map also shows the indicative location of the schematic cross sections illustrated in Figure x and Figure Y

Limited information is available to identify the possible basement structure underlying the coastal plain in the Otaki groundwater zone. Well S25/5305, located along the northern margin of Waitohu Stream intercepted basement at a depth of approximately 127 metres, suggesting the possibility of a basement 'step' along the margin of the foothills similar to that observed elsewhere on the Kapiti Coast. Such a feature could reflect displacement along normal faults at the base of the foothills or alternatively a marine platform eroded during a late Quaternary sea level transgression.

Bekesi (1996) identified the influence of a basement ridge associated with movement on the Levin fault on groundwater flow under the coastal plain as contributing to the formation of the numerous dune lakes seen in the southern Horowhenua District. No information is available to characterise basement geometry underlying the coastal plain in the Otaki groundwater zone, however the presence of multiple dune lakes in the Forest Lakes area (including Lake Waitawa, Lake Kopureherehere and Ngatotara Lagoon) may indicate a similar influence associated with basement geometry across the northern section of the Otaki groundwater zone.

6.2 Otaki zone hydrogeology

In the Otaki groundwater zone, Q1 alluvium associated with the Otaki River and Waitohu Stream host highly permeable unconfined aquifers which merge in the area west of Otaki township. This aquifer system is hydraulically connected to surface water with significant flow loss and baseflow discharge observed in alternating reaches of both the Waitohu and Otaki catchments. This aquifer system is highly permeable and is extensively utilised for domestic and irrigation water supplies, particularly along the southern boundary where a number of high yielding bores along the riparian margin of the Otaki River are utilised to supply water for reticulation on the Hautere Plain where groundwater availability is more restricted.

In the Otaki River valley an unconfined/semi-confined aquifer system occurs in a sequence of coarse, highly permeable gravel and sand within the Q2 alluvial deposits between 20 to 35 metres below ground in the area to the west of SH1. The aquifer system is extensively utilised for municipal and irrigation water supply. Given the relatively low hydraulic conductivity values observed in Q2 deposits elsewhere on the Kapiti Coast, the high values exhibited in this aquifer system are interpreted to possibly reflect reworking of the poorly sorted, silt-rich Q2 gravel materials along the thalweg of the Otaki possibly during an interstadial period in the late stages of the Otiran glaciation. The spatial extent of this aquifer system is not particularly well defined but extends west of SH1 toward the coast and between the current Otaki River at least as far north as the Waitohu Stream.

Elsewhere in the Otaki groundwater zone, groundwater is found extensively throughout the Holocene (Q1) sand deposits along the coastal margin and in older (Q5 and Q6) alluvial deposits. However, due to the relatively fine-grained nature of these deposits well yields are relatively low except in isolated, coarser gravel layers within the Q5/Q6 deposits in the Pukehou area.

6.2.1 Hydraulic properties

In the unconfined (Q1) aquifer adjacent to the Otaki River, WRC (1994) reported aquifer transmissivity values in excess of 30,000 m^2/day in shallow river gravels with a median value of 4,500 m^2/day. Woodward Clyde (1997) estimated transmissivity values of between 2,500 and 5,700 m^2/day in shallow (Q1) alluvial gravels along the southern margin of the Otaki groundwater zone near Leithbridge Road. Results of aquifer testing undertaken during installation of a shallow monitoring bore near the Waitohu Stream (S25/5332) exhibited a transmissivity value in the Q1 gravels in the range of 4,000 to 5,000 m^2/day (Hughes 1995b).

In the unconfined/semi-confined (Q2) aquifer in the lower section of the Otaki and Waitohu catchments, analysis of aquifer tests conducted on the KCDC Tasman Road bores indicate transmissivity values in excess of 20,000 m^2/day (Becca Steven, 1996), with a specific yield of around 0.25. These results suggest highly permeable unconfined conditions extend to at least 30 metres below ground to the west of Otaki township. It is also noted that a relatively direct hydraulic connection to the Otaki River is was indicated by the rapid groundwater level response to stage changes in the Otaki River observed during an aquifer test undertaken on a 35 metre deep bore at the KCDC Rangiuru Road site (Manawatu Catchment Board, 1988). Further north, aquifer testing undertaken on a 20 metre deep bore at the Otaki Golf Club indicated a moderate to high transmissivity of 2,750 m^2/day.

In the Q1 sand deposits, aquifer tests undertaken at S25/5404 and S25/5414 reflect the low hydraulic conductivity of these materials with calculated transmissivity values of 8 and 11 m^2/day respectively.

Limited aquifer test data is available for bores screened in the Q5 or Q6 alluvial deposits. Hughes (1995a) reported results from a basic aquifer test undertaken from a 27 metre deep bore screened in the Q5 sand aquifer north of Waitohu Stream which indicated semi-confined conditions with an estimated aquifer transmissivity of 350 m^2/day. In bores inferred to be screened in Q6 alluvium, WRC (1994) reported an aquifer test undertaken on a 61 metre deep bore (Q6) in the Pukehou area which indicated a transmissivity of 144 m^2/day and storage co-efficient of 6×10^{-5}. Results from a nearby bore screened between 50 and 60 metres below ground yielded a transmissivity value of 200 m^2/day and a storage co-efficient of 1.2×10^{-4} (Butcher, 1995). It is noted that this latter test showed a departure from ‘ideal’ confined conditions suggesting vertical leakage from overlying water-bearing layers in response to pumping.

Overall, although limited in number, available aquifer test data from the Otaki groundwater zone indicate a significant (up to two orders of magnitude) difference between the highly permeable Q1 alluvium and reworked Q2 gravels underlying the Otaki River floodplain, and the relatively low hydraulic conductivity’s observed in the Q1 sand and late Quaternary (Q5/Q6) alluvial deposits. Table 9 provides a summary of representative hydraulic properties for hydrostratigraphic units in the Otaki groundwater zone.

Table 9: Representative hydraulic properties for hydrostratigraphic units in the Otaki groundwater zone

Unit	T m2/day	K m/day	S	Geological Description
Q1 sand	10	~1	0.2	Fine to medium sand and silt with occasional gravels and peat layers
Q1 Alluvium	4,500	~250 - 500	0.2	Coarse sand and gravel
Q2 Alluvium	5,000 250	~250 - 500 5 - 20	? - 0.25 0.1	Coarse sand and gravel Claybound gravel and sand
Q5 Sand	350	1 - 10	0.0001	Fine sand and silt containing occasional waters of weathered gravel and organics
Q6 Alluvium	200	1 - 10	0.0001	Weathered gravels containing a high percentage of silt and sand

6.2.2 Groundwater/surface water interaction

The Waitohu Stream drains a relatively small catchment in the foothills east of Otaki. Due to the relatively short, steep nature of the catchment, flows in this stream tend to respond rapidly to rainfall events and recede relatively quickly. Reflecting the high degree of hydraulic connection with the surrounding Q1 aquifer, the middle reaches of the Waitohu Stream in the vicinity of SH1 are commonly observed to dry up during extended periods of low rainfall (WRC, 1994).

Figure 43 illustrates the spatial variation in discharge observed in concurrent gaugings undertaken on the Waitohu Stream. These data indicate a consistent pattern of flow loss between Ringawhati Road and the Golf Club during low flow conditions, with appreciable flow gain (interpreted to reflect baseflow discharge to the Waitohu Stream and a surrounding network of artificial drains) across the lower reaches between the Golf Club and the coast.

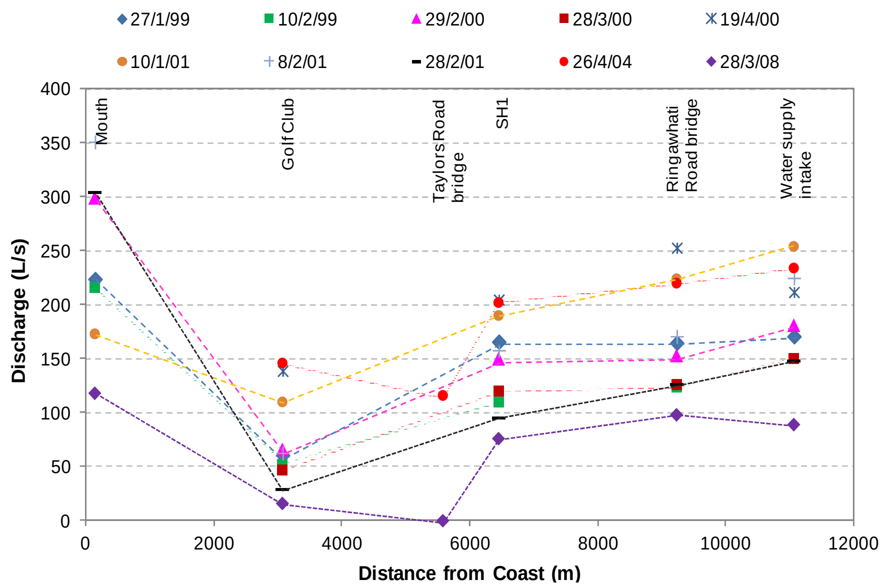


Figure 43: Concurrent gauging results from the Waitohu Stream

Figure 44 shows the observed correlation between measured flows at Rangawhati Road Bridge and the Otaki Golf Course. Based on a median flow of approximately 450 L/s at the GWRC Waitohu Stream at Water Supply Intake flow recorder site, the observed relationship suggests a loss of approximately 80 L/s (7,000 m^3/day) across this reach when discharge is at the 7-day MALF of 143 L/s at the Waikanae River at Water Treatment Plant site. This is consistent with previous estimates of flow loss from the Waitohu Stream to the surrounding riparian aquifer of between 60 to 80 L/s reported by WRC (1994). The slope of the regression (~1.05) indicates that flow losses from the Waitohu Stream increase only marginally during periods of higher flow but overall are likely to be of sufficient magnitude to make a major contribution to the overall water balance to the Q1 gravels surrounding the Waitohu Stream.

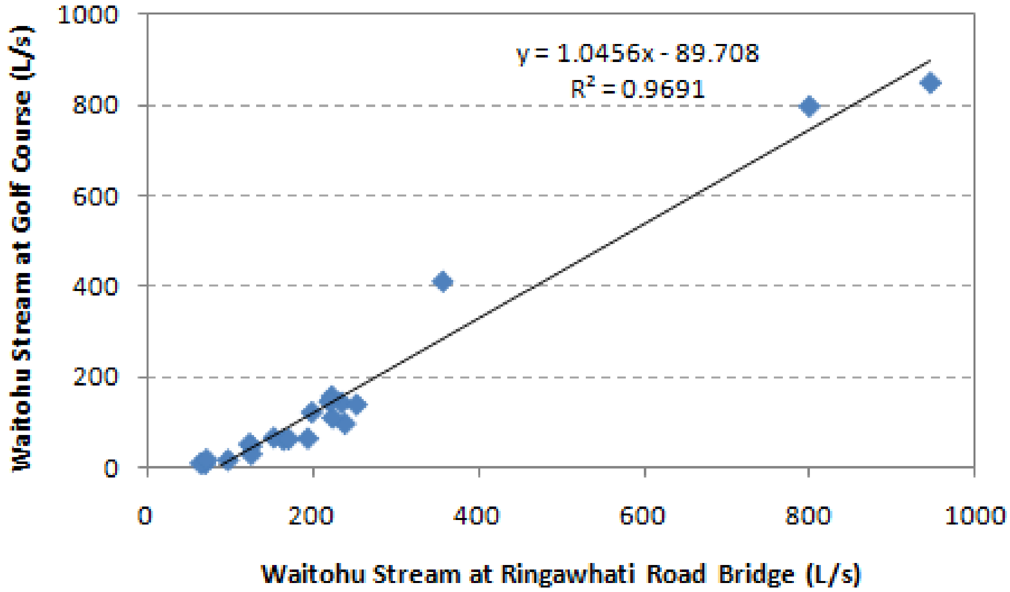


Figure 44: Correlation between discharge in the Waitohu Stream at Ringawhati Road Bridge and the Otaki Golf Course

Concurrent gauging runs in the Otaki River (Figure 45) consistently show a significant flow loss between Pukehinau and the Crystals Bend gauging site (located approximately 2 kilometres upstream of SH1). The observed flow loss over this reach is typically of the order of 1,200 to 2,000L/s (~100,000 to 170,000 m^3/day).

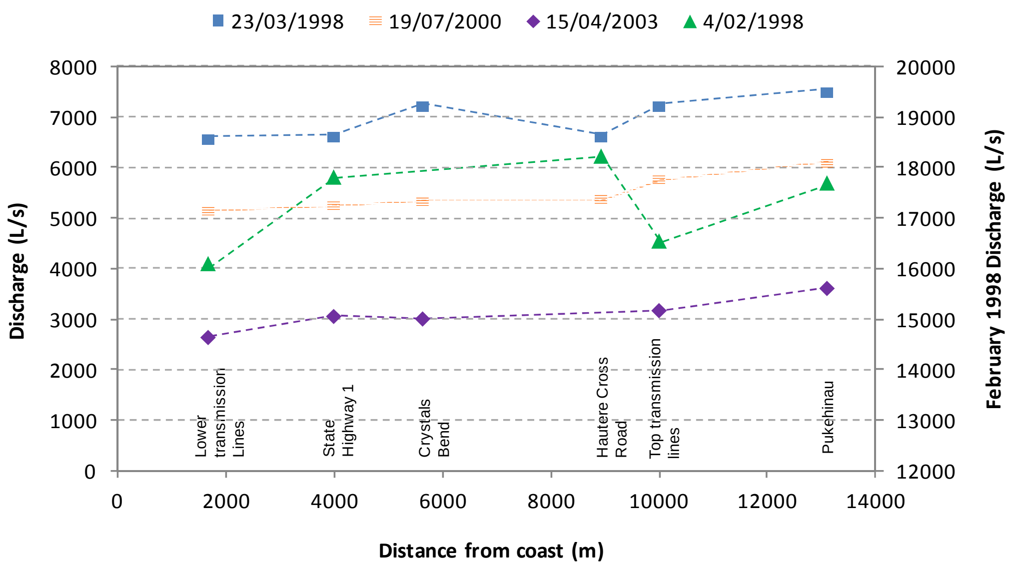


Figure 45: Concurrent gauging results from the Otaki River

A correlation between measured flows in the Otaki River at the Pukehinau and Lower Transmission Lines site (Figure 46) indicates an estimated flow loss over this reach ranges of approximately 1.6 m^3/sec (140,000 m^3/day) at median flow (16.4 m^3/s at the GWRC Otaki River at Pukehinau recorder site) to approximately 700 L/s (60,000 m^3/day) at MALF (3.9 m^3/s). It is noted that this volume of groundwater recharge is appreciably higher than the estimate of 10,500 m^3/day adopted by WRC (1994) and likely reflects a significant degree of interconnection between groundwater and surface water across the Otaki groundwater zone.

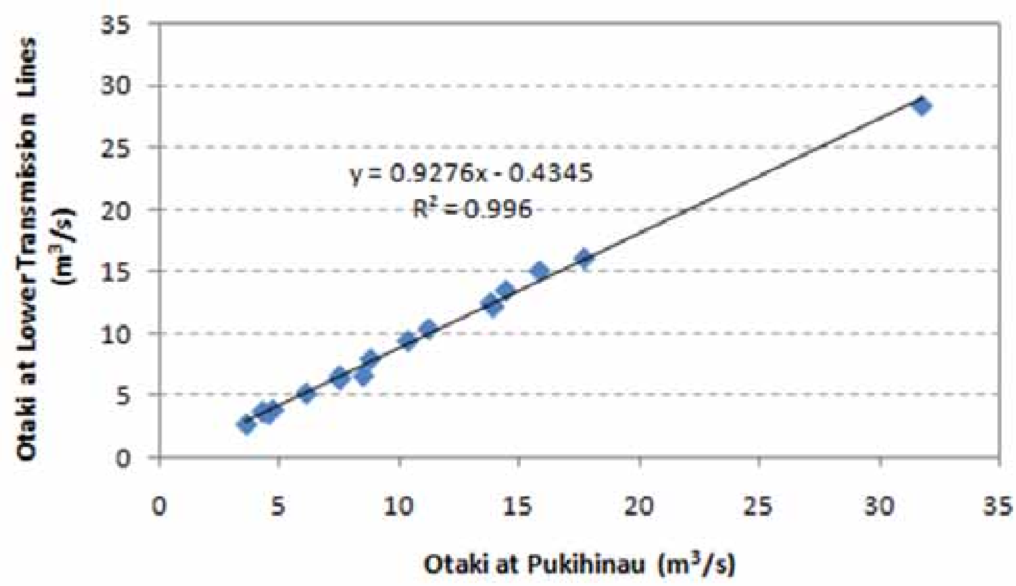


Figure 46: Correlation between measured flows in the Otaki River at Pukehinau and Lower Transmission Lines

The Waimanu Stream originates from a series of springs on the true right bank of the Otaki River approximately 5 kilometres upstream of Highway1 (Figure 44). The stream also drains a section of the higher alluvial (Q6) terrace to the north of the Otaki Valley, although flow from this area is very limited during the summer months. Concurrent gauging results indicate a relatively constant flow of about 170 L/s in the headwater springs suggesting a significant baseflow component. Spatial variations in flow down the Waimanu catchment are relatively difficult to interpret due to the effects of local abstraction (surface and groundwater) during the summer months and increased runoff from the alluvial terrace area during autumn and winter. The data suggest a relatively modest flow gain (~10 percent or within gauging error) over the 4 kilometre reach between the headwater springs and the Otaki River confluence indicating that most groundwater/surface water interaction occurs in upper reaches of Waimanu Stream.

Limited gauging data provide a median summer discharge of approximately 275 L/s in Rangiuru Stream at Rangiuru Road. Given the nature of the contributing catchment, this discharge is inferred to largely comprise drainage of groundwater from the shallow Q1 gravels behind the lower hydraulic conductivity sand deposits along the present-day coastal margin.

Insufficient data is available to quantify the hydrology of the interdunal lakes and wetlands in the northern part of the Otaki groundwater zone. Data is limited to water level records from Lake Waitawa collected by the Manawatu Catchment Board between 1975 and 1980. An analysis of this data in WRC (1995) suggested that although long term water level variations in the lake could be partially accounted for by rainfall variation, there was some evidence that nearby groundwater abstractions also affect lake levels.

6.2.3 Groundwater levels

Groundwater levels in the shallow Q1 gravels in the Otaki groundwater zone show a clear reaction to variations in Otaki River stage (Figure 47) showing there to be a high degree of hydraulic connection between the river and the unconfined aquifer along the riparian margin.

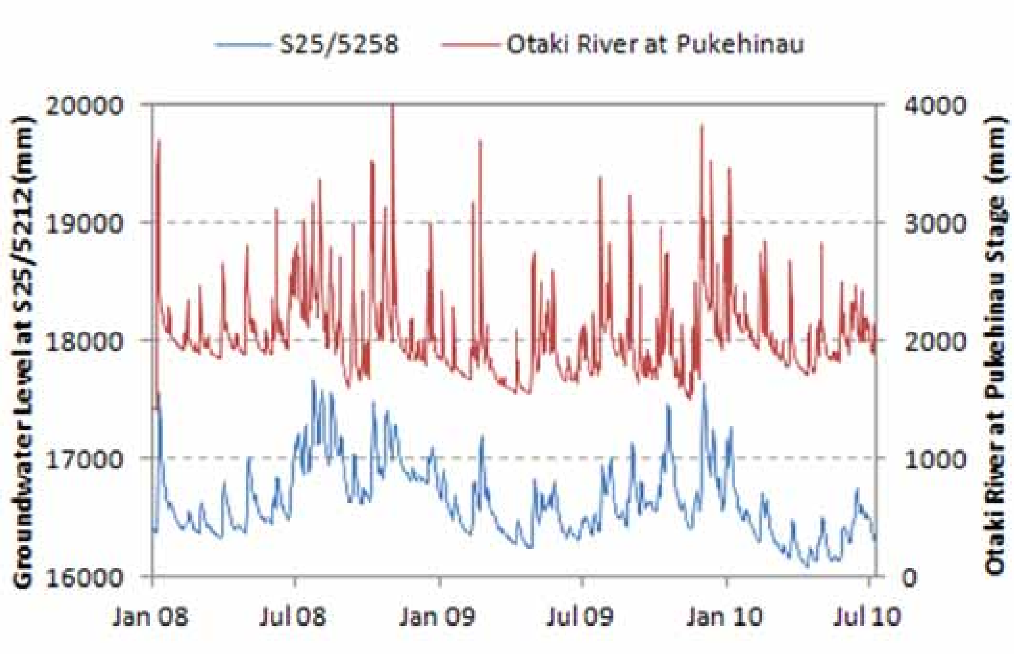


Figure 47: Plot of Otaki River at Pukehinau stage height and groundwater levels at S25/5212

A similar relationship with river stage is observed in the Q1 alluvium adjacent to the Waitohu Stream. Figure 48 demonstrates the high hydraulic conductivity characteristics of the alluvial materials and high degree of hydraulic connectivity with the stream. There is a small time lag between variations in stream stage and the groundwater levels response (approximately 4 to 6 hours).

Figure 49 shows a plot of groundwater levels recorded in the Otaki groundwater zone over the period 1993 to 2011. The data show relatively minor (~<0.5 metre), if somewhat irregular, short-term variability around a stable 'base level' in bores screened in the Q1 or Q2 alluvium associated with the Otaki River and Waitohu Stream (R26/5228, S25/5329 and S25/5287). The pattern reflects episodic variations in aquifer recharge associated with high stage events in the Otaki River (including associated rainfall recharge on the coastal plain). The peaks in groundwater level dissipate rapidly through the high permeable aquifer.

In contrast to the highly connected riparian aquifers, S25/5322 (screened at a depth of 30 metres in Q5 sediments north of the Waitohu Stream) exhibits a systemic seasonal variation of up to 3 metres more indicative of rainfall recharge. Minimum levels typically occur during autumn and highest levels during spring. Water levels at this site also show increased intra-seasonal variation likely to reflect long-term variations in rainfall.

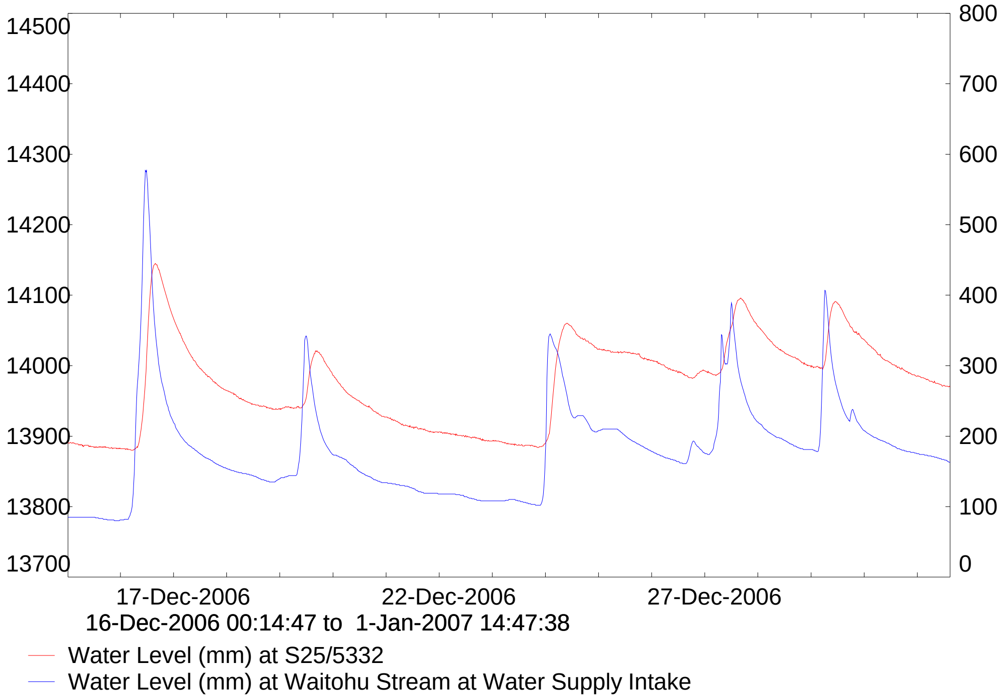


Figure 48: Short-term groundwater level fluctuations in S25/5332 in response to variations in Waitohu Stream stage

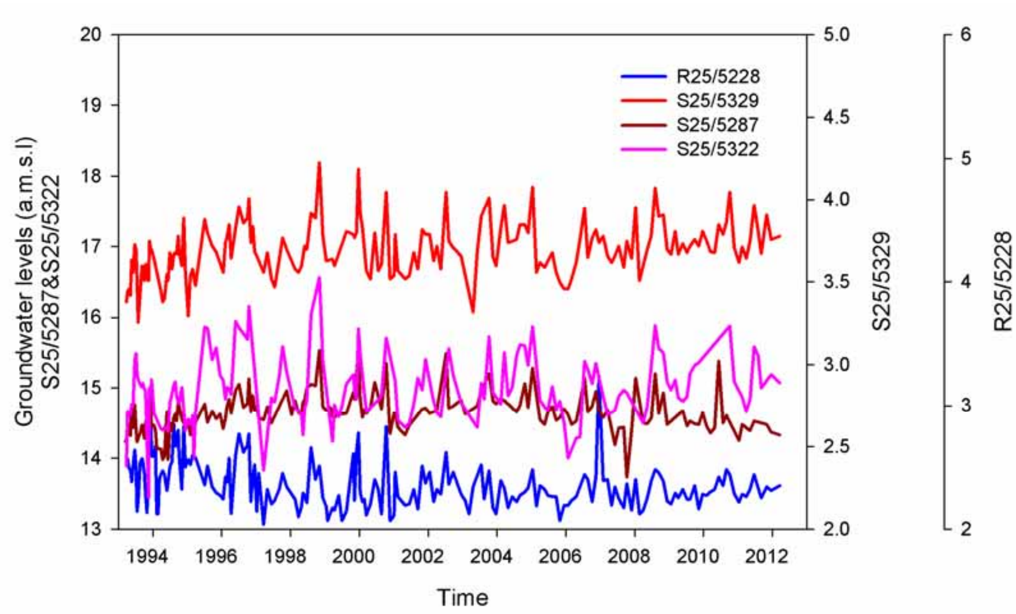


Figure 49: Groundwater levels in the Otaki groundwater zone, 1993 to 2011

6.3 Summary

The Otaki groundwater zone hosts an extensive groundwater resource in Holocene (Q1) alluvium and reworked Q2 gravels underlying the recent floodplain of the Otaki River and Waitohu Stream. These materials host a highly permeable unconfined/semi-confined aquifer system which exhibits a high degree of hydraulic connection with surface water. Holocene (Q1) sand deposits along the coastal margin north of Waitohu Stream and older Q5 sand and Q6 alluvial deposits which form a broad terrace sequence along the margin of the Tararua foothills contain appreciable quantities of groundwater in a highly heterogeneous, low hydraulic conductivity sequence of sand, silt and gravel.

Table 10 provides a summary of the physical characteristics and spatial distribution of hydrostratigraphic units identified in the Otaki groundwater zone based on a review of available geological, hydrogeological and groundwater level information.

Table 10: Summary of the physical characteristics and spatial distribution of the primary hydrostratigraphic units in the Otaki groundwater zone

Hydrostratigraphic Unit	Description	Spatial/depth distribution
Holocene (Q1) Sand	• Medium to fine sand with discontinuous layers (lenses) of gravel and silt/peat. • Relatively low bulk hydraulic conductivity (K~2-5 m/day) • Hosts a shallow unconfined aquifer system primarily recharged by local rainfall	• Primarily occurs along the coastal margin to the north of Waitohu Stream to the west of SH1 • Forms a wedge shaped deposit increasing in thickness from around 20 metres inland to up to 40 metres near the coast. May also thicken to the north
Q1 gravel	• Coarse, heterogeneous deposits of sand and gravel • Hosts a highly permeable unconfined aquifer hydraulically connected to surface water • Highly permeable (K~250 to 500 m/day)	• Underlies the recent floodplain of the Otaki River and Waitohu stream which merge to the west of Otaki township • Generally between 10 to 15 metres thick, possibly reducing in thickness along the northern margin of the Otaki floodplain
Q2 Gravel	• Poorly sorted alluvial gravel with varying amounts of silt and sand along the margins of the Otaki and Waitohu valleys • Appears to be extensively reworked under the Q1 gravels to the west of Otaki township • Forms relatively low yielding unconfined/semi-confined aquifer (K~5-20 m/day) underlying alluvial terraces. • Forms a highly permeable (K~250-500 m/day) unconfined to semi-confined aquifer hydraulically connected to overlying Q1 gravels	• Forms low alluvial terraces up to 30 metres thick along the margins of the Otaki and Waitohu floodplains. • Reworked Q2 gravels occur between 15 to 35 m bgl to the west of SH1 underlying the Q1 gravels

Hydrostratigraphic Unit	Description	Spatial/depth distribution
Q5 Sand (Otaki Formation)	• Dense/cemented medium to fine sand containing isolated gravel and organics • Hosts a relatively low hydraulic conductivity semi-confined aquifer system (K~1-10 m/day) which is primarily recharged by rainfall infiltration • May contain higher yielding relatively well graded medium to fine sand layers	• Surface exposure along terrace at base of Tararua foothills in Pukehou area and remnant terrace sequence separating Waitohu Stream and the Otaki River • Strata inferred to dip westward following profile of Otaki fan and also dip to the south following the general ~2-4^{o} tilt of the South Wanganui Basin
Q6 and older gravel and sand	• Assigned to all alluvial materials interpreted to be Q6 (Waimean Stage - penultimate glacial) and older • Poorly sorted, weathered gravel in a silty, sandy matrix • Hosts a low yielding semi-confined to confined aquifer system • Typically low hydraulic conductivity (K~5-10 m/day) and may become increasingly cemented at depth	• Surface exposure in alluvial terrace along eastern margin of the Otaki River valley • Strata inferred to dip westward following profile of Otaki fan and also dip to the south following the general ~2-4^{o} tilt of the South Wanganui Basin
Greywacke basement	• Well indurated siltstone and mudstone • May contain secondary hydraulic conductivity in joints and fractures but essentially considered to form the groundwater basement	• Form Tararua foothills to east of Otaki groundwater zone • Bore logs suggest a basement 'step' along foothills margin ~130 m blg • Basement ridge associated with Levin Fault may be associated with formation of dune lakes to the north of the Waitohu Stream

Table 11 provides a summary of the key components of the overall water balance for the Otaki groundwater zone.

Table 11: Summary of key components of the overall water balance for the Otaki groundwater zone

Component	Description	Comment
Rainfall	• Infiltration of rainfall on coastal plain	• Not determined
River Recharge	• Otaki River • Waitohu Stream	• Flow loss of 1,200 to 2,000 L/s (median ~1,600 L/s) between Pukihinau and Lower Transmission Lines • Flow loss of ~80 L/s between Water Treatment Plant and Otaki Golf Club
Baseflow Discharge	• Waimanu Stream • Rangiuru Stream • Waitohu Stream • Otaki River	• ~170 L/s • ~275 L/s • ~80-100 L/s • Reach downstream of Lower Transmission Lines not gauged but may receive appreciable baseflow
Wetland areas	• Losses due to evapotranspiration and direct evaporation	• Not determined. Large, regionally significant wetland complex in Forest Lakes area. Likely to be a relatively minor component of overall aquifer water balance
Offshore discharge	• Discharge offshore	• Not determined but likely to be a major component of overall water balance in Q1 sand areas to the north of Waitohu stream

Figure 50 and Figure 51 provide schematic illustration of the conceptual hydrogeological model for the Otaki Te Horo groundwater zone along the two section lines indicated on Figure 42.

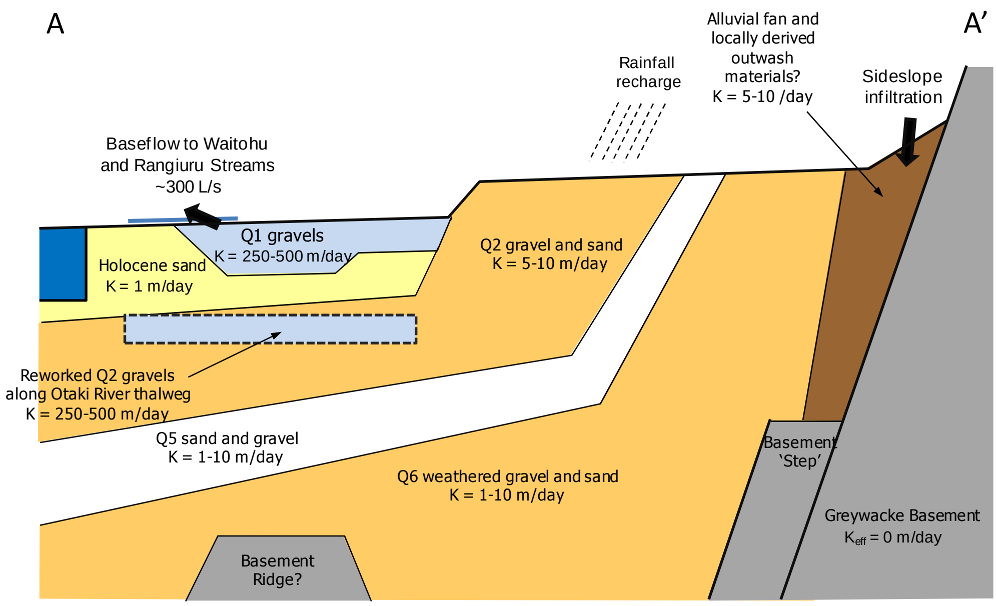


Figure 50: Schematic (west-east) cross section of the Otaki groundwater zone

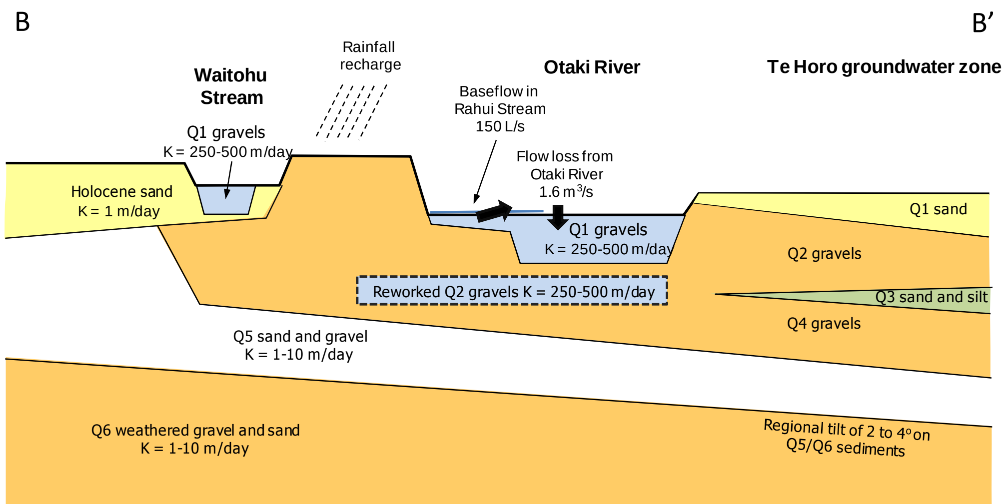


Figure 51: Schematic (north-south) cross section of the Otaki groundwater zone

7. Kapiti Coast groundwater model

7.1 Groundwater modelling purpose and objectives

The purpose of the Kapiti Coast numerical groundwater model is to facilitate the development of a sustainable groundwater allocation policy based upon a robust analysis of available hydrogeological information. The preceeding sections have presented the conceptualisation of the Kapiti Coast groundwater environment upon which the model is based.

Specific objectives of the modelling study are:

- Construct and calibrate a numerical groundwater flow model for the Kapiti Coast groundwater system using an appropriate model code to a level of complexity consistent with the models purpose and available information;

- Characterise and simulate surface water – groundwater connectivity under a range of stress conditions;

- Quantifiy of regional and sub-regional water balances and their long-term seasonal variability in response to changes in climate and abstraction stresses; and

- Quantifiy the sustainable allocation from the groundwater resource within the new management framework.

7.2 Numerical model construction

7.2.1 Model code selection

A number of numerical computer codes can simulate groundwater flow - each have inherent strengths and weaknesses. To deliver the objectives of this study, important considerations when selecting a suitable model code were:

- The requirement to represent a relatively complex layered groundwater environment and incorporate a degree of local-scale detail in certain areas.

- An ability to accurately simulate the interaction between groundwater and surface water.

- The requirement to interface with the PEST parameter estimation model to enhance calibration robustness and assist in the evaluation of model uncertainty.

The finite difference model code MODFLOW (USGS) was selected because it meets the above criteria and is widely used and is a verified code. MODFLOW was used in conjunction with the data processing interface Visual Modflow (Schlumberger Water Services, 2011).

7.2.2 Model complexity

The Murray Darling Basin Commission (MDBC, Middlemis 2001) and New Zealand Ministry for the Environment (NZME 2002) modelling guidelines define model complexity as the degree to which a model application resembles the physical hydrogeological system. A complex model ("*Aquifer Simulator*") is capable of being used for sustainable resource management policy decisions. Modelling to this degree of complexity is based on a comprehensive conceptual understanding of the groundwater system dataset and the availability of good data. To develop such models, a considerable investment in time, skills and data acquisition and analysis is required. It is generally sound practice in the development of such models to stage the process of introducing complexity.

A previous modelling study (Jones and Gyopari, 2005) represented an intial simplified approach which resulted in the development of a simple model for the Waikanae area calibrated to steady-state and transient flow conditions.

The 2012 Kapiti Coast model (this study) therefore represents a progression to a complex multi-layer simulation consistent with the purpose and objectives of the study. A sufficiently detailed conceptual understanding of the area has been developed (Chapters 2-6) and a large volume of data exist to support the development and calibration of a complex model.

7.2.3 Model domain delination

The model domain has been based upon the geological analysis and conceptualisation presented in Chapters 3-6. The groundwater system is coincident with the occurrence of late Quaternary and Holocene alluvial sediments which have accumulated within a basinal structure in the greywacke bedrock.

The model domain (Figure 52) extends from Paekakariki in the south to about 5km north of Otaki and incorporates the Holocene coastal plain and peripheral late Quaternary gravel terraces. The area covered by the model is about $172km^2$ - 38km in length and approximately 3.5km wide in the Waikanae area, increasing to about 8km in the Otaki valley area.

7.2.4 Model design, grid design

MODFLOW uses a finite difference solution method that requires the use of a rectilinear, block-centred spatial grid and one or more layers. The model grid has an area of 38,000m x 18,000m and extends 5,000m offshore to facilitate simulation of vertical discharge from deeper aquifers into the sea. The grid has been rotated into alignment with the coastline (the long, x-axis being parallel to the coastline) as shown in Figure 52**.** The default cell size is 250m x 250m across the on-shore portion of the grid, increasing progressively to 1,000m at the western off-shore boundary.

The model incorporates seven layers which correspond to the principal hydrostratigraphic units identified in the conceptual modelling phase.

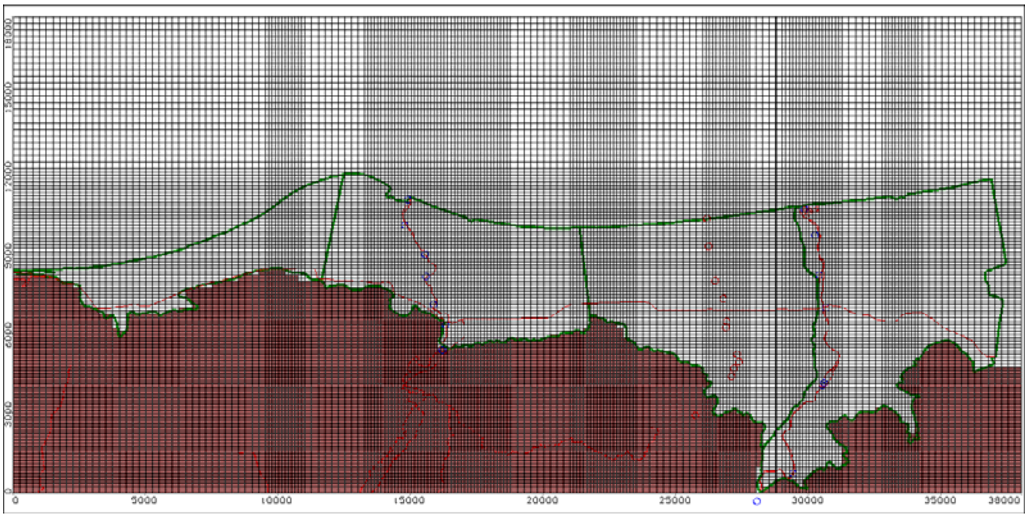


Figure 52: Model grid overlaid on basemap

7.3 Translation of the conceptual model

Hydrostratigraphic elements recognised in the conceptual hydrogeological model (Chapters 3-6) have been distilled into seven principal units for the purposes of the model. The unit description, layer assignment and their distribution within each (revised) groundwater zone are shown in Table 12. The complete hydrostratigraphic sequence occurs in the Waikanae and Te Horo zones. In the Otaki zone, the sequence becomes gradually uplifted to the north where older Q5 deposits occur at the surface and Q2 thickens substantially around the Otaki River. In the Ruamati zone, the entire sequence is sand-dominated with only occasional localised gravels.

Table 12: Principal hydrostratigraphic units represented in the numerical model

Hydrostratigraphic units	Model layers		
	Raumati zone	Waikanae & Te Horo zones	Otaki zone
Shallow unconfined Holocene sand (Q1)	1	1	1
Coarse, well-sorted Holocene (Q1) alluvium adjacent to main rivers	n/a	1	1
Late Quaternary sand/gravel/silt terrestrial alluvium and marine deposits:			
Q2 – glacial outwash gravels (‘aquifer’)	2 (sand)	1 (2)	2 (3)
Q3 – interglacial sands/silts (‘aquitard’)	3 (sand)	3	n/a
Q4 – glacial outwash gravels (‘aquifer’)	4 (sand)	4	4
Q5 – interglacial sands/silts (‘aquitard’)	5 (sand)	5	1(2,3,4,5)
Q6 - glacial outwash gravels (‘aquifer’)	6 (sand)	6	6
Q7+ - older cold and warm period sediments.	7 (sand)	7	7
Foothill alluvium, poorly sorted	1 - 7	1 - 7	1 - 7

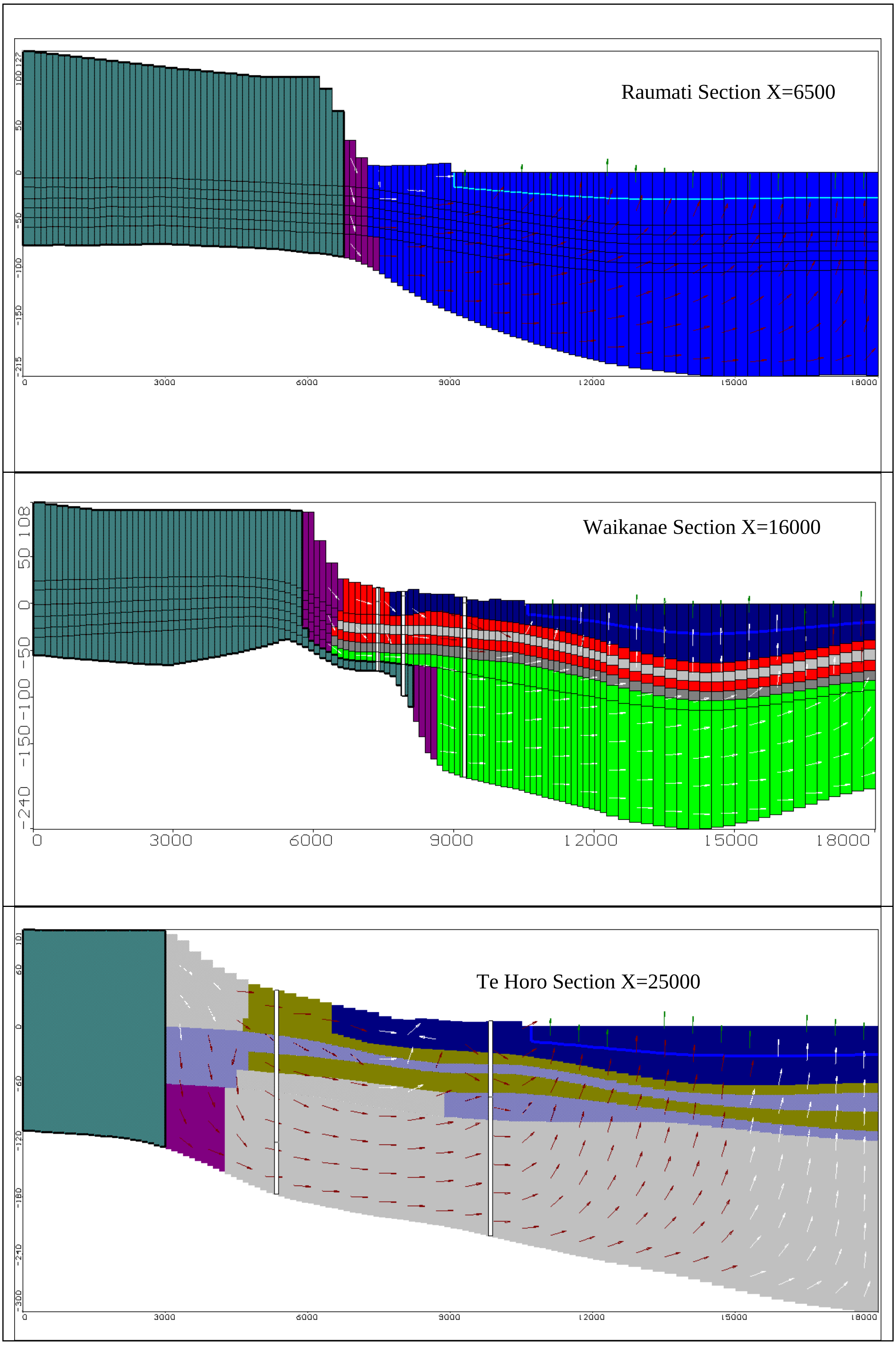
Layers in brackets indicate localised areas where they are used to represent a unit.

The layers were modelled using available bore logs and a series of interpreted geological cross sections as summarised in Chapters 3 to 6. Layer elevations were imported along a series of cross sections and then interpolated within Visual Modflow and manipulated as necessary to maintain consistency with the conceptual model. Table 13 is a summary of refined model parameters and their locations in the model domain. Figure 53 presents representative cross sections through the refined model. The refined parameters were derived through manual calibrations. Manual groundwater calibrations identified an initial twenty three (23) hydraulic conductivity zones for the catchment. Some zones were found to have similar properties and such zones were grouped together into single zones. The amalgamation of such zones resulted in 12 hydraulic conductivity zones as shown in Table 13.

Figure 53 is a presentation of cross sections of the resulting 12 hydraulic conductivity zones.

Table 13: Representative hydraulic parameter zones in the Kapiti Coast (K(x,y) = horizontal hydraulic conductivity in x and y directions, Kz = vertical hydraulic conductivity, Some zones e.g. 5 and 8 were amalgamated into other zones with similar properties during the calibration process

Zone	K(x,y) [m/d]	Kz [m/d]	Layer	Aquifer properties	Table 20	Map Colour
2	5.0	0.050	1	Shallow unconfined Holocene sand (Q1) Waikaeanae, Te Horo, Otaki	2-5	
3	250	0.50	1	River gravel (Q1) Waikanae, Te Horo	250-500	
4	300	0.49	1	Alluvium (Q1) Otaki	250-500	
6	5.0	0.52	1-7	Foothill alluvium (All areas)	2-10	
7	13	0.1	1-4	Weathered gravel sand (Q6), Te Horo (1,2,4) Otaki (1-4)	1-10	
9	2.5	0.0003	5-6	Sand (Q5), Waikanae, Te Horo	1-10	
10	3.5	0.0014	1	Shallow unconfined Holocene sand (Q1) Hautere, Waikanae	2-5	
11	20.3	0.2	3-7	Gravel and Sand (Q6, Q7) Waikanae, Te Horo, Otaki	5-30	
13	18.0	1.8	1-3	Gravel (Q2) Waikanae, Te Horo, Otaki	5-50	
14	4.9	0.047	1-4	Shallow Holocene sand (Q1) Otaki	2-5	
16	3.1	0.40	3-4	Sand-aquitard (Q4) Waikanae, Te Horo	1-10	
23	3.0	0.003	1-2	Alluvium (Q3) Te Horo, Waikanae	2-10	
				Inactive zone		


Raumati Section X=6500
Waikanae Section X=16000
Te Horo Section X=25000
0
3000
6000
9000
12000
15000
18000

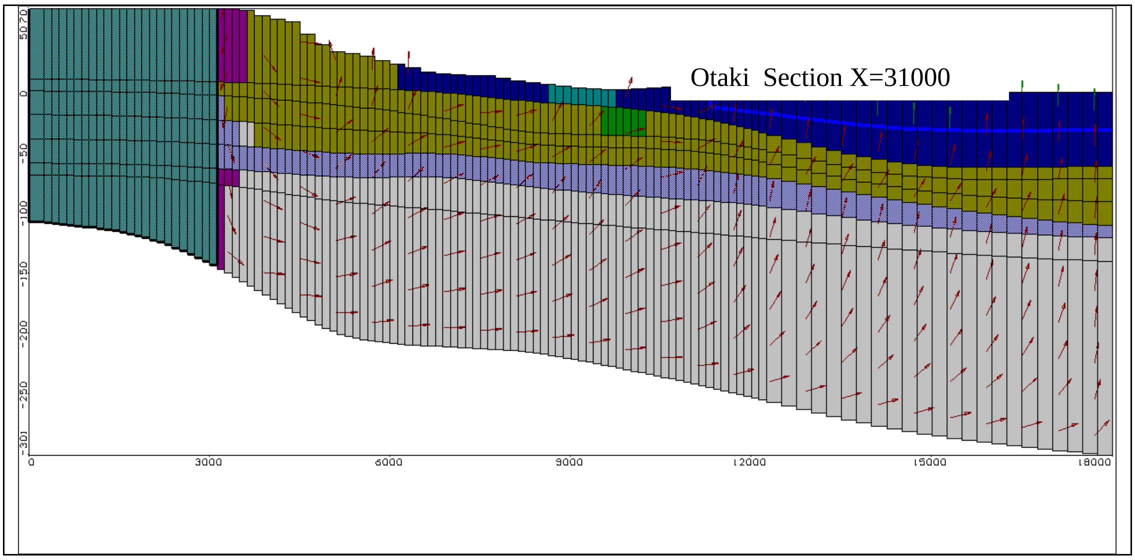


Figure 53: Groundwater numerical model representative cross sections and calculated flow direction vectors.(Light blue colour-sea boundary)

7.4 Boundary conditions

7.4.1 External model boundaries and offshore extension

A no flow boundary condition was assigned to the perimeter of the groundwater system coinciding with the greywacke basement contact in the east and south, and a flow line perpendicular to the coast in the north.

The active model domain extends 5km offshore (coincident with eastern coast of Kapiti Island) where the placement of a no-flow boundary is justified since the aquifers must terminate at the greywacke outcrop on the island. Throughflow from deeper aquifers is considered to discharge through slow leakage vertically into the sea. The offshore portion of Layer 1 was assigned a constant head condition at mean sea level (0m amsl) with the base of this layer being defined by the sea bed depth using bathymetry data. The maximum ocean depth between Waikanae and Kapiti Island is about 50-60m.

The onshore model upper surface (topography) was derived from airborne LIDAR data held by Greater Wellington (Flood Protection Division).

7.4.2 Rivers, streams and drains

The main drainage courses of the Waikanae and Otaki rivers together with the smaller Waimeha, Wharemauku, Ngarara, Mangaone and Waitohu streams interact closely with groundwater. They have spatially variable losing or gaining characteristics (see discussions and gauging data in the Chapters 3 to 6). The rivers and streams have been simulated using the Modflow Stream Routing Module (STR1) which provides the most flexible and appropriate method of representing the interaction between surface water and groundwater. The module calculates river stage in each model cell based upon flow and channel characteristics and accounts for the effects of groundwater inflows and outflows.

The bed levels of major rivers and streams were derived from flood protection survey cross sections. In the absence of such data being available for smaller streams, high-accuracy 2010 LIDAR data were used to assign bed elevations.

The STR1 stream routing module requires the inflow to the upstream reach and subsequently accounts for losses and gains throughout the length of the river. Inflows to the Waikanae River, Otaki River, Mangaone Stream and Waitahu Stream at the eastern model boundary were derived from GWRC permanent flow recorder sites at locations shown in Figure 8 (Raumati), Figure 26 (Waikanae), Figure 31 (Te Horo) and Figure 41 (Otaki). Figure 54 shows the stream and drain boundaries as applied in the numerical model. Measurements are recorded every 15 minutes and were summarised into 7-day average flows for use in the model. For spring-fed streams (such as the Waimeha), the STR1 package calculates the groundwater input to the stream from which it calculates the stage.

Streambed conductance is a parameter used by MODFLOW to control the flow of water to and from the underlying aquifer. This parameter is usually derived through trial and error in the calibration process. Bed conductance is calculated using the length of the river in each river cell (L), the width of the river (W) in the cell, the thickness of the river bed (M), and the hydraulic conductivity of the river bed material (K). The stream bed conductance, C, is described as:

$$C = K L W / M$$

The river width (W) has been derived from GWRC flood protection survey cross sections. In the absence of such data for smaller streams, high definition GIS maps were used to estimate river width. The bed thickness (M) has been held constant for each cell at 1m. The length of the reach (L) coincides approximately with the cell dimension of 250m. Assuming a hydraulic conductivity (K) of 10m/day for the bed, the river bed conductance for the Waikanae approximates 5,000 m^2/day. A combination of the above parameters and the resultant calculated conductance values produced plausible estimates of stream flow gains and losses during model calibrations.

Remaining streams and drained areas on the coastal plain were simulated with MODFLOW's Drain module. These are shown in Figure 54 and include the Mazengarb drain complex, the QE Park drainage system and the drain complex covering the area below the Hautere terrace in the Te Horo groundwater zone. The MODFLOW drain boundary condition removes water from the aquifer at a rate proportional to the difference between the head in the aquifer and the elevation of the drain bed, and can only remove water from the aquifer. The elevations of the drain cells were estimated from LIDAR data held by the Flood Protection Department of the Greater Wellington Regional Council. The conductance values for the drain beds were derived from model calibration.

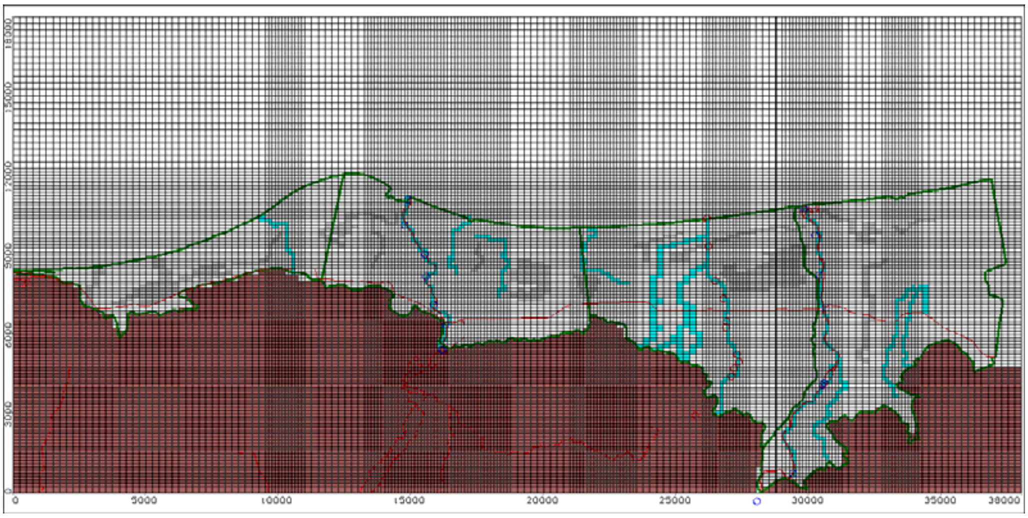


Figure 54: Showing drain (grey) and stream (green) cells

7.5 Rainfall recharge calculation

7.5.1 Methodology

Estimation of the quantity of water migrating through the soil zone to the water table has been estimated using a soil moisture balance approach. Soil moisture balance methods assume that the soil becomes free-draining when the moisture content reaches a threshold value ('field capacity') when excess water then becomes groundwater recharge. The soil moisture balance method described by Rushton et al (2006) was adopted for this study which introduces an additional concept – that of near-surface soil storage. This recognizes that potential evapotranspiration can occur on days following heavy rainfall since even though the soil profile may be dry at depth, moisture from rainfall can be held near to the soil surface. Actual evapotranspiration is calculated using the readily and total available water (RAW and TAW) based upon soil properties and the effective rooting depth. Runoff was also incorporated in a rudimentary manner using the USDA SCS runoff method (1967) which partitions rainfall between through-flow or runoff and the soil moisture store.

Base data required for the soil moisture balance model are daily climatic data (rainfall and potential evapotranspiration), and soil and runoff properties and distribution (field capacity, wilting point, rooting depth and SCS number) for the main soil groups in the study area.

7.5.2 Climate data

Daily climate data (rainfall and PET) has been provided by NIWA on a 500m^2 regional grid (Figure 55) for the period 1/7/1992 to 1/7/2011. Spatial interpolation of daily rainfall and potential evapotranspiration using a spline model (Tait and Woods 2007) into the 500m grid was undertaken by NIWA using all available climate monitoring data from both NIWA and Greater Wellington rain gauge and climate sites. Each grid square has a daily interpolated rainfall and potential evapo-transpiration record for the period 1992 to 2011. Annual average rainfall for each grid centroid was calculated and then contoured to produce the rainfall isohyet map shown in Figure 55.

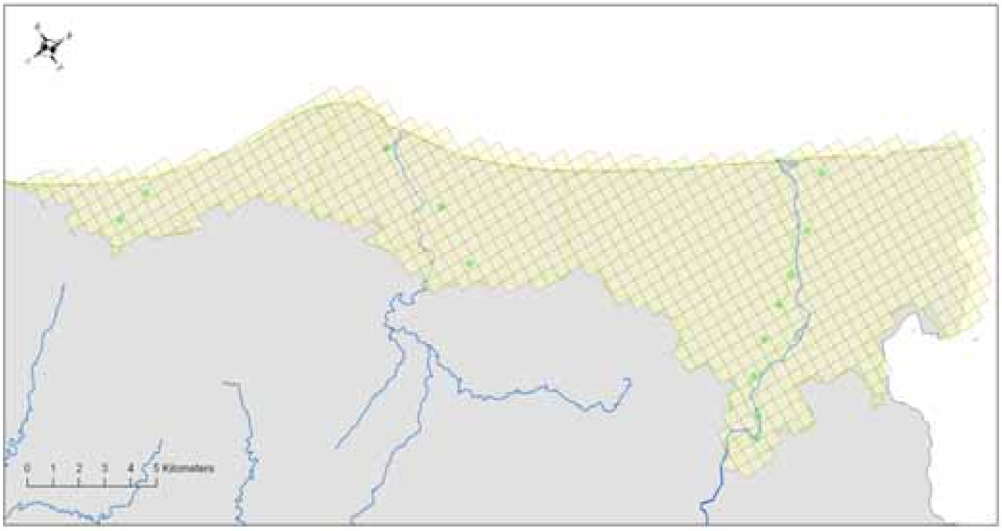


Figure 55: The NIWA 500m Wellington region climate grid (laid over the Kapiti Coast) to model rainfall and potential evaopotranspiration

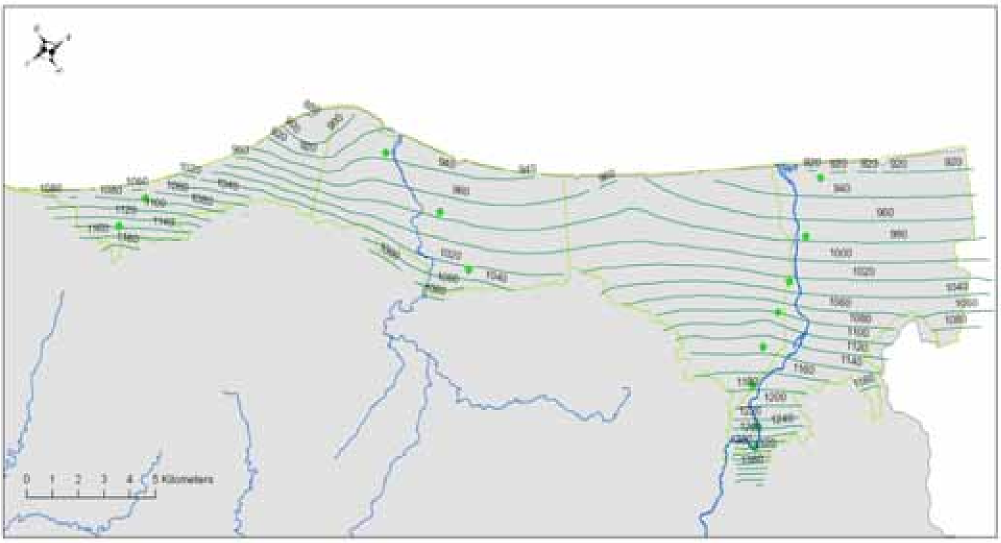


Figure 56: Annual rainfall isohyets calculated using the NIWA 500m grid interpolation data

7.5.3 Soils mapping and properties

On the basis of the NZLRI soils map, the soil types in the study area have been broadly defined as sandy or peaty in nature and to simplify the modelling process. A generalised soil map is shown in Figure 57.

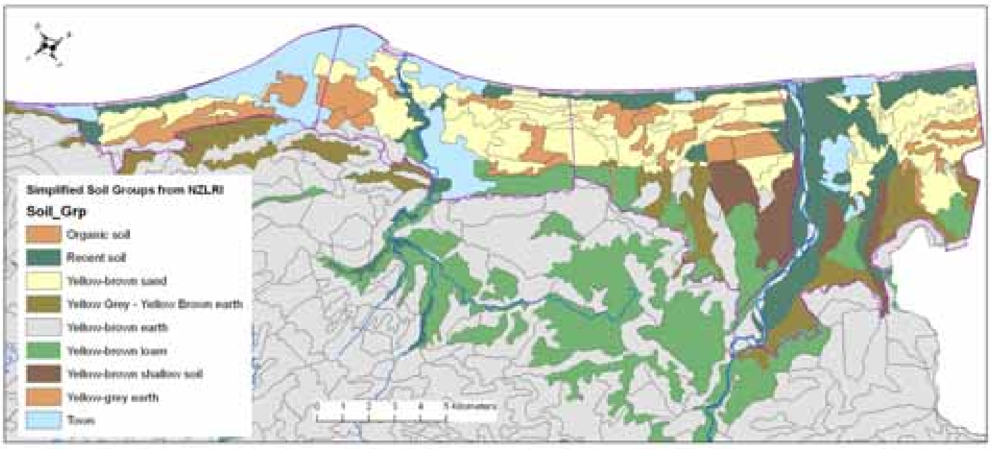


Figure 57: Simplified soils map for the Kapiti Coast (source: NZLRI)

Most of the coastal plain is underlain by windblown sand, with peaty/organic soils occurring locally within depressions. The higher terrace and fan areas against the foothills comprise either alluvial or colluvial deposits which are mantled in sandy loam, or poorly draining loess or silty loam. Two broad classes of free-draining (sandy) soil and poorly draining peaty or silt loam have therefore been used as shown in Table 14. The physical attributes for the sandy class soil have been estimated by calculating a weighted mean for each sandy soil type in the area. The attributes for the peaty loam and silt loam have been similarly derived from the predominant peat loam.

Table 14: Simplified soil groups used in the recharge model

Soil Class	Soil Parameter (mm)			
	WP	RAW	AW	FC
Sandy soils / Sandy loam	26	30	70	97
Peaty loam/silt loam/loess	100	66	211	311

7.5.4 Recharge zone delineation

A 50mmm isohyet spacing was selected as a basis for defining rainfall recharge zones to account for the rainfall gradient shown in Fig 56. Each 50mm zone was further divided into a northern and southern segment to account for any changes in rainfall pattern associated with the prominent Otaki valley (Figure 58). Table 15 lists the rainfall zones.

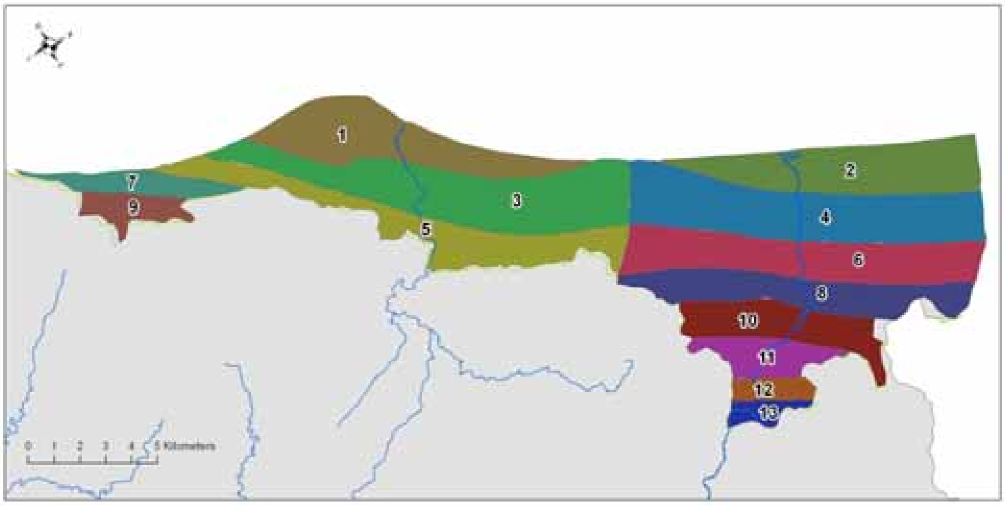


Figure 58: Rainfall zones used in the groundwater recharge model (based on 50mm rainfall isohyet intervals)

Table 15: Rainfall zones

Isohyet zone	Rainfall zone
900-950	1 & 2
950-1000	3 & 4
1050-1100	5 & 6
1100-1150	7 & 8
1150-1200	9 & 10
1200-1250	11
1250-1300	12
1300-1350	13

To take into account the soil properties and urban landcover, the soil zone map (Figure 57) and rainfall zone map (Figure 58) were superimposed resulting in 31 zones (numbered 2-32) as shown in Figure 59. Table 16 provides the soil and rainfall/PET parameters for the 31 recharge zones.

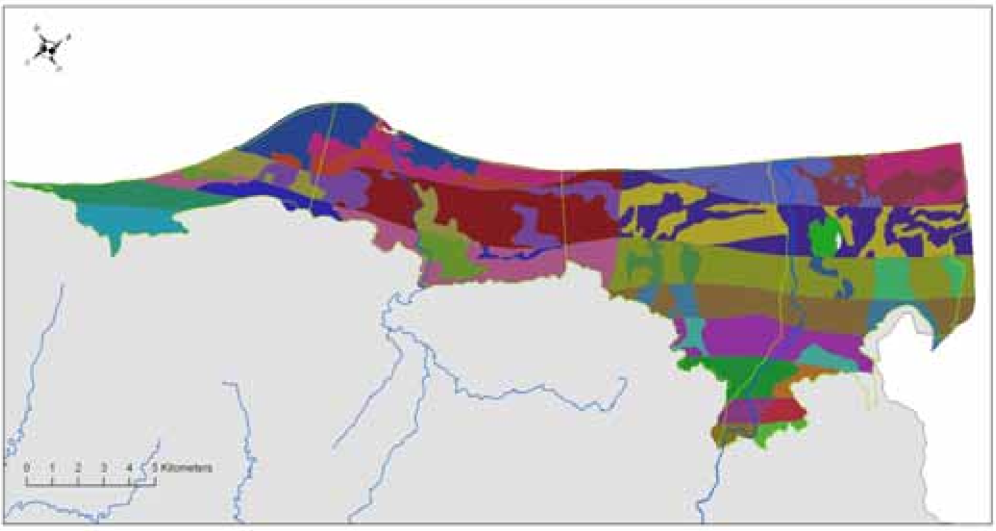


Figure 59: Recharge zones (31 in total) derived by overlying rainfall zones and soil map

Table 16: Recharge model soil and runoff parameters

Rainfall/PET Zone	Soil Type	Recharge Zone No	Wilting Point	Field Capacity	Rooting Depth	SCS Curve No.
1	Urban-Sand	2	26	97	0.5	60
1	Sand	4	26	97	0.5	60
1	Peat/loam	3	100	311	0.5	86
2	Sand	5	26	97	0.5	60
2	Urban-Sand	7	26	97	0.5	60
2	Peat/loam	6	100	311	0.5	86
3	Urban-Sand	8	26	97	0.5	60
3	Sand	10	26	97	0.5	60
3	Peat/loam	9	100	311	0.5	86
4	Sand	11	26	97	0.5	60
4	Urban-Sand	13	26	97	0.5	60
4	Peat/loam	12	100	311	0.5	86
5	Urban-Sand	14	26	97	0.5	60
5	Sand	15	26	97	0.5	60
5	Peat/loam	16	100	311	0.5	86
6	Peat/loam	19	100	311	0.5	86
6	Sand	20	26	97	0.5	60
6	Urban-Sand	21	26	97	0.5	60
7	Sand	17	26	97	0.5	60
8	Peat/loam	23	100	311	0.5	86
8	Sand	24	26	97	0.5	60
9	Sand	18	26	97	0.5	60

Rainfall/PET Zone	Soil Type	Recharge Zone No	Wilting Point	Field Capacity	Rooting Depth	SCS Curve No.
10	Peat/loam	25	100	311	0.5	86
10	Sand	26	26	97	0.5	60
11	Peat/loam	27	100	311	0.5	86
11	Sand	28	26	97	0.5	60
12	Peat/loam	29	100	311	0.5	86
12	Sand	30	26	97	0.5	60
13	Peat/loam	31	100	311	0.5	86
13	Sand	32	26	97	0.5	60

It will be noted from Table 16 that the ‘sand’ soil class also has an associated ‘urban’ designation for the purposes of allowing increased rainfall runoff in built-up areas. Modelled recharge was decreased by a factor of 0.3 in urban areas following the work of Watts (2003) who calculated run-off coefficients for four small sub-catchments of the larger Mazengarb catchment in the Paraparaumu area. These sub-catchments consisted of two moderate-density residential areas, one rural area and one low-density residential area. The average run-off coefficients are shown in Table 17.

Table 17: Rainfall runoff coefficients, Kapiti Coast urban catchments (from Watts 2003)

Catchment	Impervious cover estimate (%)	Average run-off coefficient
Rosewood	46	0.35
Realm Drive	44	0.51
Ratanui	10	0.33
Nikau (rural)	7	0.16

7.5.5 Soil moisture balance parameters and calculation

The Rushton et al. (2006) soil moisture balance calculation partitions soil moisture between near surface soil storage, actual evapotranspiration (AET) and the soil moisture reservoir. In addition to rainfall and PET, the soil moisture balance model requires four input parameters to calculate daily soil moisture deficit. These parameters are described below:

- **SCS Curve Number:** A curve number estimated for each soil type is used to calculate maximum soil retention and runoff (this is the same method used for the HortResearch ‘SPASMO’ model). The intent of the SCS classification is to partition rainfall between through-flow or runoff and the soil moisture store. The SCS number is derived from a combination of soil hydraulic conductivity and soil water storage in the moist condition (air capacity) and is not static but varies with antecedent moisture conditions and with land use. Soils were rated according to tables in SCS (1967) for land under pasture in a moist antecedent state.

- Lower curve numbers result in higher soil retention thresholds, which induce less runoff. Pasture in good condition on free draining soil has a low curve number (40-60). Pasture in poor condition on a poorly drained soil has a high curve number (90). Additional values are given in Table 5.5.1 of Rawls et al. (1992). The SCS runoff calculation also has the capacity to incorporate slope and soil moisture (Williams, 1991). Table 16 shows the adopted SCS curve numbers associated with the two soil types. The sandy soil was designated a low SCS curve number of 60 which results in negligible runoff. The peaty soils was assigned a value of 86 to reflect less well drained soils resulting in a runoff of about 10% of rainfall.

- **Total Available Water (TAW):** TAW is calculated from field capacity, wilting point and rooting depth data (Table 16).

- **Readily Available Water (RAW):** RAW is related to TAW by a depletion factor, p. The depletion factor is the average fraction of TAW that can be depleted from the root zone before moisture stress (reduction in evapotranspiration). For New Zealand conditions p should be around 0.4 to 0.6, typically it set at 0.5 for grass.

- **Fracstor:** This is the near-surface soil retention, and values are estimated. Typical values are 0 for a coarse sandy soil, 0.4 for a sandy loam, 0.75 for a clay loam (Rushton et al. 2006). A value of 0.5 was employed for this project (not the soil moisture balance model is relatively insensitive to small adjustments in fracstor).

The soil moisture balance model is then run on a daily basis using the following steps:

1. Partition the runoff component of daily rainfall using the USDA SCS runoff method.

2. Calculate infiltration to the base of the soil profile and near surface soil storage (SOILSTOR) for the end of the current day. Infiltration equates to infiltration (rainfall-runoff) plus SOILSTOR from the previous day.

3. Estimate actual evapotranspiration (AET) using potential evapo-transpiration (PET) as derived by the Priestly-Taylor (1972) equation. A crop coefficient is not applied since the crop is assumed to be pasture. Pastures in New Zealand are generally regarded to behave like the reference crop for most of the year (Scotter and Heng 2003).

4. Calculate soil moisture deficit and groundwater recharge. Recharge occurs only when soil moisture deficit is negative (i.e. there is surplus water in the soil moisture reservoir). The soil moisture deficit for the first day of the model is assumed to be zero.

7.5.6 Recharge model outputs

Figure 60 shows the modelled mean annual recharge for each of the 31 recharge zones listed in Table 16. The low zone numbers lies towards the coast where rainfall is less compared to zones adjacent to the foothills (refer to Figure 58 and Table 16). The higher recharge associated with sandy soils is evident.

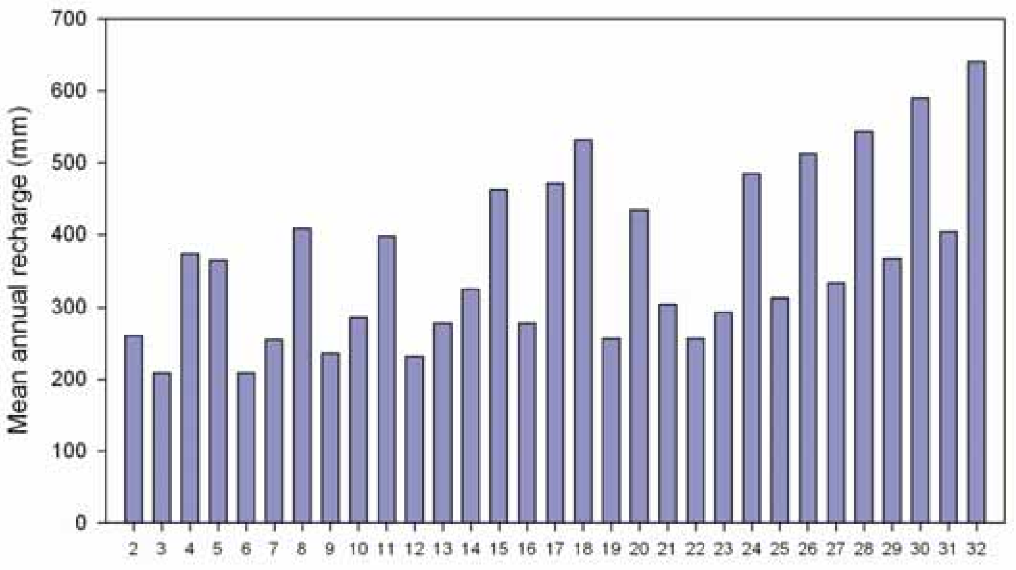


Figure 60: Modelled mean annual recharge for each zone (see Table 16 for zone properties; x axis shows zone number)

Figure 61 shows the mean annual recharge for each zone expressed as a percentage of mean annual rainfall. Again, the distinction between the lower recharge associated with peaty soils compared to sandy soils is responsible for the two-tiered nature of the plot. Recharge as a percentage of rainfall varies from 20% to about 30% where there are peaty soils, and from about 38% to 48% where there are sandy soils.

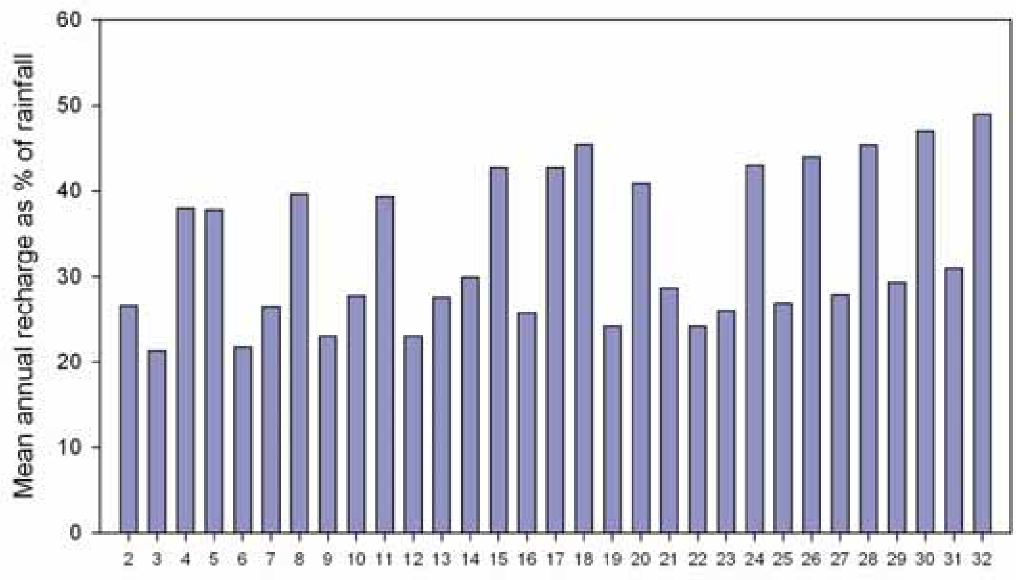


Figure 61: Modelled mean annual recharge expressed as a percentage of mean annual rainfall in each recharge zone (see Table 16 for zone properties)

7.5.7 Recharge model verification

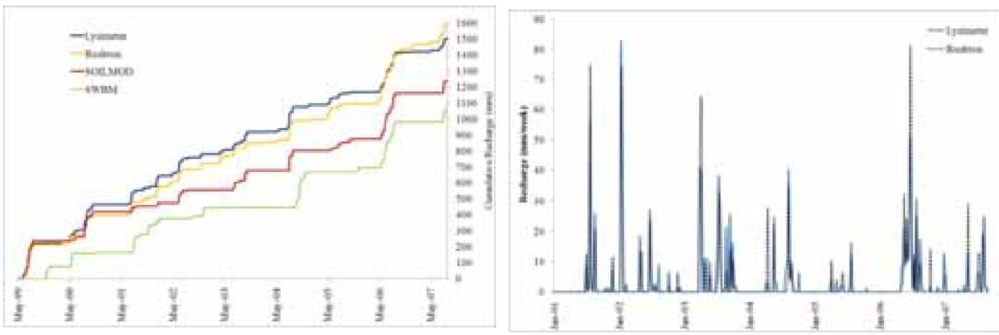
The accuracy of the Rushton soil moisture balance model was verified by comparing calculated recharge with lysimeter data from Canterbury, New Zealand. Lysimeter data for three sites were provided courtesy of Environment Canterbury. Other soil moisture balance models – SOILMOD and the Soil Water Balance Model (described by White et al. 2003) were also tested for comparison. Soil properties were kept consistent for the three models (Table 18) and are the same values as those used by White et al. (2003). No surface runoff was incorporated in these simulations.

Table 18: Soil properties used for Canterbury recharge simulations

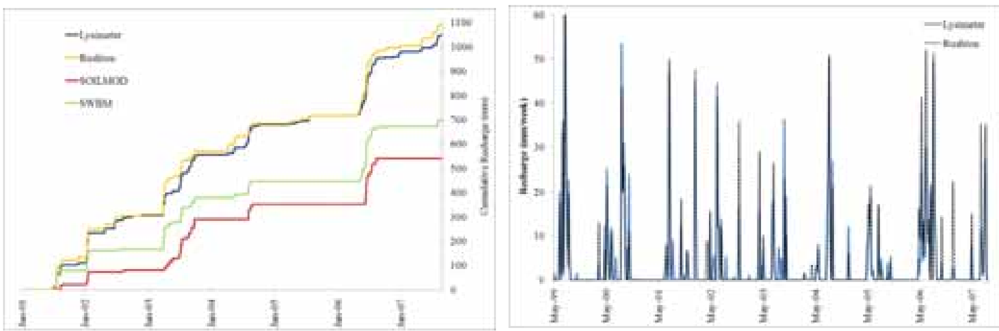
	Christchurch Airport	Lincoln University	Hororata
Soil Series	Waimakariri	Templeton	Hororata
Soil Type	V stony sandy loam	Silt loam on sand	Stony silt loam
Drainage	Excessively drained	Well drained	Well drained
Profile Depth (mm)	300	650	300-400
PAW (mm)	45	170	75
FC (mm)	115	253	189
Rooting Depth (mm)	650	650	400
FRACSTOR	0.4	0.45	0.6

Results for the three models are compared graphically with lysimeter data in Figure 62.

Airport



Hororata



Lincoln

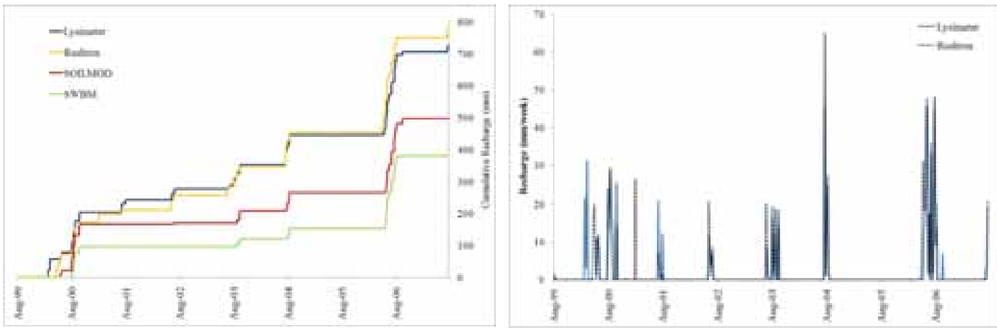


Figure 62: Hydrographs of cumulative recharge calculated by three soil moisture balance models (Rushton, SOILMOD and SWBN) compared to lysimeter data (left). Weekly recharge for the Rushton model compared with lysimeter recharge (right).

Statistics to compare the three models are provided in Table 19. The Rushton model gives the most accurate estimation of weekly rainfall recharge of all the three models. Recharge at the Airport site has been simulated most accurately, with an RMS error of 3.6 mm/wk. The estimate of recharge at the Hororata site is poorest, with an RMS error for the Rushton model of 4.2mm/wk.

The period of record for this simulation is longer than reported in White et al. (2003), which only simulated from May 1999 to March 2001. Conditions were drier than normal from 2003 to 2005 and this has led to an overall reduction in the percentage of rainfall recharge recorded at the three sites. The SOILMOD and Soil water balance models have not responded well to drier conditions, and have greatly underestimated recharge. The simulation shows that the Rushton model is more sensitive to periods of low rainfall, and accurately simulates rainfall recharge during these periods.

Table 19: Observed and modelled recharge statistics for the three Canterbury lysimeter sites. Lys - lysimeter, R - Rushton model, SM - SSOILMOD, WB - Soil water balance model

	Airport				Hororata				Lincoln			
	Lys	R	SM	WB	Lys	R	SM	WB	Lys	R	SM	WB
Total recharge (mm)	1502	1591	1234	1057	1047	1089	540	697	726	779	498	379
Mean weekly recharge (mm)	3.5	3.7	2.8	2.4	3.0	3.1	1.6	2.0	1.7	1.9	1.2	0.9
% of total rainfall	29	30	24	20	22	23	12	15	14	15	9	7
Max recharge (mm/wk)	65	67	69	85	82	81	87	85	47	65	49	46
RMS error (mm/wk)		3.6	4.7	11.3		4.2	7.0	4.4		4.0	4.1	4.1
Max weekly diff (mm/wk)		22	25	85		30	36	34		31	16	12
Min weekly diff (mm/wk)		-13	-42	-65		-16	-68	-38		-31	-41	-46
Period of record	7-May-99 - 24-Aug-07				23-Aug-99 - 28-Aug-07				2-Jan-01 - 6-Aug-07			
Total rain (mm)	5240				4682				5262			

7.6 Groundwater abstraction

7.6.1 Simulation of garden irrigation abstraction – Waikanae/Paraparaumu

There are estimated to be in excess of 4,000 garden wells in the Waikanae/ Paraparaumu urban area of less than 5m depth. Each is considered to abstract between 1 – 3 m^3/day from shallow sand or gravel aquifers during the summer period. Previous investigations (Jones and Gyopari, 2004) estimated the peak seasonal abstraction to be 5-6,000m^3/day.

Due to the large number of garden wells, a distributed abstraction approach has been adopted using the MODFLOW evapotranspiration (EVT) package. This facilitates a blanket groundwater abstraction over the entire urban area at a rate which takes into account the estimated number of irrigated properties, the irrigable area, and temporal soil moisture conditions.

Abstraction (evapotranspiration) rates were calculated using modified version of the methodology developed by Jones and Gyopari (2004) whilst retaining many of the assumptions. The revised methodology and associated assumptions are as follows:

(a) Estimation of irrigable land area

Within the Waikanae and Paraparaumu urban area, the proportion of irrigable land area was assessed on a 250 x 250 m grid by counting the number of properties in each grid square using GIS (Jones and Gyopari, 2005). Each grid square was then assigned to one of three property density classes (Figure 63):

Class 1: 0-10 properties

Class 2: 11-60 properties

Class 3: 61 – 80 properties

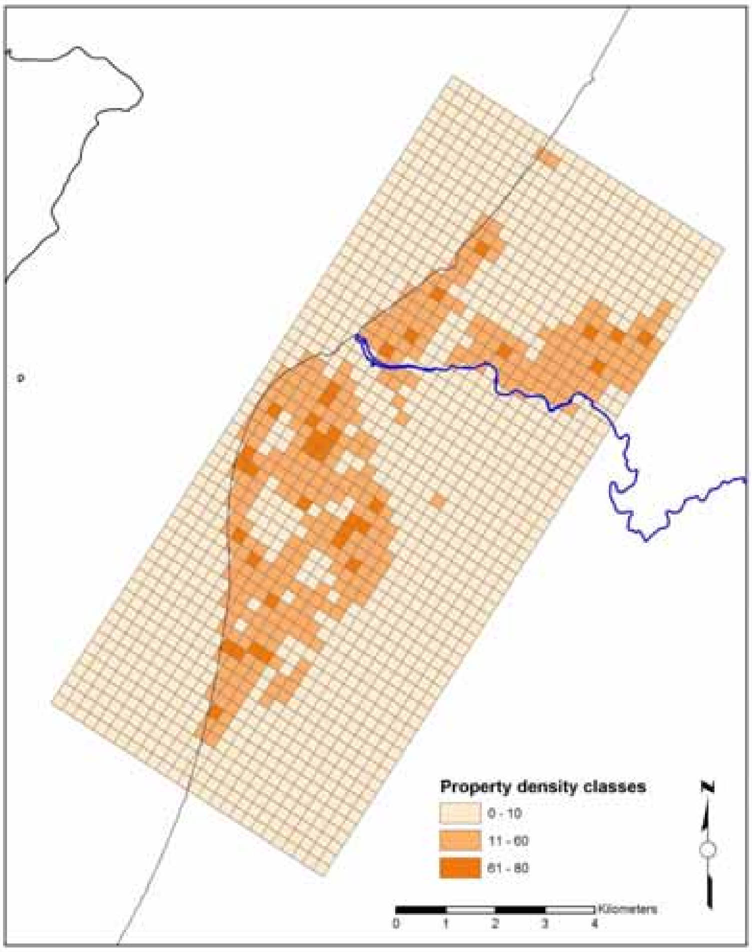


Figure 63: Kapiti Coast property density classes on a 250x250 m grid (from Jones and Gyopari, 2005)

The potential irrigable area for each class was then estimated using aerial photographs (1:15,000 scale) for several grid squares representative of each class. The potential irrigable area was defined as the area that might reasonably be irrigated (i.e. gardens and lawns). The irrigable areas defined for each class, as a percentage of the 250x250 m grid square, are as follows:

Class 1: 5%

Class 2: 15%

Class 3: 20%

Figure 63 shows that since Class 2 predominates there is reasonable justification to assign all of the urban areas to Class 2. Abstraction from Class 1 (outside the urban areas) was regarded to be negligible, and the occurrence of the denser Class 3 is rare.

A further assumption is that 50% of properties have an irrigation well. In new subdivisions, this proportion of houses with wells is thought to be about right based on well records and discussions with drillers and the Kapiti Coast District Council. In more established urban areas, the 50% assumption is probably conservative. Since all the urban area is regarded to have a Class 2 property density, the irrigable area is therefore 50% of 15% (7.5%).

(b) Irrigation demand

A reasonable assumption is that irrigation demand is driven by the amount of water required to satisfy the soil moisture deficit (SMD) – the amount of water needed to bring the soil to field capacity. The Rushton soil moisture balance model (described Section 7.5) was used to calculate SMD for a sandy soil (parameters are provided in Table 16) on a daily basis. Rainfall and potential evapotranspiration were obtained from the NIWA climate model in rainfall zone 1 (see Figure 58). The previous day's soil moisture deficit was added to the following day's rainfall to account for irrigation in the soil moisture balance model.

Figure 64 shows the calculated irrigation demand for the Paraparaumu/ Waikanae Beach between 1/7/2007 to 1/7/2008 based on soil moisture deficit modelling. Demand peaks seasonally at about 4-5mm/day averaged on a weekly basis.

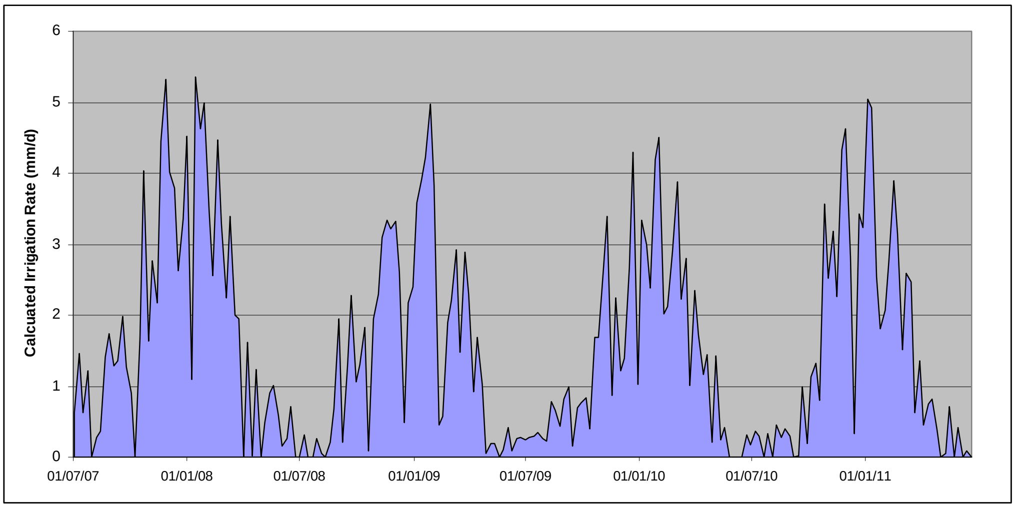


Figure 64: Irrigation demand calculated using the Rushton model for the period 1/7/2007 to 7/1/2011 based on soil moisture deficit modelling and application of irrigation equivalent to the previous day's soil moisture deficit (added to rainfall on the succeeding day)

To account for the estimated irrigable area and number of properties with irrigation wells, the irrigation demand was multiplied by 0.075 (see section 7.6.1(a)). Figure 65 shows the adjusted abstraction values which have been handled in the model using evapotranspiration cells situated over Paraparaumu and Waikanae urban areas

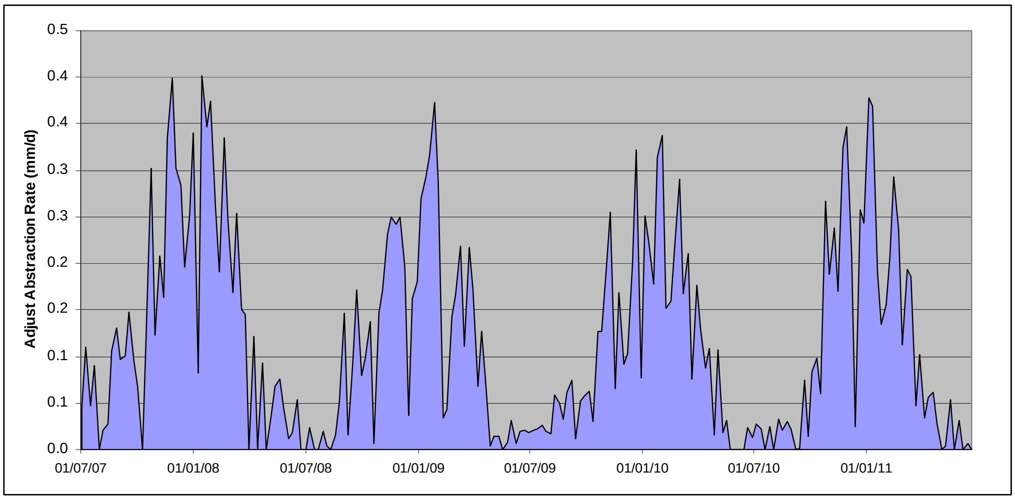


Figure 65: Spatially distributed irrigation rate adjusted to an irrigable area of 15% and the assumption that 50% of properties irrigate their gardens

(c) Validation of well pumping rates and total abstraction

Validation of the modelled irrigation rate can be made using a simple calculation to estimate the rate at which each irrigation bores pumps (estimated to be between 1-3m^3/day

For a hypothetical 250x250 m area:

> No. properties (Class 2): 11-60
>
> No. irrigation wells (50% of properties): c. 15
>
> Irrigable area (7.5%): 0.075 x 250x250 m = 4,700m^2
>
> Peak irrigation rate: 5 mm/day (see Fig 63)
>
> Therefore, peak summer well abstraction rate: (4,700 x 0.005)/15 = 1.6m^3/day

Conservatively assuming there are 4,500 garden wells (there are about 300 Class 2 grid cells in Figure 63; 300 x 15 wells per square = 4,500 wells), this equates to a peak summer abstraction rate of about 7,200 m^3/day – slightly higher than the 5-6,000 m^3/day estimated by the previous study by Jones and Gyopari (2005).

Figure 66 shows the total garden irrigation abstraction calculated using the methodology described above when it is applied to the entire urban areas of Waikanae and Paraparaumu. The annual average abstraction rate is about 2,000m^3/day whilst the peak summer rate is between about 6 and 7,000m^3/day.

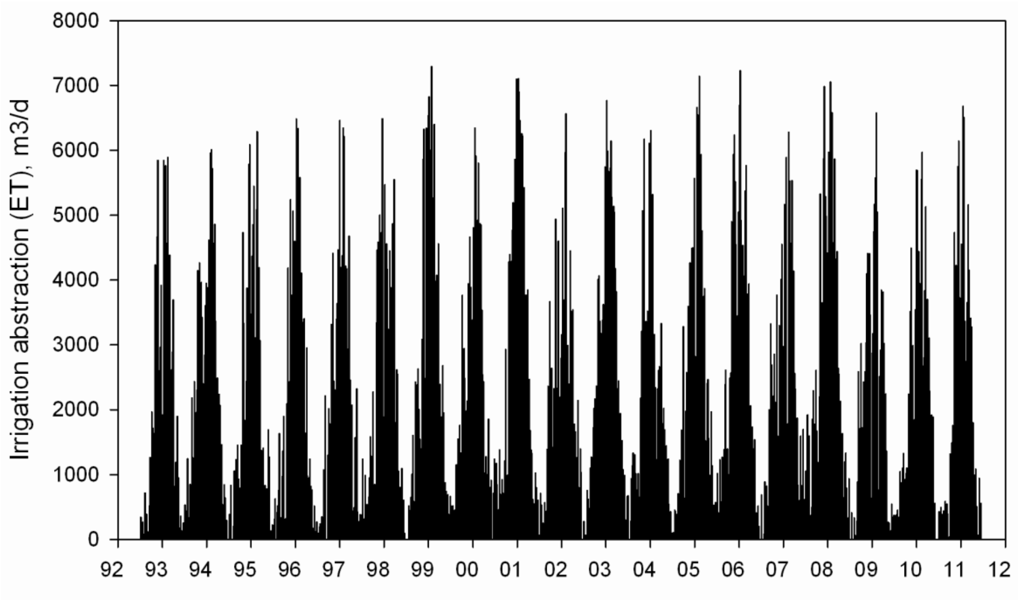


Figure 66: Simulated total abstraction from garden irrigation wells in Waikanae and Paraparaumu for the period 1992 to 2012

7.6.2 Calculation of consented groundwater abstraction

There are 93 consented wells on the Kapiti Coast with a combined consented allocation of 56,800 m^3/day. About 73% of this total is allocated for seasonal irrigation use (primarily for horticulture or cropping). Provision of water for public/community water supply constitutes the bulk of the remaining consented take. Figure 67 shows the historical consented allocation between 1990 and 2010.

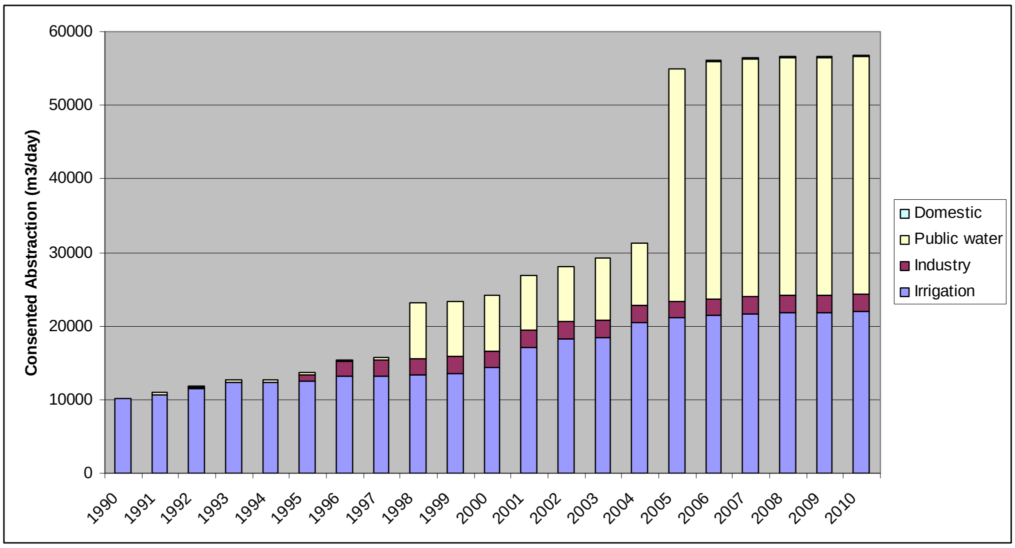


Figure 67: Consented daily allocation on the Kapiti Coast between 1990 and 2010 showing the proportions assigned to different types of user. The jump in abstraction evident in 2005 relates to the consenting of the KCDC wellfield. The plot is not reflective of the actual usage of the groundwater resource, for instance, the KCDC wellfield is a backup supply and has rarely be used to date.

Historic trends in actual groundwater abstraction will differ considerably to the consented trend shown in Figure 68 which only show the maximum daily consented volumes. To obtain an understanding of actual groundwater use is problematic since there has been no consistent monitoring of abstraction from irrigation wells which account for just under half the consented groundwater abstraction on the Kapiti Coast. Public water abstractions in the KCDC Waikanae and Otaki wellfields are however metered.

An estimation of actual seasonal abstraction from the irrigation wells has therefore been attempted using a combination of soil moisture deficit modelling and consented daily rates.

With respect to seasonal irrigation wells, the during and timing of puming will vary from year to year. The annual irrigation ‘window’ was estimated using a soil moisture deficit (SMD) threshold calculated using the soil moisture balance model described in Section 7.5.

Metering data in the Wairarapa region has shown that it is reasonable to assume that irrigation commences when the soil moisture deficit reaches about 20mm (Gyopari and McAlister 2010). Another study in the Motueka Catchment in the Tasman District (Landcare Research pers comm.) found that irrigation tends to commence when the soil moisture is about 0.5 RAW. In tis area ‘aggressive irrigators’ were observed to start pumping when the SMD reached about 15mm when they proceeded to use their full weekly allocation. Other irrigators generally started at a SMD of about 20-30mm in soils with a RAW of about 70mm.

On the Kapiti Coast where the sandy soils have a RAW of about 60mm (Table 14) irrigation should therefore start when SMD is greater than 15mm. Drawing upon the findings in both the Wairarapa and in the Tasman District, it is therefore assumed that irrigation occurs only when the SMD exceeds 20mm. SMD, calculated at a location representative of regional rainfall and soil conditions, has therefore enabled the annual irrigation scheduling (when SMD>20mm) to be estimated. A sandy soil in rainfall Zone 2 was used for this purpose.

The quantity of water abstracted from each irrigation bore is assumed to equal the consented daily rate over the entire irrigation season. This is likely to be a considerable over-estimation of the quantity of water used but, in the absence of metering information, in the context of the regional water balance, the error is likely to be insignificant since consented irrigation usage on the Kapiti Coast is relatively small (about 20,000m^3/day, see Figure 68).

7.6.3 Calculated groundwater abstraction in the Kapiti Coast

Figure 68 shows the total estimated abstraction and annual scheduling of irrigation takes from all Kapiti Coast aquifers for the period 1992 to 2011. Peak summer abstraction is approximately 26,000m^3/day which is considerably less than the consented maximum which stands at about 56,800 m^3/day. The consented maximum includes domestic, public and industrial use groundwater takes. Spikes in the dataset after 2005 relate to when the Waikanae wellfield was used.

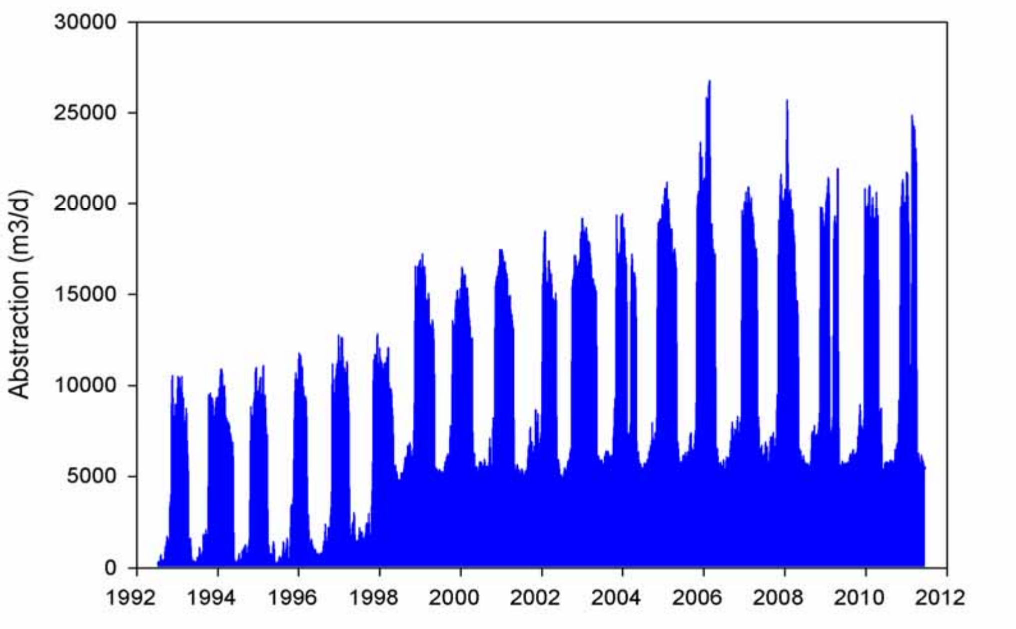


Figure 68: Simulated daily abstraction on the Kapiti Coast between 1992 and 2011

7.7 Hydraulic properties

The hydraulic properties of the hydrostratigraphic units on the Kapiti Coast were discussed for each of the groundwater management zones in Chapters 3 to 6. Table 20 contains a summary of hydraulic conductivity ranges for the different hydrostratigraphic units within each of the groundwater zones based upon pumping test information.

Table 20: Summary of hydraulic conductivity characteristics for hydrostratigraphic units on the Kapiti Coast (m/day). Large ranges reflect pumping test analyses large degree of heretogeneity in each unit.

Hydrostratigraphic unit	Groundwater Zone			
	Raumati	Waikanae	Te Horo	Otaki
Q1-Holocene sand	2-5	2-5	2-5	2-5
Q1 river alluvium	50-100 (Q1+ gravel lenses)	50-100	50-100	250-500
Pre Q1 deposits				
Q2 (‘aquifer’)	2-5 (sand)	10-50	10-20	5-20 (250-500)*
Q3 (‘aquitard’)	“	1-10	1-10	n/a
Q4 (‘aquifer’)	“	10-50	5-20	4
Q5 (‘aquitard’)	“	1-20	1-10	1-10
Q6 (‘aquifer’)	“	10-30	5-20	5-10
Q7+.	“	<5	<5	<5
Foothill alluvium	2-10	2-10	2-10	1 - 7

* in area of Tasman Road bores, local Q2 hydraulic conductivity exceeds 1000m/d

Kv – Waikanae borefiled testing: 3e-8 to 3e-9 Q5 sand aquitard

Aquifer storage properties are less well defined for Kapiti Coast aquifers. Storage parameters were estimated from the conceptual model, BECA (2012) and also through model calibrations. Storage parameters for the four groundwater management zones are are sumarised in Table 21.

Table 21: Summary of storage characteristics (unitless) for hydrostratigraphic units on the Kapiti Coast. Large ranges reflect pumping test analyses large degree of heretogeneity in each unit.

Hydrostratigraphic unit	Groundwater Zone			
	Raumati	Waikanae	Te Horo	Otaki
Q1-Holocene sand	0.001	0.002	0.002	0.002
Q1 river alluvium	$5x10^{-4}$-$5x10^{-7}$	0.25	0.15	0.25
Pre Q1 deposits				
Q2 ('aquifer')	$9.8x10^{-7}$	$5x10^{-4}$-$5x10^{-7}$	$9.8x10^{-7}$	$9.8x10^{-7}$
Q3 ('aquitard')	$5x10^{-4}$-$5x10^{-7}$	$5x10^{-4}$-$5x10^{-7}$	$5x10^{-4}$-$5x10^{-7}$	n/a
Q4 ('aquifer')	$5x10^{-4}$-$5x10^{-7}$	$2x10^{-7}$	$2x10^{-7}$	$2x10^{-7}$
Q5 ('aquitard')	$5x10^{-4}$-$5x10^{-7}$	$8x10^{-6}$	$8x10^{-6}$	$8x10^{-6}$
Q6 ('aquifer')	$5x10^{-4}$-$5x10^{-7}$	$8x10^{-6}$	$8x10^{-6}$	$8x10^{-6}$
Q7+.	$5x10^{-4}$-$5x10^{-7}$	$1x10^{-6}$	$1x10^{-6}$	$1x10^{-6}$
Foothill alluvium	0.01	0.01	0.01	0.01

7.7.1 Hydraulic conductivity zonation

Development of the hydraulic property zonation framework for the Kapiti Coast groundwater system has maintained consistency with the conceptual hydrogeological model presented in Chapters 3-6 and further refined for the numerical as summarised in Table 13. The adopted framework was used by the parameter estimation model (PEST).

Figures 68 shows the hydraulic conductivity zones assigned to each of the model layers.

Groundwater parameter zonation was developed using a combination of horizontal and vertical conductivities. Hydraulic conductivity zones are as presented in Table 13.

A) Layer1

There are seven distinct hydraulic conductivity zones in Layer 1 (K2, K3, K4, K6, K7, K13, K23) for the Kapiti Coast groundwater region. K2 represents the Holocene (Q1) sand that is characterised by medium to fine sand with discontinuous layers of gravel and silt/peat. This conductivity zone extends from the Waikanae zone to the Otaki zone and is modelled to extend further offshore. The calibrated hydraulic conductivity for this zone is 5 m/d (horizontal) and 0.05 m/d (vertical). A lower hydraulic conductivity of between 1-2 m/d is reported in the conceptual model. The Holocene sands show a reduction in both horizontal and vertical hydraulic conductivity in southern parts of the Waikanae and the Raumati groundwater zones. The lower conductivity zones are classified as the K10 zone. This zone is predominant in all layers of the Raumati groundwater zone and also was modelled to extend off-shore.

This layer also contains highly permeable unconfined aquifer Q1 gravels that are hydraulically connected to surface water systems of the Waikanae and Otaki rivers. The zonation for these gravels are K3 (Waikanae) and K4 (Otaki). The K3 hydraulic conductivity zonation has been calibrated as 250 m/d and K4 as 300 m/d. Both calibrated values are consistent with the conceptual model horizontal hydraulic conductivity values of between 250-500 m/d for these zones. Vertical hydraulic conductivity was calibrated as 0.5 m/d for both zones. Layer 1 is also characterised by K6 alluvial fan accumulation along footslopes of the Tararua range. The K6 zone has been calibrated as 5 m/d (horizontal) and 0.52 m/d (vertical) hydraulic conductivities. The K6 zone is found in all groundwater management zones and extends into deeper formations in all areas. The derived K6 values are consistent with the conceptual model derived hydraulic conductivity values of between 5-10 m/d. The K6 zone forms an important medium for shallow and deep aquifer recharge through seepage at the foothills of the Tararua range.

Layer 1 also consists of Q2 alluvium materials with varied hydraulic conductivity zones such as the moderately to poorly sorted gravel and sand unconfined/semi-confined aquifers in the Waikanae (K13). K13 hydraulic conductivity values of 18 m/d (horizontal) and 1.8 m/d (vertical) are consistent with those reported in the conceptual model Figure 31 (i.e. 10-15 m/d) and also derived from KCDC wellfield bore testing and recent 2012 testing as presented in Table 3. The GeoMean horizontal hydraulic conductivity for the Q2-4 at this location was calculated at 18 m/d. The Q2 alluvium also characterise the weathered gravel sands (K7) in the Te Horo and Otaki groundwater zones and also claybound gravels (K23) of the Te Horo zone.

Layer 2

The dominant zones in layer 2 are Raumati (K10, K6), Waikanae (K13, K6) and Te Horo (K7,K23) and Otaki (K3,K7,K21). The modelled hydraulic conductivity zonation is consistent with the conceptual models for each of the groundwater management zones.

Layer 3

The dominant zones in layer 3 are Raumati (K10,K6), Waikanae (K8,K6), Te Horo (K16) and Otaki (K7,K6). The K8 and K16 are characterised by Q2 silt, sand and organics which are present in both the Waikanae and Te Horo zones as narrow typically 10-15 meters thick heterogenous deposits. The calibrated and conceptualised horizontal hydraulic conductivity for these sands are 5 m/d (K8) for the Waikanae and 3 m/d (K16) for the Te Horo zone.

Layer 4

The dominant hydraulic conductivity zones are Waikanae (K13), Te Horo (K7), and Otaki (K7). The K13 gravel and sand in the Waikanae are described as Q4 with similar properties to Q2 gravels and sands as shown by the conceptual model in Figure 31 and also as derived from pumping test data. In the Te Horo and Otaki groundwater management zone they are presented as weathered gravels and sands of the Q6 era with slightly lower hydraulic conductivity of between 5-10 m/d. The calibrated hydraulic conductivity of 13 m/d for this zone is slightly higher.

Layer 5

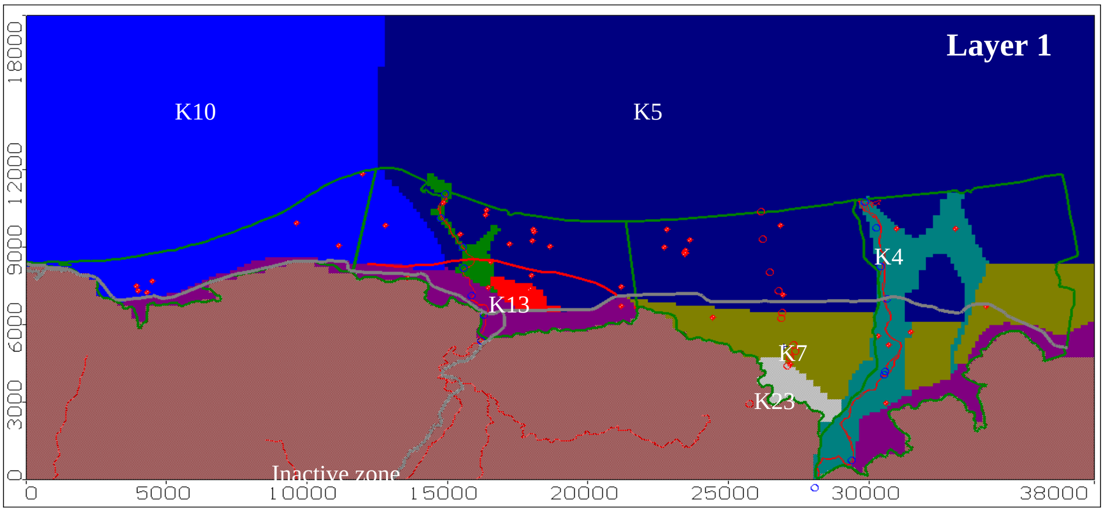
Layer 5 is described in the conceptual model as an aquitard that is present in the Waikanae and Te Horo groundwater management zones. The conceptualised hydraulic conductivity for these zones is 1-2 m/d. This layer is described in the conceptual model as a dense/cemented medium to fine sand in the Otaki zone. The conceptualised hydraulic conductivity of 25 m/d is contrary to the description of a relatively low hydraulic conductivity aquifer system. The calibrated hydraulic conductivity zone for the Waikanae was K9 (2.5 m/d horizontal and 3e-4 m/d vertical) that is consistent with the conceptualised conductivity value. The calibrated zonation (K16) for the Te Horo and Otaki is 3.1 m/d.

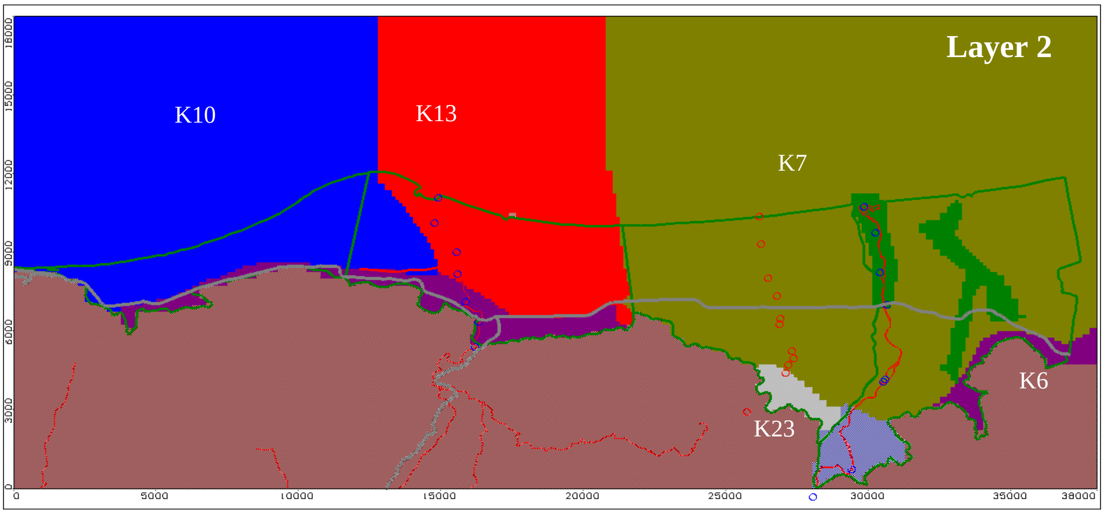
Layer 6

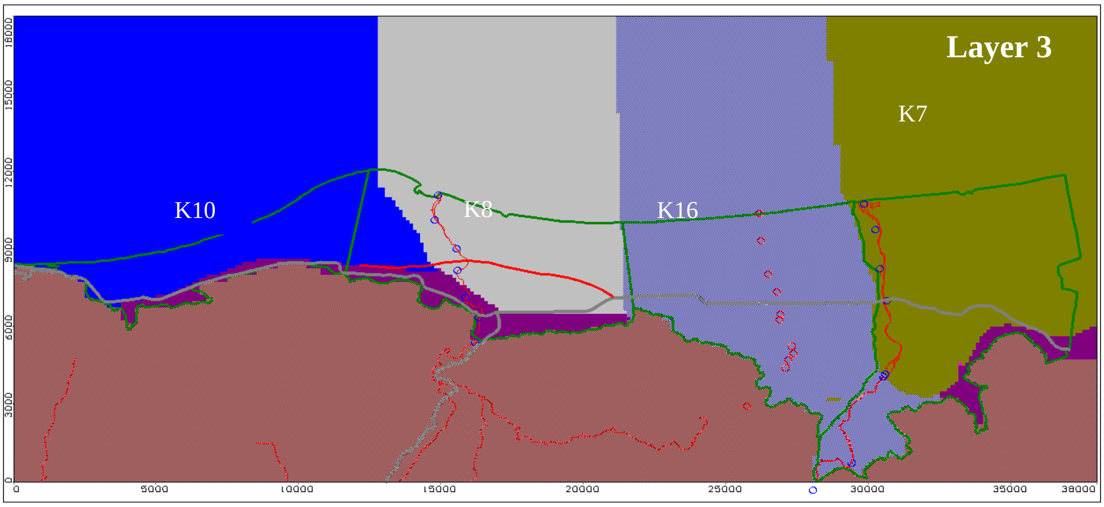
Layer 6 comprises of the Q6 gravels and sands aquifer systems. This formation is present in the Waikanae as the main deep aquifer system. The calibrated hydraulic conductivity of K11 (20 m/d) is similar to that derived through pumping tests and is higher than suggested in the conceptual model (5-10 m/d). In the Te Horo and Otaki zones, this layer was calibrated as consisting of the K8 (5 m/d) i.e similar to the conceptualised horizontal conductivity values. The Q6 gravels become increasingly thick towards the sea with thicknesses of more than 40 m off-shore.

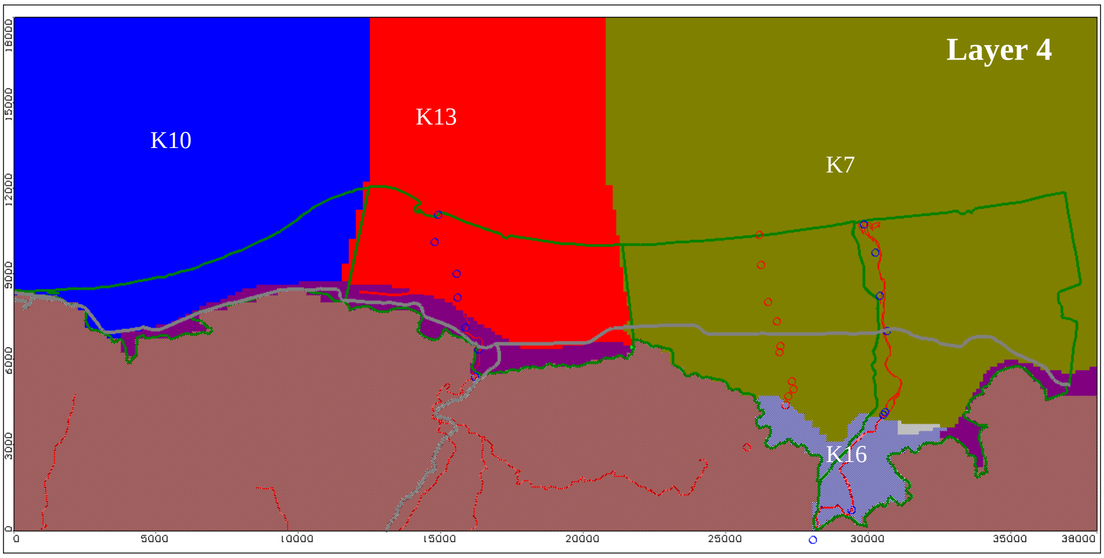
Layer 7

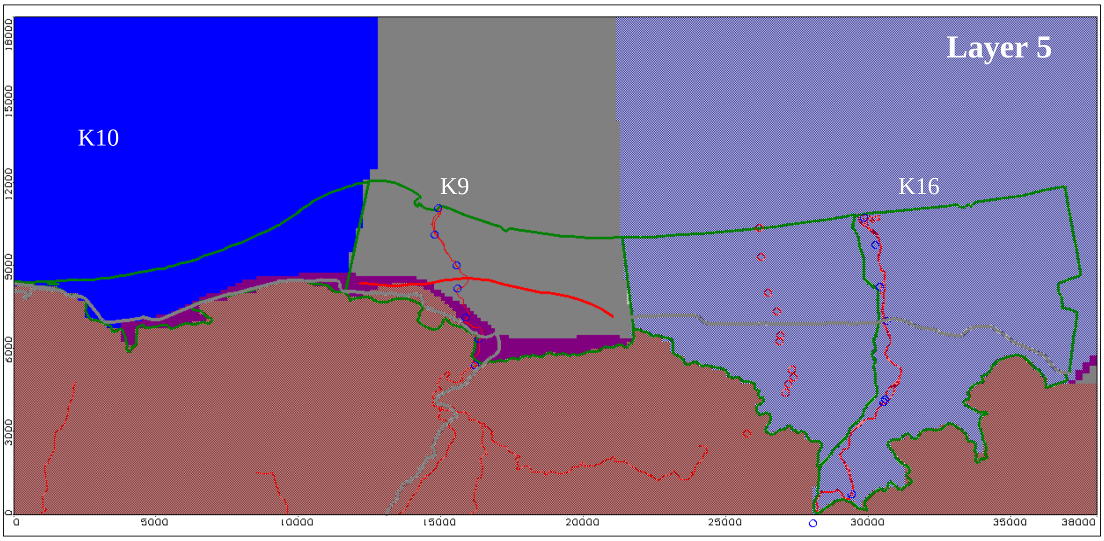
Layer 7 was calibrated as a separate layer, however the properties in this layer are similar to those in Layer 6.

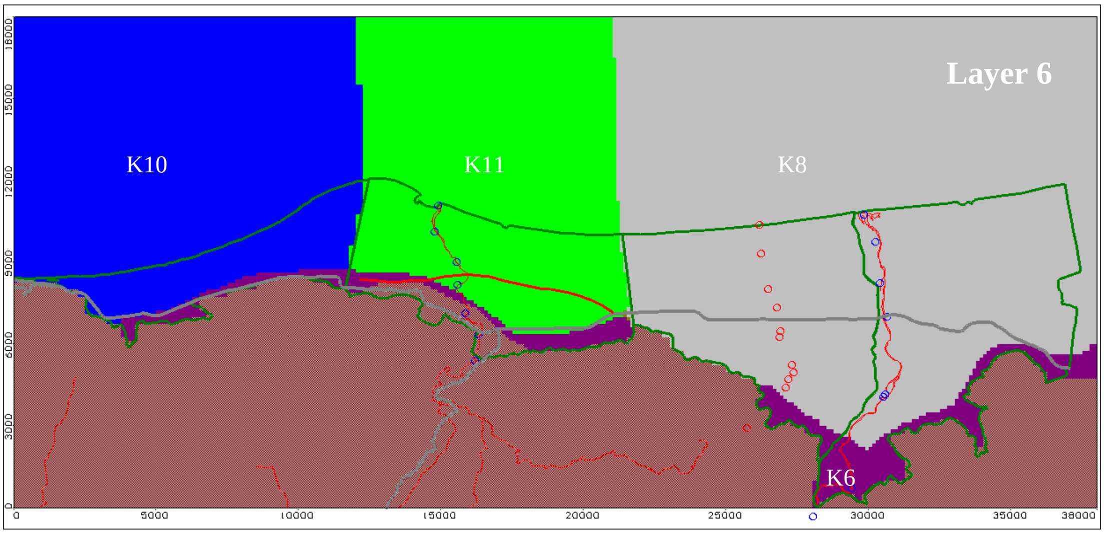

Layer 1
K10
K5
K4
K13
K7
K23
Inactive zone
0
3000
6000
9000
12000
18000
0
5000
10000
15000
20000
25000
30000
38000


Layer 2
K10
K13
K7
K6
K23


Layer 3
K10
K8
K16
K7


Layer 4
K10
K13
K7
K16
0
5000
10000
15000
20000
25000
30000
35000
38000


Layer 5
K10
K9
K16
0
5000
10000
15000
20000
25000
30000
35000
38000


Layer 6
K10
K11
K8
K6
0
5000
10000
15000
20000
25000
30000
35000
38000

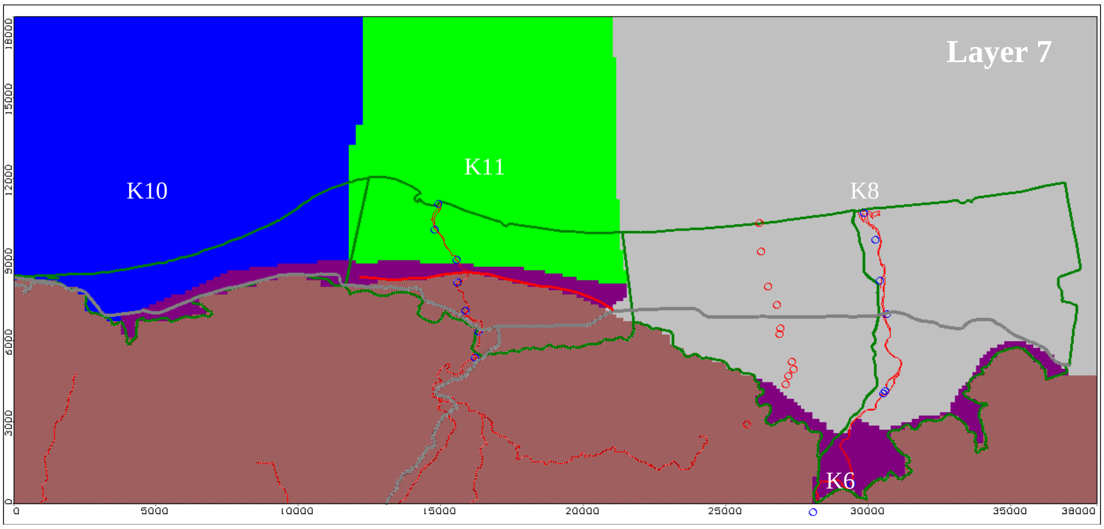


Figure 69: Hydraulic conductivity zones used in the numerical model for the Kapiti Coast showing different zones. The conductivity zones are transitional in terms of both spatial and transverse directions. K zones represent hydraulic conductivity values in both horizontal and vertical directions (Kx, Ky) for example K11 represents Kx11 and Kz11 where Ky11 is assumed to be equal to Kx11.

7.7.2 Specific yield and specific storage zones

The specific yield (unconfined storage) and specific storage zones are assigned to all layers. The model is set to either use the specific yield or specific storage depending on aquifer confinement conditions.

8. Model calibration

8.1 Calibration procedure

The Kapiti Coast MODFLOW model is categorised as an aquifer simulator of high complexity (Middlemis 2001) which has a prediction-focused purpose. The calibration methodology has therefore been designed to maximise prediction reliability using the procedure described below.

The model calibration process entails the adjustment of independent variables (parameters and fluxes) within realistic limits to produce the best match between simulated and measured data (groundwater levels and water balance components such a spring flows and measured river flow losses/gains). As such, the calibration process has an inverse approach through the adjustment of parameters such as hydraulic conductivity, storage coefficient and stream bed conductances until the solution matches observed data.

Calibration is a necessary but, on its own, not a sufficient condition that must be obtained to have a degree of confidence in model predictions. It shows that a model can reproduce system behaviour under a certain set of conditions (Middlemis 2001). Sensitivity analysis must also accompany the calibration process to assess uncertainties inherent in the calibration.

Calibration traditionally involves a manual trial and error process of systematic parameter adjustment until a relatively good fit between simulated and observed data is achieved. The manual process is time-consuming and subjective, but nevertheless a valuable first step in the model calibration process through which the conceptual model can be tested and the sensitivity of input parameters evaluated and adjusted if necessary. Automated calibration using inverse parameter estimation algorithms (such as PEST) removes some of the subjectivity of manual trial-and-error process and provides an insight to the ‘non-uniqueness’ of a model.

Manual calibration under steady state conditions was initially undertaken as a first step for the Kapiti Coast model as part of the process to evaluate and adjust the conceptual model. This was followed by a manual transient flow calibration phase to obtain a sense of model sensitivity and further test the appropriateness of the conceptual model and boundary conditions and to tune the hydraulic conductivity zonation framework.

Following completion of a manual ‘pre-calibration’ phase, the automated parameter estimation code PEST was utilised to optimise the calibration, perform a sensitivity analysis and provide information on the uniqueness, or robustness, of the calibration. The PEST calibration was performed over a three-year period during which a wide range of system stresses occurred. Lastly, a verification run was performed over a 19-year period.

8.2 Minimising non-uniqueness

Non-uniqueness is inherent in most complex groundwater flow models and arises because a number of different parameter sets can produce the same model outputs – i.e. multiple calibrations are possible using different combinations of model inputs because certain parameters (such as recharge and transmissivity) are highly correlated. The matching of measured heads alone by a ‘calibrated model’ does not mean that the hydraulic properties used in the model are correct and that the model can be confidently used for predictive purposes.

The MDBC (Middlemis 2001) modelling guidelines suggest that the following methods should be conjunctively employed to reduce the non-uniqueness of a model:

- Calibrate the model using hydraulic conductivity (and other) parameters that are consistent with measured values. The range for various parameters is justifiably restricted.

- Calibrate the model to a range of hydrogeological conditions (a wide range of climate and induced stresses such as abstraction).

- When possible, calibrate the model using measured water balance fluxes (such as spring flows, river losses/gains) as calibration targets.

The three recommendations have been implemented in the Kapiti Coast model as described below.

With reference to requirement a), during model calibration, hydraulic conductivity ranges have been guided by the pumping test analyses (Table 20) for the main aquifer units which were referenced during the calibration process as constraints.

To address requirement b), the transient model calibration and verification period covers a 19-year period over which both climate stresses and abstraction stresses have experienced a large variation. Figure 70 and Figure 71 illustrate the range in both calculated recharge (reflecting climatic conditions) and abstraction over the 19 year calibration period.

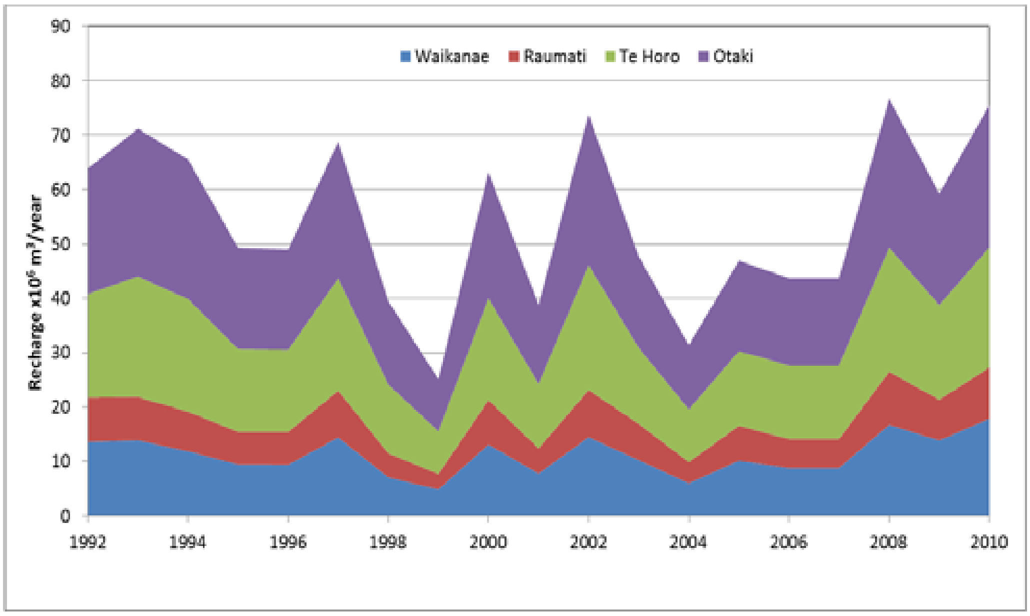


Figure 70: Summation of annual recharge calculated for the four groundwater management zones in the Kapiti Coast for the period 1992 to 2011

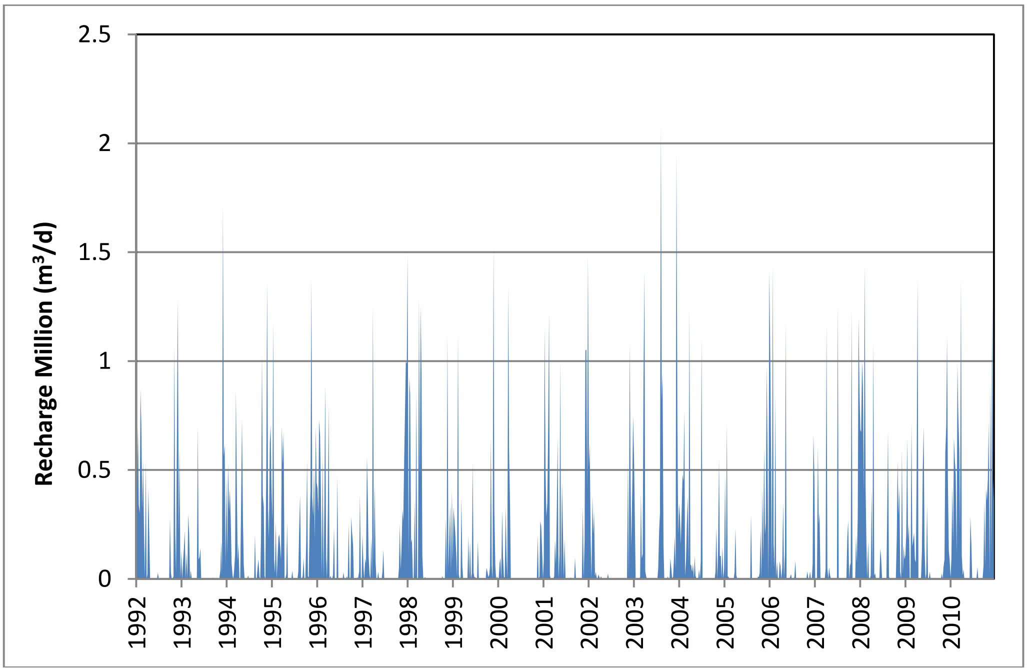


Figure 71: Modelled rainfall recharge for the Kapiti Coast catchment for the period 1992 to 2011

In terms of requirement c), Chapters 3-6 provide a description of the surface water–groundwater connection characteristics, and also provide quantification of some of the fluxes between the two systems (such as spring discharges, spatially patterns and amounts of river flow losses and gains). This data has been used to verify the calibration process to ensure that the simulated water balance is comparable to observed data.

8.3 Calibration evaluation

Model calibration has been evaluated in both quantitative and qualitative terms.

Quantitative measures included:

- Mathematical and graphical comparison between measured and simulated heads.
- Comparison between simulated and measured water balance components. Measured flow losses and gains in rivers (Chapters 3-6) and spring flows were used to constrain the calibration.

The qualitative assessment of the calibration entailed comparing simulated and observed groundwater flow patterns, comparison of model outputs with the conceptualization of the groundwater system, and evaluation of the patterns of groundwater-surface water interaction with reference to observed patterns.

The MDBC (Middlemis 2001) modelling guidelines provide a list of calibration acceptance measures which have been adopted here. The measures are summarized in Table 22.

Table 22: Calibration Acceptance Measures (after Middlemis 2001)

	Performance Measure	Criteria	Comments
1	Water balance/ numerical error: The water balance error term at the end of each model time step is the difference between total modelled inflow and total modelled outflow, including changes in storage, expressed as a percentage of total flux.	A value of less than 1% is a normal guideline for each stress period or for the entire simulation (steady state).	
2	Iteration residual error: The error term is the maximum change in heads between successive iterations.	Iteration convergence criterion should be set one or two orders of magnitude smaller than the level of accuracy desired in the model head results.	
3	Qualitative measures: Patterns of observed groundwater flow. Patterns of groundwater-surface water interaction. Patterns of aquifer response to stresses. Distributions of aquifer properties adopted to achieve calibration.	Subjective assessment of the accuracy of fit between modelled and measured groundwater levels, flow patterns, bore hydrographs, and surface water flows. Justification for adopted model aquifer property zonation and ranges of values.	Should take into consideration the adopted conceptual model, particularly relating to surface water interaction, model descretisation effects and interpolation effects.
4	Quantitative measures: Statistical measures of the differences between modeled and measured head data. Mathematical and graphical comparisons between	Use residual head statistics. Consistency between modeled head values and observed values. Comparison of simulated and measured components of the water	A range of quantitative measures should be carefully selected for use in the calibration procedure.

	Performance Measure	Criteria	Comments
	measured and simulated aquifer heads, and flow system components.	budget, including surface water flows, groundwater abstraction and evapotranspiration rates.	It is expected that any model calibration is unlikely to be good in all areas, but it should be good in critical areas.

8.4 Preliminary steady-state calibration and mass balance

It is customary practice to use a steady state simulation to test the conceptual model, ensure that the parameter zonation framework is appropriate, and check that the model predicts a realistic water balance consistent with the estimated fluxes (discussed in Section 7). The steady state process additionally serves to check on the model set-up and identify any technical problems prior to proceeding with the transient model calibration.

When an aquifer is in 'steady state', inputs and outputs (and therefore groundwater heads) are assumed to remain constant. In other words, the groundwater system is in equilibrium. True equilibrium conditions rarely occur in any groundwater system especially those which are dominated by volatile river-aquifer fluxes and highly variable rainfall recharge processes. Periods when heads and fluxes remain stable over a relatively long period of time, such as late summer or late winter, are the closest that an equilibrium condition is approached.

A preliminary steady state calibration was achieved for the period 09 March 2011 (summer conditions) and 08 June 2011(winter conditions) by manually calibrating the model to head targets prior to embarking on the transient calibration phase.

8.4.1 Results

The results of the steady state calibration run are shown in Figure 72 and the calibration statistics are shown in Table 23. The overall residual mean of the calibration is encouragingly low for both summer and winter conditions being -0.055 and -0.076 m, respectively. The highest residuals of 1.328m and -2.033 m for summer and winter conditions were for wells situated high on the fan areas. The highest summer residual was for well R26/6378 in the Waikanae groundwater zone and the highest winter residual was for well R25/5111 in the Te Horo groundwater zone. This indicated that that some adjustment in the model parameter zonation may be required in these areas. However, these maximum residuals are deemed characteristically low for such a regional groundwater model.

The scatter diagram (Figure 72) also shows that there is no systematic error involved in the spatial distribution of differences between modeled and measured heads i.e. there is no systematic over-or under prediction of heads.

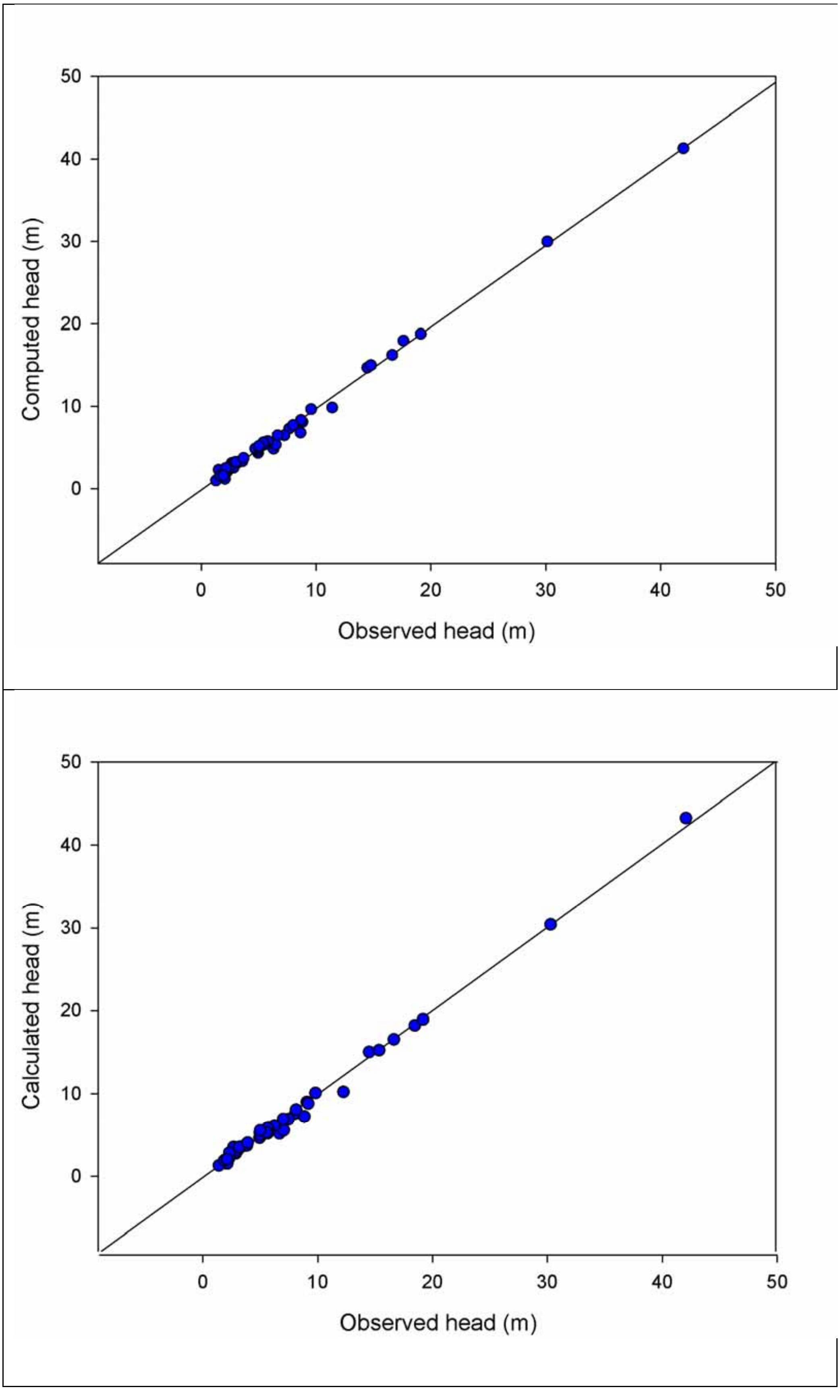


Figure 72: Steady state model head calibration model to observed fit scatter plot for summer (top plot) and winter (bottom plot). Head calibration statistics are shown in Table 23. Head data is relative to absolute mean sea level (amsl).

Table 23: Steady State calibration statistics for the Kapiti Coast model

Statistical performance measure	Calibration Statistic-Summer	Calibration Statistic-Winter	Unit
Absolute residual mean	0.332	0.356	m
Min residual	0.017	-0.005	m
Max residual	1.328	-2.033	m
Sum of residuals	-2.77	-3.90	m
Residual standard deviation	0.062		m
Observed range in head	40.85	40.66	m
Mean of residuals	-0.055	-0.076	m
Standard Error of Estimate	0.016	0.08	m
Sum of residual squares	9.51	16.46	m
Root mean square (RMS) error	0.436	0.568	m
Normalised RMS	1.067	1.397	%
Correlation Coefficient	0.999	0.997	Unit

The root mean square (RMS) statistic is an absolute measure of the calibration that is problem specific (its value is affected by the measured values). It is a good error indicator, along with the scaled RMS. The scaled RMS of less than 2% indicated that the ratio of error to total head differential is small and indicative of good match between measured and observed groundwater levels, flow gradients and flow patterns.

At a regional scale, in a heterogeneous aquifer system, the calibration is regarded as a good initial simulation and provides confidence in the conceptualization of the flow system, and the assumptions that have been adopted.

8.4.2 Steady state mass balance

A steady state water balance for typical summer and winter conditions was undertaken by selecting two days with rainfall that represented a 25 and 75 percent quartile daily rainfall. The lower and upper quartile days selected were the 23/04/2008 and 05/08/2009. The steady state mass balance (inflow and outflow rates) for these days is shown in Table 24. Inflows are river recharge and rainfall recharge. Outflow from the groundwater system is dominated by four mechanisms – discharge back into the rivers, discharge to drains, abstraction and discharge to sea.

Table 24: Steady state mass balance

Flow Component	Summer (23/04/2008)		Winter (05/08/2009)	
	Inflows (m3/d)	Outflows (m3/day)	Inflows (m3/d)	Outflows (m3/day)
Rivers Drains	152617	179361 72706	188350	211214 103215
Abstraction		14655		5967
Rainfall recharge	73523		242055	
Sub-coastal discharge to Sea		72567		89916
Totals	226140	339289	430465	410312
Change in storage	-113149		20153	

Comparison between the steady state model output and the estimated water balance for the catchment presented in Table 24 shows that the simulated flows agree relatively well will the estimated flow budget and that there is an ‘order of magnitude’ agreement. This result is encouraging as it provides confidence in the conceptualization of the groundwater system, including boundary condition assignment and aquifer stress conditions.

8.5 Transient calibration

8.5.1 Transient calibration set-up

The transient calibration model was set up using 4 years of data for the period 1/72008 – 21/6/2011. The relatively short time period was selected to ensure workable model run times for the PEST-automated calibration process. The calibration period incorporates a wide range of climatic conditions and covers the period over which groundwater abstraction significantly increased. It therefore represents a window of time in which there was a large range in system stresses to facilitate a more robust calibration.

Following the automated PEST calibration using the 4-year dataset, a verification run was performed using monitoring data covering the period 1 July 1992 to 21 June 2011 (19 years) i.e. inclusive of the of the period used in the calibration. Normally, data used in the calibration is excluded from the verification exercise, however in this case the data was included as the last four years of simulation was a period of increased abstractions and a wide range of climatic conditions. The four year period is relatively short when compared to the 19 years of simulation such that the inclusion of the calibration period did not result in simulation bias towards calibrated data.

The transient groundwater model was run with a weekly stress period - consistent with the temporal responses of the groundwater system to stresses and monitoring data availability.

8.5.2 Automated calibration (PEST)

Calibration of the transient model has been undertaken using the ‘PEST’ inverse model (Version 11; Doherty 2008) in ‘parameter estimation mode’. The PEST automated calibration process was undertaken for the period

1/72008 – 21/6/2011 using groundwater level observation targets and also water balance data relating to fluxes between the aquifer and surface water systems.

PEST utilised the parameter zonation framework described in Sections 7.3-7.8. The PEST inverse model was initially run for a single iteration to identify highly correlated parameters and insensitive parameters, resulting in the fixing of some parameters prior to proceeding to the automated calibration process.

A total of 57 'unknown' hydraulic conductivity (horizontal and vertical) and unconfined and confined storage parameters were initially presented for estimation by PEST. The unknown parameters were allowed to vary between prescribed upper and lower bounds whilst the objective function was minimised. The bounds were prescribed on the basis of pumping test data and plausible ranges for the type of material contained within the zone. As parameters reached their bounds or became insensitive during the PEST inversion process, additional zones were fixed (or tied to other zones) by manual intervention of the PEST run. Table 25 lists the initial unknown parameter zones.

Table 25: Kapiti Coast model transient PEST calibration parameter zone designation (Kx-horizontal hydraulic conductivity Kz-vertical hydraulic conductivity, Sy- specific yield, Ss- specific storage, Kx and Ky values are in m/day) Ky- lateral hydraulic conductivity was assumed equal to Kx. All PEST estimated parameters are log-transformed. Hydraulic conductivity values are in m/d and storage values are unitless.

Unknown parameter	Initial value	Lower bound	Upper bound	Fixed parameter	Value
Kx02	5	1	10	Kx01	10
Kx04	300	100	450	Kx02	5
Kx06	5	1	10	Kx06	5
Kx07	10	1	20	Kx08	5
Kx10	2.5	1	5	Kx09	2.5
Kx11	20	1	50	Kx13	18
Kx12	1.5	0.5	5	Kx17	5
Kx14	2.5	1	5	Kx22	30
Kx16	5	0.5	10	Kx18	500
Kx19	10	1	30	Kx15	200
Kx20	2.5	0.5	10	Kx03	250
Kx21	2.5	0.5	10	Kz03	0.5
Kx23	5	1	10	Kz04	0.5
Kz01	0.2	0.01	1	Kz21	0.01
Kz02	0.05	0.01	1	Kz22	0.2
Kz05	0.15	0.001	1	Kz03	0.5
Kz06	0.5	0.01	2	Kz04	0.5

Unknown parameter	Initial value	Lower bound	Upper bound	Fixed parameter	Value
Kz07	0.1	0.01	1	Kz21	0.01
Kz08	0.5	0.01	2	Kz22	0.2
Kz13	1.8	0.01	5	Kz09	0.0003
Kz14	0.05	0.0001	1	Kz10	0.0014
Kz18	50	1	100	Kz11	0.1993446
Kz23	0.003	0.00001	0.1	Kz12	0.6090436
Ss1	4.24E-06	5.00E-07	5.00E-03	Kz15	1.6
Ss2	1.00E-05	5.00E-07	5.00E-03	Kz16	0.4
Ss3	9.76E-06	5.00E-07	5.00E-03	Kz17	0.2179385
Ss4	1.00E-05	5.00E-07	5.00E-03	Kz19	0.01
Ss5	1.02E-07	1.00E-08	1.00E-04	Kz20	0.00379235
Ss6	9.08E-07	1.00E-08	1.00E-04	Kz21	0.0100179
Sy1	0.4	1.00E-02	5.00E-01		
Sy2	0.2500306	1.00E-02	5.00E-01		
Sy3	0.2494127	1.00E-02	5.00E-01		
Sy4	0.248816	1.00E-02	5.00E-01		
Sy5	0.1	1.00E-02	5.00E-01		
Sy6	0.15	1.00E-02	5.00E-01		

8.5.3 Calibration targets,observation data processing and weighting

Figures 8, 14, 31 and 41 show the locations of bores used in the model calibration. The bore details are listed in Table 26. The sites are distributed throughout the study area and measure groundwater levels at various depths ranging from less than 1m to more than 40m amsl. The data were processed to provide a representative value every seven days resulting in 16,150 head observations at the 50 monitoring sites.

The Waikanae zone had most head observations (7047), the Te Horo zone had 3793, the Raumati zone (2195) and the Otaki zone had 3115 observations. Monitoring data for bores with automatic recorders were averaged over seven days, whilst manually collected groundwater level monitoring data were used in their raw form in the calibration. The observed data points were extrapolated to the model output times at the end of each stress period. Monitoring well screens were set upon specific layers dependent upon the screen locations in each well. Where screen information was not available, screens were assumed to be located at the bottom end of the bores.

All monitoring bores were assigned a similar calibration weighting of 1 regardless of whether they were dedicated monitoring bores (either manually recorded or continuously recorded). Such an approach was deemed necessary in order to calibrate localised effects of pumping on groundwater levels.

Table 26: Kapiti Coast catchment transient model groundwater level calibration target bores -refer to Figure (Raumati), Figure 14 (Waikanae; Figure 31 (Te Horo) and Figure 41 (Otaki) for locations

Name	Station type	Name	Monitoring record	Screen depth (m)	Aquifer	Model Layer	Calibration
TE HORO ZONE							
R26/6861	MGW	Housiaux 1	25/11/04 -	6-Jul	Q1	1	1
R26/6879	AGWT	Housiaux 2	25/11/04 -	4.4-5.4	Q2	1	1
R26/6936	MGW	Housiaux 2b	23/2/05 -	2.2-5.2	Q3	1	1
R26/6880	MGW	Housiaux 3	25/11/04 -	6.6-7.6	Q4	1	1
R26/6881	CAGW	Housiaux 4	21/9/04 -	6.5-7.5	Q1	1	1
R26/6882	MGW	Housiaux 5	25/11/04 -	8.5-9.7	Q2	1	1
R26/6883	MGW	Housiaux 6	25/11/04 -	4-May	Q3	1	1
R25/5262	AGW	Jensens Deep	26/03/09 -	89.97	Q6?	6	1
R25/7086	AGW	Jensens Shal	30/03/09 -	4.3	Q4	1	1
R25/7087	AGW	Jill and Joys	30/03/09 -	4.5	Q1	1	1
R25/0003	AGW	Sims Road South	28/3/85 -	57.5-60.5	Q4	4	1
R25/5241	CAGW	Spencer	4/2/02 - 10/12/02	13-16	Q1	1	1
R25/5171	CAGW	Stevenson	15/4/09 - 25/6/10	51?	Q2?	3	1
S25/5208	AGW	Centrepoint	19/12/91 -	160m?	Q6?	7	1
S25/5200	MGW	Common Property	12/3/93 -	32-46	Q2	1	1
R25/5111	MGW	Jamieson	26/02/93 -	37.5-49.7	Q2	2	1
S25/5256	MGW	Penray	26/2/93 -	26.5-30.8	Q2	2	1
R25/5135	MGW	Windsor	30/6/82 -	83-93	Q6	5	1

Name	Station type	Name	Monitoring record	Screen depth (m)	Aquifer	Model Layer	Calibration
WAIKANAE ZONE							
R26/6284	AGW	Waikanae Park	14/7/03 -	87-90.1	Q6?	7	1
R26/6287	AGW	Rangihiroa St	16/12/02 -	3-Jun	Q1 Sand	1	1
R26/6377	CAGW	Waikanae Golf Club KCDC	11/5/05 - 5/2/07	118?	Q6?	7	1
R26/6378	AGWWQ	Rutherford Dr KCDC	13/9/06 -	122?	Q6?	7	1
R26/6557	MGW	Mazengarb Sh KCDC	23/3/93 -	23-26	Q1 Sand	1	1
R26/6558	CMGW	Mazengarb Deep	15/12/95 - 1/2/07	91?	Q6?	7	1
R26/6566	AGWWQ	Estuary Shallow	18/2/15 -	52-53	Q2	5	1
R26/6569	MGW	NZ Staff College	23/02/93 -	33-45	fan	2	1
R26/6594	AGW	WCHP Deep	30/5/94 -	73-74	W6	6	1
R26/6626	MGW	McLauchlan	26/2/93 -	15.8 ?	Q1 Sand	1	1
R26/6673	AGWWQ	Taiata Shal	18/2/05 -	32-38	Q2?	3	1
R26/6738	MGW	McCardle	26/2/93 -	?	?	1(est)	1
R26/6747	MGW	Quinn	30/6/82 -	55-69.5	Q2	4	1
R26/6884	MGW	Te Harakeke 1	14/05/02 -	5.5-6	Q1 Sand	1	1
R26/6885	MGW	Te Harakeke 2	14/5/02 -	5.5-6	Q1 Sand	1	1
R26/6886	AGW	Te Harakeke 3	14/5/02 -	5.5-6	Q1 Sand	1	1
R26/6916	AGW	WCHP Shall	10/8/94 -	20-21	Q1 Sand	1	1
R26/6955	AGWWQ	Taiata St Deep	18/2/05 -	44-46	Q2	2	1

Name	Station type	Name	Monitoring record	Screen depth (m)	Aquifer	Model Layer	Calibration
R26/6956	AGWWQ	Estuary Deep	18/2/05 -	76-78	Q6?	6	1
R26/6991	AGW	Nga Manu	18/11/05 -	3.7-4.7	Q1 Sand	1	1
R26/6992	AGW	KCDC K6	18/11/05 -	4.1-7.1	Q1 Sand	1	1
R26/7025	AGW	KCDC W1	18/11/05 -	4.7	Q1 Sand	1	1
							1
RAUMATI ZONE							1
R26/6521	MGW	Weka Park KCDC	23/2/93 -	40-41	Q2	2	1
R26/6831	AGW	Larch Grov	13/10/00 -	3.5-9.5	Q1 Sand	1	1
R26/6832	CAGW	Golf Tech	13/10/00 - 5/2/17	4-9.5	Q1 Sand	1	1
R26/6833	AGW	Maclean Park	13/10/00 -	4-8.8	Q1 Sand	1	1
R26/6503	MGW	QE 1	26/2/93 -	8.4-14	Q1 Sand	1	1
R26/6520	MGW	QE 2	12/12/94 -	6	Q1 Sand	1	1
R26/5102	MGW	QE 3	12/9/01 -	2.6-3.1	Q1 Sand	1	1
R26/6919	MGW	QE 4	12/9/01 -	5.5-6	Q1 Sand	1	1
R26/6920	MGW	QE 5	12/9/01 -	5.5-6	Q1 Sand	1	1
							1

Name	Station type	Name	Monitoring record	Screen depth (m)	Aquifer	Model Layer	Calibration
OTAKI ZONE							1
R25/5228	MGW	KCDC Rangiuru	8/4/93 -	30		2	1
S25/5212	MGW	Lutz	26/4/93 -	5-Jun		1	1
S25/5228	MGW	Andrews	26/2/93 -	??		1	1
S25/5258	AGWT	Bettys	4/4/93 -	5-Jun		1	1
S25/5287	MGW	Horo Racing	12/3/93 -	7-Oct		1	1
S25/5320	CMGW	Hunt	12/4/93 - 19/12/06	50-60		6	1
S25/5322	MGW	Edhouse	26/04/93 -	16-27		1	1
S25/5329	MGW	Laurensen	26/04/93 -	22-25		1	1
S25/5332	AGWT	Taylors	14/8/95 -	6-Sep		1	1

Name	Station type	Easting	Northing	Name	Monitoring record	Screen depth (m)	Aquifer	Model Layer
TE HORO ZONE								
R25/5123	MGW	1778282	5480785	Faith	26/2/93 -	28-32	Q2	2
R26/6861	MGW	1775689	5479431	Housiaux 1	25/11/04 -	6-7	Q1	1
R26/6879	AGWT	1775707	5479424	Housiaux 2	25/11/04 -	4.4-5.4	Q2	1
R26/6936	MGW	1775707	5479422	Housiaux 2b	23/2/05 -	2.2-5.2	Q3	1
R26/6880	MGW	1775687	5479414	Housiaux 3	25/11/04 -	6.6-7.6	Q4	1
R26/6881	CAGW	1775665	5479440	Housiaux 4	21/9/04 -	6.5-7.5	Q1	1
R26/6882	MGW	1775630	5479498	Housiaux 5	25/11/04 -	8.5-9.7	Q2	1
R26/6883	MGW	1775695	5479458	Housiaux 6	25/11/04 -	4-5	Q3	1
R25/5262	AGW	1775470	5479412	Jensens Deep	26/03/09 -	89.97	Q6?	6
R25/7086	AGW	1775295	5479894	Jensens Shal	30/03/09 -	4.3	Q4	1
R25/7087	AGW	1774698	5479298	Jill and Joys	30/03/09 -	4.5	Q1	1
R25/0003	AGW	1776328	5482692	Sims Road South	28/3/85 -	57.5-60.5	Q4	4
R25/5241	CAGW	1776911	5484260	Spencer	4/2/02 - 10/12/02	13-16	Q1	1
R25/5171	CAGW	1775090	5479101	Stevenson	15/4/09 - 25/6/10	51?	Q2?	3
S25/5208	AGW	1780182	5480785	Centrepoint	19/12/91 -	160m?	Q6?	7
S25/5200	MGW	1781182	5479785	Common Property	12/3/93 -	32-46	Q2	1
R25/5111	MGW	1778182	5479085	Jamieson	26/02/93 -	37.5-49.7	Q2	2
S25/5256	MGW	1780491	5483154	Penray	26/2/93 -	26.5-30.8	Q2	2
R25/5135	MGW	1779152	5481483	Windsor	30/6/82 -	83-93	Q6	5

Name	Station type	Easting	Northing	Name	Monitoring record	Screen depth (m)	Aquifer	Model Layer
WAIKANAE ZONE								
R26/6284	AGW	1772736	5473167	Waikanae Park	14/7/03 -	87-90.1	Q6?	7
R26/6287	AGW	1770587	5474307	Rangihiroa St	16/12/02 -	3-6	Q1 Sand	1
R26/6377	CAGW	1771404	5474797	Waikanae Golf Club KCDC	11/5/05 - 5/2/07	118?	Q6?	7
R26/6378	AGWWQ	1771995	5475389	Rutherford Dr KCDC	13/9/06 -	122?	Q6?	7
R26/6557	MGW	1768981	5471083	Mazengarb Sh KCDC	23/3/93 -	23-26	Q1 Sand	1
R26/6558	CMGW	1768982	5470935	Mazengarb Deep	15/12/95 - 1/2/07	91?	Q6?	7
R26/6566	AGWWQ	1769407	5473310	Estuary Shallow	18/2/15 -	52-53	Q2	5
R26/6569	MGW	1770929	5470578	NZ Staff College	23/02/93 -	33-45	fan	2
R26/6594	AGW	1770722	5473136	WCHP Deep	30/5/94 -	73-74	W6	6
R26/6626	MGW	1773782	5474085	McLauchlan	26/2/93 -	15.8 ?	Q1 Sand	1
R26/6673	AGWWQ	1770439	5474422	Taiata Shal	18/2/05 -	32-38	Q2?	3
R26/6738	MGW	1775682	5476685	McCardle	26/2/93 -	?	?	1(est)
R26/6747	MGW	1775247	5477235	Quinn	30/6/82 -	55-69.5	Q2	4
R26/6884	MGW	1772093	5475388	Te Harakeke 1	14/05/02 -	5.5-6	Q1 Sand	1
R26/6885	MGW	1772488	5475034	Te Harakeke 2	14/5/02 -	5.5-6	Q1 Sand	1
R26/6886	AGW	1771939	5474425	Te Harakeke 3	14/5/02 -	5.5-6	Q1 Sand	1
R26/6916	AGW	1770722	5473136	WCHP Shall	10/8/94 -	20-21	Q1 Sand	1
R26/6955	AGWWQ	1770439	5474422	Taiata St Deep	18/2/05 -	44-46	Q2	2
R26/6956	AGWWQ	1769407	5473310	Estuary Deep	18/2/05 -	76-78	Q6?	6
R26/6991	AGW	1773517	5474443	Nga Manu	18/11/05 -	3.7-4.7	Q1 Sand	1
R26/6992	AGW	1773140	5475374	KCDC K6	18/11/05 -	4.1-7.1	Q1 Sand	1
R26/7025	AGW	1772141	5473628	KCDC W1	18/11/05 -	4.7	Q1 Sand	1

Name	Station type	Easting	Northing	Name	Monitoring record	Screen depth (m)	Aquifer	Model Layer
RAUMATI ZONE								
R26/6521	MGW	1767208	5468481	Weka Park KCDC	23/2/93 -	40-41	Q2	2
R26/6831	AGW	1768770	5469188	Larch Grov	13/10/00 -	3.5-9.5	Q1 Sand	1
R26/6832	CAGW	1768215	5469629	Golf Tech	13/10/00 - 5/2/17	4-9.5	Q1 Sand	1
R26/6833	AGW	1766872	5471508	Maclean Park	13/10/00 -	4-8.8	Q1 Sand	1
R26/6503	MGW	1766253	5462295	QE 1	26/2/93 -	8.4-14	Q1 Sand	1
R26/6520	MGW	1766365	5462470	QE 2	12/12/94 -	6	Q1 Sand	1
R26/5102	MGW	1766541	5462545	QE 3	12/9/01 -	2.6-3.1	Q1 Sand	1
R26/6919	MGW	1766543	5462545	QE 4	12/9/01 -	5.5-6	Q1 Sand	1
R26/6920	MGW	1766226	5462840	QE 5	12/9/01 -	5.5-6	Q1 Sand	1
OTAKI ZONE								
R25/5228	MGW	1779182	5486286	KCDC Rangiuru	8/4/93 -	30		2
S25/5212	MGW	1784454	5482334	Lutz	26/4/93 -	5-6		1
S25/5228	MGW	1782737	5483246	Andrews	26/2/93 -	??		1
S25/5258	AGWT	1782227	5483430	Bettys	4/4/93 -	5-6		1
S25/5287	MGW	1782583	5484686	Horo Racing	12/3/93 -	7-10		1
S25/5320	CMGW	1783383	5487086	Hunt	12/4/93 - 19/12/06	50-60		6
S25/5322	MGW	1782983	5487486	Edhouse	26/04/93 -	16-27		1
S25/5329	MGW	1780583	5487986	Laurensen	26/04/93 -	22-25		1
S25/5332	AGWT	1782183	5487286	Taylors	14/8/95 -	6-9		1

8.6 Automated calibration (PEST)

8.6.1 Objective function formulation

The objective function is used to describe the match between the simulated groundwater heads and the observation data. Its formulation is therefore critical for automated model calibration and for this model the objective function was formulated as the sum of squares of residual between target groundwater levels (historic monitoring data) and model simulated groundwater levels. This sum of squares of residuals is refered to as the ‘phi’ parameter. For the same number of residuals, a smaller phi would indicate a good fit between measured and model simulated groundwater levels.

8.6.2 PEST Optimisation results

Table 27 presents the PEST optimisation results. The overall objective function (phi) reduced from 4355m^2 to 4023m^2 (i.e. 8% reduction); the contribution from each of the monitoring bores is also listed. The small reduction in the objective function indicates a good approximation of initial parameters for the model. Table 28 provides a summary of quantitative measures for the calibration quality following the automated PEST calibration procedure.

The model calibration has a high correlation coefficient (R) which is a measure of the overall unweighted goodness of fit between modelled outputs and observations. Ideally, R should be above 0.9.

Table 27 shows that Area 2 – the Waikanae dominates the objective function (phi=921 m^2). This is partly because the area has more observation bores (and residuals) in comparison to other areas, but is is also mainly due to the larger residuals associated with lack of key hydrogeological information on three wells in the Waikanae. The highest phi of 173 m^2 relates to bore R26/6991 which is located in shallow Q1 sands. The cause of the large error is not known, however, the largest residual is 0.6 m related to subdued fluctuations in observed groundwater levels compared to calculated values. A shallow (R26/6673) and deep (R26/6955) contribute 115 and 110 m^2 (phi).

The errors and scaled errors presented in Table 28 provides further details on the calibration performance for individual monitoring bores.

Table 27: Summary of PEST optimisation for the Kapiti Coast transient groundwater flow model

Objective function ----->	
Sum of squared weighted residuals (ie phi)	4355
Area 1 (Raumati groundwater zone)	
Contribution to phi from observation group "R26/6503"	22.37
Contribution to phi from observation group "R26/6520"	11.4
Contribution to phi from observation group "R26/6521"	102.28
Contribution to phi from observation group "R26/6831"	14.78
Contribution to phi from observation group "R26/6833"	19.6
Contribution to phi from observation group "R26/6919"	12.3

Contribution to phi from observation group "R26/6920"	36.14
Contribution to phi from observation group "R26/5102"	81.22
Contribution to phi from observation group "R26/6503"	22.37
Total contribution Area 2 (574 residuals)	*322.46*
Area 2 (Waikanae groundwater zone)	
Contribution to phi from observation group "R26/6557"	24.29
Contribution to phi from observation group "R26/6566"	37.71
Contribution to phi from observation group "R26/6569"	7.4
Contribution to phi from observation group "R26/6594"	5
Contribution to phi from observation group "R26/6626"	53.59
Contribution to phi from observation group "R26/6673"	114.97
Contribution to phi from observation group "R26/6738"	19.82
Contribution to phi from observation group "R26/6747"	20.39
Contribution to phi from observation group "R26/6884"	7.32
Contribution to phi from observation group "R26/6885"	14.3
Contribution to phi from observation group "R26/6886"	57.69
Contribution to phi from observation group "R26/6916"	63.95
Contribution to phi from observation group "R26/6955"	110.02
Contribution to phi from observation group "R26/6956"	79.86
Contribution to phi from observation group "R26/6991"	173.09
Contribution to phi from observation group "R26/6992"	6.52
Contribution to phi from observation group "R26/6284"	10.82
Contribution to phi from observation group "R26/6287"	47.34
Contribution to phi from observation group "R26/6378"	10.04
Contribution to phi from observation group "R26/7025	57.73
Total contribution Area 4 (1884 residuals)	921.85
Area 3 (Te Horo groundwater zone)	
Contribution to phi from observation group "R25/5262"	23.36
Contribution to phi from observation group "R26/6861"	8.171
Contribution to phi from observation group "R26/6879"	38.15
Contribution to phi from observation group "R26/6880"	20.29
Contribution to phi from observation group "R26/6881"	3.87
Contribution to phi from observation group "R26/6882"	25.94
Contribution to phi from observation group "R26/6883"	16.91
Contribution to phi from observation group "R26/7086"	20.54
Contribution to phi from observation group "R25/7087"	20.2
Contribution to phi from observation group "S25/5200"	4.25
Contribution to phi from observation group "S25/5208"	11.09

Contribution to phi from observation group "R25/5111"	16.86
Contribution to phi from observation group "R25/5135"	12.78
Contribution to phi from observation group "R25/0003"	28.98
Contribution to phi from observation group "R25/5171"	9.49
Total contribution Area 3 (1266 residuals)	260.881
Area 4 (Otaki groundwater zone)	
Contribution to phi from observation group "R25/5228"	1.16
Contribution to phi from observation group "S25/5212"	136.38
Contribution to phi from observation group "S25/5228"	18.63
Contribution to phi from observation group "S25/5258"	66.73
Contribution to phi from observation group "S25/5287"	75.67
Contribution to phi from observation group "S25/5322"	18.29
Contribution to phi from observation group "S25/5329"	66.73
Total contribution Area 1 (279 residuals)	*327*
Correlation coefficient 0.9899	
Analysis of residuals ----->	
All residuals:-	
Number of residuals with non-zero weight	4355
Mean value of non-zero weighted residuals	= 0.42
Maximum weighted residual [observation "S25/5208"]	= 2.640
Minimum weighted residual [observation "S25/5200"]	= -2.036
Standard variance of weighted residuals	= 1.085
Standard error of weighted residuals	= 1.042

Table 27 shows that Area 2 – the Waikanae groundwater zone dominates the objective function (phi=921 m^2). This is partly because the area has more observation bores (1884 residuals) in comparison to other areas.

Table 28: Measures of calibration performance for each of the four groundwater management zones in the Kapiti Coast transient groundwater flow model (head residuals)

	Error (m)					Scaled error %	
Monitoring bore	No. of residuals	Minimum	Maximum	Mean	Root mean square (RMS)	Scaled mean sum of residual (SMSR)	Scaled RMS (SRMS)
Area 1	Raumati						
R26_5102	25.00	0.81	1.55	1.33	1.81	82.07	81.22
R26_6503	5.00	-0.37	-0.11	-0.24	0.07	24.37	22.37
R26_6520	26.00	-0.25	0.66	0.30	0.17	15.33	11.40

	Error (m)					Scaled error %	
Monitoring bore	No. of residuals	Minimum	Maximum	Mean	Root mean square (RMS)	Scaled mean sum of residual (SMSR)	Scaled RMS (SRMS)
R26_6521	26.00	-1.75	-0.50	-1.17	1.48	106.74	102.28
R26_6833	156.00	-0.47	0.17	-0.11	0.03	33.35	19.60
R26_6919	24.00	0.03	1.14	0.21	0.12	19.74	12.30
R26_6920	21.00	-0.58	0.12	-0.35	0.14	38.93	36.14
Area 2	Waikanae						
R26_6284	153.00	-0.28	0.54	0.13	0.04	16.65	10.82
R26_6287	155.00	0.29	0.76	0.53	0.29	47.94	47.34
R26_6378	148.00	-1.31	0.87	0.37	0.26	14.09	10.04
R26_6557	18.00	-0.42	-0.13	-0.26	0.07	25.30	24.29
R26_6566	155.00	-0.09	0.61	0.20	0.06	45.53	37.71
R26_6569	26.00	-1.59	0.80	-0.12	0.49	41.80	7.40
R26_6594	155.00	-0.56	0.42	0.11	0.05	10.70	5.00
R26_6626	26.00	0.24	1.08	0.71	0.56	56.48	53.59
R26_6673	152.00	0.40	0.77	0.62	0.38	115.80	114.97
R26_6738	26.00	-0.38	0.82	0.32	0.23	29.76	19.82
R26_6747	24.00	-0.08	0.58	0.29	0.12	24.42	20.39
R26_6884	27.00	-0.01	0.72	0.09	0.03	12.38	7.32
R26_6885	26.00	-0.10	0.50	0.23	0.07	16.19	14.30
R26_6886	153.00	0.28	0.72	0.53	0.29	58.33	57.69
R26_6916	155.00	-0.95	-0.27	-0.47	0.23	65.90	63.95
R26_6955	152.00	0.41	0.77	0.61	0.37	110.81	110.02
R26_6956	155.00	-1.02	0.03	-0.63	0.43	83.33	79.86
R26_6991	156.00	0.44	1.29	0.91	0.87	176.71	173.09
R26_6992	153.00	-0.31	0.23	-0.07	0.01	10.47	6.52
R26_7025	151.00	0.07	0.72	0.38	0.15	59.87	57.73
Area 3	Te Horo						
R25_0003	155.00	-0.52	-0.02	-0.26	0.07	30.84	28.98
R25_5111	25.00	-1.39	-0.54	-0.97	1.01	17.44	16.86
R25_5171	53.00	-1.37	0.60	-0.15	0.24	30.31	9.49
R25_7086	116.00	-0.51	-0.07	-0.28	0.09	24.67	23.36
R25_7087	116.00	-0.05	0.30	0.11	0.02	25.15	20.54
R26_6861	25.00	-0.91	0.01	-0.22	0.09	27.78	20.20
R26_6879	119.00	-1.00	-0.06	-0.29	0.10	32.32	29.08
R26_6880	15.00	-0.99	-0.11	-0.39	0.22	46.03	38.15
R26_6881	153.00	-0.77	0.07	-0.26	0.10	23.87	20.29

	Error (m)					Scaled error %	
Monitoring bore	No. of residuals	Minimum	Maximum	Mean	Root mean square (RMS)	Scaled mean sum of residual (SMSR)	Scaled RMS (SRMS)
R26_6882	23.00	-0.67	0.17	-0.04	0.05	21.74	3.87
R26_6883	25.00	-1.11	0.47	-0.46	0.29	30.67	25.94
R26_6936	25.00	-0.97	0.90	-0.27	0.19	27.55	16.91
S25_5200	24.00	-2.20	-0.05	-0.58	0.56	5.48	4.25
Area 4	Otaki						
R25_5228	26.00	0.06	0.50	0.30	0.10	14.61	13.60
S25_5212	25.00	0.85	1.28	1.09	1.20	136.98	136.38
S25_5228	26.00	-0.30	0.33	-0.02	0.03	10.64	1.16
S25_5258	137.00	-0.68	0.24	-0.34	0.16	21.74	18.63
S25_5287	21.00	-1.61	-0.50	-1.36	1.91	76.76	75.67
S25_5322	18.00	-1.37	0.50	-0.54	0.56	25.26	18.29
S25_5329	26.00	-0.79	-0.44	-0.65	0.43	67.33	66.73
S25-5208	155						

8.6.3 Calibration validation run

Validation (or verification) is performed to test whether or not the model can be used as a predictive tool by demonstrating that the calibrated model is an adequate representation of the physical system (Middlemis 2001). Validation addresses some of the non-uniqueness issues, particularly if the verification data-set was from a distinct hydrological period.

Following the automated PEST calibration using the 4-year dataset, a verification run was performed using monitoring data covering the period 1 July 1992 to 21 June 2011 (19 years) i.e. inclusive of the of the period used in the calibration. Normally, data used in the calibration is excluded from the verification exercise, however in this case the data was included as the last four years of simulation was a period of increased abstractions and a wide range of climatic conditions. The four year period is relatively short when compared to the 19 years of simulation such that the inclusion of this calibration period did not result in simulation bias towards calibrated data.

A calibration validation run of 19 years duration was performed for the period 1 July 1992 to 1 July 2011. The PEST calibration data-set for 1 August 2008 to 6 June 2011 was incorporated into the run and therefore the validation data-set used additional monitoring data both prior to and after the PEST calibration data-set. The transient model validation run had 990 seven-day stress periods, and a run duration of 6930 days.

8.6.4 Discussion: model to measurement head fit

The information presented in Tables 28 and 29 includes several measures of goodness of fit between calculated and measured heads. The root mean square

(RMS) error is an absolute measure that is problem dependent (i.e. its value is affected by the range in the measured values). It is usually thought to be the best error measure if errors are normally distributed. The scaled root mean square (SRMS) error is a measure of the ratio of error to the total head differential and the scaled mean sum of residuals (RMSR) is an intuitive parameter that provide relative measures independent of sample size and independent of sample range.

There are cases, however, when a simulated hydrograph might agree very well with a measured hydrograph in pattern and amplitude, but differ in absolute magnitude, so that the two curves run in parallel to each other. Head based statistics will suggest a poor calibration, when in fact the calibration might be very good. For this reason the calibration statistics in Tables 28 and 29 should be considered in conjunction with the model to measurement fit plots in Figures 73 to 76. These show the simulated and observed groundwater levels for the 19-year calibration period for the head calibration targets (grouped into four groundwater management zones). The model to measurement calibration is discussed for each of the areas below.

a) Area 1

Raumati groundwater management zone

Seven observation bores were used in the analysis. Five bores (R26/6503, R26/6520,R26/6833, R26/6919 and R26/6920) had resoanable head calibration statistics with SMSR and SRMS scaled errors between 11.4 and 33.5. Two wells (R26/5102 and R26/6521) had large errors of more than 50%. Gyopari and McAlister (2010) suggested a scaled error of up to 50% as being acceptable for a complex, regional scale model.

Figure 73 shows that although the scaled errors are large, simulated head difference magnitudes are reasonable (<1m) for a regional scale model characterised by heterogenous hydraulic properties. This zone is characterised by a dense network of drains and wetlands that may influence groundwater level fluctuations. Although the influence of drains has been encorporated into the model, it is likely that some deeper wells (e.g. R26/5102) are less affected by surface water heads due to perched conditions.

Well R26/6521a 40 m deep KCDC well at Weka Park is a pumped well and the effects of pumping are well predicted by the model, however the model overpredicts well head recovery at this site.

b) Area 2

Waikanae groundwater management zone

Figure 74 shows the calibration hydrographs for the Waikanae zone. Groundwater level fluctuations in this zone show a complex relationship with surface water systems. Deep and shallow groundwater level heads are generally affected by vertical leakages (upwards and downwards) depending on location. The Waikanae river system. A visual comparison of the observed and modelled heads in Figure 74 show that there is a very good calibration in most wells in this zone. Modelled water levels respond to effects of seasonal abstraction, recharge and surface water conditions indicating that the coupled groundwater and surface water environments are accurately simulated.

c) Area 3

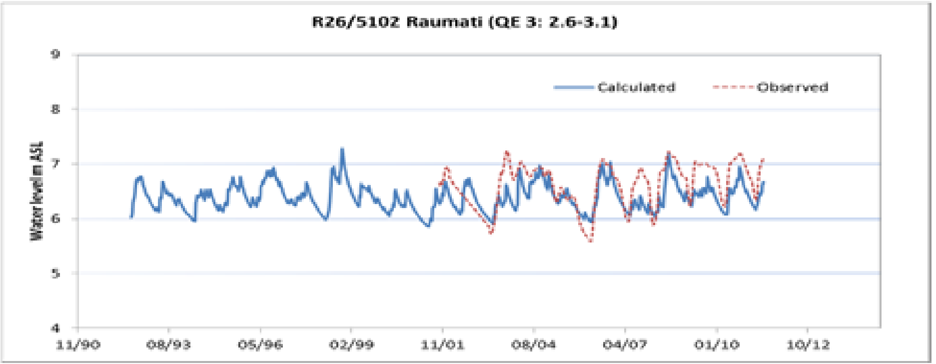
Te Horo groundwater management zone

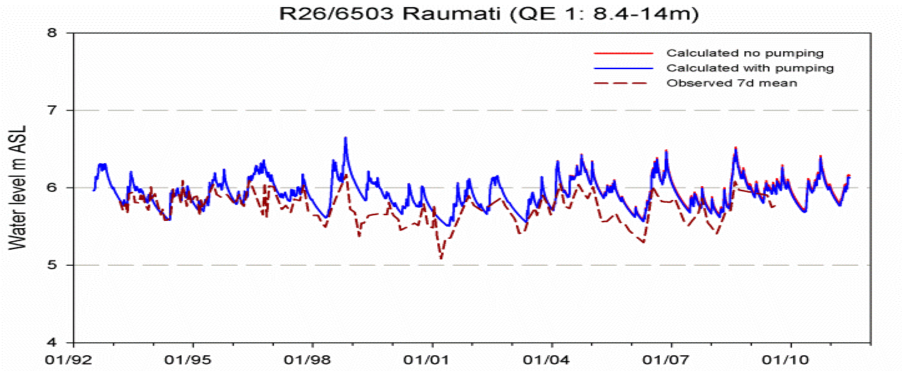
Head calibration statistics for all thirteen monitoring targets in this zone have SMSR and SRMS scaled errors of less than 50%. Figure 75 is a summary of calibration hydrographs for this zone. There is a close agreement between the simulated and observed heads in shallow and deep aquifers in this zone. A well site R26/5123 was removed from the analysis as there was no adequately verified information on the well head's reduced level.

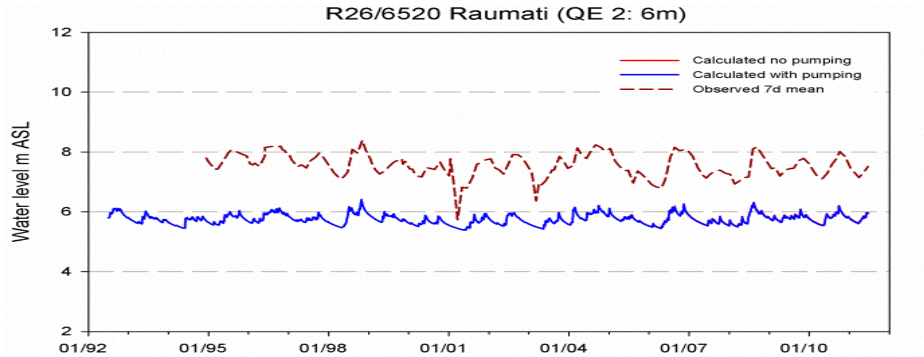
d) Area 4

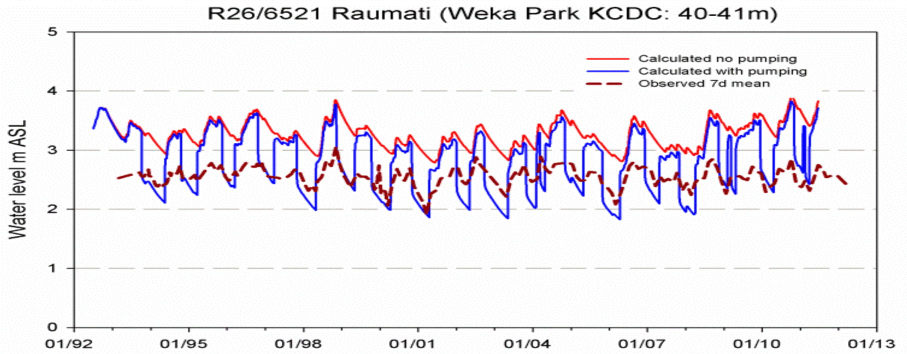
Otaki groundwater management zone

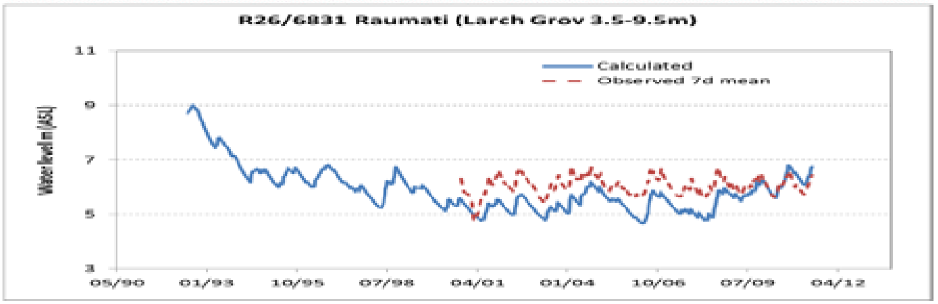
Four observation sites (R25/5228, S25/5228, S25/5258 and S25/5322) have reasonable head calibration statistics with SMSR and SRMS scaled errors of between 1 and 25%. Three wells (R25/5112, S25/5287 and S25/5329) have large errors of more than 50%. Figure 76 shows that although the errors are large, the difference between simulated and measured heads are reasonable and generally less than 1m. S25/5320 showed buffered responses to recharge which could be due to proximity to surface water features.

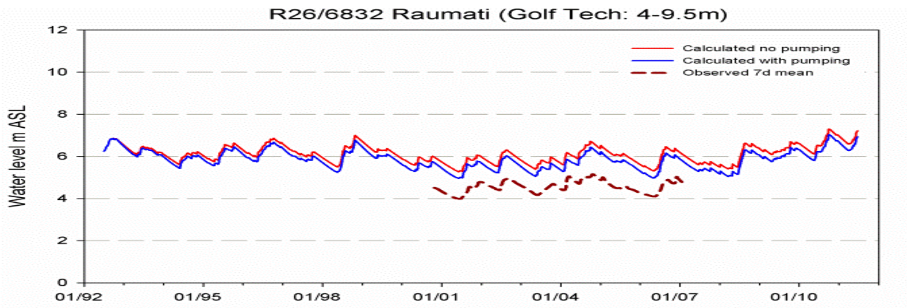

R26/5102 Raumati (QE 3: 2.6-3.1)
Calculated
Observed
Water level m ASL
9
8
7
6
5
4
11/90
08/93
05/96
02/99
11/01
08/04
04/07
01/10
10/12


R26/6503 Raumati (QE 1: 8.4-14m)
Calculated no pumping
Calculated with pumping
Observed 7d mean
Water level m ASL
8
7
6
5
4
01/92
01/95
01/98
01/01
01/04
01/07
01/10


R26/6520 Raumati (QE 2: 6m)
Calculated no pumping
Calculated with pumping
Observed 7d mean
Water level m ASL
12
10
8
6
4
2
01/92
01/95
01/98
01/01
01/04
01/07
01/10


R26/6521 Raumati (Weka Park KCDC: 40-41m)
Calculated no pumping
Calculated with pumping
Observed 7d mean
Water level m ASL
5
4
3
2
1
0
01/92
01/95
01/98
01/01
01/04
01/07
01/10
01/13


R26/6831 Raumati (Larch Grov 3.5-9.5m)
Calculated
Observed 7d mean
Water level m (ASL)
11
9
7
5
3
05/90
01/93
10/95
07/98
04/01
01/04
10/06
07/09
04/12


R26/6832 Raumati (Golf Tech: 4-9.5m)
Calculated no pumping
Calculated with pumping
Observed 7d mean
Water level m ASL
12
10
8
6
4
2
0
01/92
01/95
01/98
01/01
01/04
01/07
01/10

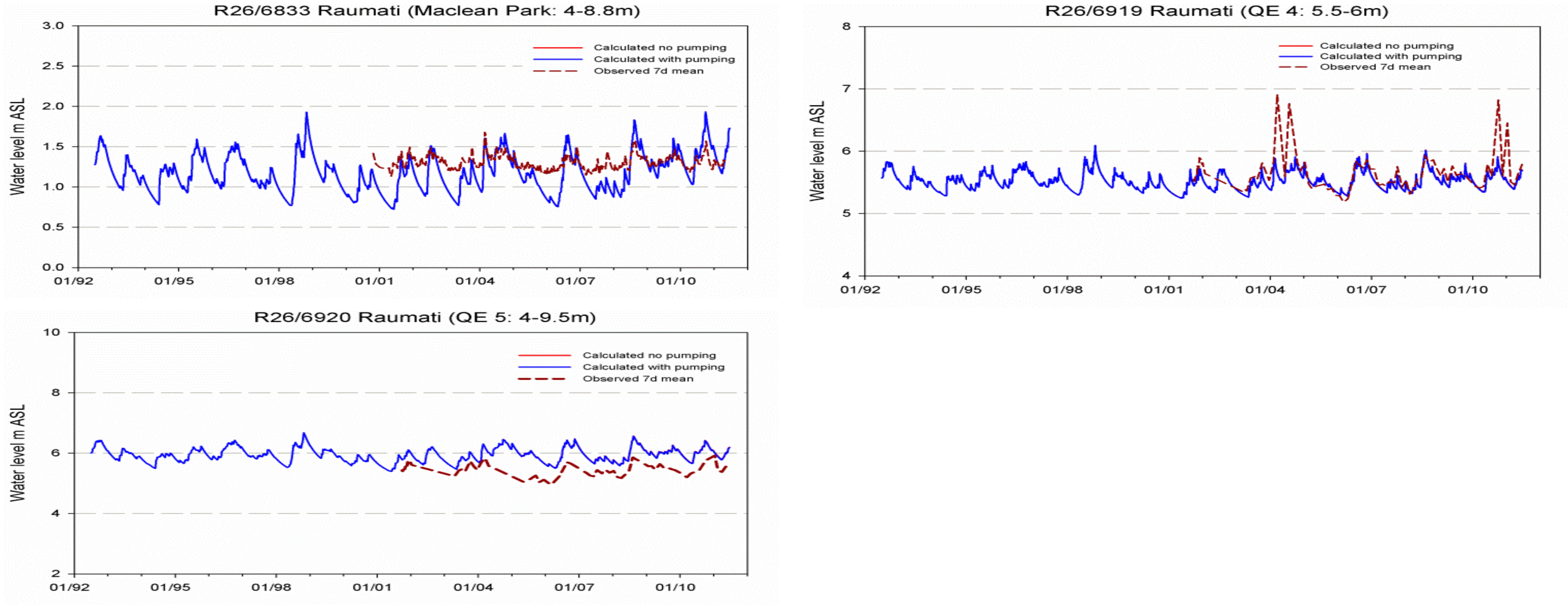
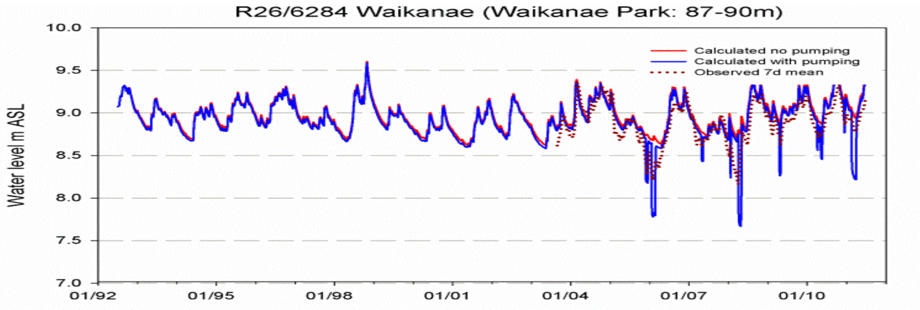
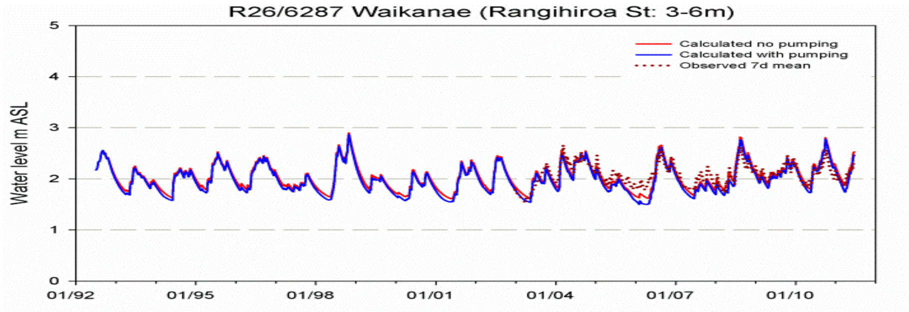
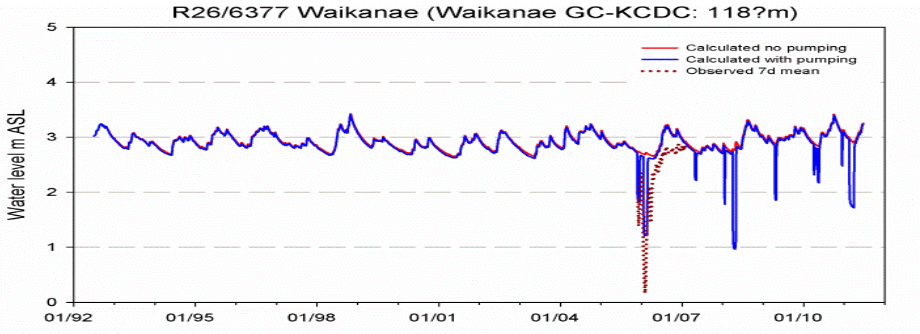
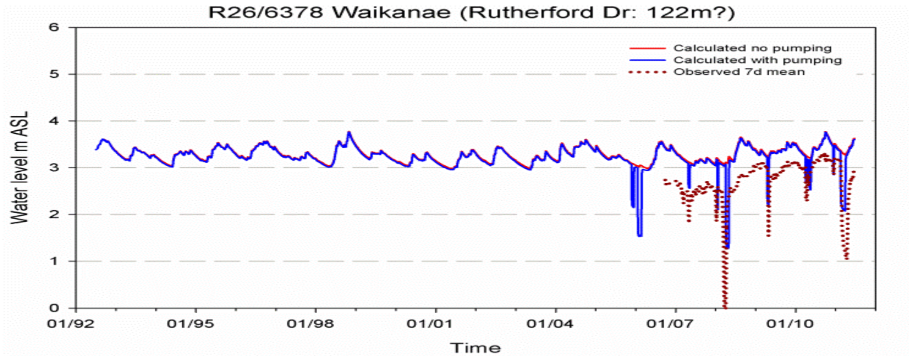


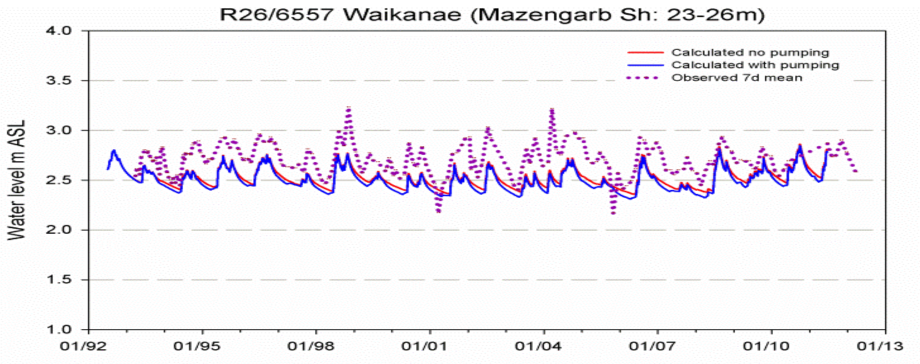
Figure 73: Transient model groundwater head calibration plots for Area 1 (Raumati zone). Broken line= observed data, solid blue =simulated head with pumping at 50% allocated volume and red solid (where present) = simulated without abstraction effects.

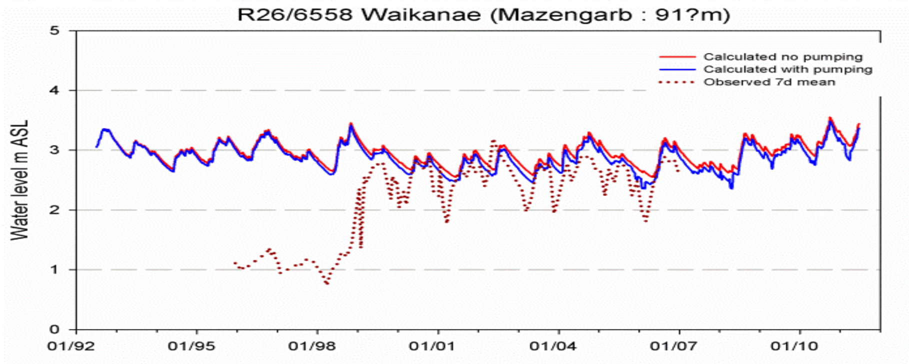

R26/6284 Waikanae (Waikanae Park: 87-90m)
Calculated no pumping
Calculated with pumping
Observed 7d mean
Water level m ASL
10.0
9.5
9.0
8.5
8.0
7.5
7.0
01/92
01/95
01/98
01/01
01/04
01/07
01/10

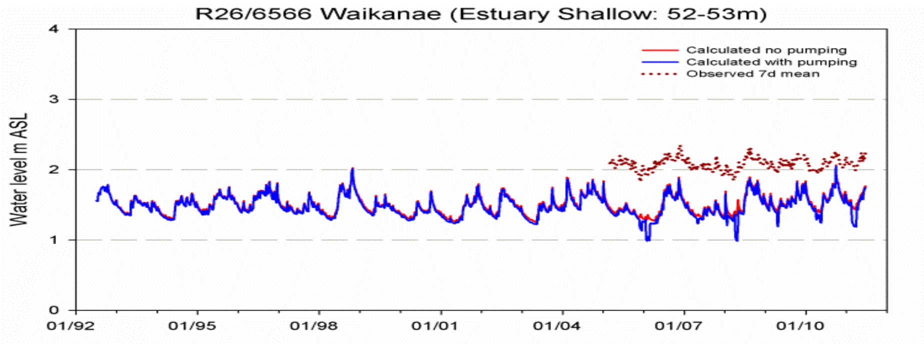

R26/6287 Waikanae (Rangihiroa St: 3-6m)
Calculated no pumping
Calculated with pumping
Observed 7d mean
Water level m ASL
5
4
3
2
1
0
01/92
01/95
01/98
01/01
01/04
01/07
01/10

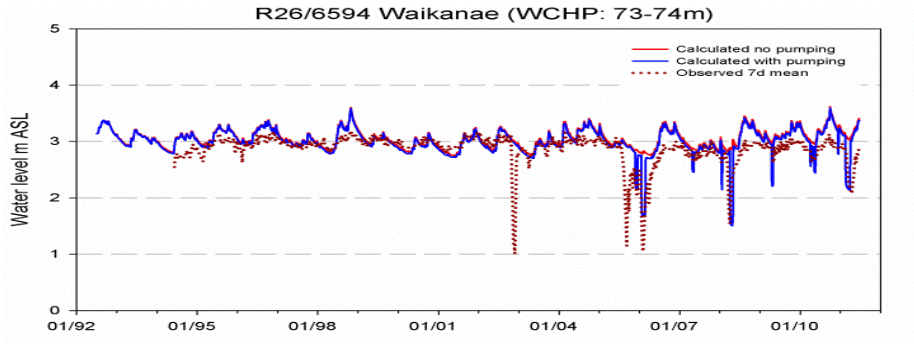

R26/6377 Waikanae (Waikanae GC-KCDC: 118?m)
Calculated no pumping
Calculated with pumping
Observed 7d mean
Water level m ASL
5
4
3
2
1
0
01/92
01/95
01/98
01/01
01/04
01/07
01/10

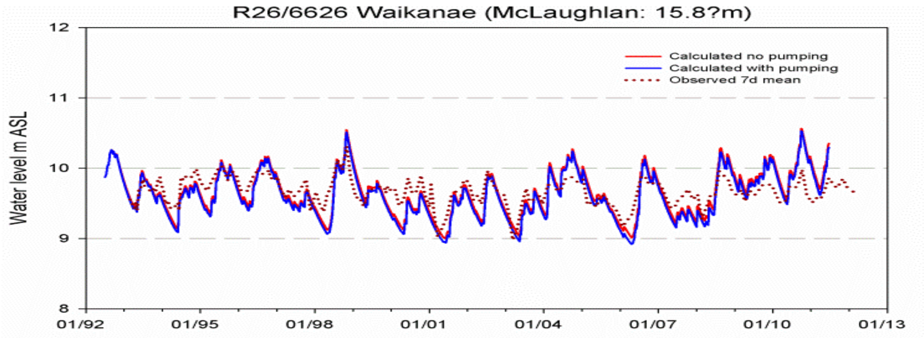

R26/6378 Waikanae (Rutherford Dr: 122m?)
Calculated no pumping
Calculated with pumping
Observed 7d mean
Water level m ASL
6
5
4
3
2
1
0
01/92
01/95
01/98
01/01
01/04
01/07
01/10
Time

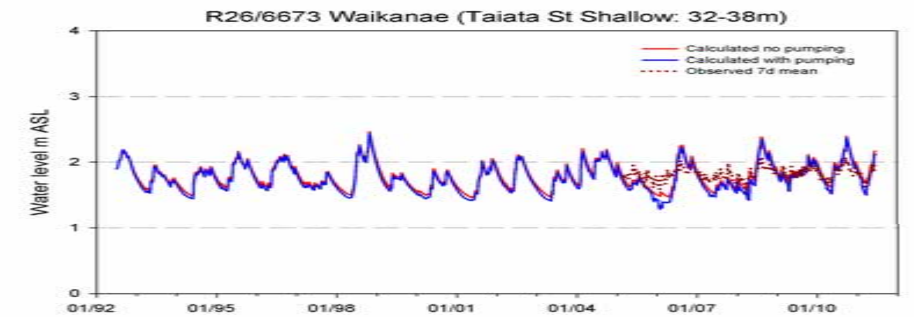

R26/6557 Waikanae (Mazengarb Sh: 23-26m)
Calculated no pumping
Calculated with pumping
Observed 7d mean
Water level m ASL
4.0
3.5
3.0
2.5
2.0
1.5
1.0
01/92
01/95
01/98
01/01
01/04
01/07
01/10
01/13

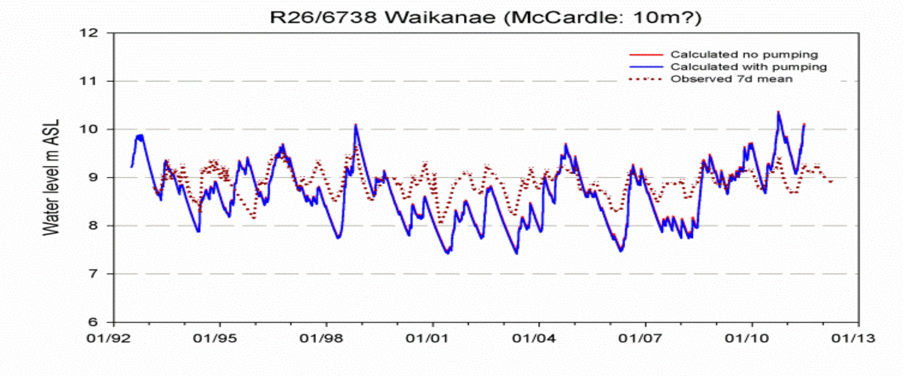

R26/6558 Waikanae (Mazengarb : 91?m)
Calculated no pumping
Calculated with pumping
Observed 7d mean
Water level m ASL
5
4
3
2
1
0
01/92
01/95
01/98
01/01
01/04
01/07
01/10

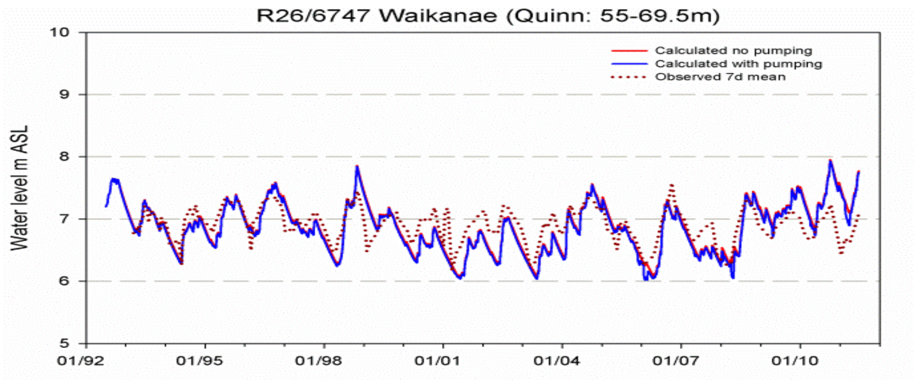

R26/6566 Waikanae (Estuary Shallow: 52-53m)
Calculated no pumping
Calculated with pumping
Observed 7d mean
Water level m ASL
0
1
2
3
4
01/92
01/95
01/98
01/01
01/04
01/07
01/10

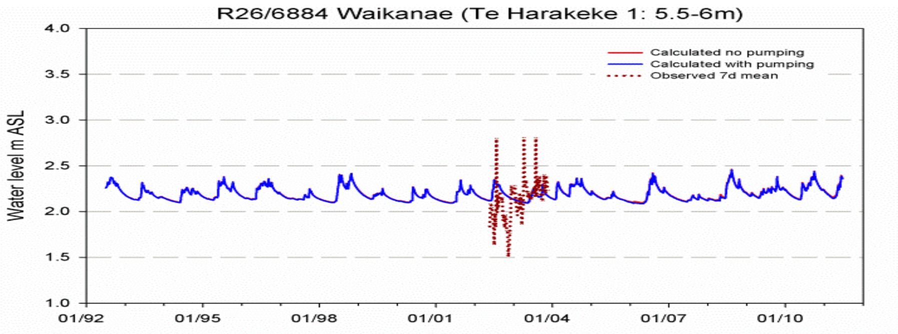

R26/6594 Waikanae (WCHP: 73-74m)
Calculated no pumping
Calculated with pumping
Observed 7d mean
Water level m ASL
0
1
2
3
4
5
01/92
01/95
01/98
01/01
01/04
01/07
01/10

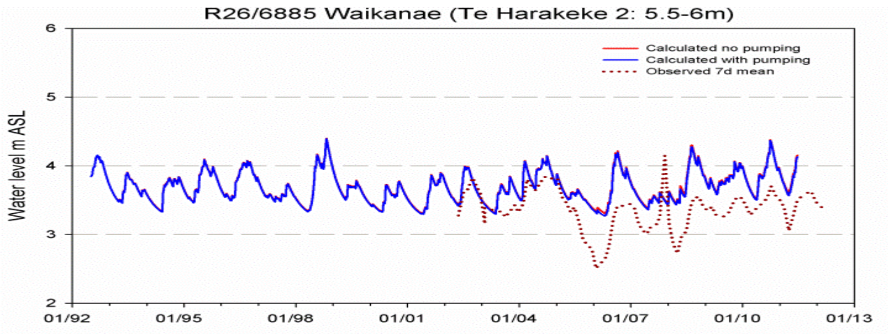

R26/6626 Waikanae (McLaughlan: 15.8?m)
Calculated no pumping
Calculated with pumping
Observed 7d mean
Water level m ASL
8
9
10
11
12
01/92
01/95
01/98
01/01
01/04
01/07
01/10
01/13

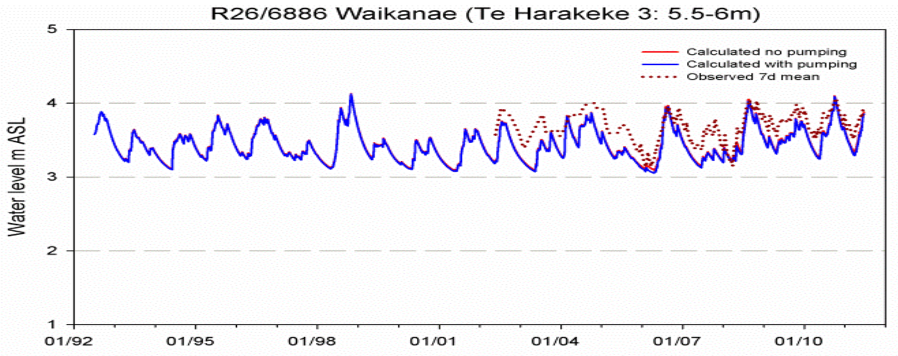

R26/6673 Waikanae (Taiata St Shallow: 32-38m)
Calculated no pumping
Calculated with pumping
Observed 7d mean
Water level m ASL
0
1
2
3
4
01/92
01/95
01/98
01/01
01/04
01/07
01/10

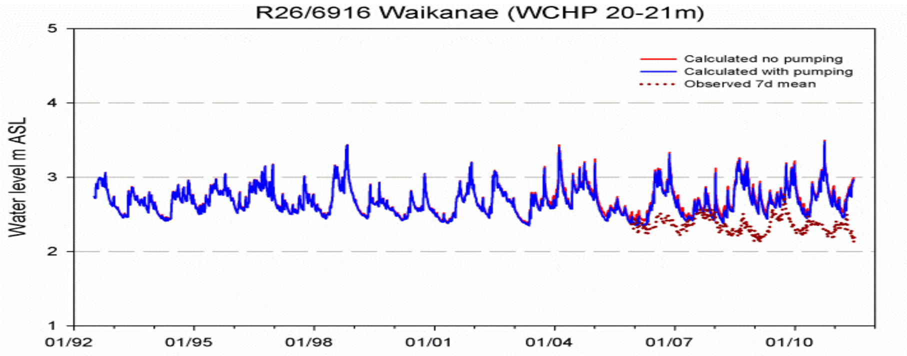

R26/6738 Waikanae (McCardle: 10m?)
Calculated no pumping
Calculated with pumping
Observed 7d mean
Water level m ASL
6
7
8
9
10
11
12
01/92
01/95
01/98
01/01
01/04
01/07
01/10
01/13

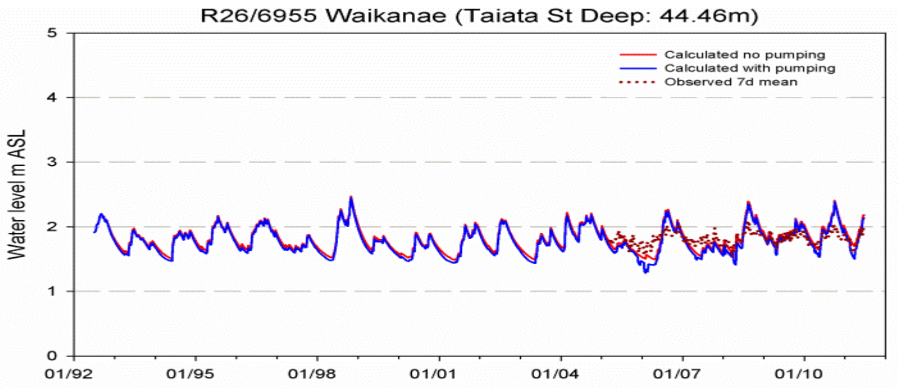

R26/6747 Waikanae (Quinn: 55-69.5m)
Calculated no pumping
Calculated with pumping
Observed 7d mean
Water level m ASL
5
6
7
8
9
10
01/92
01/95
01/98
01/01
01/04
01/07
01/10

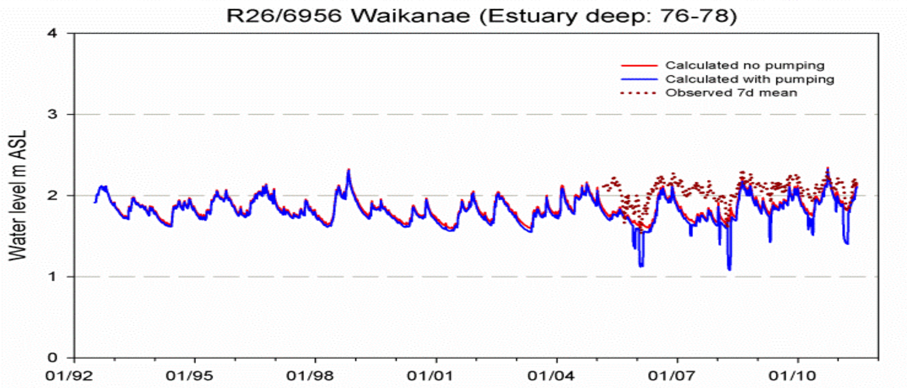

R26/6884 Waikanae (Te Harakeke 1: 5.5-6m)
Calculated no pumping
Calculated with pumping
Observed 7d mean
Water level m ASL
4.0
3.5
3.0
2.5
2.0
1.5
1.0
01/92
01/95
01/98
01/01
01/04
01/07
01/10

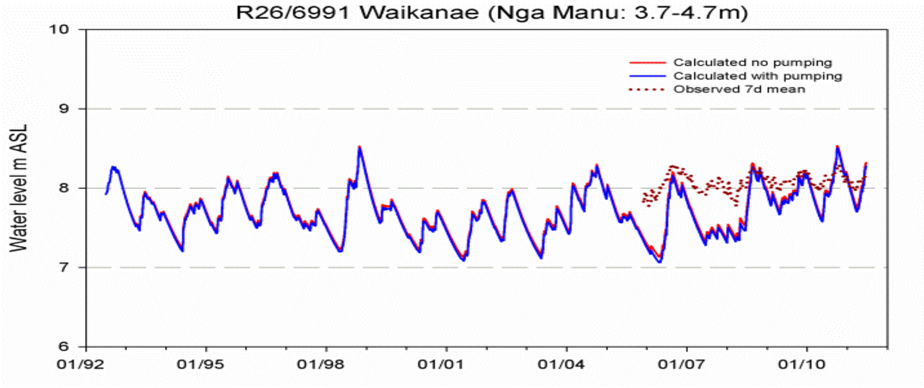

R26/6885 Waikanae (Te Harakeke 2: 5.5-6m)
Calculated no pumping
Calculated with pumping
Observed 7d mean
Water level m ASL
6
5
4
3
2
01/92
01/95
01/98
01/01
01/04
01/07
01/10
01/13


R26/6886 Waikanae (Te Harakeke 3: 5.5-6m)
Calculated no pumping
Calculated with pumping
Observed 7d mean
Water level m ASL
5
4
3
2
1
01/92
01/95
01/98
01/01
01/04
01/07
01/10


R26/6916 Waikanae (WCHP 20-21m)
Calculated no pumping
Calculated with pumping
Observed 7d mean
Water level m ASL
5
4
3
2
1
01/92
01/95
01/98
01/01
01/04
01/07
01/10


R26/6955 Waikanae (Taiata St Deep: 44.46m)
Calculated no pumping
Calculated with pumping
Observed 7d mean
Water level m ASL
5
4
3
2
1
0
01/92
01/95
01/98
01/01
01/04
01/07
01/10


R26/6956 Waikanae (Estuary deep: 76-78)
Calculated no pumping
Calculated with pumping
Observed 7d mean
Water level m ASL
4
3
2
1
0
01/92
01/95
01/98
01/01
01/04
01/07
01/10



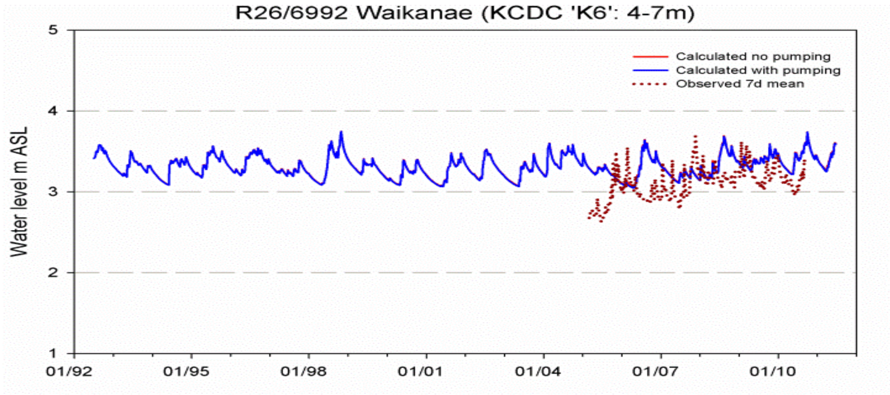
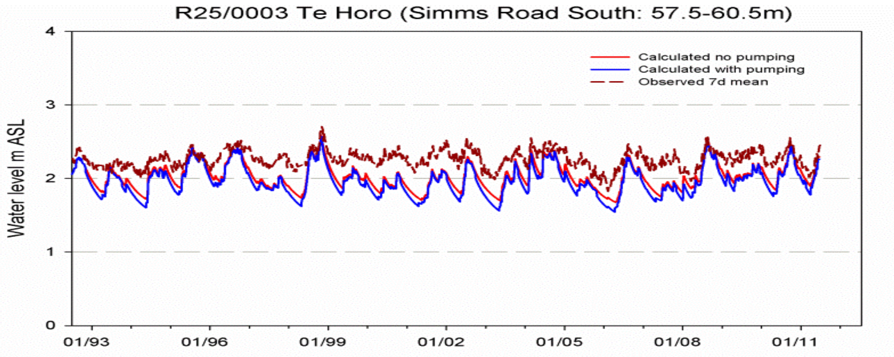
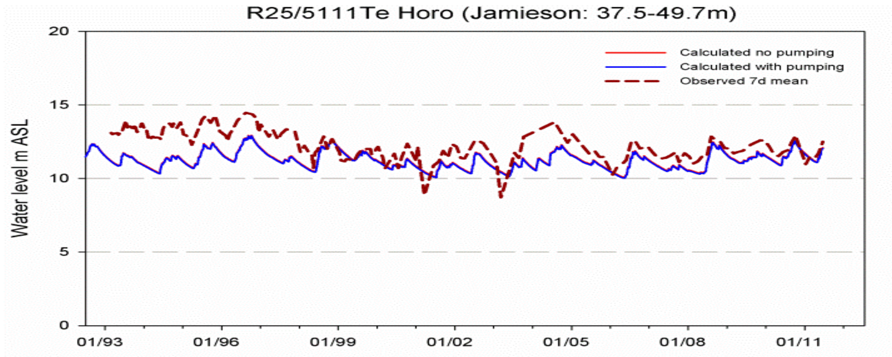
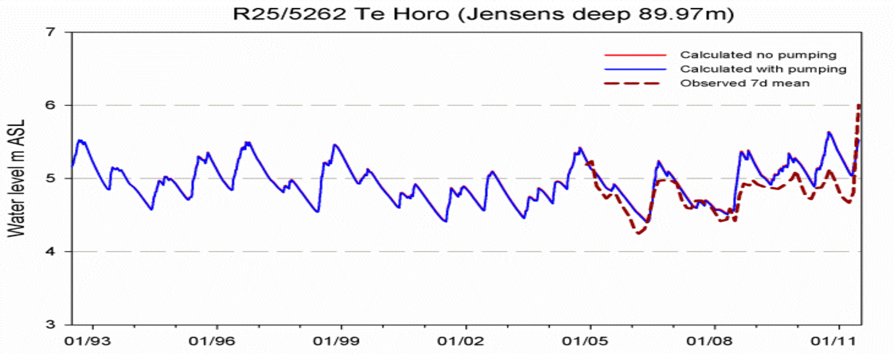
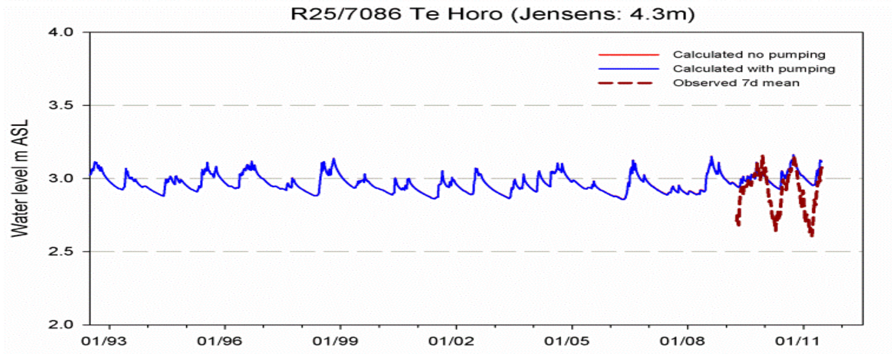


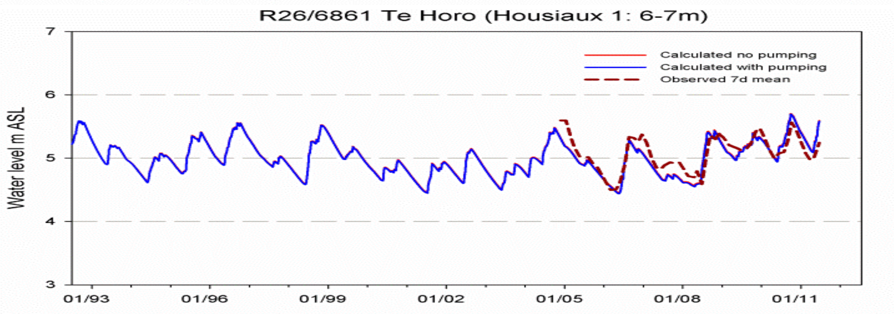
Figure 74: Transient model groundwater head calibration plots for Area 2 (Waikanae zone). Broken line= observed data, solid blue =simulated head with pumping at 50% allocated volume and red solid (where present) = simulated without abstraction effects.

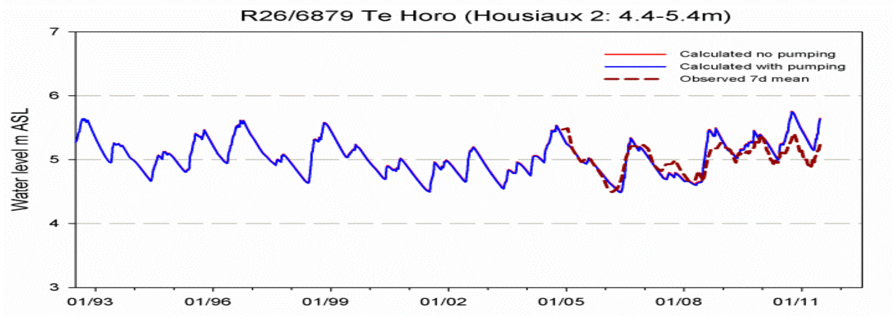

R25/0003 Te Horo (Simms Road South: 57.5-60.5m)
Calculated no pumping
Calculated with pumping
Observed 7d mean
Water level m ASL
0
1
2
3
4
01/93
01/96
01/99
01/02
01/05
01/08
01/11

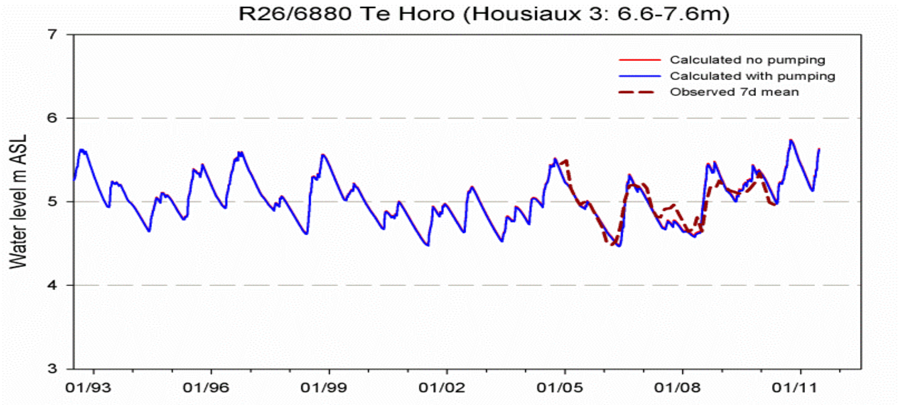

R25/5111Te Horo (Jamieson: 37.5-49.7m)
Calculated no pumping
Calculated with pumping
Observed 7d mean
Water level m ASL
0
5
10
15
20
01/93
01/96
01/99
01/02
01/05
01/08
01/11

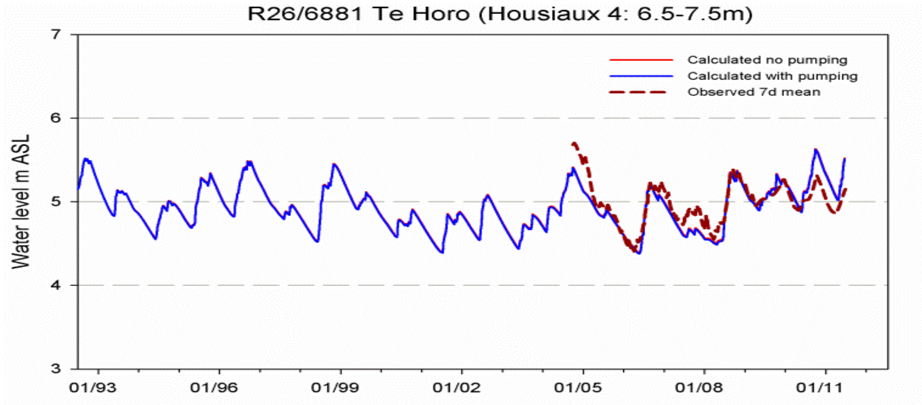

R25/5262 Te Horo (Jensens deep 89.97m)
Calculated no pumping
Calculated with pumping
Observed 7d mean
Water level m ASL
3
4
5
6
7
01/93
01/96
01/99
01/02
01/05
01/08
01/11

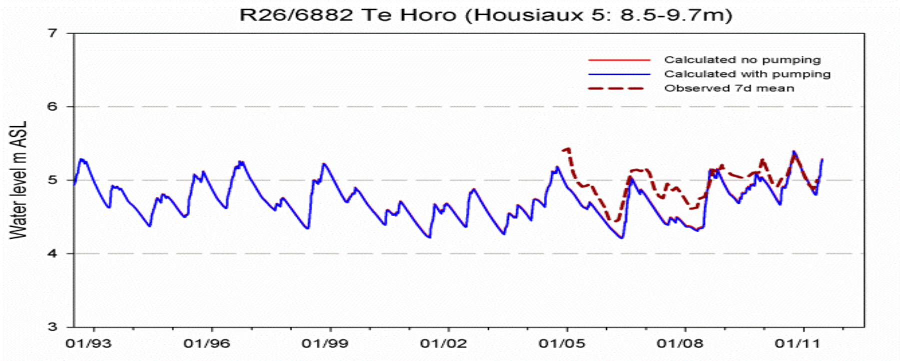

R25/7086 Te Horo (Jensens: 4.3m)
Calculated no pumping
Calculated with pumping
Observed 7d mean
Water level m ASL
2.0
2.5
3.0
3.5
4.0
01/93
01/96
01/99
01/02
01/05
01/08
01/11

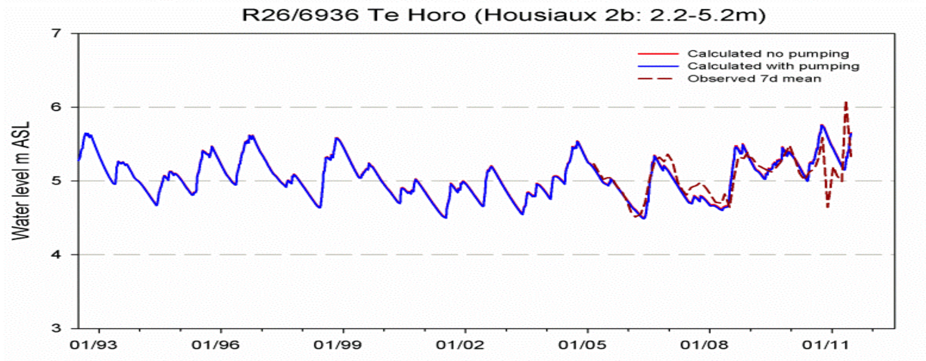

R26/6861 Te Horo (Housiaux 1: 6-7m)
Calculated no pumping
Calculated with pumping
Observed 7d mean
Water level m ASL
3
4
5
6
7
01/93
01/96
01/99
01/02
01/05
01/08
01/11

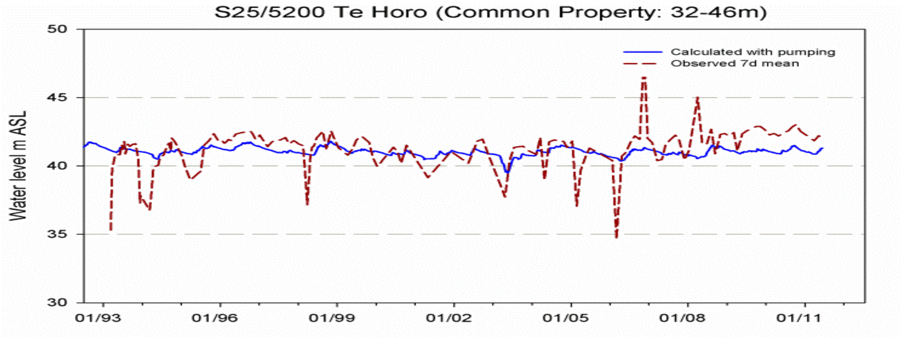

R26/6879 Te Horo (Housiaux 2: 4.4-5.4m)
Calculated no pumping
Calculated with pumping
Observed 7d mean
Water level m ASL
3
4
5
6
7
01/93
01/96
01/99
01/02
01/05
01/08
01/11


R26/6880 Te Horo (Housiaux 3: 6.6-7.6m)
Water level m ASL
Calculated no pumping
Calculated with pumping
Observed 7d mean
01/93
01/96
01/99
01/02
01/05
01/08
01/11


R26/6881 Te Horo (Housiaux 4: 6.5-7.5m)
Water level m ASL
Calculated no pumping
Calculated with pumping
Observed 7d mean
01/93
01/96
01/99
01/02
01/05
01/08
01/11


R26/6882 Te Horo (Housiaux 5: 8.5-9.7m)
Water level m ASL
Calculated no pumping
Calculated with pumping
Observed 7d mean
01/93
01/96
01/99
01/02
01/05
01/08
01/11


R26/6936 Te Horo (Housiaux 2b: 2.2-5.2m)
Water level m ASL
Calculated no pumping
Calculated with pumping
Observed 7d mean
01/93
01/96
01/99
01/02
01/05
01/08
01/11



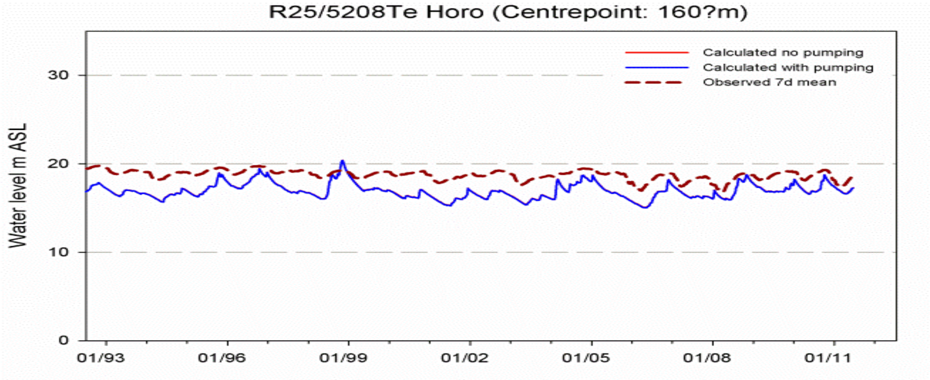


Figure 75: Transient model groundwater head calibration plots for Area 3 (Te Horo zone). Broken line= observed data, solid blue =simulated head with pumping at 50% allocated volume and red solid (where present) = simulated without abstraction effects.

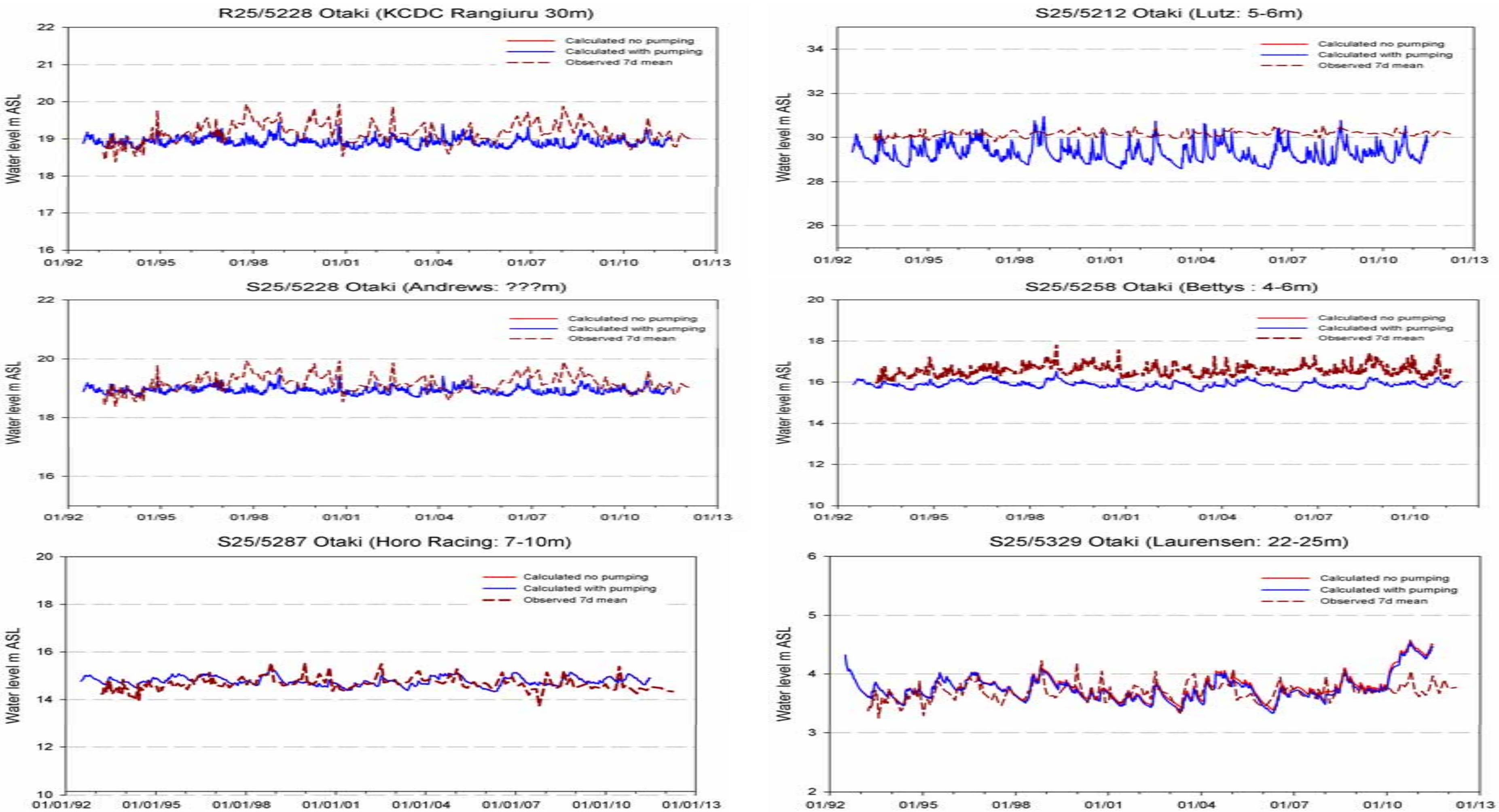


Figure 76: Transient model groundwater head calibration plots for Area 3 (Te Horo zone). Broken line= observed data, solid blue =simulated head with pumping at 50% allocated volume and red solid (where present) = simulated without abstraction effects.

8.6.5 Water balance calibration

a) Catchment scale water balance

Figure 71 and Figures 77 to 78 illustrate the simulated water balance dynamics on a bulk (catchment scale) catchment wide scale. Figure 71 depicts modelled rainfall recharge on a daily basis. Figure 77 shows modelled abstraction (50% of allocated volume), recharge, outflow to drains and net stream losses. Figure 79 depicts daily losses to surface watera and cumulative changes in aquifer storage. Figure 80 shows a comparative daily losses to surface drains and discharge to sea.

Rainfall recharge is highly variable (Figure 71) averaging 171,000 m^3/d over the 19-year calibration period. The annual average recharge for the model calibration period is 63 x 10^6 m^3- although there is a considerable interseasonal variability as shown in Figure 71.

Figure 77: Transient model calibration simulated annual catchment water balances (well abstraction, recharge, drains out and net stream loss)

Figure 77 shows that dominant net inputs to groundwater are rainfall recharge and streamflow leakage. Discharge to drains and sea (Figure 78) are the most dominant outputs. Current shallow and deep groundwater takes constitute less than 2% of recharge through direct rainfall and stream leakage.

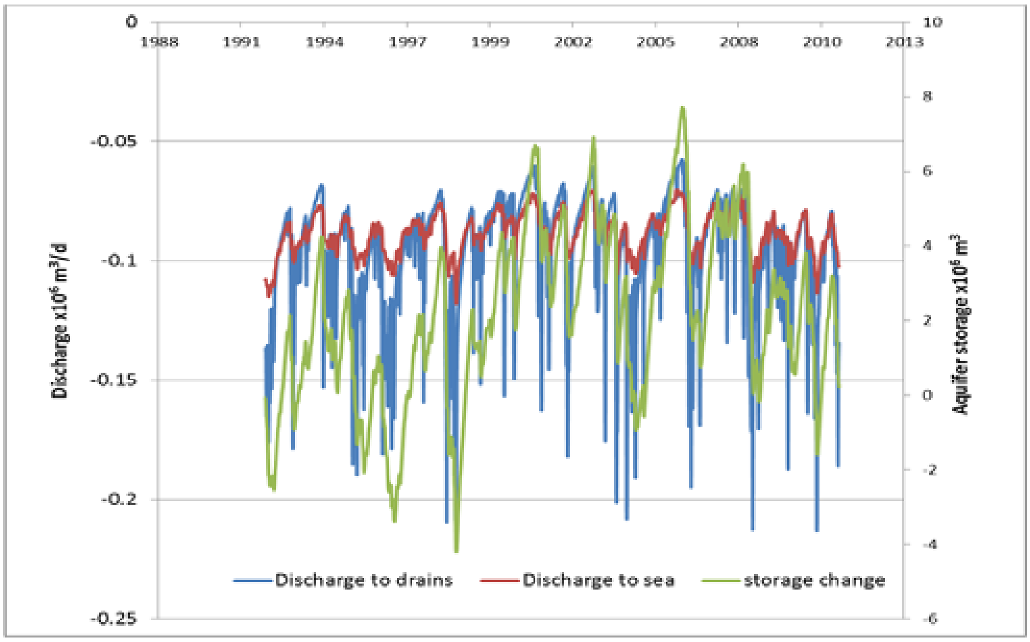


Figure 78: Transient model calibration simulated catchment water balances (simulated net fluxes to drains, sea and changes in aquifer storage)

Simulated catchment interaction between groundwater and the surface water environment is represented in Figure 78. The plot depicts, as negative flux, the total amount of water discharging from groundwater to surface drains and sea. Also shown is the change in aquifer storage that reveals reduced aquifer storage with increased losses to drains and sea. The plots also show that losses to drains are significantly larger than throughflow/discharge to sea.

At any particular time the catchment water balance for the Kapiti Coast catchment is very different. This is shown in Table 24, which displays the modelled catchment water balances for two stress periods in summer (23/04/2008) and winter (5/08/2009).

During summer, Table 24 shows that the rivers provide most of groundwater recharge (153000 m^3/d) and rainfall recharge contributes 74000 m^3/d which is balanced by discharge back into lowland rivers, spring-fed streams, drains and discharge to sea. There is also a large loss from storage (113000 m^3/d) which result in falling groundwater levels. During summer, groundwater abstraction causes approximately 13% of storage decline.

The winter water balance components showed that rainfall recharge was the dominant input to the groundwater system (242000 m^3/d)-significantly higher than river recharge (188000 m^3/d). Comparison between the two balances shows storage replenishment occuring during winter when groundwater levels recover from summer lows.

8.6.6 Groundwater management zone water balances

Figure 79 shows that the groundwater resource in the Otaki is relatively the most developed (current peak over 10000 m^3/d) relative to other zones in Kapiti. The next most developed groundwater resource, in terms of abstraction volume, is Waikanae (current peak over 8000 m^3/d). This figure also incorporates shalllow domestic wells that are widespread in this zone. The Te Horo groundwater zone has a current estimated peak abstraction rate of over 4000 m^3/d, and Raumati has a peak of 1400 m^3/d.

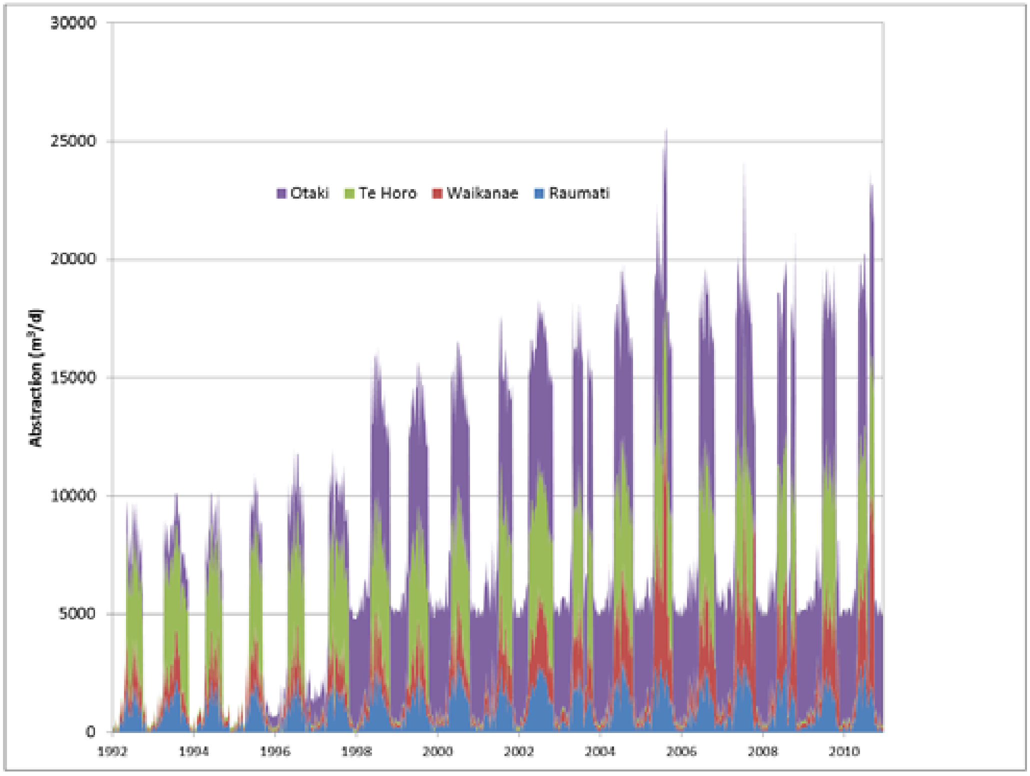


Figure 79: Simulated abstractions for each groundwater management zone

b) Simulated river, drains and spring fluxes

Spatial patterns of river flow losses and gains are discussed in Section 7.4.2 and relevant sections for each groundwater management zones in Chapters 3,4,5 and 6. Quantitative observations of river gains and losses and drain losses were used as calibration targets.

From a quantitative perspective, model calibration relied on measured flow loss and gains calculated from concurrent gauging. The observed fluxes represent irregular measurements and by no means provide a complete characterisation of the interaction between groundwater and surface water. However, they do rpovide a general guide for the magnitude and nature of the fluxes at the time of measurement.Figures 80 to 88 show transient water balance outputs for each of the river surface water reaches targetted.

Area 1 Raumati groundwater management zone

Figure 80 shows the modelled fluxes between the Wainui stream and groundwater over the entire reach. The stream is observed to lose up to 10 l/s (within 800 m) between Wainui stream below KCDC intake and SH1. The stream gains up to 25 l/s between SH1 and the stream mouth to the sea. The stream was simulated as one continuous reach from source to mouth. The model accurately simulated the total gain in flow as shown in Figure 80.

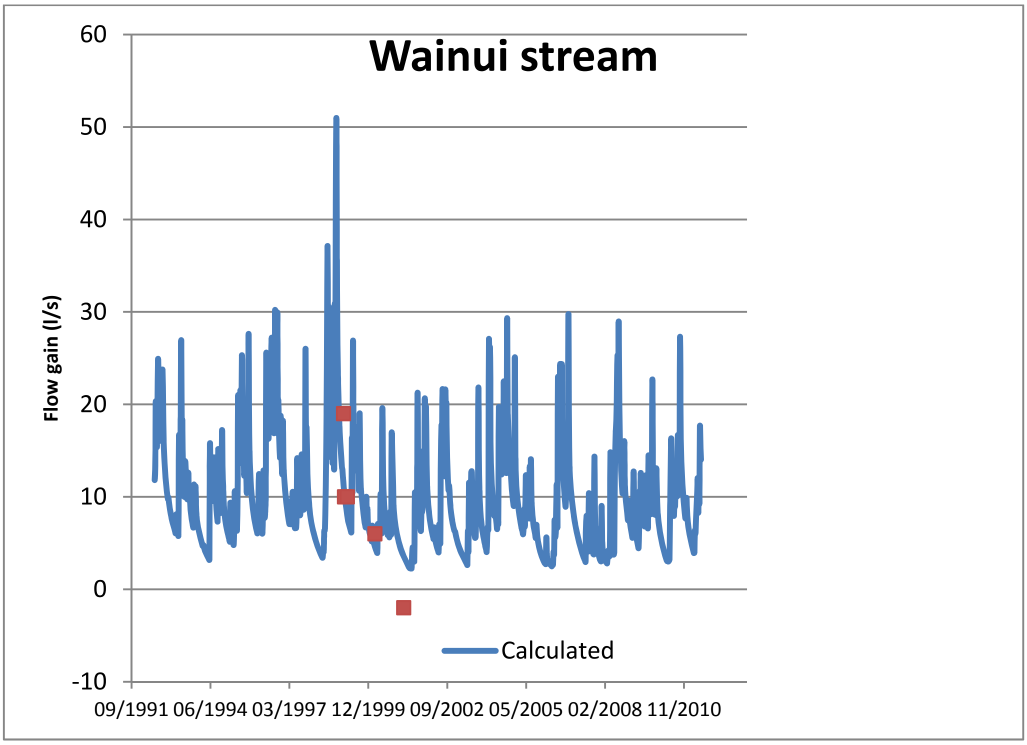


Figure 80: Simulated transient water balance for the Wainui stream for the model calibration period 1992-2011

Area 2 Waikanae groundwater management zone

Waikanae Rivers

Figures 81 and 82 show the modelled fluxes between the Waikanae River and groundwater over two reaches (see Figure 26). The river is observed to consistently lose flow between Waikanae SH1 and Jim Cooke Park (JCP) (Figure 27). Over this reach, the river loses between 200 and 500 l/s to groundwater. The simulated flow losses from groundwater shown in Figure 81 indicate a good agreement with the observed fluxes from concurrent gauging runs,

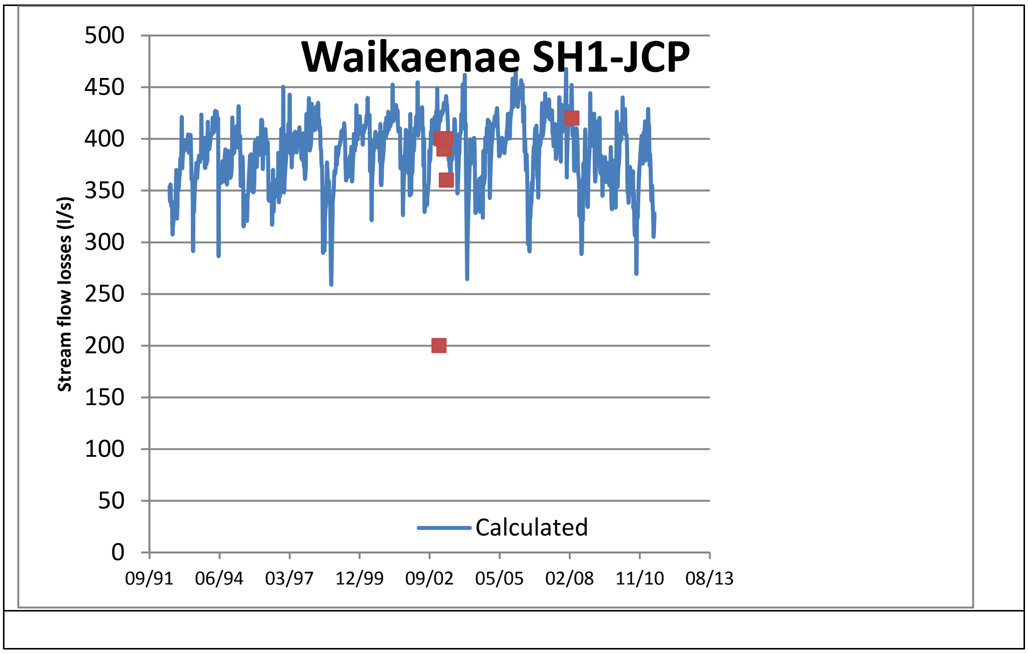


Figure 81: Simulated transient water balance and observed flows for the Waikanae River between SH1 and Jim Cooke Park for the model calibration period 1992-2011

The Waikanae has been observed to gain up to 700 l/s between Jim Cooke Park and sea mouth. There were only two gauging runs at the Waikanae river mouth. The simulated flow gains are between 0 and 350 l/s.

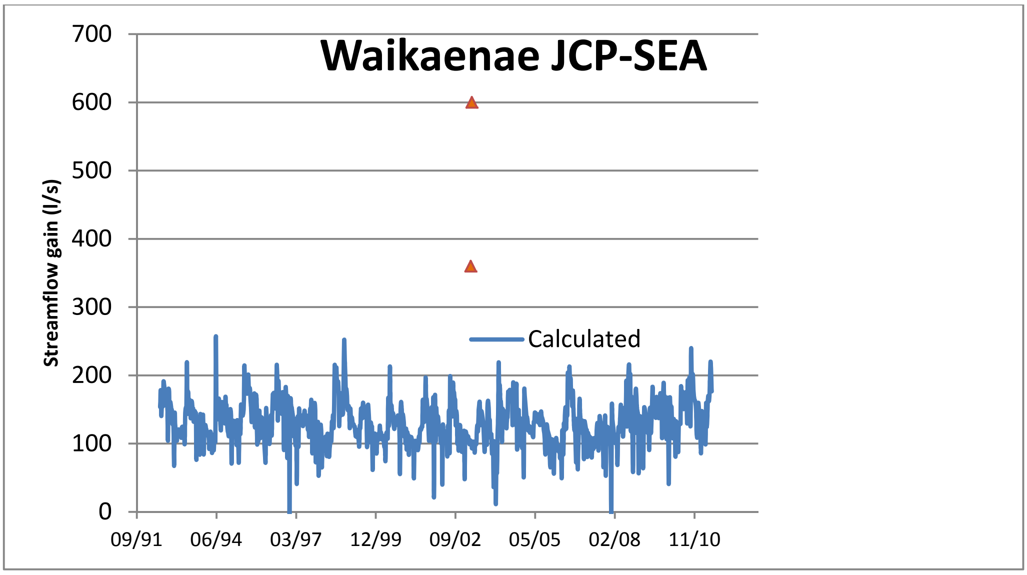


Figure 82: Simulated transient water balance and observed flows for the Waikanae River between Jim Cooke Park and Sea for the model calibration period 1992-2011. Observed flows are more than twice the modelled value but are within the same order of magnitude.

The Waimeha and Ngarara streams

The Waimeha and Ngarara streams were reported (Table 6) to gain up to 150 and 30 l/s, respectively. Simulation results (Figure 83) are in agreement with reported values where simulated gains are between 20 and 120 l/s for the spring fed Waimeha stream. The Ngarara stream is simulated to gain up to 60 l/s with an average of approximately 30 l/s, this stream drains the wetland areas north of the Waikanae.

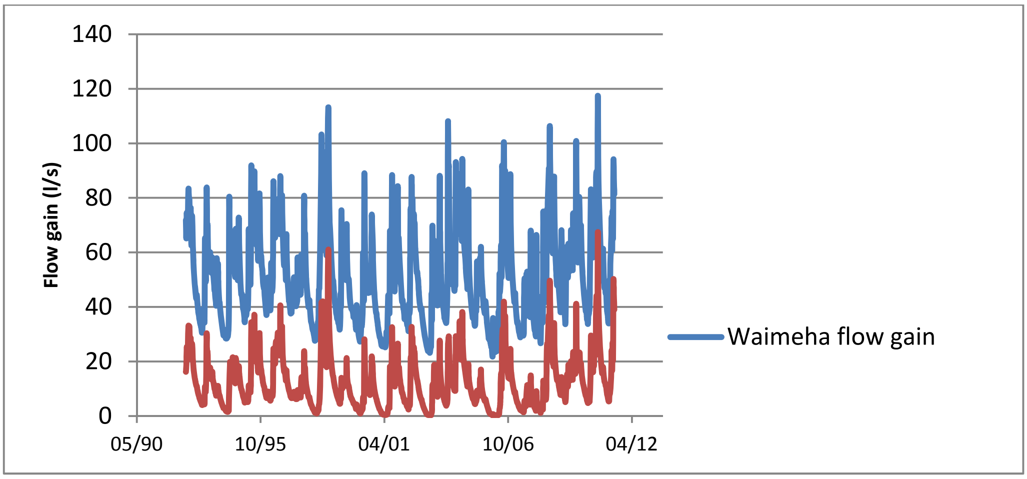


Figure 83: Simulated transient water balance and observed flows for the Waimeha and Ngarara streams for the calibration period 1992-2011

The Mazengarb drain is reported to gain up to 50 l/s. The drain has an automated flow measurement recorder and receives most of the flow from the wastewater treatment plant and also from surface stormwater drainage. Model simulated gain from groundwater strongly agrees to measured baseflow as shown in Figure 84.

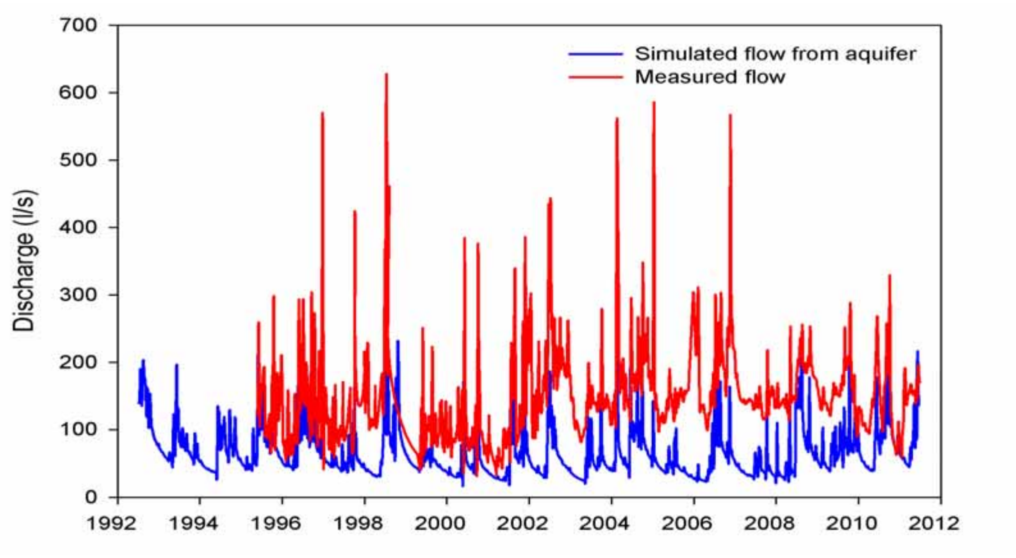


Figure 84: Simulated transient water balance and observed flows for the Mazengarb drains for the calibration period 1992-2011

Te Horo

Streamflow concurrent gaugings indicate that the Mangaone stream losses up to 50 l/s to the unconfined across the Hautere plains. The simulated flow losses shown in Figure 85 show a very good agreement with obsreved flow losses from four concurrent gauging runs.

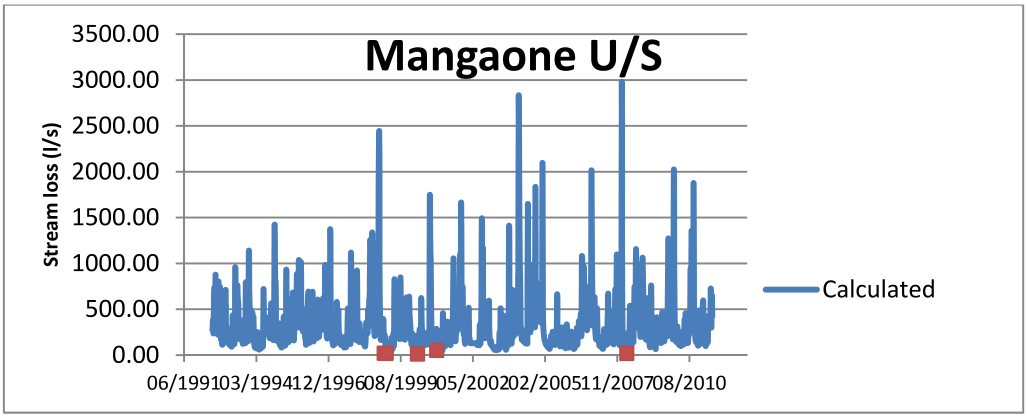


Figure 85: Simulated transient water balance and observed flows for the Mangaone U/S for the calibration period 1992-2011

Downstream of the Holocene marine terrace the Mangaone stream is reported to gain between 150 to 200 l/s from the surrounding Holocene (Q1) sand aquifer. Simulated flows to the Mangaone stream are shown together with observed gains from concurrent gaugings in Figure 85. Simulated/calculated gains closely match observed flows of up to 250 l/s as shown in Figure 86.

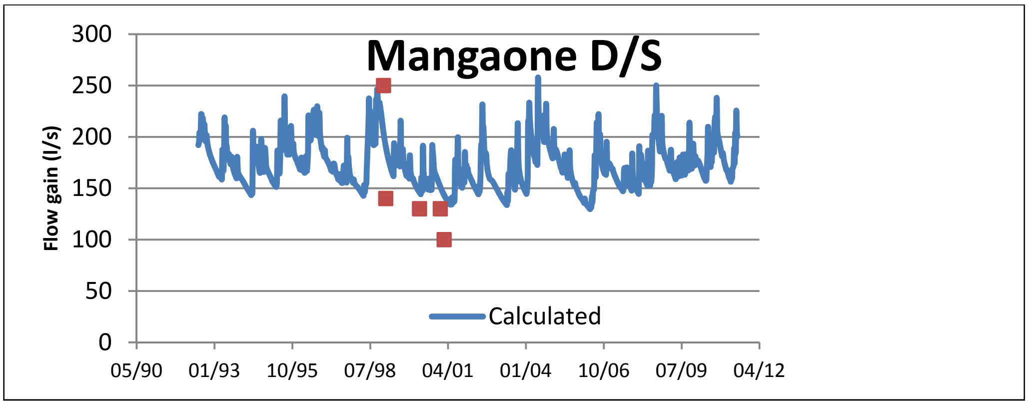


Figure 86: Simulated transient water balance and observed flows for the Mangaone D/S for the calibration period 1992-2011

Otaki River

Figures 87 and 88 showed the modelled fluxes between the Otaki River and groundwater over two reaches which correspond to concurrent river gauging surveys. Concurrent gauging runs in the Otaki River indicate significant flow losses between Pukehinau and the Crystals Bend gauging site.

The simulated fluxes from the river to groundwater closely match observed losses as shown in Figure 88. The Otaki River is simulated to gain up 1000 l/s between Crystals Bend and the sea mouth (Figure 88). There were no measured flows at the sea mouth during the gauging runs and hence no calibration data to compare with simulated flows.

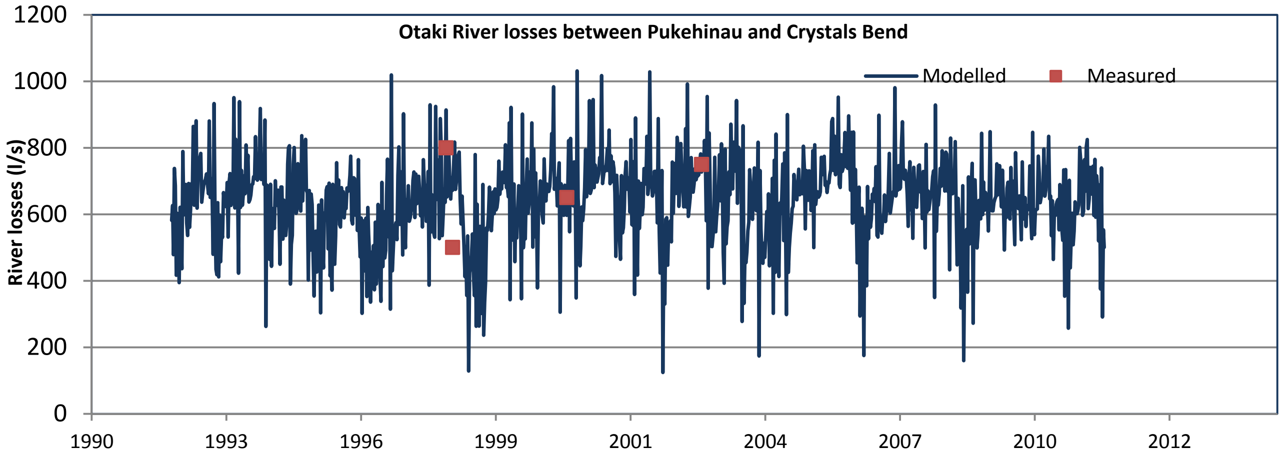


Figure 87: Simulated transient water balance and observed flows for the Otaki River between Pukehinau and Crystal Bend for the calibration period 1992-2011

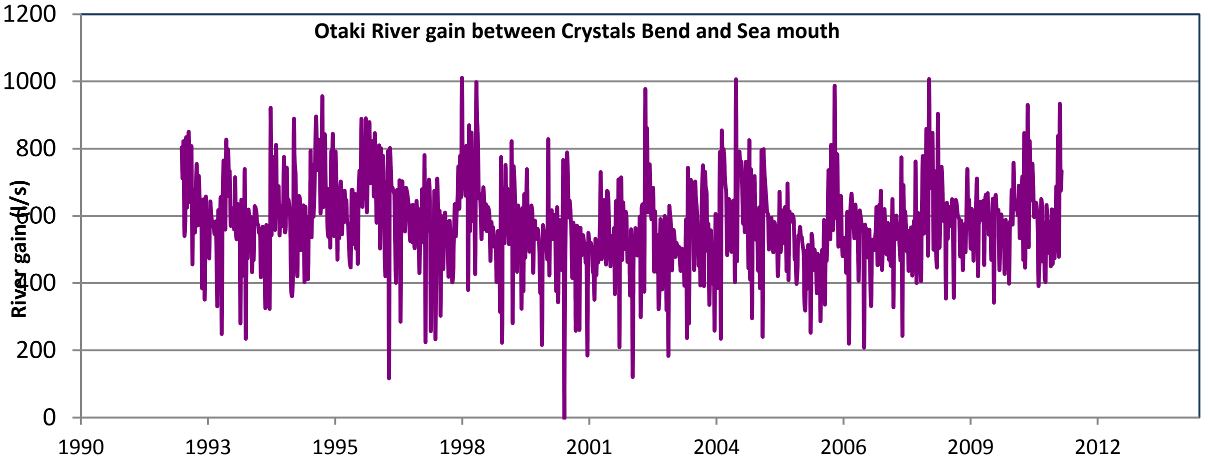


Figure 88: Simulated transient water balance for Otaki River between Crystal Bend and sea-mouth for the calibration period 1992-2011

Table 29 shows simulated groundwater balances for the four groundwater zones for a typical summer condition (9 March 2011). The smulated water balances for the zones being inflows and outflow from rivers/streams, discharge to drains, abstraction, rainfall recharge, discharge to sea and aquifer storage changes.

Simulated values show the significance of drains to groundwater discharges in all four groundwater zones. Discharge to drains is more than throughflow to the sea for Waikanae, Te Horo and Otaki zones. These areas are characerised by a dense network of drainage systems. However, interaction of groundwater with rivers and streams is the most dominant water balance component for major river systems in the Waikanae (Waikanae river), Te Horo (Mangaone stream) and Otaki (Otaki and Waitohu rivers).

Table 29: Simulated water balance for 9 March 2011 for the four groundwater management zones

	Raumati		Waikanae		Te Horo		Otaki	
Flow Component	Inflows	Outflows	Inflows	Outflows	Inflows	Outflows	Inflows	Outflows
	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)
Rivers	1113	1917	19347	21560	30944	21674	238545	228922
Drains		2780		11527		24050		40542
Abstraction		1440		8100		4260		10472
Rainfall recharge	0		0		0		0	
Discharge to Sea		12255		16720		19216		33601
Totals	1113	18393	19347	57907	30944	69200	238545	313537
Change in storage	-17280		-38560		-38256		-74992	

All aquifers lose storage during summer and the storage loss is recovered during winter rainfall recharge.

8.7 Calibrated parameter values

8.7.1 Parameter sensitivity

Parameter sensitivities are listed in Table 30 for those parameters which ramained adjustable at the end of the PEST optimisation process. PEST calculates the composite sensitivities following the calculation of the Jacobian matrix for each iteration. The relative sensitivity (obtained by multiplying the composite value by the magnitude of the log of the value of the parameter) assists in comparing the effects of different parameters of different magnitude on the calibration process.

Table 30: Parameter relative sensitivity for the Kapiti Coast transient groundwater flow model (final optimisation adjustable parameters). Kx-horizontal hydraulic conductivity , Kz – vertical hydraulic conductivity

Parameter		Relative sensitivity
kx_10	Q1 Unconfined holocene sand Raumati and Waikanae L1	0.02
kz_10	Q1 Unconfined holocene sand Raumati (L1,L2,L6)	0.05
kx_11	Q 6-7 Gravel and sand Waikanae L6	0.04
kx_16	Q4 Sand-aquitard Te Horo L4	0.06
kz_16	Q4 Sand-aquitard Te Horo L4	0.02
kx_23	Q3 Alluvium Te Horo, Waikanae	0.01
kz_23	Q3 Alluvium Te Horo, Waikanae (L7 sensitive to vertical leakage)	0.08
kx__2	Q1 Unconfined holocene sand Waikanae,Te Horo, Otaki (L1-3,L4-7)	0.06
kz__2	Q1 Unconfined holocene sand Waikanae,Te Horo, Otaki (L1-3,L4-7)	0.04
kx__3	Q1 River gravel Waikanae, (L2, L5-7) deeper groundwater levels sensitive due to leakage	0.09
kx__4	Q1 Alluvium Otaki, (L1, L2, L6) deeper groundwater levels sensitive due to leakage	0.03
kx__6	Foothill alluvium (L3,L5,L6-7) sensitive as seepage route to deeper aquifers	0.06
kx__7	Q6 Weathered gravel sand (L2,3,7) groundwater levels in Otaki L2,3 highly sensitive to parameter adjustment. Otaki and Te Horo L7 affected likely through leakage from L1.	0.47
kz__7	Q6 Weathered gravel sand (L2,L3, L6-7) shallow layers (L2-3) directly affected and deeper layers sensitive due to leakage from L1.	0.25
kx__8	Q6 Confined (L6-7) deep layers in Otaki, semi-confined in Te Horo(L2,3,5)	0.39
kz__8	Q6 Confined in Otaki	0.01
kx__9	Q5 Holocene sands in Waikanae and Te Horo (L3,5,6)	0.01
kz__9	Q5 Holocene sands in Waikanae and Te Horo (L3,5,6)	0.17

The relative sensitivities are graphically displayed in Figure 89 to help identify those parameters which affect the calibration, and to identify any parameters which may degrade the performance of the parameter estimation process (i.e. very insensitive parameters due to high degrees of correlation and/or an absence of observation data within some parameter zones). Parameter sensitivity is also partly a function of the availability of a good spread of observation data; areas or aquifer depths with little or no prior information will tend to produce apparently insensitive parameters.

Figure 89 shows that horizontal hydraulic conductivity parameters Kx10, Kx23 and Kx4 are relatively insensitive. These relate to Holocene sands mostly in the Te Horo groundwater zone. This zone is characterised by intensive surface water drains that have a greater control on groundwater fluctuations. The upper fan claybound gravels (Kx23) of the Mangaone and Otaki river systems form an effective aquitard where surface flow is perched. Deeper groundwater levels are more sensitive to vertical flow (Kz23) i.e. induce leakage. High Kz23 values in this area result in increase in confined aquifer heads.

Parameters which are highly sensitive and which were therefore estimated with a higher degree of certainty are listed in Table 31

Table 31: Summary of sensitive parameters for the Kapiti Coast transient groundwater flow model estimated with a high degree of confidence (Kx- horizontal hydraulic conductivity, Kz- vertical hydraulic conductivity)

Parameter		Relative sensitivity
kx_16	Q4 Sand-aquitard Te Horo L4	0.06
kz_23	Q3 Alluvium Te Horo, Waikanae (L7 sensitive to vertical leakage)	0.08
kx__2	Q1 Unconfined holocene sand Waikanae,Te Horo, Otaki (L1-3,L4-7)	0.06
kx__3	Q1 River gravel Waikanae, (L2, L5-7) deeper groundwater levels sensitive due to leakage	0.09
kx__6	Foothill alluvium (L3,L5,L6-7) sensitive as seepage route to deeper aquifers	0.06
kx__7	Q6 Weathered gravel sand (L2,3,7) groundwater levels in Otaki L2,3 highly sensitive to parameter adjustment. Otaki and Te Horo L7 affected likely through leakage from L1.	0.47
kz__7	Q6 Weathered gravel sand (L2,L3, L6-7) shallow layers (L2-3) directly affected and deeper layers sensitive due to leakage from L1.	0.25
kx__8	Q6 Confined (L6-7) deep layers in Otaki, semi-confined in Te Horo(L2,3,5)	0.39
kz__9	Q5 Holocene sands in Waikanae and Te Horo (L3,5,6)	0.17

The most sensitive parameter is horizontal conductivity of the main aquifers of the catchment-the Q6 weathered gravels in the Otaki and Te Horo groundwater management zones (Kx7 and Kx8). Parameters representing deeper groundwater in the Waikanae groundwater management zone are also highly sensitive and therefore were estimated with greater accuracy. Groundwater levels were also highly sensitive to the vertical conductivity(Kz9) of Q5 sands in the Waikanae and Te Horo groundwater management zones. Vertical hydraulic conductivity controls leakages between deep and shallow aquifers in these areas.

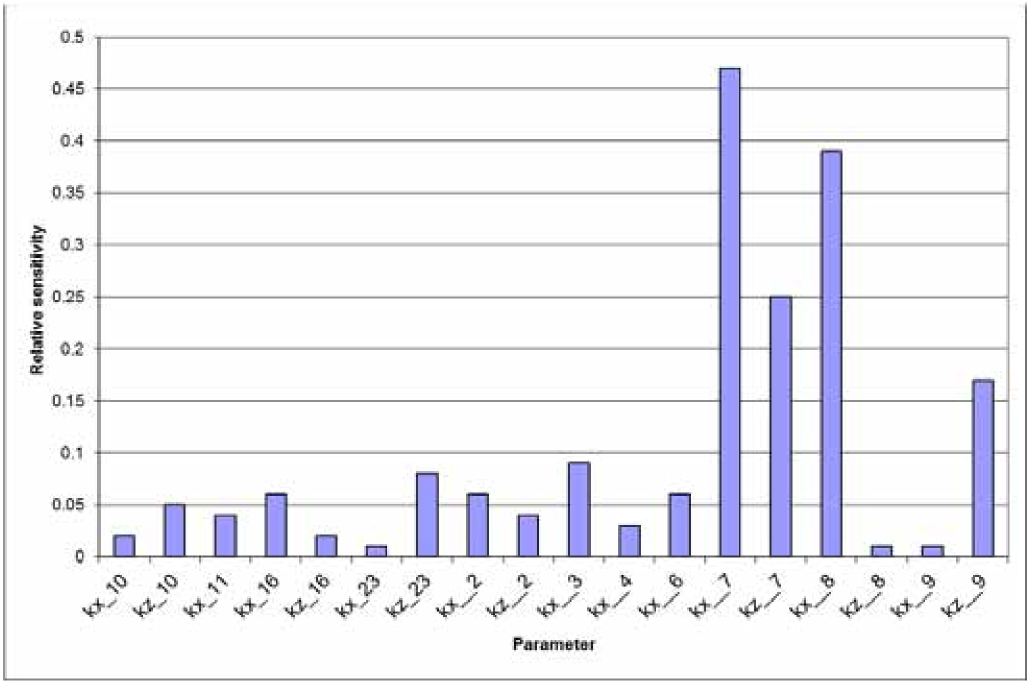


Figure 89: Relative parameter sensitivities for adjustable parameters estimated by PEST

8.8 Summary

The Kapiti Coast catchment transient-flow groundwater model was calibrated for the period 1992-2011 to groundwater level and mass balance observations. The calibration was evaluated in both qualitative and quantitative terms by comparing the simulation results with field measurements. Simulated mass balances and groundwater heads exhibit a good overall visual and statistical fit to observed data.

The calibration was qualitatively assessed by comparing simulated and observed groundwater flow patterns to ensure that the model outputs were consistent with the conceptualisation of the groundwater system. The observed pattern of groundwater-surface water interaction was also replicated by the model.

The appropriateness of the conceptual hydrogeological model at regional scale was validated through the calibration. This is particularly relevent given the geological complexity of the aquifer system and the broad interpretations of the structure and deformation of the aquifer sequences. From this outcome it is clear that the regional groundwater system behaves as a hydraulic continuum.

8.9 Model limitations

There are a number of limitations and assumptions associated with the Kapiti Coast groundwater model. These are outlined below.

- *Homogeneous domains*: the aquifer system is highly heterogeneous, on both microscopic and macroscopic scales. The fluvial depositional environment and active tectonism have resulted in a highly heterogeneous groundwater flow system comprising a mixture of coarse permeable gravels and less permeable sands and silts. The model generally assumes discrete areas of homogeneous material using a mesh size of 250–500 m and does not consider local-scale heterogeneity. The model can therefore only reliably provide useful information at a regional or sub-regional scale and will be unable to accurately simulate small areas in detail.

- *Surface water flow gaugings*: the concurrent flow gauging database is limited in both the number of gaugings and the number of gauging locations. It therefore provides a relatively broad characterisation and flux quantification of groundwater–surface water connections. The gaugings are also restricted to low flow conditions and therefore the modelled losses and gains to rivers are calibrated to seasonal low flows and not to higher flows. However, it is under low flow summer conditions when surface waters are most vulnerable to the effects of abstraction.

- *Historic groundwater abstraction records*: historical groundwater abstractions used for the model calibration were synthesised using a theoretical pumping regime based upon climatic and soil conditions. It assumes every irrigator behaves in a similar way and optimises their use of water to suit soil moisture conditions. In reality, this will not be the case. It is recommended that policies for requiring monitoring of both surface water and groundwater abstractions be developed.

- *Recharge model*: assumptions and estimates were made when assigning hydraulic parameters to soil properties for recharge modelling. Recharge calculation is sensitive to some parameters, such as rooting depth and SCS runoff curve number. Particularly with higher rainfall areas near the Tararua Range, the infiltration-runoff partition will be dependent upon soil moisture conditions and runoff will be higher when the soil is fully saturated (i.e. recharge may be over-estimated during wet periods). A soil moisture-dependent runoff coefficient should ideally be used, but is reliant upon adequate catchment runoff characterisation – at present lacking. The model assumed recharge to have been well calculated and the recharge parameter was not used for parameter estimation in in PEST. However, verification of the model through the water balance calibration of the model serve to verify the accuracy of the recharge calculations.

Despite the above limitations and assumptions, the calibration outputs provide confidence that the transient numerical Visual Modflow model provides a good representation of the Kapiti Coast groundwater system. It can be appropriately used to investigate resource sustainability through the simulation of various theoretical abstraction scenarios.

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