North Otago Volcanic Aquifer Study

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Foreword

Otago's prosperity is largely based on water. The Waitaki River represents a significant water resource for the Otago region and increasingly provides an important source for North Otago; however, despite the large total water volumes present in the region's water bodies, many areas of Otago are short of water. In many cases irrigation is critical to the continued well-being of the people and communities who rely on the primary production it supports.

Otago Regional Council's (ORC) Regional Policy Statements for Water provide for the Otago people and communities having access to water for their present and reasonably foreseeable needs.

Groundwater is frequently the sole or major source of water to supply basic water needs to communities and stock watering. Currently, groundwater only supplies a small proportion of irrigation needs; however, there is increasing pressure for people to turn to groundwater because surface water supplies are heavily allocated. Over-abstraction of groundwater can result in loss of supply to other users and, therefore, careful management is required to keep abstraction rates sustainable.

Groundwater resources have varying rates of recharge and often form a complex dependency with adjacent water courses, wetlands and stream networks. The effects of inappropriate land and water use and development on groundwater quantity and quality are often long-term, and in some cases permanent. It is therefore important that particular consideration be given to the protection of aquifers for the continuing benefit of present and future generations.

Through ORC's Regional Plan: Water (the Water Plan) and Annual Plans, we ensure linkage with the community to deliver the efficient use and protection of our groundwater aquifers.

This report describes the hydrogeology of the North Otago Volcanic Aquifer (the Aquifer) and suggests future management options. It is based on local knowledge, monitoring data and groundwater modelling. The best way forward is to use to advantage this valuable resource while maintaining control so that over-abstraction does not occur. This is a complex topic and further monitoring and review of the aquifer will continue to ensure a sustainable allocation.

Executive summary

The groundwater bearing volcanic marine sediments surrounding Oamaru have been classified under a variety of names and hydrogeological schemes. This study has chosen to group the variously associated sediments, such as tuff, limestone, basalt, siltstone and diatomite, into a single aquifer unit named the North Otago Volcanic Aquifer (the Aquifer). This delineation recognises the shared groundwater flow patterns and its function as a distinct hydrological unit.

The Aquifer has been shown to contain modest quantities of groundwater within consolidated volcanic sediments or sediments with volcanic associations that display moderate to low permeability in aquifer testing. The aquifer is replenished by the infiltration of rainfall draining through the overlying soils. The pattern of such soil drainage is governed by the soil-water properties of the overlying soil, which are revealed to be very retentive. Consequently, considerable and intense rainfall is required to initiate soil drainage that replenishes the aquifer. The seasonal groundwater recharge pattern is profoundly affected by this feature, and some years have passed without any soil drainage to replenish the system whatsoever.

The Aquifer features unusual water quality, including elevated sodium and nitrate. The high sodium concentrations are due to natural geochemical interactions with volcanic minerals in the aquifer. The high and excessive nitrate concentrations are thought to be associated with the predominant cropping and market gardening land use on the overlying land. Sophisticated statistical analysis of chemistry data has generally confirmed the grouping of groundwater chemical composition with the most directly associated geological formation.

Groundwater computer modelling was conducted to assist assessments of current and future groundwater management. Model parameter optimisation and calibration utilised continuous climate and groundwater level data measured from the area over the previous ten years. Final calibration produced a transient groundwater model that was successfully calibrated to the range of climate and pumping stresses experienced over this period. The completed model evaluated the following:

- The effect of pumping from the aquifer's irrigation bores at percentages of the existing allocation ranging from 0%, 30%, 50%, 100% and 150%.
- The effect of the aquifer not receiving the largest significant recharge pulse in the past ten years i.e. replacing a wet year with a drought year.

The modelling results demonstrated a mostly proportional effect of increasing groundwater pumping on both aquifer groundwater levels and the outflows from the aquifer to surface water (such as Waiareka Creek or the Pacific Ocean). Similarly, manipulation of the recharge pattern within modelling scenarios to remove recharge from certain years revealed a significant effect on groundwater levels and outflows. The sections of the Aquifer coastline that are protected from seawater intrusion by the presence of fine capping sediments do not indicate any vulnerability in model scenarios to groundwater flow reversal that would initiate seawater intrusion of the aquifer. The only part of the coast with a degree of vulnerability to seawater intrusion is the Kakanui Estuary where seawaters come into direct contact with volcanic sediments. Once again, model scenarios did not find flow reversal, although they did indicate a lower threshold against seawater intrusion than the rest of the coastline.

Suggested future management options include:

- Use of a new boundary to define the Aquifer.
- A groundwater management area to be established in the Kakanui Estuary zone to protect against seawater intrusion.
- New lower restriction levels on Webster Well (J41/0178) for the whole Aquifer and removal of the restriction levels on Isbister Well (J41/0198).
- A total allocation limit of **7 million cubic metres per year** from the Aquifer.
- Publicity on the high nitrate status of the eastern aquifer to ensure the community is informed.
- Promotion of appropriate bore and well construction that avoids some past drilling approaches and their adverse effects on groundwater levels or quality.

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1. Introduction

The North Otago Volcanic Aquifer is a valuable water resource for the parts of Waitaki District underlain by the volcanic sediments. The residents and land managers of the land north, west and south of Oamaru have noted the presence of groundwater in the volcanic sediments since the area was settled in the mid-1800s. Private wells, bores and springs provide water in the district for domestic supply, stock water and irrigation, relying largely on the shallow volcanic sediments. Continued access to groundwater of acceptable quantity and quality is important to residents living and farming over the aquifers. The aquifers are also an integral part of the hydrological make-up of the area, including the sustenance of dry-weather flow in some creeks. Accordingly, groundwater management based on an adequate understanding of the groundwater systems containing the water resource is required.

Past investigations had assigned the aquifer names in accordance with the Waiareka Volcanic Tuff in the west and Deborah Volcanics more to the east, thereby labelling them the Waiareka Aquifer and Deborah Aquifer, respectively. Since 1993, a variety of fresh issues have arisen in relation to the Aquifer and a body of monitoring data have been collected. This report reviews this technical information and guidelines for future groundwater management.

The report's objectives are as follow:

1. To describe the Aquifer in the context of past and new information.

2. To review groundwater level and quality data for the Aquifer gained over twenty years of investigation and monitoring since 1985.

3. To develop a conceptual model of the hydrology of the aquifers, including hydraulic properties, recharge, discharge and water use.

4. To develop a numerical model of net rainfall recharge across the aquifer.

5. To develop a numerical model of groundwater flow within the aquifer for the determination of large scale and cumulative impacts of changes in groundwater use and climate variability.

6. To develop management guidelines for optimum groundwater exploitation alongside critical environmental constraints.

2. Setting and background information

2.1 History of previous studies

Until quite recently, the principal geological reference for the Oamaru district was that of Gage (1957), which described the accumulation of Tertiary aged (2 to 65 million years before present) sediments forming the district's landscape. Subsequently, the 1:250,000 scale Waitaki Q-map (Forsyth et al, 2002) is the most current geological map that incorporates the stratigraphic framework of Edwards (1991) and Gage (*ibid*) plus a regionalised stratigraphic nomenclature. Burt W. Collins of the New Zealand Geological Survey (NZGS) undertook a survey of the district's wells and bores and prepared a hydrological report (Collins, 1953) and a Royal Society paper (Collins, 1954) on the occurrence of groundwater in the district. These studies were followed up by Mutch (1963) in a water report by the NZGS based on well data. The Water and Soil Conservation Act was promulgated in 1967 and stimulated more integrated water resource management and the licensing of water use, especially after groundwater was incorporated in the Act by amendment in 1981. A visiting Israeli expert in groundwater described the groundwater resources of the Kakanui Basin including the area containing the volcanic aquifers (Mandel, 1974), in the early 1970s.

As a result of being engaged by a consortium of 22 landowners throughout North Otago, Simon Carryer carried out an assessment of the groundwater development prospects for each property and the district generally (Carryer, 1983). Mr Carryer was active since 1977 in investigating the limestone, tuff, sand and lignite resources of the area, including groundwater conditions, for New Zealand Cement Holdings Ltd. His recommendations for extensive privately financed groundwater exploration and development were not taken up by members of the consortium, who preferred to lobby the Government for water resource solutions for the district. In 1982, the district suffered a severe drought resulting in significant loss in pastoral and arable production and consequent economic losses. In 1983, a steering group with representatives from the then Ministry of Agriculture and Fisheries, Ministry of Works and Development, Department of Scientific and Industrial Research, Otago Catchment Board and the North Otago Groundwater Group began planning for a groundwater investigation, including a request for funding from the National Water and Soil Conservation Authority. Approval was secured in late 1984 and the bulk of investigations were commenced by the Otago Catchment Board in early 1985, including the employment of a geo-hydrologist in April of that year. This investigation was focused upon the Papakaio Aquifer, Waiareka Volcanics, Deborah Volcanics and Kakanui Alluvium, essentially all of the potentially useful groundwater geological formations. The study continued until 1993, including the undertaking of farm bore surveys, drilling, geophysics (down-hole and surface), aquifer testing and water quality sampling. The study experienced contractual difficulties with drillers and the loss of the catchment board geo-hydrologist in the late 1980s. The study was completed by Dugald MacTavish of Irricon Consulting under a contract to review, complete and report in early 1993 following local government amalgamation and absorption of the catchment board within the Otago Regional Council (ORC, 1993).

Subsequently, unpublished reports with relevance to the volcanic aquifers were prepared for ORC (ORC, 2000 and ORC, 2001) and Holcim NZ Ltd (Kingett Mitchell, 2006). Preparations for the regional water plan gave rise to a background technical report by ORC outlining the synthesis of the knowledge of Otago aquifers including North Otago (ORC, 1998). The Otago Regional Plan: Water (Water Plan) came into force in February 2004 and included management provisions for the Aquifer. The area was divided into a number of overlapping zones within the plan:

- A combined North Otago Volcanic Aquifer, merging the Waiareka and Deborah Aquifers, and part of the Kakanui – Kauru Alluvium Aquifer / Groundwater Protection Zone (map C10) comprising 93.6 square kilometres (km^2).
- Waiareka Water Take Restriction Zone and Deborah Water Take Restriction Zone (map D2) comprising 63.8 km^2.

The aquifer mapped zone (map C10) extends over much of the land underlain by volcanic sediments whereas the take restriction areas are approximately 68% the size, concentrated on the southern portion of both aquifers and around the larger concentrations of groundwater abstraction. The existing groundwater management of these zones and areas is outlined further in this report in Section 5 and mapped in Figure 5.1.

2.2 Geology and physiography

The Aquifer lies within downlands and tablelands west and south of Oamaru township, North Otago. Figure 2.1 shows the area’s geography and location within Otago as an insert. Weston is the central township of the aquifer zone and lies to the west of the much larger Oamaru township, which is the seat of the Waitaki district. The principal surface water drainages overlying the aquifer are Waiareka Creek (within the Kakanui Catchment), Awamoa Creek and Oamaru Creek (which drain individually to the coast). Landon Creek is largely ephemeral and found in the far north of the area.

As with any area of complex stratigraphy, the Oamaru area has received generations of geological categorisation and classification. This inevitably leads to many overlaps and changes to previous geological formation or unit names. For instance, the most recent geological map for the area (Forsyth et al, 2002) changes the names of the Totara Limestone to the Ototara Formation, along with many other subtle or gross alterations of the previous stratigraphy. This report acknowledges this new stratigraphic scheme, but tends to rely upon the consensus naming of strata developed at the time of the 1980s – 1990s North Otago Groundwater Investigation (ORC, 1993). The reasons are to preserve internal consistency with other ORC publications and avoid confusion for a wider readership. The main exception is dropping use of the Papakaio Formation and instead referring to the Taratu Formation in common with all Eastern Otago while distinguishing the Papakaio Aquifer as the groundwater system within the Taratu Formation. Figure 2.2 and Figure 2.3 show the geological sequence and correlation with the geo-hydrological strata. Broadly speaking, the sediments making up the volcanic aquifer comprise the following strata and geological materials:

- Waiareka Tuffs: Marine tuff beds, columnar-jointed basalt intrusions, pillow lavas, siltstones with volcanic ash inclusions and occasionally diatomite.

- Totara and McDonald Limestones: Marine carbonate sediments, including massive, fine-grained limestones and calcareous siltstones, often with significant volcanic associations.
- Deborah Volcanics: Marine tuffs, pillow lavas, columnar-jointed basalts, crystal breccias, ash beds and siltstones with significant volcanic influences.

It is important to note that there are seldom precise stratigraphic boundaries between these strata and that they were all deposited in a sea of varying sea floor depths close to a subsurface volcanic eruption that ultimately extended above sea level for brief periods. Below the base of the volcanic sequence are marine sediments without volcanic influences and deposited in deeper water. These are classified as the Tapui Glauconitic Sandstone, and the slightly later, the Raki Sandstone. Despite bearing the name of a sandstone, these sediments are fine, very silty and consequently of quite low permeability. Overlying the volcanic sequence are once more, deeper-water fine marine sediments, including Gee Greensand and the Rifle Butts Formation. These capping sediments over the volcanic sequence are also of low permeability. The strata from the Tapui Glauconitic Sandstone to the Rifle Butts Formation span the Eocene, beginning 54 million years (Ma) ago, up to middle Miocene, ending 18 Ma. In places, such as beneath the north part of Oamaru, the sedimentary thickness of the volcanic sequence is over 500 m, including 245m of Deborah Volcanics, 30m of limestone and 235m of Waiareka Volcanics. In the east and along the coast line, the sequence tends to be capped by a thickness of Gee Greensand and Rifle Butts Formation. In the west of the Waiareka Creek Catchment, the volcanic sequence is thinner for sedimentary reasons and also extensively thinned through erosion since being exposed by crustal uplift and faulting in the Pliocene and Quaternary (6 Ma to present).

The recognised faulting and folding structures deforming the volcanic aquifers include the following:

- Teanaraki Fault in the northwest of the area near Enfield, which truncated and preserved the volcanic sediments from deeper erosion by its down-faulting to the east.
- Awamoa Fault in the east of the area just to the south of Oamaru and Cape Wanbrow. This fault is a small offset with the downthrown side to the west, thereby thickening the sequence of Gee Greensand and Rifle Butts Formation on the east side (Figure 2.2).
- Springfield Fault is a deep-seated north-south trending normal fault interpreted solely from seismic surveys of the Waiareka Valley (O'Connor, 1992).
- Ardgowan Syncline is a down-fold trending south – north from the headwaters of Awamoa Creek to Devil's Creek. This fold is the larger and most discernable of a set of folds that also produces an alternating series of anticlines (up-folds) and synclines (down-folds) throughout the volcanic sequence (Figure 2.2).

Beneath the Tapui Glauconitic Sandstone and Kauru Formation is the Paleocene – Cretaceous Taratu Formation, which contains the Papakaio Aquifer. The Taratu Formation, in turn, overlies the schist basement rocks. The Taratu and basement rocks are at least 200 m below sea level throughout the Aquifer area and often deeper due to the regional dip of the sequence and the thickness of sedimentary materials below the base of the Waiareka Tuff. A single deep bore, called the Mitchell Bore (J41/0273), has been drilled through the volcanic sequence to the Taratu Formation to tap the Papakaio Aquifer. This 454m artesian bore in the Waiareka Valley extended over 310m below ground before it hit the top of the Taratu formation. The cost and technical difficulties in drilling at such depth is the reason that very few bore holes penetrating into the Papakaio Aquifer are found east of the westernmost margin of the volcanic sequence.

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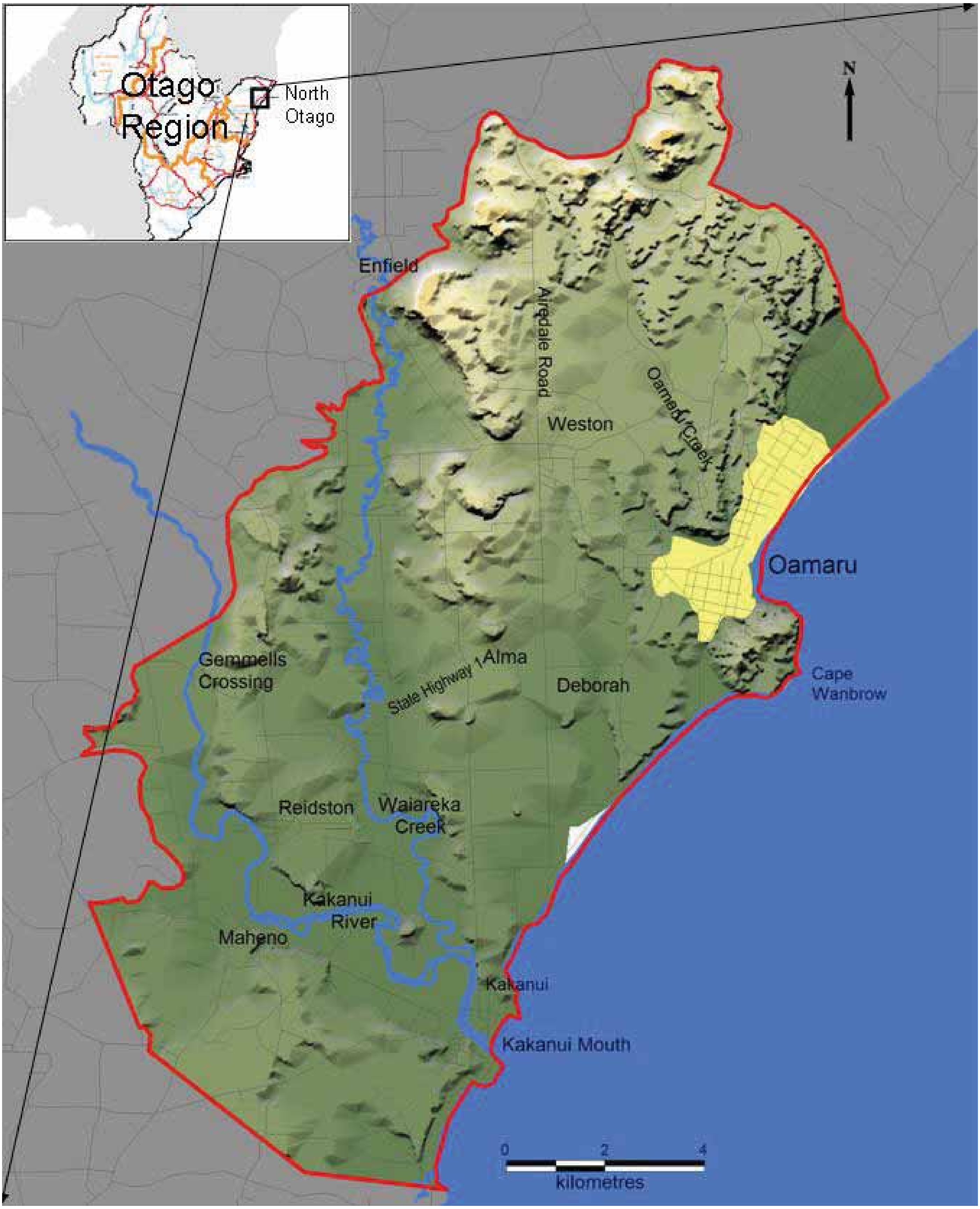


Figure 2.1 **Location and geography of the North Otago Volcanic Aquifer. Location in Otago also shown in insert box for regional orientation. Margin of study area shown in red**

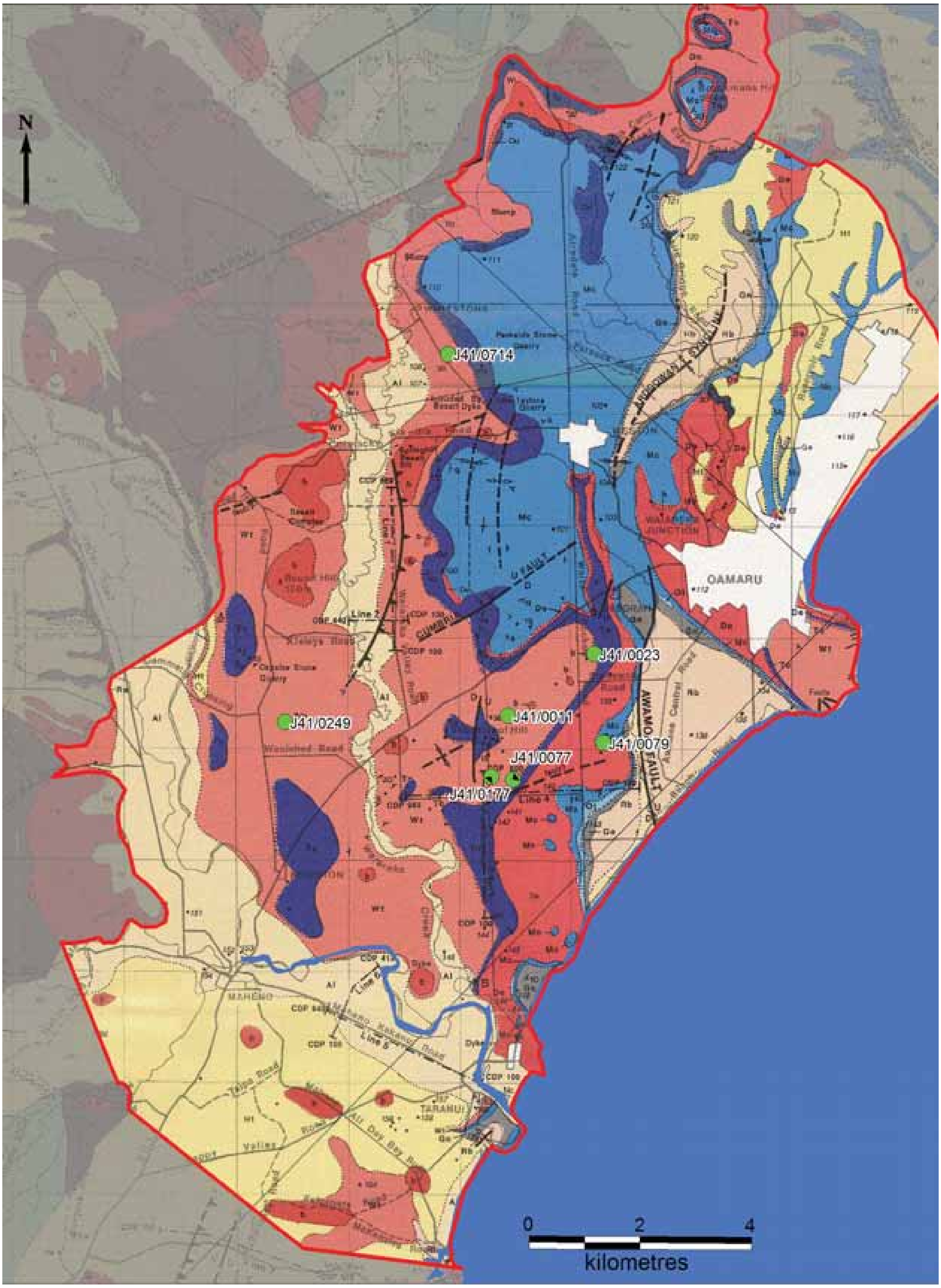


Figure 2.2 **Geological map of the North Otago Volcanic Aquifer with groundwater management area highlighted.**
Location of aquifer test bore sites also shown (ORC, 1993)

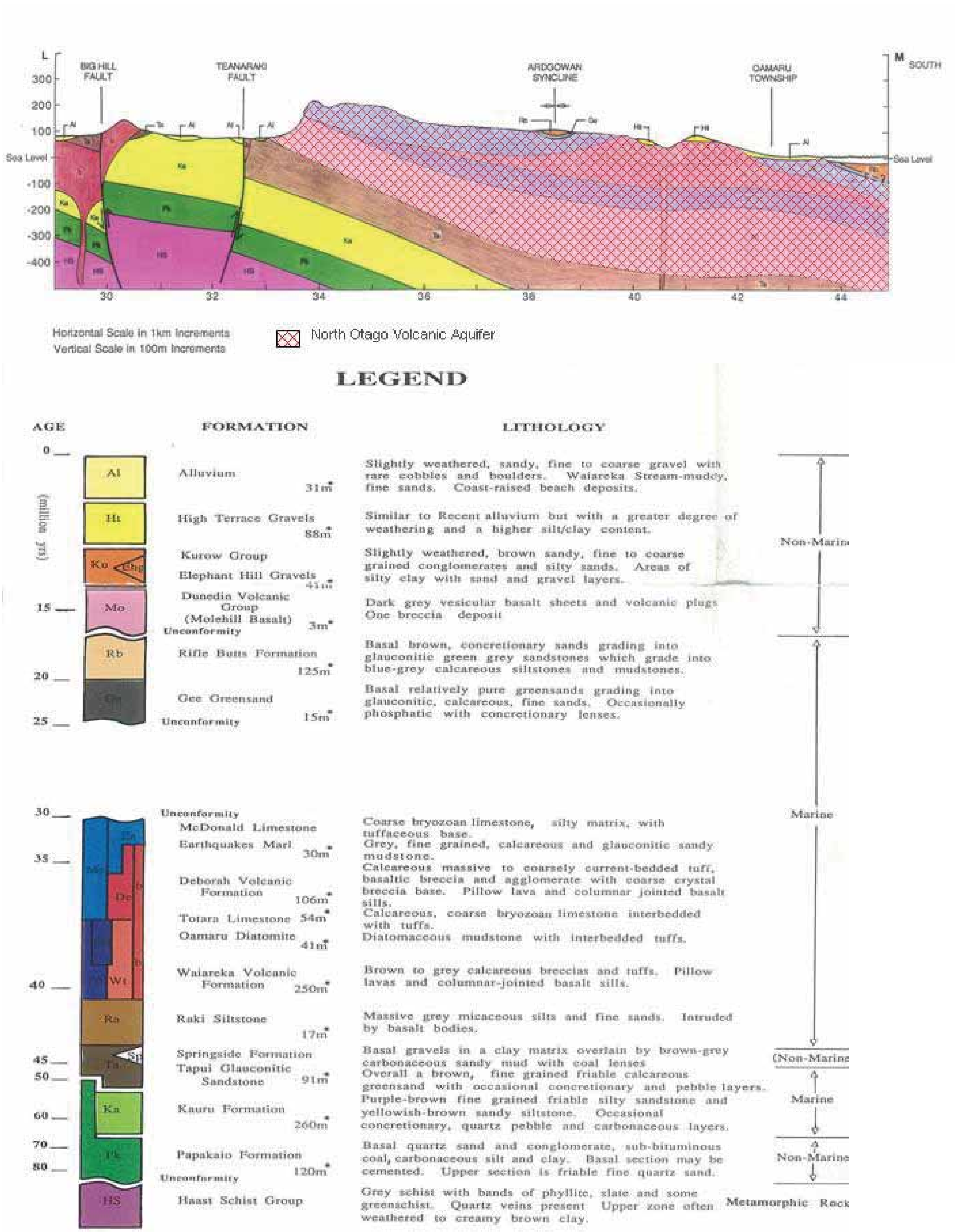


Figure 2.3 Representative cross-section from NW to SE through Oamaru and stratigraphic column / legend for the geological units contained in the geological map and cross-section (ORC, 1993)

2.3 Climate and land use

The North Otago area has a temperate climate characterised by strong oceanic influences from air streams from the Pacific coast and those prevailing air streams from the southwest and northwest that are tempered by passing over elevated parts of the South Island interior. The area is thus strongly affected by the predominant air stream direction in terms of the temperature, evaporative potential and rainfall pattern. Non-seasonal climate patterns, primarily the El Nino / La Nina southern circulation and the Pacific Decadal Oscillation can have a profound effect on the climate and hydrology of the North Otago area by changing the balance of air streams crossing the district. El Nino is well known for producing summer droughts under relentless northwest winds such as the significant droughts of 1982 and 1999.

The mean annual temperature average for Oamaru is 10.5ºC, with the warmest month being January and the coldest being July. The rainfall record closest to the centre of the Aquifer has a recorded mean annual rainfall of 580mm. The same mean annual rainfall total at Grandview in the east of the Aquifer was 446mm. Potential evapo-transpiration tends to exceed annual rainfall, which is normal for the climate region to which the area belongs. This induces significant soil moisture deficits in the late spring, summer and much of the autumn in most years. Soil moisture surpluses, when runoff and groundwater recharge can occur, tend to be confined to the winter and early spring periods.

Land uses in the area overlying the volcanic aquifer are dominated by pastoral and arable agriculture. Market gardening and cropping is concentrated in the east of the area within an approximate triangle defined by the locality of Alma, Oamaru township and Kakanui township. Additional small areas of glass-house market gardening are found around Alma. A significant land use change is underway in the Waiareka Valley as a result of the roll-out of the Downlands Irrigation Scheme which began in 2007. The scheme brings surface water from the Waitaki River into the upper Waiareka Valley and associated downlands by means of a diversion, pump lift and buffering storage. The distribution of the irrigation water is primarily by buried pipeline, although a surface water transfer utilising Waiareka Creek is also part of the scheme. The scheme's irrigation capacity is sufficient to cover much of the valley's agricultural soils with water exceeding most years' soil moisture deficit. This allows irrigated pastoral (mostly dairying) and arable agriculture to expand in extent and intensity. Due to current commodity prices, much of the shift in land use will be out of sheep fattening and into irrigated dairy grazing.

The soils overlying the volcanic aquifers are grouped into six main categories from approximately 35 sub-classes and variants. The soils contain most of the soil series common to North Otago, but also feature the Waiareka and Te Anarki series local to the Waiareka Creek Catchment. The soils tend to be deep, no shallower than 20cm and commonly deeper than 90cm (0.9m). Soil textures are dominated by silt loams and clay loams, combined with some lesser silty clay and fine silty sand. The soil – water parameters of field capacity for these soils range from 620 mm to 48 mm, with an area-weighted average of 307mm. Such soil field parameters are considered high compared with a typical New Zealand soil, which has significance to groundwater recharge. This is discussed further in the sections covering soil hydrology and groundwater recharge modelling.

2.4 Groundwater use and occurrence

In the 1880s, hand-dug wells were used for domestic and stock water. Cropping agriculture, mainly for wheat on agricultural estates, was dry land based and did not require irrigation. By the 1920s, there was the culmination in the swing from estate based cropping that began in the late 1880s, towards the spread of smaller dairy units for cheese production. These dairy farms and rural subdivisions led to the spread and increase in number of wells and increasingly narrower diameter bores. The 1950s, wool and sheep meat boom led to a post-War increase in bores drilled with the local Taylor's Drilling rotary drilling rig. This rotary rig was capable of drilling faster and deeper through the softer parts of the volcanic sediments using a tricone drill bit, whereas previously, without the rotary rig, shallow wells or bores were only feasible in these materials by means of hand or cable tool drilling. Consequently, the effective cost for bores in the volcanic aquifers came down and the feasibility of locating groundwater within a deeper sequence increased. The ability to reach a greater number of fractures and fissures in the volcanics and to penetrate deeper beneath the water table was thus significantly increased. All drilling was privately funded and in response to specific needs for water. In the 1970s and 1980s irrigating from groundwater was becoming more common although the capacities of the new submersible pump units were still limited. The spread of rural water schemes in this period saw less reliance on groundwater for domestic and stock water, so many domestic wells or bores fell into disuse.

For a period in the 1980s, groundwater based irrigation was seen as a solution to serious water deficits in North Otago. While most attention fell upon the Papakaio Aquifer and Kakanui Alluvium, the volcanic aquifers were considered to have potential, especially given the possibility that fractured basalt intrusions would yield volumes of water suitable for irrigation. The North Otago Groundwater Investigation report of 1993 had the foreword comment that "a number of successful irrigation boreholes in the Enfield Basin raised hopes that groundwater might provide a solution (however) groundwater is not found to be the panacea we all hoped for" (Arthur Budd, chairperson of the resource planning committee, Otago Regional Council in ORC, 1993). This reflected the new understanding that the district's groundwater resource was naturally limited by low permeability and water quality factors.

There are 40 current groundwater abstraction resource consents issued for irrigation from the Aquifer. There are a further five general use agricultural groundwater take consents, one pit dewatering and one community water supply also allocated groundwater through consents. This is in addition to the approximately 350 records of wells, bores and a small number of pits from which groundwater can be pumped for permitted domestic, stock and general groundwater uses in the area of the volcanic aquifers. Clearly, the groundwater resource holds considerable importance to the residents of the area. Figure 2.4 maps the location of the Aquifer bores and wells as defined within the ORC well records database.

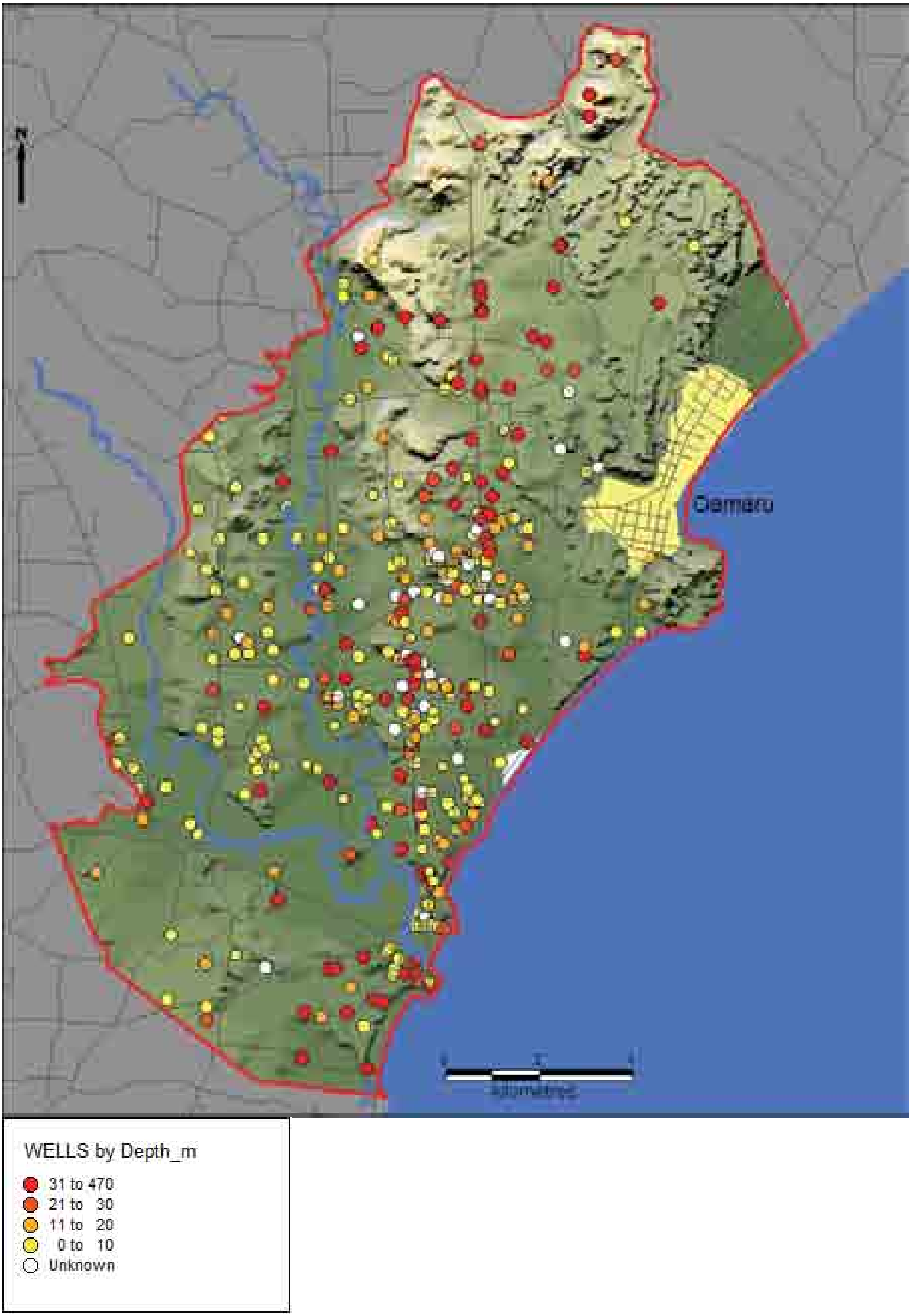


Figure 2.4 Location and depth class of bores and wells within the North Otago Volcanic Aquifer

The volcanic sediments comprise the following:

- Marine deposited tuffs and ash falls
- Volcanic breccias
- Pillow lavas
- Limestone, inter-bedded with tuff deposits
- Columnar-jointed basalts
- Marine siltstones
- Diatomaceous siltstone.

For the purposes of describing the occurrence of groundwater in the area, the purely marine sediments, such as the Totara Limestone, McDonald Limestone and siltstones, are lumped with the volcanic sediments as conjoined layers sharing groundwater within the same system. This is significant since the previous investigations had used the limestone formations to divide the sequence into the Waiareka and Deborah Aquifers. This study has highlighted the belief that the distinction is somewhat artificial and lacking in a hydrological rationale for making such a division.

The sediments have compacted through time, especially following being subjected to structural compression and uplifted to their current height in the last two million years. Tuffs and basalts were already consolidated during their deposition, cooling and subsequent weathering. Through compaction and consolidation the volcanic and associated sediments have lost much of their original pore space. Subsequently, the sediments have been subjected to stresses resulting in fracturing and jointing. In addition, tuffs and basalts have formed voids in the shape of solution vugs that create pore space for groundwater flow. Similarly, calcareous limestones develop solution voids once they are uplifted, even temporarily, above the regional water table. The degree of solution void formation in North Otago limestones is not thought to be significant, although localised voids have been noted. The result is that the volcanic sediments contain groundwater in a variety of pore compartments with varying degrees of hydraulic communication from one compartment to the next. This allows the consolidated volcanics and associated sediments to function as aquifers, albeit aquifers of low to moderate permeability.

3. Groundwater quality

3.1 Historic groundwater quality surveys

The first major water quality survey commenced in 1985 in conjunction with the North Otago Groundwater Investigation. In relation to the sampling and analysis of volcanic aquifer groundwaters, the principal water quality issues of note were as follows:

- High Sodium Absorption Ratio (SAR) due largely to elevated sodium concentrations and the potential for consequent soil damage.
- High nitrate nitrogen concentrations in the majority of sampled Deborah Aquifer groundwater and a significant minority of Waiareka Aquifer groundwater.

If saline or high sodium groundwater is used to irrigate crops or pasture then there is a gradational potential for loss of soil structure as a result of calcium ions being displaced by sodium ions. The SAR is a screening tool that helps indicate the potential for soil damage. Elevated sodium is found in volcanic aquifers as a natural result of alteration and decomposition of some of the volcanic minerals in the tuff deposits. This was noted in the 1993 North Otago Groundwater Investigation report. Recommendations were also made to attempt to manage the potential for inappropriate applications of high SAR groundwater to sensitive soils.

Nitrate and nitrite are inorganic molecules of nitrogen that are highly soluble and mobile in water. Nitrate is usually the predominant form of inorganic nitrogen in groundwater. Nitrate nitrogen concentrations in Deborah Aquifer groundwater were found to have been commonly elevated above usual or background levels, and in most cases substantially in excess of the 11.3 g/m^3 drinking water quality standard. Figure 3.1 maps the distribution of nitrate nitrogen throughout the Aquifer as measured in bores and wells scattered across the aquifer in the late 1980s. The highest nitrate concentrations in groundwater tend to cluster in the Alma – Deborah – Kakanui area.

The usual sources of nitrogen leading to nitrate accumulation in shallow groundwater are as follow:

- Fertilisers that are leached from the soil nitrogen store
- Mineralisation of soils as a result of cultivation or fallowing of bare soils
- Poor treatment of septic tank soakage
- Urine and dung patch leaching through the soil
- Organic effluents being applied to the soil at rates higher than the nitrogen cycling capacity of the soil.

Nitrate nitrogen concentration in groundwater is usually governed by soil and recharge processes or the amount of dilution available within the underlying aquifer. These processes were noted in the 1980s to 1990s groundwater investigations; however, the investigation was not able to draw any more definitive conclusions as to the probable mechanism of groundwater contamination.

The Deborah Aquifer Status Report (ORC, 2000) was afforded the opportunity of reviewing at least ten years of groundwater quality data from four wells / bores distributed across the Deborah Aquifer. There was usually not any significant trend of increase or decrease in either sodium or nitrate nitrogen concentration in the historic data that could not be explained by other mechanisms such as sampling error.

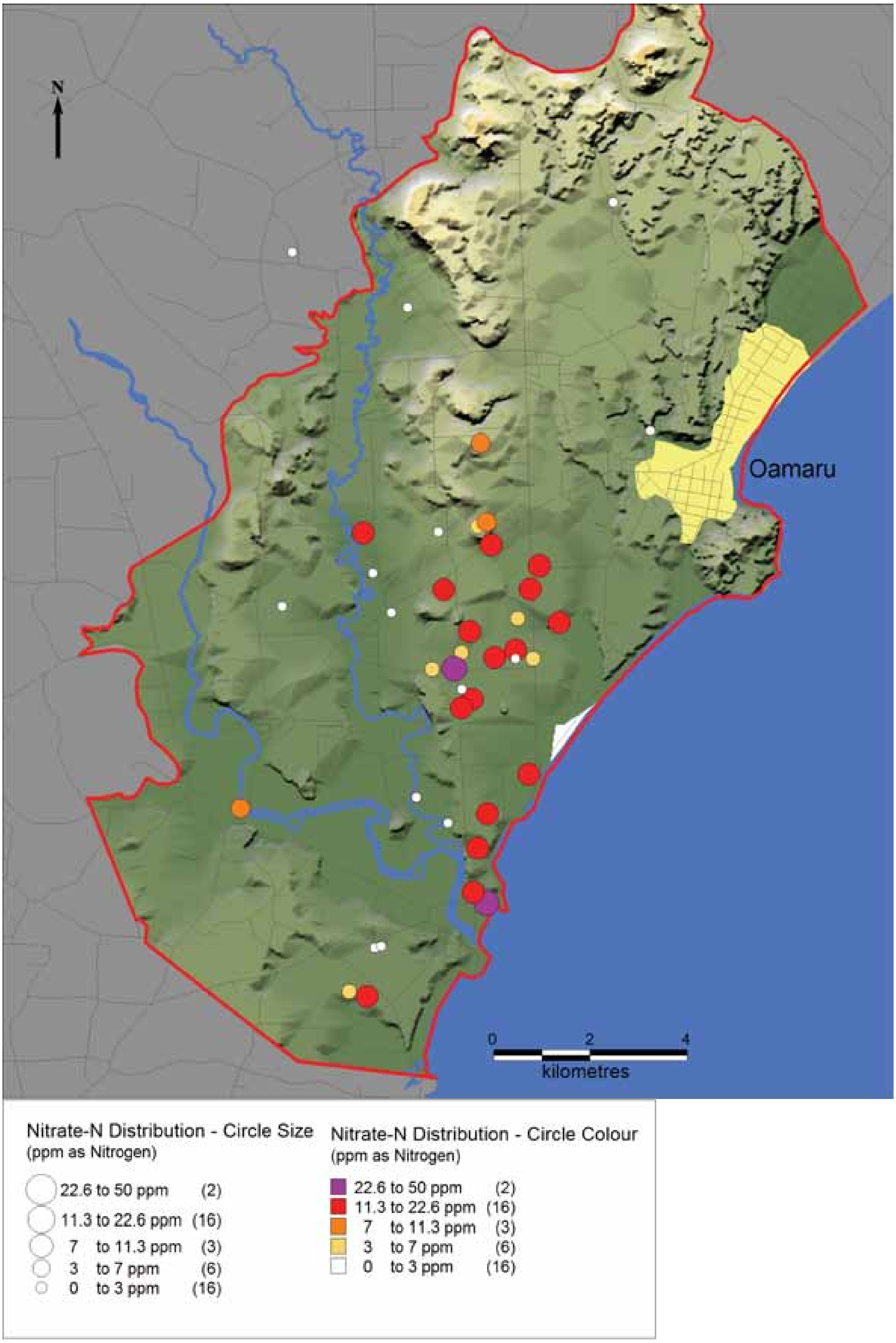


Figure 3.1 **Distribution and concentration of groundwater nitrate nitrogen throughout the North Otago Volcanic Aquifer as measured in surveys in 1985 – 1987**

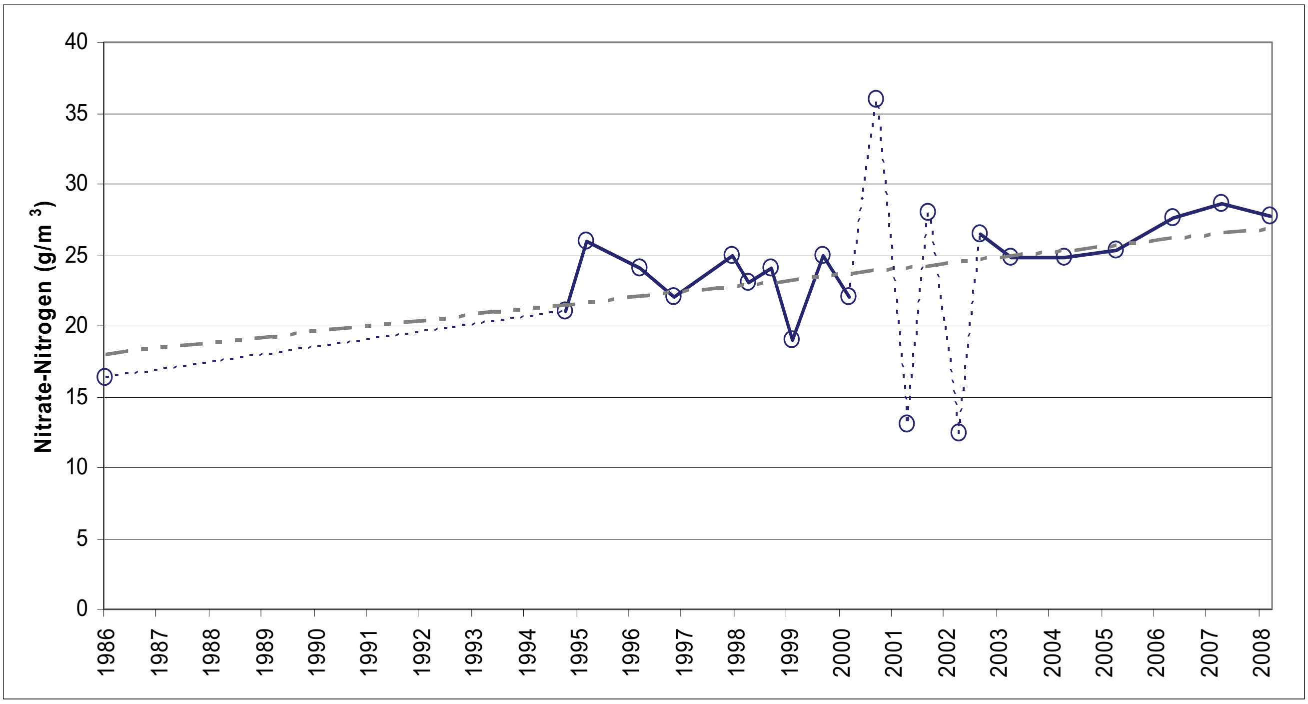


Figure 3.2 Trend in groundwater nitrate nitrogen in well J41/0008 near Alma in the core of the elevated nitrate-N zone

The nitrate nitrogen record of well J41/0008 comprises the most complete record of monitoring in the Aquifer. The nitrate nitrogen record displays some widely spaced measurements (1986 – 1995) and periods of abnormal volatility (2000 – 2002); however, the overall long-term trend is discernible and marked with the grey, dashed line indicating the linear trend line fit. This trend line suggests a steady increase of approximately 10 gNO_3-N/m^3 measured over 22 years, or a ½ g/m^3 per year.

3.2 Current groundwater quality

ORC maintains a State of the Environment (SOE) monitoring network including the Deborah and Waiareka Aquifers. The sampling frequency of the SOE monitoring has been annual. The frequency will change to six-monthly from 2008 onwards as a result of a region-wide review of SOE groundwater monitoring. In April 2007, the sodium and nitrate / nitrate nitrogen concentration in three SOE monitoring wells within the volcanic aquifers area were reported as in Table 3.1.

Table 3.1 Sodium and Nitrate-nitrite Nitrogen concentrations of SOE monitoring wells, April 2007

Well no	Depth (m)	Sodium (g/m^3)	Nitrate-nitrite N (g/m^3)*
J42/0084	3.6	78.7	19.1
J42/0113	9.1	80.2	21.3
J41/0008	20	59.3	28.6

* Drinking water Maximum Acceptable Standard (MAV) for nitrate nitrogen = 11.3 g/m^3
MAV for nitrite nitrogen = 0.92 g/m^3

The respective wells' concentrations of sodium have not changed in a significant manner since the monitoring time series for these wells began in October 1994. The nitrate-nitrite nitrogen concentrations would be a cause for health concern if consumed, particularly among vulnerable individuals such as infants with milk formula mixed using groundwater.

3.3 Multivariate statistical methods for assessment of groundwater chemistry

The groundwater chemistry data were used by GNS Science to develop a conceptual understanding of the hydrogeology through evaluation and characterisation using hierarchical cluster analysis and discriminant analysis techniques (Daughney, 2008).

For this statistical investigation, 81 monitoring sites were used from within the North Otago area encompassing bores from five different hydrostratigraphic units. The bores were assigned to one of the following units:

- Alluvium
- Deborah Volcanics
- Waiareka Volcanics
- Limestone unit
- Papakaio Aquifer.

The study assessed the typical groundwater chemistry for each hydrostratigraphic unit and found significant but subtle differences between the units. The comparisons are based on Kruskal-Wallis tests and Multiple Range tests conducted at the 95% confidence level. The units are differentiated in Table 3.2 by only a small number of parameters, including:

- Waiareka Volcanics vs Deborah Volcanics
- Waiareka Volcanics vs Limestone unit and
- Deborah Volcanics vs Limestone unit.

The investigation also used hierarchical cluster analysis to provide independent comparison to the units as defined by hydrostratigraphy. The results showed a general consistency with the hydrostratigraphic units. The third part of the investigation predicted the likelihood of each well tapping the defined hydrostratigraphic unit using discriminant analysis. The defined unit was confirmed for 78% of the monitoring wells. The Alma area showed the highest number of sites with a misclassification, i.e. classifications contrary to that which was expected prior to the statistical analysis. Table 3.2 lists the classifications and significant hydro-chemical variations.

Table 3.2 Summary of significant hydrochemical variations between hydrostratigraphic units

	Alluvium	Deborah	Limestone	Papakaio
Deborah	Compared to Alluvium, Deborah wells are deeper and have higher Na, Ca, Mg, HCO3, Cl, conductivity and pH. There is no difference in K, SO4, NO3, NH4 or PO4.			
Limestone	Compared to Alluvium, Limestone wells are deeper and have higher conductivity. There is no difference in Na, K, Ca, Mg, HCO3, Cl, SO4, NO3, NH4, PO4 or pH.	Compared to Deborah, Limestone wells have lower Mg. There is no difference in depth, Na, K, Ca, HCO3, Cl, SO4, NO3, NH4, PO4, conductivity or pH.		
Papakaio	Compared to Alluvium, Papakaio wells are deeper and have higher Na, Ca, Mg, Cl, SO4 and conductivity. There is no difference in K, HCO3, NO3, NH4, PO4 or pH.	Compared to Deborah, Papakaio wells are deeper and have higher SO4 and NH4 and lower HCO3, NO3 and pH. There is no difference in Na, K, Ca, Mg, Cl, PO4 or conductivity.	Compared to Limestone, Papakaio wells are deeper and have higher SO4 and NH4 and lower NO3. There is no difference in Na, K, Ca, Mg, HCO3, Cl, PO4, conductivity or pH.	
Waiareka	Compared to Alluvium, Waiareka wells are deeper and have higher Na, K, Mg, HCO3, Cl, conductivity and pH. There is no difference in Ca, SO4, NO3, NH4 or PO4.	Compared to Deborah, Waiareka wells are deeper. There is no difference in Na, K, Ca, Mg, HCO3, Cl, SO4, NO3, NH4, PO4, conductivity or pH.	Compared to Limestone, Waiareka wells have higher pH and lower Ca. There is no difference in depth, Na, K, Mg, HCO3, Cl, SO4, NO3, NH4, PO4 or conductivity.	Compared to Papakaio, Waiareka wells are shallower and have higher HCO3, NO3 and pH and lower SO4 and NH4. There is no difference in Na, K, Ca, Mg, Cl, PO4 or conductivity.

Note:
Highlights indicate hydrostratigraphic units that are differentiated by only a small number of parameters (Daughney, 2008) i.e. share stronger affinity.

4. Groundwater hydrology

4.1 Groundwater flow pattern

Although speculation has been recorded in reports that subsurface exchanges with the Papakaio Aquifer, the predominant source of replenishment for the volcanic aquifers, has always been thought to be recharge by the drainage of excess soil water after the effects of evaporation and transpiration i.e. rainfall recharge. The high soil water retention or field capacity of North Otago volcanic soils are such that the frequency of soil drainage to the aquifer is low, commonly a few times per year. Such recharge patterns produce a typically notchy pattern in the time series – water level plot. Figure 4.2 and Figure 4.3 in Section 4.3 illustrate this water level pattern as winter recharge, usually following heavier rainfalls, leading to distinct rises of the water table.

To investigate the current groundwater flow patterns and levels a series of static water level monitoring was carried out during February, March and April 2008. A well/bore head elevation survey was carried out on 25 monitored bores and 15 stream sites within the study area during the March survey. The results of the monitoring and survey are presented in Appendix A.

The water table is found at its highest elevations under the higher tablelands within the volcanic aquifers area. The lowest water table elevations are found along the axis of the lower Waiareka Valley and the Kakanui Estuary. Broadly, volcanic aquifer flow gradients are from higher elevation ridges and tablelands towards the Pacific Ocean, Waiareka Creek, Oamaru Creek or the Kakanui Estuary. There is a relatively simple pattern of groundwater flow within the volcanic aquifer as determined from water table surveys using individual bores / wells and contouring shown in Figure 4.1. On the north side of the Kakanui Estuary, the Waiareka Aquifer would appear to recharge in the rolling land along the aquifer's western boundary and flow east into Waiareka Creek. This is balanced by south-western flow into the east bank of Waiareka Creek. Along a line approximated by the townships of Weston and Kakanui, there is an apparent flow divide between the groundwater flowing towards Waiareka Creek and those where the water is flowing in the direction of the Pacific coast. By any measure, Waiareka Creek is a significant receptor for groundwater within the Waiareka Aquifer.

4.2 Aquifer properties and confining status

The Aquifer is known to contain groundwater within pores, fractures, joints, fissures and other voids. These discontinuities within the rock mass need to be interconnected with surrounding pore space for groundwater flow to be feasible. The steep gradients observed in the water table survey in an area of low recharge is enough of an indication to infer that the bulk permeability (as hydraulic conductivity) is low to moderate. The North Otago Groundwater Investigation undertook or reported several pumping tests of the volcanic aquifers, including three tests reported explicitly in the report appendices. In every case, the pumping tests utilised drawdown measurements in the pumped bore only, which produces a reliable value of transmissivity only. Due to the fractured / fissured rock characteristics, identifying the hydraulic conductivity with any reliability is problematic also. Table 4.1 lists the results of tests and transmissivities reported in the North Otago Groundwater Investigation (ORC, 1993) plus more recent testing. Figure 2.2 illustrating the geology of the Aquifer also plots the location of the bores subjected to aquifer tests of the Aquifer.

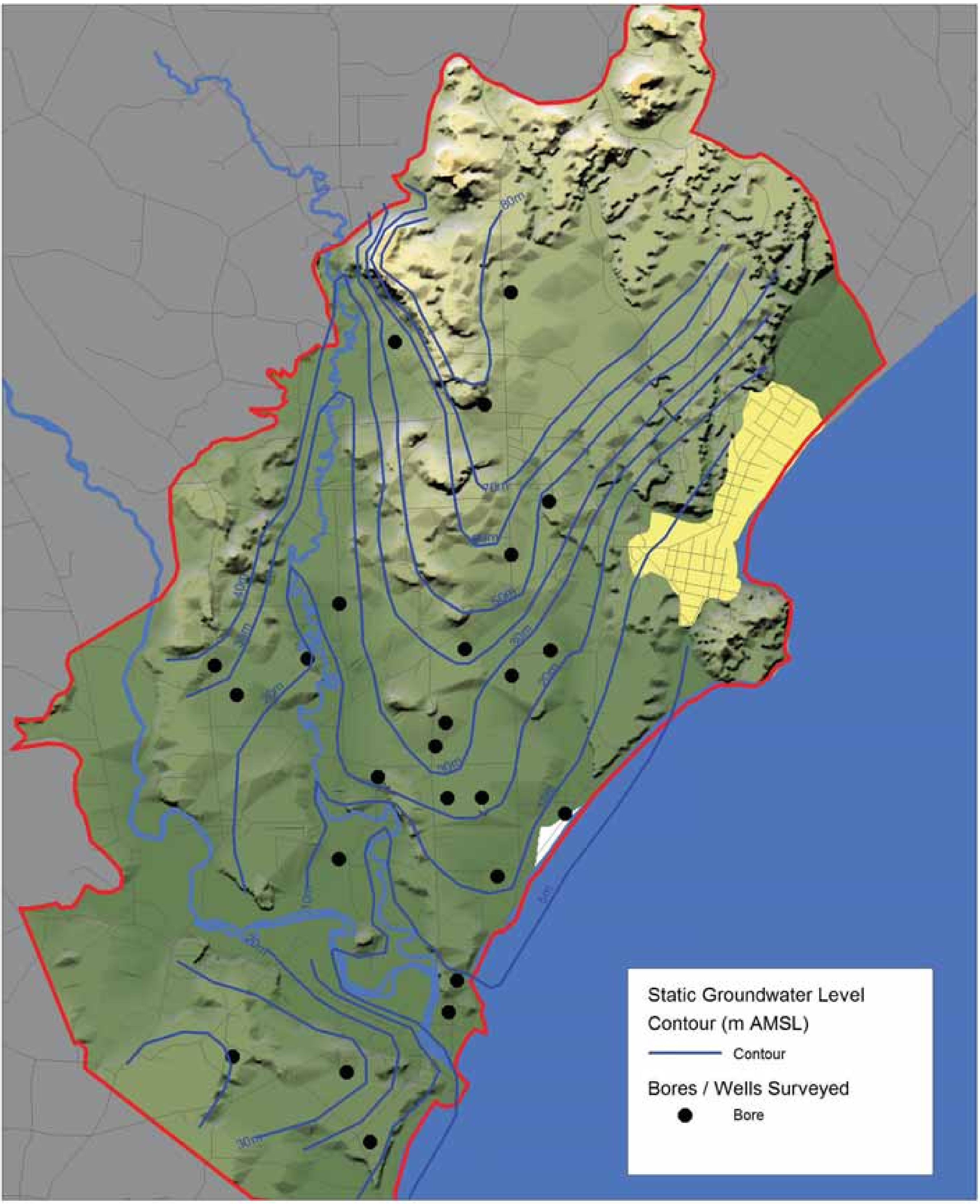


Figure 4.1 **Water table contour map of the North Otago Volcanic Aquifer. Static water level data from March 2008 water table survey.**
Surveyed creek and river water level elevations were also used in drawing the contours

Table 4.1 Aquifer transmissivities for the North Otago Volcanic Aquifer as derived from pumping tests

Well no	Depth (m) / aquifer	Transmissivity (m^2/d)	Comments
J41/0714	70m Waiareka Tuff	15	Holcim NZ Ltd test bore
J41/0023	12m Waiareka Tuff	80 (double porosity)*	H F Yee bore, test in 1992, NOGI calculated $83m^2/d$. Diameter: 200 mm.
J41/0011	11.7m Waiareka tuff	5.4 (double porosity)*¥	N Young well, test in 1992, NOGI calculated 21 m^2/d. Diameter: 900mm
J41/0249	90m Waiareka Tuff	33 (double porosity)*	L Morgan bore, test in 1992, NOGI calculated 85 m^2/d. Diameter: 200 mm.
J41/0177	90.7m Deborah Volc	14	J Webster bore. Parameter from NOGI Table 5.3
J41/0077	15.2m Deborah Volc	30	G Gin bore. Parameter from NOGI Table 5.3
J41/0079	29.9m Deborah Volc	40	G Elvidge bore. Parameter from NOGI Table 5.3

Note:
* Recalculated as part of 2008 investigation. Double porosity best fit in each case.
¥ No allowance for well storage included in 2008 analysis despite large well diameter.
NOGI = North Otago Groundwater Investigation (ORC, 1993)
The positions of the respective aquifer test bores are shown on Figure 2.2.

The operating drawdowns in volcanic aquifer bores are relatively deep. This is reflected in the low specific capacities[1], typically 0.5 to 1.5 litres per second per metre of drawdown, derived from measured pump rate and operating bore water levels. What is striking about the test results for transmissivity of the volcanic aquifers is the low permeability that the values indicate. There is usually an implicit bias in pumping test results used in water resource studies due to the lower yielding parts of the aquifer (dry holes) being avoided for construction into wells. Accordingly, pumping tests are usually undertaken in the more permeable depths of the aquifer where wells or bores are preferentially developed. Furthermore, the selection of pumping test sites is usually over-represented with the higher yielding of all of the bores or wells in the district rather than a random selection of testing sites. Recognising this bias and acknowledging the low permeability results compared to other Otago groundwater systems, the implication is that the area's aquifers have generally low bulk permeability. Wells and bores in this aquifer have been developed due to the lack of any other feasible water supply alternative rather than its abundance. This study will have the opportunity to estimate the aquifer bulk hydraulic conductivity during the calibration and parameter estimation phase of numerical modelling.

Due to the fracture and fissure occurrence of groundwater within the volcanic aquifer, the drawdown response in pumping tests displays a dual confined / unconfined signature. That is to say, the initial drawdown curve is consistent with that of a confined aquifer; however, subsequently, the drawdown rate is more consistent with that of an unconfined aquifer. Determination of aquifer storage coefficients have been obtained in only one instance of aquifer testing in the volcanic aquifer near Weston where an observation well was used. The Holcim cement plant site investigation bore was pumped at approximately 2 l/s with an observation bore only 10m distant. The test derived an initial storage coefficient as storativity of 4×10^{-4}. This storativity is analogous to the aquifer's confined storage coefficient, but which is not sustained for more than a few hours. Analysis of longer term

[1] **Specific Capacity** is the bore pumping rate divided by the corresponding drawdown. The specific capacity is a function of bore screen efficiency and the permeability of the surrounding aquifer.

drawdown while testing the Holcim bore (J41/0714) indicated a shift to a storage coefficient of approximately 1 x 10^{-2} (1 %), although aquifer tests are known to be inconsistent in providing accurate storage data. Independent comparisons of recharge-inducing rainfall events and water table rise in the aquifer at Webster well (J41/0178) suggested that the average unconfined storage coefficient was 0.10 or 10 % (ORC, 2000). More recent comparisons using modelled aquifer recharge and the level record from monitoring well J41/0178 for the spring 2000 high rainfall event suggest a specific yield of 0.09 (9 %) for this part of the aquifer around the Webster well.

On balance, most information on the landward portions of the Aquifer points to it behaving as uncomplicated unconfined aquifer with artefacts of fracture / fissure flow evident in aquifer test analysis. The aquifer displays unconfined recharge and flow towards the nearest down-gradient perennial water body. There are exceptions, such as where the aquifer is overlain by the Gee Greensand and Rifle Butts Formation. These fine marine sediments appear to form a semi-confining layer over the volcanic aquifer. The Gee Greensand and Rifle Butts Formation lap onto the top of the Deborah Volcanics for much of the coastal zone and presumably thicken out to sea. Hence, the volcanic aquifer is largely semi-confined or confined for much of its potential contact with the Pacific Ocean.

The sole reliable indication of significant interaction with an adjoining aquifer is that of the volcanic aquifer and the Kakanui Alluvial Aquifer from Gemmells Crossing to the Kakanui Estuary. Groundwater levels in the Waiareka Aquifer lie significantly higher than the adjoining and overlying alluvial aquifer. Hence, the flow gradient is predominately from the volcanics into the base of the alluvium. So, one would expect the volcanics to contribute groundwater to the alluvium. Indeed, the North Otago Groundwater Investigation (ORC, 1993) speculated, with some justification, that the inflow of volcanic aquifer groundwater was a strong influence on alluvial groundwater chemical composition downstream of Gemmells Crossing on the basis of elevated sodium concentration and electrical conductivity.

4.3 Determination of groundwater recharge

The determination, or at least estimation, of groundwater recharge is a central concern in water resource studies such as this one, in which the aim is to develop a framework for resource allocation. Some groundwater systems, and their associated soils and climates, have a relatively constant or regular rate of recharge. Such settings include aquifer recharge areas with thin / non-retentive soils, thin unsaturated zones, a consistent rainfall or evaporation pattern through any year and a relatively simple connection to sites of aquifer discharge. The water balance in these settings shows little variability from year to year and groundwater levels track predictable patterns in response to system recharge balanced by discharge. At the other extreme, settings with irregular climatic controls on rainfall or evaporation, retentive or low permeability soils, thick underlying unsaturated zones, and relatively complex interactions with other sites of inflow and outflow, display considerable variability in their groundwater levels through time. Furthermore, the ability to de-convolute the observed variability in groundwater levels and attribute these to causative factors is rare. Recharge patterns through time in the latter systems tend towards irregular episodes or pulses of recharge, and are characteristic of semi-arid or Mediterranean climates.

An examination of the soil water balance of the area overlying the volcanic aquifer was undertaken as part of this investigation. The relevant field capacities and Profile Available Water (PAW) capacities for the soil classes overlying the Aquifer were defined with the assistance of Landcare Research and mapped across the Aquifer surface (see Figure 4.4). The climate data for the period 1997 to 2007 was obtained for most relevant rainfall and climate measurement sites in the area. This list was reduced to three climate sites; Clifton Falls, Glenrowan and Grandview. Utilising the soil-water parameters, mapping of the various soil classes and the climate data for rainfall and Potential Evapo-Transpiration (PET), this study employed a soil-moisture water balance model. The model methodology was based on the Rushton approach (Rushton et al, 2006). The modelling of soil moisture hydrology in the soils overlying the Aquifer is covered in more detail in Appendix B. The modelling for the period 1997 to 2008 showed drainage of soil water through the soil profile as distinct episodes. These drainage events were relatively short and did not occur in every year, so the area's recharge could be called irregular or episodic. Figure 4.2 shows the distribution of modelled recharge through the period for the western Waiareka Zone (Zone 2).

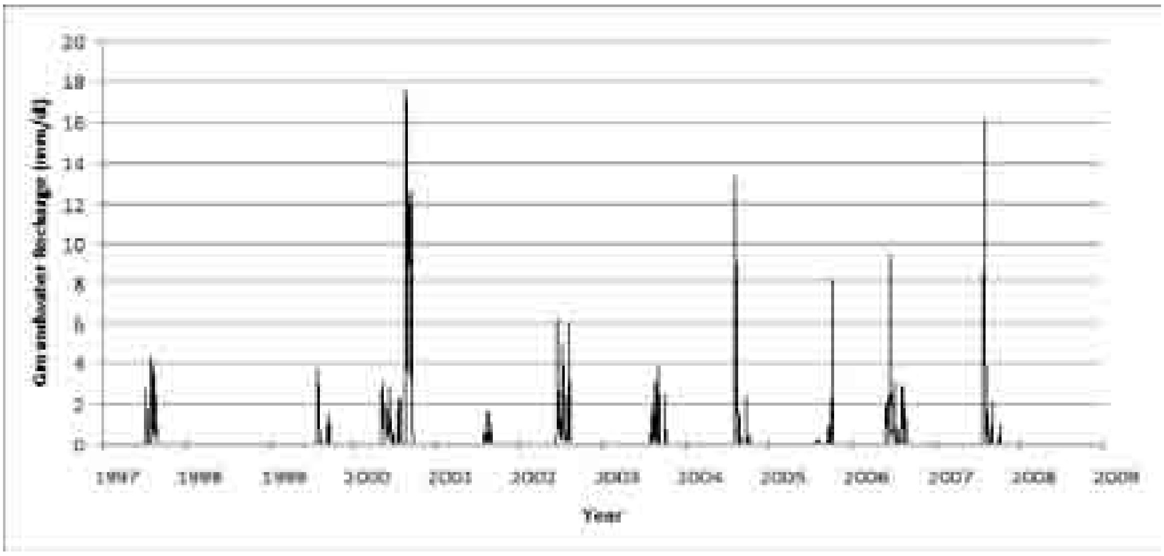


Figure 4.2 Modelled groundwater recharge for the western Waiareka Zone (Zone 2)

The soil classes overlying this zone have a field capacity of 270 mm, which is quite retentive. Soil-moisture water balance modelling determined that 15.9% of mean annual rainfall drains to recharge groundwater and a further 1.3% runs off as overland surface flow during heavy rainfall. The remainder is lost to the system as evapo-transpiration to the atmosphere. The groundwater recharge events tend to occur in the period from May to August in the years in which recharge occurs. The episodes are distinct, lasting up to a month, but frequently shorter periods. In 1998, no recharge occurred in the Western Waiareka Zone whatsoever. In the wet year of 2000, two recharge episodes occurred, the first in late May and the second in late August.

In the eastern zone encompassing the eastern Waiareka Catchment and Deborah Volcanics area (Zone 1, see Figure 4.4), there were years of zero recharge in 1998 and 2001, and in 2003 only 21mm of recharge drained through the soil. This was due to the much higher field capacity of 620mm compared to Zone 2. Comparison of the resulting groundwater recharge graph against the measured groundwater level hydrograph revealed a broadly similar but less regular pattern of recharge compared to the western Waiareka Zone. Figure 4.3 illustrates the correspondence between episodes of renewed recharge and increases in groundwater level. The striking feature of this correspondence is the sharp increases in groundwater level in response to the onset of recharge. The groundwater level peaks are also proportional to the intensity of modelled recharge. For example, the lengthy recharge event of the winter of 2000 reached modelled intensities of 11 mm/d (7-day averaged) over four weeks, inducing a groundwater level rise of 2.7m. By comparison, the recharge episode of the winter of 2003 reached a recharge intensity of only 1.3mm (7-day averaged) and induced only the mildest inflection in the groundwater level. The timing of the rise in groundwater level and the onset of recharge is very close as illustrated in the exploded view of the August 2000 recharge event. The episode was triggered by a three-day rainfall approximately equivalent to a downpour at 1 in 20 year average recurrence interval 72 hour rainfall event, of 105mm. This initial event was sufficient to load the soil with moisture beyond the field capacity and trigger recharge in response to accumulating falls over the following month.

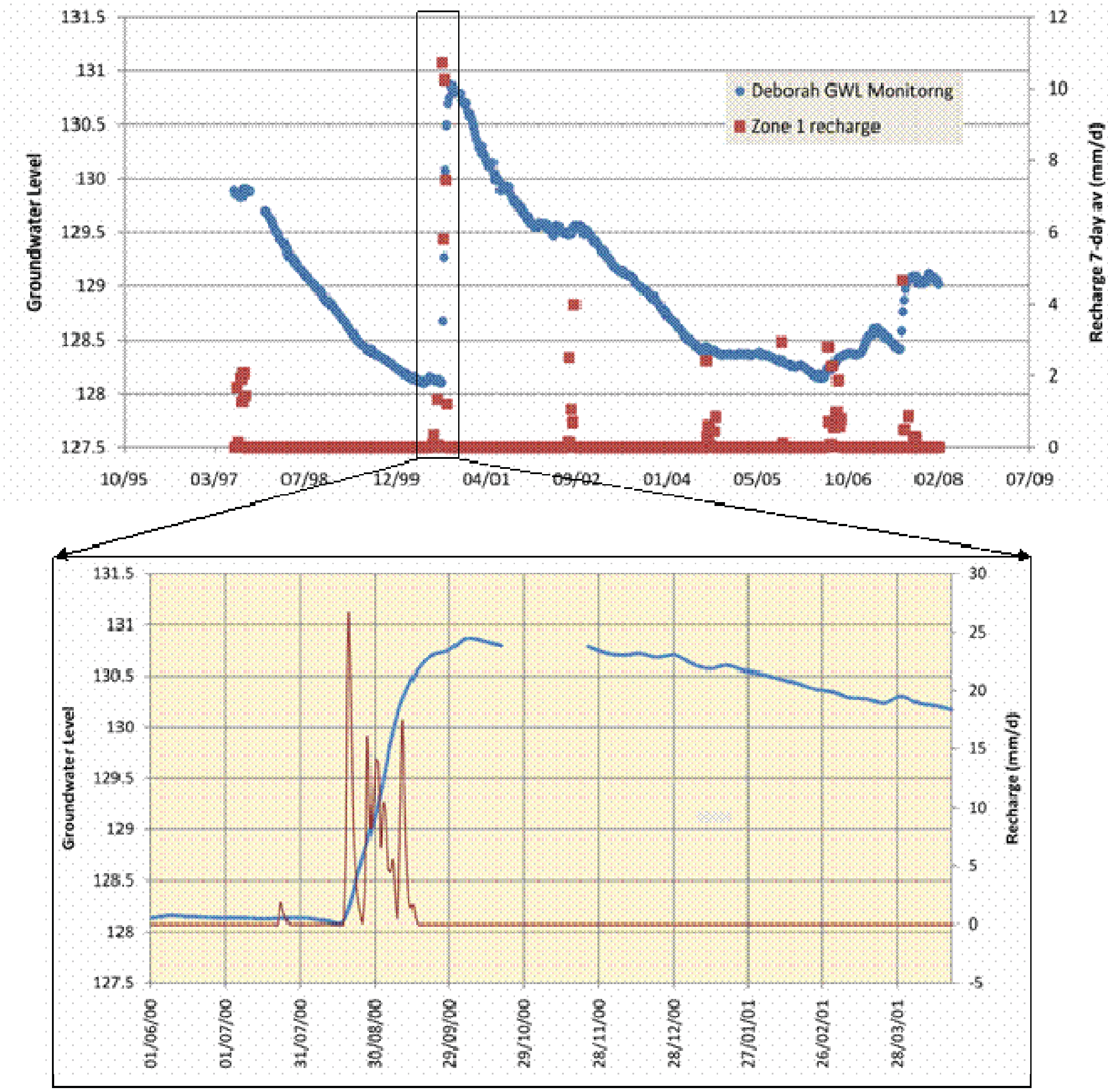


Figure 4.3 Modelled groundwater recharge and corresponding groundwater level for the eastern Deborah Zone (Zone 1) and the period 1997 to 2007. Lower, exploded insert shows the timing of the winter 2000 recharge episode. Recharge is in daily time steps rather than 7-day averaged

Note: Groundwater Level is plotted in metres with respect to Otago Metric Datum, which has its zero 100m below mean sea level. Hence, sea level is 100m ODM and ODM can be converted to mean sea level by subtracting 100m.

In the spring of 2000, the response of the water table was to rise almost immediately and peak at 2.7m higher than before the wet period. After the peak, the water table began to decline as the aquifer re-balanced the inflow with lateral groundwater flow outwards in the direction of discharge boundaries, mainly the lower Waiareka Creek, Oamaru Creek and offshore.

Figure 4.4 lays out the position of the six soil categories covering the Aquifer, with distinct mean field capacity classes.

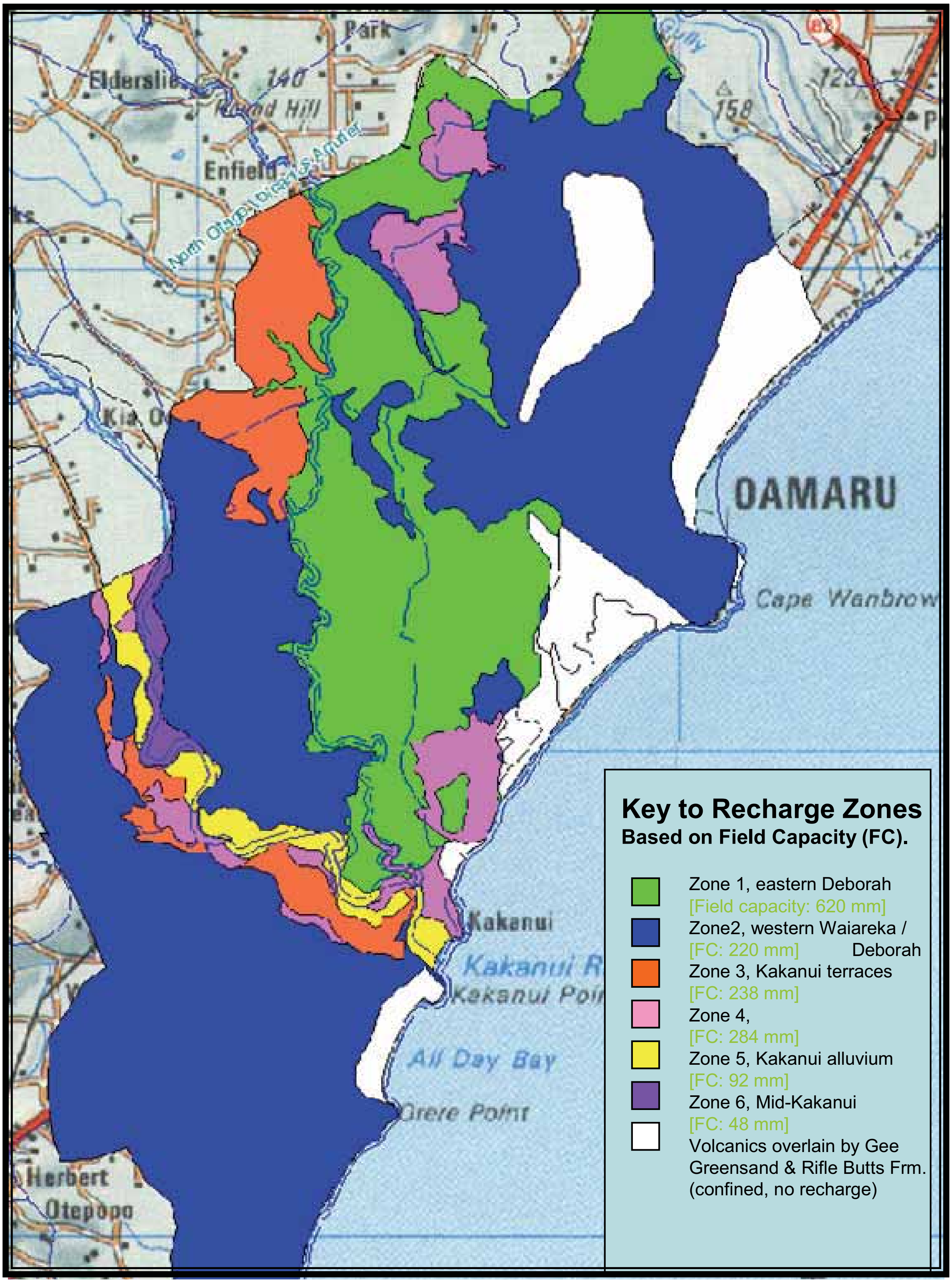


Figure 4.4 **Distribution of classified soil water property zones across the North Otago Volcanic Aquifer**

This characteristic recharge pattern revealed by soil-moisture water balance modelling has great significance to the groundwater response availability and water quality of the Aquifer, as following chapters will explain. Firstly, the recharge of the aquifers is irregular and the quantity of recharge is inconsistent. Compared to gravel terrace stony soils and alluvial aquifers in a humid climate that receive regular and consistent sprinklings of recharge up to 40% of annual rainfall, the Aquifer cannot be relied upon to the same degree to receive consistent recharge. While an average annual recharge rate can be calculated from the modelling results over multiple years, the false impression is created that each and every year will experience recharge of a certain amount. This irregular episodicity has several consequences, which are summarised as follow:

- The normal expectation of uniform annual recharge is not justified by reality in North Otago.

- Groundwater level rises and falls are under the direct influence of the dual stresses of climate-driven recharge and aquifer-controlled discharge.

- Groundwater levels in wet years with considerable recharge are dominated by distinct recharge pulses.

- Groundwater levels in dry years, or those without any recharge at all, are dominated by the discharge rate, which is delineated by a natural decay function.

- Multi-year trends are governed to some extent by the accumulation of wet and dry years in the preceding five years. The net volume of groundwater recharge over time is therefore important to the height of groundwater levels at the end of a multi-year period.

- The rate of groundwater discharge is a smoothed reflection of multi-year trends in groundwater levels.

- In most years, the aquifer receives a single winter pulse of soil drainage containing the mobile soil-moisture leachate rather than the more steady drizzle of soil drainage as in other climates or soils.

- As a result, the soil leachate is more likely to be concentrated with the accumulated store of solutes in the soil and displaced by the recharge pulse.

- The recharge pulse would come through the unsaturated zone somewhat rapidly as a sustained wetting front until it accretes on top of the water table.

- Groundwater solutes, including contaminants derived from soil drainage disperse as a result of lateral groundwater flow and dispersion; however, the degree of dispersion is significantly lower than aquifers with more regular and consistent recharge due to a lower quantity of flushing.

4.4 System boundaries

The primary vertical limits on the extent of the North Otago Volcanics are the upper and lower contacts with adjoining parts of the Tertiary sedimentary sequence as can be seen in Figure 2.3 of the representative cross-section and stratigraphic column. The under-side contact is with the Tapui Glauconitic Sandstone or its lateral correlative, the Raki Sandstone. Both units are of low permeability and great thickness, making them aquitards and a vertical boundary to groundwater exchange. Overlying the Aquifer in a small portion of its landward occurrence is the Gee Greensand and Rifle Butts Formation. These capping units also limit the discharge of groundwater and provide confining pressure conditions in the coastal zone or the Ardgowan Syncline. The presence of basaltic intrusions in the form of vertical dikes and sub-horizontal sills is a complicating factor in the definition of system boundaries as many intrusions project across the stratigraphic boundaries or faults into surrounding geologies. Some zones of intrusions undoubtedly provide additional compartments of groundwater within fracture systems adjacent to the tuff, tuffaceous siltstone and limestone deposits. This aspect of intrusion-hosted groundwater was not thought to be sufficiently significant to groundwater hydrology to specifically address.

The known discharge zones are as follows:

- Waiareka Creek
- Awamoa Creek
- Oamaru Creek and tributaries
- The Kakanui Alluvium
- The Kakanui Estuary
- Offshore flow beyond the coastline.

Seepage discharge into springs contributes to the baseflow of the water body. During dry weather the seepage is more noticeable since it is not masked by upper catchment surface water, and the seepage is also intensively evaporated and transpired. Profiling of groundwater level gradients across the coastline north of Kakanui township suggests that volcanic aquifer groundwater flows beneath the Gee Greensand – Rifle Butts Formation cap and eventually emerges at marine springs and seabed seepage. The Kakanui Estuary appears to have seepage within the seepage zone as suggested by the suppressed volcanic aquifer groundwater levels surrounding the estuary. The absence of confining sediments over the volcanics in the area of the estuary is likely to contribute to the difference between the rest of the coastline and the estuary.

4.5 System water balance

A water balance for an aquifer comprises an accounting of inflows minus outflow, plus or minus storage components. For any aquifer, the water balance is couched in long-term periods due to the need to include long-term repeated episodes of recharge and discharge. Generally, an annual water balance period is chosen for groundwater system balances, as this is more likely to include the year's complete recharge and the system's discharge without significant remainders held in storage. The episodicity of recharge in the volcanic aquifer results in substantial differences in the magnitude of recharge from one year to the next and complicates the ability to set a water balance period and timing of exchanges between the groundwater system and the surface. For the purposes of this report, a mean annual recharge based on averaging of ten years of rainfall and recharge data (1997 to 2007) is used.

The system water balance is comprised of the following components:

- Rainfall-excess soil drainage, that becomes aquifer recharge
- Evaporation at seepage margins such Waiareka Creek and Awamoa Creek
- Evaporation at a handful of groundwater filled pits in the Deborah Aquifer
- Seepage outflow at seepage margins, which sustains surface water base flow in the Waiareka, Awamoa and Oamaru Creeks, while also contributing to the Kakanui Alluvium and Kakanui River
- Offshore outflows that eventually passes out as seepage through the seabed
- Groundwater pumping for domestic, stock, irrigation and pit dewatering purposes.

The sole known input to the system of any consequence is the drainage of excess soil water through the soil profile and unsaturated zone to the underlying water table as groundwater recharge. This recharge occurs extensively over most of the Aquifer surface, except for the areas of seepage, the Kakanui Alluvium and the confined area under the Gee Greensand – Rifle Butts Formation. The seepage margins and Kakanui Alluvium will refuse recharge to the underlying volcanics because of the low permeability of the fine sediments and the opposing pressure gradient. The confined areas will not receive recharge because of the intervening fine sediments. The central confined area between Cape Wanbrow and just north of Kakanui township is noted for the presence of surface springs marked on North Otago Groundwater Investigation Map 3 (ORC, 1993). These springs are interpreted to be the expression of recharge that is prevented from percolating through the fine sediments to the Deborah Formation. Table 4.2 lists the current information on the balance of inflows and outflows to the volcanic aquifer.

Table 4.2 System-wide groundwater balance for the North Otago Volcanic Aquifer (227 km²)

	Inflow (Mm^3/yr)	Outflow (Mm^3/yr)
Rainfall recharge	20.5	
Evaporation (seepage margins)		4.7 Waiareka Creek 0.7 Awamoa Creek Total: 5.4
Evaporation (pits)		0.1 (estimate)
Seepage outflows as baseflow		1.6 Waiareka Creek 0.2 Awamoa Creek 4.3 Kakanui / Estuary Total: 5.8
Offshore flows*		8
Groundwater pumping¥		0.9
Total	20.5	20.5

* Estimated by subtraction, not measured.

¥ Allocated volume is 4.4 Mm^3/yr. Assumption is that actual use rate is 20% of paper allocation.

5. Groundwater management

5.1 Current management framework

The primary groundwater management framework for the North Otago Volcanics Aquifer, Waiareka Aquifer and Deborah Aquifer is set out in the Otago Regional Plan: Water (Water Plan). The relevant sections of the Water Plan control the drilling of bore holes, constructing bores, taking groundwater and surface water, and the discharge of contaminants into water or onto land. In addition, the Water Plan includes specific controls on activities relating to groundwater.

5.1.1 Controls over drilling and bores

Prior to 1988, drilling or bore construction activity was unregulated in any way in North Otago. The Otago Catchment Board Bylaw 1988 introduced the requirement of an application for a bore permit when drilling a bore or well for groundwater abstraction. Currently, drilling over the Aquifer zone (Water Plan Map C10) and drilling and construction of bores (for the purpose of taking groundwater) is, in all cases, a controlled activity requiring a conditional consent for the period of bore development. Using a bore for taking water is considered separately in the Water Plan. If the use of a bore fits within the permitted water take criteria, then the consent for bore construction is all that is required by the applicant. Permitted activities include the uses protected in the Resource Management Act 1991, namely the reasonable needs of humans and animals for domestic and stock water, respectively. A permitted use category, irrespective of end-use, is created in the Water Plan with a volumetric allowance of 25,000 litres per day (l/d), providing the instantaneous discharge of the bore is less than 1.5 l/s. This allows for the normal operation of a 4-inch diameter single phase, bore pump of the type commonly used for single homestead or rural residential water supplies.

5.1.2 Controls over the taking of groundwater

Since 1967, the taking of groundwater required the application for a water right from the Regional Water Board, in this case, the Otago Catchment Board. Prior existing uses were notified to the Regional Water Board and became deemed water uses. New takes of groundwater for more than permitted volumes are discretionary activities, requiring possession of a resource consent to take groundwater.

Consent holders falling inside the Waiareka and Deborah Take Restriction Zones (Water Plan Map D2) are subject to controls by ORC, including the jurisdiction of a water allocation committee and minimum groundwater levels triggering partial or complete curtailment of abstraction. Figure 5.1 outlines the range of aquifer and groundwater management areas invoked over the Aquifer.

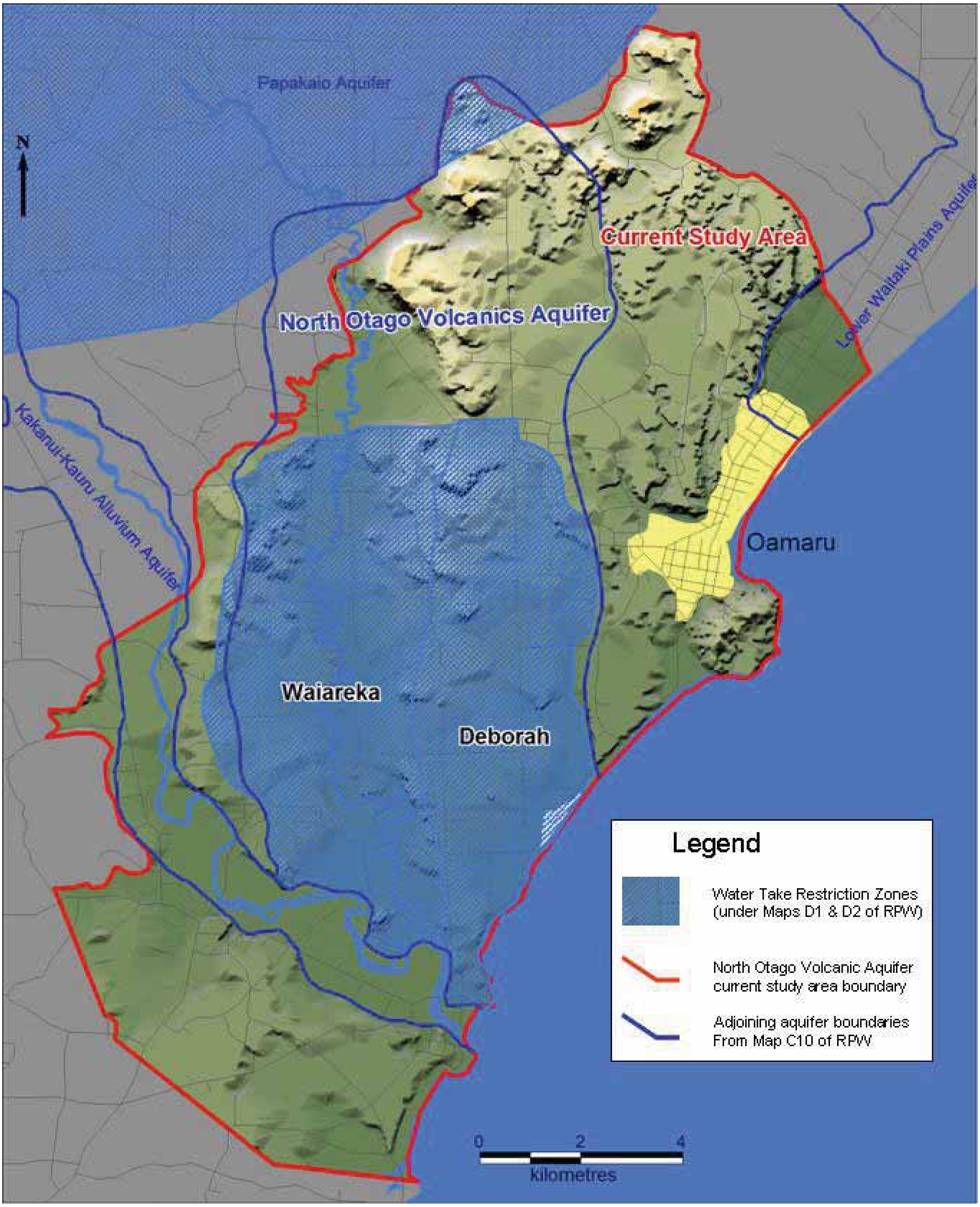


Figure 5.1 Groundwater management zones adopted for the North Otago Volcanic Aquifer and adjoining areas
Note: RPW = Otago Regional Plan: Water (ORC, 2004)

Two trigger level bores have been specified in the Water Plan; the Webster well (J41/0178) for the Deborah Aquifer, and Isbister bore (J41/0198) for the Waiareka Aquifer. The trigger bores are specified in Schedule 4 of the Water Plan. Within this schedule, groundwater levels at the trigger bores are permitted to fluctuate 3m between the maximum recorded groundwater level and the 100% curtailment restriction level. Intermediate curtailment levels are set at 2m and 2.5m below the groundwater level maximum at 25% and 50% curtailment, respectively. The mean annual maximum groundwater levels in the Waiareka and Deborah trigger bores are set in Schedule 4 of the Water Plan at 30.8m and 24.2m above mean sea level (AMSL), respectively. Figure 5.3 can be referred to for a graphical representation of the trigger level in the Webster well.

In November 2000, the Deborah Aquifer allocation of groundwater was capped by the ORC at 2.7 million cubic metres per year (Mm^3/yr), which was thought to represent the groundwater allocated at the time. The Deborah Water Take Restriction Zone comprises a land surface area of 27.95 km^2 and Figure 5.1 shows its extent. One of the concerns expressed by the ORC in closing the aquifer for further allocation was that of a perceived risk of seawater intrusion within 1km of the coast if high groundwater pumping was to coincide with drought. In April 2004, the Waiareka Aquifer's allocation was capped by ORC at 0.43 Mm^3/yr and the granting of further consents closed. The Waiareka Water Take Restriction Zone comprises a land surface area of 35.9km^2 and Figure 5.1 shows its extent. The primary concern motivating capping and closing of the aquifer against further allocation was the potential for the loss of baseflow to Waiareka Creek. The creek was considered to be over-allocated for surface water and further loss of baseflow was considered undesirable.

The special water resources management of the Kakanui – Kauru Alluvium was recognised and codified in the Water Plan as a special scheduled area. In essence, the Kakanui – Kauru Alluvium is a shallow aquifer closely associated with the Kakanui River hydrology. Accordingly, the aquifer is defined and to be managed as if it was a surface water body. Specifically, the alluvium and any bores drawing on it are subject to the minimum flow restrictions of the Kakanui River. Discretionary takes of groundwater from the alluvium needs to be allocated access to the primary allocation as may be available from the allocation schedule of the Kakanui River. A section of the Kakanui – Kauru alluvium passes through the boundaries of the Aquifer on the way to Kakanui Mouth. This complicates the groundwater management within the overlapping of groundwater management zones. For example, a bore drill into the Kakanui – Kauru Alluvium will be managed within the Aquifer if the bore screen extends into the volcanic sediments beneath the Alluvium, or within the Alluvium if the screen does not extend beyond its base; however, there is known to be a degree of groundwater interchange between these aquifers and bore construction is also often imprecise as to which aquifer would be drawn on the most heavily.

5.1.3 Current groundwater allocation

Figure 5.2 maps the distribution of current groundwater takes granted by ORC. In some cases, the allocation related to the pumping from a groundwater-filled pit or pond, in which case a colour distinction is made in the map.

The precise current annual allocation for the Aquifer is not easily determined due to variability in the conditions relating to volume imposed on water permits. Annual limits have not been imposed on groundwater permits in the past, although they are now a standard condition on any groundwater take. The annual allocation volume was determined through a series of steps depending on the specific water permit conditions. Firstly, if an annual limit was stated within consent conditions it was used. If no annual limit was stated and the purpose of the take was irrigation, the lesser of the following was used: the monthly limit multiplied by 8 (irrigation season) or the irrigated area multiplied by an annual reasonable and efficient irrigation requirement volume. The annual reasonable and efficient volume is based on the report Irrigation Requirements for North Otago by Lincoln Environmental 2003. A soil plant available water (PAW) of 100mm was used to give a value of 6,490 m^3/ha. This method is currently used to set annual limits on new or replacement groundwater take consents.

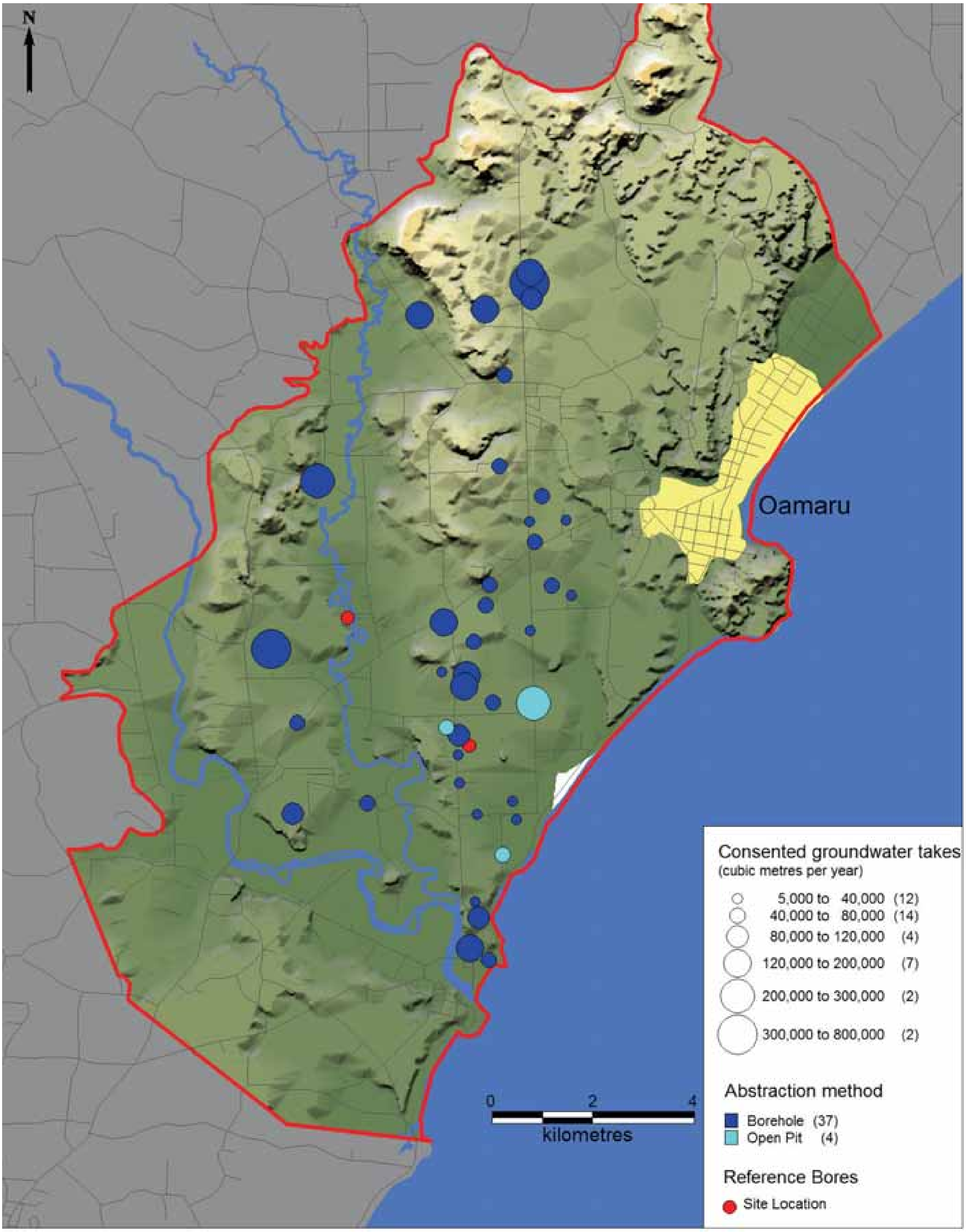


Figure 5.2 **Distribution of individual groundwater takes throughout the North Otago Volcanic Aquifer.**
This includes scaled symbols indicating the relative groundwater allocation associated with each

5.2 Future management framework

5.2.1 National Environmental Standards

At a national level, there are currently one operative and one proposed National Environmental Standard (NES) with application to the future management of the Aquifer. These standards can be summarised as follow:

1. The National Environmental Standard for Sources of Human Drinking Water.
2. The Proposed National Environmental Standard on Ecological Flows and Water Levels.

The NES for sources of human drinking water would have the effect of preventing the granting of consent for groundwater take or discharge if the grant would lead to contamination of existing public water supplies serving a population of 500 or more people. This NES came into being in December 2007 and passed into application in June 2008. The Aquifer area contains community water supply abstraction points on the Kakanui River via takes or gallery wells in the alluvium for the following water supplies as specified in the register of community water supplies:

- Reidston (population 110) from Reidston Bore near State Highway 1.
- Maheno (population 280) from Maheno Bore (J42/0015) near SH1.
- Kakanui (population 500) from Kakanui River at Taipo Road.

In addition, the Weston – Enfield water supply, serving a population of 2,200 people, is drawn from a gravel pit approximately 300m from the Kakanui River just outside the Aquifer area at Robbs Crossing. So, the only water supply within the Aquifer area, and with a population of 500, or over is the Kakanui supply. This supply derives its raw water from the Kakanui River, so would be only indirectly affected by the groundwater quality of the volcanic aquifer.

The proposed NES on ecological flows and water levels sets minimum standards for limiting the volumetric allocation of groundwater and setting of surface water minimum flows. While the Water Plan contains provisions curtailing groundwater pumping, the Water Plan does not set a volumetric allocation limit.

Accordingly, the effect of the NES on ecological flows and water levels would be to set an interim limit on allocation for new applications until an alternative allocation restriction is reflected in the Water Plan. The NES specifies that the maximum percentage of mean annual recharge that may be allocated for consumptive abstraction is 35% in inland aquifers, and 15% in shallow, coastal aquifers (predominantly sand). The NES does not retrospectively affect existing resource consents or over-ride any operative water plan containing groundwater allocation limits; however, in the absence of a Water Plan provision specifying the volumetric allocation limit for the Waiareka and Deborah Aquifers, the NES would have the effect of setting caps on the maximum allocation to discretionary groundwater takes. The Water Plan is not considered to have a groundwater allocation regime in terms of the NES.

Given our knowledge of the mean annual recharge rates of the Aquifer, the area of 227km^2 included in this study has a mean annual recharge estimate of 20.5 Mm^3/yr. Groundwater allocation under the ecological flows and water levels NES once operative, would thus be limited within this area to 7.2 Mm^3/yr if the aquifer was considered to be inland or 3.1 Mm^3/yr if the aquifer was considered coastal[2]. The difficulty in specifying the average annual recharge is significant given the now acknowledged episodicity of recharge in a soil and hydrogeological setting where some climate years would not contribute any recharge whatsoever. This is explored further in sections concerning groundwater modelling where a 10-year modelling period was selected.

5.3 Groundwater monitoring

5.3.1 State of the Environment monitoring

Monitoring is an integral part of groundwater management due to the information the results of monitoring provide on the effectiveness of management policies or implementation. State of the Environment (SOE) monitoring of groundwater resources has been carried out in the Aquifer since approximately 1996. The monitoring breaks down into groundwater level and groundwater quality monitoring, and these are often combined at the same monitoring point.

The most important SOE groundwater level monitoring in the area are the two continuous and telemetered wells known as the Deborah-Webster Well (J41/0178) and Waiareka-Isbister Well (J41/0198). The Deborah-Webster Well (J41/0178) and Waiareka-Isbister Well (J41/0198) have a more or less continuous record since August 1986 and December 1997, respectively. The recorder data is available on the internet for the public's information. The respective water management committees also make use of the data to manage the abstraction of groundwater within the context of the level restrictions set out in section 5.1.2 above. Figure 5.3 and Figure 5.4 illustrate the restriction level and groundwater level fluctuation for the Water Take Restriction Zones.

[2] Unlikely since the proposed NES qualifies the definition of coastal with the descriptors "shallow coastal aquifer, predominantly sand".

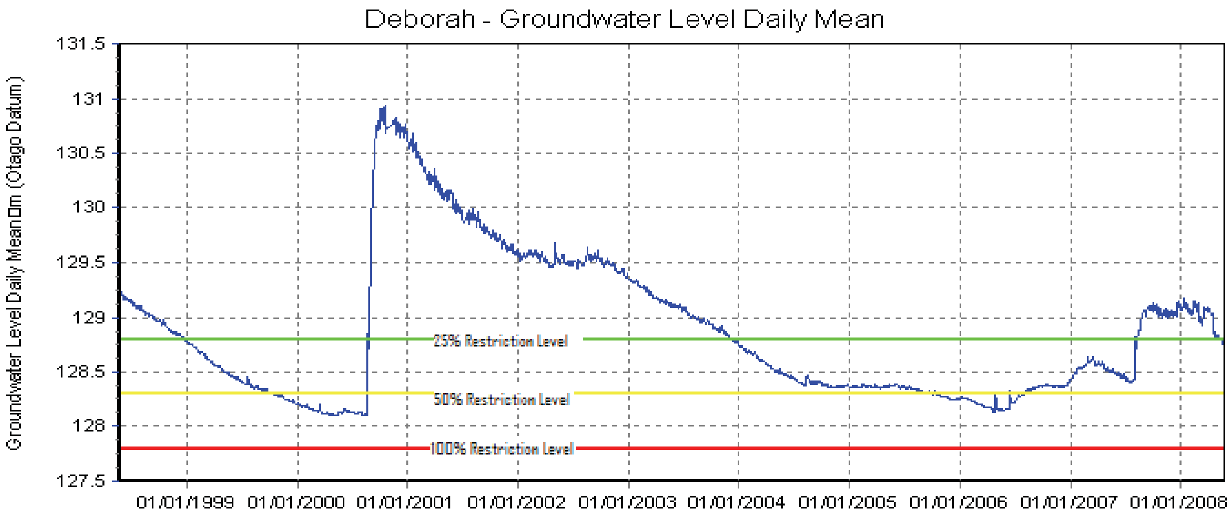


Figure 5.3 The Deborah-Webster Well (J41/0178) groundwater level record for the last 10 years plotted against the relevant water take restriction or trigger levels

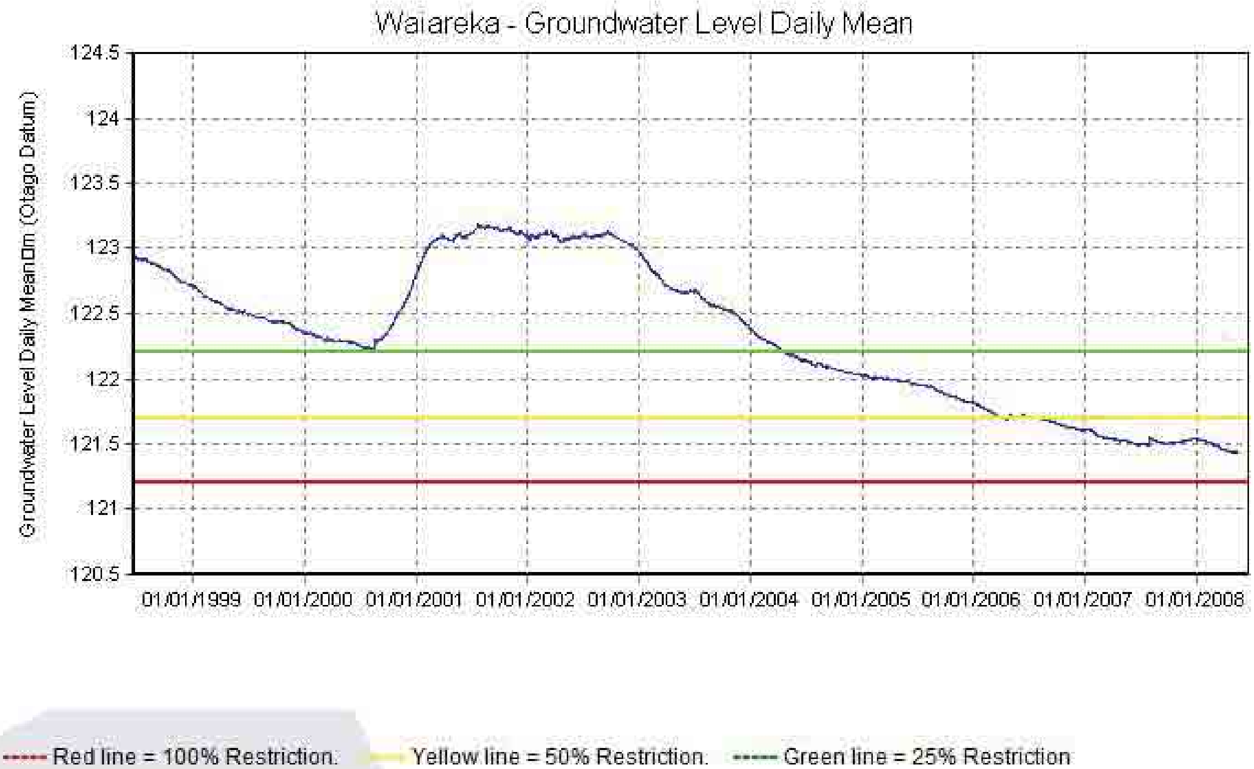


Figure 5.4 The Waiareka-Isbister well (J41/0198) groundwater level record for the last 10 years plotted against the relevant water restriction or trigger levels.

In addition, approximately 30 wells and bores have been monitored manually to provide a non-continuous groundwater level record. Currently, about 20 wells or bores are monitored for groundwater level. Of these, four are monitored for groundwater quality twice yearly.

5.3.2 Self monitoring by consent holders

Resource consents issued for the taking or discharging in ways that may affect the underlying aquifer will often include a requirement for self-monitoring of groundwater take, discharge, level or quality. In the Aquifer, such self-monitoring is most prevalent as the monitoring of volumetric flow meters to record the volume of groundwater taken in discretionary takes. A handful of groundwater take consents include the requirement to record periodic groundwater levels during the irrigation season. The provisions for self-monitoring are primarily the result of the implementation of the Water Plan, which became operative in February 2004. The short period for the implementation phase to date, and the fact that some of the recent consents are yet to be fully exercised, has resulted in little self-monitoring data being available for this study.

Nonetheless, a 2006 – 2007 compliance survey of permitted use and discretionary groundwater takes in the Deborah Water take Restriction Zone provided significant new data on actual groundwater use in that area. The comparisons of the volumetric flow meter readings between November 2006 and November 2007 indicated that the holders of groundwater take consents took approximately 19% of the total aquifer allocated annual volume. The individual proportions of allocation volume taken ranged from 1.4% and 95.6% of the respective allocated rate for the well or bore. Figure 5.5 shows the results of the compliance survey in terms of the difference between allocated and actual use for individual groundwater take consents encountered in the survey of the Deborah Aquifer.

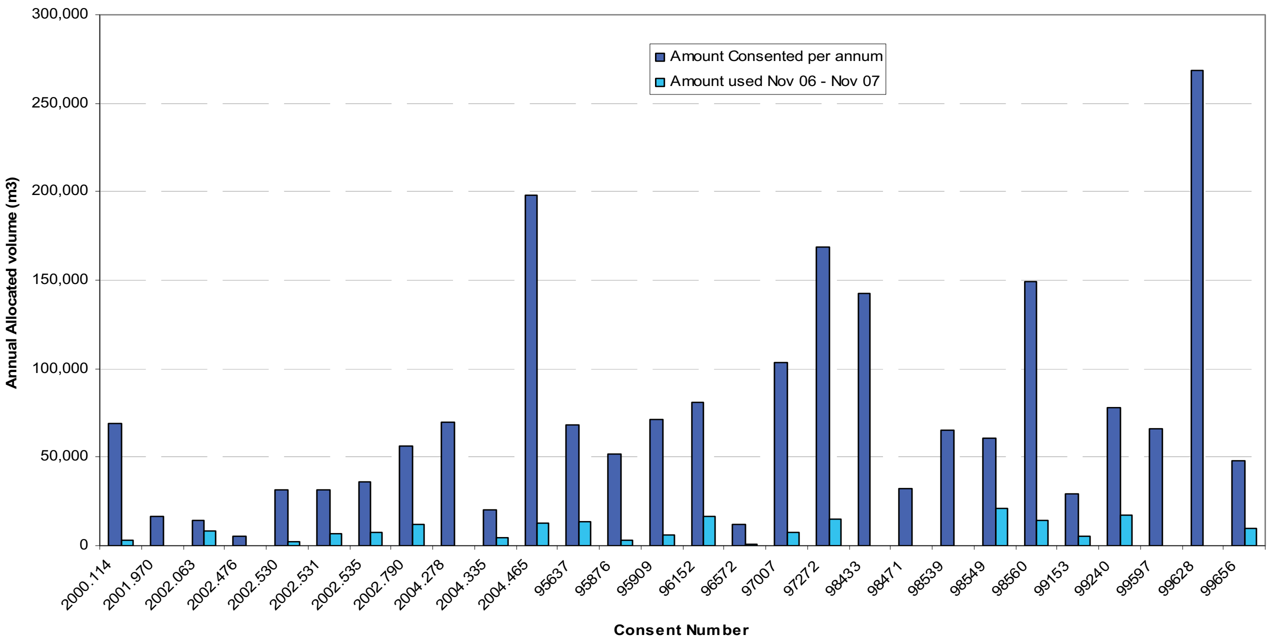


Figure 5.5 Difference between allocated and actual use for individual groundwater take consents issued to wells and bores within the Deborah Aquifer

6. Numerical groundwater model

6.1 Modelling objectives

The following objectives were set in approaching the modelling of the Aquifer –

- To establish a transient-flow numerical model for the Aquifer based upon the conceptualised groundwater system and calibrated under transient system stresses.

- To determine the mass-balance for the aquifer system including temporal variation in aquifer fluxes and levels under a range of climatic conditions.

- To simulate the aquifers response to different abstraction scenarios as a basis for developing allocation and aquifer management policy.

6.2 Description of model

The modelling exercise utilised the MODFLOW model code in the Groundwater Vistas implementation. Appendix D outlines the model formulation in more detail.

6.2.1 Grid design

The geological and hydrological margins referred to above were utilised to set the limits of the model domain. A four layer vertical grid pattern was deployed and the grid of active cells extended into the Pacific Ocean. The pattern of progressively shelving and thickening sediments seaward noted from land and offshore drilling was repeated in the model framework. The model top was set at land surface or sea level for the respective landward and seaward portions of the aquifer. A 200m x 200m grid mesh was set as the default, although cell size expansion up to 750m was allowed for the seaward zones.

6.2.2 Boundaries

As noted above, the Aquifer is largely unconfined and recharged by the remainder of rainfall after runoff, evaporation and transpiration at the surface. This simplifies the model boundaries arrangement, since all other boundaries are impermeable or discharge boundaries. Surface water bodies such as the Kakanui River, creeks crossing the aquifer's land surface and the ocean receive the net outflow of the water balance. These were simulated with a series of river, drain and constant head boundary types.

6.2.3 Aquifer parameters

The parameters outlined in the description of the aquifer were used to guide and initialise the parameters used in the model; however, the final profile of aquifer parameters was tuned with the use of numerical parameter optimisation, sensitivity analysis and calibration using historic groundwater level data. Despite this process, the final calibrated aquifer parameters remained largely within the range of measured parameters.

6.2.4 Recharge

The Rushton recharge model described previously and in Appendix B was used in setting model recharge rates in space and time. These recharge rates were also assessed by parameter optimisation, sensitivity analysis and automated calibration. In general, recharge rates were not varied from those determined from soil-moisture modelling.

6.2.5 Steady state calibration

Steady state calibration was undertaken using the snap-shot of groundwater levels measured throughout the aquifer and corrected to mean sea level datum in March 2008. Steady state calibration typically utilises mean or median groundwater levels; however, an extensive time series of distributed levels are required from which to calculate such statistical calibration targets and these were not available for North Otago. The steady state calibration, nonetheless, achieved acceptable match between the measured and modelled groundwater levels throughout the aquifer.

6.2.6 Transient calibration

Transient (time-variant) calibration was to the most intensive stage of model calibration. Groundwater level hydrographs were available for matching against model output for two locations; the Deborah-Webster Well (J41/0178) and the Waiareka-Isbister Well (J41/0198). The full transient calibration process including an analysis of parameter sensitivity and automated optimisation of parameters is describe more fully in Appendix D; however, the result was the production of a model that was capable of emulating the variation in groundwater level observed over 10 years of record.

Figure 6.1 shows the matching between measured and modelled groundwater levels at the Webster Well (J41/0178). While the hydrographs of measured and modelled levels did not plot directly atop each other, the hydrographs track each other’s mid-points. Also importantly, there is little long-term drift or long-term divergence from one hydrograph trend line to the other. Figure 6.2 displays a similar pattern for matching modelled groundwater level with measured values over the past 10 years of record at the Isbister Well site (J41/0198). The modelled hydrograph in each case tends to display more volatility and sharp crested transitions from recharge to discharge dominated phases. It is speculated that the difference in volatility is at least partly due to the time lags and smoothing of the arrival of recharge pulses provided by the unsaturated zone. The groundwater model is not capable of simulating such unsaturated zone dynamics, and this is the possible explanation for the differences in rates of change for the modelled and measured hydrographs.

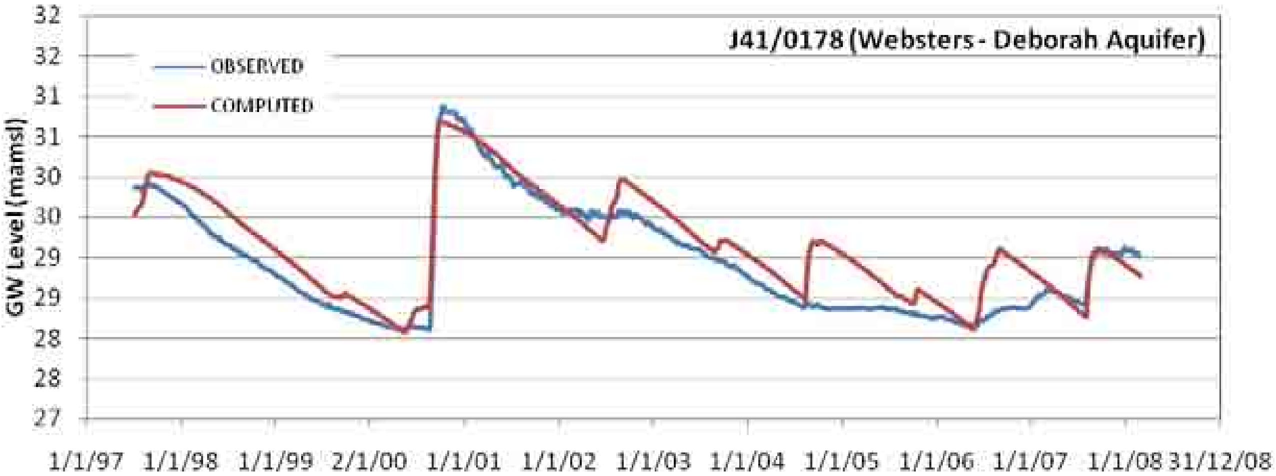


Figure 6.1 Hydrographs of measured and modelled groundwater level at the Webster Well (J41/0178) using the finally calibrated transient model

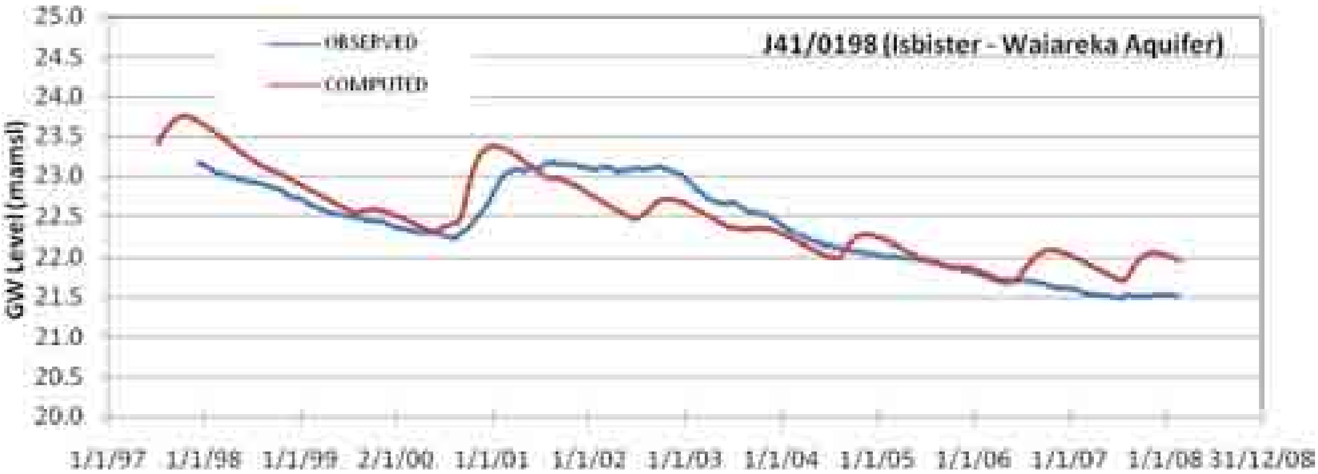


Figure 6.2 Hydrographs of measured and modelled groundwater level at the Isbister Well (J41/0198) using the finally calibrated transient model

6.3 Model scenarios

Scenarios are the 'what if' phase of groundwater model utilisation. Instead of looking retrospectively at recorded groundwater conditions and comparing these to model behaviour as in the calibration process, scenario modelling attempts to simulate groundwater behaviour that has yet to occur. Typically, the modelling project will pose a number of questions that are phrased as model scenarios. In the case of the Aquifer the central questions are posed as follows:

- What is the optimal and sustainable groundwater allocation volume and which parts of the aquifer are stressed as this pumped volume is exceeded?
- What might be the effect of different climate conditions?

In the case of determining optimal groundwater allocation, the transient model was used to simulate the results of pumping groundwater at a range of rates:

- 0% of current allocation within the full study area
- 30% of current allocation
- 50% of current allocation
- 100% of current allocation
- 150% of current allocation.

It should be recalled from Section 5 that actual use of the Aquifer groundwater in the Deborah zone in 2006 – 2007 was a small percentage of the paper allocation that has been issued by ORC and remains current at this time. Model simulations related to actual pumping, but are referenced to the allocation volume.

It has already been noted that the recharge timing of the Aquifer is a response to climate and soil mediated conditions and recharge is episodic rather than regular. If recharge is not guaranteed from one year to next, then what would the effect be of removing a significant recharge event from the climate input of the model? Accordingly, the climate variability scenario examines the effect on the long-term groundwater levels and flows of the aquifer not receiving the substantial recharge from the winter of 2000. In each scenario outlined, the transient model uses the climate driven recharge record from 1 July 1997 to March 2008.

6.3.1 Groundwater pumping simulations

These simulations assumed uniform, invariant groundwater pumping over a 154 day (22 week) period each year. The quantities that were changed from scenario to scenario were the annual irrigation pumping volume. Table 6.1 lists the percentages of annual allocation, the corresponding whole aquifer pumped volume and the ultimate volume that could be pumped. In scenarios involving 100% and 150% of allocation, the pumping of groundwater caused groundwater lowering sufficient to strand some wells within the model above the groundwater level. As a consequence, when the groundwater level drops below the model well intake height, the model shuts off pumping for that well. This modelling effect is relevant to real-world conditions since the water level dropping below the submersible pump intake height of a well will cause the well to cease pumping. Table 6.1 makes this distinct as "specified annual pumping volume in model" and "2006-07 pumping achieved in model". Where there is difference between these two columns, it is due to the drying out of top layer cells in MODFLOW that has the effect of turning off the associated well until the cell re-wets. Such dehydration of cells occurred in modelling of the 100% and 150% of allocation scenarios.

Table 6.1 Groundwater pumping scenarios

Percentage of allocation	Specified annual pumping volume in model (m^3/yr)	2006 – 07 Pumping achieved in model (m^3/yr)
0% of allocation	0	Same
30% of allocation	1,395,149	Same
50% of allocation	2,325,249	Same
100% of allocation	4,650,498	4,310,768
150% of allocation	6,975,747	6,360,361

The groundwater pumping was spread among the irrigation bores, wells or pits in accordance with their proportion of annual allocation.

6.3.2 Groundwater recharge variance simulations

These simulations assume that the 1997 – 2008 climate and recharge pattern are unchanged, except that the double recharge events in the winter of 2000 are clipped out of the model input. As outlined in Section 4.3, the groundwater recharge in the winter of 2000 provided substantial replenishment and reset the groundwater levels for several years following. The years of 1999 and 2001 also had particularly weak recharge, so the winter 2000 recharge pulse was especially beneficial. As the recharge events are largely independent from year to year, the absence of the substantial recharge from a particular year is a distinct possibility.

Projections of possible future changes to North Otago climate are not particularly clear in terms of the impact on rainfall and groundwater recharge rate. North and East Otago appears to be transitional between the South Otago area which is expected to experience greater rainfall and south Canterbury that is expected to receive less; however, mean annual temperatures are excepted to rise approximately 2ºC by the year 2090 (Wratt and Mullan, 2007). A warmer atmosphere can hold more moisture (about 8% more for every 1°C increase in temperature), so the potential for heavier rainfall certainly exists in all parts of the nation. Since winter recharge of the Aquifer is initiated in most instances by heavy rainfall, then an increase in the frequency or intensity of heavy rainfall in North Otago is highly likely to increase annual recharge overall. This effect of climate change potential may compensate for the possible increase in the frequency and duration in droughts. By the 2080s, severe droughts (defined as the present-day one-in-twenty (1:20) year drought) are projected to occur at least *twice as often* as currently in inland and northern parts of Otago (Wratt and Mullan, *ibid*). While it is feasible that increased frequency of droughts may have little effect on recharge rates, they have the potential to substantially increase the need for pumping of groundwater.

The groundwater recharge variance simulations consequently considered the reduction in recharge in two contexts:

- Reduced recharge and groundwater pumping at 30% of allocation
- Reduced recharge and groundwater pumping at 100% of allocation

These scenarios attempt to simulate current and possible future groundwater pumping intensities. The reduced recharge and 100% allocation pumping scenario is directed at evaluating the effects of these compounding stresses on the aquifer.

6.4 Scenario results

The results of the scenario modelling can be presented as plots of modelled groundwater level, groundwater flow or groundwater level decline (also known as drawdown). Since the transient model is used for the scenarios, time series plots provide the most information of changes in level or flow within each scenario simulation. The water level decline is also illustrated as a map view of contours showing the intensity and geographic extent of drawdown caused by groundwater pumping in the 100% of allocation scenario. It should be recalled that the transient model was calibrated to the 30% of allocation scenario and that this scenario is closest to the current level of *actual* groundwater pumping.

The groundwater level plots generally displayed lower levels for greater pumping or reduced recharge. The following groundwater level plots display this effect for several strategic points in the Aquifer. Each level plot is formatted so that the level axis covers 12m of level fluctuation rather than a variable range. In this way the reader is better able to compare level plots from point to point.

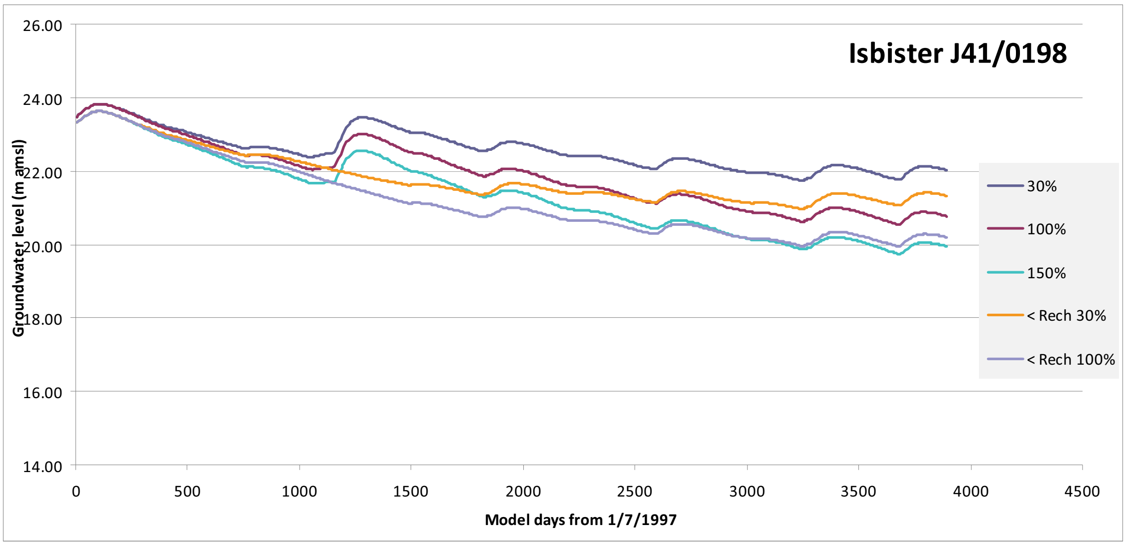


Figure 6.3 Level plot of modelled groundwater level at the Isbister Well (J41/0198) from July 1997 to early 2008[3]

The Isbister Well (J41/0198) location is not particularly sensitive to pumping or climate stresses due to fewer consented groundwater takes in the location and its proximity to Waiareka Creek. In fact, the levels after 10 years of simulation show a difference of only 2m between all scenarios.

[3] Note: < Rech 30% is the low recharge scenario with 30% of allocation from the pumping bores and < Rech 100% is the low recharge scenario with 100 % of current allocation as outlined in Section 6.3.2.

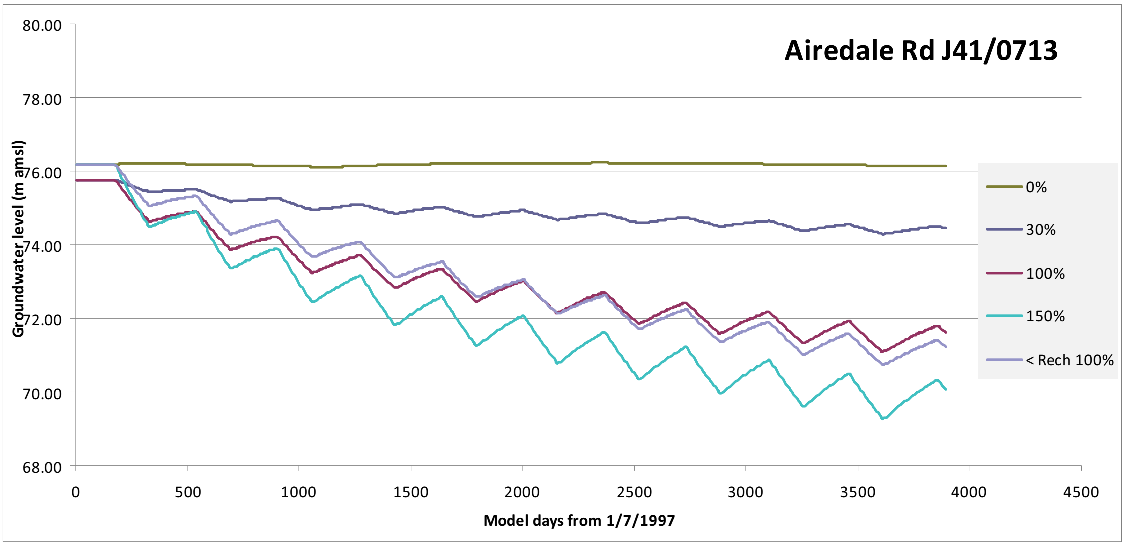


Figure 6.4 **Level plot of modelled groundwater level at the Airedale Road bore J41/0713**

The Airedale Road area by comparison to Isbister Well location shows a much greater response to pumping stresses. In fact, pumping is the predominant control on the groundwater levels. The effect of removing the recharge event in winter 2000 seems to have little influence on the groundwater levels (compare 100% and < Rech 100%).

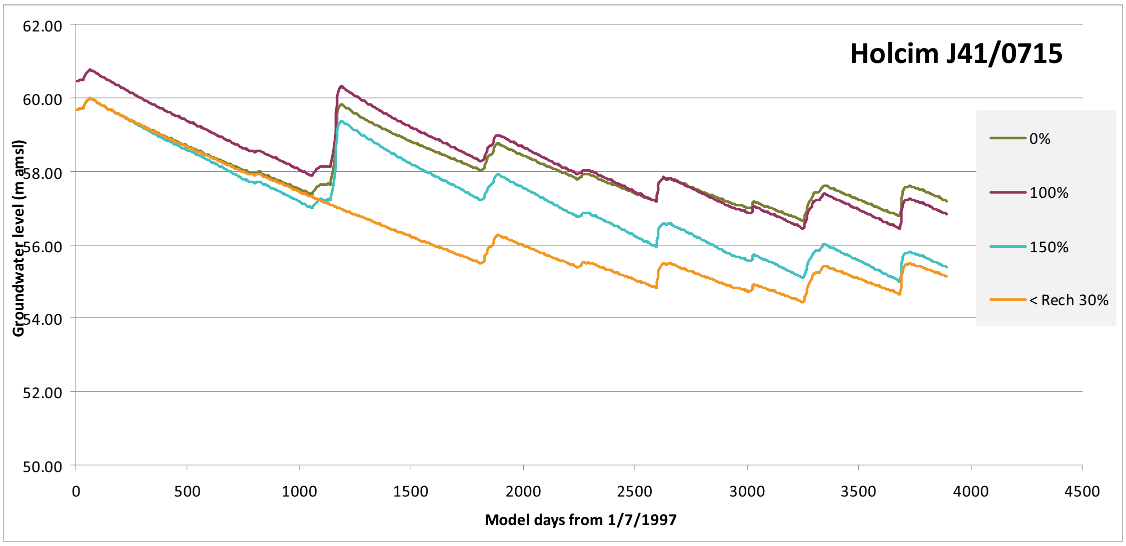


Figure 6.5 **Level plot of modelled groundwater level at the proposed Holcim borefield in the northwest of the Aquifer**

In the area of the proposed Holcim development (J41/0715) there is only a 2m separation between scenarios. In fact, climatic conditions (low recharge) can be seen to have just as much effect on groundwater levels as increasing abstraction to 150% of allocation.

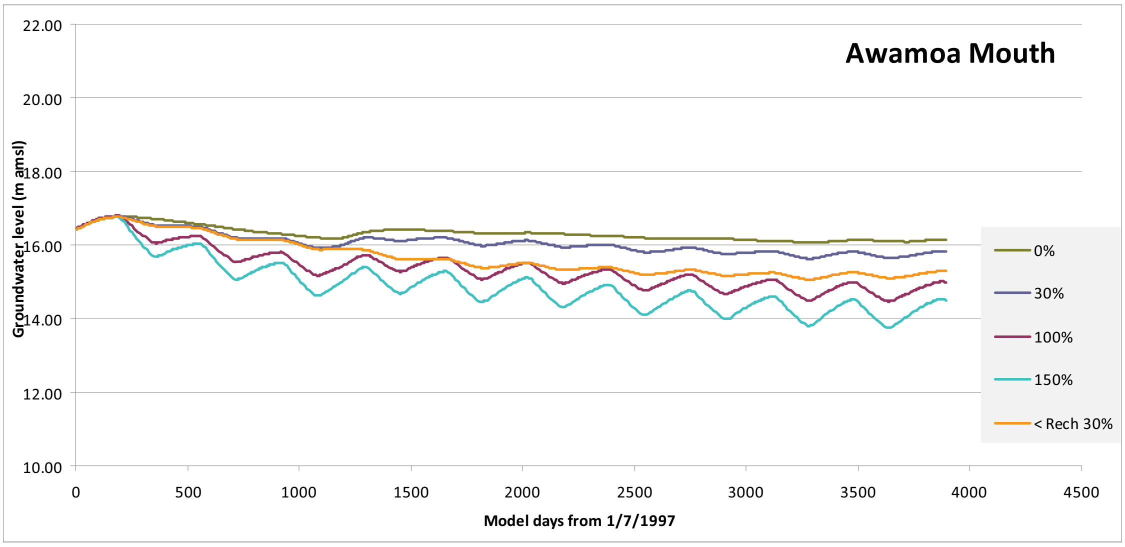


Figure 6.6 Level plot of modelled groundwater level at the Awamoa Mouth on the Pacific coast line

Groundwater levels at the coast are important to maintain above mean sea level to prevent seawater intrusion to the aquifer. The levels at Awamoa Mouth, south of Oamaru are well above sea level in all scenarios (14 m) due to the confined pressure state of the volcanic aquifer beneath the Gee Greensand / Riffle Butts Formation capping.

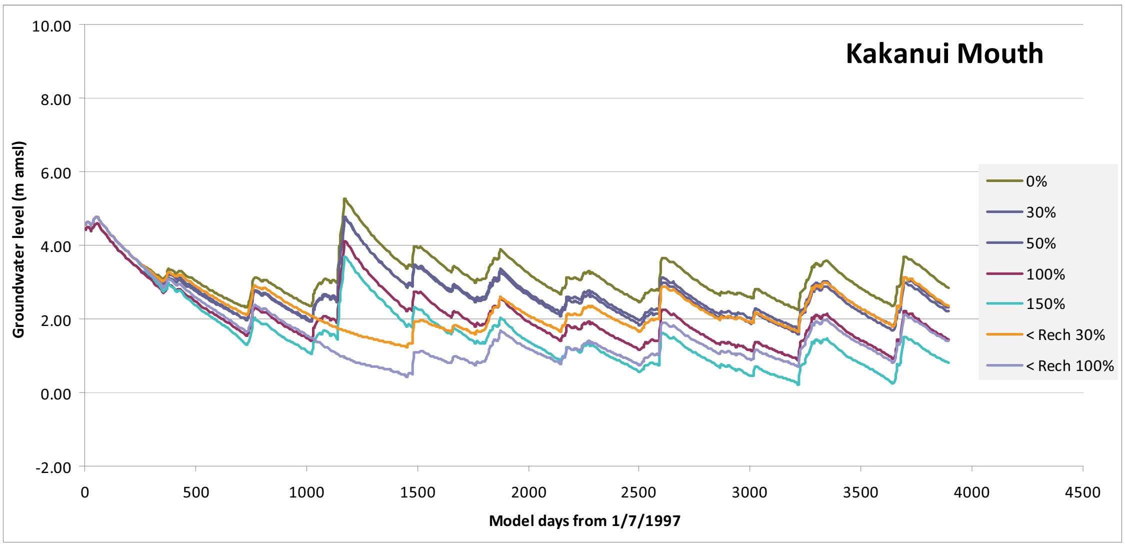


Figure 6.7 Level plot of modelled groundwater level at the Kakanui Mouth

Groundwater levels at Kakanui Mouth at the head of the Kakanui Estuary are much closer to mean sea level, which is an indicator of vulnerability to sea water intrusion; however, no scenario caused the groundwater level to fall below sea level at any time in the simulations, indicating that the outward flow of fresh groundwater could be maintained. The groundwater level in this zone would appear to be more sensitive to the effects of groundwater pumping than recharge change as the lowest groundwater level in 2007 – 2008 is caused by pumping at 150% of allocation.

The model scenario results can also be expressed in terms of aquifer flow rates at boundaries or strategic margins (such as the coast line) in the aquifer. The following plots express the change in aquifer flow rate as a function of time.

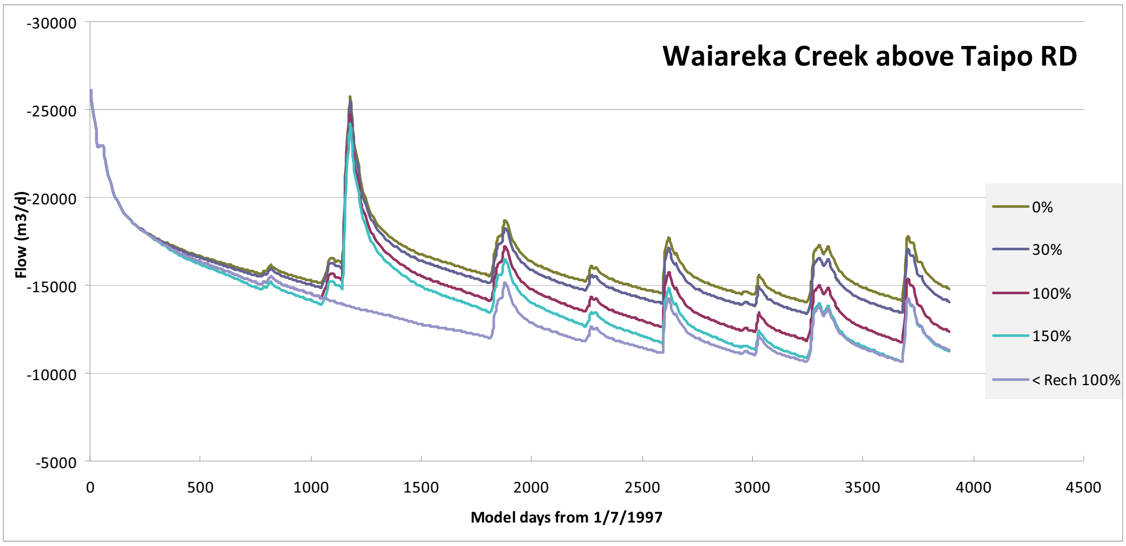


Figure 6.8 **Modelled aquifer outflow (seepage) into Waiareka Creek upstream of Taipo Road, which is an approximation of the groundwater contribution measured at the Taipo Road river flow recorder before evapo-transpiration is removed from the creek**

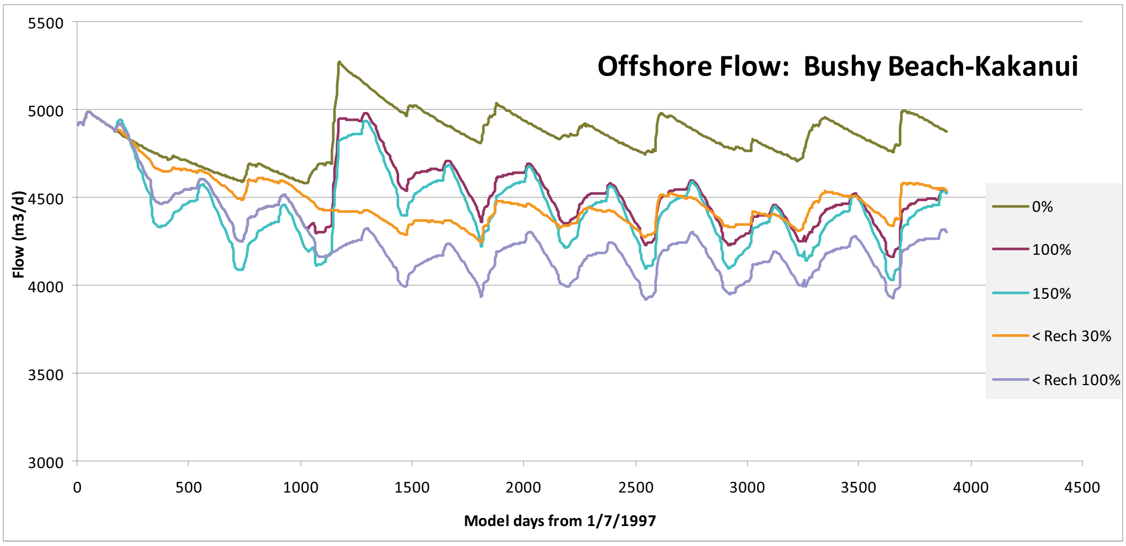


Figure 6.9 **Modelled aquifer outflow passing under the length of exposed coast line north of Kakanui towards Cape Wanbrow**

The aquifer maintains a healthy outflow of fresh groundwater into the seaward submarine springs and seeps on the continental shelf. It is interesting to note that reduction in recharge makes a significant effect on the magnitude of outflow.

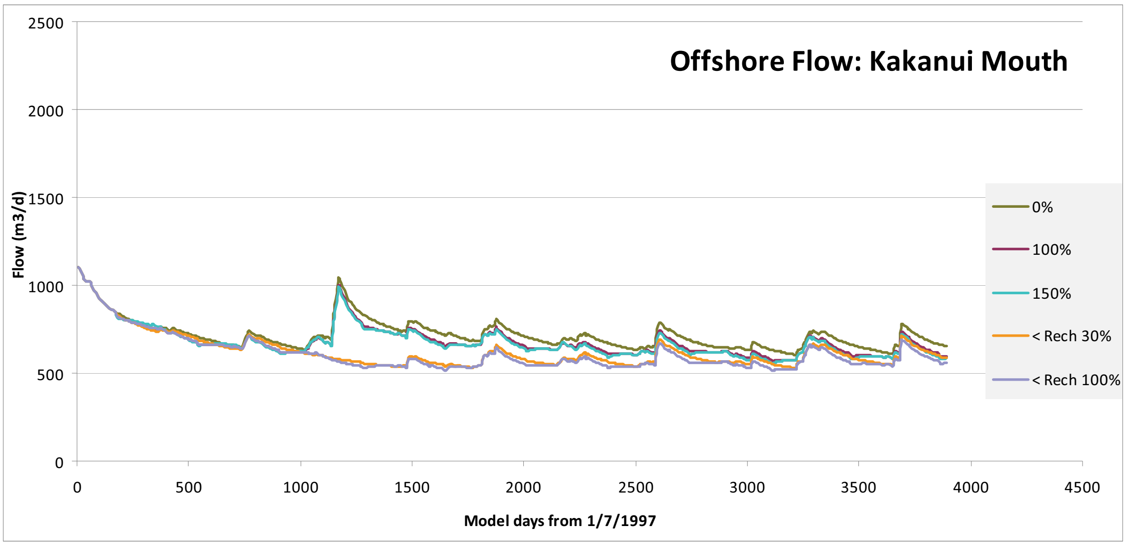


Figure 6.10 Modelled aquifer outflow passing beneath the coast at Kakanui Mouth

The aquifer outflow at Kakanui Mouth is much less in magnitude than in the exposed coast line indicated in Figure 6.9 due to the shorter length of coast at the mouth. In common with the coast outflows to the north, the reduction in recharge has a greater effect than changes in groundwater pumping. Despite the changes in outflow rate, the polarity of groundwater flow at this point on the coast remains positive throughout the simulations. Sea water intrusion would become a risk if the outflow of groundwater stagnated and began to reverse.

Groundwater resources can also be adversely affected by a generalised decline in groundwater level in a discrete area. To examine the modelling for this across the whole aquifer a drawdown contour map was produced that attempts to show the decline caused largely by groundwater pumping at bores and wells. A complicating factor is that in a multi-layer, stratified aquifer the drawdown effect will be spread across a number of model layers. This is an effect of both vertical groundwater gradients in the model and the fact that model wells are screened at one layer or another, but never across more than one layer. Accordingly, the drawdown map for ultimate groundwater pumping at 100% of allocations integrates drawdowns in three model layers in the two-dimensional map.

The resulting drawdown contour map illustrates how the northern, more elevated part of the Aquifer experiences the greatest drawdown, especially within Layer 3. Secondary areas of coalescing level decline are clustered around Kakanui township and the Kakanui Estuary. A handful of individual centres of drawdown can be seen in Figure 6.11 on the west side of Waiareka Creek. These drawdowns appear to be self induced and do not coalesce into more generalised declines in groundwater level.

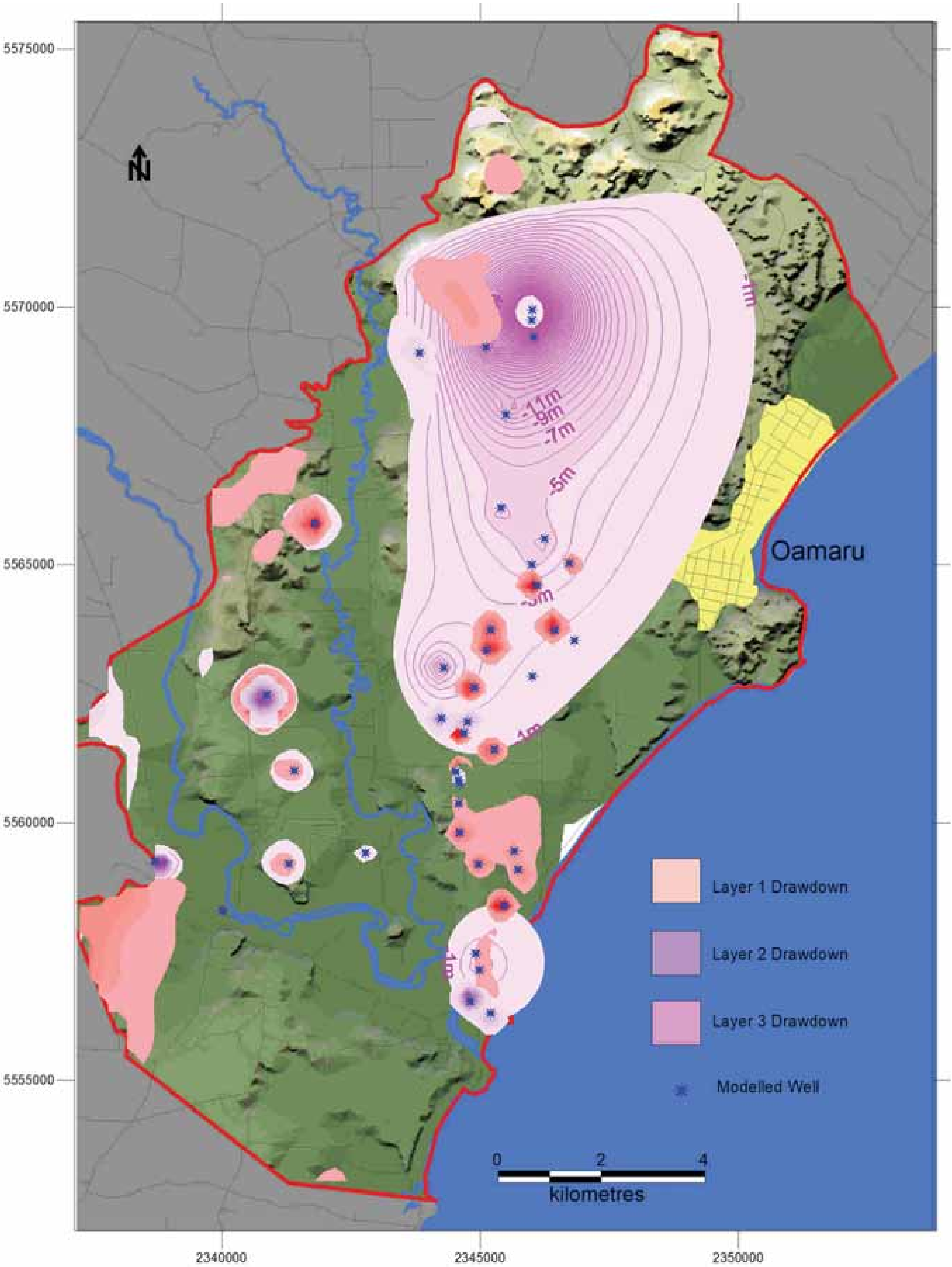


Figure 6.11 **Colour flood and contour map of modelled groundwater level decline in the top three model layers as a result of modelled groundwater pumping at 100% of allocation.**
Colour flood areas extend outwards to a cut-off at -1 m

6.5 Groundwater modelling discussion

The groundwater modelling calibration, sensitivity analysis and parameter optimisation highlighted the fact that the Aquifer does not display permeability in the vertical plane as high as the permeability in the horizontal plane. This is referred to technically as vertical anisotropy, and may be the result of the mode of secondary permeability features such as fractures, fissures and joints in the sedimentary rockmass. If these secondary voids are preferentially clustered along horizontally oriented bedding planes, then the result is significantly higher permeability laterally rather than vertically. This is deduced from the modelling process as a strong contrast between the permeabilities in either plane. Model sensitivity analysis found the parameter of vertical hydraulic conductivity was a very sensitive parameter in the model development. Analysis of the calibrated model pointed to there being very little groundwater circulation in the deep compartments of the volcanic aquifer.

As an upshot of this phenomenon of vertical differentiation or compartmentalisation, deep groundwater abstractions tend not to have the same effect on surface water tables and seepage rates; however, deeper focused groundwater abstractions do tend to induce substantial localised drawdown in the deep layers. Figure 6.11 suggests that drawdown from deep screened bores in layer 3 in the north of the volcanic aquifer coalesces into a generalised groundwater level decline. Multi-screening would have the effect of distributing the drawdown, but also has undesirable depressurisation impacts as discussed below. The drawdown effect of deep screened bores is more profound than similar magnitudes of groundwater pumping from shallow depths, such as in the Alma area.

The baseflow of Waiareka Creek is a big part of the aquifer water balance and this seepage boundary is an important determinant in the shape of the groundwater flow pattern. Similarly, the relationship between the Kakanui – Kauru Alluvium has become clearer through the process of developing the groundwater model; however, the quantity of groundwater that the volcanic aquifer contributes is not very significant compared to the water balance volumes flowing in the Kakanui River, which is in direct hydraulic connection with the alluvium. So, Waiareka Creek and secondary seepage zones such as Awamoa Creek and Oamaru Creek are more sensitive to fluctuation in groundwater fluctuations than the Kakanui River and associated alluvium.

The outflow of groundwater at the coastline occurs at lower annual volumes (about half) compared to the baseflow contribution to Waiareka Creek. Combined with the seepage contribution to the Kakanui - Kauru Alluvium, the seepage to creeks is a significant internal exchange of groundwater from the volcanic aquifer. The outflow from the volcanic aquifer beyond the coast line is rather more sensitive to changes in recharge than changes in pumping. This is largely because the loss of the winter 2000 recharge event was of a higher magnitude of groundwater lost to the aquifer compared to the modelled increase in pumping. Maintenance of the outflow to submarine seepages and springs is vitally important to the continued health of the volcanic aquifer, since a stagnation or reversal of groundwater flow across the coast line would ultimately lead to seawater intrusion risk.

The Aquifer has been found to have an irregular, episodic pattern of recharge, relatively unrelated to the annual recharge totals for any particularly year. Instead, the occurrence and intensity of recharge is governed by rather more haphazard factors of rainfall timing and intensity over a discrete period in the winter of each year. The predictability of recharge in the Aquifer is thus significantly lower than other aquifers in Otago. It would be very attractive to base groundwater allocation limits for the volcanic aquifer on the balance of recharge received in the foregoing five years, but in a regulatory context such an approach may be unworkable. In the place of such an approach, the groundwater level based restrictions are proposed to be extended across the whole volcanic aquifer and revised to more realistically reflect the effects of natural recharge variability.

Analysis of the modelling scenario results also supports the need to recommend a volumetric cap on the groundwater that can be allocated from the Aquifer. The simulation of the 150% of allocation pumping scenario indicated no adverse effects. In the following section this information has been used to set a recommended allocation cap covering the whole of the Aquifer. The modelling scenario analysis gives the confidence that, combined with the revised restriction levels at the Webster Well, the Aquifer allocation can be applied to the whole aquifer while avoiding undesirable impacts.

7. Resource allocation and monitoring Recommendations

This section is intended to translate the scientific and technical findings of review, conceptual analysis and numerical modelling associated with this study into directions for future groundwater management and monitoring activities by ORC within the Aquifer.

7.1 Groundwater allocation

7.1.1 Summary of current allocation method

The allocation regime currently applying to the Aquifer has been outlined. To summarise the current groundwater management of the groundwater allocation, the following points can be made:

- The Water Plan does not specify a volumetric allocation limit on the granting of groundwater takes from the aquifer.

- ORC has closed the Aquifer from further allocation from the Map D2 areas of the aquifer at a maximum 2.7 Mm^3/yr for the Deborah Water Take Restriction Zone and 0.43 Mm^3/yr for the Waiareka Water Take Restriction Zone.

- Groundwater abstraction in the Map D2 Waiareka and Deborah Water Take Restriction Zones (and occasionally adjoining bores affecting the zones) is regulated by the relevant monitoring well restriction levels and by the guidance of the respective water allocation committees that are deputised to manage the Aquifer on behalf of ORC.

The underlying intentions of the above groundwater allocation management practices have been to avoid the possibility of seawater intrusion across the coast line, avoid problematic decline in groundwater levels and maintain the beneficial seepage outflows into Waiareka Creek, Awamoa Creek, Oamaru Creek Catchment, plus the Kakanui Alluvium.

7.1.2 Potential for seawater intrusion

The potential for seawater intrusion is more complex than originally conceived when groundwater restrictions were set in the late 1990s. There is little likelihood of the freshwater – seawater interface crossing the sea coast into the landward parts of the aquifer along the exposed coastline in view of the following factors:

- Existing groundwater gradients and the presence of the fine sediment capping the volcanic aquifer would oppose sea water intrusion along the exposed coast line.
- Groundwater pressures along the exposed coastline presently stand at least 5m above mean sea level and have shown no significant change since the levels were first surveyed in 1987.
- The current measured groundwater pressures and gradients imply that the exposed coast is underlain by at least 200m of fresh groundwater and that the aquifer is flowing fresh outwards under the sea bed.

However, these conditions are absent in the Kakanui Mouth and Kakanui Estuary area where seawater and brackish water extends inland beyond the fine sediment capping and upstream for some distance. As a result, the Aquifer is in direct contact with saline and brackish marine waters. Groundwater levels in the mouth and estuary area are measured as being below 5 m elevations and commonly close to sea level. This may be as a result of the aquifer in this area being unconfined and in hydraulic communication with sea level. This is the sole area of vulnerability to sea water intrusion. There is also significant uncertainty as to the magnitude of future sea level change. In the past 30 years, there has been a rise in sea level of approximately 8cm, mainly as a result of thermal expansion of global ocean water. Future projections of global sea level are very uncertain, although the consensus position is that continued rise will be at rates greater than the past rate. Rising sea levels would be likely to increase the conditions conducive to sea water intrusion in the Kakanui Estuary zone. As a result, this study recommends that references to sea water intrusion vulnerability of the aquifer be restricted to the Kakanui Estuary zone. Figure 7.1 illustrates the potentially affected estuary and aquifer zone as defined by the 7.5 m groundwater contour.

It is suggested that a special groundwater management zone is established. The special groundwater zone would impose higher levels of assessment of the effects for new and replacement consent applications. The zone would also have the ability to apply special conditions on bore construction and groundwater take consents. A special-purpose monitoring bore may need to be established in a strategic location in the zone for determining the potential for seawater intrusion of groundwater, and potentially for managing abstraction during critical periods.

7.1.3 Controls on groundwater levels

Most of the decline in groundwater levels for the past 10 years of record can be explained as the balance of recharge and discharge under natural gradients. The estimated actual use of groundwater based on surveys of volumetric flow meters suggests that groundwater pumping represents only 6% of the aquifer water balance at present. Despite this relatively small influence on aquifer outflows, the Aquifer has been subject to restrictions since autumn 2004 in the Waiareka Water Take Restriction Zone. The Deborah Water Take Restriction Zone has been subject to extended restrictions from 1999 to 2001, and subsequently from 2004 to 2007. These restriction periods are considered within this study to be primarily induced by climatic episodes and recharge conditions rather than the intensity of groundwater pumping. Restrictions on pumping at current levels of actual use would have had little influence on the fall or rise in groundwater levels, as numerical modelling has demonstrated. As a result, this study suggests that the range of restriction levels be extended so that the restrictions come into play during more extreme climatic conditions or actual pumping-induced groundwater depletion. Restriction levels are considered by this study to have some utility as a drought response tool; however, they are an imprecise tool for managing localised groundwater level decline and generalised depletion of the Aquifer.

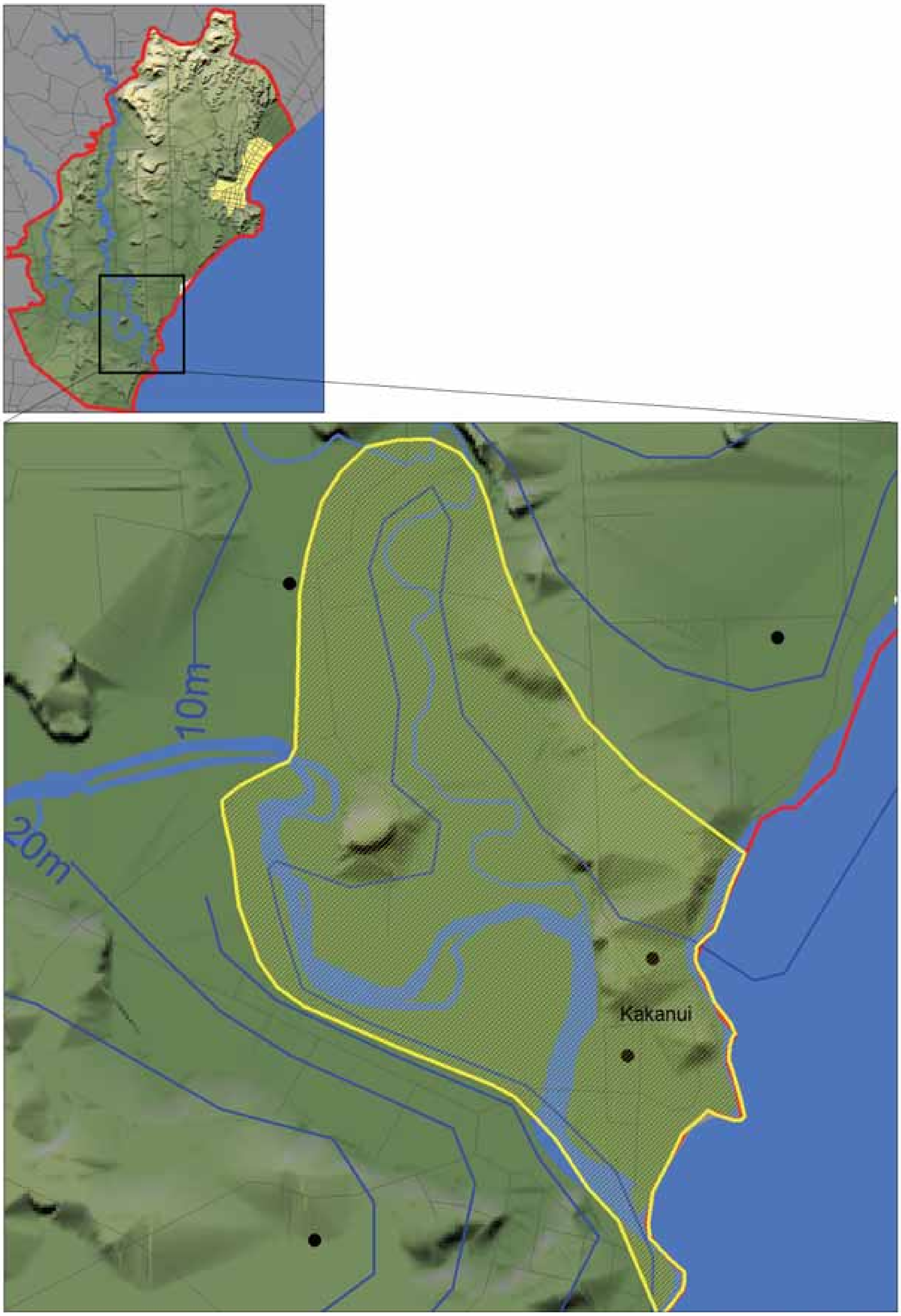


Figure 7.1 **Potentially affected seawater intrusion zone around the Kakanui Estuary within the yellow margin.**
Solid blue lines indicate interpolated groundwater level contours from Figure 4.1. This delineated zone is recommended for special groundwater management

It is suggested that the Waiareka-Isbister Well (J41/0198) be continued at this point as a monitoring bore but that it is no longer used as a reference bore with restriction levels. Two new areas are suggested for continuous monitoring bores. The area north of Weston which is under pressure from several new groundwater takes and the Kakanui township area and environs within the 5m groundwater elevation contour to monitor levels and salinity against seawater intrusion. There may be potential in these areas to use existing or permit holders' bores. Alternatively, special-purpose drilling may be required.

It is considered that Deborah-Webster Well (J41/0178) is situated in an appropriate location (central to the high use area) and has a good record of levels over the last 20 years, so that it should continue to be used to apply restrictions. The restriction levels on this bore can be changed due to the results of the modelling. The modelling within this study showed a significant decline in levels (falling to 22 m AMSL) in the vicinity of the monitoring bore in the low recharge scenario and 100% allocation (Figure 7.2). This combined impact of climatic conditions and groundwater pumping is more suitable to mitigation using abstraction restrictions. The scenario of 30% allocation with lower recharge reached 25m AMSL, and can be considered a scenario highly climate-affected and low abstraction influence. Therefore, the lowest restriction level for Deborah-Webster Well (J41/0178) can be set at 25m, with 50% cut off at 26.5m and 25% restriction at 26m. It is suggested that these restriction levels should apply to the whole Aquifer.

The restriction levels as suggested will prevent dramatic drops in groundwater levels up to 9m as shown in the low recharge 100% allocation scenario, but will allow the use of the resource during natural times of low recharge by allowing up to an approximately 6m drop in groundwater levels.

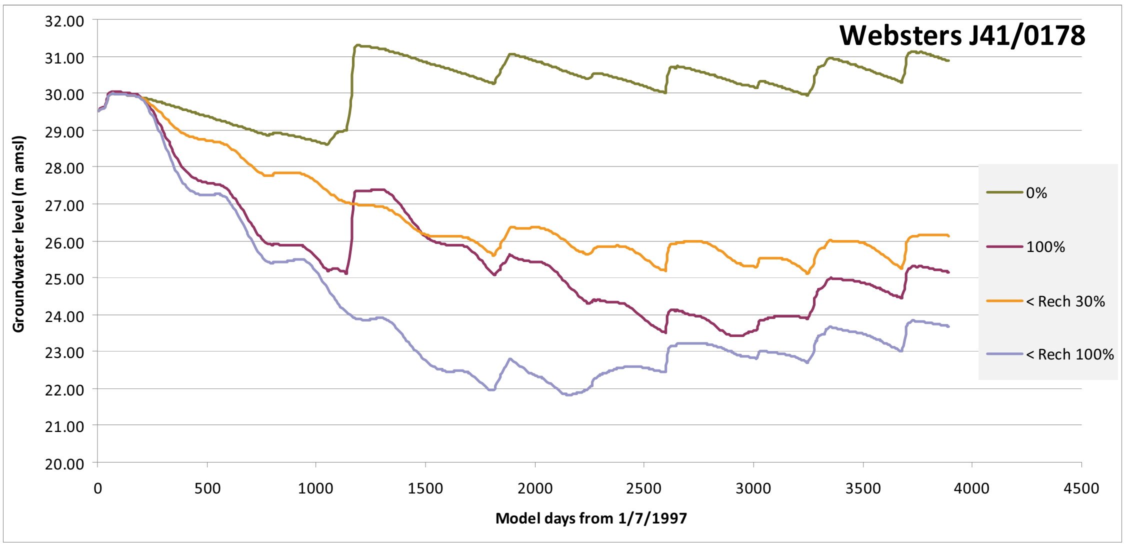


Figure 7.2 Hydrograph of simulated groundwater levels at the site of the Webster Well (J41/0178).
Note: < Rech 30% is the low recharge scenario with 30% of allocation from the pumping bores and < Rech 100% is the low recharge scenario with 100 % of current allocation as outlined in Section 6.3.2

7.1.4 Stream baseflow contribution

The groundwater contribution as baseflow to Waiareka, Awamoa and Oamaru Creeks are most significant to each of the creeks during dry weather. Only Oamaru Creek has much freshwater ecological value. While Waiareka Creek is considered to be highly degraded, it still sustains a short-fin eel and inanga population. One consequence of a lower groundwater level over a wide area is change to the flow contributing to creek baseflow. Accordingly, maintaining groundwater levels within limits consistent with natural variation would preserve the continuation of baseflow to the Aquifer's creeks.

Although the Kakanui Alluvium receives seepage from the adjoining volcanic aquifer, the volume of water gained from this source (approximately 4 Mm^3/yr) is small when compared to the mean flow of the Kakanui River (approximately 140 Mm^3/yr at the Mill Dam recorder). Marginal changes in the groundwater contribution from the Aquifer would be balanced by changes in flux from other recharge sources with an influence on the alluvium.

The base flow contribution and evaporation/transpiration in the riparian zone of Waiareka Creek in the different model scenarios ranges from 14,150 m^3/day with no pumping to 11,750 m^3/day under 100% allocation pumping. This is only a 17% change in the outflow from groundwater to the stream/riparian zone. Increasing the allocation to 150% of current allocation only reduces the outflow by another 8% in the model to give 10,650 m^3/day. Considering that a large proportion of the outflow is lost through evaporation and transpiration, this level of sensitivity is not considered significant to limiting the use of the resource. Accordingly, the maintenance of baseflow to Waiareka Creek is not considered to be a prime or even secondary determinant in setting allocation volumes or trigger groundwater restriction levels.

7.1.5 Allocation limits – outflows and recharge

The current allocation as a proportion of average annual recharge is 22%, leaving 78% to flow outwards to creek seepage zones, the Kakanui – Kauru Alluvium and the coastal zone. In terms of the definitions within the proposed NES for Ecological Flows and Water Levels, the current level of allocation would be considered a medium level of abstraction. This same proposed NES gives a conservatively set value of 35% for the maximum allocation of groundwater as a proportion of average annual recharge (see Section 5.2). From an average annual recharge to the Aquifer of 20.5 Mm^3/yr, this maximum allocation volume is equivalent to 7.2 Mm^3/year. Previous allocation limits within the D2 Water Take Restriction Zones were set to guard against any potential for seawater intrusion during drought; however, considering that the modelled natural outflows along the exposed coastline are not significantly affected by increasing the allocation to 150% of allocation (approximately 6.9 Mm^3/y), this justification for limiting use may no longer be appropriate.

It is suggested that the allocation limit for the Aquifer should be set at **7 Mm^3/year**. This limit allows for more resource use than current allocation given the extended area of the aquifer and improved knowledge of the hydrogeology including recharge characteristics and response to pumping through groundwater modelling. The suggested groundwater allocation would operate alongside the revised groundwater level restriction triggers to be placed on the Webster Well (J41/0178). The groundwater level restriction would provide an additional safeguard against adverse effects of pumping-induced and climate-driven groundwater level declines.

7.2 Groundwater quality management

Setting sea water intrusion to one side, the primary water quality issue under human influence in the Aquifer is that of elevated nitrate nitrogen concentrations in bores and wells, particularly those within the east of the aquifer. This area is characterised by intensive grazing, cropping and market gardening. The Alma – Deborah – Kakanui triangle is one of the largest areas of cropping and market gardening in Otago as a result of the favourable soil and climatic conditions within the area. The area is comparable to some extent with the Pukekohe market gardening district to the south of Auckland (Enviro-Link, 2000). Pukekohe groundwater is also found within fractured volcanic rocks and is associated with elevated nitrate nitrogen concentrations (Cathcart, 1996).

7.2.1 Possible causative factors

Market gardening is recognised for its high leaching losses in other areas compared to cropping or intensive grazing. The measured nitrogen leaching losses from Pukekohe market garden soils growing potatoes approach 300 kilograms per hectare per year (kgN/ha/yr). By way of comparison, leaching losses under dairy units have been estimated at 40 – 45 kgN/ha/yr (Enviro-Link, 2000). Market gardening involves the exposure of significant areas of bare soil to the air and consequent nitrogen mineralisation. Market gardening is also made possible with the application of high loads of mineral fertiliser. Crop rotation, shallow rooting and the occasional use of nitrogen fixing cover crops increase the amount of oxidised nitrogen in the soil nitrogen store. Mineral and oxidised nitrogen is then readily displaced by soil drainage initiated by heavy rainfalls.

This study has advanced the theory that the episodic soil drainage following heavy initiating rainfall results in high concentrations of nitrate nitrogen percolating to the underlying aquifer. In other New Zealand unconfined aquifers nitrate also accumulates in the aquifer, but is substantially dispersed and diluted by subsequent or adjoining low nitrate soil drainage. In the Aquifer context, the tight clustering of market gardens and low frequency of recharge to the underlying aquifer is thought to maintain the groundwater nitrate concentrations at levels close to the original soil drainage i.e. approximately 20 gNO_3-N/m^3. It should be stressed that while a correlation can be drawn between North Otago market gardening and high nitrate concentrations, there is no direct evidence linking them.

7.2.2 Current policies

Policies within the Water Plan refer to the need to recognise the risk of soil leaching leading to groundwater contamination. Specifically, the Water Plan objectives 9.4.18 and 9.4.19 relate to the following risk factors:

- Changes in land activities resulting in leachate discharges
- Existing land use activities with the potential for leachate discharges
- Point source discharges of water or contaminants

- Excavations or stripping of the soil mantle of capping layers that would increase the vulnerability of underlying groundwater.

Groundwater Protection Zones are defined in the Water Plan to identify vulnerable aquifers; however, the Aquifer is not mentioned at any level in the schedule of Groundwater Protection Zones appended to the Water Plan. Consequently, the Water Plan does not trigger specific groundwater quality protection provisions in the form of rules or other methods (methods other than rules such as liaison, information sharing, promotion of sustainable activities or education).

The elevated nitrate nitrogen status of the groundwater has been persistent over at least 20 years of measurement. It shows few clear signs of worsening or improving, and no significant active measures to manage groundwater quality are known to be undertaken in the area. The ORC response has been ongoing monitoring. Groundwater in the elevated nitrate nitrogen areas should not be consumed as drinking water because the water quality in most bores consistently exceeds the maximum acceptable value (MAV) and is in places over twice the MAV of 11.3 gNO_3-N/m^3. So, some of the volcanic aquifer wells and bores represent a water quality risk of health concern present in terms of nitrate nitrogen status. As a result, the continuing high nitrate status should be noted, allied authorities advised and the community advised that the aquifer has areas of non-potable groundwater.

7.3 Bore construction management

7.3.1 North Otago bore construction practices

Bore construction in terms of the drilling technique, casing materials, screening materials, bore flushing and bore head completion has a bearing on groundwater effects. In the Aquifer, bore construction is variable. Often for simplicity and cost savings bores into the volcanic sediments have been cased in mild steel for a short depth from the surface and allowed to be left uncased to full depth. The strength properties of the volcanic sediments are such that the bored hole would resist collapse and remain uncased for the life of the bore.

Shallow wells down to a maximum depth of 20m were historically hand dug or excavated with other means. The wells are by definition larger diameter than 600mm. The standard of historic well's construction varied from one well-sinker to the next, but often a high standard of dry-stone walling was installed using Oamaru stone (cut blocks of massive limestone); however, such casing seldom provided a high standard of preventing surface water from entering the well due to the porous nature of such a well construction.

Many deep bores (i.e. > 100 m depth) in the Aquifer are either uncased below the water table or multiply screened. A significant example of this tendency is drawn from bore J41/0574, which was drilled in February 2003. The total bore depth was 276m below ground. The bore penetrated limestone, siltstone and a significant thickness of volcanic sediments, mostly tuff to the full depth of 276m. The bore was constructed in 300mm diameter steel casing to 16m. Into this was telescoped slotted 250mm diameter steel casing to a depth of 135m. From 135m to 276m the bore was entirely open-holed. The intermediate slotting extended from 20m to 90m depth. So, the eventual bore was screened across a 211m thickness of aquifer from 20m to 276m, with a 45m wide blank section below 90m depth. The depth to water in the bore lay at approximately 12m at the time of bore construction.

7.3.2 Issues with past and current bore construction

The main issues with bore construction can be summarised as follow:

- Cascading inflows to uncased wells and bore holes
- Surface water contamination of wells lacking sealing
- Groundwater level decline caused by long open holes and multiple screening of deep bores.

Cascading inflows occur when groundwater enters at a height above the pumped bore water level. In some cases, the higher level inflow galleries are perched water tables that eventually bleed themselves dry following the installation of the uncased bore. In other cases, the gallery inflow, as part of the saturated zone, ends up cascading down the air-filled bore by the self-induced drawdown effect. The former instance will lead to the desaturation of perched water tables that may be important as a source for a spring or seep.

The problem of well contamination through lack of a surface seal against surface water is more significant to the owner of the well concerned. Instances of bacterial or nitrate contamination by this vector have been described for such unprotected wells in New Zealand, and in some areas it is known to be a chronic problem. If a well is used for monitoring groundwater quality, the presence of short-circuiting surface waters would give a false positive for contamination.

Substantial declines in natural groundwater levels can be induced by inappropriate multiple screening. The pre-conditions for such declines are as follow:

- Stratified aquifers with pressure differences from layer to layer
- Moderate or steep terrain
- Significant down-ward groundwater level gradients.

The Aquifer has these pre-conditions, particularly in the high ground in the north of the aquifer. The extended multi-screening of bore J41/0574 was intended to maximise the groundwater production capacity of the bore. But, due to the significantly steep downward pressure gradients, the groundwater levels in the surrounding aquifer have been lowered without any groundwater pumping. This effect is as a result of the bore hole becoming a direct conduit for higher pressure groundwater to descend to lower pressure compartments of the Aquifer. The Aquifer's pressure state thus equalises and falls to an average of the pressures accessed by the screened section of bore hole. This effect is particularly problematic in the maintenance of shallow seepages and springs.

8. Conclusions and recommendations

8.1 Seawater intrusion risk

8.1.1 Conclusion

This study has determined that little potential for seawater intrusion exists along the exposed coast line and that the Aquifer should not be considered a coastal aquifer; however, the estuarine zone represents a potential future risk of seawater intrusion due to topographic, geomorphic and hydrogeological reasons.

8.1.2 Management options

- A special groundwater management area could be established in the Kakanui Estuary zone.
- The special groundwater management area could be used to resolve matters that would exacerbate the potential for seawater intrusion such as groundwater pumping and bore construction.
- The special groundwater area could also be capable of resolving any regulatory conflicts between the management zones of the Aquifer and the Kakanui – Kauru Alluvium that fall within the special zone.
- Monitoring of groundwater levels, groundwater pumping and groundwater salinity in the special groundwater management zone could be continued and expanded in response to any increased risk of seawater intrusion.

8.2 Groundwater levels pumping restrictions

8.2.1 Conclusion

The current restriction levels set for the Webster well (J41/0178) and Isbister Well (J41/0198) are overly restrictive and not effectively managing groundwater resource matters on their own.

8.2.2 Management options

- The Webster Well (J41/0178) could become the trigger bore for the whole Aquifer.
- The Aquifer could be managed through a set of combined measures including a fixed groundwater allocation limit (see Section 2.3) backed up by restriction groundwater levels that serve to prevent adverse effects.
- The 100% restriction groundwater elevation in the Webster Well (J41/0178) should be set at 25m (125.0 m ODM).
- The 50% restriction groundwater elevation in the Webster Well (J41/0178) should be set at 25.5m (125.5 m ODM).
- The 25% restriction groundwater elevation in the Webster Well (J41/0178) should be set at 26m (126.0 m ODM).

8.3 Groundwater volume allocation limit

8.3.1 Conclusion

This study has determined that a maximum of 7 million cubic metres per year can be allocated from the whole Aquifer.

8.3.2 Management options

- A groundwater allocation cap could be set over the Aquifer that comprises a total of all groundwater allocations up to **7 million cubic metres per year**.
- The assessment of new and replacement groundwater take resource consents could conform with this volumetric allocation cap, while evaluating more localised adverse effects such as competitive drawdown between concentrations of irrigation bores and effects on fresh surface water.

8.4 Elevated groundwater nitrate management

8.4.1 Conclusion

The eastern and central portion of the Aquifer is subject to elevated nitrate nitrogen concentrations in shallow groundwater. These concentrations have been mostly consistently high since monitoring began in the 1980s. The Aquifer is the most extensively nitrate contaminated aquifer in the region, and notable on a national scale. While possible causative factors from market gardening have been suggested, the mechanisms for the persistent nitrate nitrogen contamination have not been conclusively isolated.

8.4.2 Management options

- The occurrence and persistence of the nitrate nitrogen contamination of parts of the aquifer could be indicated to allied authorities such as Waitaki District Council, Public Health South and Ministry of Agriculture and Forestry.
- Steps could be taken to advise the community and individual well / bore owners of the continued nitrate nitrogen status of the aquifer at levels that are of significant health concern.

8.5 Bore construction

8.5.1 Conclusion

Acknowledged impacts on groundwater quantity and quality can arise from less than optimal bore construction. While the extended usable lifetime of wells and bores means that the impacts of existing structures will persist into the future, preventative steps are suggested for new bores and wells.

8.5.2 Management options

- Drilling and bore construction in the Aquifer could follow the Australia – New Zealand Standard for Environmental Drilling of Soil and Rock (NZS 4411:2001).
- The practice of multi-screening of substantial sections of the volcanic aquifer could be subject to resource consent assessment and technical review for the potential of adverse effects on aquifer groundwater levels and pressure.

9. References

Carryer SJ. 1983. Preliminary report on the groundwater resources of the Kakanui Basin with a proposal for their investigation and development for irrigation. Prepared by Simon J Carryer, Consulting Geologist for 22 landowners in North Otago.

Cathcart S. 1996. An investigation of the nitrogen contamination of an unconfined, shallow fractured, basaltic aquifer at Pukekohe, South Auckland, New Zealand. M.Sc thesis, University of Auckland.

Collins BW. 1953. Groundwater in the Oamaru District. NZ Geological Survey, Hydrological Report 104, Dept of Scientific and Industrial Research, Christchurch.

Collins BW. 1954. Sources of groundwater in North Otago. Proceedings of the Royal Society. Vol. 82, 1954-55.

Daughney CJ. 2008. Multivariate statistical methods for assessment of groundwater chemistry in the Waiareka and Deborah Aquifers, Otago, GNS Science Report, 2008/XX.

Eco-Link Ltd. 2000. Implications of Groundwater Nitrate Standards for Agricultural Management. Technical Paper 2000/15 Commissioned by MAF Policy and prepared by Eco-Link Ltd in May 2000.
http://www.maf.govt.nz/mafnet/rural-nz/sustainable-resource-use/resource-management/groundwater-nitrate/grwatnt.htm#P38_114

Edwards AR. 1991. The Oamaru Diatomite. NZ Geological Survey, Paleontological Bulletin 64, Dept of Scientific and Industrial Research, Wellington.

Forsyth PJ (compiler). 2002. Geology of the Waitaki area; 1:250,000 Q-Map series. Institute of Geological & Nuclear Sciences, Lower Hutt.

Gage M. 1957. The geology of the Waitaki subdivision. New Zealand Geological Survey Bulletin 55. NZGS, DSIR, Wellington.

Kingett Mitchell. 2006. Cement Manufacturing Proposal, Weston Option; Appendix 15 Water Management Strategy for Holcim NZ Ltd. Prepared by Boffa Miskell Ltd and Kingett Mitchell Ltd for Holcim NZ Ltd.

Lincoln Environmental. 2003. Irrigation Requirements for North Otago. Report No 4661/1.

Mandel S. 1974. Groundwater in the Kakanui Basin, North Otago. Unpublished report of the Hebrew Research Centre, Jerusalem, Israel.

Mutch AR. 1963. Water Report S136 Oamaru. Internal report of New Zealand Geological Survey, DSIR, Wellington.

O’Connor RM. 1992. Thrust faulting near Oamaru from seismic reflection profiles. New Zealand Journal of Geology and Geophysics, Vol. 35, p243 – 247.

ORC. 1993. North Otago Groundwater Investigation. Prepared by IRRICON Ltd for Otago Regional Council, March 1993, Dunedin. ISBN 0-908922-06-X.

ORC. 1998. Groundwater, Background Report 3: Proposed Regional Plan Water for Otago. Otago Regional Council, February 1998, Dunedin.

ORC. 2000. Draft Deborah Volcanic Aquifer Status Report. Unpublished report of Otago Regional Council groundwater scientist, Dunedin.

ORC. 2001. Waiareka – Deborah Volcanic Aquifer cross-sections and groundwater occurrence. Unpublished report of Otago Regional Council groundwater scientist, Dunedin.

Rushton KR, Eilers VHM, Carter RC. 2006. Improved soil moisture balance methodology for recharge estimation. Journal of Hydrology (UK) Vol. 318, p379-399.

Wilding A and Sweetman LAD. 1971. Endeavour-1 Well Completion Report. Prepared by BP Shell Aquitaine Todd Petroleum Developments for the Ministry of Economic Development, Crown Minerals, Petroleum Report Series No. PR303, Wellington.

Wratt D and Mullan B. 2007. Climate Variability and Change; Climate Change Scenarios for New Zealand. National Institute of Water and Atmospheric Research Ltd, NIWA Science, Wellington.

Appendix A: Monitored static water levels and survey results

Table A. 1 Monitored bores for the North Otago Volcanic Aquifer and static water levels over 3 months

Well number	Name	Static water level on 10/04/2008	Notes from 10/04/2008	Static water level on 8/03/08	Static water level on 4/02/08
J41/0047	Young F	-4.205		-4.125	-4.060
J41/0008	Reggie Joe	-8.955		-8.710	-8.570
J41/0015	Fukuhara	-2.320		-3.195	-2.080
J41/0019	De Rews P	-3.890		-3.780	-3.625
J41/0166	Wallace D	-5.050		-4.850	-4.950
J41/0177	Webster J	-9.920		-9.685	-9.440
J41/0188	Isbister E	-12.105		-12.085	-12.080
J41/0198	isbister	nd		-9.660	nd
J41/0219	Arney	6.930		-6.855	-6.870
J41/0244	Cooper L	-5.900		-5.840	-5.875
J41/0247	Leaman D & S	-9.275		-9.175	-9.230
J41/0249	Morgan L	-12.110	Pump off 2 hrs	-9.230	-8.400
J41/0374	McKenzie M	-2.780		-2.820	-2.750
J41/0392	Kane B	-8.900		-8.430	-7.915
J41/0582	Taylor M	-13.185		-13.125	-13.100
J41/0713	Eckhold GJ	-21.220	Pump off 45 mins	Pump running	-16.100
J41/0715	Holcim	-10.185		-10.130	nd
J42/0001	Robertson	-18.095		-17.870	-18.100
J42/0003	McClea D	-5.120		-4.970	-5.05
J42/0006	McLean J	-9.430		-9.355	-9.3
J42/0031	Dalgety J & B	-8.085		-8.000	-8.115
J42/0076	Robins (ex Van Zyl)	-24.250		-25.410	-24.3
J42/0084	Lim D	-4.270		-4.140	-4.235
J42/0113	Robbins A (ex Ormandy G)	-7.630		-7.195	-6.78
J42/0123	Lowe B (ex Wycherley S & W)	-17.660	Pump off 3 hrs	-19.500	-16.51

Table A. 2 Location and elevation of monitoring bores and benchmark locations on local creeks

Well number / benchmark	WL 4-2-08 or bed level	Owner	Easting	Northing	Height
J41/0047	-4.060	Young F	2345132.071	5563342.178	45.16
J41/0008	-8.570	Reggie Joe	2344761.199	5561949.512	43.28
J41/0015	-2.080	Fukuhara	2346013.985	5562837.742	32.84
J41/0019	-3.625	De Rews P	2346723.207	5563312.653	32.58
J41/0166	-4.950	Wallace D	2342787.706	5564181.403	25.89
J41/0177	-9.440	Webster J	2344579.534	5561509.154	44.01
J41/0188	-12.080	Isbister E	2340606.928	5563018.195	44.3
J41/0198	nd	Isbister	2342390.634	5563098.334	31.33
J41/0219	-6.870	Arney	2343503.929	5560937.304	30.56
J41/0244	-5.875	Cooper L	2345459.742	5560560.313	33.19
J41/0247	-9.230	Leaman D & S	2346991.125	5560251.454	16.29
J41/0249	-8.400	Morgan L	2340874.242	5562470.479	31.29
J41/0374	-2.750	McKenzie M	2346469.055	5565985.919	51.79
J41/0392	-7.915	Kane B	2345501.377	5567901.48	89.16
J41/0582	-13.100	Taylor M	2346054.957	5565129.96	63.93
J41/0713	-16.100	ECKHOLD G J	2346012.34	5569938.85	94.43
J41/0715	nd	Holcim	2343826.457	5569093.369	67.36
J42/0001	-18.100	Robertson	2340806.672	5555709.251	57.78
J42/0003	-5.05	McClea D	2342927.032	5555412.303	37.75
J42/0006	-9.3	McLean J	2342433.427	5552562.248	20.31
J42/0031	-8.115	Dalgety J & B	2343516.408	5554181.064	27.56
J42/0076	-24.3	Robins (ex Van Zyl)	2344985.808	5557133.862	28.01
J42/0084	-4.235	Lim D	2345741.709	5559081.506	16.64
J42/0113	-6.78	Robbins A (ex Ormandy G)	2344830.665	5556528.969	6.1
J42/0123	-16.51	Lowe B (ex Wycherley S & W)	2342781.128	5559398.074	26.71
Awamoa Creek1	1.48		2347165.202	5563317.186	21.06
Awamoa Creek2	3.82		2347271.833	5565164.058	36.93
Awamoa Creek3	2.50		2346049.784	5567045.794	66
Oamaru Creek1	3.35		2349861.577	5565616.097	9.68
Oamaru Creek2	3.60		2348859.721	5565923.077	18.07
Oamaru Creek3	4.15		2348501.355	5568643.087	60.82
Oamaru Creek4	2.65		2347012.474	5567689.741	68.07
Waiareka Creek7	0.20		2343660.768	5560138.565	5.38
Waiareka1	4.72		2342869.056	5571240.147	44.86
Waiareka2	4.25		2343067.437	5569562.497	39.82
Waiareka3	1.71		2342685.937	5567481.899	29.73
Waiareka4	1.60		2342504.371	5565624.786	25.51
Waiareka5	1.62		2342140.621	5564161.008	20.75
Waiareka6 (Nth end of Bridge)			2342377.233	5561825.297	15.5
Waiareka6 (Sth end of bridge)	nd***		2342357.232	5561807.94	15.31

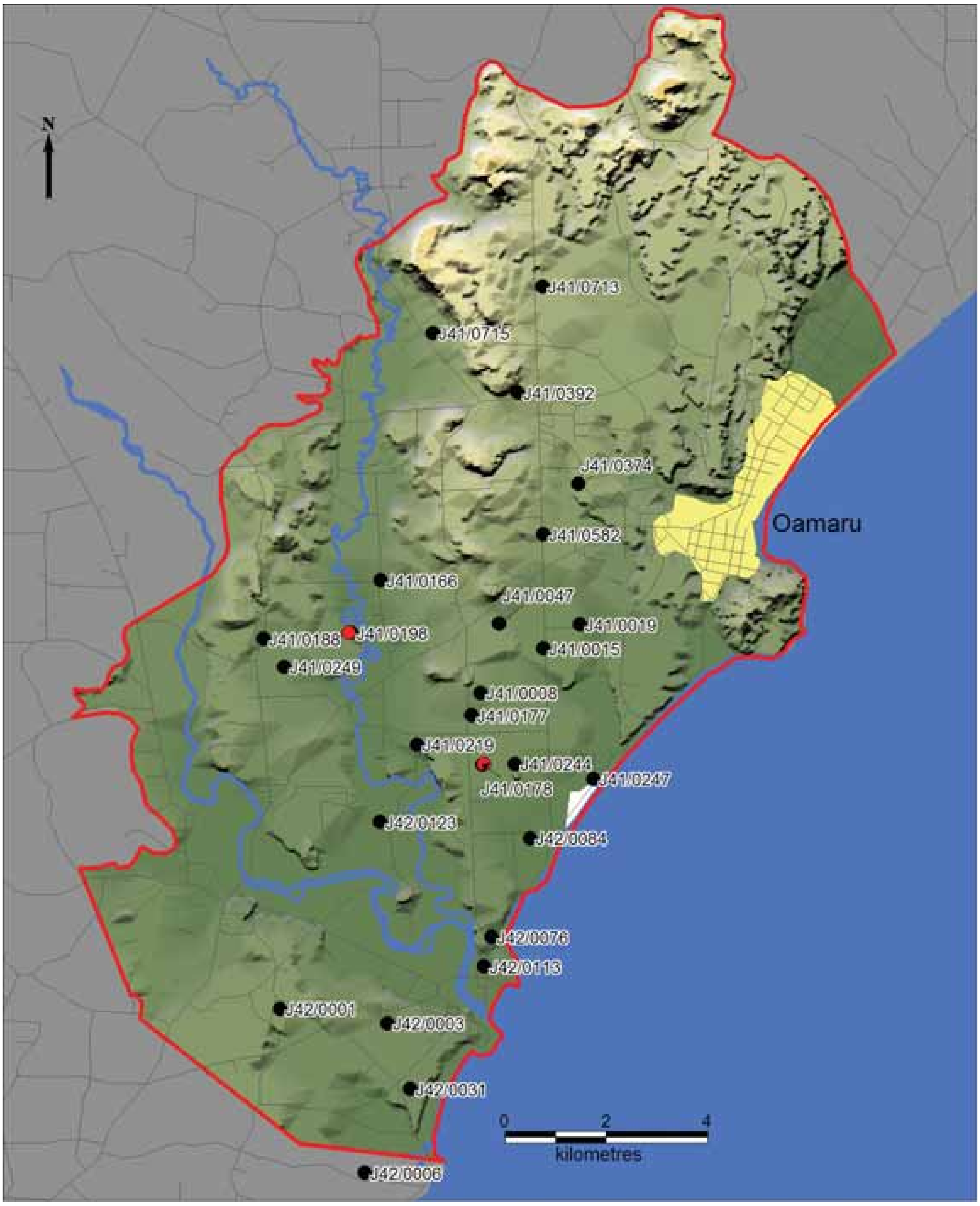


Figure A. 1 Location of monitored bores for the North Otago Volcanic Aquifer study

Appendix B: Rainfall recharge modelling

(Prepared by Mark Gyopari, Phreatos Ltd)

1. Direct recharge (rainfall infiltration)

The principal recharge source to the Aquifer system occurs through rainfall infiltration. Estimation of the quantity of water migrating through the soil zone to the water table is often made using a soil moisture balance approach. Soil moisture balance methods are based on the assumption that the soil becomes free-draining when the moisture content reaches a threshold value (field capacity) excess water becomes groundwater recharge. Soil moisture balance calculations determine soil moisture conditions on a daily basis and estimate recharge when the field capacity is exceeded.

Rushton (et al, 2006) have recently described a new soil moisture balance methodology which is appropriate for use in North Otago. This model estimates recharge using a daily soil moisture balance based on a single soil store. Actual evapotranspiration is calculated in terms of the readily and total available water - parameters which depend on soil properties and the effective depth of the roots. The model introduces a new concept; near surface soil storage, which allows some infiltration to be held near to the soil surface to enable continuing potential evapotranspiration on days following heavy rainfall even though the soil is dry at depth.

Base data required for soil moisture balance models are daily climatic data (rainfall and potential evapotranspiration), spatial distribution of soil types and related soil properties (field capacity and wilting point), and vegetation cover (crop rooting depth).

The soil moisture balance algorithm consists of a two-stage process: calculation of near surface storage, followed by calculation of the moisture balance in the subsurface soil profile. The near surface soil storage reservoir provides moisture to the soil profile after all near surface outputs have been accounted for. If there is no moisture deficit in the soil profile, recharge to groundwater occurs.

The Rushton model has also been adapted for this study to take into account runoff using a USDA Soil Conservation Service (SCS) runoff curve number model. The SCS runoff model is described in Rawls (et al, 1992).

2. Soil moisture balance modelling spreadsheet

Spreadsheet calculations for soil moisture balance have been set up to follow the algorithms given in the appendix of Rushton (et al, 2006). The calculation involves four steps:

1. Calculation of runoff using the USDA SCS runoff method.

2. Calculation of infiltration to the soil zone (*In*), and near surface soil storage for the end of the current day (*SOILSTOR*). Infiltration (*In*) as specified by the Rushton algorithms is infiltration (Rainfall-Runoff) and *SOILSTOR* from the previous day.

3. Estimation of actual evapotranspiration (AET). PET is derived by the Priestly-Taylor (1972) equation. A crop coefficient is not applied since the crop is assumed to be pasture. Most pastures in New Zealand behave like the reference crop for most of the year (Scotter and Heng, 2003).

4. Calculation of soil moisture deficit and groundwater recharge. Recharge occurs only when the 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.

The steps outlined above partition soil moisture between near surface soil storage for the following day, AET, and the soil moisture deficit/reservoir respectively. In addition to rainfall and PET, the soil moisture balance model requires four different input parameters to calculate daily soil moisture deficit. These parameters are described below.

SCS Curve Number: A curve number needs to be estimated for each soil, which is used to calculate maximum soil retention of runoff (this is the same method used for the HortResearch SPASMO model). Lower curve numbers result in higher the soil retention thresholds, which induce less runoff. Pasture in good condition on free draining soil has a low curve number (40). 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). The North Otago model assumes that slope is always less than 5 degrees, and soil moisture is not considered.

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

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 ET). For NZ conditions *p* should be around 0.4 to 0.6, typically 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, 2006).

3. Recharge model inputs

The inputs to the soil moisture balance model are rainfall, potential evapotranspiration and the soil properties described above for each distinct soil zone present in the study area.

Rainfall

The accuracy of recharge modelling is heavily dependent upon the quantification of daily rainfall and characterisation of the spatial rainfall pattern across the model area.

Mean annual rainfall in North Otago lies in the range of 500-700mm, with stations in the lower Waitaki Catchment and coastal lowlands near Oamaru recording between 508-542mm (ORC, 2000). Examination of rainfall isohyets for the area shows there to be no significant rainfall gradient across the project area.

ORC have monitored rainfall at Grandview since 1987. This site is located between Oamaru and the Kakanui River mouth and about 2km inland from the coast in the Deborah groundwater zone (Figure B. 1). NIWA have also operated several rainfall sites in the area, although there is only one which is currently active just north of the project area near Windsor (I50087, 8 years of data). Discontinued NIWA site I50085 is in the north part of the project area near Enfield and has a 22-year record for the period 1977 - 1999.

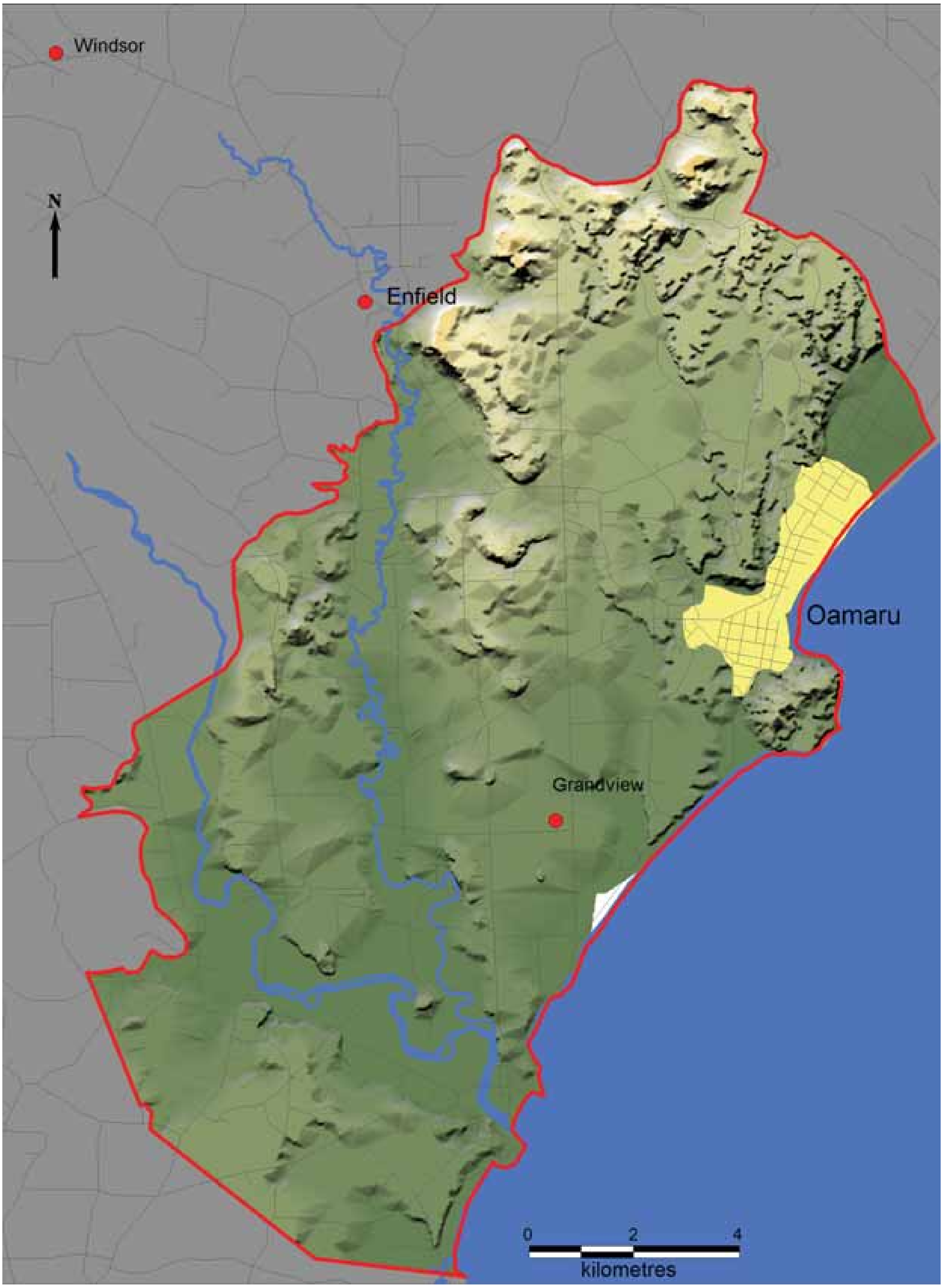


Figure B. 1 Location of rainfall stations referred to in discussion on climate data

The ORC Grandview and NIWA Enfield sites therefore provide reasonably long-term rainfall records for the northern and southern parts of the Waiareka Catchment within the model area.

Table B. 1 provides a summary of the mean annual and monthly statistics for these sites. The dataset for both sites provide a closely comparable mean annual rainfall of about 560-570mm. The monthly means are similar and any differences are not regarded to be significant because the sites provide data for different periods. The conclusion drawn from this comparison, and through examination of the annual isohyets pattern, is that there is an insignificant variation in rainfall across the model area. The ORC Grandview record has therefore been used for recharge modelling.

Table B. 1 Mean monthly and annual rainfall statistics for long-term data for stations in the Waiareka Catchment

	ORC at Grandview 1987 - present	**NIWA I50085 at Enfield 1977-1999**
Jan	56	48
Feb	45	50
Mar	40	58
Apr	44	41
May	37	43
Jun	40	44
Jul	40	53
Aug	45	38
Sep	41	34
Oct	44	43
Nov	52	43
Dec	66	67
Annual	***556***	***570***

Potential evapotranspiration

Reference crop (pasture) potential evapotranspiration (PET) has been estimated using the Priestly-Taylor (1972) method. The PET data were derived from NIWA climate stations at Windsor on the northern edge of the project area; however, data is only available for this site from November 2000 to present. Since the soil moisture balance model was run from July 1997 to present, earlier PET data were derived from the NIWA station at Palmerston, some 50km to the south. Although the Palmerston site is some distance away from the project area, it experiences similar climatic conditions and comparison of the PET data for both sites shows a high degree of consistency as shown in Figure B. 2. The data show peak summer potential evapotranspiration rates of 5-6mm/day for the reference crop (pasture).

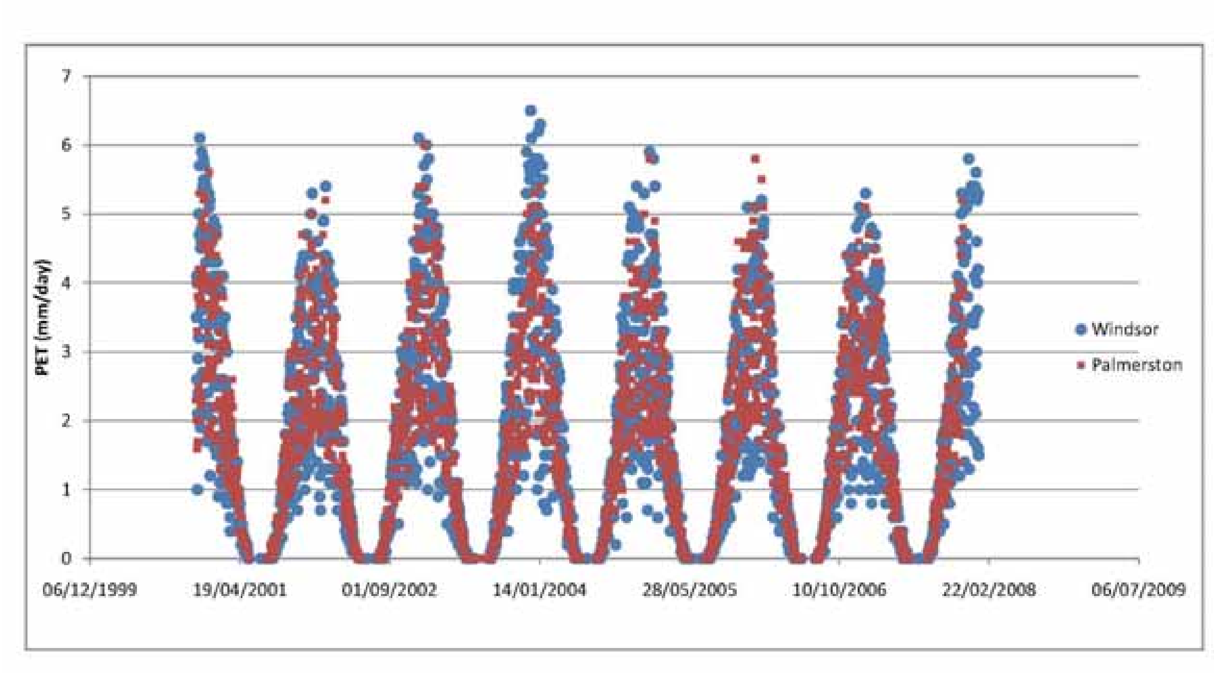


Figure B. 2 PET for Windsor and Palmerston

Soil properties

Soil moisture balance modelling requires knowledge of the spatial distribution of principal soil types and a knowledge of their physical properties in terms of water storage capacities. For this study, Landcare Research was commissioned to provide an evaluation of the soils within the project area based upon the New Zealand Soils Database. This work entailed the following process in order to quantify field capacity (FC), wilting point (WP), profile available water (PAW) and profile readily available water (PRAW):

- Matching mapped soil series with the same or similar soil series within the national soils database.
- Determining the average FC and WP as percentages for these soil classes to 1 m depth.
- Multiplying the percentage FC and WP values by the estimated rooting depth of the soils, for soils with rooting depth less than 1 m. (Moderately deep soils were estimated to have and average rooting depth of 0.7 m, shallow soils 0.45 m, stony soils 0.35 m and very stony soils 0.2 m.). This provided an estimate of FC and WP in mm for the profile.
- PAW was determined by subtracting WP from FC.
- PRAW was determined by multiplying PAW by a ratio of PRAW/PAW found from the database for similar soils. In the case of shallow and stony soils the ratio was modified according to expert opinion. As soils become shallower, the percentage of PRAW/PAW becomes larger.

Estimation of SCS number proved a more difficult parameter to characterise. The intent of the classification is to help partition rainfall or irrigation into through-flow or runoff. The SCS number may be considered to be derived from a combination of soil permeability and soil water storage in the moist condition (air capacity). The SCS number is not static but varies with antecedent moisture condition and with land use. Soils were rated according to tables in SCS (1967) for land under pasture in a moist antecedent state. The SCS number was increased or decreased according to their relative permeability and air capacity.

Table B. 2 provides a summary of properties assigned to the six dominant soil classes in the study area and Figure B. 4 is a map showing the soil zones.

Table B. 2 Soil properties used in the Rushton soil moisture balance model. Soil zones represent an amalgamation to six predominant types

Zone	FC	WP	Root	Depl Fact	SCS	Fractstor	TAW	RAW	% PPN = Recharge
1	620	360	650	0.35	50	0.9	170	60	14.6
2	220	117	1000	0.45	50	0.9	103	46	22
3	238	105	1000	0.5	60	0.5	133	66	19
4	284	162	1000	0.4	65	0.5	122	49	21
5	92	24	1000	0.6	45	0.5	68	41	28
6	48	12	1000	0.6	40	0.5	36	22	35

Table B. 2 also shows percentage of annual rainfall which becomes groundwater recharge as calculated by the Rushton spreadsheet model. The proportions represent the annual average for the 10-year model period (1997-2008).

The Fractstor parameter was increased during calibration to 0.9 from 0.75 to spread out and slow down recharge events in recognition of the presence of a thick, low permeability unsaturated zone. The hydrographs for monitoring wells in the volcanics indicate that recharge tends to occur only after prolonged rainfall and occurs as a smeared slug over several weeks, rather than as short spikes. The amount of recharge applied to any particular event is less due to greater losses to evapotranspiration; however, the duration over which it is applied is extended as shown by Figure B. 3.

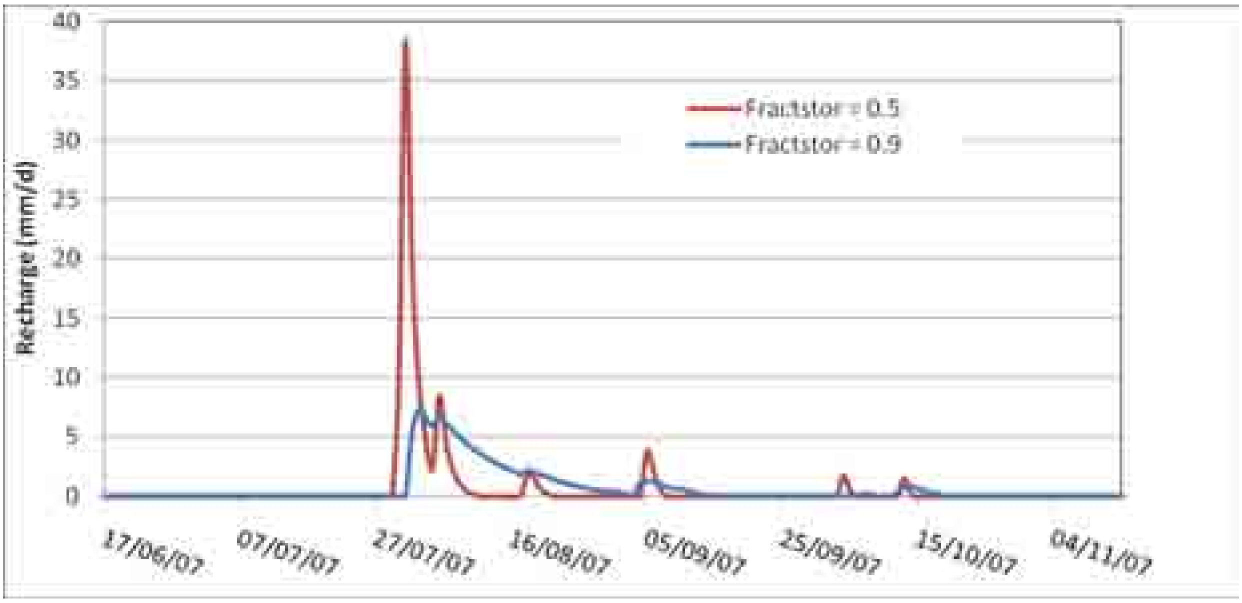


Figure B. 3 Effect of changing Fractstor on recharge application

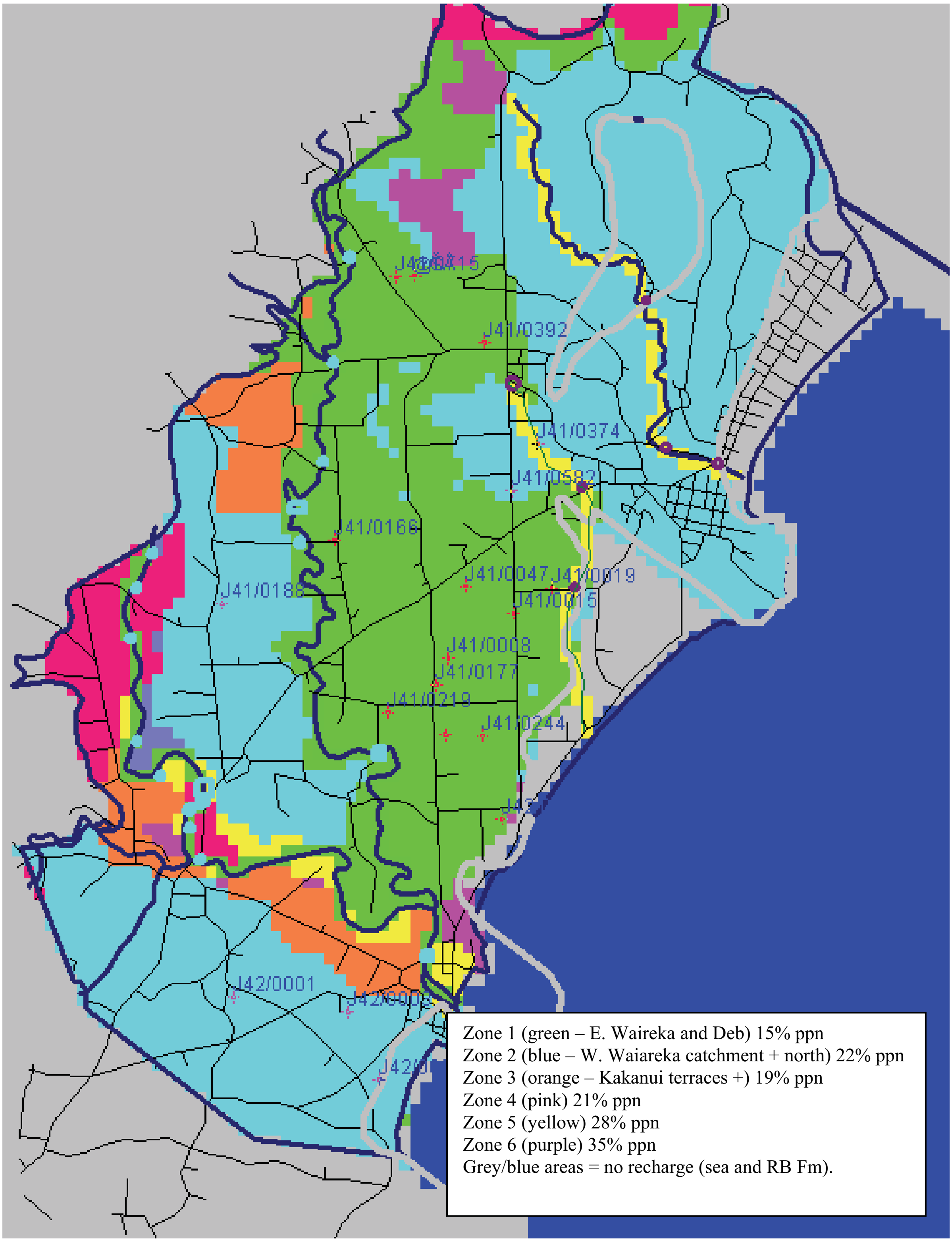


Figure B. 4 Recharge zones based on soil property mapping

4. Recharge model outputs

Calculated recharge inputs for the 10-year model calibration period (1997 – 2008) for the predominant soils zones 1 and 2, which cover the volcanic aquifer outcrop areas, is shown in Figure B.5.

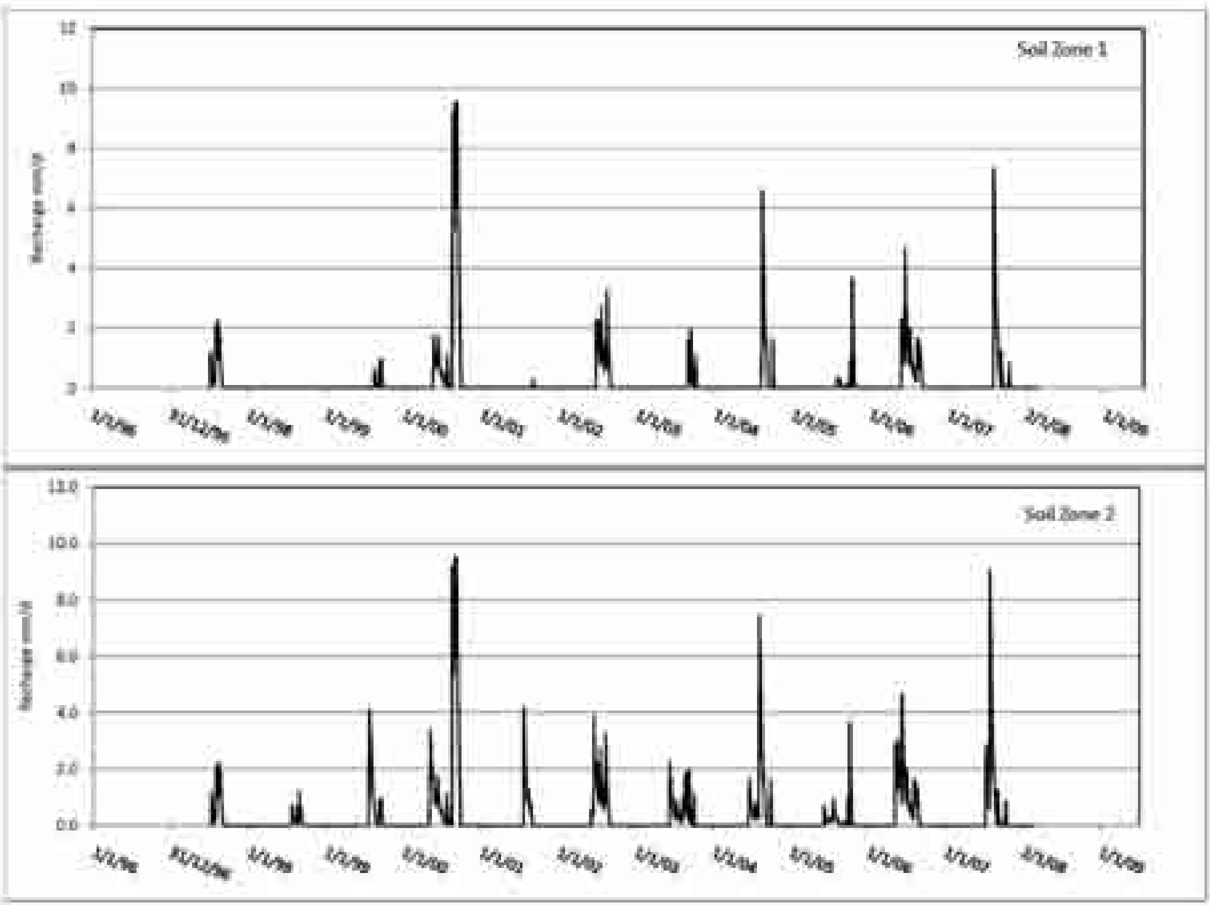


Figure B. 5 Modelled recharge for soil zones 1 and 2 (Deborah and Waiareka volcanics outcrop)

References

Allen R., Pereira LS, Raes D, Smith M. 1998. Crop evapotranspiration: guidelines for computing crop water requirements, Irrigation and Drainage Paper 56. FAO, Rome. Pp.300.

Milne JDG, Clayden B, Singleton PL, Wilson AD. 1995. Soil description handbook. Manaaki Whenua Press, Lincoln, New Zealand. Pp. 157.

Rawls WJ, Ahuja LR, Brakensiek DL, Shirmohammadi A. 1992. Infiltration and soil water movement. In: Maidment DR (ed.), 1992. Handbook of Hydrology. McGraw-Hill, New York.

Rushton KR, Eilers VHM, Carter RC. 2006. Improved soil moisture balance methodology for recharge estimation. Journal of Hydrology 318, Pp. 379-399.

SCS. 1969. National Engineering Handbook, Section 4, Hydrology. Soil Conservation Service (USDA).

Williams JR. 1991. Runoff and water erosion. In: Hanks J, Ritchie J (eds.). Modelling plant and soil systems. Agronomy Monographs No 31, Crop and Science Society of America, Madison, Wisconsin.

Appendix C Consented groundwater takes within the North Otago Volcanic Aquifer

Well number	Consent number	Type	Depth (m)	Easting	Northing	Annual allocation (m^3)	Irrigation area (ha)	Maximum daily quantity (m^3)	Maximum monthly volume (m3)	Use
J42/0140	2000.114	Open pit	10	2345470	5558387	68640	40	286	8580	Irrigation
J41/0214	2001.970	Borehole	11.5	2344584	5560367	16200	15	135	1350	Irrigation
J41/0272	2002.063	Borehole	19.2	2344257	5562021	14400	36		1800	Irrigation
J41/0017	2002.476	Borehole	11.5	2346831	5563527	5000	10	32		Irrigation
J41/0267	2002.530	Open pit	10	2344576	5560820	31449	8		5241	Irrigation
J42/0124	2002.531	Borehole	Unknown	2344966	5559184	31449	19		2995	Irrigation
J42/0118	2002.535	Borehole	84	2344923	5557456	36000	13		4500	Irrigation
J42/0158	2002.667	Borehole	71.3	2341300	5559200	110070	40	604	18345	Stockwater, irrigation
J42/0115	2002.790	Borehole	27	2345200	5556300	56000	22	404	7000	Irrigation
J41/0574	2003.137	Borehole	276	2346000	5569739	435000	140		77760	Irrigation
J41/0595	2003.883	Borehole	43.6	2341400	5561000	71390	11	363	11165	Irrigation
J41/0047	2004.278	Borehole	10.75	2345128	5563335	69840	23.5		5820	Irrigation, horticulture
J41/0043	2004.335	Borehole	7	2346725	5565025	20000	9	86	2500	Irrigation
J41/0008	2004.465	Borehole	20	2344759	5561952	198000	44	768	16500	Irrigation, horticulture
J42/0123	2005.664	Borehole	66.5	2342779	5559408	72000	12		9000	Irrigation
J41/0714	2007.182	Borehole	70	2343824	5569101	120000				Plant supply
J41/0023	95637	Borehole	12.48	2346444	5563728	68000	17		8500	Irrigation
J41/0295	95876	Borehole	50	2345400	5566100	52000	19		6500	Irrigation
J41/0293	95909	Borehole	33	2346250	5565500	71390	11			Irrigation
J41/0048	95938	Borehole	10	2345205	5563735	40000	23.5		5000	Irrigation
J42/0076	96152	Borehole	70.1	2344984	5557132	81125	12.5			Irrigation
J41/0249	96170	Borehole	90	2340874	5562476	778800	120			Irrigation
J41/0015	96572	Borehole	36.5	2346009	5562836	12000	4	900	1500	Irrigation
J41/0254	97007	Borehole	18	2344594	5560754	103840	16			Irrigation
J41/0087	97272	Borehole	18	2344695	5561733	168740	26			Irrigation
J42/0126	98433	Borehole	18.8	2344818	5556528	142780	22			Irrigation
J42/0074	98471	Borehole	9.3	2344608	5559810	32450	5			Irrigation

Well number	Consent number	Type	Depth (m)	Easting	Northing	Annual allocation (m^3)	Irrigation area (ha)	Maximum daily quantity (m^3)	Maximum monthly volume (m3)	Use
J42/0084	98500	Borehole	3.6	2345740	5559082	14400	3	8	1800	Irrigation
J41/0011	98539	Borehole	11.7	2344890	5562612	64900	10			Irrigation
J41/0378	98549	Borehole	41	2346100	5564600	60480	30	252	7560	Irrigation
J41/0380	98560	Borehole	84	2344300	5563000	149270	23	432		Irrigation
J42/0077	99044	Borehole	Unknown	2345660	5559448	14400	13.7	90	1800	Irrigation
J41/0388	99153	Borehole	53	2346000	5565000	29032	16	173	3629	Irrigation
J41/0713	99157	Borehole	75.5	2346014	5569943	188210	29			Stockwater, irrigation
J41/0390	99180	Borehole	103.5	2346042	5569418	97350	15	864		Irrigation
J41/0392	99240	Borehole	60	2345501	5567908	77760	18	324	9720	Irrigation
J41/0399	99363	Borehole	126	2345120	5569220	129800	20			Dewatering
J41/0239	99597	Open pit	6	2344350	5560917	66240	30	276	8280	Irrigation
J41/0084	99628	Open pit	5.5	2346073	5561391	268872	55	1120	33609	Irrigation
J41/0367	99640	Borehole	101.8	2341800	5565800	259600	40	2376		Irrigation
J41/0085	99656	Borehole	14.6	2345276	5561411	48000	18	200	6000	Irrigation
			Total annual allocation =			**4,374,877**				

Note: The Annual Allocation volume was determined through a series of steps depending on the specific resource consent conditions. Firstly, if an annual limit was stated within consent conditions it was used. If not the lesser of; the monthly limit multiplied by 8 (irrigation season) or the irrigated area multiplied by an annual required volume was used. The annual required volume is based on the report Irrigation Requirements for North Otago by Lincoln Environmental 2003 by using a soil PAW of 100 mm the report gives 6,490 m^3/ha. This method is currently used to set annual limits on new or replacement consents.

Appendix D Numerical modelling

(prepared by Mark Gyopari, Phreatos Ltd)

1. Model Design

1.1 Model objectives

The objectives for the Aquifer model are as follows:

- Establish a transient-flow numerical model for the Aquifer based upon the conceptualised groundwater system and calibrated under transient system stresses.

- Determine the mass-balance for the Aquifer system including temporal variation in aquifer fluxes and levels under a range of climatic conditions.

- Simulate the Aquifer's response to difference abstraction scenarios as a basis for developing allocation and aquifer management policy.

1.2 Model code selection

The USGS finite difference numerical code MODFLOW (Harbaugh et al, 2000) was used to model the Aquifer. The Groundwater Vistas data processing interface software (Environmental Simulations Inc, 2007) was used to build the model, assist with the calibration process including parameter optimisation, and process the output data.

1.3 Grid design

MODFLOW uses a finite difference solution method that requires the use of a rectilinear, block-centered multi-layered spatial grid. The NOVA model was built within a grid domain of 27 x 29km with a uniform cell size of $200m^2$ over the on-shore area of aquifer. The grid has been continued about 12km offshore to enable the simulation of the submarine extension of the groundwater system. The grid spacing was increased progressively to 750m over the offshore aquifer area.

The grid has not been rotated since the principal regional groundwater flow vector is to the east (Figure 4.1)[4]. The model has been constructed using four layers – the rationale behind the layer structure is discussed below.

The active model domain is delineated by the basal contact of the Waiareka or Deborah Aquifers with underlying formations or major structures. Figure D.1 shows the active model area and grid design.

[4] Figure references are provided in two forms; Figure 4.1 refers to a figures contained in the main report and Figure D.1 refers to a figure contained in this Appendix D.

1.4 Conceptual hydrogeology and numerical adaptation

The relatively simple groundwater flow pattern (Figure 4.1) and aquifer test data suggest that the volcanic, carbonate, siltstone and basalt intrusive sequence within the study area behaves as a single hydraulically connected entity. Development of secondary permeability and porosity as a result of fracturing and solution processes is responsible for the creation of the hydraulic continuum, albeit with a high degree of heterogeneity.

The apparently complicated structure shown by the geological map (Figures 2.2 and 2.3) does not appear to disrupt groundwater flow patterns and individual features in the model area are not regarded to represent significant internal flow boundaries. Considerable heterogeneity does, however, exist at a local due to the presence of complex geological structures, lithological changes and variation in the development of secondary permeability and porosity.

Regional-scale modeling of the groundwater system is reliant upon a representation of the large-scale (or bulk) hydraulic nature of the aquifer system and does not need to consider the complexities present at a local scale. In reality, it would be impossible to characterise local scale heterogeneities without embarking upon a lengthy and intensive field investigation programme.

The approach adopted in the development of the numerical model has therefore been to assume a continuous unconfined aquifer system (becoming confined with depth), with spatially variable hydraulic properties controlled principally by the degree of secondary permeability and porosity development – a function of lithology and/or structural influences. The NOVA model outputs show that the regional-scale representation of the aquifer is a valid and accurate approach for the analysis of the North Otago groundwater system.

Outer model boundaries

The active model domain is delineated by the basal contact of the Waiareka or Deborah volcanic with underlying low permeability formations or major structures. Most of the western model boundary represents the basal contact between the Waiareka Volcanic Formation and the underlying Raki Siltstone and Tapui Glauconitic Sandstone along the Kakanui valley. The northern boundary is delineated by the Teanaraki Fault or the contact with the underlying low permeability formations. The southern boundary follows a flow line perpendicular to the coast from the southern end of All Day Bay to the inland contact between the volcanics and underlying formations.

The offshore boundaries follow flow lines perpendicular to the shoreline to an arbitrary point about 12km offshore where it is believed the volcanics formation grade distally into a finer-grained marine facies equivalent as shown in the Endeavour 2 oil exploration wells (Wilding and Sweetman, 1971).

Figure D.1 shows the locations of the aquifer boundaries. All external model boundaries are assigned no-flow (impermeable) conditions.

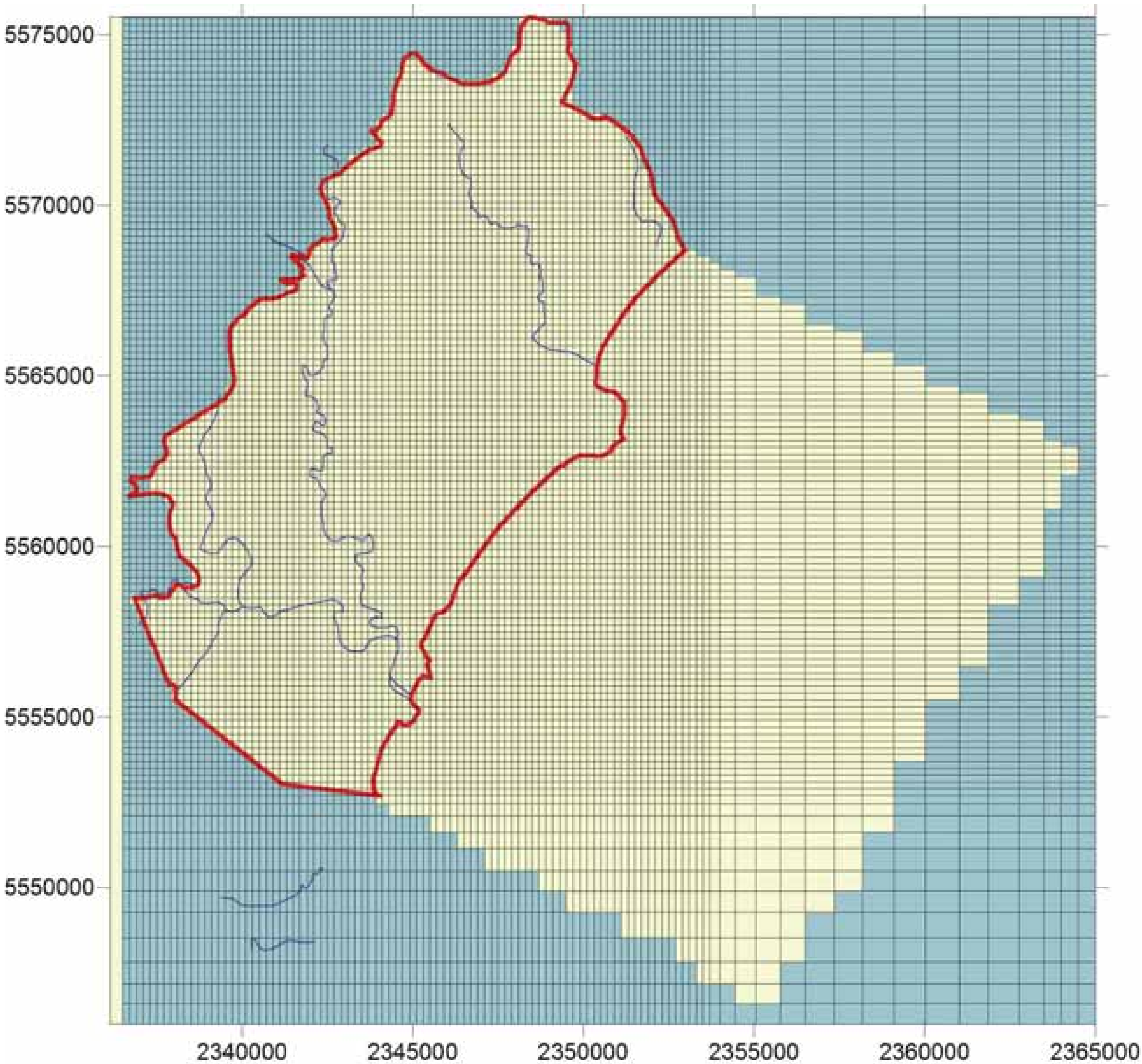


Figure D. 1 Groundwater model grid and model domain. Landward boundary of the Aquifer shown in red

Model base

Geological cross sections produced for the North Otago Groundwater Investigation project (ORC, 1993; Figures 3.6-3.9) interpret the depth of the Waiareka Volcanic Formation to increase from zero near the western margin (where the contact with underlying Raki and Tapui formations is exposed), to over 400m at the coast, and deepening offshore. These sections lines, together with information derived from bore logs, and the perceived basin morphology have been used to determine the base of the volcanics aquifer flow system. Figure D.2 shows the interpreted base of the groundwater system which takes the form of a basin structure.

Model top

The top of the model is represented by the surface topography or sea level. Topographic data were derived from the 1:50,000 topographic map and level interpolated between 10m contour levels.

Layers

Four layers have been used in the model to vertically descretise the thick aquifer sequence. The base of Layer 2 corresponds to the base of the Rifle Butts and Gee Sandstone formations which overlie and confine the Deborah Volcanic Formation in a wedge thickening offshore from the coastline. The offshore extent of the aquitard incorporates the lateral facies change of the volcanics into finer-grained distal marine sediments. Figure D.3 shows an east-west section through the centre of the model (row 73) to illustrate the layer structure of the model.

Layer 1 is assigned a MODFLOW layer type 1 condition (unconfined), whereas all underlying layers are assigned layer type 0 (confined).

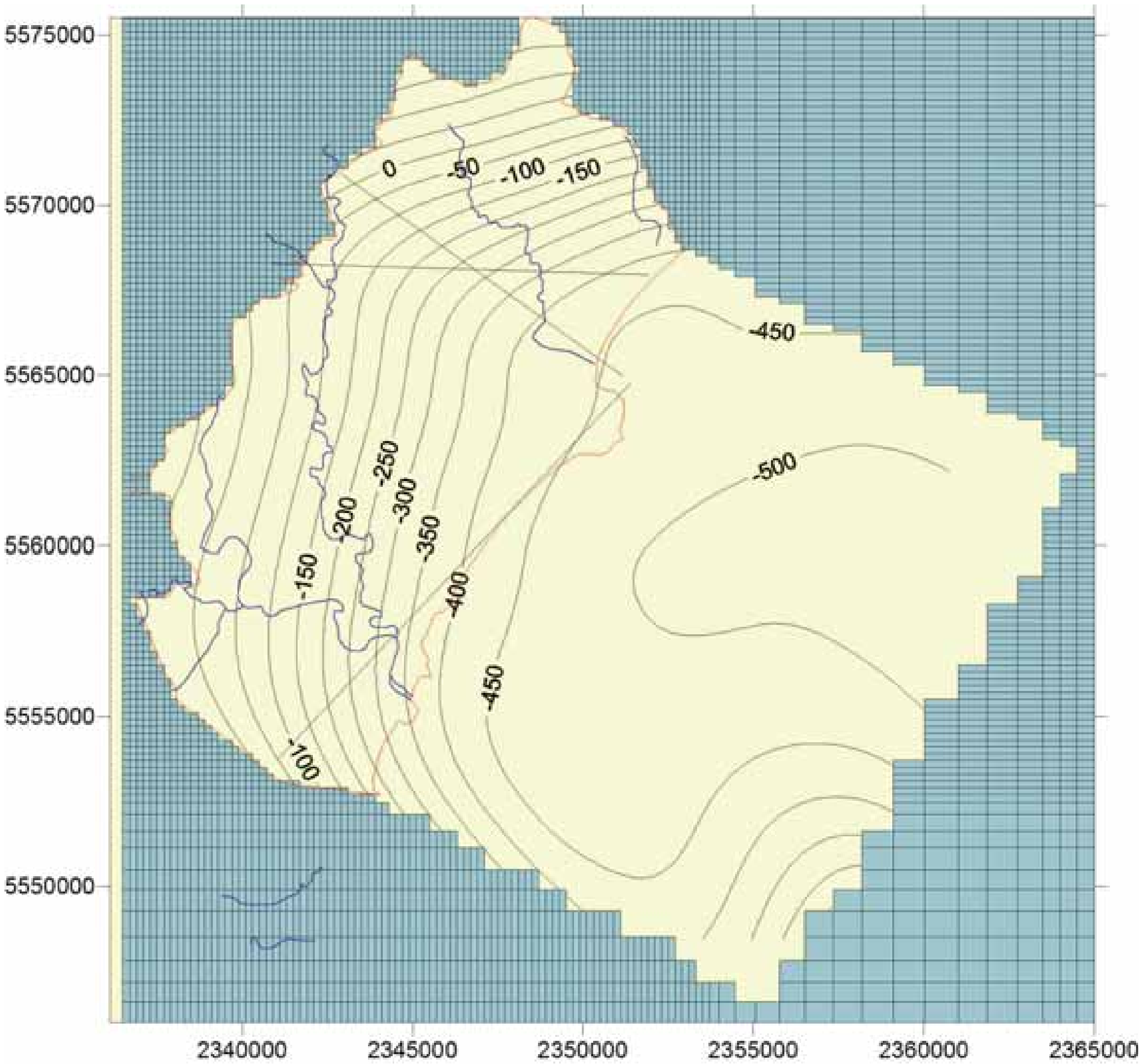


Figure D. 2 Contour map of model base representing interpreted base of Waiareka Volcanic Formation

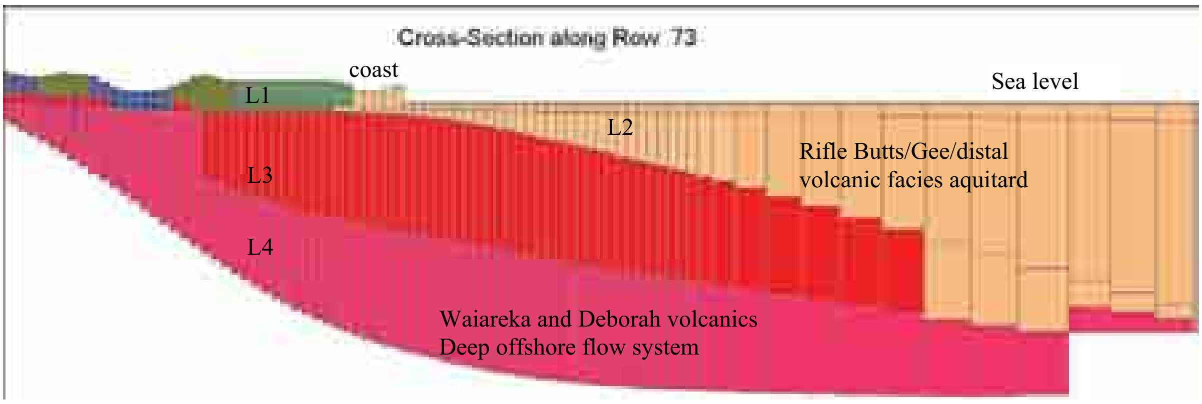


Figure D. 3 East-west section through model showing layer structure showing offshore aquifer extension and transition to less permeable lithology and overlying aquitard

1.5 Boundary conditions

1.5.1 Waiareka Creek and Kakanui River: Modflow stream boundaries (STR1)

The Waiareka Creek and Kakanui River are the dominating groundwater discharge boundaries within the aquifer system. The Waiareka Creek is also an important surface water system which is potentially being adversely affected by groundwater abstractions.
The stream boundaries have been simulated using the MODFLOW STR1 Package. Surveyed data carried out during early 2008 on the Waiareka Creek (Appendix A) were used to assign the stage heights and gradients for this system. Historic survey data were used to define the Kakanui River bed and stage heights.

Figure D.4 shows the Waiareka Creek surveyed bed profile. The stream boundary stage height for the Waiareka Creek has been held constant at survey summer levels throughout the transient model simulations since the depth of water does not change significantly throughout the year except following heavy rainfall.

A bed conductance parameter is required by MODFLOW for the STR boundary type to control the flow transfer rates to and from the underlying aquifer. This parameter is not easily measurable and 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 Waiareka Creek width varies between about 1m and 5m. Streambed vertical hydraulic conductivity was assumed to be about 0.1m/day (the same as the underlying Waiareka Volcanics Formation estimated hydraulic conductivity). This equates to a streambed conductance of about $50m^2$/day per $200m^2$ grid cell. Subsequent calibration modeling required this value to be increased to 80 m^2/day.

1.5.2 Springs: Modflow drain boundaries (DRN)

Major spring-fed streams in the model area are the Oamaru Creek and the Awamoa Creek. Both have relatively minor flow characteristics and have been simulated using the MODFLOW Drain (DRN) boundary conditions. This type of boundary will only permit water to be taken out of the aquifer when the water table is modeled above the base of the drain cell (the spring elevation). When the water table drops below the base of the drain cell, flow into the spring ceases. Flow from the aquifer to the drain cells (spring flow) is controlled by the value used for the drain bed conductance and the drain bed elevation. The drain bed elevations were derived from 2008 survey (Appendix A). Bed conductance values were obtained through a trial and error process during calibration resulting in a value of $100m^2$/d.

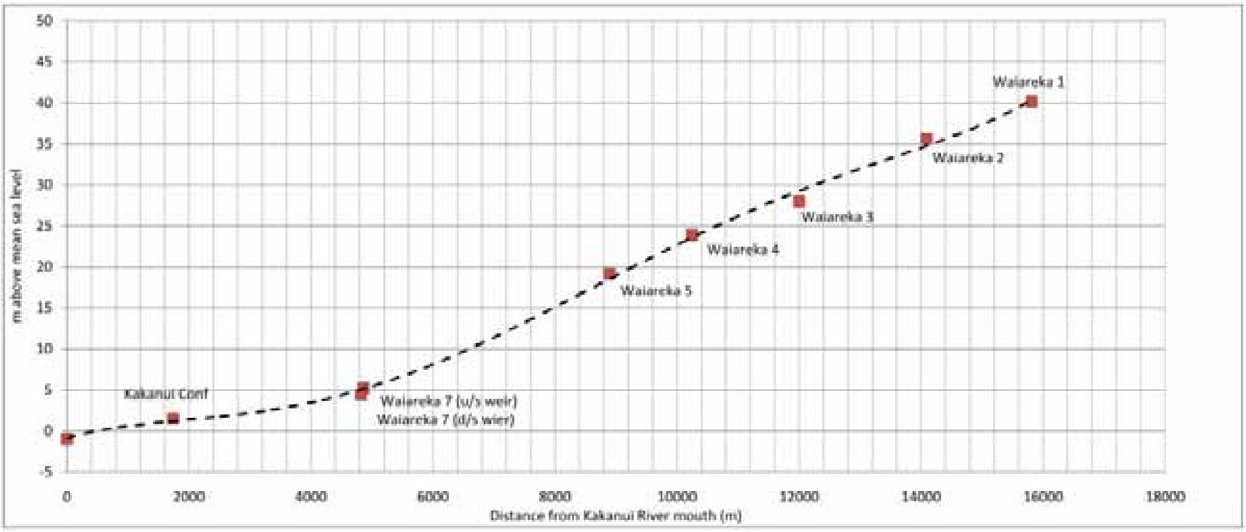


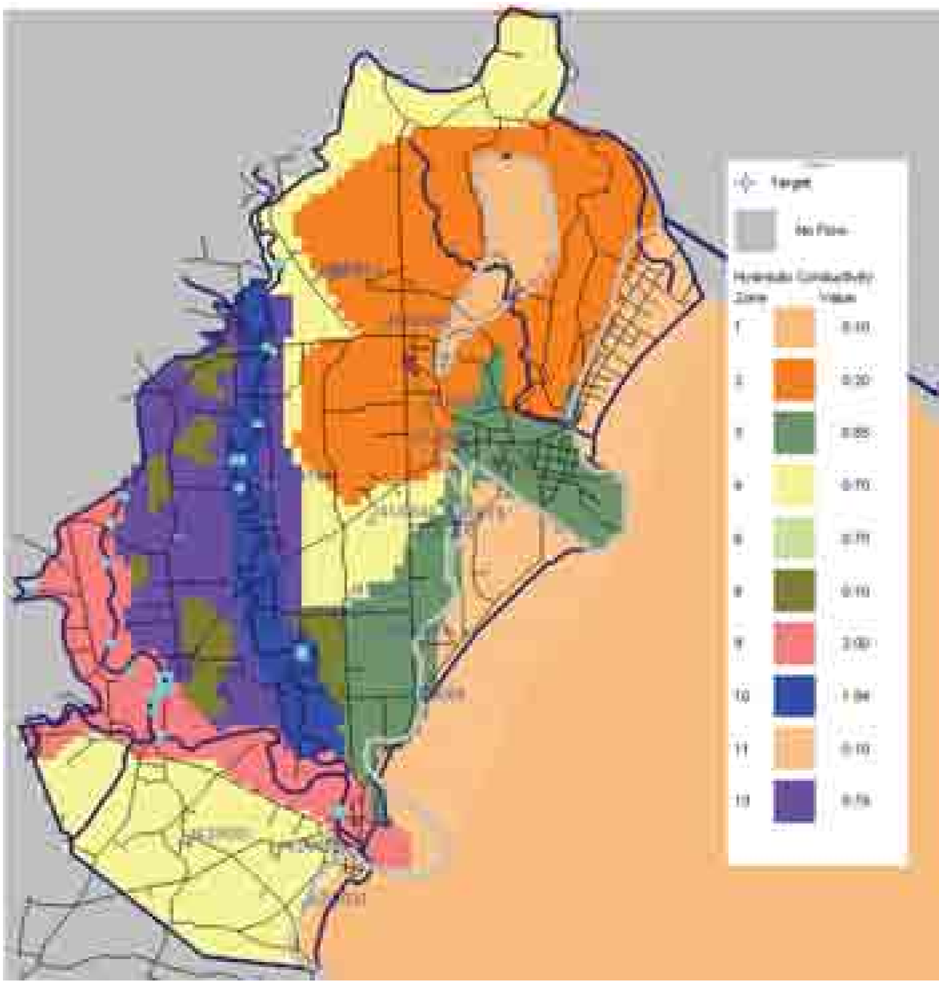
Figure D. 4 Waiareka Creek bed profile from near Enfield (Waiareka 1) to the confluence with the Kakanui River and Kakanui Mouth

1.6 Aquifer properties

The hydraulic properties of the volcanic aquifers are discussed in detail in Section 3.4. Transmissivity values have been derived from assessment of reliable pumping tests and re-analysis of the data (Table 4.1). The transmissivity values in the range of 15-80m^2/day suggest low hydraulic conductivity values, particularly since the pumping tests are likely to provide values biased towards more productive areas. The bulk hydraulic conductivity has therefore been derived through the calibration process, but on the basis of the available test data is estimated to be in the range of 0.5-2m/day.

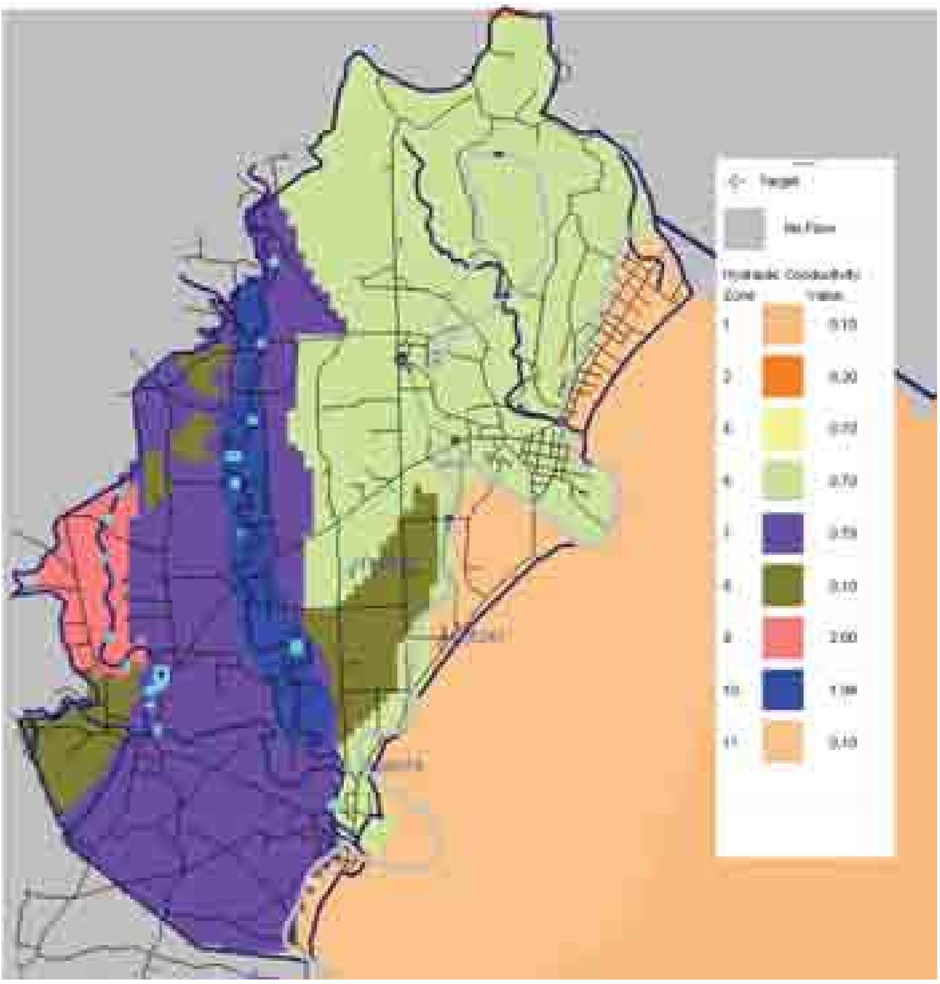
Figure D.5 shows the hydraulic conductivity zonation developed using the conceptual model for the groundwater system, and subsequently refined during the model calibration process. The zonation in Layers 1 and 2 represent the outcrop geology comprising the Waiareka and Deborah volcanics, McDonald and Totara limestones, Rifle Butts Formation, basalt intrusive and the Kakanui Alluvium.

Many of the zones representing the volcanics aquifers have very similar hydraulic conductivity values (0.7-0.9m/day) and are a product of the calibration process. The limestone/carbonate sequences were assigned significantly lower hydraulic conductivity values on the basis of their field properties and poor yielding nature.

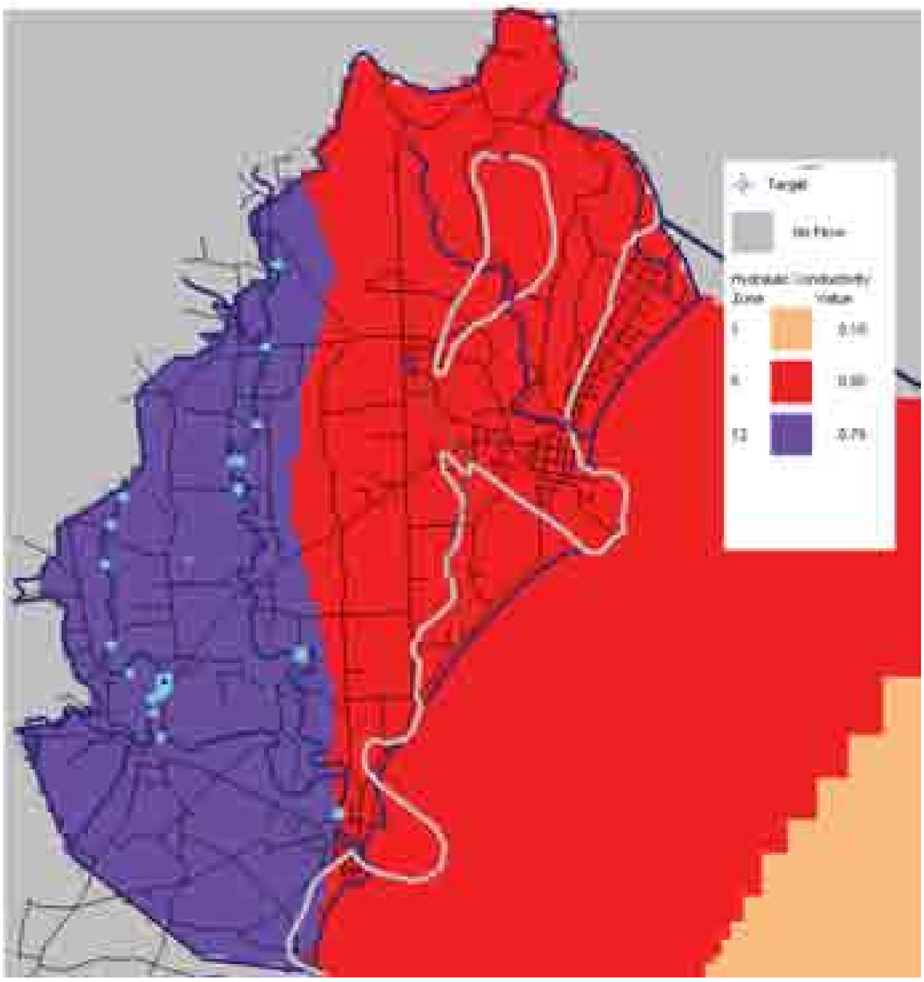


Layer 1 (Kx,y)

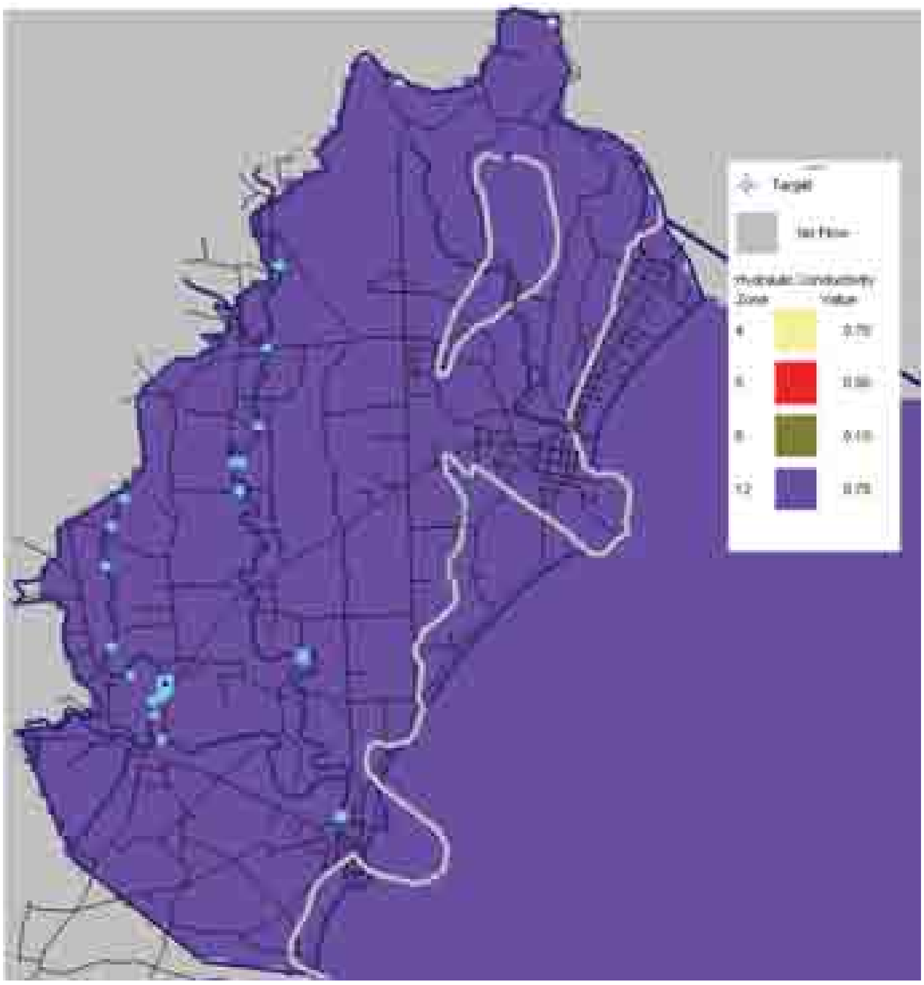
Figure D. 5 Calibrated hydraulic conductivity zones for Layers 1 to 4 (L1 – L4)


Target
No Flow
Hydraulic Conductivity
Zone Value
1 0.10
2 0.20
9 2.00
11 0.10

Layer 2 (Kx,y)



Layer 3 (Kx,y)



Layer 4 (Kx,y)

1.7 Rainfall recharge modelling

The principal recharge source to the Aquifer system occurs through rainfall infiltration. Estimation of the quantity of water migrating through the soil zone to the water table has been modelled using a daily soil moisture balance method. Appendix B provides a description of the methodology for calculating recharge. The recharge model provides average annual recharge values of between 15% and 22% of average rainfall. Section 4.3 and Appendix B provide further discussion of the rainfall recharge dynamics for the Waiareka Catchment.

1.8 Groundwater abstraction

Over 4.7M m^3/year, or 31,400m^3/day, of groundwater has been allocated from the North Otago Volcanics Aquifer system. The allocation to some 40 consent holders is almost entirely seasonal, being for irrigation use. Table D.1 lists the current groundwater consents in the project area, which includes three abstractions from the Kakanui Alluvium.

Annual water meter readings have been undertaken by ORC since 2006. Reliable abstraction data is available for some of the consented wells for the 2006-2007 irrigation season only. The data is, however, incomplete due to the high incidence of non-functioning water meters and an inconsistency in annual reading scheduling (about one third of the readings are unreliable). The data, however, do help to provide some indication of the actual amount of water used as a proportion of total allocation. The range in the percentage of use for 2006-07 was 10-40% of the annual allocation, with a mean use of 15% annual allocation. It is difficult, on the basis of the observed variability for 2006-07, to predict abstraction rates for any individual well unless water meter data are available.

Clearly, there remains uncertainty regarding the actual amount of water used each year. For the purposes of model calibration, it has been assumed that 30% of the annual allocation is used every year over a 150 day irrigation season commencing at the beginning of each year.

Table D.1 Consented groundwater takes in the North Otago Volcanic Aquifer and Kakanui Alluvium

Well no	Grid east	Grid north	Total annual allocation m^3	Consent max. daily abstraction 150-day season	30% max daily abstraction (150-day)	Import group
J42/0015	2340015	5558285	65884	439	132	3 - Kakanui Alluv +
J41/0017	2346831	5563527	5000	33	10	1 - Deborah
J41/0085	2345276	5561411	48000	320	96	1 - Deborah
J41/0254	2344594	5560754	103840	692	208	1 - Deborah
J41/0267	2344576	5560820	31449	210	63	1 - Deborah
J41/0293	2346250	5565500	71390	476	143	1 - Deborah
J41/0295	2345400	5566100	52000	347	104	1 - Deborah
J41/0378	2346100	5564600	60480	403	121	1 - Deborah
J41/0380	2344300	5563000	149270	995	299	1 - Deborah
J42/0074	2344608	5559810	32450	216	65	1 - Deborah
J42/0076	2344984	5557132	81125	541	162	1 - Deborah
J42/0084	2345740	5559082	14400	96	29	1 - Deborah
J42/0118	2344923	5557456	36000	240	72	1 - Deborah
J42/0124	2344966	5559184	31449	210	63	1 - Deborah
J42/0140	2345470	5558387	68640	458	137	1 - Deborah
J42/0058	2338704	5559249	318010	2120	636	3 - Kakanui Alluv +
J42/0115	2345200	5556300	56000	373	112	3 - Kakanui Alluv +
J41/0399	2345120	5569220	129800	865	260	2 - Waiareka
J41/0043	2346725	5565025	20000	133	40	1 - Deborah
J41/0574	2346000	5569739	435000	2900	870	1 - Deborah
J41/0008	2344759	5561952	198000	1320	396	2 - Waiareka
J41/0011	2344890	5562612	64900	433	130	2 - Waiareka
J41/0015	2346009	5562836	12000	80	24	2 - Waiareka
J41/0023	2346444	5563728	68000	453	136	2 - Waiareka
J41/0047	2345128	5563335	69840	466	140	2 - Waiareka
J41/0048	2345205	5563735	40000	267	80	2 - Waiareka
J41/0087	2344695	5561733	168740	1125	337	2 - Waiareka
J41/0239	2344350	5560917	66240	442	132	2 - Waiareka
J41/0249	2340874	5562476	778800	5192	1558	2 - Waiareka
J41/0272	2344257	5562021	233640	1558	467	2 - Waiareka
J41/0367	2341800	5565800	259600	1731	519	2 - Waiareka
J41/0388	2346000	5565000	29032	194	58	2 - Waiareka
J41/0390	2346042	5569418	97350	649	195	2 - Waiareka
J41/0392	2345501	5567908	77760	518	156	2 - Waiareka
J41/0714	2343824	5569101	120000	800	240	2 - Waiareka
J42/0123	2342779	5559408	72000	480	144	2 - Waiareka
J42/0126	2344818	5556528	142780	952	286	2 - Waiareka
J42/0158	2341300	5559200	110070	734	220	2 - Waiareka
J41/0214	2344584	5560367	16200	108	32	1 - Deborah
J41/0595	2341400	5561000	71390	476	143	1 - Deborah
J41/0713	2346014	5569943	188210	1255	376	1 - Deborah
J42/0077	2345660	5559448	14400	96	29	1 - Deborah
	Totals:	Volcanics	4,269,245	28,462	8,538	
		Total area	**4,709,139**	**31,394**	**9,418**	
			m^3/year	m^3/day	m^3/day	

The locations of the consented groundwater abstractions are shown in Figure 5.2.

2. Model calibration

2.1 Calibration approach

Model calibration has entailed a two-step process of initial trial steady state calibration followed by a more intensive transient-time calibration procedure.

The steady state calibration has the main purpose of testing the conceptual groundwater model and undertaking an initial parameter sensitivity analysis. It also provides a check on the boundary conditions and water balance estimation.

Upon satisfactory steady state calibration, further calibration of the model under transient stresses has been performed and evaluated against time-varying water level monitoring and river/spring gauging data. The transient calibration has involved an iterative process of manual input parameter adjustment, automated sensitivity analysis, and parameter optimisation using the PEST algorithm.

2.2 Steady-state simulation

When an aquifer is in steady state, the inputs and outputs, and therefore groundwater heads, remain constant. In reality, an aquifer is never in a truly steady state condition and the closest they approach this condition is when heads remain stable over a relatively long period. This condition rarely occurs in the Aquifer which is dominated by erratic recharge pulses and intervening drainage conditions whereby levels steadily decline until the next recharge event (there can be several years between significant recharge events). Steady state calibration is therefore regarded to be a model trial under a random stress condition coincident with the availability of groundwater head data.

Concurrent groundwater level monitoring data for the model area are available for February-March 2008 and this dataset has been used for steady state calibration. Normally, a summer condition would be inappropriate for a steady state calibration since it represents a seasonal extreme. But for reasons discussed earlier, the volcanics system does not display regular seasonal cycles. The bore hydrographs for the Websters and Isbisters wells (Figures 5.3 and 5.4 illustrate the well hydrograph) show that during the 2008 summer there is a continuing long-term drainage condition in the Waiareka Aquifer, and a recharging condition in the Deborah Aquifer.

Steady state calibration has been achieved by manually calibrating the model to head targets measured in 24 wells, and then undertaking a sensitivity analysis before proceeding to a transient calibration and more detailed parameter optimisation modelling. The monitoring wells are distributed across the model domain, concentrated mostly in the shallower levels of the Waiareka and Deborah volcanics.

Aquifer properties developed during the steady state calibration process, and further refined following the transient calibration, are shown in Table D.4. Recharge values derived from the calibration are listed in Table D.2. These represent 16-22% of average annual rainfall and are consistent with the recharge model (Appendix B).

Table D.2 Calibrated steady state recharge values

Recharge zone	Calibrated value mm/d	Calibrated value mm/yr
1	0.25	90
2	0.36	130
3	0.3	110
4	0.3	110
5	0.3	110
6	0.3	110

Abstraction wells were not activated during the steady state calibration due to the difficulty and unrealistic nature of simulating a steady-state abstraction.

The results of the steady state calibration run are shown in Figure D.6 which also contains a summary of calculated heads and residuals along with the calibration statistics. The overall residual mean of the calibration is encouragingly low at -1.23m. Of the twenty-four calibration targets used, only three show a residual error of greater than 5m and seven a residual error of greater than 2m. The highest residual is -10.9m for well J42/0031 located south of the Kakanui River in the High Terrace Gravels area where relatively little is known about the hydrogeology. It is possible that perched aquifers occur in this area within overlying terrace alluvium which would account for the low modeled level.

The standard deviation/range statistic shows how the errors relate to the overall gradient across the model. The average error of 4.7% is also indicative of an apparent good calibration fit.

Figure D.7 shows the modeled head distribution over the model domain for Layer 1. The groundwater divide between the Deborah and Waiareka Aquifer systems, as well as the strong control exerted by the Waiareka Creek discharge zone, are clearly prominent features of the flow system. Comparison to Figure 4.1, constructed using observed data, shows a good agreement with the simulated regional flow pattern.

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

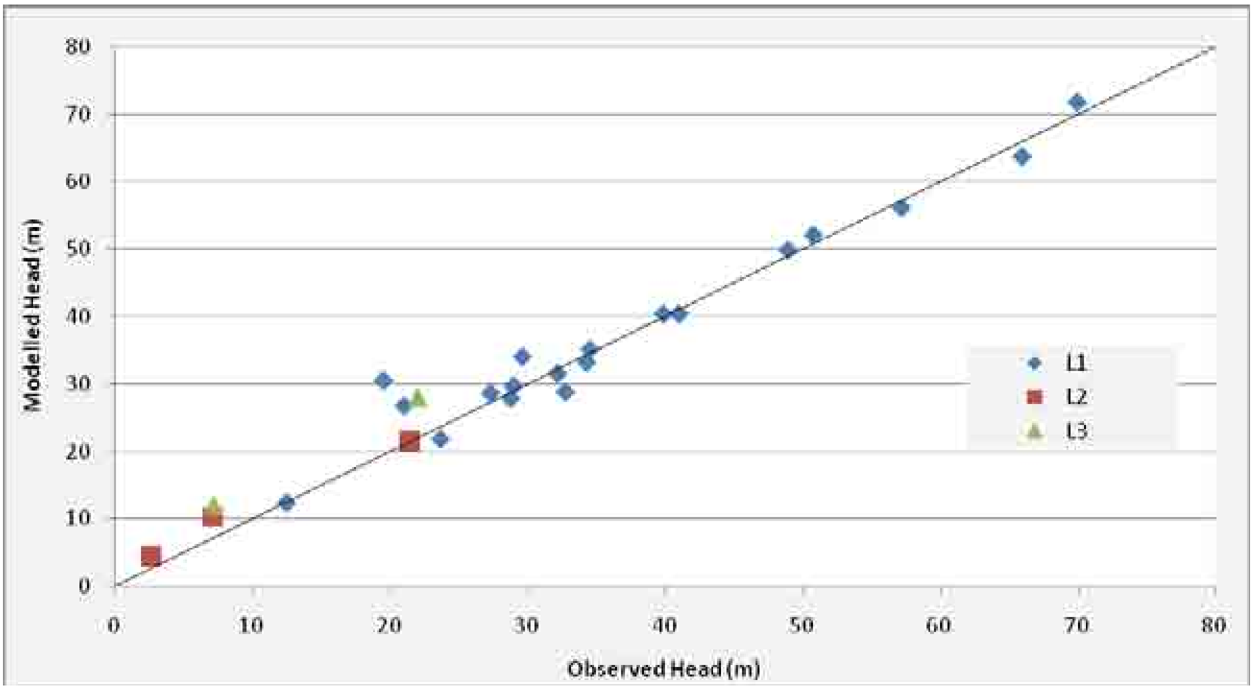


Figure D. 6 Steady state calibration results and associated table

Name	X	Y	Layer	Observed	Computed	Weight	Group	Residual
J41/0047	2345132	5563342	1	41.035	40.3275	1	2	0.707498
J41/0008	2344803	5561997	1	34.57	35.05257	1	2	-0.48257
J41/0015	2346014	5562838	1	29.645	33.94405	1	2	-4.29905
J41/0019	2346752	5563313	1	28.8	27.8371	1	3	0.962896
J41/0166	2342683	5564210	1	21.04	26.72125	1	2	-5.68125
J41/0177	2344580	5561499	1	34.325	33.13553	1	2	1.189472
J41/0188	2340590	5563018	1	32.215	31.52188	1	3	0.693118
J41/0219	2343679	5560991	1	23.705	21.77981	1	2	1.925189
J41/0244	2345437	5560560	1	27.35	28.61013	1	3	-1.26013
J41/0247	2346967	5560251	2	7.115	10.24286	1	3	-3.12786
J41/0249	2340854	5562470	3	22.06	28.05888	1	2	-5.99888
J41/0374	2346469	5565986	1	48.97	49.81571	1	3	-0.84571
J41/0392	2345478	5567878	1	70	71.80527	1	3	-1.80527
J41/0582	2345986	5565110	1	50.805	52.03544	1	3	-1.23044
J41/0715	2343826	5569093	1	57.23	56.08032	1	2	1.149677
J42/0001	2340807	5555690	1	39.91	40.29949	1	2	-0.38949
J42/0003	2342927	5555412	1	32.78	28.79175	1	2	3.988248
J42/0031	2343516	5554163	1	19.56	30.48681	1	2	-10.9268
J42/0076	2344986	5557134	2	2.6	4.42186	1	3	-1.82186
J42/0084	2345804	5559007	1	12.5	12.31399	1	3	0.186009
J42/0123	2342781	5559381	3	7.21	11.9655	1	2	-4.7555
Waia_lsb	2342148	5562962	2	21.51	21.62617	1	1	-0.11617
Websters	2344849	5560574	1	29.014	29.71552	1	1	-0.70152

Calibration statistics	
Residual mean	**-1.265**
Res. std. dev.	**3.1679**
Sum of squares	**279.28**
Abs. res. mean	**2.3549**
Min. residual	**-10.92**
Max. residual	**3.9882**
Range in target values	**67.4**
Std. dev./range	**0.0470**

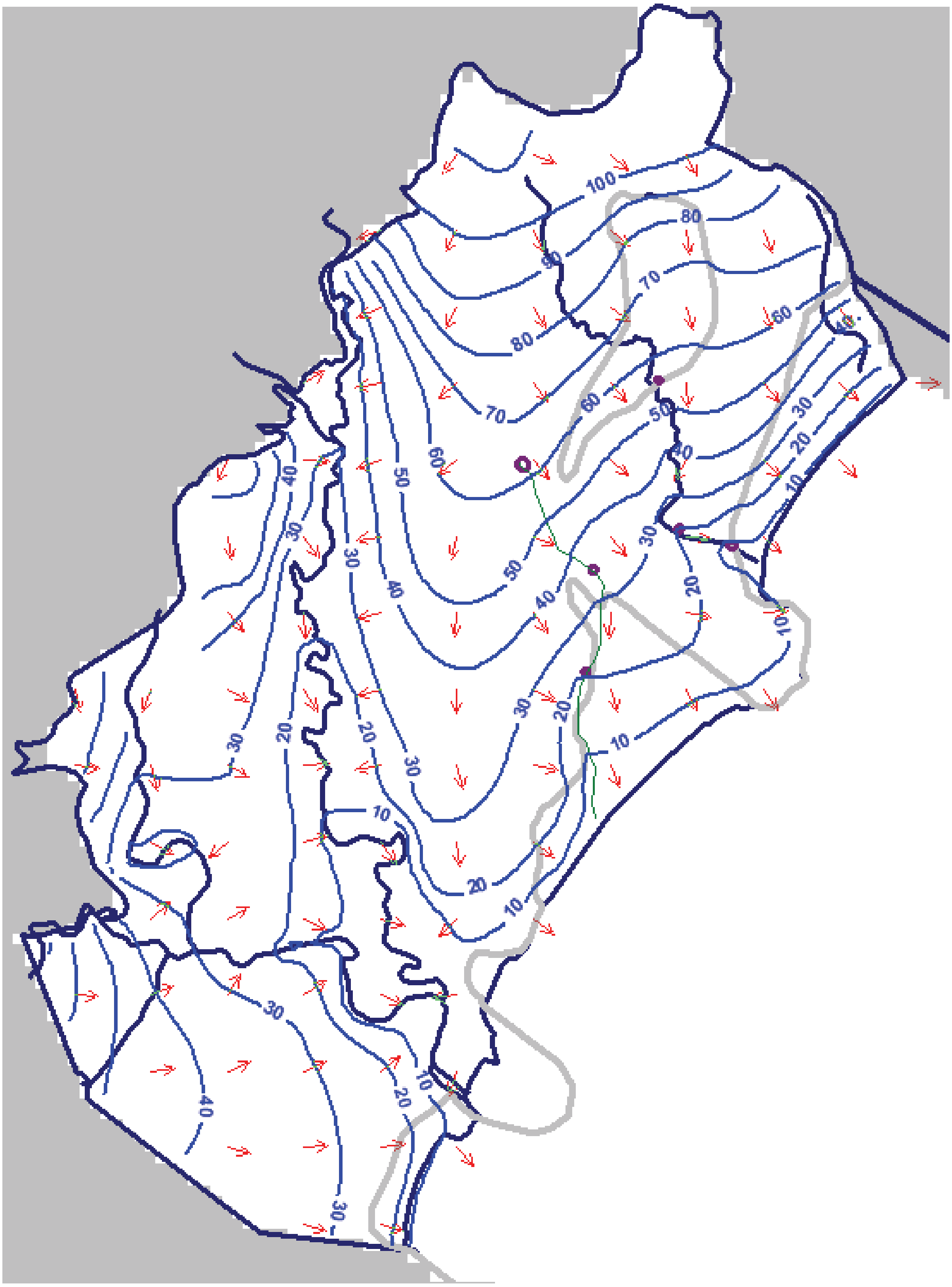


Figure D. 7 Steady state modelled head distribution (Layer 1)

Steady state mass balance

The steady state mass balance is shown in Table D.3. Inflows are solely rainfall recharge and outflow is dominated by discharge to rivers. The predominant outflows are to the Kakanui River and Waireka Creek, and also offshore discharge to the sea. All flows are relatively small, reflecting the overall low permeability of the system.

Table D.3 Steady state mass balance (March 2008 calibration)

Flow Component	Inflows (m^3/d)	Outflows (m^3/day)
Rivers: Waiareka (u/s Taipo Rd) Kakanui (+ Waireka d/s Taipo Rd)		 13,865 19,620
Drains (Oamaru + Awamoa Ck)		9,614
Constant Head to coast		13,016
Rainfall recharge	56,107	
Totals	**56,107**	**56,115**

Steady state sensitivity analysis

Numerical model calibrations are often non-unique and numerous combinations of parameter values can result in the same head distributions. A sensitivity analysis is therefore useful to determine the degree of confidence which may be placed on the calibration. Generally, the more sensitive a parameter is to change, the more confidence can be placed in its value, depending upon its degree of covariance with other parameters (parameter co-variance is explored during the transient model calibration).

Sensitivity analysis is performed by systematically varying all model parameters by small factors and recording the sum of squares of residuals as a measure of the changes in head distribution. The results of the sensitivity analysis are graphically shown in Figure D.8. Parameters have been multiplied by factors of between 0.5 and 1.5 in 0.1 increments.

The model is most sensitive to Kx,y4 and Kz4 – the eastern Waireka and Deborah volcanic aquifers in model layers 1 and 2. The model is also sensitive to recharge in zones 1 and 2 (the predominant recharge zones). Since hydraulic conductivity and recharge are characteristically correlated parameters, confidence in their estimation can be gained only through the reasonable prior knowledge of hydraulic conductivity magnitude. The remaining parameter zones are relatively insensitive but since they are mostly sub-zones within the volcanics system and likely to possess similar hydraulic properties, the calibration for these zones is therefore considered to be reasonable.

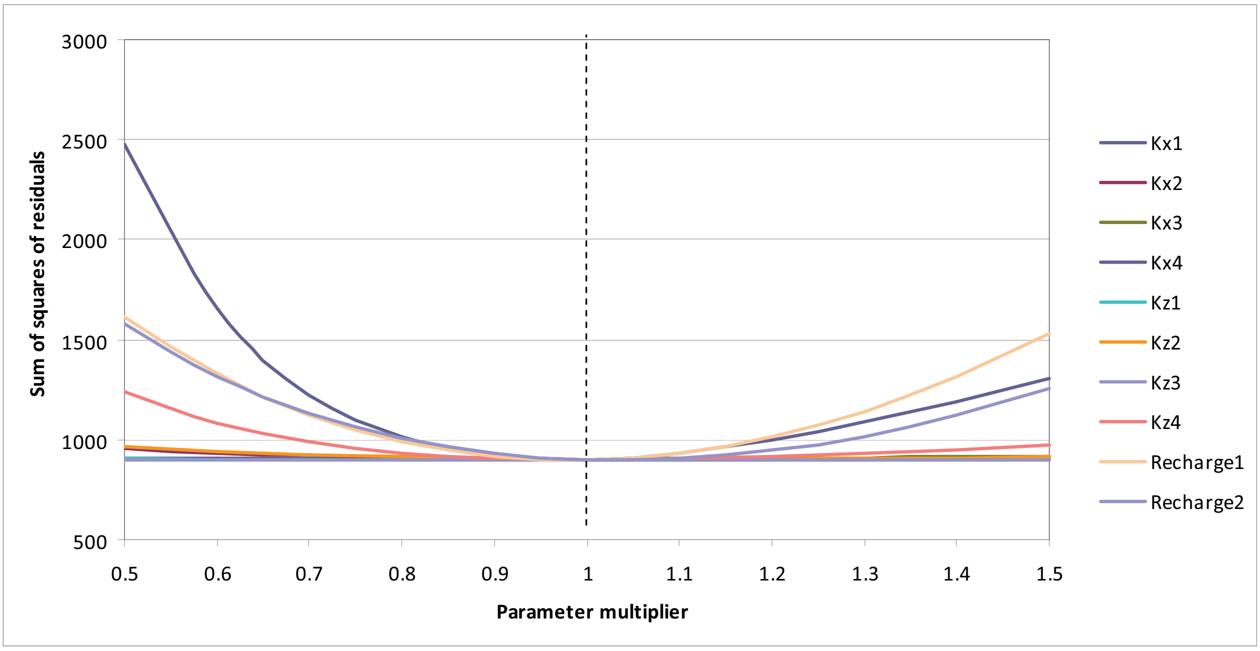


Figure D. 8 Graphical representation of sensitivity analysis

2.3 Transient modelling

A transient model calibration has been developed to verify and refine the steady-state model to ensure that it is able to simulate temporal stress conditions as a basis for assessing abstraction sustainability.

The transient model builds on the simpler steady state simulation by optimizing for specific yield and specific storage. Adjustment to the hydraulic conductivity inputs and temporal recharge modeling are also integral components of the transient calibration process.

Calibration of the model uses monitoring bore hydrographs, additional intermittent groundwater level measurements, and flow measurements or estimates for creeks and streams. The calibration process has employed both manual adjustment procedure and automated parameter optimisation using PEST.

Transient model design and initial inputs
The transient model structure is the same as the steady state model except that additional hydraulic conductivity zones have been introduced (Figure D.5). Recharge estimation methodology and model inputs are described in detail in Appendix B.

Groundwater abstractions were incorporated in the transient model calibration and were assumed to be pumping at 30% of their annual consented rates over a 150-day period commencing at the start of each year. In the absence of annual meter data, the same pumping rate has been applied to each year of the simulation.

The period July 1997 – March 2008 has been used for the transient model calibration as continuous aquifer head observations are available for this period. Selection of appropriate stress period length depends upon the availability of data. On the basis of an assessment of the dynamics of the groundwater system and data availability, a seven-day stress period was chosen to provide sufficient temporal variability for calibration. The transient model therefore incorporates 556 seven-day stress periods and runs for 3892 days.

Starting heads conditions are critical for successful transient calibration. Monitoring well hydrographs (Figures 5.3 and 5.4) show that the groundwater heads follow long cycles of drainage and short periods of irregular recharge. It is therefore important to begin the transient simulation using a head distribution similar to the heads measured in July 1997. The steady state calibrated heads are conventionally used as a starting condition; however, given the slow response of this system to stresses and the occurrence of periods of declining level, starting heads were derived from running the transient model from an initial head condition set at the top of layer 1. A stress period in the simulation output which matched the July 1997 head conditions was then chosen as a starting condition.

Calibration targets

There are only two long-term groundwater level monitoring sites with the volcanics aquifer – the Wesbsters bore (J41/0178) in the Deborah Aquifer, and the Isbister bore (J41/0198) in the Waiareka Aquifer. The monitoring records for theses sites are shown on Figures 5.3 and 5.4, and their locations are shown on Figure 5.2. Additional head targets used for the calibration are the 2008 groundwater level survey data and also gauging data for the Waiareka Creek.

Transient calibration

Optimised values for hydraulic conductivity, specific yield and specific storage are shown in Table D.4. The calibration process involved an initial manual trial and error approach during which the numbers of hydraulic conductivity zones was increased to represent large-scale heterogeneity evident within the volcanics sequence. PEST was then run on hydraulic conductivity and storage zones exhibiting moderate to high sensitivity, and also the main recharge zones.

Table D.4 Optimised aquifer parameters

Hydraulic conductivity zone	Formation	Kx,y m/day	Kv m/day	Specific yield/ specific storage
3, 6	Deborah volcs	0.7 - 0.85	0.001 (Z3) 0.0003 (Z6)	0.1/0.0034-0.00001
4, 13, 6	Waiareka volcs	0.7 – 0.79	0.00036 (Z4) 0.0003 (Z6) 0.1 (Z13)	0.1/0.0034-0.00001
10	Waiareka Ck zone	1.94	0.007	0.1/0.0034-0.00001
8	Totara Lst + basalts	0.1	0.001	0.1/0.0034-0.00001
2	McDonald Lst	0.2	0.001	0.1/0.0034-0.00001
9	Kakanui Alluvium	2	0.05	0.1/0.0034
5, 12	Deep volcanics	0.5-0.78	0.0005 (Z5) 0.1 (Z12)	/0.0001
1, 10	Rifle Butts/Gee	0.1	0.001	0.1/0.00001

The hydraulic conductivity zones are shown in Figure D.5. Calibrated aquifer properties fall within the range of values derived from pumping tests (Section 4.2), although regional bulk hydraulic conductivity values are lower, probably due to the bias inherent in the test data. The specific yield values agree well with assessed values of about 10%.

Some emphasis has been placed on matching simulated head to observed heads, particularly at the two long-term monitoring wells (Webster and Isbister), although it is acknowledged that reliance on only two water level monitoring sites for transient calibration within a regional aquifer system is not ideal. For this reason, additional measurements made at specific times have also been incorporated in the calibration.

Figure D.9 shows the calibration for the two long-term groundwater level monitoring sites. The simulated levels closely follow measured levels, particularly with regard to overall trends and the impacts of recharge events. The simulated heads at both calibration sites shows a higher variability associated with small recharge events (the simulated heads are quite peaky). This response is a result of the recharge model immediately applying recharge to the water table as soon as it drains through the soil moisture store. In reality, there is a thick low permeability unsaturated zone (up to about 10m thick) which will tend to attenuate recharge and smooth out the impacts of recharge events. Accurate simulation of recharge application to the water table would require modelling flow through the unsaturated zone (which is beyond the scope of this study); however, it is regarded that the recharge model is applying the correct overall quantity of recharge associated with each recharge event – it is just applying it over a shorter period than appears to occur naturally.

Figure D.10 shows the results of the transient calibration in the form of a scatter plot showing all groundwater head level measurements for March 2008 as well as the hydrograph data to ensure that the model is simulating regional flow gradient correctly. Associated with the scatter plot are the calibration statistics which indicate an overall close fit between the observed and modelled head data as shown by the error of 9% (std. dev/range) and the residual mean of -0.08m.

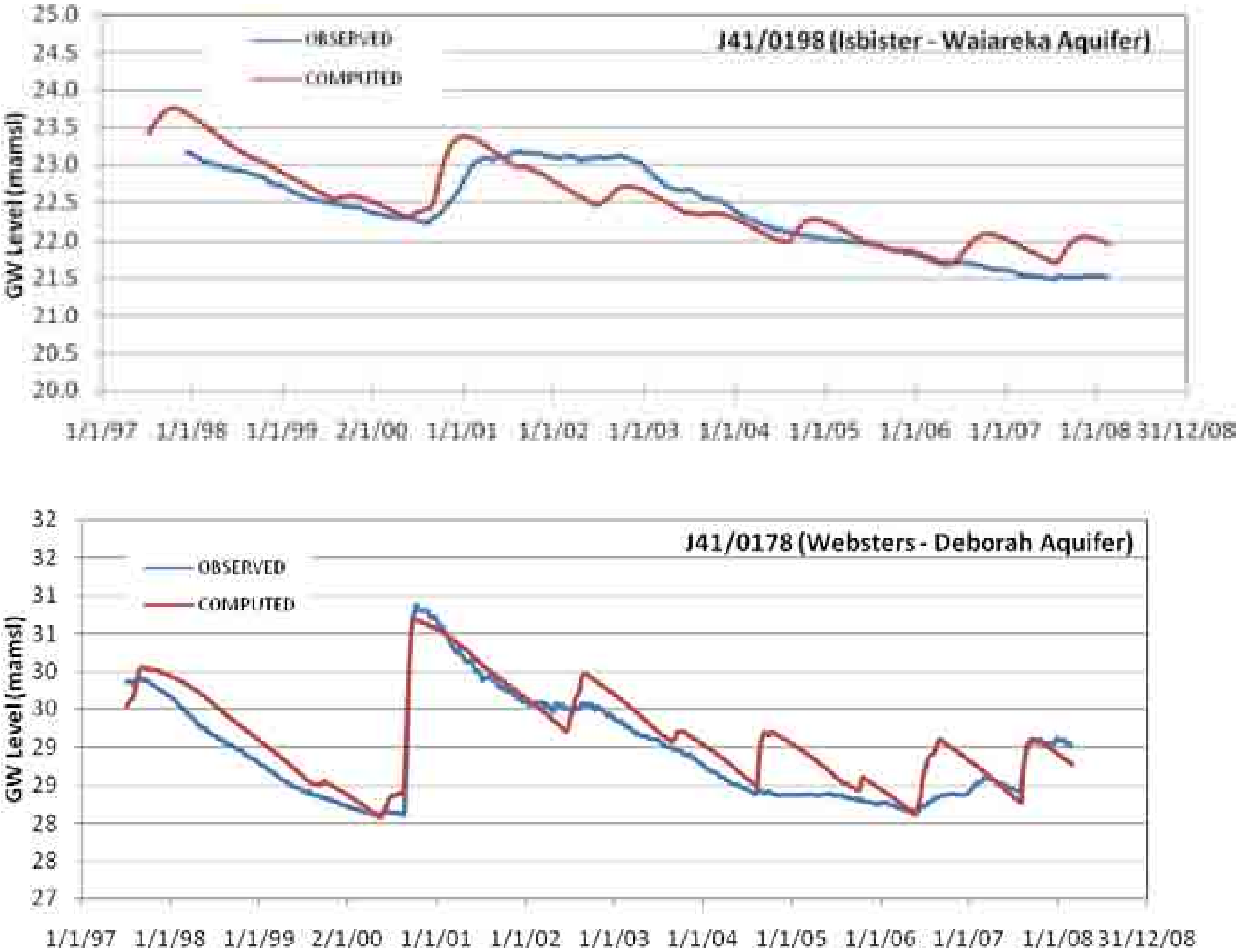


Figure D. 9 Transient calibration plots

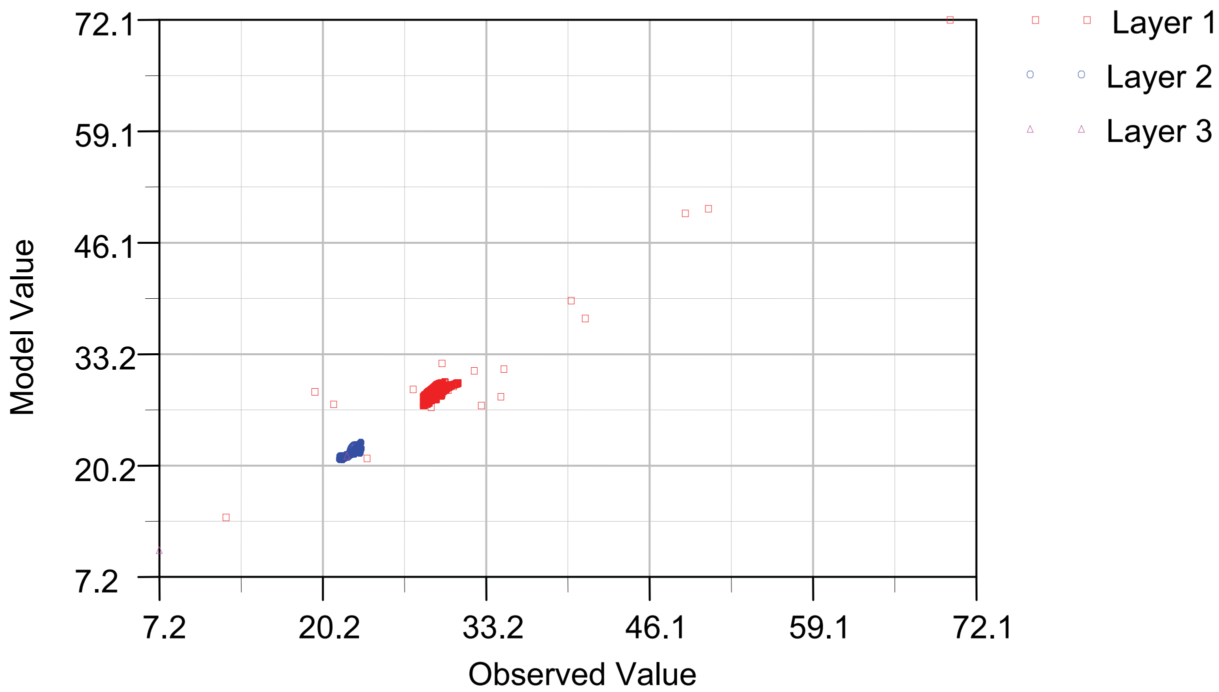


Figure D. 10 Transient calibration scatter plot and calibration statistics

Calibration statistics

Residual mean	-0.07751
Res. std. dev.	0.565021
Sum of squares	337.6155
Abs. res. mean	0.262642
Min. residual	-9.21131
Max. residual	6.124103
Range in target values	62.79
Std. dev./range	0.008999

Transient mass balance

Figure D.11 shows the simulated mass balance plots for principal flow components. The variable recharge inputs are evident which can vary by a factor of up to 18 between years (100,000 – 1.8M m^3/year). The impacts of large recharge event in the spring of 2000 (a result of a prolonged rainfall period) is responsible for the large rises in water level observed most prominently in the Webster monitoring bore (Figure D.9). Successive years of low recharge are responsible for the observed long-term recessions observed in the monitoring bore hydrographs, for example from 2000-2002.

Flows to the Waiareka Creek have been slowly declining since the 2000 recharge event with summer low-flow discharge being about 13,500m^3/day (156 L/sec). This decline mirrors the natural decline in groundwater level observed in the Isbister monitoring bore (Figure D.9) which appears to be a result of climatic conditions rather than abstraction. The simulated outflow to the creek is somewhat higher than the measured summer flow of less than 50 L/sec at Taipo Road; however, it is regarded that there is a loss to evapotranspiration along the valley floor through the riparian vegetation, and from direct evaporation along the 10km reach within the model area.

The simulated summer flow in the Oamaru Creek is about 3,500m^3/day (40 L/sec). Again, losses to evaporation and evapotranspiration mean that the actual flow in the creek is expected to be significantly less than this.

Table D.5 provides the model mass balance outputs for a spring recharge event during the week of 5/8/2007, and an early summer period (24/2/2008) for comparison. The recharge event produced a large increase in storage (storage-out component) resulting in the rise in groundwater levels associated with this event (Figure D.9). There is a relatively small change in flow to the Waiareka Creek, although in reality surface runoff would result in a significant flow increase during prolonged rainfall periods (the flow balance only represents groundwater baseflow to creeks and rivers).

Table D.5 Transient mass balances for two stress periods (5/8/2007 and 24/2/2008)

	Stress period 527 5/8/2007	**Stress period 556 24/2/2008**
Storage IN	2,302	65,712
Recharge IN	1,384,885	0
Total flow to rivers OUT	-70,360	-33,549
Flow to drains OUT	-11,538	-7,936
Flow to sea (CH) OUT	-11,663	-11,490
Well OUT	0	-9,419
Storage OUT	-1,293,641	-3,370
Balance error	0%	0%
Flow to Waiareka Creek (u/s Taipo Rd)	-15,400	-14,000
Flow to Oamaru Creek	-6,000	-3,800

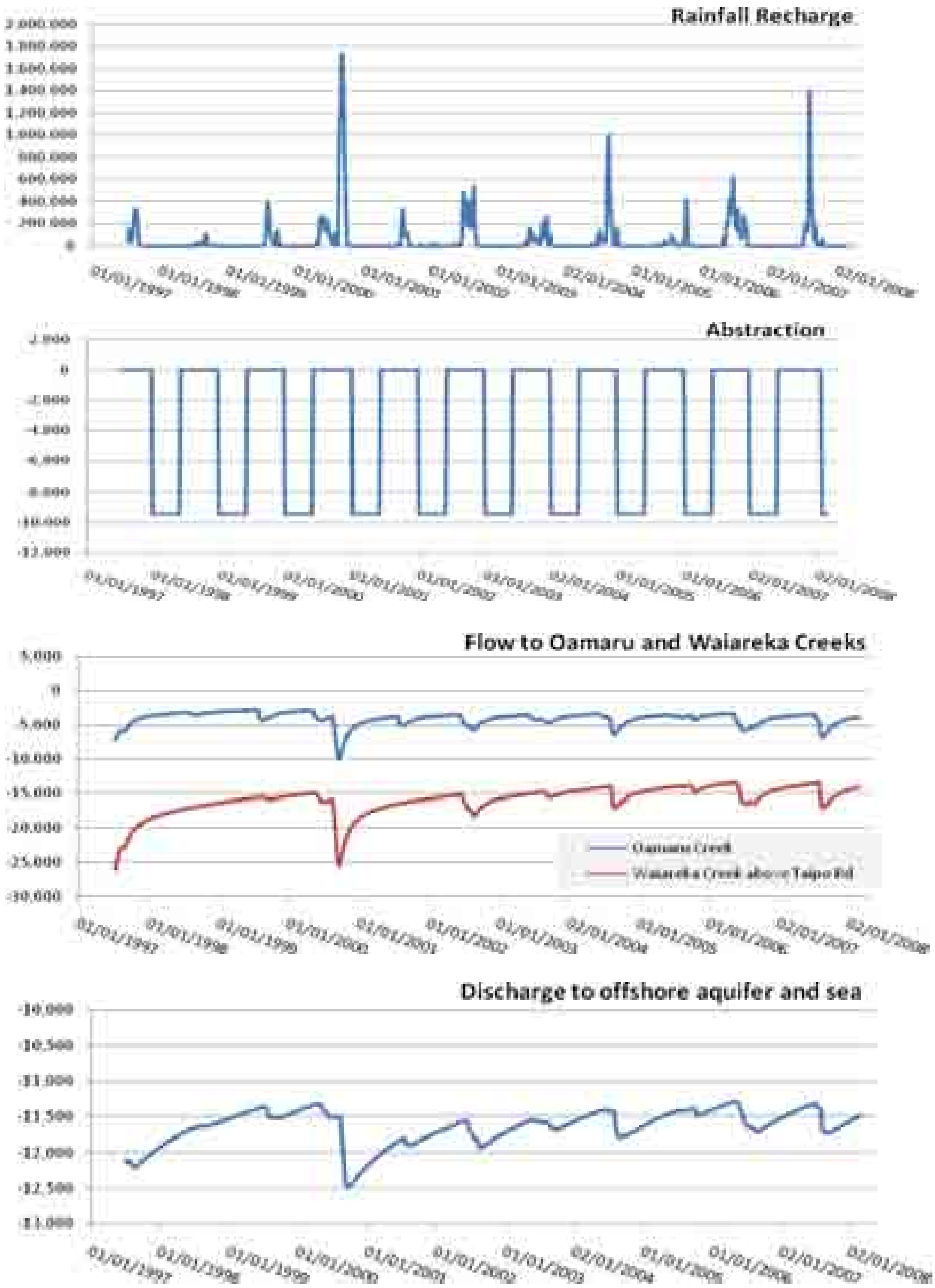


Figure D. 11 Transient calibration mass balance plots

Parameter sensitivity and uncertainty analysis

Sensitivity analysis has been performed on all model parameters using the transient model by systematically varying all model parameters by small factors and recording the sum of squares of residuals as a measure of the changes in head distribution. Parameters were multiplied by factors of between 0.5 and 1.5 in 0.1 increments.

The results of the sensitivity analysis are shown by the series of plots in Figure D.12. The analysis shows that, in terms of (horizontal) hydraulic conductivity, zones Kx3 (Deborah Volcanics), Kx10 (central Waireka Volcanics, along creek), kx12 (deep volcanics in layers 3 and 4), and Kx13 (shallow Waiareka Volcanics in western catchment) are all sensitive parameters. In terms of vertical hydraulic conductivity, zone kx10 is the most sensitive (Waiareka volcanics along creek axis). Other zones are also mildly sensitive (kz3, kz4, kx8).

The model is sensitive to Sy1 (specific yield in Layer 1), and Ss3 (specific storage in Layer 2). It is not at all sensitive to specific storage in the deeper model layers. Recharge to Zone 1 (eastern Waiareka Catchment) is also a sensitive parameter, while recharge to Zone 2 (western catchment) is less so.

If a parameter is sensitive to change, generally more confidence can be placed in its estimation depending upon its covariance with other parameters. The PEST algorithm has been used to determine the covariance of the more sensitive parameters to further assess the levels of confidence that can be placed on the optimised parameter values. Recharge has been excluded from this analysis since a good degree of confidence has been placed in its estimation using the modeling process described in Appendix B.

The covariance matrix calculated by PEST is shown in Table D.6. The matrix diagonal value (shaded) provides an indication of the degree of confidence which can be placed in each of the parameters. The lower the relative value on the diagonal, the greater the confidence in its estimate. Most of the parameters have very low values and can be considered to be well-constrained, except for Kx10 (Waiareka Creek zone) and kx13 (shallow Waiareka Volcanics in western catchment area) which have high relative values and are less well constrained.

Table D.6 Covariance matrix for sensitive model parameters

	kx12	**kx10**	**kx3**	**kx13**	**kz10**	**kz4**	**kz3**	**sy1**	**ss3**
kx12	3.88E-02	-8.72E-02	2.18E-03	-9.74E-02	4.62E-04	-3.61E-06	-4.09E-06	-1.43E-05	1.83E-04
kx10	-8.72E-02	0.4557	-3.68E-03	0.1505	-2.33E-03	6.84E-06	9.31E-06	-1.95E-05	-5.89E-04
kx3	2.18E-03	-3.68E-03	1.14E-03	-1.10E-02	3.96E-06	-3.02E-07	-2.34E-06	2.36E-05	-2.81E-07
kx13	-9.74E-02	0.1505	-1.10E-02	0.5207	-3.86E-05	1.28E-05	1.45E-05	2.17E-04	3.33E-06
kz10	4.62E-04	-2.33E-03	3.96E-06	-3.86E-05	1.47E-05	-1.94E-08	-4.07E-08	8.06E-07	5.11E-06
kz4	-3.61E-06	6.84E-06	-3.02E-07	1.28E-05	-1.94E-08	1.09E-09	3.89E-10	9.49E-09	3.09E-09
kz3	-4.09E-06	9.31E-06	-2.34E-06	1.45E-05	-4.07E-08	3.89E-10	7.69E-09	8.23E-08	-2.56E-08
sy1	-1.43E-05	-1.95E-05	2.36E-05	2.17E-04	8.06E-07	9.49E-09	8.23E-08	1.52E-05	-9.71E-08
ss3	1.83E-04	-5.89E-04	-2.81E-07	3.33E-06	5.11E-06	3.09E-09	-2.56E-08	-9.71E-08	3.26E-06

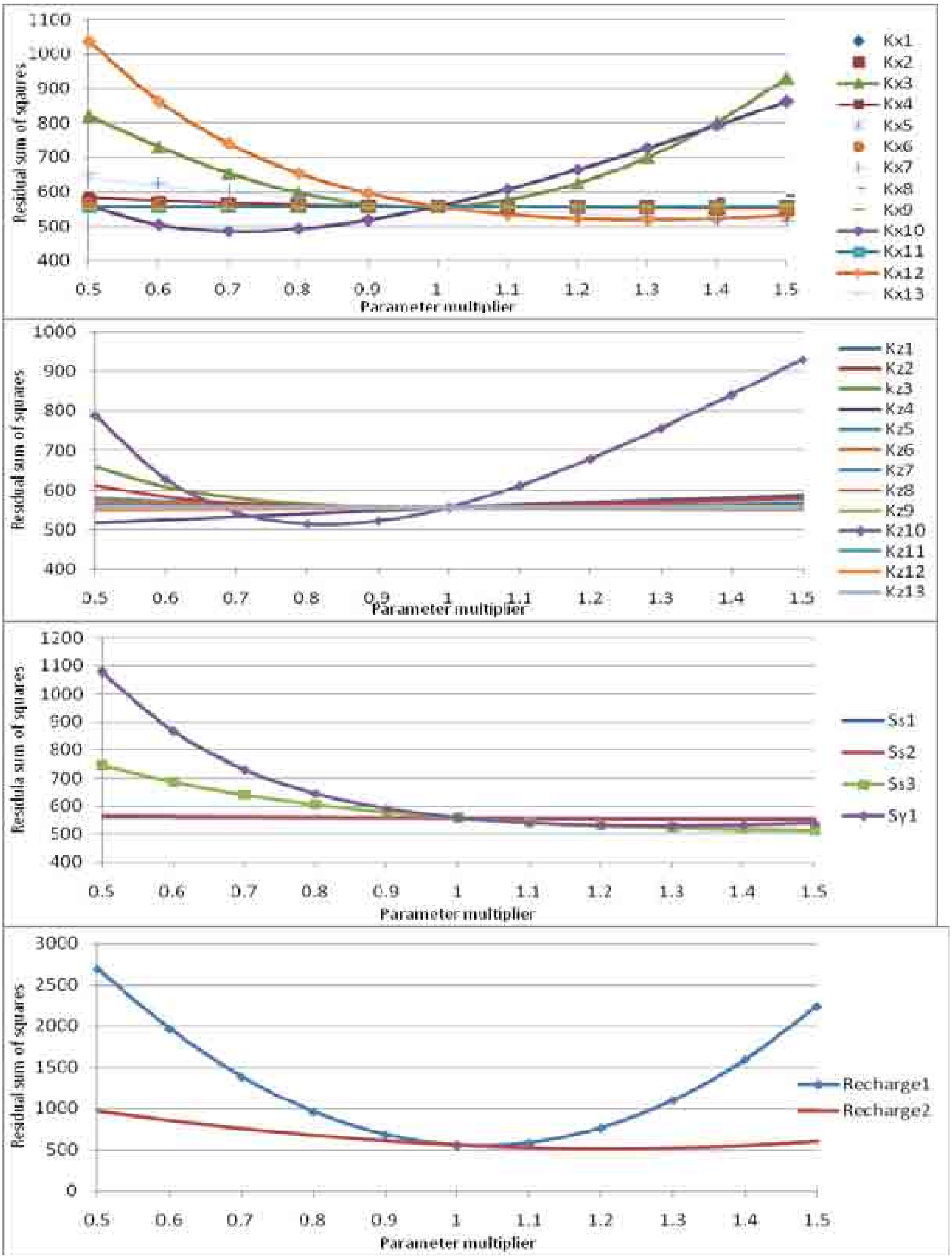


Figure D. 12 Sensitivity analysis for transient calibration

The correlation coefficient matrix (Table D.7) is calculated from the covariance matrix and shows how the parameters are correlated with each other. The diagonal elements are always unity and the off-diagonal elements are between 1 and -1. The closer an off-diagonal element is to 1 or -1 the more highly correlated are the two parameters associated a particular cell of the table. There are three sets of parameters which show a relatively high degree of correlation (shown as bold): kz10 with kx10, kz3 with kx3, and ss3 with kz10. A lower degree of confidence can therefore be placed in the estimation of these values; however, since these zones within the Aquifer are of similar value to more robustly estimated adjacent zones, it is assumed that their optimisation may be relatively well-constrained also.

In conclusion, the sensitivity analysis and PEST parameter optimisation algorithm suggest that the parameter values for the predominant areas of the volcanics aquifer can be considered reasonably well-constrained. Exceptions include kx10 and kz10 (the hydraulic conductivity zone aligned with the Waiareka Creek), and kx13 in the western part of the Waiareka Catchment. These zones contain relatively few target head sites and therefore parameter optimisation is less reliable in these areas.

Table D.7 Correlation coefficient matrix

	kx12	**kx10**	**kx3**	**kx13**	**kz10**	**kz4**	**kz3**	**sy1**	**ss3**
kx12	1	-0.6561	0.3289	-0.6854	0.6119	-0.5556	-0.2372	-1.87E-02	0.514
kx10	-0.6561	1	-0.1614	0.309	**-0.899**	0.3066	0.1573	-7.40E-03	-0.4833
kx3	0.3289	-0.1614	1	-0.4527	3.06E-02	-0.2707	**-0.7907**	0.1799	-4.61E-03
kx13	-0.6854	0.309	-0.4527	1	-1.39E-02	0.5364	0.2292	7.73E-02	2.56E-03
kz10	0.6119	**-0.899**	3.06E-02	-1.39E-02	1	-0.1532	-0.1211	5.39E-02	**0.7377**
kz4	-0.5556	0.3066	-0.2707	0.5364	-0.1532	1	0.1343	7.38E-02	5.18E-02
kz3	-0.2372	0.1573	**-0.7907**	0.2292	-0.1211	0.1343	1	0.2411	-0.1619
sy1	-1.87E-02	-7.40E-03	0.1799	7.73E-02	5.39E-02	7.38E-02	0.2411	1	-1.38E-02
ss3	0.514	-0.4833	-4.61E-03	2.56E-03	**0.7377**	5.18E-02	-0.1619	-1.38E-02	1

References

Environmental Simulations, Inc. 2007. Guide to using Groundwater Vistas. Environmental Simulations, Inc., Reinholds, Pennsylvania.

ORC, 1993: North Otago Groundwater Investigation. Prepared by IRRICON Ltd for Otago Regional Council, March 1993, Dunedin. ISBN 0-908922-06-X.

McDonald MG and Harbaugh AW. 1984. A modular three-dimensional finite difference groundwater flow model: US Geological Survey Open-File Report 83-875. Pp. 528.

Modflow-2000, the U.S. Geological Survey modular ground-water model - user guide to modularization concepts and the ground-water flow process. By AW Harbaugh, ER Banta, MC Hill, and MG. Mcdonald. U.S. Geological Survey open-file report 00-92 Reston.

Wilding A and Sweetman LAD. 1971. Endeavour-1 Well Completion Report. Prepared by BP Shell Aquitaine Todd Petroleum Developments for the Ministry of Economic Development, Crown Minerals, Petroleum Report Series No. PR303, Wellington.