Lower Taieri Groundwater Allocation Study

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Foreword

Otago's prosperity is largely based on water. The Taieri River represents a significant water resource for the Otago region and increasingly requires intensive water husbandry to meet the needs of the community. 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.

The 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 or for the assured purity of secure aquifers. 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 the Regional Plan: Water and our 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 Lower Taieri Basin groundwater system 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

This is a technical study based on available data and an assessment of environmental impacts. The results can be used in future policy setting after full public consultation looking at all socio-economic issues. Currently there are relatively low volumes of groundwater pumping in the Lower Taieri Basin compared to the basin's potential groundwater resource use. The majority of consented groundwater is utilised to supply Mosgiel Township with municipal water, and a minor quantity for associated industry. A handful of small agricultural irrigation takes from bores make up the rest of the allocated groundwater, bringing the combined basin groundwater allocation total to 2.4 million cubic metres per annum (in units of Mm^3/yr). There are a large number of domestic and stock water supply bores throughout the basin, which combined draw only modest quantities of water from the groundwater system.

Groundwater basin setting

The Lower Taieri Basin is a tectonic depression resting between two major faults. There are three significant river systems; Silver Stream, Taieri and Waipori crossing the plains. As such, the basin has become a site for deposition of a substantial thickness of sand, gravel, silt, clay and peat deposits. These sediments are saturated from near surface and the groundwater system is thought to extend to depths of over 200 m below the surface. The basin has no direct exposure to the sea coast, although brackish tidal water extends from Taieri Mouth up a bedrock gorge into the basin as far as Lake Waipori. In the Mosgiel area the mixtures of sediments are highly variable and thinly layered with discontinuous silt lenses. By contrast, the West Taieri area is more consistently layered with more distinct, traceable silt, sand and gravel layers. There is a fine-grained estuary deposit set down when a marine embayment filled the basin. It covers three quarters of the basin from Henley to as far as Riccarton Road, but not as far as Mosgiel. This Waihola Silt-Sand has low permeability, tending to confine and pressurise the underlying gravel layers to produce confined aquifers.

Groundwater flows

The basin's groundwater system as a whole is replenished by recharge from rainfall and the infiltration of river water. The lower reaches of the basin's rivers receive the balance of groundwater as seepage through their river beds. Some inflow also takes place into the West Taieri Drainage Scheme as a result of upward groundwater seepage from the underlying aquifer. There is a general direction of groundwater flow from the Mosgiel area, where much of the recharge occurs, to low lying areas such as the West Taieri Drainage Scheme and Waipori – Waihola Lake wetlands complex. The Taieri River around Outram, the Silver Stream near Mosgiel and the Waipori River upstream of Berwick are all important in replenishing the groundwater system as well. Figure 1 illustrates the layout of the basin, including a schematic cross-section with the aquifer systems groundwater flow directions.

Groundwater quality

The Lower Taieri Basin currently has few water quality impacts related to human activities. A small area of the basin around Mosgiel is susceptible to elevated nitrate concentrations. However, the remainder of the groundwater system has natural geochemical factors suppressing nitrate levels through denitrification. Prevailing elevated iron, manganese and corrosivity levels exist through much of the groundwater system. However, these conditions are both natural and ambient.

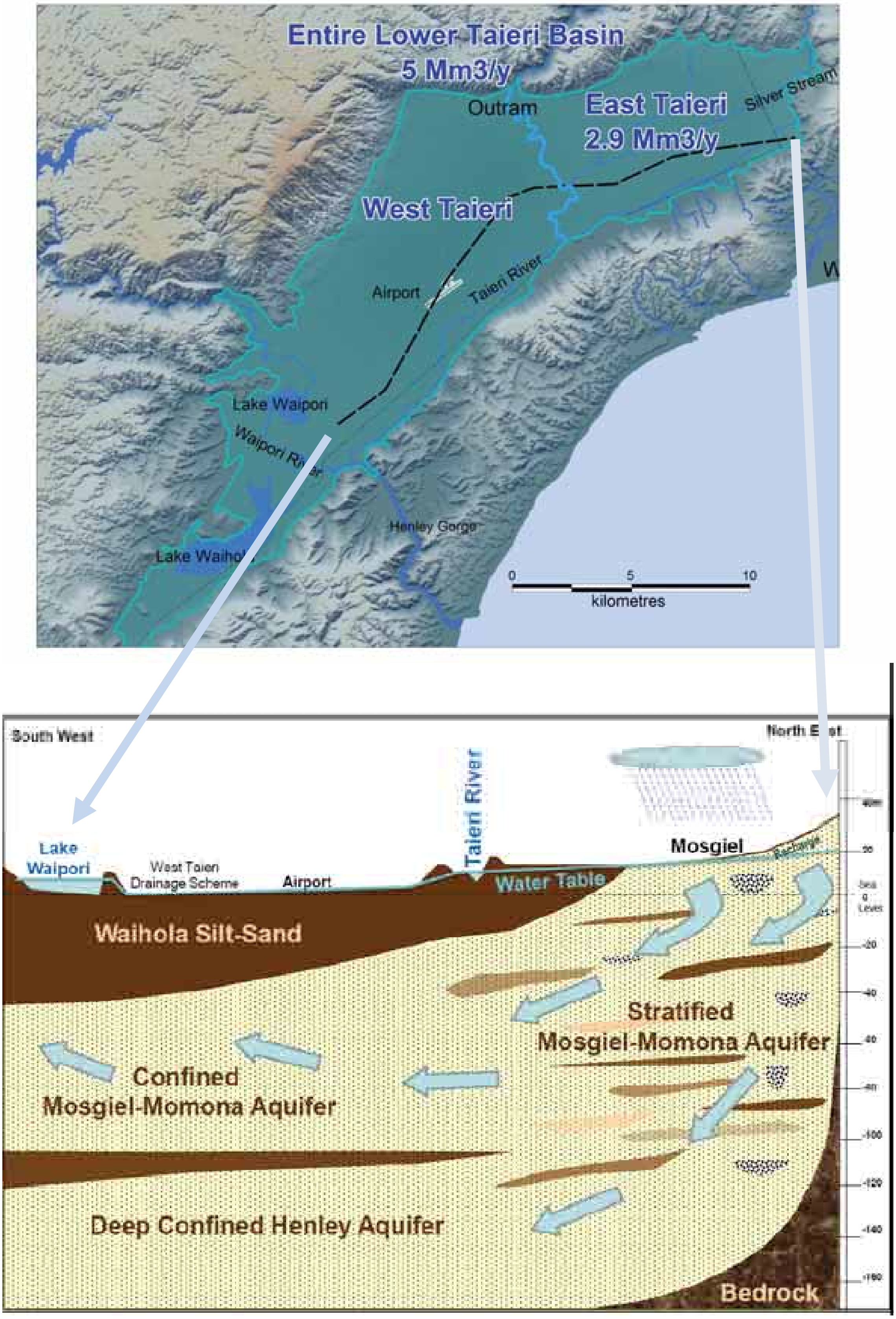

Figure 1 Map view of Lower Taieri Basin, including schematic cross-section from Wingatui to Lake Waipori showing groundwater flow directions as arrows

Numerical model & allocation settings

A numerical groundwater model was developed to assess the sustainable groundwater resource and determine the potential groundwater allocation limits and restriction levels for the basin. The rationales of applying both allocation limits and level restrictions are as follows:

- allocation limits address cumulative effects of combined groundwater extraction on the aquifer and connected surface water, and
- restriction levels form a "back-stop" role in easing the effects of declining groundwater levels.

The basin has been divided into East and West zones due to the distinctions in the potential impacts of groundwater pumping. The East Taieri zone has a greater potential impact of pumping on the flow of the Silver Stream, which justifies a more stringent allocation limit being placed on it. The consented allocation within East Taieri is already 2.2 Mm^3/yr. Any further groundwater development in the East Taieri is more likely to eventuate in close proximity to Mosgiel. Limiting increased allocation to a total of 2.9 Mm^3/yr would lessen the likelihood of substantial effects on the Silver Stream during low flows while opening the groundwater allocation open for modest expansion. However, the suggested limit could increase the flow loss from the Silver Stream by up to 25 litres per second. The modelling and assessment of available scientific data identified the following allocation volume limits for the Lower Taieri Basin:

Zone	Suggested Groundwater Allocation Cap	Current consented allocation
East Taieri	2.9 Mm^3/yr	2.2 Mm^3/yr
Entire Lower Taieri Basin	5.0 Mm^3/yr	2.4 Mm^3/yr

The Lower Taieri Basin allocation limit of 5 Mm^3/yr represents approximately 12% of mean annual recharge of 43 million cubic metres per annum to the basin's aquifers from all sources, including rainfall recharge and river infiltration. This is illustrated graphically in Figure 2.

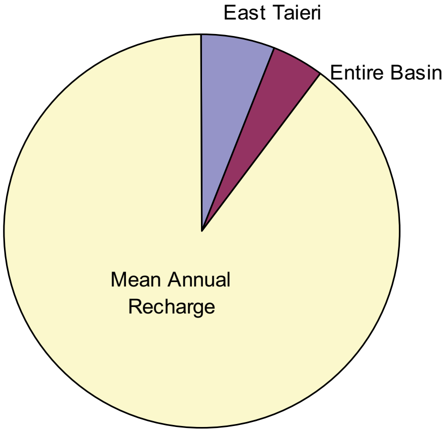

Figure 2 **Proportions of water allocation of 5 Mm^3/yr relative to the full Mean Annual Recharge in the Lower Taieri Basin**

The West Taieri zone is comparatively undeveloped, yet groundwater modelling suggests that further groundwater abstraction up to 3 Mm^3/yr could be allowed without causing adverse effects on the aquifer or adjoining surface water systems. There is the potential for beneficial effects of such abstraction on reducing the requirement for drainage system pumping.

Groundwater level restrictions

It is also suggested the Lower Taieri – East Water Take Restriction Zone levels in Schedule 4 of the Regional Plan: Restriction Levels are amended as follows:

Units: m AMSL	Recorded Maximum	25% Restriction	50% Restriction	100% Restriction
Harley Bore P2	12.9	10.7	10.3	9.9

The amended restriction levels are higher than the current levels (as illustrated graphically in Figure 3) and therefore they may reduce the impact of groundwater abstraction in the Mosgiel area on the Silver Stream during dry seasons.

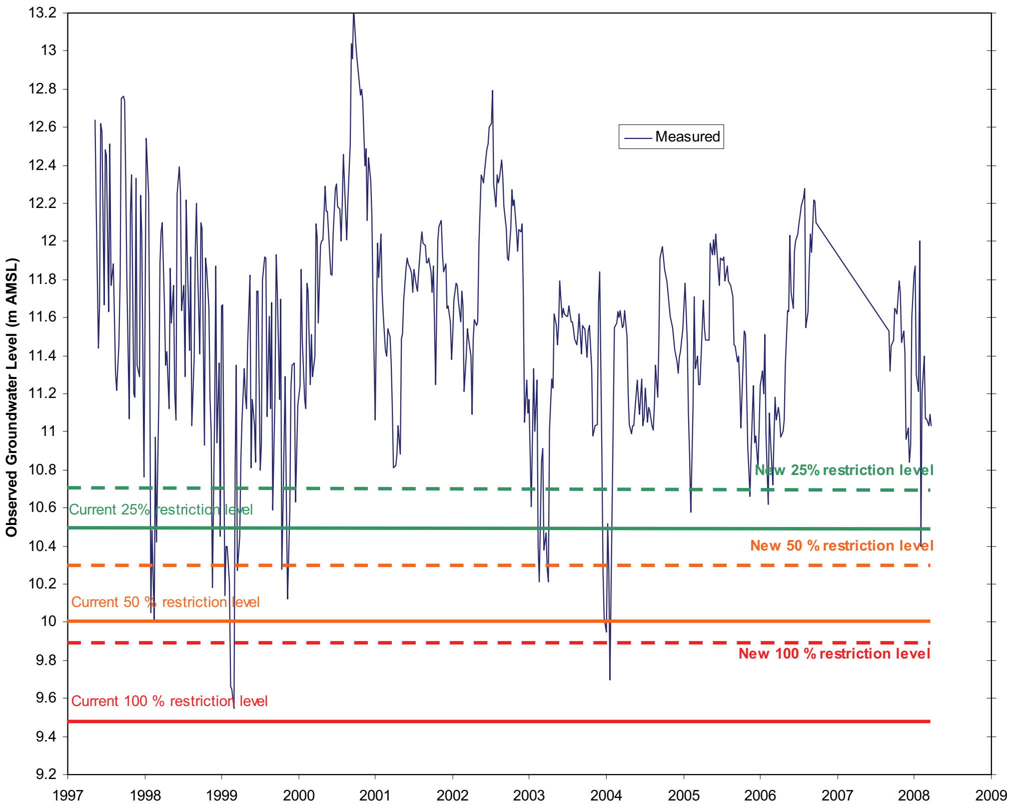

Figure 3 Illustration of current and new restriction levels for Harley Bore. New restriction levels are dashed

Note: When groundwater levels reach the restriction levels consented groundwater users are required to reduce their takes by the stated percentage.

The numerical model was also used to assess the possible impact of sea level rise on the groundwater system as the lower Taieri River and lakes are in the tidal range currently. By raising sea level in the lower basin surface water bodies by 1.5 metres, adjoining groundwater levels also rise by the same amount. Providing that flood defences can be adapted and strengthened to hold back the surface waters, there should be no significant sea water intrusion of the Lower Taieri Basin aquifers.

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1. Introduction

The Lower Taieri Groundwater Basin is a distinct hydrological unit, being surrounded on all sides by low permeability rock and only being connected with the wider Taieri Catchment by the Taieri River, Silver Stream, Waipori River, and ultimately the Henley Gorge section of the Taieri River to the Pacific Ocean (Figure 1.1 and Figure 4.2). Since European settlement in the mid 1800s, the Lower Taieri Basin has been drained and transformed from its previous predominant marsh and wetland character to grazed pasture. With this clearance and drainage, the Lower Taieri Plains have developed a substantially altered hydrology, plus a thirst for groundwater to supplement the water resources obtained from surface water.

The economic and community wellbeing values gained from the groundwater of the Lower Taieri Basin have been more appreciated in recent years. Mosgiel derives its entire community water supply from underlying groundwater, as do many of the rural residential private water supplies outside built-up areas. The Dunedin City Council (DCC) had cast its eyes over the groundwater of the Mosgiel district in the post-War period and pumped water from the ground adjacent to the Taieri River at Outram, but the DCC ultimately obtained the bulk of its water from Deep Stream via a 60km system of pipelines. Larger Taieri Plains' industries and primary production units typically obtained their water supplies independently utilising the basin's aquifers, although this pumping has diminished to minor levels in recent years. Ecological and intrinsic values for the basin's groundwater resources reside in the role that groundwater flows play in the modified hydrological systems, such as seepage to drains, lakes and wetlands.

The responsibility for the management of the Lower Taieri Groundwater Basin resides primarily with the Otago Regional Council (ORC). Several investigations and management programmes have been instituted by the ORC since 1993 to maintain or enhance the water resource. A variety of groundwater management measures was eventually applied to the basin with the promulgation of the Regional Plan: Water for Otago (Water Plan) by ORC in 2004. Nonetheless, water management regimes require periodic re-adjustment, as does the scientific consensus around the conceptualisation of a basin's hydrological processes. This groundwater basin study is intended to update the published knowledge of the Lower Taieri and provide a scientific basis for the setting of a revised groundwater allocation estimate for the community to consider.

The report's objectives are as follows:

- To describe the Lower Taieri Groundwater Basin in terms of its geology, groundwater characteristics and interactions with adjoining water resources.

- To develop a conceptual understanding of the groundwater basin and its operative processes.
- To develop a numerical model that replicates past and future groundwater system behaviour.

- To utilise these technical tools in determining and setting limits on groundwater management for the future sustainability of the Lower Taieri Groundwater Basin.

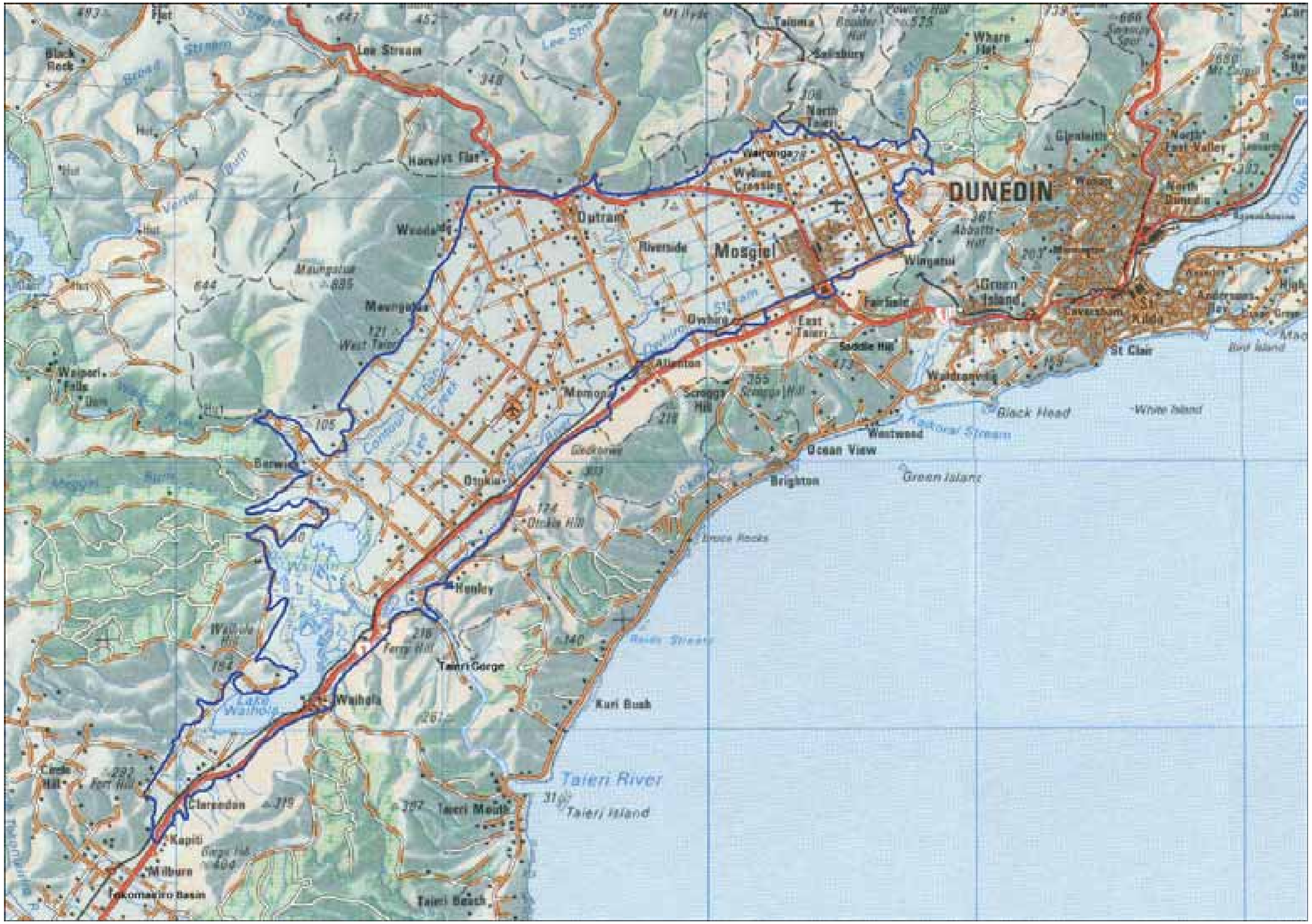

Figure 1.1 Location of the Lower Taieri Groundwater Basin

2. Setting and background information

2.1 History of previous studies

The Lower Taieri Basin was settled by European settlers in the 1860s and the first published examination of its groundwater potential was in 1910. The rich history of previous geological and groundwater investigations since then is detailed in Appendix A, and this account references 19 separate reports, scientific papers and publications on the subject.

2.2 Geology and physiography

The Quaternary geology of the Lower Taieri Basin tends to reflect the depositional and tectonic influences of the most recent two million years. The Lower Taieri Plain lies in a north-east trending tectonic depression, the Lower Taieri Basin, some 40km long and 5-10 km wide (Barrell et al., 1999). The plain extends from Abott's Hill in the north-east some 30 km to lakes Waipori and Waihola in the south-west, with a total area of 210 km^2. The plain ranges in elevation from 40m above sea level at its northern end to about sea level at Waipori and Waihola Lakes in the southern end (Dickinson et al., 2000). The southern end of the basin is separated from the Tokomairiro Basin by a low bedrock divide near Milburn (Dickinson et al., ibid). The basin is tectonic in origin, since the western and eastern basement blocks have become up-thrust relative to the basin's floor through the tectonic action of faults at the margins. The basin's western margin is defined by the Maungatua and North Taieri faults, while the eastern margin is defined by the Titri Fault. The floor of the basin has subsided as well, and the basin's outlet to the sea has only been kept open through the down-cutting processes of the Taieri River as the seaward hills have been up-faulted. The basin floor is currently inferred to be 300m below sea level, and the basin has consequently filled with sediments of Tertiary and Quaternary age since re-activation of the eastern bounding Titri Fault. Figure 2.1 illustrates this arrangement of the Lower Taieri Basin and associated faulting.

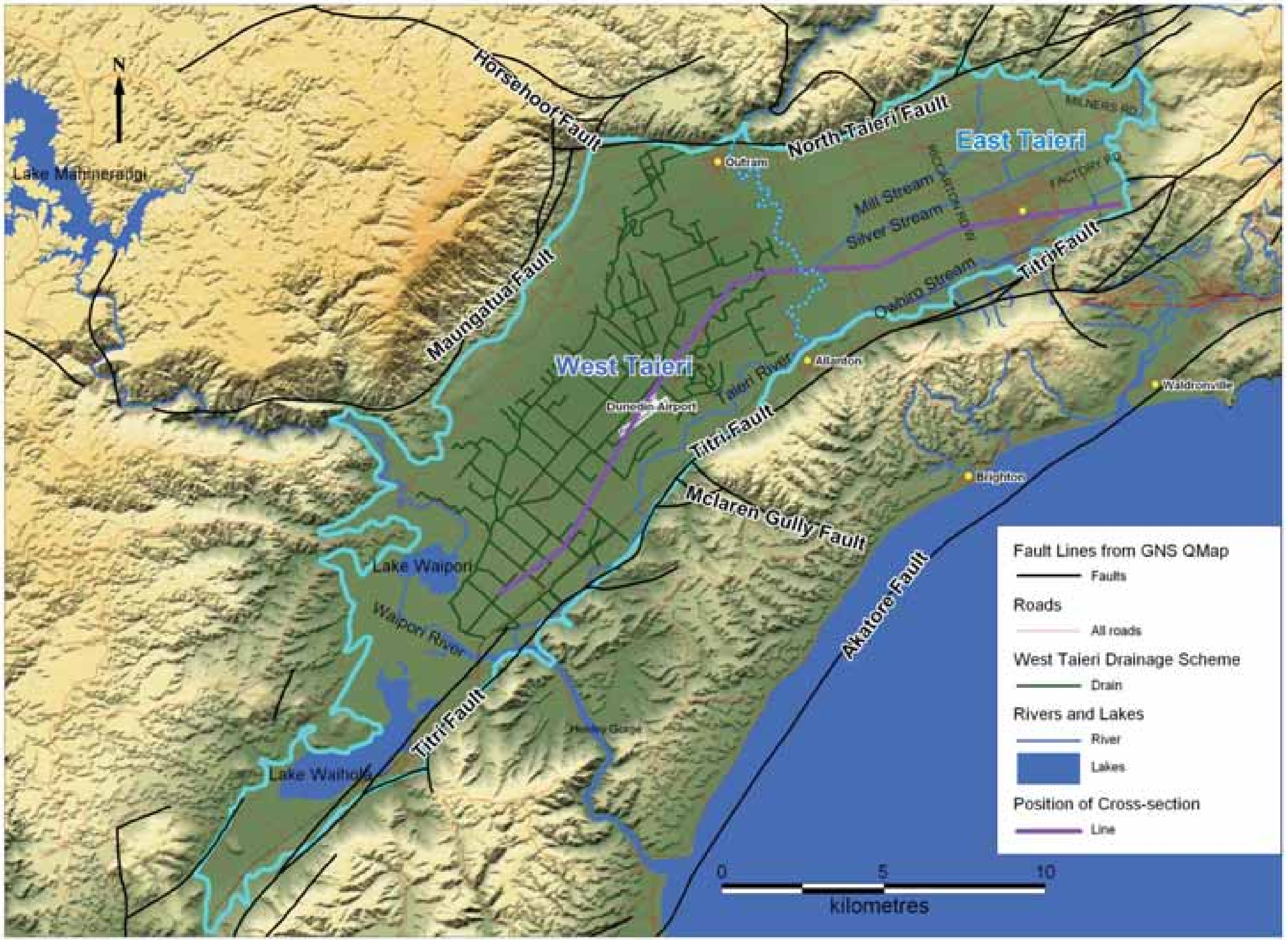

Figure 2.1 Fault positions in relation to the Lower Taieri basin. Position of the West Taieri Drainage scheme and cross section line position is also shown. Note the location and alignment of the cross section marked from Wingatui to Lake Waipori for Figure 2.2

The resulting basin is filled with sediments from both the Quaternary age (2 million years to present) and older Tertiary [65 to 2 million years Before Present (BP)] age. The Tertiary sediments are largely inferred by extrapolation from other localities in East Otago, although earliest Tertiary-age Henley Breccia can be seen in outcrop in the eastern part of the basin, particularly in its namesake locality. Cenozoic-Cretaceous age terrestrial sands, pebble conglomerate and lignite grouped within the Taratu Formation make up the flanks of the basin in the Waironga area. Tertiary age volcanics of the Dunedin Volcanic Complex make up additional flanks of the basin in the Wingatui and Waironga areas. Otherwise, the Tertiary sediments that may be located at the base of the basin have not been definitively confirmed by drilling, due to a lack of drill holes deep enough to reach a depth inferred to coincide with their presence in the basin. The sole estimates of the depth of contact with the Haast Schist basement rocks under the basin has been by geophysical gravity surveys (reported in Litchfield et al., 2002), which are of an approximate and uncertain nature. The shallower Quaternary geology of the basin is better known from drill hole logs.

The basin was rapidly inundated by the sea and estuary waters following the post-glacial rise in global sea levels to their current level, stabilising approximately 4,000-8,000 years BP. All of the West Taieri and much of East Taieri became a coastal embayment or estuary as far up the basin as the outskirts of Mosgiel. The newly inundated embayment and estuaries filled with silty sediments, resulting in a consistently silty or clayey sand layer in the shallow basin sediments. This horizon is commonly termed the “Waihola Silt-Sand” (Barrell et al., 1999; and Litchfield et al., 2002), and thickens up to 25m in the south-west towards the basin exit (see Figure 2.2). In the areas that have this shallow Waihola Silt-Sand, the groundwater in gravel beneath the sand is semi-confined. Thus, the Waihola Silt-Sand deposit, where it is present in the basin, is significant in dividing the groundwater system into vertically segregated compartments.

The gravel-dominated Quaternary sediments beneath the Waihola Silt-Sand are known from a relatively small number of water bores that tap the top of the semi-confined aquifer, and deeper bores such as the airport investigation bores (I44/1003, I44/1006, I44/0919, I44/1035, I44/1036, and I44/0921). The geological information from the Waipori 99-1 bore pointed to there being two aquifers beneath the Waihola Silt-Sand, the so-called “Confined Mosgiel-Momona Aquifer and Henley Deep Aquifer”. The base of the Henley Deep Aquifer was still not reached before the end of drilling in Waipori 99-1 at 154.3m BGL (approximately 155m below mean sea level). The Confined Mosgiel-Momona Aquifer was also encountered in drilling at Dunedin International Airport (e.g. I44/0921). Although drilling stopped at the top of the Henley Deep Aquifer, a marker lignite bed common to both bore logs was encountered at the same stratigraphic level as in Waipori 99-1. This marker bed, the Waipori Aquitard, divided the Confined Mosgiel-Momona Aquifer and Henley Deep Aquifer. Figure 2.2 illustrates the geological and aquifer configuration as a cross-section from Mosgiel to Lake Waipori.

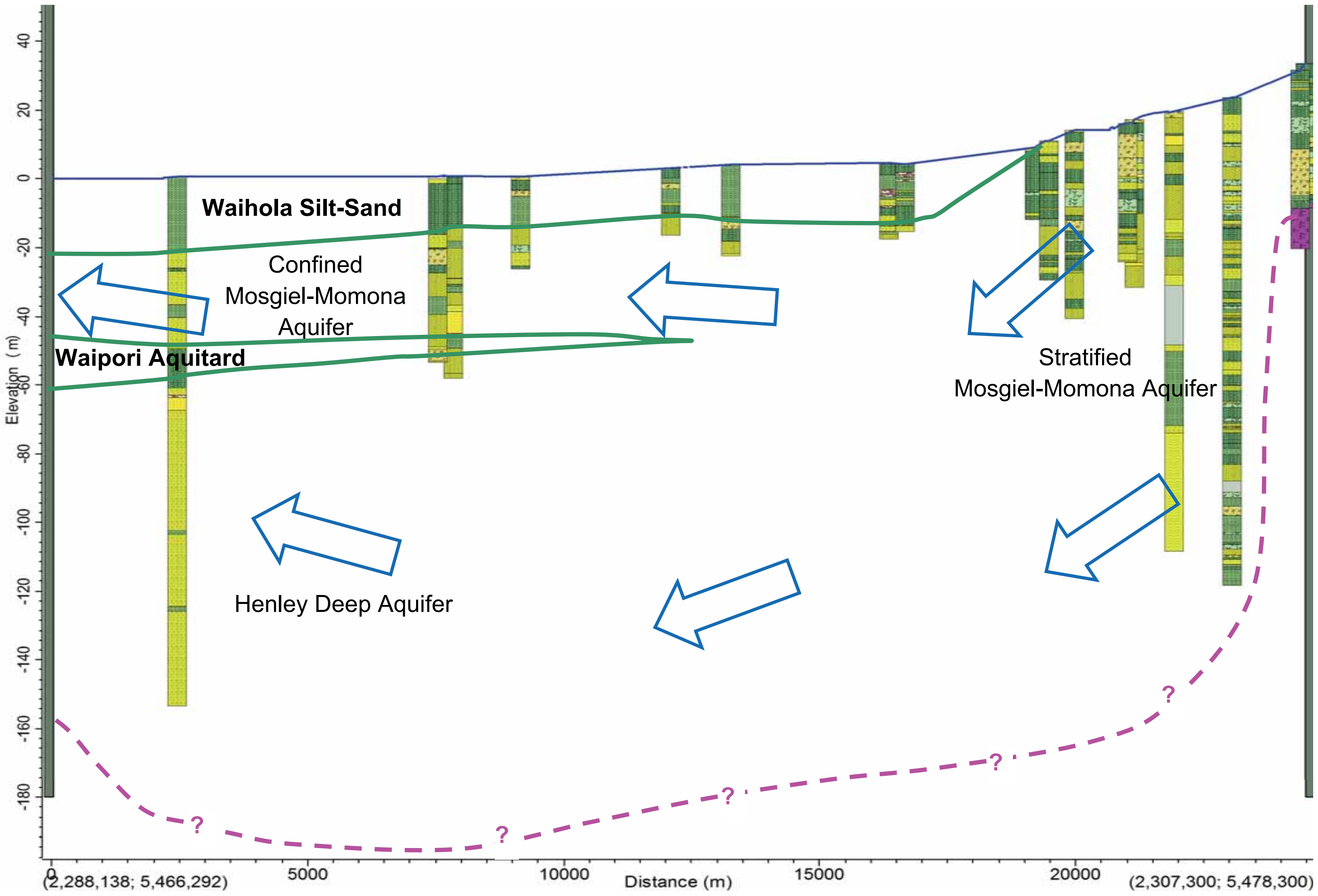

Figure 2.2 Cross section from south-west to north-east in the Lower Taieri Basin (see figure 2.1 for position). Green layers represent silts and clays, yellow more porous sands and gravels and the pink layer is basement rock

The Quaternary sediments of the Mosgiel area are characterised by high sedimentary variability. The composition is significantly more chaotic than the more consistent and extensive patterns noted for the West Taieri (above). The Waihola Silt-Sand extends into the East Taieri, perhaps as far as the Riccarton Road line, but not as far as Mosgiel (Litchfield, 2002). Bore logs in the Mosgiel-Wingatui areas note rapid transitions from one lithology (i.e. sediment type or predominant grain size) to the next and generally poorer sorting (i.e. sediments containing a wider range of grain sizes rather than a tighter clustering of grain size distribution). Bore log descriptions with indefinite compositions such as “silty sandy clay-bound gravel” are much more common in the Mosgiel district. These poor sorting and sediment variability features are inferred to be a result of the proximity to sediment sources such as the Silver Stream, Mill Stream, Owhiro Stream and hill slope outwash channels, relatively jumbled modes of deposition dominated by flood flows.

The principal water courses of the Lower Taieri Plains are the Taieri River, Silver Stream and Waipori River, which enter the Plains at the exits of their respective schist-rock gorges. Remaining predominant hydrologic features include Lakes Waipori and Waihola, the intervening wetland complex, and drainage creeks or channels. The Taieri River enters the plains at Outram and meanders south, turning south-west at Allanton before exiting the basin at Henley Ferry. The river joins with the Waipori River at this point, assumes a tidal character while cutting an exit to the Pacific Ocean through the seaward range in a canyon called the Henley (or sometimes Lower Taieri) Gorge.

The Maungatua Range makes a strong western flank to West Taieri and crests a broad ridge at an altitude of 895m. The southern edge of the Barewood-Hindon Plateau forms the north-western flank of the Plains from Outram to Waironga. The landscape influence of the mixed volcanic rocks and terrestrial-marine sediments of the south-west Dunedin sequence can be seen in the physiography of Boulder Hill, Abbott’s Hill, Chain Hills and Saddle Hill, in the north-eastern extent of the basin. The seaward range continues south at declining altitudes from Saddle Hill (473m), Scrogg’s Hill (355m) and Otokia Hill (174m) before being truncated by the Henley Gorge of the Taieri River.

2.3 Climate and land use

The climate of the Taieri Basin is sub-humid cool-temperate, characterized by mild summers and cold winters (Lichfield et al., 2002). Mean annual temperature is in the range of 10-11 ºC, the median summer air temperature is 14 ºC and the winter median air temperature is 8 ºC. Mean annual rainfall is between 700mm and 800mm in the Taieri Basin and around 1,200mm in some of the surrounding hills, such as the Maungatua Range. Rainfall is distributed over the seasons fairly evenly, although winters are the driest. Mean annual pan evaporation was 780mm for the period March 1963 to May 1983 at Dunedin International Airport, although actual annual evapo-transpiration against the grass reference crop is approximately 566mm.

The Lower Taieri Plains are almost entirely floored in grassed paddocks, except for the two small wetlands areas in East Taieri and the larger Waipori-Waihola Wetland Complex. The wetlands contain willows, flax and indigenous wetland species (raupo and mingimingi scrub). A substantial majority of the Lower Taieri Plains land surface outside these wetlands (i.e. under artificial drainage) is given over to the grazing of sheep, dairy cattle and horses. Forage cropping is primarily to support these grazing land uses. Market gardening was formerly significant in the Outram area, although some small operations and berry farming persist. The land management systems range from large commercial dairying operations to rural residential lifestyle blocks. Urban or semi-urban built-up areas are located at Mosgiel, Kinmont, East Taieri, Allanton and Outram, and comprise a total of about 600 hectares of land. In addition to primary industry, the Lower Taieri Plains contains secondary processing, manufacturing and service industry land uses.

2.4 Groundwater use and occurrence

Groundwater utilisation originally developed as a transition from shallow wells to small diameter driven tube wells, and eventually to deep bore development (e.g. Wingatui Bore). By far the most commonly used contemporary bores are now 4-inch and 6-inch[1] steel-cased bores, fitted with short, terminal screens (typically, 1m to 3m screen lengths). These are used for a relatively limited number of applications: domestic, stock, dairy shed, drip irrigation and general agricultural water uses. There is relatively little irrigation on the Lower Taieri Plains, and Resource Management Act (RMA) consents are generally being exercised mostly as a dry-year 'insurance' facility. On a volumetric basis, the Mosgiel water supply is the largest utilisation of Lower Taieri groundwater, followed by the extraction and re-injection of groundwater used in 'ground source' heat exchangers at Dunedin International Airport.

Groundwater is found throughout the Quaternary sequence, but higher volumes or yields of groundwater tend to be concentrated within coarser grained parts of the deposits such as sands, sandy gravels and coarse gravels. The Lower Taieri Basin is characterised by larger sediment grain size segregation in West Taieri and more variable patterns of grain size distribution in East Taieri.

The Mosgiel and North Taieri areas do not have the semi-confined conditions found further down-gradient in the Lower Taieri Plains. The water-bearing layers in East Taieri tend to be more highly stratified, although short-term pumping tests display apparent semi-confined phenomena (see section 3.3: "Aquifer Properties"). However, in terms of longer-term hydrologic behaviour, the groundwater response is closer to a stratified, unconfined aquifer. In common with unconfined aquifers, the groundwater of the Mosgiel and North Taieri areas displays the following phenomena inconsistent with semi-confined or confined pressurisation conditions:

- High to moderate nitrate concentrations at depth, indicating the infiltration of soil drainage.
- Consistently downward vertical groundwater pressure gradients.
- An absence of laterally continuous and recognisable confining layer(s).

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[1] Casing diameters are still sized in inches or their metric millimetre equivalents, e.g. 4-inch = 101 mm, 6-inch = 152 mm, 8-inch = 203 mm.

A few areas of flowing artesian groundwater condition remain at Wylie's Crossing in the East Taieri and the lower West Taieri Drainage Scheme area, although there are some signs that these areas diminished in the 20th century. The potential mechanism for a reduction in flowing artesian conditions may be the effects of land drainage causing long-term drawdown. The greatest depths to groundwater are noted in deeper bores in North Taieri and the least depth to water is observed beneath lower-lying, drained areas.

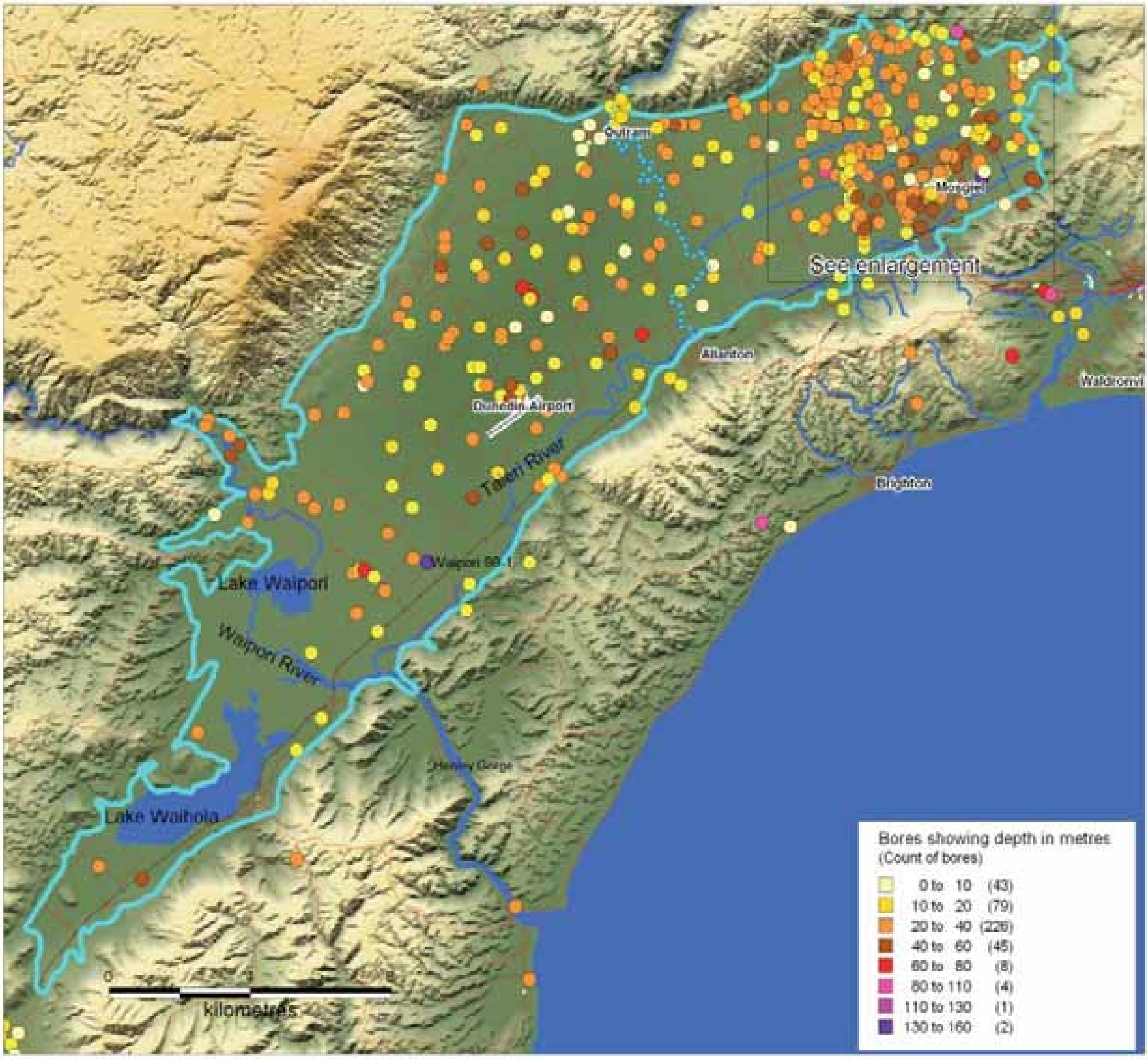

Figure 2.3 Bore locations and depths within the Lower Taieri Basin

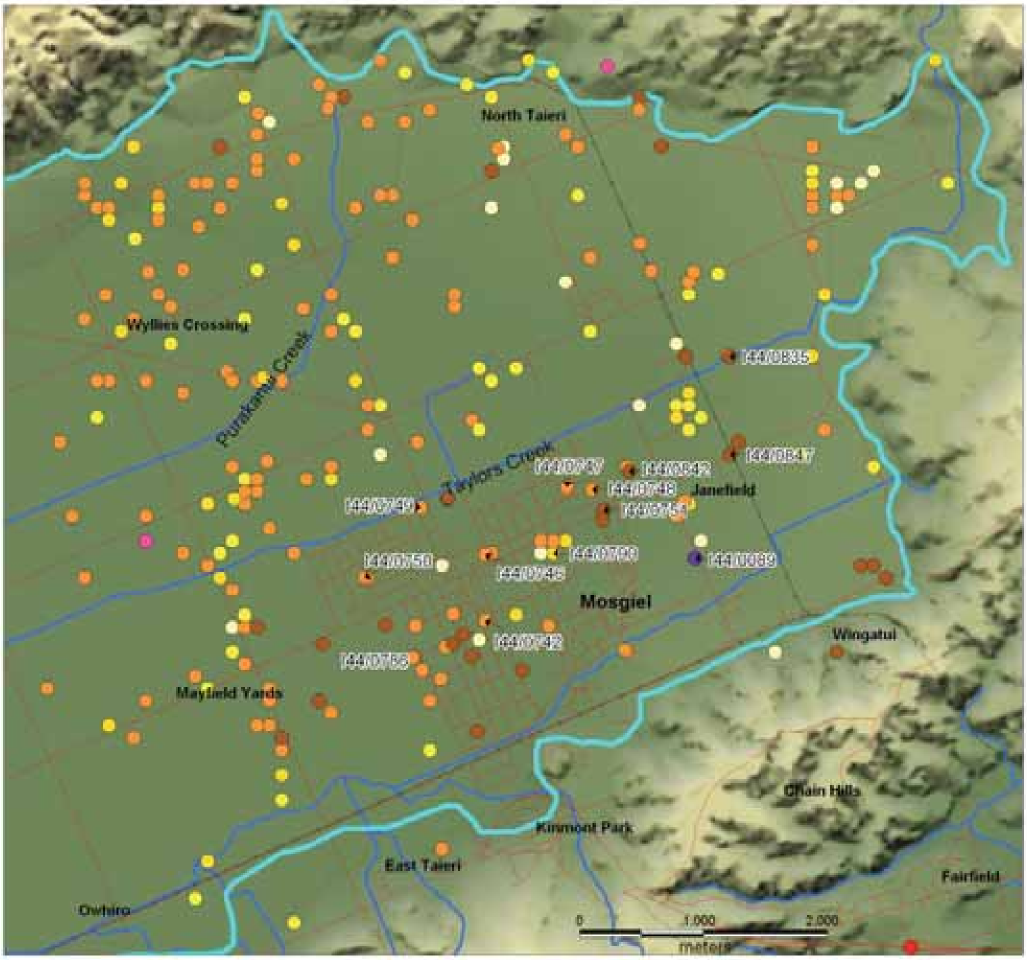

Figure 2.4 Bore locations in Mosgiel area showing bore numbers for some of the key bores in the area

3. Groundwater hydrology

3.1 Groundwater Flow Pattern

The prevailing groundwater flow pattern exhibited in water level surveys indicates elevated groundwater levels in the North Taieri area, north of Mosgiel, and declining with distance south-west (Figure 3.1). The land surface of the Taieri Plains follows a similar pattern: the ground level lies at about 30m AMSL north of Mosgiel and grades down to within a couple of metres of sea level (100m OMD) in the south-west at Henley. Within this broad pattern of groundwater elevations, there are a few distinct transitions:

- The pumping of the Mosgiel bores over many decades appears to have induced the formation of a hollow in the groundwater surface, with groundwater flow converging on the hollow from up-gradient recharge areas.
- School Swamp in the East Taieri functions as a discharge zone for this part of the groundwater system and a similar convergence of local groundwater level contours.
- The Taieri River from its emergence onto the Plains at Outram and downstream to Allanton appears to control the shape of the groundwater level surface.
- The West Taieri Drainage Scheme gives rise to a large scale deflection of the groundwater level surface.
- The Lake Waipori Wetlands Complex (LWWC) is a strong local control on adjacent groundwater levels.

The groundwater contour map (shown in Figure 3.1), based on 52 levelled bores measured in mid-May 1994 (IRRICON and Royds Consulting, 1994), is still the definitive groundwater level contour map for the Lower Taieri Basin. The map shows that the lowest groundwater contour coincides with the mean water level of 0.4m AMSL at Henley Ferry, which is effectively the local "mean sea level", once the tidal exchange resistance of the Henley Gorge is considered. The groundwater level contours are relatively widely spaced, across the West Taieri, which indicates low gradients. In East Taieri, there is a steeper groundwater level gradient, from approximately 28m AMSL at Black's Bridge (over the Silver Stream) down to 3.5m AMSL, where the East Taieri meets the river.

Most groundwater levels were measured from bores with a "mid-range" of depth, typically 15m to 35m below ground level (BGL). In the Mosgiel area, there is a distinct downward vertical hydraulic gradient. However, within the south-western part of the basin near Henley, the vertical pressure differences are negligible. This pattern implies strong infiltration gradients in the Mosgiel area and weak seepage gradients in the discharge zones.

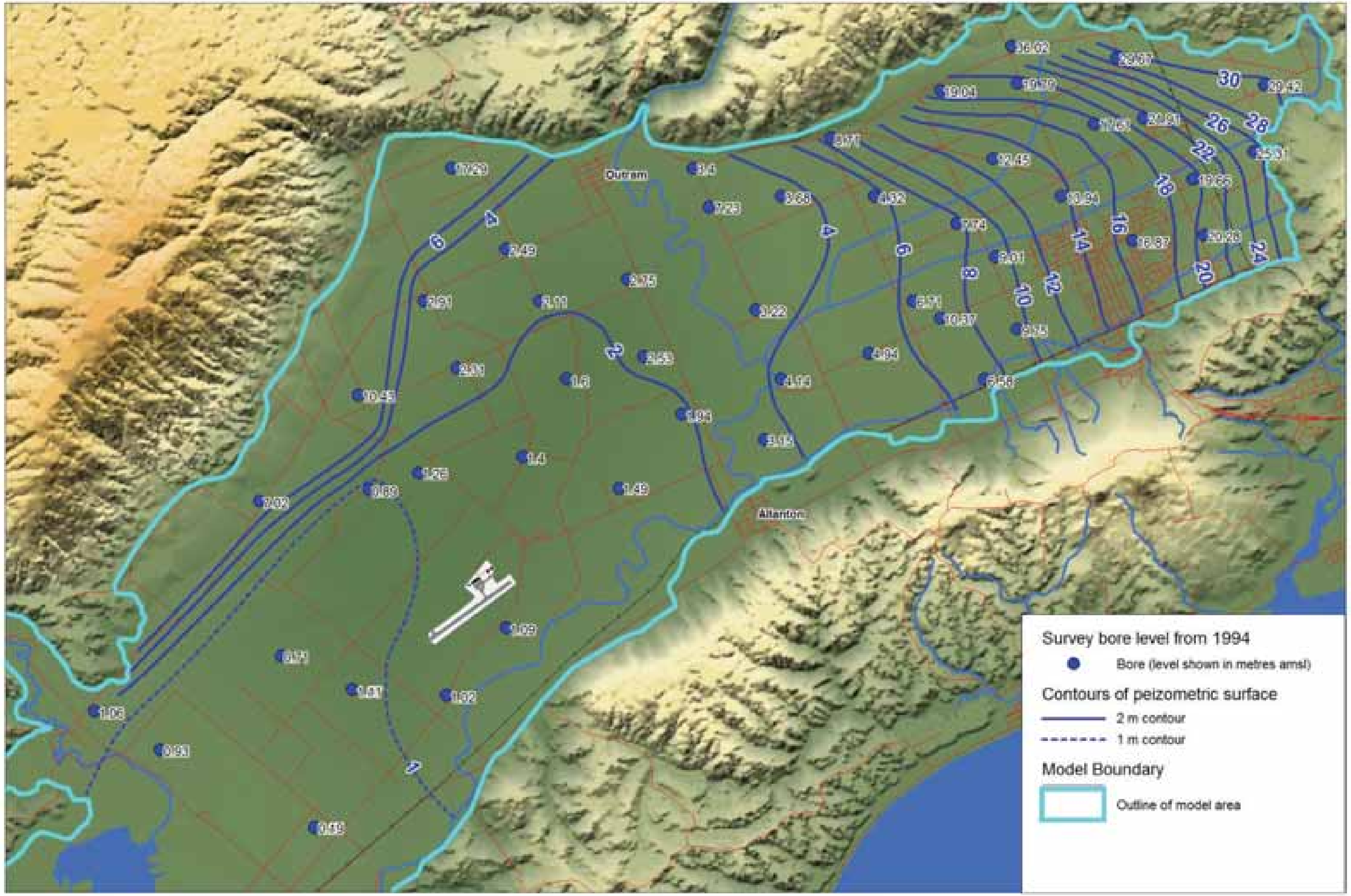

Figure 3.1 Contours of potentiometric surface from the 1994 survey of groundwater levels. Groundwater flow direction is perpendicular to the contours

3.2 Groundwater level through time

3.2.1 Woollen Mills shallow well

The earliest record of groundwater level goes back to 1922 for the shallow well (I44/0790) used by Mosgiel Woollen Mills (Collins, 1950). The record reported and graphed in Collins (1950) extended from that date to 1949, a continuous record spanning 27 years. Significantly, the record relates to measurements taken every Monday morning before pumping was required in the mills, from a well of only 6.1m depth. The measurements are, therefore, unlikely to have drawdown interferences from either self-induced or nearby pumping, and were taken from the unconfined aquifer that is more directly influenced by climatic fluctuations. As such, the record is suitable for inferring the influence of climate-related recharge effects on the groundwater in Mosgiel. Figure 3.2 shows the hydrograph that was recorded in this manner.

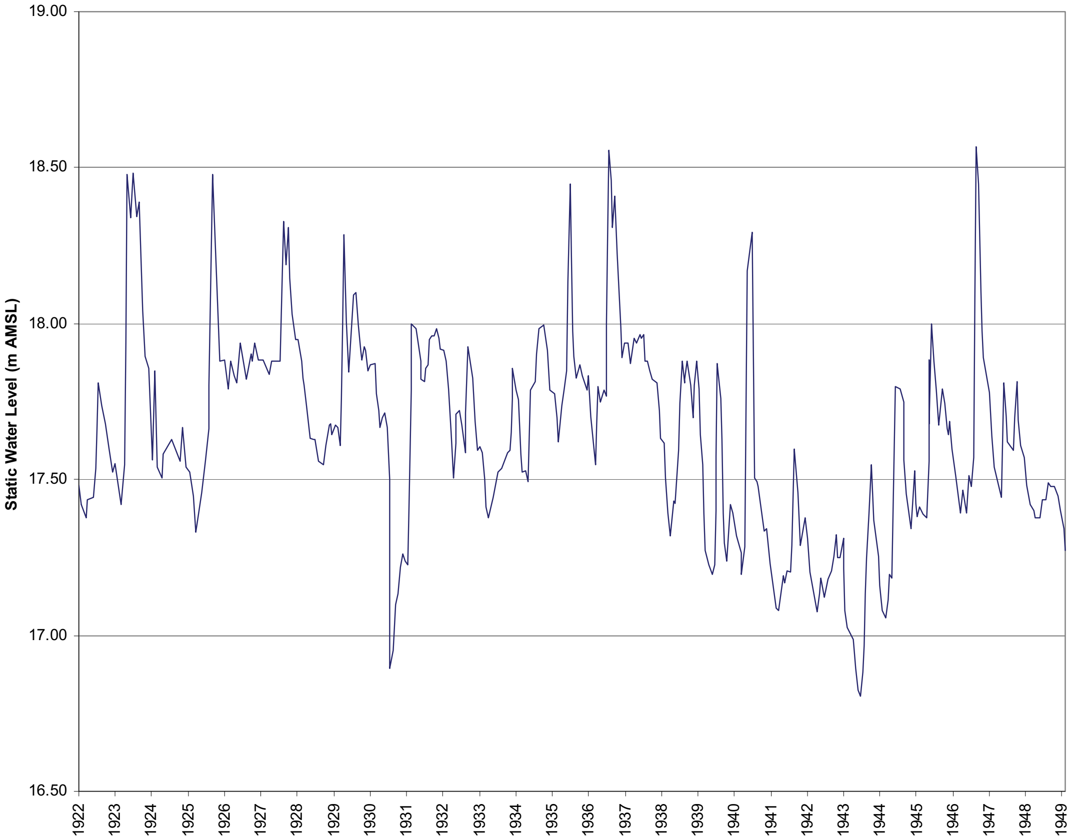

Figure 3.2 Graphical plot of the water level record as taken every Monday in the Mosgiel Woollen Mills shallow well (I44/0790) prior to pumping resuming for the week

Of note is that total water table variability is within 2m of rise and fall. When the water table hydrograph is compared with the rainfall recorded at Whare Flat (9 km to the north-east), the resulting plot reveals some degree of response to rainfall in water table rises. Figure 3.3 shows the correlation as side-by-side plots of the water level and rainfall daily totals for period 1922 to mid-1943.

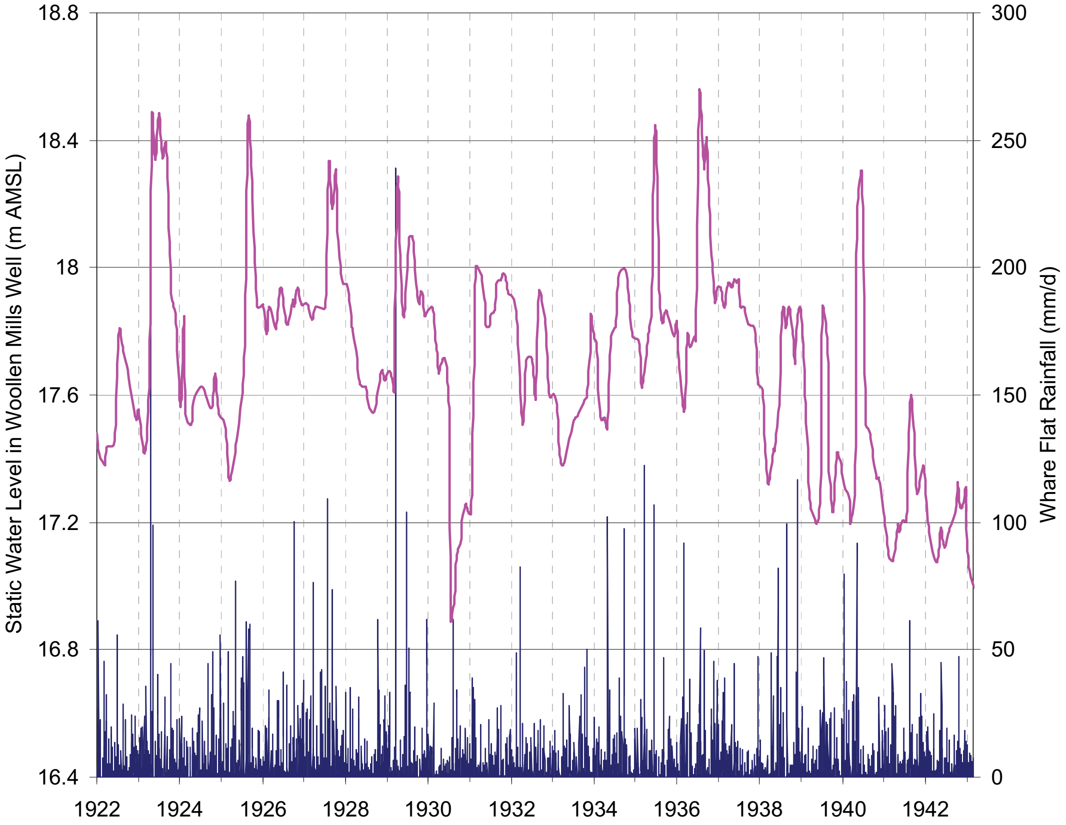

Figure 3.3 **Side-by-side plot of the Mosgiel Woollen Mills water level and corresponding Whare Flat rainfall**

The correspondence between higher rainfall and water table rises suggesting that rainfall-driven recharge is the dominant mode of replenishment for the shallow groundwater in the Mosgiel area. Assuming an unconfined storage coefficient of specific yield of 20%, the 2m level fluctuation implies a recharge rate of approximately 400mm/yr. This question will be explored further in Section 5.4: Determination of Recharge.

3.2.2 Mosgiel Borough Yard Deep Bore

An independent record, of the piezometeric (semi-confined groundwater level), measured in the Old Yard Bore (I44/0742) in Mosgiel during 1948 and 1949 was also reported in Collins (1950). The level record spanned the period of testing at the Wingatui Bore and indicates the groundwater level within one of the deeper water-bearing layers beneath Mosgiel.

The Mosgiel Old Yard Bore was not itself pumping during the three aquifer tests conducted at the Wingatui Bore during late July and early August. This allowed the drawdown effect resulting from the distant Wingatui Bore pumping to be discerned in Old Yard Bore. This bore in Mosgiel registered a 0.26m fall during the first pumping test when the Wingatui Bore was pumping at a rate of 26l/s. Further information concerning the use of this data in deriving aquifer properties is outlined in Section 3.3: Aquifer Properties and Confining Status.

3.2.3 ORC Automated Level Recording

The ORC groundwater surveys in the Lower Taieri Basin began in May 1994. Although new to groundwater level recording, the ORC rolled out a programme of level monitoring in strategic positions. The first automated, continuous groundwater level records began in April 1995 at Janefield Bore (I44/0849), near Mosgiel, and Momona Bore (I44/0848), near the Dunedin International Airport in the West Taieri. This automated record was followed by Harley Bore (I44/0842, December 1995), Donnelly Bore (I44/0835, February 1996), Outram Bore (I44/0838, April 1997) and Waipori 99-1 (I45/0007, July 2006). The Janefield Bore's (I44/0847) record was discontinued in July 1999, because the multi-level Harley Bore P2 piezometer had proved to be a superior monitoring site by then.

The Harley Bore and Donnelly Bore level records are segregated into deeper and shallow groundwater piezometer records, and labelled "P2" for the deeper piezometer settings (36.5-39.5 m; and 41.0-43.0 m, respectively) and "P6" for the shallowest piezometers (5.5-7.5 m; and 7.0-9.0 m, respectively). The intention and effect of segregating the groundwater level records in this way is to contrast the deeper water-bearing layer which most closely reflects the water supply layer, with the shallow, unconfined water-bearing layer. The Harley and Donnelly Bore P2 piezometers show quite different record trends due to the relative distances to the closest Mosgiel water supply bores. The Harley Bore is only 350m away from the Severn Street (I44/0748) and Battleaxe Bore (I44/0751), and 500m from the Cherry Drive bores No. 1 (I44/0747) and 2 (I44/0743). The Donnelly Bore is more than 1,600m away from these bores and set on the opposite bank of the Silver Stream. Predictably, the P2 piezometer hydrographs at the Harley Bore display the hallmarks of starting and stopping the Mosgiel water supply bores. Equally, the Donnelly Bore hydrograph in the P2 piezometer is much smoother, displaying much subdued Mosgiel pumping drawdown response.

The shallow P6 peizometers in the Harley and Donnelly bores also display contrasting hydrograph patterns, despite being both screened in the same shallow, unconfined compartment. The difference in this case is their proximity to the Silver Stream. The Harley Bore is 500m from the river, while the Donnelly Bore is less than 40m away.

3.3 Aquifer Properties and Confining Status

3.3.1 Bulk Parameter for Mosgiel - Momona Aquifer

Several aquifer tests have been performed in the Lower Taieri Basin. The first was the observation of a 26l/s continuous test pumping of the Wingatui Bore (I44/0089), in Wingatui Road, from 27 to 30 July, 1947 (Collins, 1950). A recent analysis by ORC of this three-day aquifer test, using steady state drawdown-distance data, derived a transmissivity for the screened water bearing layers (18m to 53m depth). Figure 3.4 shows the semi-logarithmic plotting of the drawdown measured in observation bores at differing radii from the Wingatui Bore and the corresponding final drawdown.

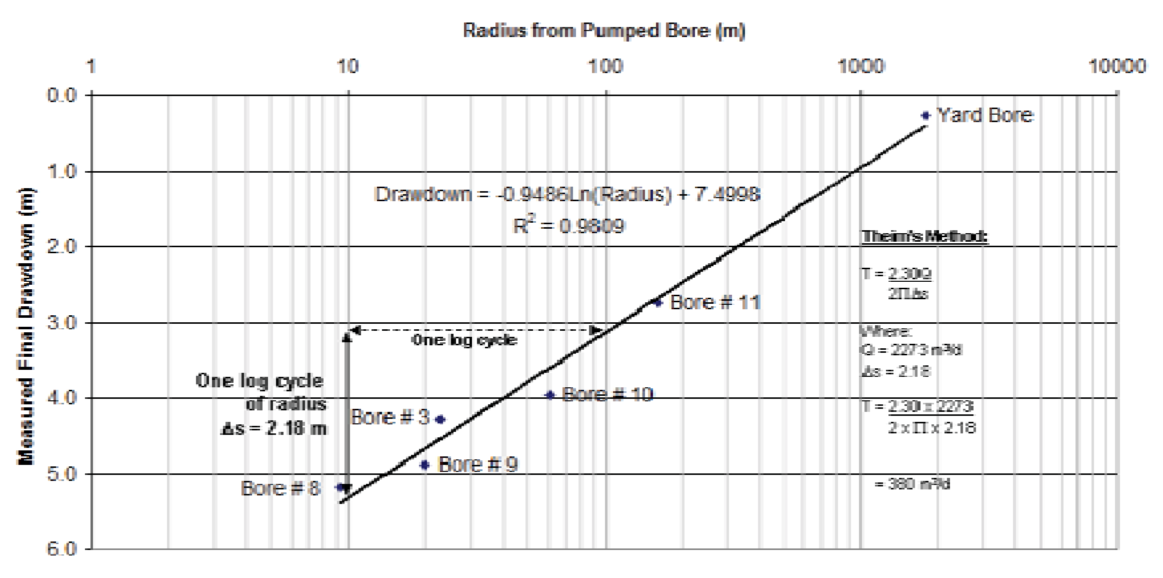

Figure 3.4 Plot of the relationship between measured final drawdown at the close of the three-day aquifer test at Wingatui Bore (I44/0089) in July-August 1947 and the radius of the measurement point from the pumped bore

The DCC had installed a dozen observation bores in an array of distances from the production bore and these were monitored during the pumping test. The Mosgiel Old Yard Bore (I44/0742) was also monitored during the test and this drawdown is also plotted above. The Theim method was used to derive a transmissivity from the slope of the semi-logarithmic trend line connecting the drawdown measurements. Figure 3.4 illustrates the plotting of the trend line and the calculations used in the Theim method. The derived value for transmissivity was calculated at approximately 400m^2/d. When the screened length was considered, the bulk permeability could be estimated at 10 m/d. These derived parameters are thought to be broadly reflective of the bulk hydraulic parameters of the water-bearing layers in the 25m to 50m depth range utilised in the Mosgiel District. To this extent, the 1947 aquifer test result is very useful in providing this parameter and demonstrating the connectivity of water-bearing layers in the Mosgiel area.

3.3.2 Outram Bridge well field unconfined aquifer

Dunedin City Council engineers conducted aquifer tests on the Outram Bridge well field (well records I44/0753 and I44/0736) in November 1964. The interpretation of these tests in 1964 gave a transmissivity of 17,000 m^2/d. In 1990, consultants conducted follow-up aquifer tests for Dunedin City Council in the vicinity of the well field site (GCNZ, 1990). The interpretation of the GCNZ tests on the same well field gave a transmissivity of 14,500m^2/d. Subsequent testing in 1996 (AquaFirma, 1996) used an eleven-day pumping test, a combination of conventional curve fitting to drawdown-time data and transient groundwater modelling to derive a set of aquifer parameters as follow:

- Transmissivity = 14,000m^2/d
- Permeability = 1,410m/d

- Specific yield = 0.20 or 20 %
- Adjoining river conductance = $500m^2/d$.

The aquifer testing relates solely to the DCC Outram well field, which is thought to be a restricted zone of higher permeability. Investigation drilling and profiling of geophysical resistivity measurements indicated that the higher permeability conditions declined markedly from 200m to 300m downstream of the Outram Bridge on the southern edge of the well field (AquaFirma, 1996).

3.3.3 Individual Mosgiel water bearing layers

A total of ten pumping tests were conducted on Mosgiel water supply bores from 1970 to 1990, often as drilling completion tests. Six of these tests could be analysed for hydraulic parameters [Old Yard (I44/0742), Ayr St (I44/0782), Battleaxe (I44/0751), Reid Ave (I44/0746) and Watt St (I44/0750)]. The derived ranges in transmissivity and permeability lay between 1,250 and $80m^2/d$, and 123 and 61m/d, respectively. However, these results bear a bias as only the most successful and efficient bores were integrated into the water supply; thus, the sample over-represents higher permeability zones of the groundwater system. Testing of the Mosgiel water supply groundwater system was also undertaken in 1996 (IRRICON and Royds Consulting, 1997). Pumping effects of the Severn (I44/0748) and Ayr Street (I44/0782) bores in turn were observed at a number of bores in the Mosgiel district, including the purpose built multi-level observation bore, the Harley Bore. Both tests derived transmissivities of approximately $500m^2/d$.

An irrigation bore (S.A. Mitchell, I44/0452) immediately to the north-west of Mosgiel was also analysed in the IRRICON and ESR (1997) report, and derived a figure of $300m^2/d$ for transmissivity for the 2.6m thick water-bearing-layer. All aquifer testing in the Mosgiel district indicated the order of magnitude for storativity (a measure of aquifer storage capacity) to be about $1 \times 10^{-}4$. Leakance is a measure of the ability of a semi-confined aquifer to exchange groundwater with adjoining aquifer. In the few instances when leakance could be derived from aquifer testing, the value lay in the realm of $2 \times 10^{-}4$ /day, indicating light semi-confining conditions.

3.3.4 Mosgiel district shallow, unconfined aquifer

The Donnelly Bore P6 piezometer and its hydrograph were used to estimate the shallow unconfined aquifer's permeability as part of this study. Hydraulic Diffusivity Analysis can be used where there is a concurrent surface water level record. In this case, the stage record for Silver Stream at Taieri Depot was used to provide the simultaneous river level hydrograph. The channel cross-section at Donnelly Bore and at Taieri Depot were compared and naturalised to standardise the rise in river stage at both sites. Figure 3.5 shows the respective water level rises for same flood event in February-March 2009.

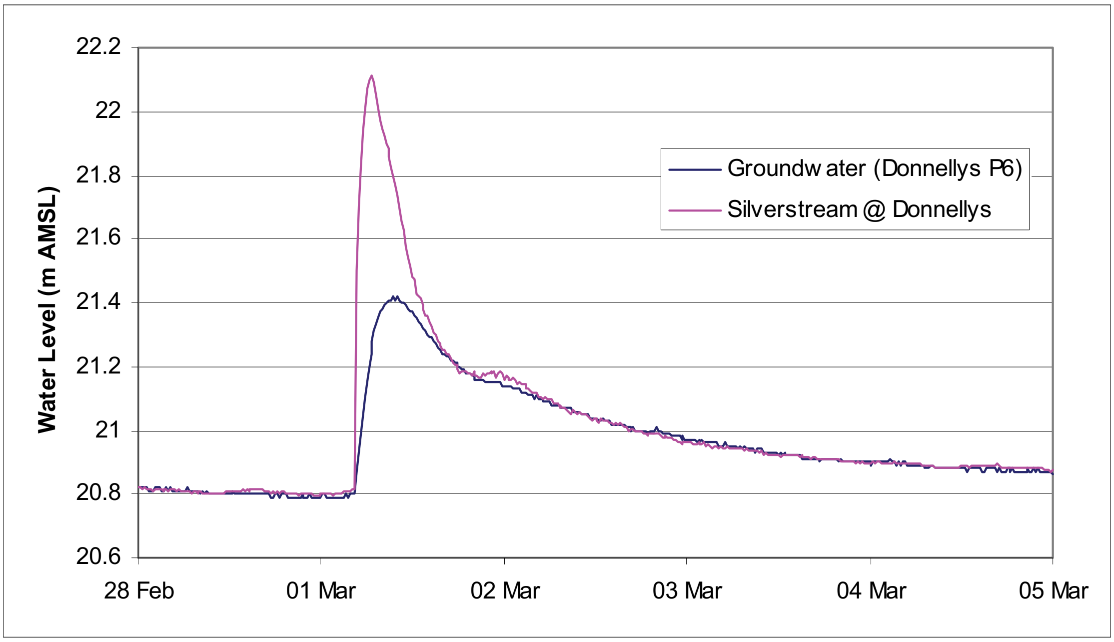

Figure 3.5 Concurrent water level rise in Donnelly Bore P6 piezometer and Silver Stream during a flood in the Silver Stream following summer low flow in February 2009

Figure 3.5 shows the timing and magnitude of the rise in both surface water and the adjoining shallow, unconfined groundwater. The diffusivity analysis allowed the derivation of a diffusivity coefficient. The diffusivity coefficient was readily converted into an aquifer transmissivity, which in the case of the Donnelly P6 piezometer on 1 March 2009 was calculated to be 1,470m^2/d. The dual recorded flood event and analysis also demonstrated that the Silver Stream rests on the same water level as the shallow, unconfined layer and “pumps” water into the water-bearing layer in response to high flows. During the waning phase of the flood, the shallow aquifer declines at the same rate as the Silver Stream, suggesting that the shallow aquifer is discharging the flood surcharge back to the Silver Stream in response to the flood recession. The inferred consequence is that the shallow groundwater system responds by slightly lagging the Silver Stream level changes, but does not attain the flood peak water level. Following the flood peak the shallow aquifer appears to decline at the same rate as the Silver Stream, suggesting that the discharge of the water is “pumped” into the aquifer by the flood during the flood recession. In this manner, the shallow aquifer provides “bank storage” to the Silver Stream. There are no other known aquifer test measurements of the shallow, unconfined layer in the Mosgiel district.

3.3.5 West Taieri: Mosgiel-Momona Confined Aquifer

Three aquifer tests with observation bores were undertaken in farm bores of the West Taieri (IRRICON, 1997). Hydro-stratigraphically, these bores and their respective observation bores would appear to penetrate through the Waihola Silt-Sand aquitard and into the top of the Mosgiel-Momona Confined Aquifer which is characteristic of the West Taieri. The test derived parameters can be summarised as follows:

- Transmissivity range: 740 to 1,530m^2/d
- Permeability: 110 to 150m/d
- Storativity range: 1.2 x 10^{-4} to 3 x 10^{-4}
- Leakance: approximately 1 x 10^{-10} /d

The Mosgiel – Momona Confined Aquifer was also the subject of aquifer testing at Dunedin International Airport, Momona (unpublished data, Opus International Consultants Ltd, August 2008). Initially, partially penetrating bores screened in the top of the Mosgiel-Momona Confined Aquifer were tested in 2004. These tests on bores of approximately 30m depth derived transmissivities of between 1,200m^2/d and 1,600m^2/d. Subsequently, more closely supervised tests using fully penetrating extraction/injection bores and observation bores in 2007 and 2008 derived the following results:

- Transmissivity range: 650 to 850 m^2/d.
- Storativity range: 9 x 10-3 to 7 x 10^{-4}

It is inferred that the tighter range in aquifer transmissivity results achieved in the later tests is a partial consequence of the newer test bores being fully penetrating. It is also clear from recent aquifer testing results that a much less variable pattern of hydraulic properties is expressed within the West Taieri aquifer tests than the Mosgiel area testing. This more consistent pattern for the West Taieri accords with observations as to sedimentary geology. Unfortunately, there has been no known aquifer testing of the Henley Deep Confined Aquifer under the West Taieri, which is characterised from only one drill hole (Waipori 99-1) as a thick, almost continuous sand and gravel measures from its top at 60m to a depth of at least 154m.

The aquifer testing at Momona by Dunedin International Airport also helped to estimate the permeability of the Waihola Silt-Sand aquitard. A comparison of the second extraction bore test (I44/1036) at the airport and an observation bore (I44/1006) indicated a vertical flow resistance (c-value) across the aquitard of approximately 33 days. The leakance parameter and the thickness of the aquitard were used to derive a permeability of 0.1m/d for the overlying Waipori Silt-Sand. Such permeability would still be capable of allowing moderate seepage fluxes across the aquitard.

3.3.6 Storage coefficients

Storage coefficients are sensitive to the pressure state (e.g. unconfined or confined) of the aquifer or water-bearing layer they are derived from. In the case of the stratified, unconfined groundwater area in the Mosgiel district, the pressure status is often ambiguous. For short-term measurements, such as pump testing, the apparent pressure state is semi-confined with apparent storativity values less than 1×10^{-3}. However, the true groundwater system behaviour is closer to water-bearing layers that represent local enhancement of permeability in the horizontal plane. Vertical movement of groundwater is quite feasible as demonstrated by the presence of elevated nitrate-nitrogen concentration in the water-bearing layers used for water supply beneath Mosgiel.

Accordingly, this duality in pressure state and storativity values means that the results for storage coefficients from pumping tests should be used in groundwater computer modelling with considerable caution. Fortunately, the unconfined specific yield coefficient for sandy gravel and associated alluvial sediments is well established from international or national aquifer testing. Table 3.1 lists representative values of specific yield (unconfined storage coefficient) for alluvium (Kruseman and de Ridder, 1994).

Table 3.1 Representative values of specific yield in alluvial deposits

Material	**Specific yield (%)**
Coarse gravel	23
Medium gravel	24
Fine gravel	25
Coarse sand	27
Medium sand	28
Fine sand	23
Silt	8
Clay	3
Peat	44

Only one pumping test in the Lower Taieri groundwater system has allowed the derivation of specific yield. This was the 11-day pumping test in the Outram bores, which was analysed using a transient computer model (AquaFirma, 1996). The derived specific yield was 20%, which is broadly consistent with the table value of specific yield for coarse gravel.

Confined storativity has also been measured in several observed aquifer tests. The full range of all plausible storativity values measured in either semi-confined aquifers or stratified water-bearing layers was from 1×10^{-4} to 9×10^{-3}. This range of values is consistent with semi-confined pressure status.

3.4 Determination of groundwater recharge

Groundwater recharge is the replenishment of the groundwater system by incoming flows or fluxes of water. The main potential sources of recharge can be summarised as follows:

- Rainfall excess recharge as soil drainage, otherwise known as Land Surface Recharge (LSR)
- River-stream recharge as infiltration of surface water into the groundwater system
- "Range-front" recharge, where surface runoff from slopes overlooking plains infiltrate at the transition between slope and plain.

Land Surface Recharge (LSR) is examined in the context of the constraints that climate and soil profiles impose on such recharge, and is the subject of recharge modelling in Appendix B attached to this report. A groundwater system can also be naturally recharged by upward seepage of groundwater from deep circulation. In view of the low bulk permeability of the bounding Haast Schist rock, the possibility of deep circulation appreciably contributing to recharge is low.

Three high-volume, perennial rivers cross the Lower Taieri Plains, namely the Taieri, Silversteam and Waipori. These water courses are known to have zones of alluvium with enhanced permeability where they enter the basin that would allow the infiltration of surface water if the surface water–groundwater gradient favoured such an exchange. Several investigations (IRRICON and ESR, 1997; Holmes, 2003) have attempted to quantify the exchange between the respective rivers and the Lower Taieri groundwater system. The results have been contradictory and have certainly proved elusive to previous investigators. It is the authors' expectation that the recharge from the rivers to the aquifers would be dynamic in response to relative water levels and the timing of level changes, thus complicating the quantification of such recharge.

3.4.1 Silver Stream recharge

Previous investigations for the ORC had determined that the Silver Stream was the "primary source of recharge to the main aquifer system, estimated at 80% or more of current groundwater pumpage" (IRRICON and ESR, 1997). The same investigation found that net losses from the Silver Stream to groundwater equated to 60l/s to 80l/s. Approximately 29l/s losses were estimated from same-day, multiple-site gaugings of the Silver Stream between Puddle Alley and Wingatui Road (IRRICON and ESR, ibid). Subsequent gaugings by Master of Science student Gillian Holmes (2003) during five gauging runs in 2001 suggested a different pattern, by indicating substantial gains in stream flow at Silver Stream flow rates between 400l/s and 900l/s. Holmes concluded that the Silver Stream gained flow from groundwater as it crossed the North Taieri plain. However, the two gauging runs conducted at Silver Stream flow rates below 200l/s also suggested losses to groundwater between Puddle Alley and Wingatui Road. Two possibilities to account for the contrasting conclusions for groundwater exchange with the Silver Stream in the reaches above Mosgiel could be advanced:

- Higher flow rates have obscuring factors hindering the observation of loss of Silver Stream flow to the ground

- The magnitude of the higher flow rates masks the ability to determine losses due to larger absolute inaccuracies, and
- Tributary inflows from side creeks or drains dominate the change in flow from site to site [refuted by (2003) refuted].
- The accuracy of the gauging methods is not capable of adequately resolving the magnitude of losses to groundwater.

Inferences as to the recharge sources for the Mosgiel area of the basin have also been informed by examination of the age or chemical stratification of Mosgiel groundwater. In particular, the mass balance of certain constituents drawn in Mosgiel Township suggests that the Silver Stream was a minor source of the water coalescing in the water supply layers (25m to 50m depth).

To resolve this uncertainty as to groundwater-surface water interchange upstream of Mosgiel, in early 2009, this investigation set out to repeat the same-day, multiple-site gauging approach followed by ORC (1997) and Holmes (2003) with the following enhancements:

- Multiple gauging runs (i.e. on multiple occasions) would be undertaken to assess the level of accuracy inherent in the gauging
- Low flows at or below 100l/s would be chosen, and gaugings conducted in low flow conditions would be less likely to be confounded by tributary inflows
- The sites chosen for repeat gaugings were also within the zone considered to be the most likely to experience the most important interchanges between groundwater and surface water.

The furthest gauging site upstream was placed just downstream of the Flagstaff Creek-Silver Stream confluence, thus removing the Flagstaff inflow from possible interferences to interpretation of the gauging runs.

More accurate gauging equipment was available (to conduct gaugings) in 2009 than was available to the ORC in 1997.

It was fortunate that the investigation coincided with a period of settled climate conditions and stable flow in the Silver Stream during January and February 2009. Table 3.2 lists the results of the three gauging runs, and figure 3.6 shows the flow on 19 February 2009.

Table 3.2 Results of ORC Silver Stream gauging runs, 15 January to 19 February 2009

Site	**Flow (litres per second)**		
	15 Jan 2009	**3 Feb 2009**	**19 Feb 2009**
Invermay Farm	125	97	94
Puddle Alley	136	98	100
Railway Bridge	121	86	73
Wingatui Road	137	72	64
Gordon Road	136	82	68
Riccarton Road	150	90	59

The results from gauging runs on 3 and 19 February suggest losses between 26l/s and 36l/s between sites at Puddle Alley and Wingatui Road. The gauging run on 15 January is less plausible, given that the factors cited above in relation to gauging runs wereconducted at higher stream flow rates. These results suggest that losses to groundwater between Puddle Alley and Wingatui Road are consistent with the 29l/s derived from the single gauging run in 1996 (IRRICON and ESR, 1997).

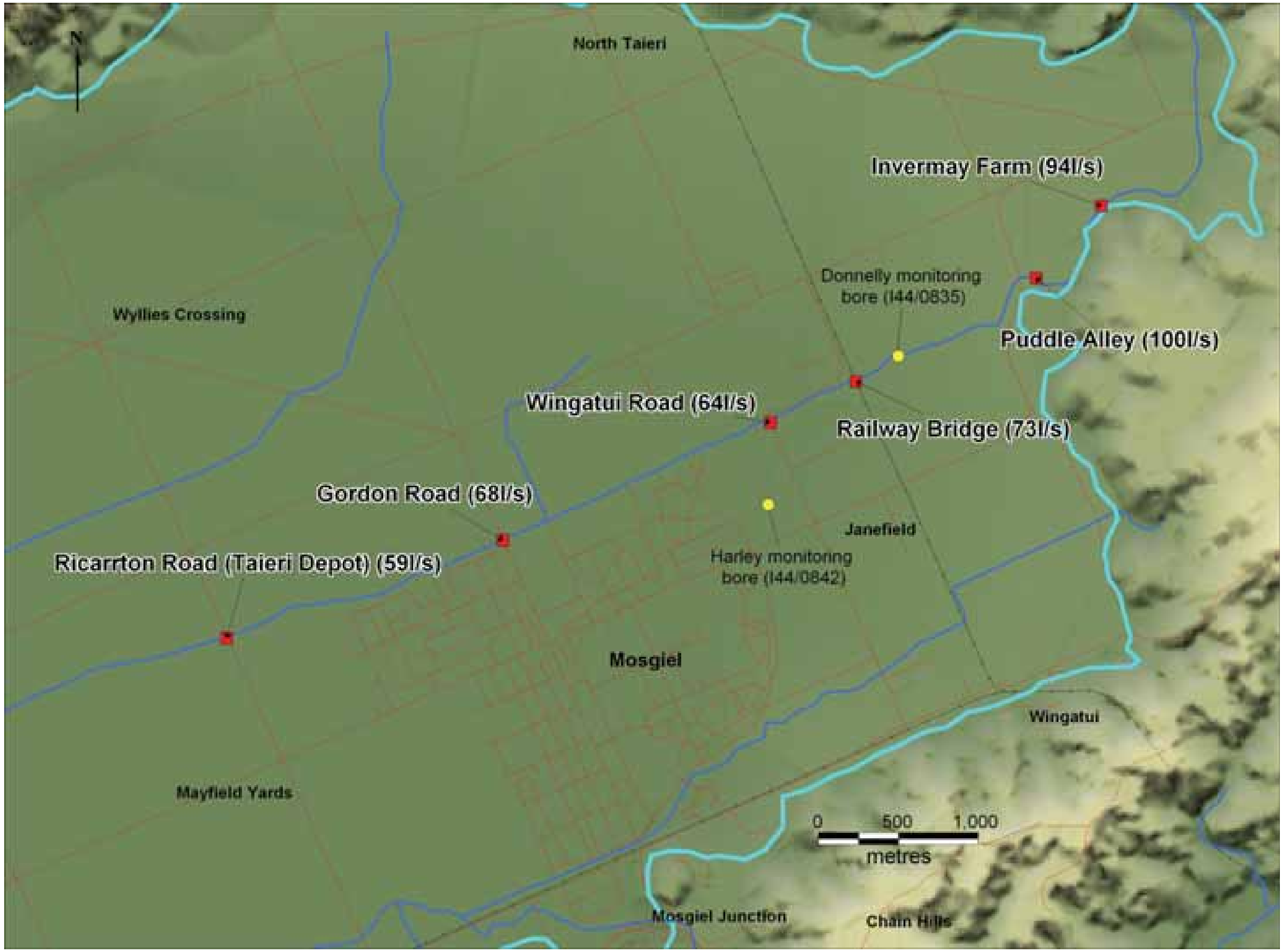

Figure 3.6 Position of flow gauging sites on Silver Stream and flow on 19 February 2009

There was clearly a temporal and antecedence factor in the magnitude of losses to groundwater from the Silver Stream. This is illustrated by the difference in loss rate between 3 February and 19 February, despite the initial flow in the Silver Stream being the same (~100 l/s) in both gaugings. It was speculated that the hydraulic gradient between the Silver Stream and shallow groundwater was the controlling factor. For argument's sake, if the level difference between the Silver Stream and shallow groundwater had been greater on the second of the February gauging runs, the rate of loss to groundwater could also have been expected to be higher.

Two sets of level sensors and dataloggers were installed at the Donnelly Bore site in February 2009 during low flow in the Silver Stream test the significance of water level differences. One level sensor-datalogger set was installed in the channel of the Silver Stream; the other set was installed in the shallowest Donnelly piezometer (P6), which measures the groundwater level of the saturated gravels between 7.5m and 9.5m depth. The dataloggers thus measured the fluctuations of the river and adjoining groundwater simultaneously. The heights were surveyed for both the Silver Stream datalogger and the shallow bore cap, allowing the water levels to be plotted on the same height datum (Mean Sea Level). The water levels were observed throughout the steady flow period and throughout two minor flood in the Silver Stream from 20 to 23 February when the flow rate jumped from 60 l/s to 18,300l/s, which raised river levels by 1m. During this period, 125mm of rain fell in the Silver Stream headwaters and 52mm fell in Mosgiel. The transducers revealed the level change peaking at 22.1m in the Silver Stream at Taieri Depot and 21.4m at Donnelly's Bore. Figure 3.5 shows the simultaneous water level plot of river stage height and shallow groundwater level in the adjoining unconfined aquifer. The differences in magnitude and timing of the respective level peaks during the high flow event allowed the derivation of the hydraulic diffusivity between the Silver Stream and the shallow groundwater. From this parameter, the groundwater parameters of transmissivity and permeability were calculated. Appendix C details the investigations at the Donnelly's Bore site, including the hydrograph and cross-sections of the Silver Stream and groundwater levels.

Significantly, the level plot at Donnelly's Bore revealed apparent fluctuations in the head differences and interchange characteristics between the river and shallow groundwater. The inference is that the small downward hydraulic gradient between the river into the shallow groundwater promotes losses of river water, as is suggested from the concurrent gauging investigation. As the river levels rise during the high flow event, the gradient steepens, suggesting that losses increase. At a given point, the river level peaks and begins to fall, before the same is exhibited in the groundwater level. As the river level drops below the groundwater level, a gradient is created promoting the reversal of interchange into the river. This period of overlap is short-lived and is overtaken by a return to the previous downward gradient into the shallow groundwater.

The investigations in the Mosgiel area into recharge from the Silver Stream drew the following conclusions:

- There is a recharge of river water to the shallow groundwater between Puddle Alley and Wingatui in the order of 30l/s during low flows in the Silver Stream
- Due to the downward hydraulic gradient, shallow groundwater makes its way slowly to lower water-bearing layers in the groundwater system

- In this manner, the Silver Stream is a partial source of recharge to the deeper water supply aquifer, albeit mixed with waters of other origin and having taken years to end up at that depth.

The polarity and magnitude of groundwater recharge to the aquifer may change as a function of the relative state of the following:

- Silver Stream flow rate and stage height, and
- Shallow groundwater level in the water bearing layer in closest connection with the river
- Periodic high flows such as freshes and floods produce a coupled succession of inflows and outflows with shallow groundwater and the Silver Stream, commonly termed “bank storage”
- Thus the Silver Stream is in a dynamic equilibrium with the adjoining groundwater, which is upon occasion perturbed by low and high flow events.

Range-front recharge along some of the basin margins has also proved to be problematic for estimation and there is little conclusive evidence that it is operative to any significant level. Indeed, the evidence of continuity of flow in tributary flow crossing from the hill front to the Taieri Plains (i.e. the streams or creeks do not appear to dry up on crossing onto the plain), and the observed apron of silty material, tend to diminish the possibility of range-front recharge in the Lower Taieri Basin.

3.5 System boundaries

Groundwater system boundaries typically comprise the following:

- Impermeable boundaries, such as margins against low permeability sediments or rock
- Fixed head boundaries, such as a sea or lake shore line
- River boundaries, such as a stream or river features flowing through the groundwater system
- Discharge boundaries, such as wetlands, springs, drains or creeks, that serve to receive the seepage outflows of the groundwater system.

The Lower Taieri Basin is relatively rare in being entirely encircled by impermeable basement rocks, both Haast schist and Henley breccia. Inputs to this basin come via the three rivers, the Taieri, Silver Stream and Waipori, that enter the basin through gorges cut into the schist basement. The basin discharges into wetlands such as School Swamp and the Lake Waipori Wetlands Complex, drains or as groundwater pumping at bores. The groundwater system has none of the more complicated “notional” boundaries such as those placed on groundwater divides or assumed inflows to account for exchange within an adjoing groundwater system. However, the basin does have one factor hampering an understanding the operation of boundaries: the inability to flow-gauge the outflow at Henley Ferry, due to the flood and ebb tidal flows also passing this point in the system.

The West Taieri Contour Channel is an artificial flood protection and drainage channel cut as part of the West Taieri Drainage Scheme. The Contour Channel intercepts streams draining the range-front of the Maungatua Range before they can enter the drainage scheme area, and conducts the water south-westward into Lake Waipori under low gradient, as the name Contour Channel implies. The objective achieved by the operation of the Contour Channel is to relieve the drainage scheme of the addition of a substantial part of the run-off that would otherwise burden the pumped drain network. However, the groundwater contour map for the area also shows a significant fall in groundwater level in the vicinity of the Contour Channel, which suggests that the channel is active in bounding the groundwater system along its alignment.

3.6 System water balance

A water balance for a groundwater basin is an accounting of the normal inflows and outflows from the basin. The types of inflows are typically land surface recharge as drainage of soil moisture through the soil profile and the infiltration of surface water where water bodies make contact with the aquifer. Outflows include aquifer loss to surface water, wetlands, lakes or groundwater pumping. In many instances of groundwater basins, these water balances can be reasonably accurately estimated, using flow measurements of soil hydrology, and flow loss accounting, using multiple-site stream gaugings, or measurement of spring flows and metering of groundwater abstraction. In the case of the Lower Taieri Basin, the opportunity to measure many of these critical zones of groundwater surface water exchange is hampered by inherent factors of the basin’s hydrology and physiography.

The basin is crossed by no less than three significant rivers. On average, river inflows of approximately 40 cubic metres per second (m^3/s), equivalent to an annual inflow of 1,200 million cubic metres per annum (Mm^3/yr), enter the basin as the Taieri, Silver Stream and Waipori Rivers. The largest complication affecting the ability to estimate a basin water balance is the inability to measure the basin surface water outflows. Surface water leaves the basin through the Henley Gorge, which is tidal. Due to the high tidal flux over-printing the fresh water outflow, there is no ability to measure how much water leaves the basin and to close a basin-wide water balance. There are also few discrete groundwater outflows that could be independently measured. The high water table of much of the low-lying portions of the basin dictate that much of the potential groundwater recharge is ‘refused’ and diverts more directly to the artificial drainage network. In addition, it is inferred that temporal changes in land surface recharge are balanced in the aquifer by shifts in the exchange of water with the Taieri River and the lakes wetland complex.

Investigations and modelling by Schallenberg et al., 2000; and Schallenberg, Burns and Peake, 2003 attempted to carry out accurate water balance calculation in studies spanning several years and concluded that groundwater contribution to Lake Waipori averaged $10.4m^3/s$ (Schallenberg, Burns and Peake, ibid). As will be demonstrated in the sections of this report covering the numerical model and Appendix D, this rate of seepage from the groundwater system to the surface water surface system is implausibly high and is more likely to represent the inherent uncertainty in the water balance quantities. The work of Schallenberg et al., (2000), and Schallenberg, Burns and Peake (2003), serves to illustrate the significant difficulty in developing meaningful water balance accounting for the Lower Taieri Basin.

The consequence of these restrictions on estimating a basin water balance is that any reasonably accurate basin aquifer water balance would best be generated with the assistance of a calibrated numerical model of the groundwater system. A water balance has been generated in the manner and reported in the groundwater modelling section of this report.

4. Groundwater Quality

4.1 Historic groundwater quality surveys

As a public health measure, Dominion Chemist periodically monitored the groundwater quality of the Mosgiel Borough. The first comprehensive groundwater quality monitoring of the Lower Taieri Basin was conducted as part of the ORC sponsored groundwater survey (IRRICON and Royds Consulting, 1994). The survey included 100 bores or wells and analysed for iron and nitrate-nitrogen, in addition to the field parameters of temperature, electrical conductivity and pH. Mapping of the results displayed a distinct pattern of elevated nitrate-nitrogen (>1 g/m^3) in the Mosgiel-North Taieri District and low nitrate-nitrogen (<1 g/m^3) south-west of a line approximated by Riccarton Road. The pattern mirrored the iron concentration in Lower Taiei Basin bores or wells. In the West Taieri, iron was found in elevated concentrations of up to 128 g/m^3. A transition from < 1 g/m^3 iron concentration from East Taieri to West Taieri tended to coincide with the line of the Taieri River between Outram and Allanton. Electrical conductivity contouring of results of the 1994 survey (IRRICON and Royds Consulting, 1994) displayed a distinct pattern in the West Taieri, where levels over 100mS/cm were found along the southern margin of the West Taieri (Momona-Henley area).

A similar nitrate-iron concentration pattern was found in a follow-up survey of 103 bores and wells across the Lower Taieri Basin in 2002 (Kensington et al., 2004). The highest nitrate nitrogen concentrations in groundwater were encountered in North Taieri, between Milner Road and Factory Road. The West Taieri was found to have largely low nitrate nitrogen concentrations (< 1 g/m^3), except for several bores in the Woodside-Maungatua area that tap range-front alluvial fans. Ammonia nitrogen was closely correlated with low nitrate and elevated iron. A fifty bore survey of the Mosgiel-North Taieri area by IRRICON and ESR (1997) examined the correlations between nitrate, iron and oxidation- reduction (redox) potential. This survey indicated a relationship that nitrate-nitrogen concentration exhibited a sudden threshold at a redox potential of approximately +100 mV and was thereafter strongly negatively correlated with iron concentration, (i.e. nitrate fell precipitously at redox potentials below this threshold value). The analysis of Kensington et al., (2004) placed the threshold observed in groundwater results as coinciding with the transition from stratified unconfined to confined aquifer pressure conditions, as defined by the margin of the Waihola Silt-Sand in Litchfield et al., (2002).

In the area of the basin with a susceptibility to nitrate-nitrogen accumulation, the North Taieri, there has been a degree of fluctuation in the groundwater monitoring record. Figure 4.1 shows the trend through time, recorded in bore I44/0819, as part of the State of the Environment (SOE) monitoring.

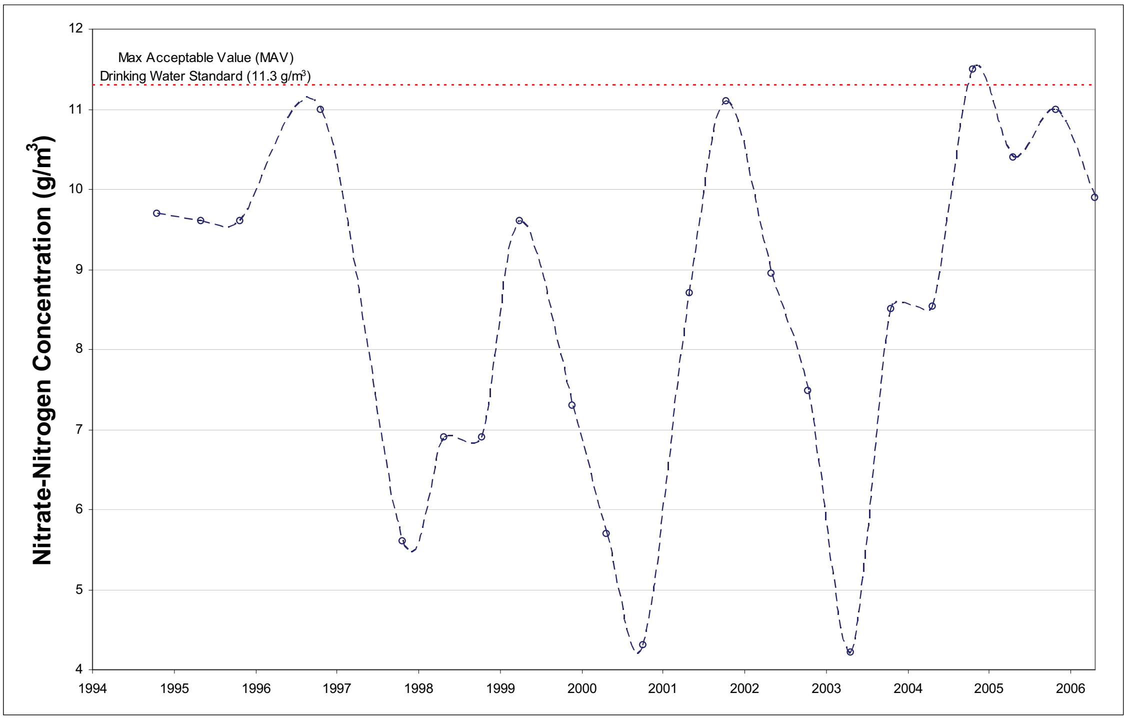

Figure 4.1 **Groundwater nitrate fluctuation in North Taieri bore.**

4.2 Current groundwater quality

4.2.1 Nitrate

The Lower Taieri Basin has few water quality issues induced by human activity. The primary induced groundwater quality limitation is that of nitrate-nitrogen concentration restricted to the stratified unconfined water-bearing layers in the north of the basin closest to Mosgiel. These areas are geographically restricted to a small part of the basin in Mosgiel and North Taieri by reduction-oxidation geochemical conditions, as discussed above. The Mosgiel township water supply from bores beneath Mosgiel contains varying concentrations of nitrate-nitrogen, (between 0.5g/m^3 and 5g/m^3), and averages 3.2 g/m^3 on a volume-weighted basis (IRRICON and ESR, 1997).

Nitrate-nitrogen is implicated by epidemiological evidence in both acute and chronic ill-health if consumed in water in excess of certain concentrations. The drinking water standard adopts a maximum acceptable value for nitrate of 50g/m^3, which is equivalent to a nitrate-nitrogen concentration of 11.3g/m^3. The standard is primarily protective of human infant health and the risk of methylglobanaemia. Higher concentrations are attributed to more chronic digestive organ disorders and carcinogenicity effects in people of all ages.

Nitrate is a natural soil and groundwater constituent, but it becomes elevated under grazing or cropping agricultural land, as a result of nitrogen being lost from the soil nitrogen store and soil drainage beyond the rooting zone, also known as leaching. In general, the more intensive the agricultural system, the higher the leaching rate through the soil. In this sense, water quality limitation from high nitrate-nitrogen leaching can be induced by agricultural intensification.

4.2.2 Iron

The primary natural groundwater quality limitation is the presence of elevated iron in Lower Taieri groundwater. Iron dissolves in groundwater from geochemical processes that are assisted by the presence of organic material in the water-bearing layers and by reduced geochemical conditions. Dissolved iron enters bores and wells in the ferrous (Fe^{2+}) form when groundwater is pumped from the ground. In contact with air and oxygen, the iron in groundwater rapidly transforms to the ferric (Fe^{3+}) form and typically precipitates to solid form as ferric hydroxides. This transition is seen in groundwater discharging from a bore following pressure equilibration and results from contact with dissolved oxygen. The transition also causes significant variability and sampling error in groundwater iron monitoring results. Consequently, trend analysis of groundwater iron concentration is seriously hampered by sampling error, making it difficult to separate sampling error from genuine fluctuations in the groundwater iron concentration.

IRRICON an ESR (1997) conducted a detailed field and laboratory investigation into iron occurrence in Lower Taieri Basin groundwater. They found the following in relation to the question of iron occurrence and ionic speciation of iron:

- High levels of free CO2 in groundwater creates corrosive groundwater conditions conducive to elevated iron concentrations in the absence of dissolved oxygen (i.e. reduced)
- The sources of iron are iron minerals in the Quaternary sediments
- Reduced and corrosive conditions in the groundwater dissolve the iron oxides in these minerals and liberate iron into solution in the ferrous state (Fe^{2+})
- Groundwater that has been exposed to the air contains ferric iron in either macro-precipitate or colloidal form. Macro-precipitates can be filtered out, while colloid iron precipitation will persist following filtration
- Heterotrophic iron bacteria are adapted to consume iron in subsurface settings and were found in many of the Lower Taieri bores sampled containing elevated dissolved iron.

Iron in Lower Taieri Basin groundwater is sometimes problematic for the following reasons:

- Elevated iron concentrations affect the palatability and aesthetics of the water
- Precipitates can stain plumbing fixtures and laundry using high iron water in the water supply
- Drip irrigators and sprayers can become clogged by precipitates
- Irrigated vegetables can be stained or discoloured if exposed to elevated iron water
- Farm ruminants (sheep or cattle) consuming high iron stock water can suffer dietary imbalances due to iron forming chemical complexes with copper.

The New Zealand drinking water standard maximum acceptable value (MAV) for iron is $0.2 g/m^3$ on the basis of “appearance, taste and odour”. Most bores or wells south-west of Riccarton Road and in the Mill Creek catchment have concentrations in excess of the MAV on a routine basis (IRRICON and Royds Consulting, 1994; and ORC SOE monitoring).

4.2.3 Manganese

Manganese is a similar natural metal contaminant to iron. In the Lower Taieri Basin groundwater manganese becomes elevated in the same geochemical conditions that lead to elevated iron. The New Zealand drinking water standard maximum acceptable value (MAV) for manganese is 0.4g/m^3 on the basis of "appearance, taste and odour". The taste threshold is considered to lie at 0.1g/m^3 and staining of laundry may occur at concentrations above 0.04g/m^3. The mean manganese concentration in eight SOE bore water samples taken in March 2000 was 0.18g/m^3, median 0.01g/m^3, and the highest value was 1.1g/m^3, which was the sole result to breach the MAV in that round of sampling. An earlier survey of 11 bores in 1997 (IRRICON and ESR, 1997) found 63% of bores exceeded 0.04g/m^3 and 45% exceeded 0.1g/m^3 for manganese. So, manganese groundwater levels often exceed the taste threshold and frequently exceed the laundry staining threshold in both cases.

4.2.4 Salinity

Salinity is an issue in a small pocket of the West Taieri groundwater, particularly within the West Taieri Drainage Scheme perimeter. The Lower Taieri River at Henley Ferry, plus distributary branches of lakes Waipori and Waihola, are tidal (ORC, 1995), and much of the basin has been inundated by the sea during the last few thousand years. Surface water saline intrusions penetrate these water bodies for up to 15km from the mouth (Schallenberg and Kresbach, 2001). Of significance to groundwater salinity, the marine and estuarine sediments of the Holocene age Waihola Silt-Sand were deposited under saline or brackish conditions. As the saline and then brackish surface water was progressively displaced downstream following the mid- to late Holocene sea level rise, the Lower Taieri Basin gradually shifted to freshwater status, driven to a large extent by the freshwater inputs from the rivers entering the basin (Litchfield et al., 2002). The onset of freshwater conditions stimulated the onset of freshwater flushing of the Quaternary sediments' groundwater. This process moved down the basin towards the outlet at Henley Ferry until there is the current situation of a largely fresh groundwater body with brackish influences.

There is the observed brackish groundwater already mentioned above in Section 6.1, Historic Groundwater Quality. In addition, the Miller Road site on the Main Drain of the West Taieri Drainage Scheme has experienced a change from having relatively stable concentrations of constituents in drain water, since 1998, displaying a volatile trend with episodes of elevated salinity (ORC, 2002 and ORC water quality records). The salinity source is inferred to be upward seepage of underlying groundwater containing brackish groundwater still not completely flushed through with freshwater since 4,000 years BP. The most likely compartment containing brackish groundwater not yet completely flushed of saline groundwater would be the Waihola Silt-Sand layer. This layer directly incorporated sea water during its deposition and has a low hydraulic conductivity and slow pore velocities under existing gradients. Figure 4.2 shows the very low-lying, low gradient nature of the lower Taieri Plains.

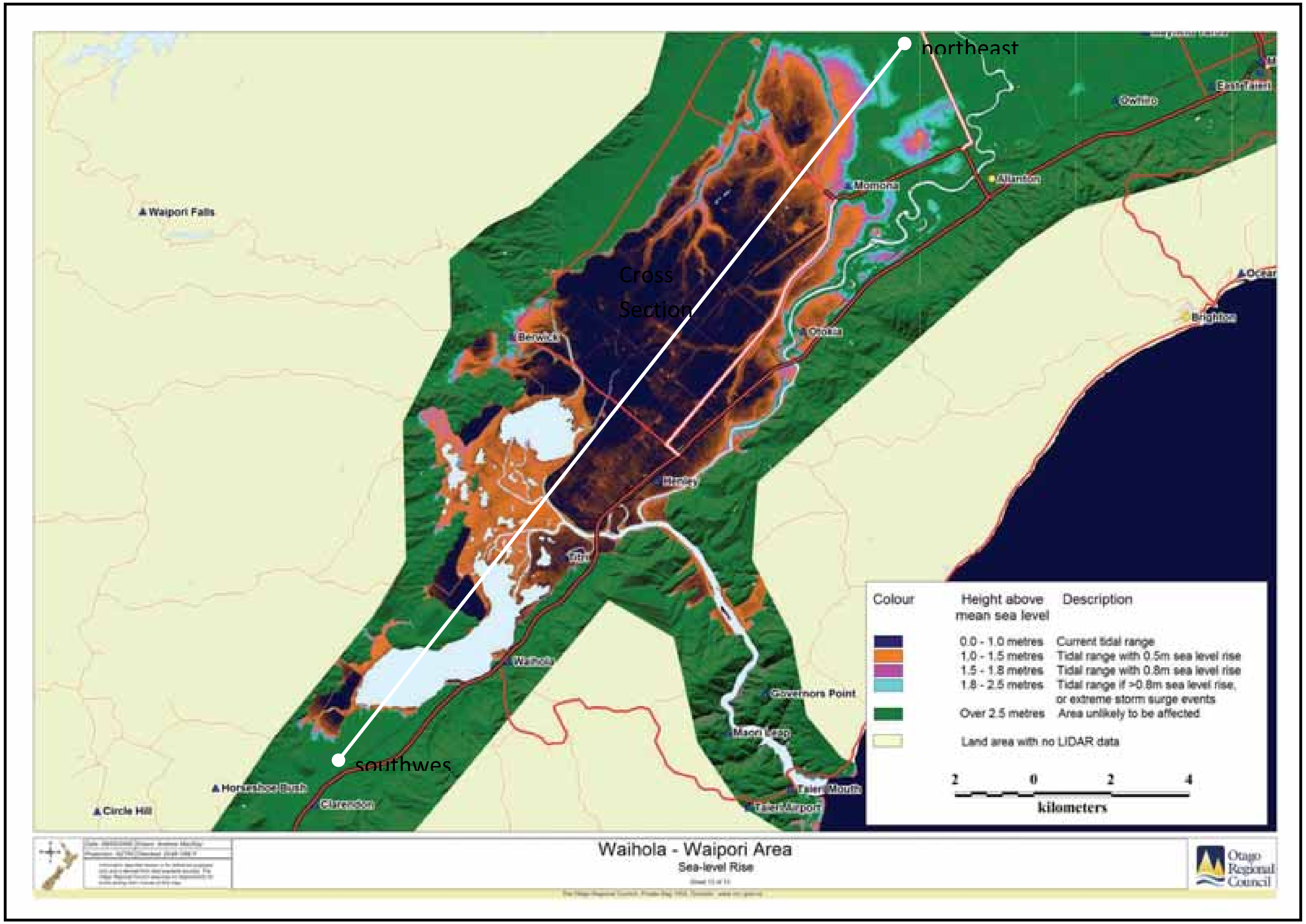

Figure 4.2 Ground surface elevation of the West Taieri and Lake Waipori Wetlands Complex area using LIDAR elevation data and colour-flood contouring. Contouring referenced relative to tidal range maxima

Salinity is potentially a future water quality issue for West Taieri. Global sea level has been rising in small increments since early last century. There has been an estimated 0.28m (±0.05m) rise on the Otago coast since 1900 (Gehrels et al., 2008). The International Panel on Climate Change (IPCC) estimates a potential sea level rise of between 0.18m and 0.5m. A potential upper range for sea level rise, according to IPCC Fourth Assessment (IPCC, 2007), with contributions from Greenland and Antarctica melting lies between 0.7 and 0.8m[2]. On the basis of the literature, the ORC assumes a probable sea level rise of up to 1.5m in the next century.

Tidal fluctuations currently extend all the way up the Lower Taieri rivers to Henley, Lake Waipori and Lake Waihola. The mean tidal range on the Otago coast is 2.2m (i.e. approximately 1.1m AMSL on high tide and -1.1m MSL on low tide). The measured range of fluctuation at Henley Ferry is 0.7m AMSL on high tide and 0.0m MSL on low tide. The tidal range is thus reduced to 0.7m. The mean water levels in these tidal reaches of the Lower Taieri are within the high tide–low tide range. The difference in tidal range and the elevational position of mean sea level is explained by the tidal losses caused by the impeded movement of flood and ebb tidal flows within the narrow Henley Gorge. Figure 4.2 shows the surrounding Lower Taieri Basin land surface relative to mean sea level. Induced by this tidal flux, a wedge of brackish to saline water periodically intrudes into the Henley Gorge of the Taieri River from Taieri Mouth and pushes a mixture of sea water and fresh water into Lakes Waipori and Waihola (Schallenberg et al., 2000). Estimates of the tidal flux that passes the gauging point at Henley Ferry range from 116 m^3/s (Schallenberg, Burns and Peake, 2003) to $147m^3/s$ (ORC, 1995), which is several times the mean freshwater inflow to the Lower Taieri Basin (ORC, ibid). Under expected rises in sea level, the tidal flux would inevitably rise also.

A combination of flooding and sea level rise could provide critical tests of the flood protection and drainage infrastructure in the West Taieri-Lake Waipori Wetland Complex zone of the Lower Taieri Basin. Figure 4.3 shows the effect of an $800m^3/s$ flood in the Taieri River during April-May 2006 on the water level, as measured at Henley. The Taieri River at Henley was raised by up to 1.5m above the peak High Water Springs (HWS) level for over two days until flood waters had subsided.

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[2] However, independent estimates of sea level rise in the next century are higher than IPCC estimates suggesting that the release of glacier ice from polar land ice sheets may raise sea levels around the globe by between 1 m (Rahmstorf, 2007) and "several metres (up to 5m)" (Hansen, 2007).

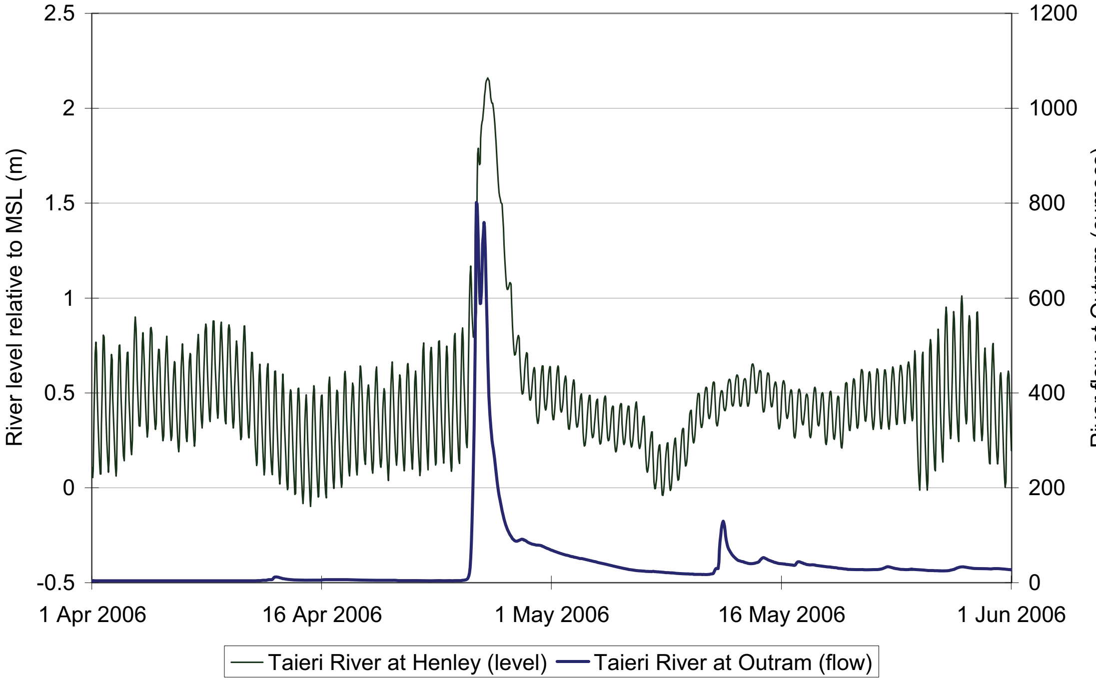

Figure 4.3 **The effect of Taieri River flooding on Taieri River at Henley water level**

4.3 Age of groundwater & aquifer stratification

Groundwater in stratified groundwater systems can display a range of ages related to the disparate groundwater residence time. Some clues as to groundwater age can be drawn on the basis of trace isotope ratios and water chemistry. The ability to determine or estimate the age of the groundwater at different levels in the system has a definite advantage in helping to characterise groundwater hydrology in the past and present.

Most of the attention on dating groundwater has focussed on the Mosgiel water supply bores. The first Tritium dating of Mosgiel district groundwater was undertaken in early 1996 in various piezometers installed in the Harley Bore (I44/0842). The Harley Bore is a multi-level piezometer installation, with six piezometers ranging in depth from the base of water-bearing layers tapped in nearby Mosgiel upwards to the upper-most unconfined water table. Table 4.1 shows the results of the sampling and analysis for Tritium at the Harley Bore.

Table 4.1 **Results of Tritium ratio analysis for Harley Bore (I44/0842) piezometers at different depths**

Piezometer	Tritium Ratio	Inferred Age (yr BP)
P6, Shallow, unconfined	2.59 ± 0.11	< 10 to 30
P5 (12.3 m – 14.3 m depth)	2.74 ± 0.11	< 10 to 30
P4 (19.5 m – 21.5 m depth)	2.81 ± 0.06	< 10 to 30
P2 (36.5 m – 39.5 m depth)	0.36 ± 0.02	30 to 45
P1 (47.5 m – 48.5 m depth)	0.04 ± 0.01	40 to > 50

Table 4.1 suggests that there is an increasing age trend with depth. This polarity of the inferred trend is consistent with trends observed in similar hydrogeological settings, where deeper circulation of groundwater typically comprises older groundwater.

The bores of the Mosgiel town water supply were sampled and analysed for CFC and Tritium ratio in 2003 by the Dunedin City Council. The Mosgiel water supply bores are screened at depths ranging from 28m to 40m below ground, which have already been correlated as the depth range of the ‘water supply water-bearing layers. Table 4.2 lists the results for the nine supply bores beneath Mosgiel.

Table 4.2 Summary of CFC and Tritium dating of groundwater from Mosgiel water supply bores in 2003

	Depth (m)	CFC$_{11}$ age	CFC$_{12}$ age	Tritium ratio	Inferred age
Watt St I44/0750	31 - 34	_	_	1.04 ± 0.04	50
Old Yard I44/0742	29 - 33.1	42	46	0.501 ± 0.023	50
Ayr St I44/0744	37 - 40.3	46	43	0.417 ± 0.026	53
Reid Ave I44/0746	28 - 34	_	_	1.21 ± 0.04	49
Cherry Dr #1 I44/0747	30.1 - 36.5	_	_	0.829 ± 0.033	50
Cherry Dr #2 I44/0753	30.5 - 36.5	_	_	0.793 ± 0.32	50
Severn St I44/0748	36.6 - 39.6	40	42	0.489 ± 0.027	52
Battleaxe I44/0751	37.1 - 40.1	40	41	0.452 ± 0.025	52
Eden St I44/0749	30.5 - 33.5	_	_	1.45 ± 0.04	11 to 48*

Note:
_ indicates sample analysed but did not return a valid or plausible result.
* indicates a range of possible ages suggested by the results, the extremes of the range are given.

The most notable difference between the CFC ages and Tritium ages are an offset of up to ten years in dating of the same bore. It should be noted that CFC dating techniques have the highest resolution and accuracy from the 1970s onwards (i.e. < 35 years and less), and have diminished accuracy in the 1950s and 1960s when Tritium ratios were at highest levels of contrast. The depth ranges of the Mosgiel bores are closest to the 36.5m to 39.5m (P2) piezometer in the Harley Bore. Comparing the inferred ages of the Harley Bore and the Mosgiel bores, the Harley Bore groundwater at a similar depth may be inferred to be at a slightly younger age. A possible explanation for this difference is that the Harley Bore P2 piezometer lies at least 300m up-gradient of the Mosgiel bores and the travel time between them is consistent with the noted age difference.

Additional evidence of flow stratification can be drawn from the water chemistry of the Harley Bore multi-level piezometer installation. Table 4.3 lists the results of chemical analysis for chloride and nitrate ions in each of the piezometers.

Table 4.3 Results of chemical analysis for Chloride & Nitrate-N in groundwater drawn from the Harley Bore (I44/0842) Piezometers in Early 1996

Piezometer # and depth (m)	Chloride (g/m^3)	Nitrate-N (g/m^3)	Tritium age (yr BP)
P6, 5.5 m to 7.5 m	21	6.6	< 10 to 30
P5, 12.2 m to 14.2 m	22	7.2	< 10 to 30
P4, 19.5 m to 21.5 m	18	3.2	< 10 to 30
P3, 29.0 m to 31.0 m	18	1.9	(not determined)
P2, 37.5 m to 39.5 m	17	0.8	30 to 45
P1, 47.5 m to 48.5 m	14	0.1	40 to > 50

The results show a clear reduction in concentration with increasing depth and age. In the case of chloride, there are two main sources in groundwater recharge: sea aerosol depositions in rainfall, which should have remained relatively consistent for the last 5,000 years; and the agricultural application of potassium chloride on pasture. Farming applications of potassium chloride have gone through a steady increase since the intensification of grazing in the Taieri Plains following the Second World War (60 years BP). So, it is consistent with the age profile of the stratification observed in the Harley Bore that chloride concentration goes through a steady increase as well. Nitrogen inputs and losses to agricultural soil have increased over the same period. So, it is perhaps unsurprising to observe similar increasing concentration with decreasing depth. An alternative explanation could be the destruction of nitrate-nitrogen by assimilatory denitrification as the deeper groundwater becomes post-oxic. This is not supported by the depth trend for the Harley Bore in which both the low iron concentration and the high redox potential do not favour denitrification conditions until depths exceeding 40m.

The volume-weighted average for chloride and nitrate-nitrogen concentration in Mosgiel water supply bores versus that of the Silver Stream and adjacent shallow groundwater in the Harley Bore are listed in Table 4.4.

Table 4.4 Calculated and measured Chloride and Nitrate-N concentrations in various waters potentially recharging the water supply aquifer(s)

	Chloride (g/m^3)	Nitrate-N (g/m^3)	Tritium age (yr BP)
Mosgiel bore water (volume-weighted average)	20.8	3.2	48 - 53
Silver Stream water mean	12.9	0.2	<< 1
Shallow groundwater @ Harley Bore (5.5 – 7.5 m)	21	6.6	< 10 - 30

The assumption is justifiably made that both chloride and nitrate-nitrogen are relatively conservative in oxygenated groundwater, such is found in the Mosgiel district; although this is more obviously the case with chloride. Furthermore, it can also be assumed that the average Mosgiel bore concentration should be reflective of the source(s) of aquifer recharge, since the mass of conservative ions should be fixed once the recharge waters enter the groundwater system. On the face of the values in Table 4.4 above, Silver Stream water is unlikely to be a major source of the groundwater pumped at Mosgiel since it contains insufficient mass for either chloride or nitrogen to produce the concentrations seen in the water supply bores. Shallow groundwater (derived largely from soil drainage) is more likely to be the predominant source of the groundwater pumped from the water supply depths (30m to 40m) beneath Mosgiel. The basis for this inference is the elevated chloride and nitrogen observed in monitoring of the water supply bores. There is also some room in the comparison of concentrations to suppose that the water supply also contains a substantially lesser amount of Silver Stream water.

5. Groundwater management

5.1 Current management framework

5.1.1 Controls over drilling and bores

In 1988 the Otago Catchment Board issued Bylaw 88, which required the application for a bore permit for the establishment of a water bore or well. This passed into the Transitional Regional Plan of Otago Regional Council in 1991. The Transitional Regional Plan was eventually superseded by the Water Plan in 1999, for which the groundwater provisions were generally not subject to appeal. The Water Plan passed appeal hurdles in February 2004, and included provisions regulating the drilling of holes and installation of bores.

The entirety of the Lower Taieri Basin north-east of the Waihola-Waipori Lake Wetland Complex is encompassed in the Lower Taieri Aquifer in the context of the Water Plan. Thus, any drilling within the basin requires an application for land-use consent (bore permit). In addition, any installation of bores would also otherwise trigger the land-use consent requirement. Well records (including records of bore, wells and infiltration galleries) have been collected by a variety of means since 1994, not least of which were regional council surveys. There are over 1,100 well records in the Lower Taieri Basin, about half of which were first collected as a result of field surveys. However, the last ORC field survey of the Lower Taieri Basin was in 1997, and subsequently the most significant means of collecting information on bores are through the consent process or compliance surveys.

The Water Plan also has special policies (9.4.15 and 9.4.16) which relate to the Lower Taieri aquifers. These policies cite special issues of corrosion of bore-casing materials and above-ground artesian pressure present in the Lower Taieri aquifers. Policy 9.4.15 relates to requirements for appropriate construction and corrosion resistance that prevent chronic or run-away leakage of artesian pressure. Policy 9.4.16 requires rigorous sealing, certification and decommissioning, as appropriate, of either operational or disused bores to prevent uncontrolled leakage. Both policies are to be implemented through the bore consenting process and guidelines issued by ORC. In practice, since the promulgation of the Water Plan in the early 2000s, there has been little application of special conditions, five-yearly bore certification or issuance of special guidelines envisaged in these two policies. It should be noted that the AS / NZS 4411:2001 “Environmental Standard for Drilling of Soil and Rock” has been specified as a condition in Otago bore consents since 2005, and this performs the same purpose as the ORC guidelines. The AS / NZS 4411:2001 standard specifies the use of appropriate materials, seal, decommissioning and artesian flow control required for the Lower Taieri. The difficulty arises when comparing existing bore installations against the standard, since the bulk of the more significant features of an appropriate installation is buried deep underground with little avenue to inspect it.

5.1.2 Controls over the taking of groundwater

The Resource Management Act 1991 continued the assumption made in previous water legislation which specified that the reasonable needs of people and stock can be obtained from natural water, including groundwater, without requirement for resource consent. This permitted activity is extended to general water uses under the Water Plan (clause 12.2.2.2(c)(ii)), which allows for up to 2.5l/s to maximum of 30m^3/d to be drawn from Taieri basin groundwater without recourse to resource consent. Above these permitted activity quantity limits, the water user is required to apply for resource consent to take groundwater as a full discretionary activity.

Following an amendment to the Water and Soil Conservation Act (WSCA) 1981, groundwater was placed under its auspices. Prior to the WSCA amendment, the Otago Catchment Board recorded existing groundwater uses as evidence of pre-existing use rights. This provided authorisation for a significant number of Lower Taieri Basin groundwater takes. After 1981, the Otago Catchment Board and Regional Water Board issued water rights to a small number of additional groundwater take activities. With the passing into law of the Resource Management Act (RMA) 1991, the ORC took the consenting requirements of the catchment board into the Transitional Regional Plan. Section 14 of the RMA also stipulated that the taking of groundwater for more than reasonable domestic or stock water required resource consent.

The Water Plan (2004) placed restriction levels on the taking of groundwater benchmarked to a monitoring bore located in each of the Lower Taieri groundwater water take restriction zones: Lower Taieri-East and Lower Taieri-West. The nominated monitoring bores are the Harley Bore (P2 piezometer) and Momona Bore, for the East Taieri and West Taieri zones, respectively. In each case, the taking of groundwater is restricted by the concurrent groundwater level in the appropriate monitoring bore. For example, all groundwater pumping under resource consent is required to stop when the mean 30-day static water pressure falls below 9.5 m AMSL in the East Taieri and -1.0m MSL West Taieri-West. Intermediate, partial restrictions of 50% and 25% curtailment of allocated groundwater take are required when the relevant level falls below specified levels. For example, when the 30-day water level mean in piezometer P2 of the Harley Bore falls below 10.0m, AMSL pumping would be required to be reduced by 50% of the consent rate, or when the Momona Bore falls below 0.0m AMSL, pumping would be required to be reduced by 25% of the full allocated rate.

5.1.3 Current groundwater allocation

There are currently seven consents for seasonal irrigation using Taieri Basin groundwater. The Mosgiel township water supply is authorised by an omnibus of a further eight consents applying to each of the eight bores taking water throughout the township. The maximum annual Mosgiel water supply allocation is 1.8 million m^3/yr. The combined total annual take allocated for those 15 groundwater takes across the Lower Taieri basin amounts to approximately 2.4 million m^3/yr, 2.2 Mm^3/yr of which is allocated with the East Taieri water take restriction zone around Mosgiel. This is the current allocation issued to consent holders in the Lower Taieri Basin. Approximately 0.08 million m^3/yr is estimated to be required in the Lower Taieri Basin for permitted stock, domestic and minor water use, which would increase the total basin-wide consented and permitted water use allocation to approximately 2.5 million m^3/yr.

Three private groundwater takes have conditions requiring observance of the level restrictions, two in East Taieri and one in West Taieri. The consents for the DCC Mosgiel water supply are partially subject to the East Taieri level restrictions, but only for the quantity of groundwater used for garden or lawn watering. Other than the level restriction regime outlined above, no other formal groundwater allocation cap is set for the Lower Taieri Basin. The Water Plan policy 9.4.2 gives priority to the avoidance of "exceeding the annual renewable yield of the aquifer", but does not have the explicit facility to limit the granting of groundwater allocation within the consent process.

5.2 Future management framework

5.2.1 National environmental standards

At a national level, there is currently one operative National Environmental Standards (NES) with relevance. The National Environmental Standard for Sources of Human Drinking Water has the effect of preventing the granting 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 water supplies of Mosgiel and Outram serve more than 9,200 and 844 people respectively. The population threshold is therefore triggered in each case. The NES becomes a consideration in assessing resource consent applications with any possibility of causing contamination of either water supply.

5.2.2 The Water Plan, Proposed Plan Change 1C

Proposed changes to the Water Plan under Proposed Plan Change 1C would provide for the ability to set a maximum allocation volume on selected aquifers specified in a new schedule (Schedule 4A). Alternatively, in the absence of a specified aquifer, an allocation cap in Schedule 4A, the plan change default allocation would limit the maximum proportion of mean annual recharge that could be allocated to groundwater take to 50%. This default allocation restriction is specified in Policy 6.4.10A.

In addition, the proposed changes sought to bring a degree of commonality to the management of surface water and groundwater. Riparian groundwater would be allocated and managed as for surface water if within 100m of a perennial water body. Connected groundwater and surface water would be jointly allocated for bore-water body separation distances further than 100m. An estimate of the bore-pumping depletion effect would be used in setting the allocation from surface water.

Of interest is the timing of the respective future groundwater allocation regimes under Plan Change 1C and the proposed NES on Ecological Flows and Water Levels. Even with the promulgation of the changes to the Water Plan, the application of a groundwater allocation cap would need to await a further change to the plan which would add the Lower Taieri aquifers and the allocation volume to the table in Schedule 4A. Should the proposed NES on ecological lows and water levels come into force earlier and in its current shape, then the allocation cap of 35% on mean annual recharge would likely become the interim limit.

5.3 Groundwater monitoring

5.3.1 State of the environment monitoring

State of the Environment (SOE) monitoring is undertaken for the Lower Taieri Basin's groundwater resource in terms of the following:

- Automated, continuous groundwater level / pressure at four locations
- Harley Bore (piezometers P2 and P6)
- Outram Bore
- Momona Bore
- Waipori 99-1 Bore (piezometers 1 – 4)
- Manual, periodic dip measurements of depth to water in an additional 17 bores throughout the basin
- A total of nine bores are sampled on a six-monthly basis and analysed for the standard SOE suite of analytes

The SOE monitoring is intended to define a baseline of groundwater level/pressure and water quality. A by-product of the SOE monitoring is that calibration data is available for groundwater modelling such as is outlined in subsequent sections of this report.

5.3.2 Self monitoring by consent holders

The Dunedin City Council has been the main consent holder to provide significant self-monitoring of groundwater pumping rates at each of the eight Mosgiel bores. Tables of pumping rates have been available for bores providing the Mosgiel water supply since at least 1990. In recent years, these tables have been able to be differentiated for each supply bore and each day of the month. Prior to 2003, the differentiation extended to monthly totals, sometimes broken up into supply bores. Figure 5.1 shows the multi-year pattern of groundwater consumption in the Mosgiel water supply.

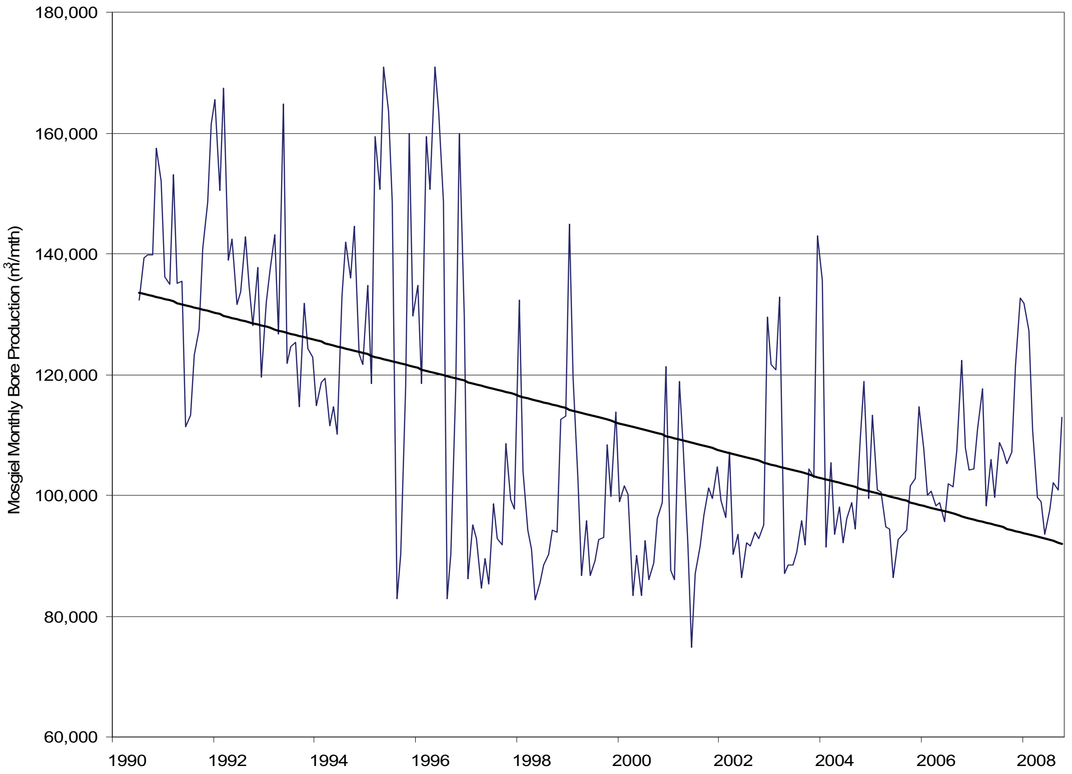

Figure 5.1 **Graph of total monthly groundwater consumption in the Mosgiel water supply, as taken from nine DCC bores. The black line shows the long-term trend. Since 2004, the consent limit has been set at 161,200 m3/month**

The DCC water supply takes have a discernable influence on the groundwater levels recorded at the Harley monitoring bore (IRRICON and ESR, 1997). The scale of the volumetric groundwater take beneath Mosgiel is also such that it causes a generalised depression in the groundwater level surface (IRRICON and ESR, 1997) around Mosgiel. Accordingly, since these monitoring bores would be used in the calibration of any transient model of the basin, the pumping activity needs to be included in the steady state and transient groundwater modelling.

Self-monitoring data for other consented groundwater takes in the Lower Taieri Basin are sparse due to this being a recent requirement of water consents and also because of the relatively small number of consents issued to private water users in the Lower Taieri Basin. Figure 5.2 shows an example of self-monitoring by a private water user for a period of recorded groundwater use (consent 2002.341) at a 7 ha hazelnut orchard in the East Taieri.

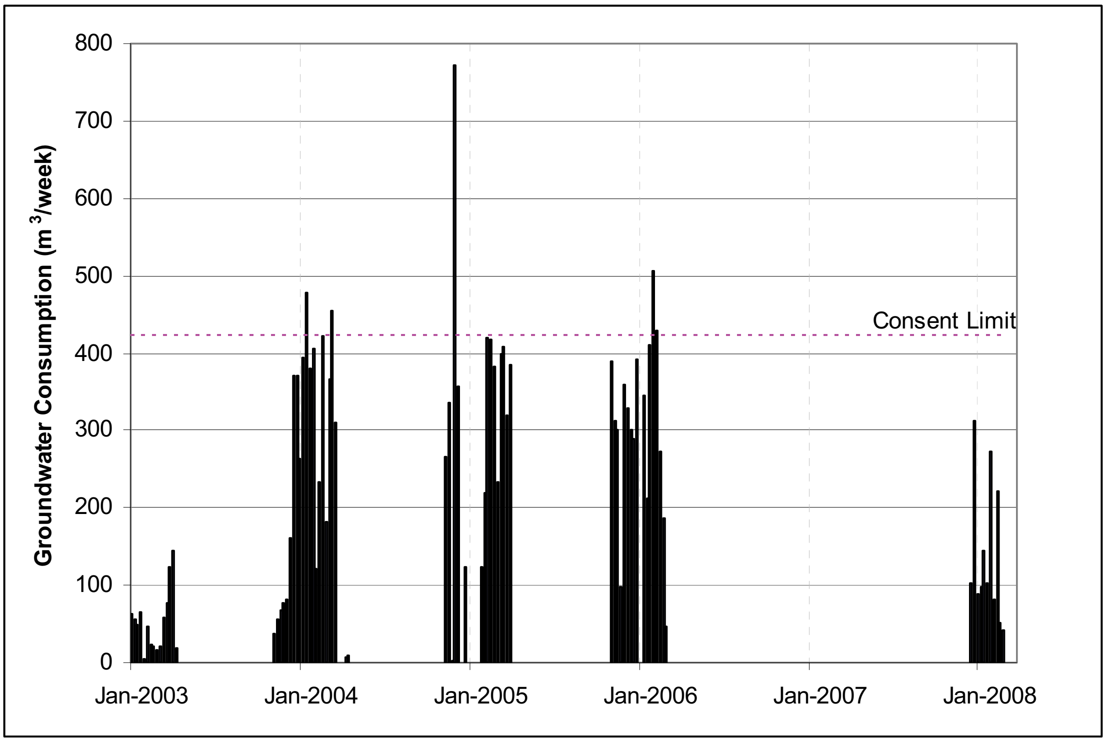

Figure 5.2 Plot of weekly groundwater consumption as measured as a condition of resource consent for Lower Taieri Basin bore (I44/0964)

Figure 5.2 illustrates the highly seasonal and inter-seasonal pattern of water use in this context. The whole of the 2006-07 growing season did not require irrigation for the hazelnut trees, as can be discerned from the above plot. The plot also illustrates that irrigators sometimes take substantially less than their allocated total. The heaviest irrigation season led to the taking of 5,252m^3, while the maximum annual allocation available under the consent would be 14,928m^3/yr, which was approximately three times that taken.

The difference between the consent use rates and actual use rates are an acknowledged feature of water allocation in many parts of Otago. The ORC is seeking to institute almost universal metering of consented water takes. One justification of metering is to enable consent renewals to be undertaken with the benefit of actual use information for the existing activity. It is recognised that some degree of freeboard needs to be maintained between the actual use volumes and the allocation volume. However, it is also the ORC's policy to close the gap between actual and allocated volumes of take to more realistic margins. Such progressive closure provides greater facility for relying on the allocation volume reflecting actual use and eventually optimising water allocation and management in the region.

6. Numerical groundwater model

6.1 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.

6.1.1 Grid design

It was ultimately decided that the numerical model would follow a three-layer scheme. Table 6.1 lists the model layers and their relation to basin stratigraphy.

Table 6.1 Vertical layering system adopted for numerical modelling and correspondence with groundwater system units recognised in the conceptual model

Layer number	Semi-confined zone	Stratified zone
Layer 1	Waihola Silt-Sand	Stratified Mosgiel-momona aquifer
Layer 2	Confined Mosgiel-momona aquifer	Stratified Mosgiel-momona aquifer
Layer 3	Henley deep aquifer	Henley deep aquifer

Figure 6.1 shows a schematic representation of the vertical model layering system adopted for numerical modelling. This figure follows the cross-section alignment selected for illustrating the geology and hydrogeology in preceding sections. While the layers extend along the full model section, the hydraulic behaviour is divided into the semi-confined and stratified zones marked primarily by the margin of the Waihola Silt-Sand. The main automated groundwater level monitoring sites falling on the cross-section line, Harley Bore P2, Momona and Waipori 99-1 are also marked.

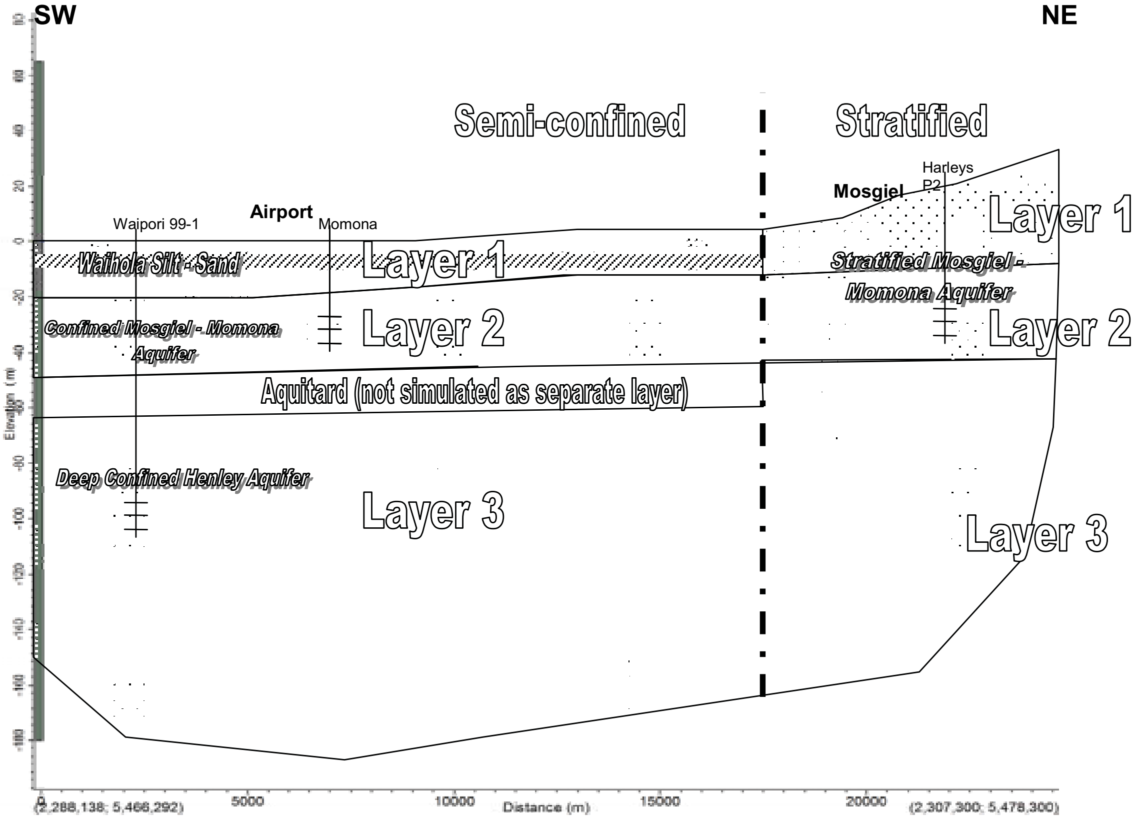

Figure 6.1 Schematic cross-section representation of layer system adopted for numerical modelling

Layer 1 and 2 extended over the entirety of the Lower Taieri Basin between basement rock margins; while Layer 3 was simulated to occur as an elongate, kidney-shaped outline against the seaward margin defined by the Titri Fault. The Waipori Aquitard between the Mosigiel-Momona Aquifer and the Henley Aquifer is not geometrically or explicitly simulated in the model. However, the ability in MODFLOW to specify a leakage parameter for the interaction between aquifers is used in the place of a distinct model layer. The confining effect imparted by the Waihola Silt-Sand is explicitly simulated by the low hydraulic conductivity specified in Layer 1 throughout the areas underlain by this deposit.

The uniform grid cell sizing selected was 200m by 200m, giving a cell extent of 4 ha. The model domain was specified at a width of 15km and a length of 41.4km. For the purpose of optimising the model grid geometry, map grid north was rotated 38° east of true north. This aligned the Lower Taieri Basin so that the principal long axis of the basin lay parallel to model grid north.

6.1.2 Boundaries

The following model boundaries were employed in the simulation of the Lower Taieri Basin model:

- Head No Flow (HNF) boundaries simulating the impermeable basement rock margins to the sedimentary basin

- River (RIV) boundaries internal to the sedimentary basin, which simulate the presence of the three rivers - Taieri, Silver Stream and Waipori - within Layer 1
- Drain (DRN) boundaries simulating the presence of the artificial drainage network, primarily with the West Taieri area
- Constant Head (CHB) boundaries simulating the presence of Lake Waipori and Lake Waihola in the western portion of the basin
- Wells (WEL) are a form of boundary condition used in the Lower Taieri Basin model to simulate groundwater takes.

The Lower Taieri Basin is very conveniently situated in being entirely surrounded by either Haast Schist basement rocks, Henley Breccia or Dunedin Volcanic Complex rocks. None of these formations provide much potential for any significant hydraulic communication with adjoining basins or the Pacific Ocean. To this extent, there is no need to accommodate groundwater exchanges between the basin and an adjoining basin, which simplifies the setting of model boundaries.

The major hydrological inputs to the basin are the three rivers. In the context of the groundwater model, the three rivers perform a critical balancing role in much the same way as they do in reality. All three rivers lose water to the groundwater system in the upstream reaches crossing the basin, and subsequently gain groundwater in their lower reaches. The Waipori and Taieri tend to be gaining in their low gradient and tidal reaches. The Silver Stream tends to flip over to a gaining reach downstream of Riccarton Road. All river boundaries were applied to Layer 1.

The West Taieri Drainage Scheme network and the drains associated with School Swamp were simulated using drain boundaries within Layer 1. Drains in MODFLOW have the effect of stripping groundwater levels higher than the drain elevation, but do not inject water back into the system once groundwater level falls below. This is the same role performed by the drainage scheme drains. The drain water levels are strictly maintained by cleaning the bed to preserve the design gradient and pumping the terminal end of the drainage network, such as at Waipori Pump and Mill Creek Pump.

The application of constant head boundaries for the tidal lakes Waipori and Waihola was selected since these water bodies naturally maintain a substantially steady water level elevation. Constant head boundaries may also gain or lose water through interaction with the modelled aquifer to maintain this constant height, which is the role performed by the lakes. The tidal influence was not simulated in the transient model due to the self-cancelling fluctuation effects of tidal level changes and offset by the use of mean water level. The time step used in the transient model was set at seven days, so direct simulation of tidal level changes would have been redundant at such a time scale.

Well boundaries were not employed in the usual MODFLOW implementation. Instead, the analytical element well features implemented in the Groundwater Vistas package were utilised to simulate the presence of pumping bores in the simulation. The analytical element well implementation provides greater flexibility and better scale independence that the MODFLOW well boundary. Five of the nine Mosgiel water supply bores were implemented in this fashion. The simulated bores were screened across the entire thickness of Layer 2.

6.1.3 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.

The following parameters were explicitly simulated within the model:

- hydraulic conductivity (in lateral and vertical planes)
- storativity
- unconfined storage coefficient (specific yield)
- land Surface Recharge (LSR).

6.1.4 Hydraulic conductivity

In model calibration the hydraulic conductivities used proved to be the most sensitive parameter. Approximately eleven hydraulic conductivity zones with common value were specified across the model. Internal to each zone, the hydraulic conductivity in the lateral and vertical plane were discrete. No differences between lateral hydraulic conductivity in the column plane (easting) and row plane (northing) were specified, since there was not strong evidence of lateral anisotropy evident from field data. In MODFLOW, the vertical hydraulic conductivity can be used in calculating the leakage between model layers and this approach was used in the Lower Taieri Basin model.

6.1.5 Storage coefficients

Storage coefficients only impart sensitivity upon model results in transient modelling, since storage affects the timing of exchanges in groundwater compartments. In the stratified Mosgiel-Momona aquifer the unconfined storage coefficient of specific yield would have dominant effect. In the area of the Mosgiel-Momona Aquifer capped by the confining Waihola Silt-Sand, the confined storativity would have a dominant effect.

6.1.6 Recharge

The Rushton recharge model described in Appendix B, was used in setting model L and surface recharge rates in space and time. These recharge rates were further refined by parameter optimisation, sensitivity analysis and automated calibration within the MODFLOW model.

Adjustment of the Land Surface Recharge component of total recharge under calibration is important in the modelling of the Lower Taieri Basin, due the expectation that there would be significant ‘refused’ recharge in some basin soils. In the case of refused recharge, where soil water excess is discharged into run-off or more likely into the drainage network, the recharge rates calculated to reach the groundwater using the recharge model are unrealistically high. Model calibration offers the ability to adjust the effective recharge rates in accordance with the indications provided by sensitivity analysis and trial-and-error calibration.

6.1.7 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. Two data-sets of steady-state calibration were formulated:

1) Groundwater level averaged in the six automated groundwater level monitoring bores in the Lower Taieri Basin (Harley, Janefield, Donnellys, Outram, Momona and Waipori 99-1).
2) The snap- shot of elevation-corrected groundwater levels measured in the May 1994 survey by IRRICON and Montgomery Watson (1994).

In general, it is considered acceptable to average the groundwater levels over a several years and use the mean groundwater level for comparison against steady-state simulation results. This was possible for the records of the six automated level sites. In general, where multi-level groundwater hydrographs were available, such as at Harley Bore, Donnelly Bore and Waipori 99-1, the shallowest piezometers was selected for use in calibration, as these were most responsive to climatic and surface water influences.

While the six automated groundwater monitoring site average levels were used initially for coarse steady state model calibration, the need for a wider spread of groundwater calibration necessitated the addition of the 1994 snapshot groundwater levels. The snapshot levels were used as if they represented long-term averages.

6.1.8 Transient calibration

Transient (time-variant) calibration was the most intensive stage of model calibration. The calibration data-set available for transient calibration encompassed the level records at the following monitoring bores:

- The Harley Bore (I44/0842) in the P6 shallow piezometer for calibration of Layer 1
- The Harley Bore (I44/0842) in the P2 deep piezometer for calibration of Layer 2
- The Outram Bore (I44/0838) for calibration of Layer 1
- The Momona Bore (I44/0848) for calibration of Layer 2
- A partial record of the Waipori 99-1 Bore (I45/0007) for calibration of Layer 3.

These groundwater level records were formatted for consistency with the almost twelve year calibration period (28-Apr-1996 to 23-Mar-2008) and the seven day stress period used in the transient simulation.

6.2 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. In the case of the Lower Taieri Basin, the principal concerns relate to the size of the sustainable groundwater resource and drainage. The questions to be answered by modelling are:

- 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 sea level conditions?

Simulations of changes in rainfall or evaporation as a result of climate change are not readily resolvable in this case. Accordingly, scenarios of groundwater pumping volumes and changes to the lake/river/groundwater levels (base levels) are the primary scenarios to be tested.

Under existing resource consents, the East Taieri already has annual volumes of approximately 2.2 million cubic metres (Mm^3/yr) allocated, primarily to the Dunedin City Council for the Mosgiel water supply, under existing resource consents. The secondary East Taieri groundwater extraction centre was simulated at the Silver Fern Farms abattoir in Duke’s Road, which has an annual allocation of 0.3Mm3/yr. 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.

The “base scenario” reflects the climate of the last 12 years and the current actual groundwater use rates (approximately 60% of allocation).

- Scenario 1 70% of current allocation
- Scenario 2 100% of current allocation
- Scenario 3 150% of current allocation
- Scenario 4 300% of current allocation

In addition, the potential levels of groundwater allocation for the West Taieri were simulated by modelling a network of hypothetical farm irrigation extraction centres based on work previously undertaken on the West Taieri allocation in 1997 (IRRICON, 1997). Six groundwater extraction centres were located in the upper central West Taieri area and the total hypothetical West Taieri pumping was shared equally between the six. One of the extraction centres was placed to coincide with the sole existing irrigation groundwater take in the West Taieri owned by C.J. Nelson (consent number 2002. 374). Table 7.2 lists the groundwater pumping imposed within the five model scenario simulations. As the hypothetical West Taieri groundwater pumping was assumed to supply irrigation, the pumping was concentrated within five months of the spring, summer and autumn of each of the twelve simulation years.

6.2.1 Groundwater pumping simulations

Table 6.2 lists the simulated pumping scenarios for the East Taieri and West Taieri allocation zones. It is important to note that given the small amount of groundwater extracted in the West Taieri by bores that the pumping simulated within these scenarios is a highly hypothetical projection of possible future expansion.

Table 6.2 Groundwater pumping scenarios and pumping rates

Scenario	East Taieri pumping volume in model (Mm^3/yr) (plus % current allocation)	West Taieri hypothetical pumping expansion (Mm^3/yr)
Base scenario	1.3 (60%)	0.1
Scenario 1	1.5 (70%)	0.5
Scenario 2	2.0 (100%)	1.0
Scenario 3	2.9 (150%)	1.5
Scenario 4	5.7 (300%)	3.0

6.2.2 Rises to groundwater system base level

As has been previously noted, ORC is using an ultimate sea level rise of 1.5m. In order to determine the effect of global sea level rise, a rise in the water levels of lakes Waipori, Waihola, the lower Taieri and Waipori rivers were imposed within a model simulation envisaging no change to the base scenario groundwater pumping rates. This simulation assumes that sea level rise is gradual enough to allow the raising of flood embankments separating the lakes and rivers from the low-lying farmland. The scenario considers that the farmland, particularly within the West Taieri Drainage Scheme perimeter, is kept in a dry condition through continuation of drainage to peripheral pumping stations.

The objective of this scenario is to establish the resulting changes to the groundwater and drainage systems. The scenario is not able to directly establish the onset of seawater intrusion, although the relative groundwater gradients can be examined for indications as to the potential for such intrusion. Assuming a final stabilised mean sea level 1.5m higher than today's, the assumed lower river water level was simulated to rest at 1.65m AMSL on the Taieri River downstream of the Silver Stream confluence and the Waipori River downstream of Greenbank. The lakes and lake wetland complex water level would clearly also rise from 0.43m AMSL to 1.65m AMSL under sea level rise, and this was simulated in the groundwater model.

6.3 Scenario results

6.3.1 Groundwater pumping simulations

The simulated increase in pumping volume from one simulation to the next resulted in lower groundwater levels and shifts in the exchange of groundwater between the aquifer and adjoining river or drain. The MODFLOW model responded to the increases in groundwater extraction by redistributing groundwater flows and level. In general, the intensity of groundwater level decline was dependent on proximity to extraction centres.

In East Taieri all groundwater extraction was centred on Mosgiel at DCC bores and the Silver Fern farm bore (I44/0743) on Duke's Road. Due to the differences in how the model and stratified groundwater system measure pressure, the levels determined in modelling have been subsequently corrected to levels specific to the Harley Bore P2 piezometer. Figure 6.2 illustrates the simulated Harley Bore groundwater levels measured in the Layer 2 of the model, which approximates to the water supply water-bearing-layer monitored in the Harley Bore P2 piezometer.

Figure 6.2 **Time series plot of simulated groundwater level for the Harley Bore P2 piezometer**

Figure 6.2 illustrates the lowering in groundwater level as measured at the Harley Bore P2 piezometer. The time series plot is also annotated with the relevant restriction levels used to manage groundwater decline in the East Taieri water take restriction zone. Only Scenario 4 is seen to transgress the 25% restriction level without breaching the 50% restriction level.

The primary **potential** impacts of Mosgiel groundwater pumping are as follows:

- depletion of the water supply water-bearing-layers
- excessive drawdown affecting bores
- depletion of the flow of the Silver Stream.

Long-term decline of the groundwater levels would be a sign of depletion of the water supply water resource. Long-term depletion means that the sustainability of the groundwater is jeopardised, and it has less resilience to declines in recharge or increases in groundwater extraction. Drawdown beyond the range of normal fluctuations is an acute effect of groundwater resource depletion directly related to groundwater pumping. Drawdown-related falls in groundwater level have the ability to propagate significant distances away from the centres of extraction and affect surrounding water bores. There is an already noted mild drawdown effect centred on Mosgiel, which is likely to be the result of the long history of groundwater extraction by Mosgiel water supply and Mosgiel industries.

Field investigations held during 2009 found that the Silver Stream has been contributing at least 30l/s of its flow in low flow periods to the shallow water-bearing-layers, which in turn partially replenishes the groundwater drawn by DCC bores from within the deeper water supply water-bearing-layers. This pattern was replicated in the base scenario model with a net 25l/s of Silver Stream flow being contributed to Layer 1 in the river boundary reach adjoining Mosgiel. The mean annual 7-day low flow (MALF7d) for the Silver Stream at Taieri Depot, immediately downstream of Mosgiel, is 0.056m^3/s (56l/s). This is after the effects of losses to the aquifer. The middle reaches of the Silver Stream downstream of the Taieri Depot are significant as a trout spawning and rearing habitat for the Lower Taieri River. Due to the channel morphology of this part of the Silver Stream, there is a sudden flow threshold change to instream habitat values once the wetted stream detaches from the vegetated margins (Matt Dale, ORC Resource Scientist, pers. comm. 3 June 2009). At this threshold the available instream habitat in low flow shifts from 80% to 20%. Because of this threshold effect and the uncertainty as to the flow defining it, the optimal environmental flow for the Silver Stream is uncertain. The Dunedin City Council surface water take on the upper Silver Stream at the McQuilkan's Creek confluence (Whare Flat) is authorised by consent to take up to 127l/s, but controlled by a downstream residual flow of 23l/s. This is the only other water allocation constraint on the management of the Silver Stream.

Figure 6.4 illustrates the results of the scenario simulations with respect the balance of gains and losses from the Silver Stream with the shallow water-bearing-layers of the Stratified Mosgiel-Momona Aquifer at Mosgiel. The time series plot shows in the base scenario that the exchange between stream and groundwater is a mixture of net losses and gains. The losses to groundwater dominate the upstream section of Reach 11 of the Silver Stream and represent positive exchange in Figure 6.3, while groundwater returns (gains) dominate the downstream section of the reach. The plot shows that temporal fluctuations cross from net losses to net gains for the combined reach indicated, by shifting from positive to negative exchange values, respectively. The mid-point in the base scenario and Scenario 1 tends towards the negative; (i.e. net gain).

The modelled time series plots for Scenario 3 and Scenario 4 on Figure 6.3 display increased losses from the Silver Stream in proportion to the increases in groundwater pumping. Thus, there is a discernable effect of increased extraction on the flow of the Silver Stream that could exacerbate the negative effects of seasonal low flows. The time series plot has been used to quantify the typical increase in Silver Stream losses. The 50% increase over the allocated volume simulated in Scenario 3 induced an additional 25l/s loss from the Silver Stream. The 200% increase in pumping simulated in Scenario 4 induced an additional 160l/s loss.

Given that the Mean Annual Low Flow (MALF) is approximately 56l/s, a potential increase in losses to groundwater up to 160 l/s would have the potential to dewater the Silver Stream during low flows, which is inconsistent with regional policy. The possibility of additional stream surface water losses of the order of 25l/s is potentially more acceptable, so Scenario 3 at 150% of current consent allocation could be considered to be a more viable option in setting groundwater allocation for the East Taieri water take restriction zone.

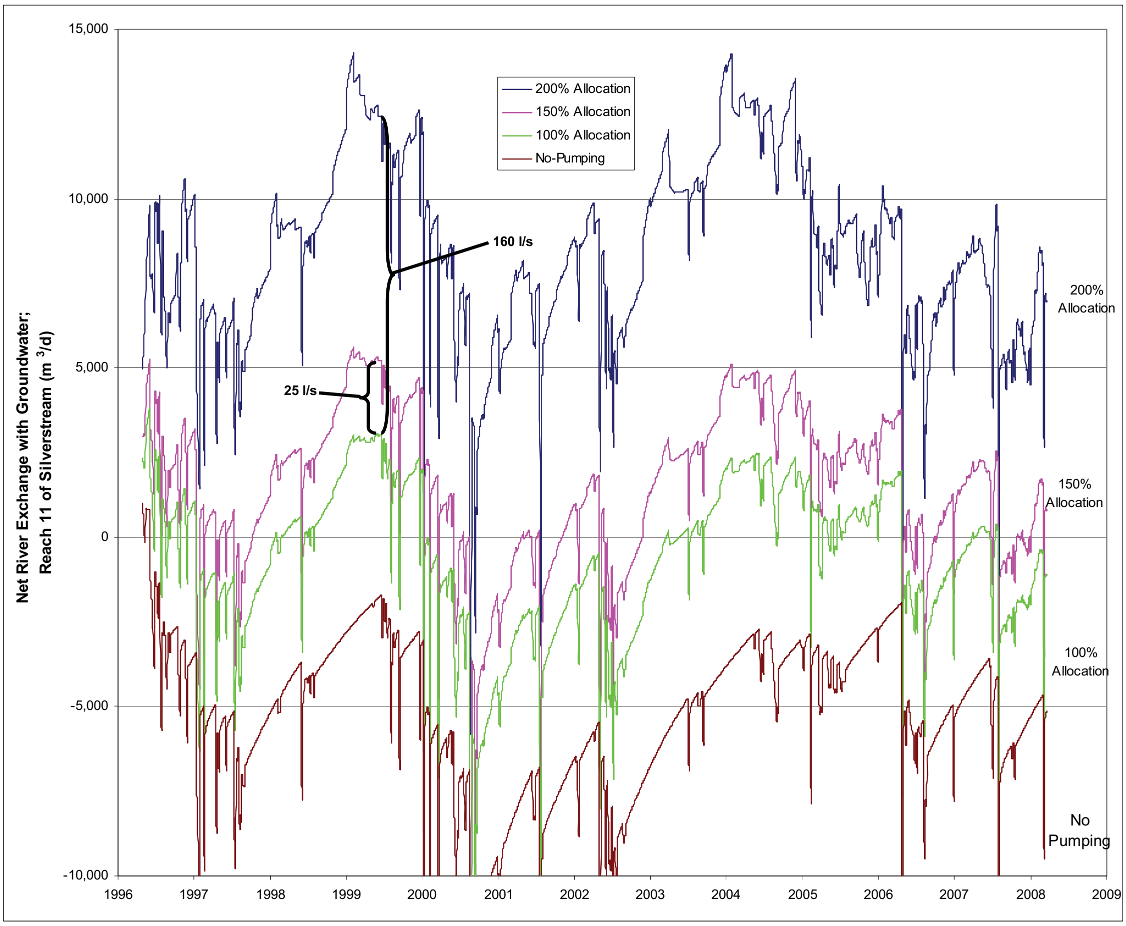

Figure 6.3 Time series showing the balance of inflow and outflow to/from the aquifer with the Silver Stream from Invermay to Taieri Depot (Reach 11). The difference in net groundwater exchange with the Silver Stream is shown with brackets and the appropriate quantities

In the West Taieri, increases in the groundwater pumping from the confined Mosgiel-Momona aquifer expressed affected groundwater levels, exchanges with the Taieri River and the required drainage collecting in the West Taieri drainage scheme. Primarily, the bulk of the response to the groundwater pumping was expressed as diminished seepage that would otherwise have been caught in the drainage network. This manifests as a 85l/s reduction in the drainage water pumped into Lake Waipori by the Waipori Pumping Station, as a consequence of groundwater extraction of 3 Mm^3/yr, as in Scenario 4. Groundwater pumping increases induced declines in groundwater level and discernable drawdown effects surrounding simulated pumping centres in the West Taieri. The drawdown effect expresses in both Layer 1 and Layer 2, which correlate with the Waihola Silt-Sand Aquitard and the confined Mosgiel-Momona aquifer, respectively. The change in river exchange is negligible. The remainder of the groundwater drawn by the simulated hypothetical pumping would initially come from aquifer storage, but ultimately from increased infiltration of net recharge into Layer 2.

6.3.2 Rises to groundwater system base level

As simulated water levels rose in the water levels in the lower rivers, lakes and lake wetlands complex, the groundwater in Layer 1 rose as well. The extent and intensity of groundwater level rise is shown in Figure 6.4, below.

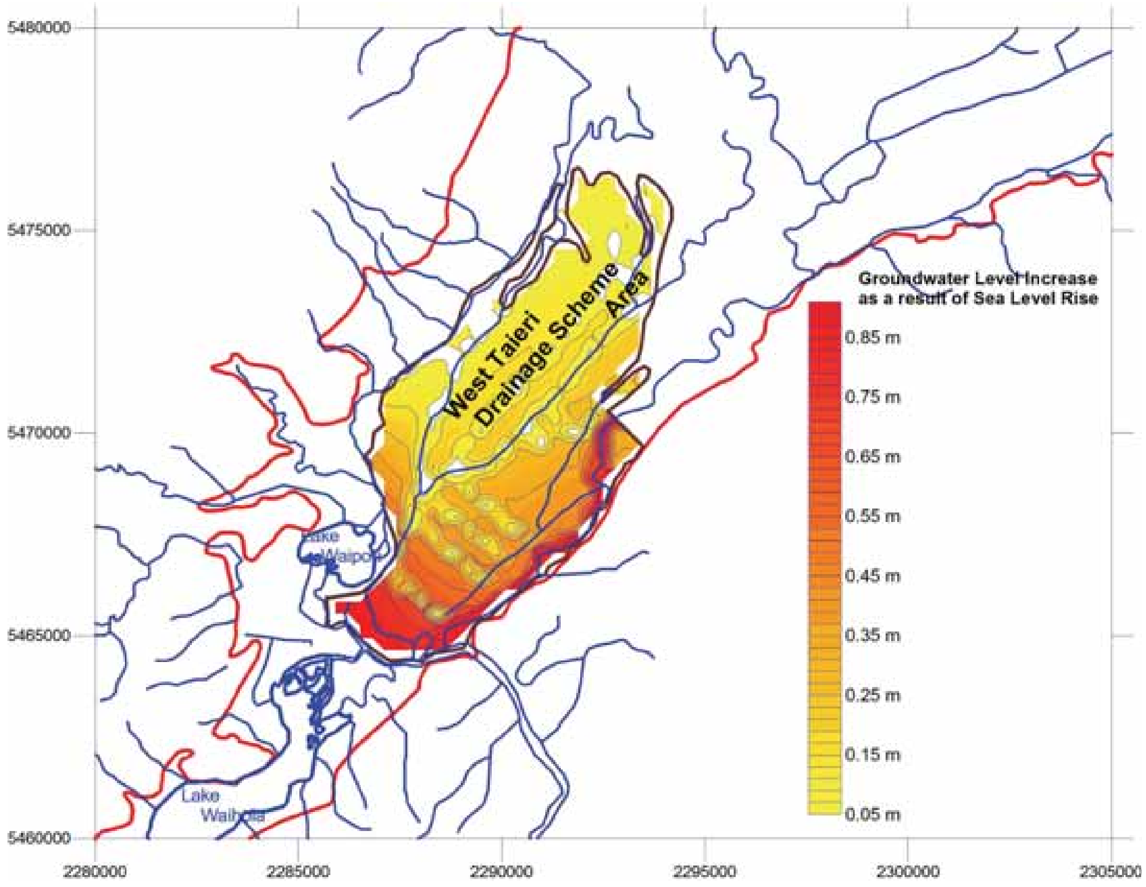

Figure 6.4 Colour flood and contours of the intensity of groundwater level rise adjoining the lower rivers and lakes following sea level rise of 1.5 m above current mean sea level

The simulated rise in groundwater level as a consequence of sea level rise was highly constrained by the drainage network of the West Taieri Drainage Scheme. The higher intensity rises up to 0.9m are closest to the rivers or Lake Waipori and more distant from drains. The model simulation indicates that the drainage network intercepts an additional 55l/s of groundwater following the sea level rise.

6.4 Groundwater modelling discussion

6.4.1 Calibration and fitness of models for prediction

Sensitivity analysis and steady-state calibration allowed respectable replication of the behaviour of the Lower Taieri Basin groundwater system. The principal failings of the model in the stratified aquifer Mosgiel area were the limited ability to model individual water-bearing-layers or to replicate the steep vertical hydraulic gradient. This notwithstanding, the transient calibration achieved for the shallow aquifer near Mosgiel was strong.

The transient calibration to the Momona groundwater level record, which measures the confined Mosgiel-Momona Aquifer, failed to achieve the full range of fluctuation recorded in nature. This is partially explained by the dichotomy between the micro-scale of monitoring measurements and the meso-scale of model results, including partial penetration of the monitoring bore.

The overall calibration achieved in transient simulation, approximately 3% ratio of standard deviation of error divided by the range of calibration levels (RMSE/Range), is comfortably within the 5% recommended for basin-scale groundwater modelling. The Lower Taieri Basin suffers a number of potential difficulties for achieving transient calibration: chiefly, a low density of hydraulic parameter measurements, the expectation of significant refused groundwater recharge, and the pivotal but poorly characterised role of the rivers in balancing recharge and discharge across the basin. The model also enjoyed some advantages: primarily, the certainty about boundary condition at the margin and the fixed heads imposed on groundwater levels in the lake wetland complex and West Taieri Drainage Scheme area. In the face of these, the current model compares favourably with previous modelling projects (IRRICON, 1997; Murray and Edge, 2001) in the calibration performance.

6.4.2 Groundwater pumping scenarios

The system had previously been recognised as being sensitive to groundwater pumping at Mosgiel in terms of the likely effect on the Silver Stream (IRRICON and ESR, 1997). The current study has delineated the exchange between the Silver Stream and groundwater system with more precision, and integrated this within the transient model. The current study determined that much of the groundwater pumped at Mosgiel was derived from soil drainage, but that a portion came from the Silver Stream and that the groundwater system maintained a diffuse linkage to the river. Consequently, the ability to predict the effect of an increase in Mosgiel pumping is improved.

Modelling allowed the identification of the main adverse effect of increased pumping at Mosgiel as increased losses from the Silver Stream to the stratified aquifer. Comparison of the range of scenarios and their effects indicated that limiting any increase in Mosgiel groundwater allocation to no more than 50% offset the worst impacts groundwater pumping on groundwater levels and Silver Stream flow losses.

The scenario examination of increases in groundwater pumping in the West Taieri was highly theoretical as there is not yet a tradition of appreciable groundwater use for irrigation in this area. It is doubtful that future irrigation would be embarked on in view of the relatively wet nature of many West Taieri soils under ditch drainage soil water management. The water table in the drained soils are very shallow under the influence of upward groundwater pressures and the low-lying nature of the fields in the drainage scheme area. However, it was considered prudent to consider some degree of groundwater pumping in case future groundwater use in the West Taieri included a degree of extraction for irrigation, primary processing, industrial or public water supply purposes.

Groundwater scenario modelling is indicative of the West Taieri, being relatively insensitive to the effects of groundwater pumping, even up to 3 $\mathrm{Mm^3}$/yr. The principal effect of pumping at this level was to diminish the requirement for drainage, which is mostly a beneficial effect. The localised drawdown impacts would require individualised management to prevent bore-to-bore pumping interference.

7. Resource allocation and monitoring recommendations

7.1 Groundwater allocation

7.1.1 Summary of current allocation mechanisms

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 groundwater basin.
- Groundwater abstraction is regulated by the relevant monitoring well restriction levels at Harley Bore P2 for East Taieri and Momona Bore for West Taieri.
- The underlying intentions of the above groundwater allocation management practices have been to avoid the possibility of aquifer depletion and depletion of the Silver Stream through increased flow losses through its bed.

The Lower Taieri Basin has only a small number of consent holders to take quantities of groundwater that are less than minor. Appendix E lists the groundwater takes currently issued with consents in the Lower Taieri Basin. Groundwater is taken at Mosgiel for public water supply and a diminishing amount for industry. Elsewhere there are a handful of consents issued for farm or nursery purposes, but the quantities authorised are comparatively minor. Water is sometimes taken out of the ground using the DCC borefield at Outram, but this is known to be almost exclusively Taieri River water entering via bank filtration so it is not included in Appendix E or in the allocation total. Groundwater is taken at Dunedin International Airport, Momona, but it is re-injected into the same water-bearing-layer in the same quantity once thermal energy has been extracted and is thus volume-neutral. The conclusion is that there is one consent holder in the Lower Taieri Basin of any consequence for groundwater allocation, and that is the Dunedin City Council for its Mosgiel water supply. The consents for this allocation were last set in 2004, with the requirement to renew them in 2038. Numerical model has pointed to the current actual groundwater pumping and allocated pumping being sustainable. Accordingly, any future allocation of groundwater in the Lower Taieri Basin up to the perceived limits of sustainability would be shaped by new applications. In many instances, the land uses that might stimulate expansion in groundwater requirement are not yet present on the Taieri Plains.

7.1.2 Potential for seawater intrusion

Much of the Lower Taieri Basin lies at or slightly above mean sea level. There are slight estuarine influences in the salt composition of the lower Taieri and Waipori rivers, and the lakes. However, the freshwater inputs from the main rivers have freshened the lower basin over the past 5,000 years to the point that it is now primarily freshwater. Relict salty groundwater is suspected of seeping into the West Taieri Drainage Scheme, but this inferred to be a long-standing flushing process rather than modern seawater intrusion of the groundwater system.

The Lower Taieri Basin is currently protected by the schist rock of the seaward range from having any direct contact with the Pacific Ocean. The sole connection to the sea is via the Henley Gorge from Taieri Mouth on the coast and upstream to Henley Ferry.

Currently, mildly brackish surface waters ebb and flow within the lower river and lakes by way of this connection. The lower rivers, lakes and wetlands are largely confined to their beds and flood berms by a system of artificial flood embankments.

Future sea level rise is an area of significant conjecture. However, sea level rise is a mechanism whereby saltier surface water could be brought into the lower river system. Higher water levels in the Henley Gorge might increase the wetted area of the gorge, and the tidal compartment in the lower rivers and lakes would certainly increase. The increased tidal flows within the lower basin would be likely to increase the general salinity as the freshwater was overloaded by tidal exchanges comprising seawater. At a sea level increase of 1.5m, the expectation is for the tidal areas to be at least estuarine with respect to salinity.

Estuarine conditions in the lower rivers and lakes of the basin would not by themselves be reason enough for seawater intrusion. The movement of salty water into the landward portion of an aquifer generally requires a gradient promoting such movement. The classic example is a simple coast aquifer sloped to flow into the adjoining sea. Through over-pumping the water level gradient from the land to sea is locally reversed, allowing seawater to compensate for the pumping-induced drawdown by moving inland. However, in the case of the Lower Taieri Basin, the groundwater system discharges a substantial portion of its water balance outwards as seepage into rivers, lakes, wetlands and drainage ditches. This gradient will not be reversed by rising sea level, although the gradients may flatten and groundwater levels would rise.

Localised water level contrasts may still be significant at 1.5m of sea level rise in promoting incipient seawater intrusion, though. It is easier to imagine a salty Lake Waipori, separated by only a flood embankment, with a 3.5m head difference to the adjacent West Taieri Drainage Scheme land, giving rise to localised seawater intrusion through the ground. The inflow rates of any such intrusion should be tempered by the low permeability of the Waihola Silt-Sand, through which the salty water would have to permeate. Predicting such localised effects, including seepage backflow through flood embankments, is generally beyond the resolution and capabilities of the basin-wide MODFLOW model.

7.1.3 Controls on groundwater levels

The Lower Taieri Basin is divided into two groundwater management zones and restricted in accordance with groundwater levels monitored at Harley Bore, near Mosgiel, and Momona Bore, near Dunedin International Airport. The restriction levels were set in the background technical report (ORC, 1998) supporting the Water Plan. In essence, the levels for the Harley Bore were set so as not to exacerbate a drop in level of more than 3m below the highest recorded level in the P2 piezometer. At Momona, the objective was not to exacerbate a drop in level beyond -1.0m AMSL (i.e. 1m below mean sea level), meaning that a maximum decline of 2.24m below the previous highest recorded level in the monitoring bore. The proposed mechanisms for avoiding these falls in level are to curtail the taking of groundwater from within the respective water take restriction zones at a graduated percentage of restriction tied to groundwater levels in the respective monitoring bores. The restriction steps are 25%, 50% and 100% of the full allocated pumping rate. The rationale for the restriction levels assumes that allocated groundwater pumping activity has a significant influence on the monitored groundwater level. Thus, a drop in level beyond a pre-set curtailment level triggers a direction to groundwater consent holders for curtailment by the relevant percentage of full allocation under current consents.

In the Lower Taieri-East context, two small groundwater takes amounting to less than 0.03Mm^3/yr of consented allocation are subject to level restrictions pegged to the Harley Bore P2 piezometer. The major Mosgiel water supply consents are largely exempt from the restriction levels, with only the non-domestic portions of the water use subject to curtailment. In practice, these restrictions are to be achieved by watering bans implemented by the Dunedin City Council. The Harley Bore P2 piezometer record is quite volatile, as a consequence of the monitoring bore's close proximity to Mosgiel water supply bores, particularly Severn Bore and Cherry Drive Bores. Figure 7.1 shows the full historic groundwater level record as instantaneous measurements (in blue) and monthly level means (in red over plot).

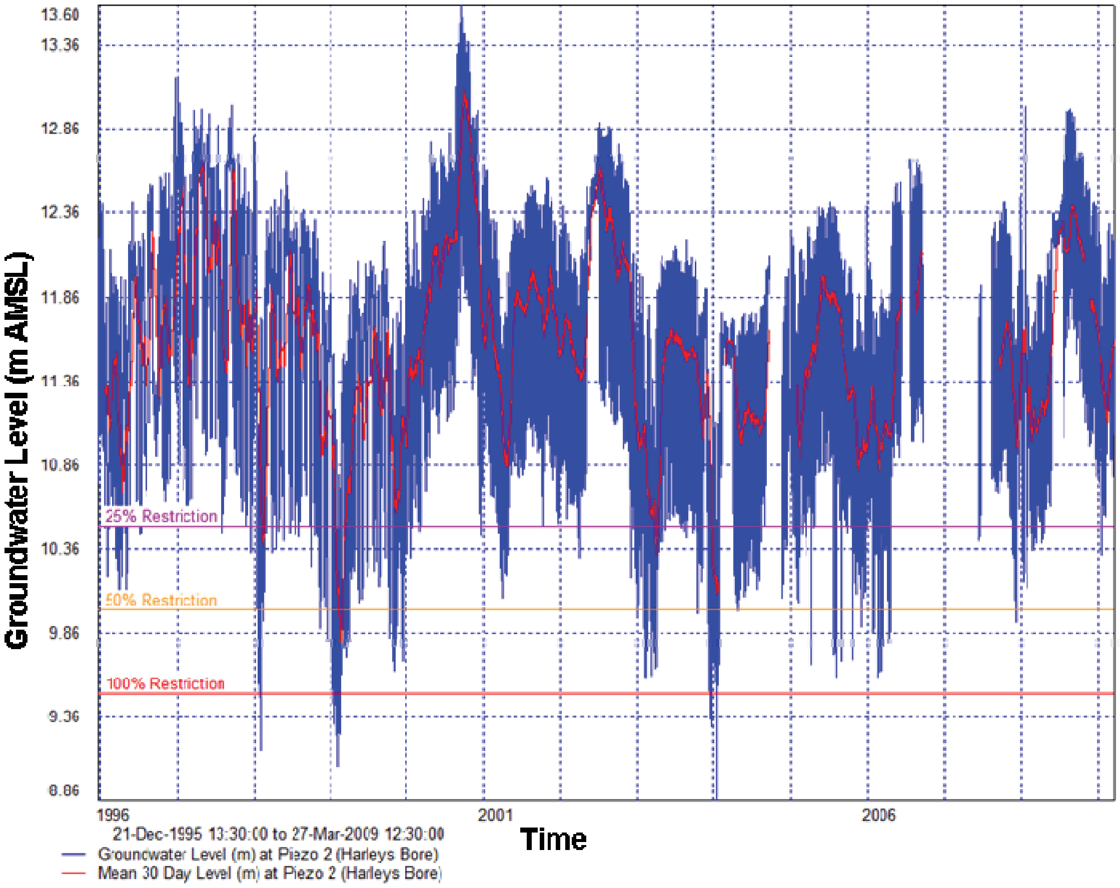

Figure 7.1 Full historical groundwater level plot recorded at Harley Bore P2 piezometer, including 30 day mean (in red) and restriction levels

The 50% restriction level has been breached in the historic record by the 30 day mean level (referred to in the Water Plan) on only one occasion, and not at all since the effect of the Plan in February 2004. The 25% restriction level has been breached on four occasions, and not at all since February 2004.

Figure 7.2 shows the full historic groundwater level record for the Momona Bore within the West Taieri zone. It is much less volatile than the Harley Bore, being sheltered from proximity to major groundwater takes, although pumping and re-injection of heat pump water has been practised in the airport grounds since 2007.

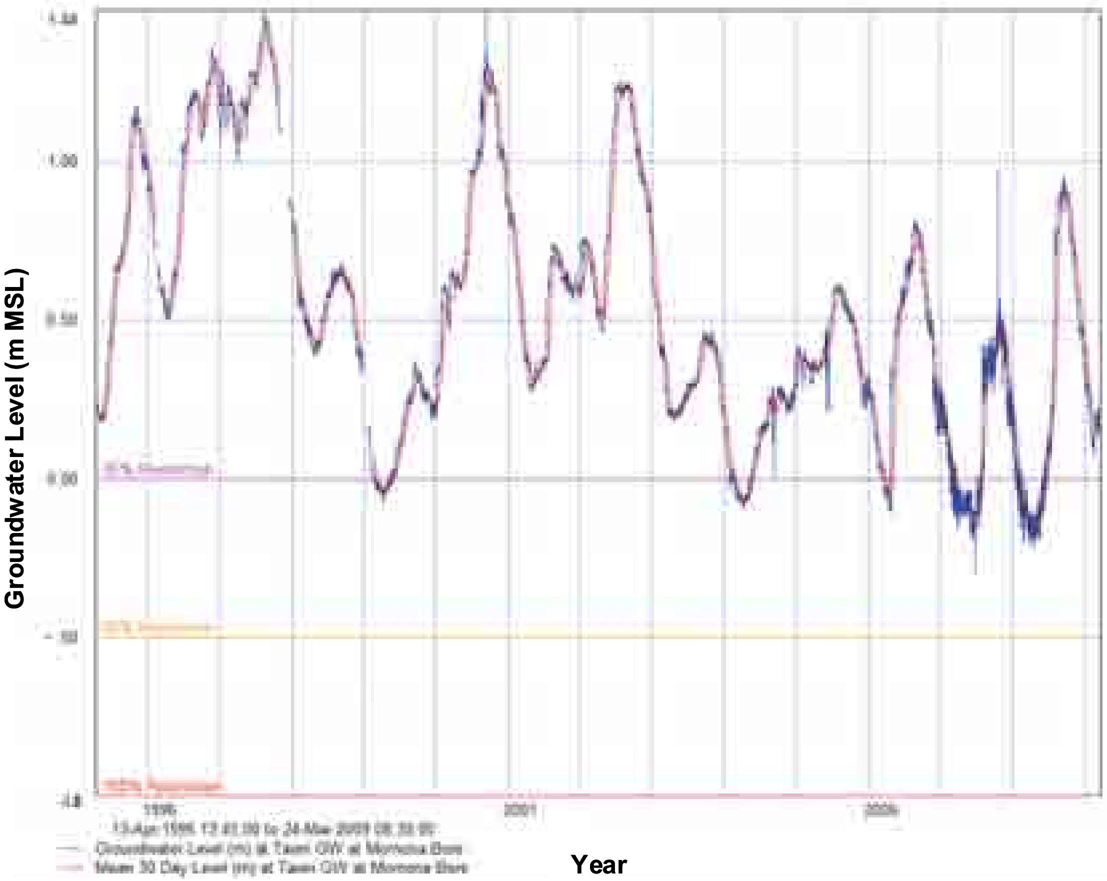

Figure 7.2 **Full historical groundwater level plot recorded at Momona Bore, including 30-day mean and restriction levels**

The 25% restriction level has been breached by the 30-day mean level on five occasions, four times since February 2004. Much of the fluctuation at the Momona Bore is the result of land surface recharge pulses, river level changes and barometric shifts affecting the semi-confined aquifer. Given the small volumes of groundwater subject to curtailment in either water take restriction zone, any beneficial recovery effects of complying with the restriction are probably minimal. Changes in the ambient environment, particularly land surface recharge pulses, river level changes and barometric shifts, caused the groundwater levels to recover and pass above the restriction levels rather than any groundwater pumping curtailment response.

The other impediment to optimal effectiveness of the restriction level approach is the necessarily arbitrary nature of the selection of the restriction levels, particularly those of the Lower Taieri-East zone, as monitored at Harley Bore P2 piezometer. It was not known, at the time of setting the restriction levels within the (then) proposed Water Plan, what the critical groundwater levels for the water supply aquifer would be. Accordingly, a somewhat arbitrary 3m below peak for the 100% restriction level was specified for most water take restriction zones in Otago (ORC, 1998).

On the basis of the numerical modelling undertaken looking at the optimal groundwater taken in the Mosgiel area for maintaining acceptable losses in the Silver Stream, an earlier onset and more tightly graduated set of restriction levels is recommended in Table 7.1 and Figure 7.3, as follows:

Table 7.1 Schedule of suggested amendments to restriction levels for the Lower Taieri-east water take restriction zone in accordance with the maintenance of Silver Stream flow rates

Reference bore	**Aquifer maximum height (m AMSL)**	**Restriction levels (m AMSL)**		
	(Level adjusted since 1998 for a new peak in 2000)	25% Restriction	50% Restriction	100% Restriction
Harley Bore P2	12.9	10.7	10.3	9.9
Existing RPW, schedule 4 levels	12.5	10.5	10.0	9.5

The suggested schedule raises the onset of the 25% restriction level and brings in the more stringent restriction levels sooner. Coincidentally, the total range from the aquifer maximum height to the 100% restriction level is 3.0m.

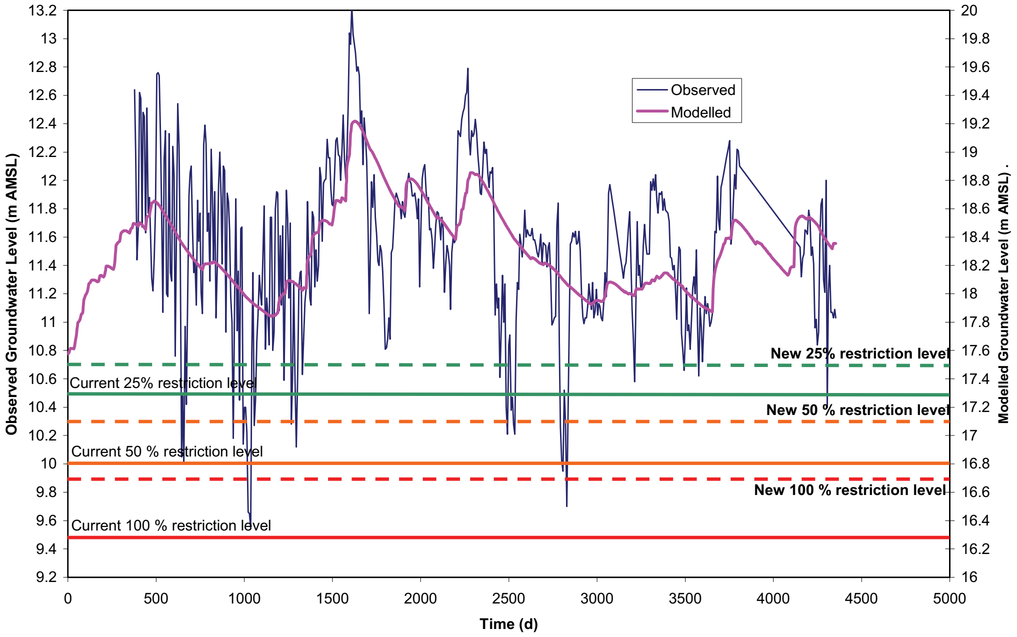

Figure 7.3 Plot of average weekly levels from Harley Bore P2, the adjusted modelled groundwater levels at the site and the suggested new restriction levels

The Lower Taieri-West water take restriction zone as monitored at the Momona Bore, is less arbitrarily restricted. The fundamental base level for this zone is mean sea level. The 100% restriction level seeks to cut off large groundwater takes when levels decline past the Low Water Spring (LWS) tide level, which lies at approximately -1.1m MSL. Due to the contact that the West Taieri groundwater system makes with tidal waters this is a sensible approach. Accordingly, it is recommended that the current restriction levels in the Lower Taieri-West water take restriction zone are retained, although the level datum should be benchmarked to actual sea level rather than historic sea level, in order to preserve the effectiveness of the restriction level.

7.1.4 Surface water baseflow contribution

The Lower Taieri Basin groundwater system provides significant baseflow contribution to the lower Silver Stream downstream of Riccarton Road (Taieri depot), the middle reaches of the Taieri River and the lower reaches of the Taieri and Waipori rivers. The baseflow contribution to the lower Silver Stream is ecologically significant, as has already been described. The contribution is the net effect of the losses to the groundwater system alongside Mosgiel and the gains to the Silver Stream downstream. Increases in Silver Stream losses as a result of Mosgiel water supply pumping reduced the net groundwater contribution to the Silver Stream during low flows. Low flows are the most ecologically significant period in terms of changes to critical habitat.

The groundwater contribution becomes less important to the Taieri and Waipori rivers downstream of the tidal transition, since groundwater contributions are swamped by the relatively static base level, are small in comparison to the tidal exchange, and fluctuations in groundwater contribution would thus have little impact on habitat, cultural or recreation values. The Taieri River upstream of Allanton and the Waipori River upstream of Berwick are also potentially receptors of baseflow, but in a functional sense are not particularly vulnerable to fluctuations in groundwater contribution.

The tidal lakes, Waipori and Waihola, seem not to receive significant groundwater contribution, according to numerical modelling results. The net gain of these lakes from groundwater was indicated to be approximately 38l/s in numerical modelling. This quantity can be set alongside the mean annual catchment freshwater inflows of almost 8,000l/s which the lakes receive, let alone the 116,000 l/s of tidal flux that exchange through the lakes with each tidal cycle (Schallenberg et al., 2003).

Accordingly, on the basis of current knowledge, the Silver Stream is the sole water body in the Lower Taieri Basin that merits groundwater management to protect instream values. The depletion of the Silver Stream by losses to groundwater can be most appropriately managed by the aforementioned groundwater allocation limitation for the Lower Taieri-East water take restriction zone of 2.9Mm3/d and the adoption of the amended restriction levels suggested for the Harley Bore.

7.1.5 Allocation limits – outflows and recharge

It is proposed that the Lower Taieri Basin groundwater allocation be set for the basin as a whole and for each water take restriction zone (East and West). The proposal can be summarised as follows:

Water take restriction zone	groundwater allocation cap
Lower Taieri-East	2.9Mm^3/yr
Lower Taieri-West	3Mm^3/yr
Lower Taieri Basin	5Mm^3/yr

This total allocation is substantially less than the mean annual recharge of the Lower Taieri Basin and is estimated to represent perhaps only 12% of mean annual recharge of the groundwater system from all sources (i.e. land surface rainfall recharge, river losses and other surface water contributions). However, groundwater pumping in the East Taieri is inevitably going to develop in close proximity to Mosgiel. In this area, the

Silver Stream is the value requiring protection from increased groundwater pumping. So, limiting increased allocation to a total of 2.9Mm^3/yr would lessen the possibility of substantial effects on Silver Stream low flows. There is currently a total of 2.2Mm^3/yr of groundwater allocated to a variety of uses in the East Taieri.

The West Taieri area is less likely to attract significant increases in groundwater pumping. Nonetheless, the West Taieri aquifers have an ability to provide groundwater without significant adverse effects up to 3Mm^3/yr, as was demonstrated in numerical modelling. Local effects such as drawdown may require additional site-specific assessment were large production bore to become developed in the West Taieri to exploit the available allocation in the future. There are currently only 0.2Mm^3/yr allocated to consents for irrigation with groundwater in the West Taieri.

7.2 Groundwater quality management

7.2.1 Possible causative factors

The shallow groundwater in North Taieri-Mosgiel area displays some potential for elevation with respect to nitrate-nitrogen. Outside this small area of the Lower Taieri Basin, geochemical conditions favour denitrification of oxygenated forms of dissolved nitrogen such as nitrate. The causative agent in nitrate accumulation is intensified agriculture, particularly intensive grazing or cropping.

The Mosgiel water supply is the sole water source for up to 9000 individuals and the groundwater system supplying it requires management as a watershed. Potential groundwater quality degradation has been extensively examined in relation to diffuse agricultural contaminants (IRRICON and ESR, 1997) and the North Taieri landfill leachate emissions (IRRICON and Royds Consulting, 1994; IRRICON, 2005). However, little attention has been directed towards addressing the handful of contaminated sites in the recharge zone of the Mosgiel water supply. The contaminated sites primarily relate to past or ongoing industrial activity, but also include abandoned industrial landfills of buried waste within former gravel pits.

Underground petroleum storage tanks have a worldwide history of spilling petrol, diesel or fuel oil into the ground without detection for some time and in quantities that locally contaminate shallow groundwaters. Continuation of the policies requiring double skinned tanks with low corrosion potential and interstitial gas monitoring for new tanks, plus product gain/loss accounting, goes some way towards minimising the risk of incidental releases.

Elevated iron and manganese concentrations in groundwater are a natural phenomenon not readily attributable to human activities. However, bore construction and the depth of screening has some influence over the concentrations experienced by the groundwater user.

Shallow groundwater is sometimes contaminated with faecal bacteria, usually from grazing animals, or effluent discharges into the ground, such as septic tank soakage. The pattern of contamination is typically haphazard in ground conditions and the timing of contamination events, making prediction of the causative factors difficult. However, Lower Taieri Basin shallow groundwater tends to be dominated by conditions generally hostile to bacterial persistence.

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 (GPZs) are defined in the Water Plan to identify vulnerable aquifers. In the Lower Taieri Basin, three separate groundwater protection zones have been defined:

- GPZ-A and GPZ-B areas to the north of and surrounding Mosgiel
- a GPZ-A area surrounding Outram township
- a GPZ-A area surrounding Berwick and upstream to the terminus of the Waipori Gorge.

These zones have been defined primarily on the presence of shallow water table and recharge areas, but also considering the coincidence with areas of higher density settlement. The large protection zones surrounding Mosgiel and the up-gradient recharge areas are primarily to protect the Mosgiel water supply. A further regulatory layer of protection is provided by the National Environmental Standard (NES) for Drinking Water Sources. This NES constrains the ability of the ORC to issue resource consent that could have the effect of contaminating the Mosgiel water supply. In addition, the ORC's setting of permitted uses under its plans needs to consider the possibility of water supplies being adversely affected. This last provision is given some effect by the Water Plan requirement of consent approval for domestic effluent discharges falling within a GPZ-A area that would otherwise be permitted. The consenting process allows specific assessment of the contamination potential and includes the possibility that the application would be declined if the effects were found to be unacceptable.

7.3 Bore construction management

7.3.1 Bore construction practices

Past bore surveys of the Lower Taieri Basin have found a wide range of states of repair and standards of original bore construction within the large samples of the basin's total stock of wells and bores. Bores currently installed (large diameter wells are extremely uncommon in modern installations) are generally well constructed with casing materials and specialised screens. There is a current trend towards PVC plastic screens set at the base of steel casing as a response to past problems iron bacteria clogging, particularly where slotting of mild steel casing had been used in the past.

7.3.2 Issues with past and current bore construction

Groundwater pressure maintenance, corrosion, water quality protection and screen efficiency issues have arisen with past practices of bore construction.

7.3.2.1 Pressure maintenance

The chief loss of aquifer pressure is actually as a result of letting bores under flowing artesian pressure run to waste. There is a myth among the rural community that an artesian bore will clog up if not allowed to flow continually. There are also marginal advantages to using artesian groundwater for stock water by allowing the water to simply overflow the drinking trough. The problem with allowing bores to run to waste is that it induces a permanent loss of pressure surrounding the bore concerned and the diversion of artesian groundwater into surface water when the water might serve a better environmental service by remaining in the aquifer. Field investigations in the West Taieri noted the continuous discharge of many small diameter artesian bores flowing to waste, and the area's water balance contains appreciable discharge of water into the drainage system in this manner (IRRICON, 1997).

Little information pointing to multiple screening was found in the course of data analysis. An exception was the Dunedin City Corporation deep well, the Wingatui Bore, which used slotted sections across a large profile to maximise the yield to this production bore. There is no direct evidence to link the practice in this particular case to persistent drops in groundwater pressure in the adjoining Stratified Mosgiel-Momona Aquifer. It is possible that employing the practice of multiple screening in the West Taieri, where aquifers are more distinct, would have greater deleterious effects on groundwater pressures and quality.

7.3.2.2 Corrosion of bore-casings

The groundwater of the Lower Taieri Basin is recognised for being aggressive and giving rise to metal corrosion (IRRICON and Royds Consulting, 1994; IRRICON and ESR, 1997). Two policies (9.4.15; and 9.4.16) in the Water Plan cite this tendency to control the adverse effects of bore-casing corrosion on the groundwater resource of the Lower Taieri Basin and the Papakaio Aquifer. Generally, the issue or effect of bore casing corrosion is the potential for loss of pressure integrity and the mixing of groundwaters from a variety of depths, resulting in unanticipated water quality effects. In severe cases, artesian aquifers may discharge directly into unconfined superficial water-bearing-layers, with the consequent loss of groundwater resource from an otherwise secure aquifer.

The five-year re-certification process for bores in the lower Taieri Basin has not eventuated. The drilling industry environmental standard, AS / NZS 4411:2001 "Environmental Standard for Drilling of Soil and Rock", specifies the use of corrosion resistant materials in settings that warrant it, and emphasises the separation of aquifers or water-bearing-layers to the satisfaction of the requiring authority (i.e. Otago Regional Council). The adherence to the Standard has been made a condition of consent applications to drill or construct a bore since 2004.

7.3.2.3 Water quality protection

The chief issue with water quality protection is that of bore-head soakage protection. Most of the bores currently installed include a casing driven from the surface to the top of the screen by a casing advancer method variously named TUBEX, ODEX or Concentrix. The under-reaming drill bit cuts a hole for the casing and the casing advancer pushes against a 'shoe' welded to the bottom of the casing by a series of blows with a pneumatic reciprocating hammer. The drill casing is usually a neat fit to the drill hole itself and is most commonly left in place for the final completion without the benefit of any further sealing. In instances of drilling through loose sediments, it would be protective of groundwater quality for a surface seal with a free-draining profile to conduct standing surface water away from the bore head and prevent it tracking down the side of the casing or overflowing into the inner-bore casing.

7.3.2.4 Screen efficiency

Low screen efficiency by whatever cause is sometimes an impediment to efficient groundwater utilisation and resource management. Aquifer-induced and screen loss-related drawdown have the effect of lowering the operational water level in any bore. The screen loss-related drawdown component is a product of the configuration and materials used in constructing the bore for water extraction. Stainless steel wire-wound well screens are vastly more efficient than oxy-acetylene cutter slotted mild steel casing used in place of a specialised screen. Aquifer drawdown can come from two sources; the head losses due to the pumping of the bore and the declines induced by the pumping of other bores. When conflicts over groundwater amenity occur they usually centre on competitive drawdown, where bores pumping simultaneously amplify the depth of drawdown on each other.

If screen loss-related drawdown can be minimised, then competitive drawdown between groundwater users is also reduced. Screen efficiency of even the best screen materials can be reduced by the effects of iron bacteria. Mats of these bacteria can colonise the screen apertures and cause significant drawdown, to the point of bore pump failure. Iron bacterial infection can be avoided or minimised by drilling and pump contractors sterilising equipment between different bores. Bores can also be sterilised in-situ, using strong oxidising agents such as sodium hypochlorite solution.

8. Conclusions and recommendations

8.1 Seawater intrusion risk

8.1.1 Conclusion

Despite the lower basin surface water system being tidal and brackish water being present upon occasion, there would appear to be few hydraulic gradients that would promote seawater intrusion. Sea level rise, combined with increased groundwater pumping could change this situation, and in extreme instances could result in brackish water intruding into parts of the groundwater system.

8.1.2 Management options

Observance of current groundwater level restrictions and adherence to caps on groundwater allocation volumes would serve to minimise the intrusion risk. Site-specific assessment of certain vulnerable locations may be required should the salt content of the lower basin's surface water system change significantly in the future.

8.2 Groundwater levels pumping restrictions

8.2.1 Conclusion

The current restriction levels set for the Lower Taieri-East water take restriction zone were found not to be sufficiently protective. Slight tightening of the restrictive levels would allow the current level of groundwater allocation and even modest expansion.

8.2.2 Management options

This report suggests revising the Lower Taieri-East water take restriction zone restriction levels as follows:

Reference bore	**Aquifer maximum height (m AMSL)**	**Restriction levels (m AMSL) (Note: AMSL = Above Mean Sea Level)**		
	(Level adjusted since 1998 for a new peak in 2000)	25% Restriction	50% Restriction	100% Restriction
Harley Bore P2	12.9	10.7	10.3	9.9

The reference datum for Lower Taieri-East water take restriction zone restriction levels, as measured at the Momona Bore should be "Mean Sea Level" rather than Otago datum. The reason is that should sea level rise and the mean sea level datum be lifted in response, the restriction level would remain physically relevant.

8.3 Groundwater volume allocation limit

8.3.1 Conclusion

Neither of the Lower Taieri water take restriction zones have limits on groundwater allocation volume. The Proposed Plan Change 1C provides the ability to set such limits for optimal groundwater resource management. Technical evaluation of the results of numerical modelling has provided the basis for suggesting allocation limits for inclusion in Schedule 4A of the Water Plan if and when the plan changes become effective. It should be noted that increasing the allocation in the Lower Taieri East zone to 2.9Mm^3/yr could increase the impact on the Silver Stream by up to 25l/s.

8.3.2 Management options

It is proposed that the following groundwater allocation volume limits be set for the Lower Taieri Basin as follows:

• Water take restriction zone	Groundwater allocation cap
• Lower Taieri-East	2.9Mm^3/yr
• Lower Taieri-West	3Mm^3/yr
• Lower Taieri Basin*	5Mm^3/yr

Note:
* The Lower Taieri Basin (Map C15) encompasses both the Lower Taieri – East and – West water take restriction zones (Map D4).

8.4 Bore construction

8.4.1 Conclusion

There are several issues relating to the construction of bores in the Lower Taieri Basin. Many of these issues, but not all, are held in common with much of the rest of the region’s aquifers. The most pressing and pertinent relate to bore-casing corrosion and flow, artesian bores being allowed to run to waste.

8.4.2 Management options

It is suggested that bore construction be managed through the consent process in accordance with policies 9.4.15 and 9.4.16.

Appendix A History of previous studies

Significant studies of the geology and groundwater resources of the Lower Taieri Basin

The first known appraisals of the groundwater resources of the Lower Taieri Plains were made by Professor J. Park, Professor W.N. Benson and a drilling contractor, J.M. Stewart, in the early part of the twentieth century.

Professor J. Park was an eminent Otago geologist. He compiled a report (Park, 1916) on prospects within the Taieri Plains for artesian groundwater development. In it, he recognised the likely considerable thickness of the Taieri Basin, but considered it an unpromising source of water supply for Dunedin City, containing “too many unknown elements to be satisfactory”. Later at the request of the City Engineer, Professor W.N. Benson (1930) similarly found few grounds for recommending the area’s groundwater system for development, due largely to the observed variability in alluvial composition and groundwater quality. Although the letter is undated, Mr J.M. Stewart responded to a similar request from the Dunedin City Council, at about the same time as that of Prof. Benson. In the letter, Mr Stewart expressed a contrary view from the geology professors and considered that sufficient promise and precedent existed for the basin to be further evaluated for groundwater exploration (presumably utilising his services). It was during this period from the 1920s to the 1940s that a moderate amount of groundwater development was occurring at individual farms and factories located on the Taieri Plains.

By the time that the country’s first hydrogeologist (groundwater geologist), Mr B.W. Collins, was invited to investigate groundwater phenomena in the Mosgiel district, there were already at least two dozen wells or bores being used there. Mosgiel Borough was utilising bores for town water supply, the industries of Mosgiel were using wells and later bores, farms were drawing groundwater for stock water and Dunedin City’s water supply had been augmented by pumping out of the Wingatui Road Bore into the Council’s water race running towards Dunedin (Collins, 1950). Thus, by 1950, the basic shape of water resource development that exists today had been put in place. The DCC Wingatui Bore proved to be the catalyst for Mr Collins’ investigation of the area’s groundwater resources, since heavy test pumping, following completion of the bore was perceived to have led to groundwater level declines. For its time, the Collins (1950) report was close to a comprehensive qualitative assessment, covering geology, aquifer geometery, relative aquifer properties, level fluctuations, climate influences and drawdown between bores. He also found that the Wingatui Bore could exert a drawdown effect on the Mosgiel Yard Bore operated by Mosgiel Borough Council, and that basin recharge in the Mosgiel district would largely be controlled by net rainfall.

Following the 1950s with the abandonment of the Wingatui Bore, the Dunedin City Council’s use of Lower Taieri water resources shrank to the gallery well field, adjacent to the Taieri River at Outram. The Mosgiel Borough Council also installed a wider bore network throughout Mosgiel to strengthen the town water supply and reduce water distribution costs. Following amalgamation of Dunedin City and Silverpeaks County (successor council for Mosgiel Borough) in 1989, the combined council joined the two supplies at Wingatui Reservoir allowing Mosgiel to be supplied from the larger network. The Mosgiel bores continued their previous operation in serving the township.

This was essentially the setting encountered in the first groundwater investigation undertaken in 1994 by IRRICON and Royd's Consulting (1994) under contract to ORC. The IRRICON and Royd's Consulting (1994) report comprised a primary revision of all known information on the Lower Taieri Basin and several field surveys of the basin's groundwater conditions. Significantly, a basin-wide groundwater level survey was combined with the sampling of 100 bores to characterise the system as a whole. The North Taieri Landfill, which had been a county council disposal site for several decades, was investigated for potential groundwater contamination as part of the 1994 study. The perceived high stress areas of the basin around Mosgiel and Outram were examined in more detail in the IRRICON and ESR report (1997). This investigation concentrated largely upon the perceived problem areas of North Taieri, Mosgiel water supply and Outram, with a particular emphasis on groundwater quality protection. The 1997 IRRICON and ESR study included substantial field investigation, mainly drilling and installation of piezometers in the Mosgiel area. A concurrent investigation was undertaken of groundwater quantity matters in the West Taieri area by IRRICON (1997).

Many of the groundwater management recommendations of the IRRICON and Royds (1994), IRRICON and ESR (1997) and IRRICON (1997) reports were integrated into management guidelines in preparation for the Water Plan as a background report (ORC, 1998). Subsequently, the Water Plan contained several specific provisions relating to groundwater management, including the following:

- Groundwater quality protection zones surrounding Mosgiel, Outram and Berwick.
- Two separate take restriction zones: Lower Taieri-East and Lower Taieri-West, controlled by restriction levels at the Harley and Momona monitoring bores, respectively.

Another legacy of the IRRICON and ESR (1997) investigation was the instrumentation of the Harley Bore near Mosgiel, the Hyslop Bore at Outram and the Momona Bore at Dunedin International Airport.

The studies of the Lower Taieri Basin in the 1990's seemed to spawn a number of non-ORC geological and groundwater investigations. An investigation into Quaternary age alluvium by GNS Science (Barrell et al., 1998) re-evaluated the previously held concepts of the Taieri Basin. This included the initial indications from the drill core recovered from the Victoria University of Wellington research drill hole, Waipori 99-1. Victoria University reported on the results of drill hole analysis derived from Waipori 99-1 (Dickenson et al., 2000), including core description, dating (Uranium-Thorium and radiocarbon) and groundwater pressure within multi-level piezometers. These four piezometers at Waipori 99-1 were later instrumented by the ORC in 2004. The primary objective of the Waipori 99-1 drilling programme was to unravel climate influence on terrestrial basin formation. The dating of sediments allowed the Quaternary sediments of the Lower Taieri Basin to be attributed to the last 50,000 years and therefore the last global glacial cycle of recorded geological history. As a result, the tectonics of the Lower Taieri Basin were better understood and a more reliable geological history of the basin was put together in Barrell et al., (1999). Litchfield (2001) discussed the timing and magnitudes of crustal movements alongside the sediments trapped between crustal blocks. The synthesis of this geological information fed into groundwater research by the University of Otago on the geochemistry of the groundwater system (Litchfield et al, 2002).

The ORC sponsored the development of a groundwater model for the Lower Taieri Basin by the University of Otago's Geography Department in 2001 (Murray and Edge, 2001). The model project entailed reducing the various sources of information available for the basin and developing a computer model to simulate the groundwater system. The groundwater model was considered unfinished, because of the death of the principal researcher (Murray) and the graduation of the post-graduate student undertaking the day-to-day model development (Edge). Consequently, a follow-up modelling project was undertaken by another post-graduate Geography student, Gillian Holmes. Her project involved more advanced calibration and attempted verification of the computer model. It also included some primary data collection in areas identified as crucial to the understanding of system behaviour (Holmes, 2003).

The Zoology and Chemistry departments of the University of Otago had also been collaborating on the water chemistry and hydrology of the Waipori-Waihola Wetlands Complex since 2000 (Schallenberg, Bishop, Copson and Burns, 2000). This extended water, salinity and nutrient mass balances over a number of years, including supporting field characterisation and experiments (Schallenberg, Peake and Burns, 2000). These investigations culminated in a water balance model with evaluation of the ecological effects on the water quality of the wetlands complex, in particular (Schallenberg, Burns and Peake, 2003; ORC, 2000). An examination of the water chemistry and ecological significance of the Lower Taieri groundwater, undertaken by the University of Otago's Geography and Chemistry Departments (Kensington et al., 2004), revealed the zonation of nitrogen species in the Lower Taieri water-bearing layers and aquifers.

In 2005, one of the original authors of the IRRICON and Royd's Consulting (1994) and IRRICON and ESR (1997) reports undertook a contamination risk assessment of the closed North Taieri Landfill (IRRICON, 2005). This included a groundwater computer model of the East Taieri groundwater compartment east of the Taieri River. This modelling project shed more light on the functioning of the groundwater system providing the Mosgiel water supply. A follow-up groundwater contamination monitoring report supplemented the modelling study with a review of groundwater quality monitoring (IRRICON, 2006).

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Appendix B Rainfall recharge modelling

Direct recharge (rainfall infiltration)

One of the more important sources of recharge to the Lower Taieri Basin groundwater 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’) and 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 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 run-off using a USDA Soil Conservation Service (SCS) run-off curve number model. The SCS run-off model is described in Rawls et al., (1992).

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 run-off using the USDA SCS run-off 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) was made utilising the potential evapotranspiration (PET) derived from the Penman (1963) 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 run-off. This is the same method used for the HortResearch SPASMO model. Lower curve numbers result in higher the soil retention thresholds, which induce less run-off. 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 run-off calculation also has the capacity to incorporate slope and soil moisture (Williams, 1991). The Lower Taieri 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 and 0.75 for a clay loam (Rushton, 2006).

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 the Lower Taieri Basin lies in the range of 600-800mm, with stations in the Lower Taieri catchment and coastal range between Signal Hill and Taieri Mouth. Examination of rainfall isohyets shows there to be no significant rainfall gradient across the project area, although strong gradients are apparent against the Maungatua range-front.

The MetService and its predecessors have monitored rainfall at Dunedin Airport since 1972. This site is located in the West Taieri and the airport is labelled in Figures 2.1 and 2.3. NIWA has also collated rainfall data for several rainfall sites in the area, although there are only three which are currently active in the Lower Taieri Basin (Dunedin Aero (I50922), Mosgiel town (I50932) and Balmoral (I50821).

Potential evapotranspiration

Reference crop (pasture) potential evapotranspiration (PET) has been estimated using the Penman (1963) method. The PET data were derived from NIWA climate stations at Dunedin Airport in the centre of the project area.

Soil properties

Soil moisture balance modelling requires a 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 on 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 1m depth

Multiplying the percentage FC and WP values by the estimated rooting depth of the soils, for soils with rooting depth less than 1m. Soils were either estimated to have average rooting depth of either 0.65m, or 0.21m. The rooting depth 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 run-off. 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 B1 provides a summary of properties assigned to the eight dominant soil classes in the study area, and Figure B1 is a map showing the soil zones.

Table B. 1 Soil properties used in the Rushton soil moisture balance model. Soil zones represent an amalgamation to eight predominant types

Zone	FC	WP	Root	Depl fact	SCS	Fractstor	TAW	RAW	% Rain = recharge
Zone 1	260	650	0.3	39	0.4	117	35.1	13.3%	Zone 1
Zone 2	170	650	0.3	74	0.25	210	59	8.9%	Zone 2
Zone 3	250	650	0.3	80	0.25	200	100	7.9%	Zone 3
Zone 4	200	650	0.3	68	0.25	130	63	13.8%	Zone 4
Zone 5	117	650	0.3	74	0.25	103	46	15.5%	Zone 5
Zone 6	120	210	0.3	60	0.25	210	90	21.6%	Zone 6
Zone 7	110	210	0.3	55	0.25	170	70	24.0%	Zone 7
Zone 8	35	210	0.3	50	0.75	55	35	29.9%	Zone 8

Table B1 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 12-year model period (1996-2008).

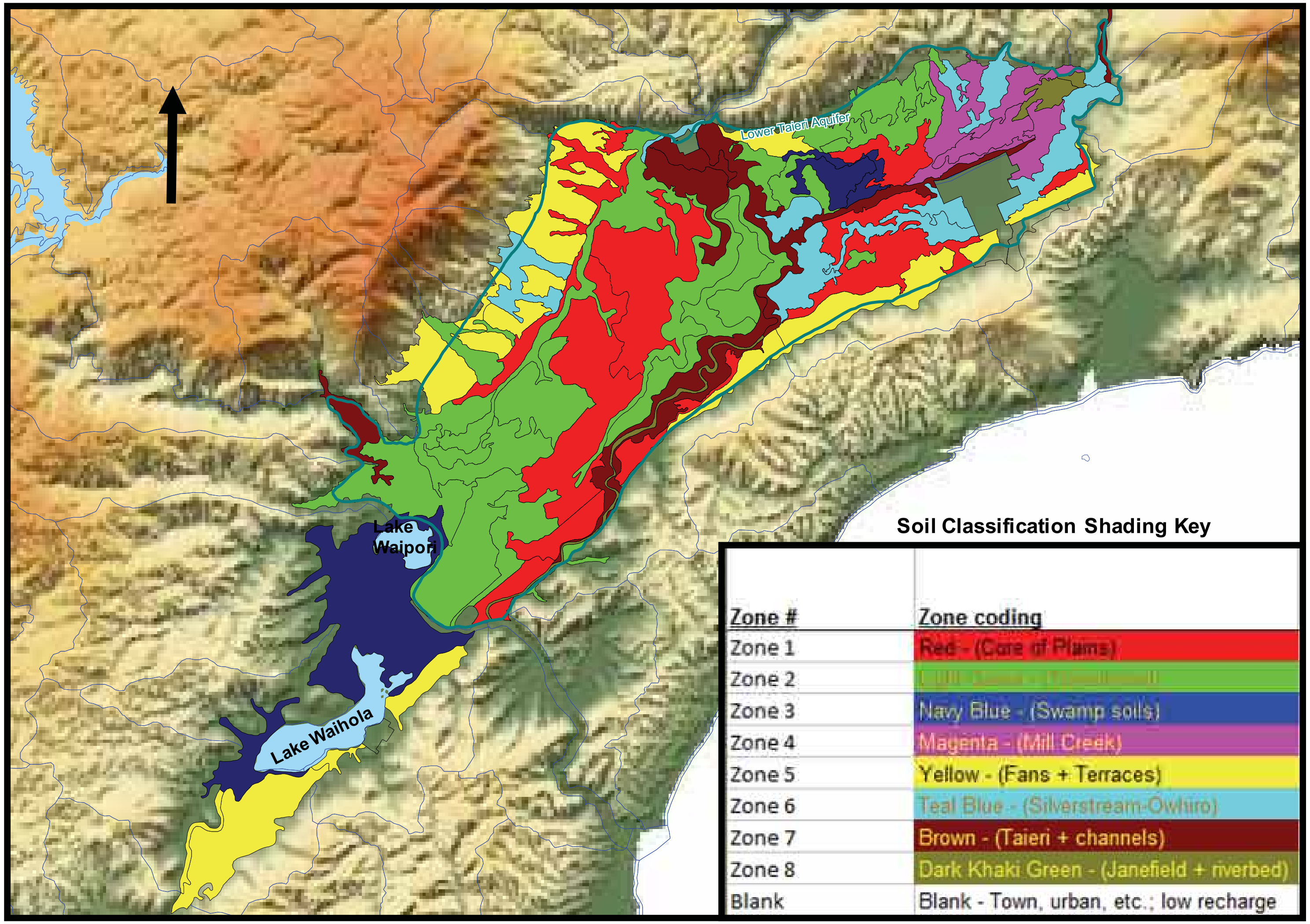

Figure B. 1 Lower Taieri Basin recharge zones based on soil property mapping

Recharge model outputs

Calculated recharge inputs for the 12-year model calibration period (1996-2008) for the predominant soils zones 1 and 6, which contrast with the recharge response for differing soil- water properties, are shown in Figure B2.

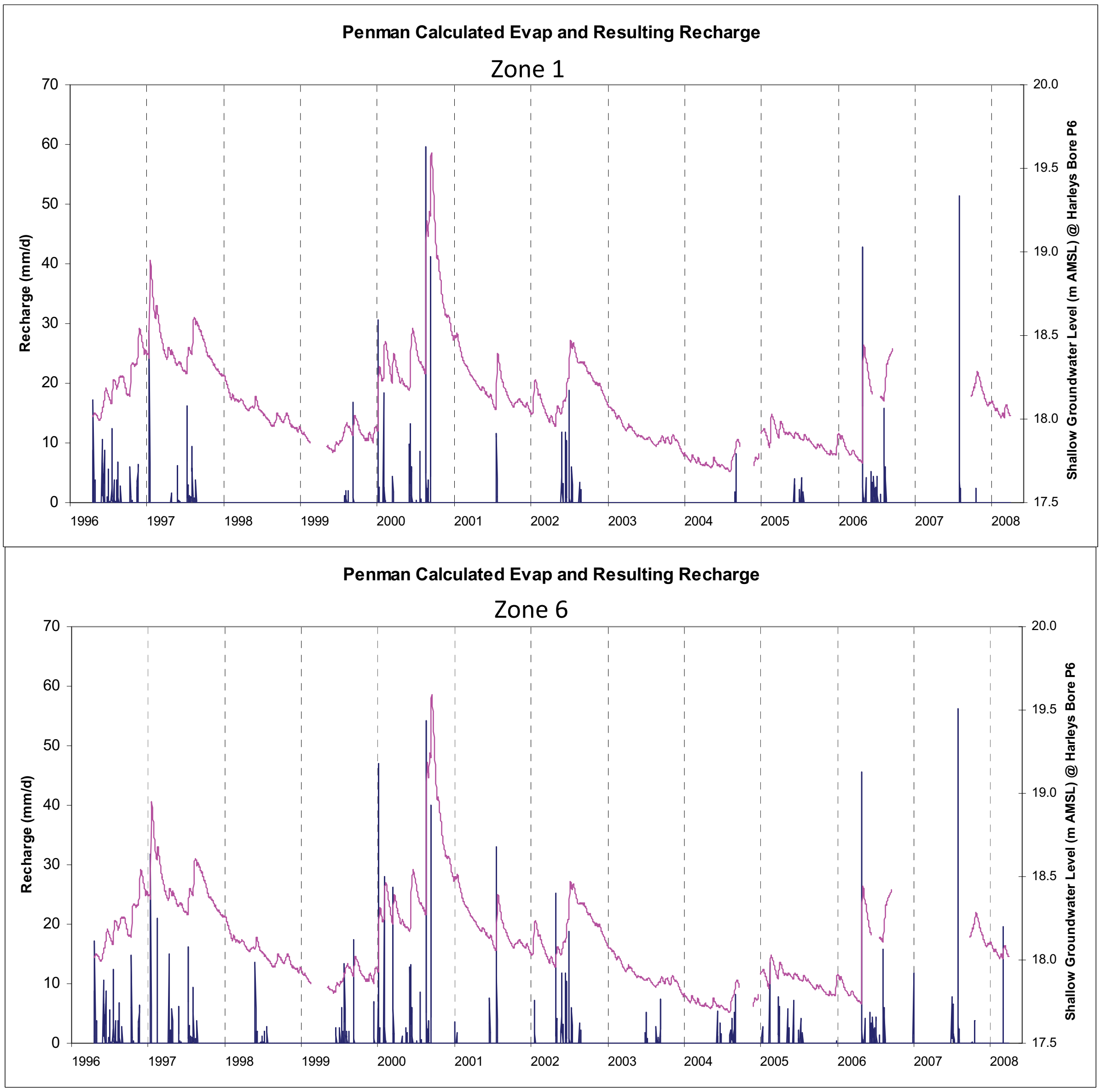

Figure B. 2 Recharge model output showing the differing recharge pattern for soils contained within Zone 1 compared with Zone 6

For all of the soil-recharge zones, the percentage of annual rainfall that contributed to groundwater recharge was subsequently calculated and summarised in Table B2.

Table B. 2 Percentage of annual rainfall becoming recharge

Zone coding	
Zone 1	13.3%
Zone 2	8.9%
Zone 3	7.9%
Zone 4	13.8%
Zone 5	15.5%
Zone 6	21.6%
Zone 7	24%
Zone 8	29.9%

Extrapolated across the basin, the volume of recharge was calculated for all zones and is summarised in Table B3 below:

Table B. 3 Mean recharge depths and Volumes for each recharge zone

Zone #	Penman % of rain	Area (km^2)	Recharge (m/d)	Recharge (m^3/yr)
Zone 1	13.3%	36.73	0.00024	3,226,613
Zone 2	8.9%	61.32	0.00016	3,612,979
Zone 3	7.9%	21.54	0.00014	1,121,570
Zone 4	13.8%	9.30	0.00025	846,351
Zone 5	15.5%	34.65	0.00028	3,536,954
Zone 6	21.6%	17.05	0.00039	2,421,025
Zone 7	24.0%	16.79	0.00043	2,656,573
Zone 8	29.9%	2.58838	0.00054	509,839
Urban etc.	2.0%	6.07	0.000036	79,983
	Total	206.0		18,011,886

Taking the total recharge volume and total area, the mean depth of recharge across the whole Lower Taieri Basin was determined in modelling to be approximately 90mm/yr. As is evident in reading the section on numerical groundwater modelling in the main report and in Appendix D, calibration of the model to field data required alteration in the effective recharge rates to achieve reasonable correlation. Possible explanations for the recharge rate changes during calibration include:

Enhanced recharge in certain situations due to range front losses or surface water infiltration.

Refused recharge in areas where land drainage is active or low permeability subsoil, which limits the infiltration of recharge.

Despite differences in individual recharge rates as a result of model calibration, the quantum of calibrated recharge across the wider basin remained within 15% of the total recharge implied in recharge modelling by the methods above.

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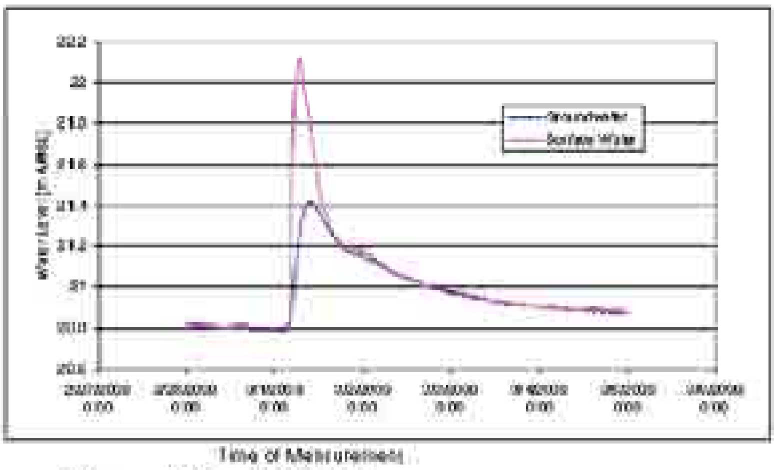
Appendix C Results of simultaneous level monitoring at Donnelly Bore and Silver Stream

Instruments were installed in the Donnelly Bore and the adjoining Silver Stream in early 2009. The following provides further details for the results of the investigations described in section 3.3.4, figure 3.5 and section 3.4.1.



SWL_avg 20.79 3/1/2009 3:30
DWL_avg 21.42 3/1/2009 10:00
ΔH = 0.63 m
SWL_boundary 20.798 3/1/2009 1:30
DWL_boundary 22.115 3/1/2009 6:45
ΔH_0 = 1.317 m
Δt = 10800 s
h = 4.998
Kx = 4.00
A_{xx} = 5.9675
Distance = 40 m
[illegible] 15.8 from P6 bore log
[illegible] 15.8 from P6 bore log
$S_{unconfined}$ = 0.2 dimensionless

$\mathrm{erfc}(\lambda) = \Delta H / \Delta H_0$
$= 0.48$
$\lambda = 0.50$

$\alpha = x^2 / 4\lambda^2 t$
= 0.085091 m²/s

T = 0.017018 m²/s
1,470 m²/d

246 m/d

$\Delta H(x,t) = \Delta H_0 \,\mathrm{erfc}(\lambda)$

Where
$\Delta H(x,t)$ = change in water level through space and time
ΔH_0 = the change in the water level of the boundary
$\mathrm{erfc}(\lambda)$ = the complementary error function for lambda ($\lambda = x / 2\sqrt{\alpha t}$)
x = distance from boundary
t = time from start of water level rise

Figure C. 1 Water levels and diffusivity calculation

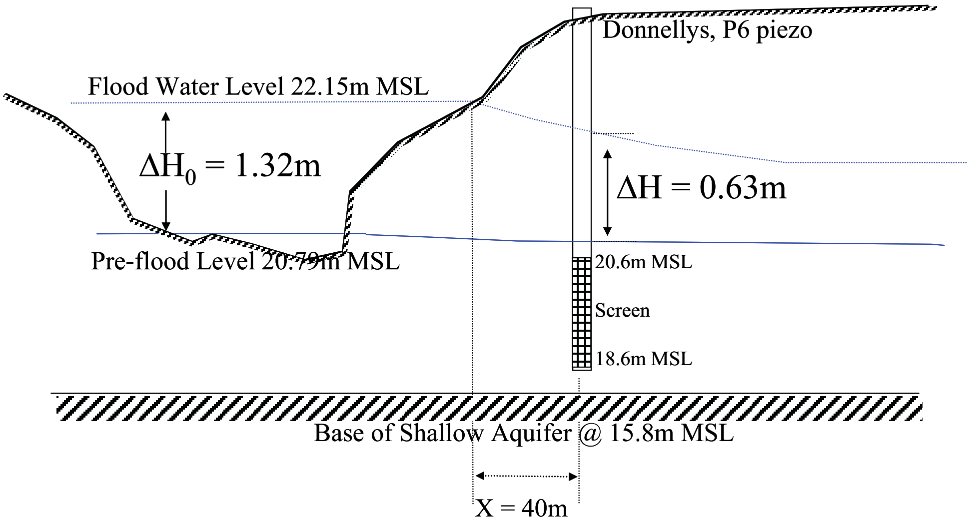


Figure C. 2 Cross-section of Donnelly Bore and Silver Stream water levels

Figure C.2 shows the spatial relationship of the levels and dimensions used in the equation for diffusivity in Figure C.1. The flood water level in the Silver Stream *peaked during two flooding events in February and March 2009. The flooding level of* 22.15m AMSL relates to the flood peak of 1 March. Figure C.3 shows the relevant water levels in the Silver Stream.

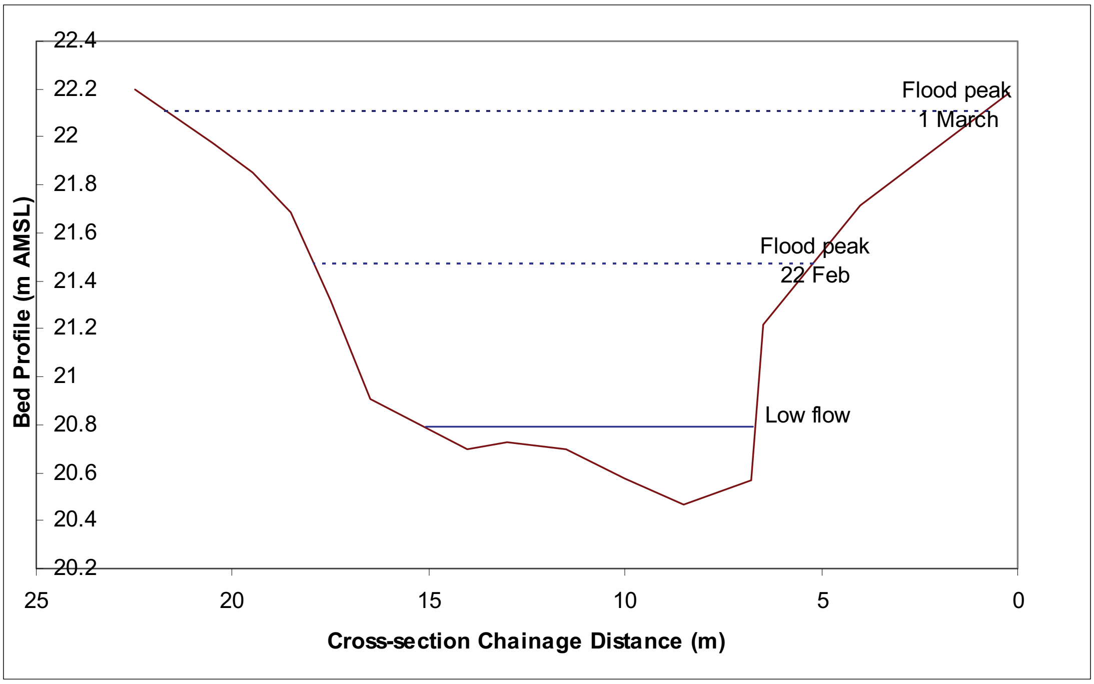


Figure C. 3 Silver Stream bed profile & water levels measured in 2009.

Appendix D Numerical modelling

Model objectives

The objectives for the Lower Taieri Basin model are as follows:

- Establish a transient-flow numerical model for the Lower Taieri Basin volcanic aquifers 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 aquifers response to difference abstraction scenarios as a basis for developing allocation and aquifer management policy.

Model code selection

The USGS finite difference numerical code MODFLOW (Harbaugh et al., 2000) was used to model the Lower taieri Basin groundwater system. The Groundwater Vistas data processing interface software (Environmental Simulations Inc., 2007) was used to build the model, assist with the calibration process including sensitivity analysis and process the output data.

Grid design

MODFLOW uses a finite difference solution method that requires the use of a rectilinear, block-centered multi-layered spatial grid. The Lower Taieri Basin model was built within a grid domain of 15 x 41.4km, with a uniform cell size of 200m^2 over the aquifer surface. The grid has been rotated from map north to optimise the geometry for the NE-SW orientation of the basin (Figure 2.1 and Figure D1)[3]. The rotation entailed rotating model north 38^0 to the east from true map north. This allowed elongated strips of model rows to cross parallel to the basin axis rather than as semi-diagonal strips that would result from an un-rotated grid, thereby minimising the number of model cells.

The model has been constructed using three layers. The rationale behind the layer structure is discussed below.

The active model domain is delineated by the basal contact of the Cenozoic sediments (i.e. late Tertiary and Quaternary), with underlying consolidated formations or major structures. Figure D1 shows the active model area and grid design.

Conceptual hydrogeology and numerical adaptation

The relatively simple groundwater flow pattern (Figure 3.1) and geological structure, suggests that the groundwater circulates with the "tub" of the basin without any significant interchange with the materials at the margin of the basin. To this extent, the basin is self-contained without significant flow interchanges to adjoining basins.

Regional-scale modelling 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

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[3] Figure references are provided in two forms: Figure 2.1 refers to a figure contained in the main report, Figure D1 refers to a figure contained in this Appendix D.

characterise local scale heterogeneities without embarking upon a lengthy and intensive field investigation programme. In particular, the gravel-silt layering that is observed throughout much of the basin could not be resolved into discrete aquifer-aquitard layers without substantial intensification of the layering structure.

The approach adopted in the development of the numerical model has therefore been to assume a continuous stratified aquifer system becoming confined with depth. However, as a result of the combination of the Waihola Silt-Sand deposit (which acts as a semi-confining layer) and the increasing segregation of the Quaternary basin fill-sediments into silty aquitards and gravelly aquifers in the West Taieri, confining properties were incorporated within the model. The Lower Taieri Basin model outputs show that the regional-scale representation of the aquifer is a valid and accurate approach for the analysis of the groundwater system.

Outer model boundaries

The active model domain is delineated by the basal contact of the Cenozoic sediments with either the Otago Schist or similar consolidated rocks, such as the Henley Breccia or Dunedin Volcanic Complex. These are consolidated materials with bulk hydraulic conductivities that are substantially lower than the Cenozoic sediments, which provides a significant permeability contrast to allow the boundaries to be simulated as no-flow impermeable boundaries.

Figure D1 shows the locations of the aquifer boundaries. All external model boundaries are assigned no-flow (impermeable) conditions.

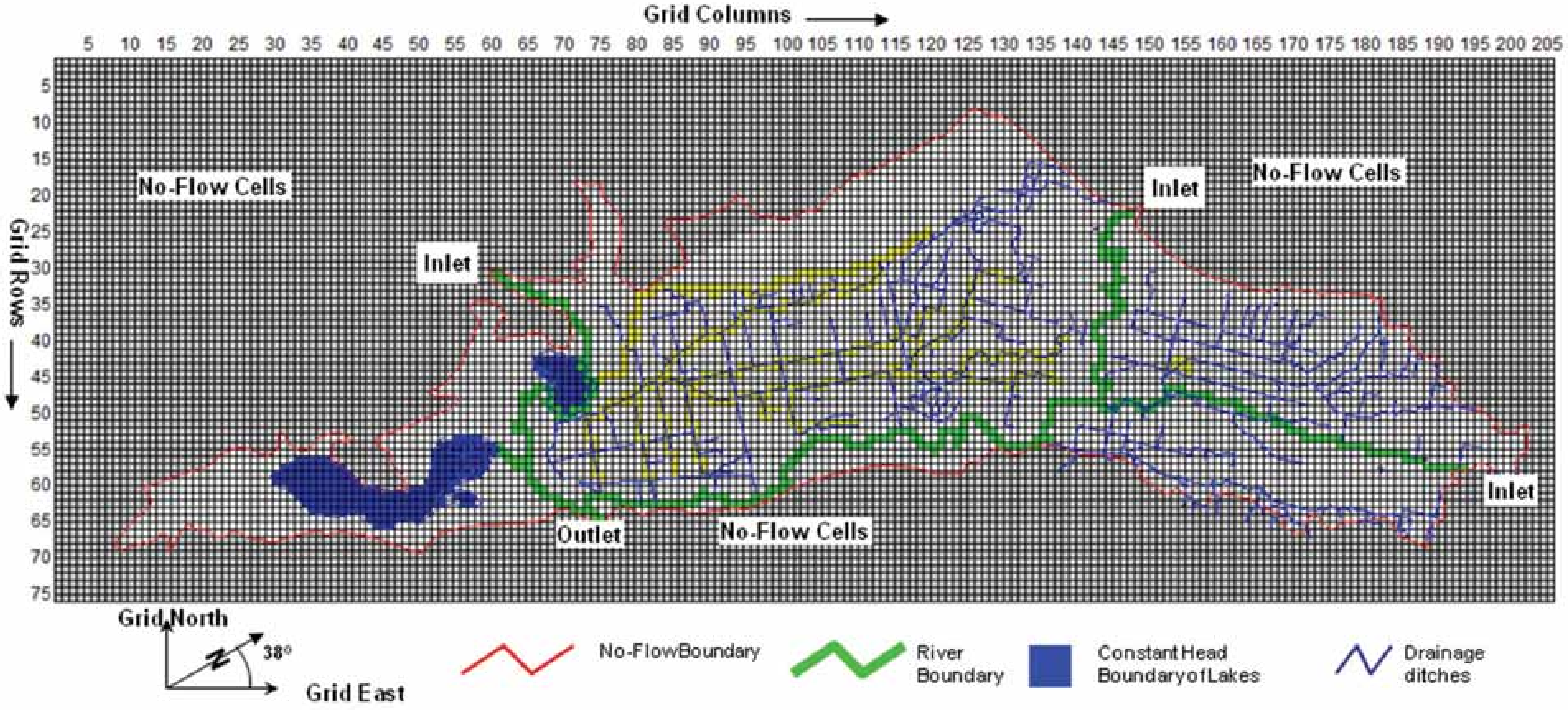

Figure D. 1 Representation of model boundaries and grid features. True map North is oriented 38° from grid east as illustrated by the modified north arrow

Model base

Very little is known about the base of the sediments and groundwater system with only a handful of Taieri Basin bores having touched the basement. A significant stratigraphic drill hole (a.k.a. Waipori 99-1) failed to penetrate more than 50,000 years into the geological pre-history of the Quaternary sediments, despite extending more than 150m below mean sea level. Figure D2 shows the interpreted base of the groundwater system, which takes the form of a basin structure. It also delineates the maximum lateral extent of Layer 3 in the MODFLOW model framework.

Model top

The top of the model is represented by the surface topography. Topographic data were derived from the LIDAR digital terrain model for the Lower Taieri Basin. The LIDAR topographic data has a resolution at least as good as 0.1m.

Layers

Three layers have been used in the model to vertically discretise the thick aquifer sequence. The base of Layer 3 corresponds to the Quaternary sediment – consolidated rock contact. Figure D3 shows a NE-SW section through the centre of the model to illustrate the layer structure of the model schematically. Layer 1 is assigned a MODFLOW layer type 1 condition (unconfined) and Layer 2 unconfined (unconfined, transmissivity varies), whereas the underlying layer 3 was assigned layer type 0 (confined).

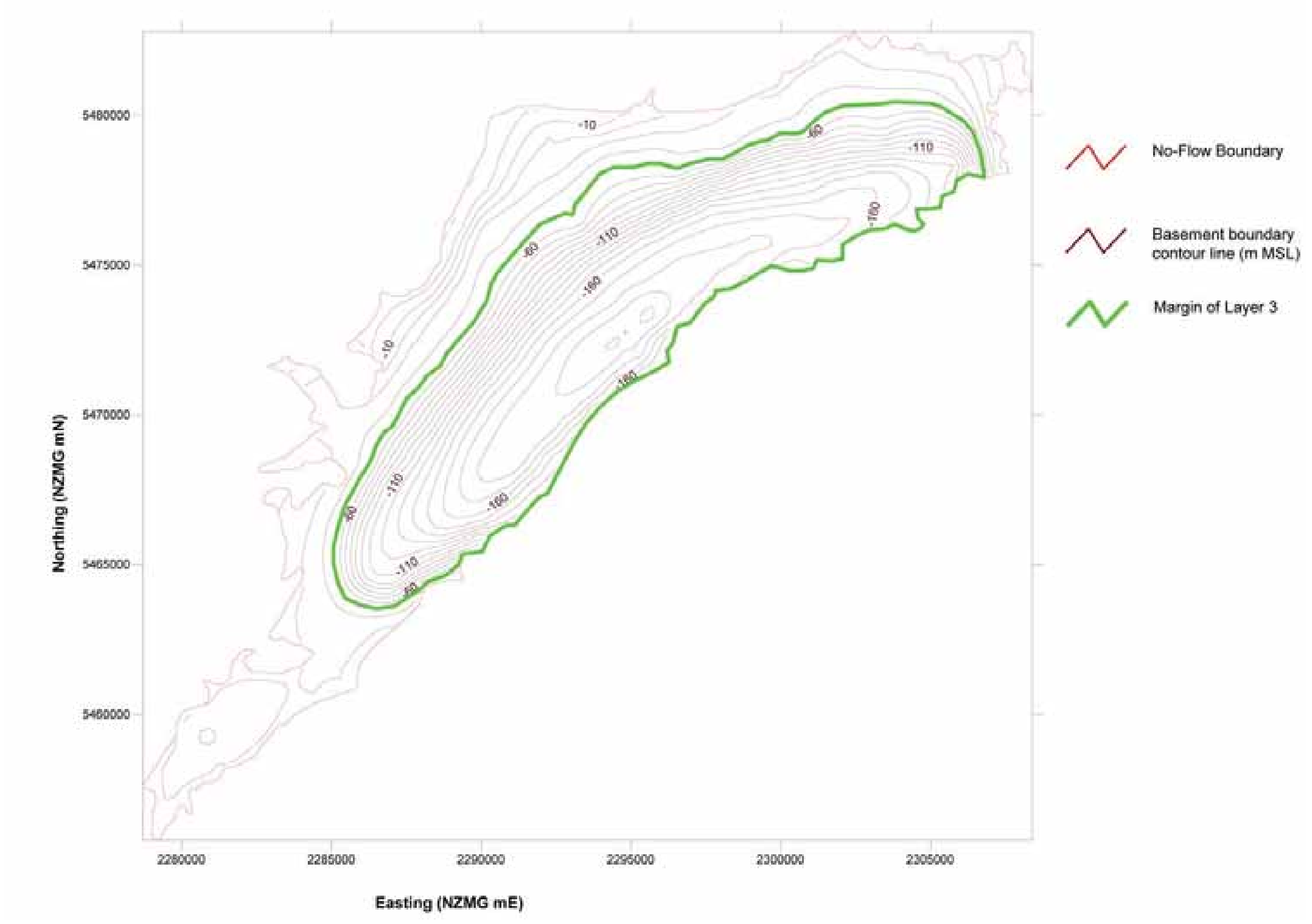

Figure D. 2 Contours of the base of the Lower Taieri Basin, as simulated in the groundwater model

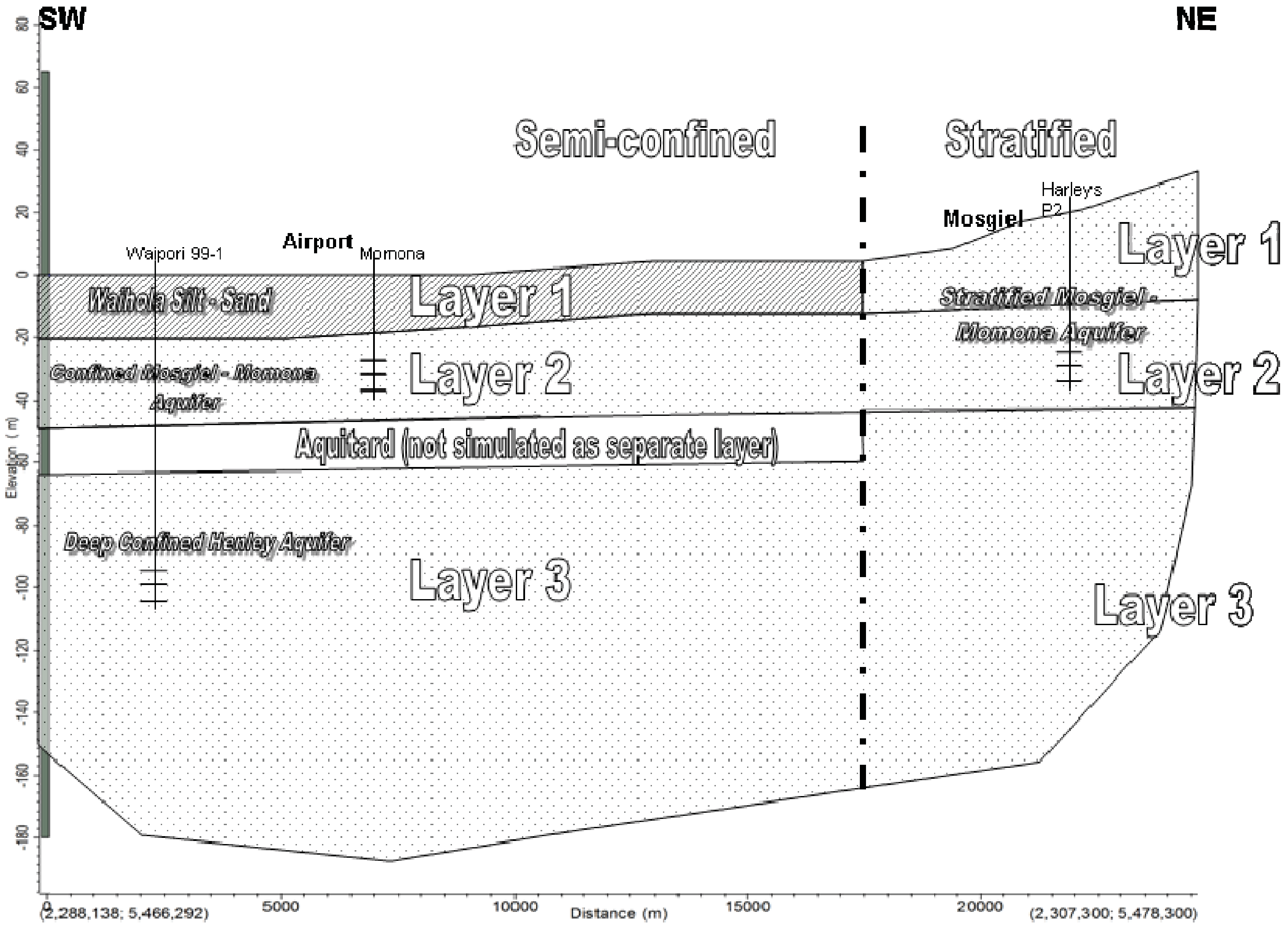

Figure D. 3 Schematic of the arrangement of model layers as a profile from Lake Waipori to Mosgiel

Boundary conditions
Taieri, Silver Stream and Waipori Rivers (RIV)

The major surface water courses crossing the Lower Taieri Basin were simulated in the MODFLOW model architecture.

Figure D4 shows the profile of the surveyed beds of three rivers in the Taieri Basin as taken from various gauging and stage recording sites used in flood prediction. The stream boundary stage height for the three rivers has been varied throughout the transient model simulations, since the surface water system has been noted to be a strong influence on groundwater level at monitoring sites such as Donnellys Bore P6 (I44/0853) and Outram Bore (I44/0838).

A ‘bed conductance’ parameter is required by MODFLOW for the RIV 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 river width varies between about 3m and 25m. Streambed vertical hydraulic conductivity was assumed to be about 100m/day (in line with estimates made at Outram). This parameter varied significantly, mostly under the influence of changeable river width. Subsequent calibration modeling did not indicate that river conductance was a sensitive term in the model.

Drainage System: Modflow drain boundaries (DRN)

MODFLOW drain boundaries were used to simulate the role that the Contour Channel, School Swamp (in the East Taieri), and the West Taieri Drainage Scheme play in the basin’s geo-hydrology. All drain boundaries were assigned a specified drain water level and invert level which controlled the interaction of the boundary with the adjoining model layer. These levels were assigned on the basis of drainage engineering drawings held for the Lower Taieri drainage districts.

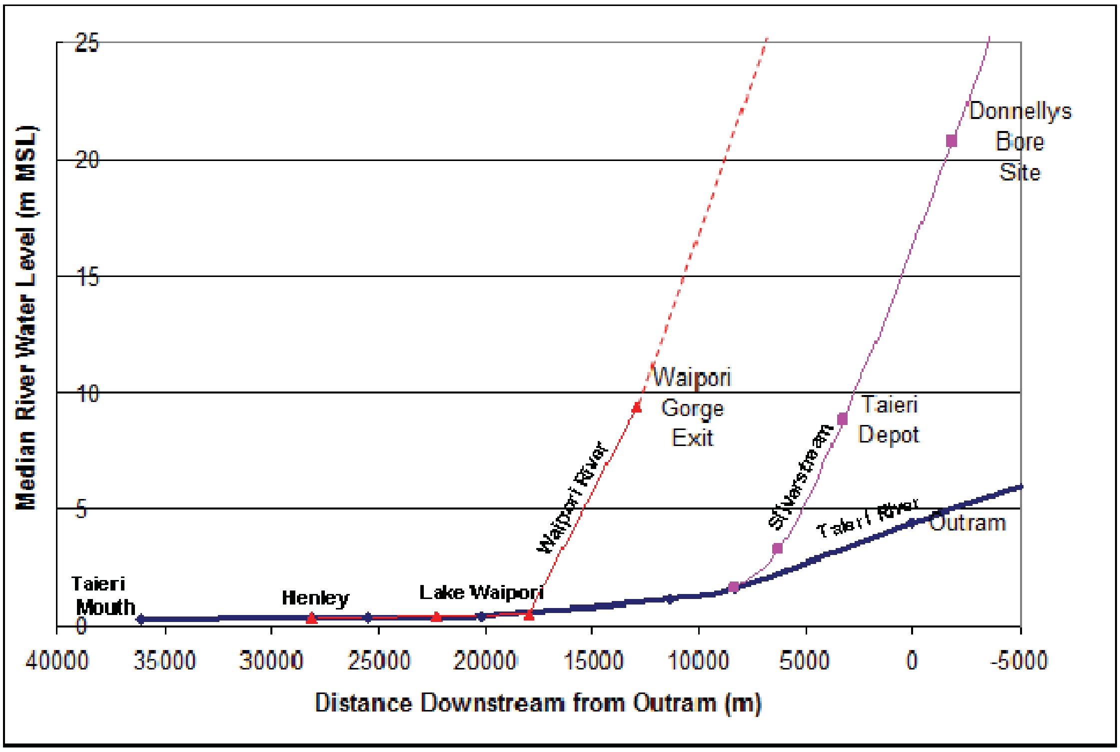

Figure D. 4 **Bed profile of the three Lower Taieri Basin rivers: Taieri, Silver Stream and Waipori**

Aquifer Properties

The hydraulic properties of the Lower Taieri Basin are discussed in detail in Section 3.4 of the main report. Transmissivity values have been derived from assessment of reliable pumping tests and re-analysis of the data and used in the initial assignment of hydraulic conductivity. The bulk hydraulic conductivity has been derived through the calibration process. Several new hydraulic conductivity zones distributed laterally throughout the model have been added in the course of calibration.

Figure D5 shows the hydraulic conductivity zonation developed during the model calibration process. The zonation in Layers 1 and 2 represents the stratified aquifers, semi-confined (Layer 2) aquifer and the aquitard defined by the presence of the Waihola Silt-Sand. The hydraulic conductivity zones are shown in Figures D5 and D6 for Layers 1 and 2, respectively. Layer 3 is entirely Zone 4 hydraulic conductivity.

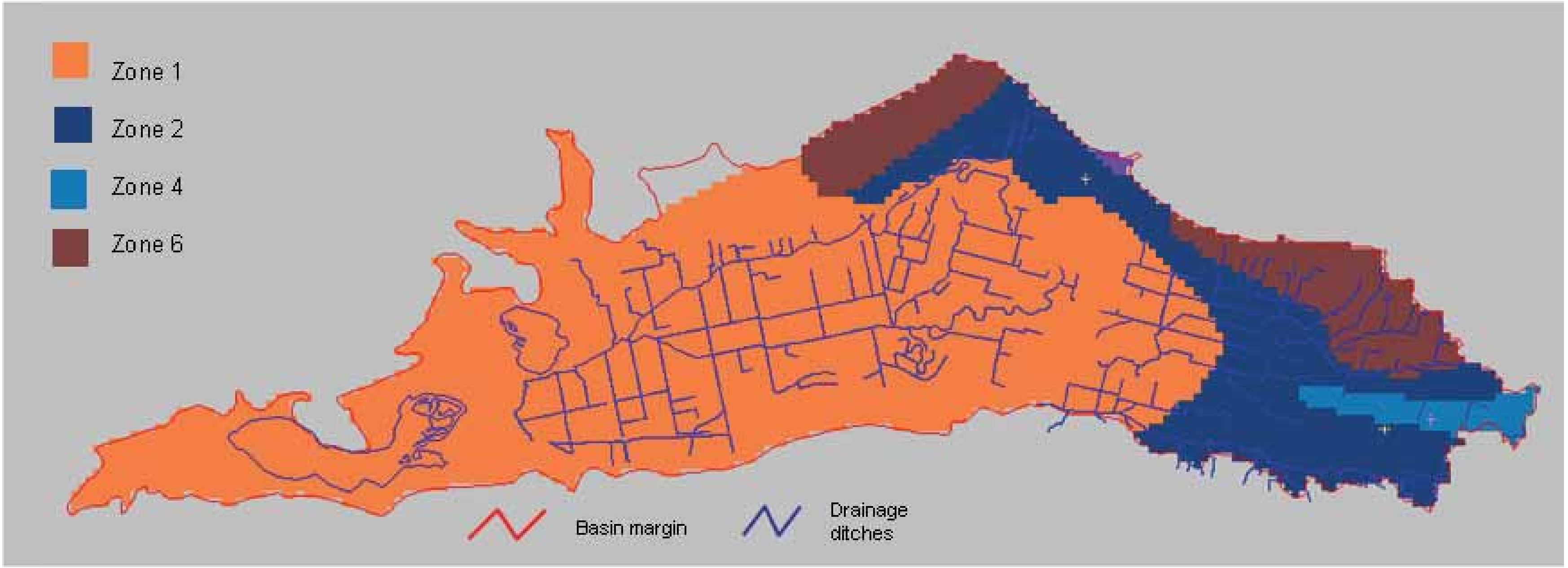

Figure D. 5 Hydraulic conductivity zonation of Layer 1

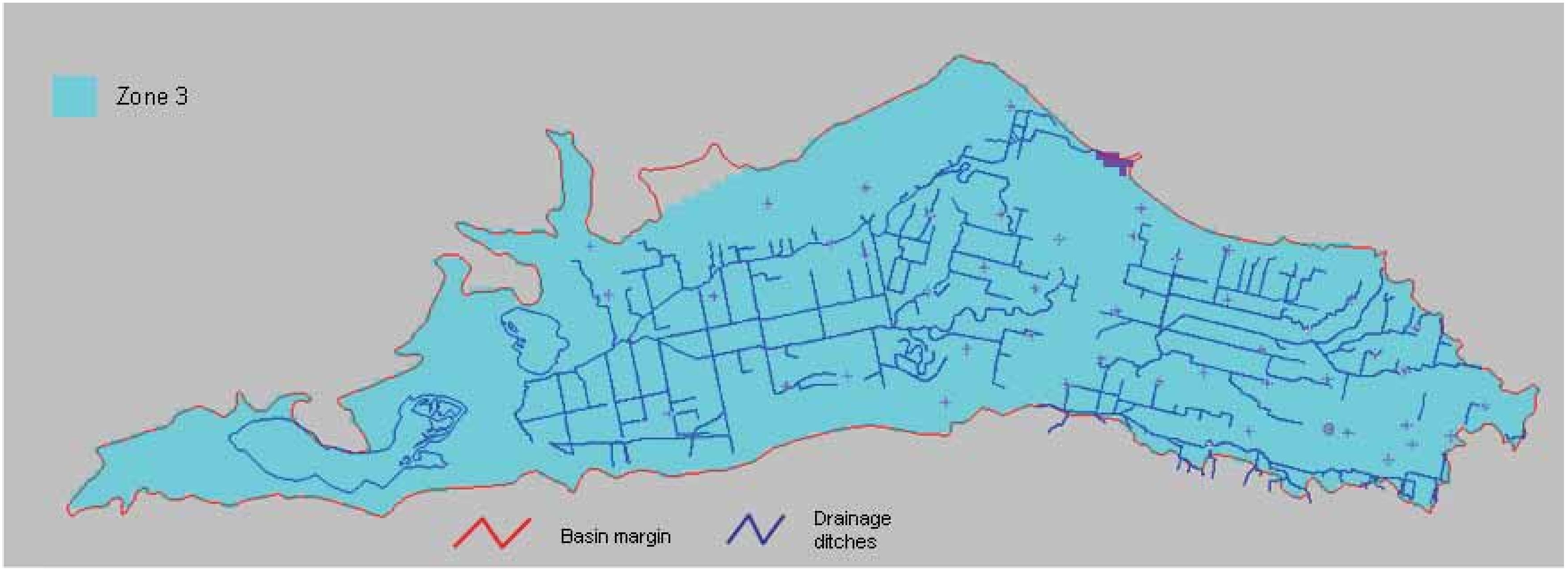

Figure D. 6 Hydraulic conductivity zonation of Layer 2

Rainfall recharge modelling

The principal recharge source to the Lower Taieri Basin groundwater 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 3.4 and Appendix B provide further discussion of the rainfall recharge dynamics for the Lower Taieri Aquifer.

Groundwater abstraction

Over 2.4M m^3/year, or 6,575m^3/day, of groundwater has been allocated from the Lower Taier Basin system. The allocation to some eight consent holders is partly seasonal for irrigation, but primarily public and industrial water supply that is non-seasonal in nature. Table D1 lists the current groundwater consents in the project area.

Annual water meter readings have been undertaken by the ORC since 2006. Reliable abstraction data is available for some of the consented wells for the 2006-2007 irrigation season only. While the data is 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). They do 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.

Table D. 1 Consented groundwater takes in the Lower Taieri Basin

Consent Number	Owner	Total annual allocation m^3	Subject to restriction Levels	Water take restriction zone
2000.456	Dunedin City Council – Mosgiel Water Supply	1,825,000	Partial (non-drinking water supply only)	L Taieri – East
2001.372				L Taieri – East
2001.373				L Taieri – East
2002.248				L Taieri – East
2002.249				L Taieri – East
2002.250				L Taieri – East
2002.251				L Taieri – East
2002.317				L Taieri – East
2002.318				L Taieri – East
2001.850	Silver Fern Farms Ltd	24,000	NOT subject to Schedule 4	L Taieri – East
2002.341	Williams Family Trust	1,866	Subject to Schedule 4	L Taieri – East
2000.438	Wallis' Nurseries Ltd		NOT subject to Schedule 4	L Taieri – East
2000.222	Fenton B & Hore S A	1,872	Subject to Schedule 4	L Taieri – East
2002.374	Nelson C J	118,010	NOT subject to Schedule 4	L Taieri – West
2005.233	Oke Hampton Ltd	47,888	NOT subject to Schedule 4	L Taieri – West
2004.632	Waterside Farms	31,104	Subject to Schedule 4	L Taieri – West
2004.971	Dunedin Int. Airport	Non-consumptive	NOT subject to Schedule 4	L Taieri – West
	Annual Total:	2,359,887 m^3/yr		

Model 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-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.

Steady-state simulation

When an aquifer is in a ‘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 the heads remain stable over a relatively long period of time. 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 May 1994, and this dataset has been used for steady-state calibration. In addition, the long-term mean groundwater level for the five monitoring bores in the basin were also used for steady-state calibration. Normally, a snapshot water level survey would be inappropriate for a steady state calibration since it represents a snapshot in time specific to the antecedent and current conditions at the time of undertaking the survey. This lack was considered insufficient however, justification for excluding the use of the snapshot survey, which otherwise had considerable utility in distributing the area of the model that could be calibrated.

Steady-state calibration has been achieved by manually calibrating the model to head targets measured in 55 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 30m to 40m bore depth range.

Aquifer properties developed during the steady-state calibration process, and further refined following the transient calibration, are shown in Table D4. Many of the zones representing the water-bearing layer defined in permeability zonation have very similar hydraulic conductivity values (0.01 - 1000 m/day) and are a product of the calibration process. Figures D5 and D6 illustrate the hydraulic conductivity zones of Layer 1 and Layer 2 following calibration. Recharge values derived from the calibration are listed in Table D2. 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	0.240	88
2	0.042	15
3	0.022	8
4	0.140	51
5	0.550	201
6	1.500	548
7	0.000	0
8	0.001	0
9	0.000	0

During steady-state calibration groundwater extraction in Mosgiel for the town's water supply was simulated as being in operation at a rate of 4,000m^3/d, a rate which has coincided with the groundwater pumping long-term mean since 1991.

The results of the steady-state calibration run are shown in Figure D7, and listed in Table D1, 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 -0.02m. Of the 55 calibration targets used, only four show a residual error of greater than ±2m and eight show a residual error of greater than ±1m. The highest residual is +3m for well I44/0020.

The standard deviation/range statistic shows how the errors relate to the overall gradient across the model. This value is 3.8%, where any value of standard deviation/range less than 5% is considered acceptable for a basin-scale groundwater model. Figures D8 and D9 show the modeled head distribution over the model domain, primarily for Layer 2. Comparison with Figure 3.1, 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 as a good initial simulation and provides confidence in the conceptualization of the flow system and the assumptions that have been adopted.

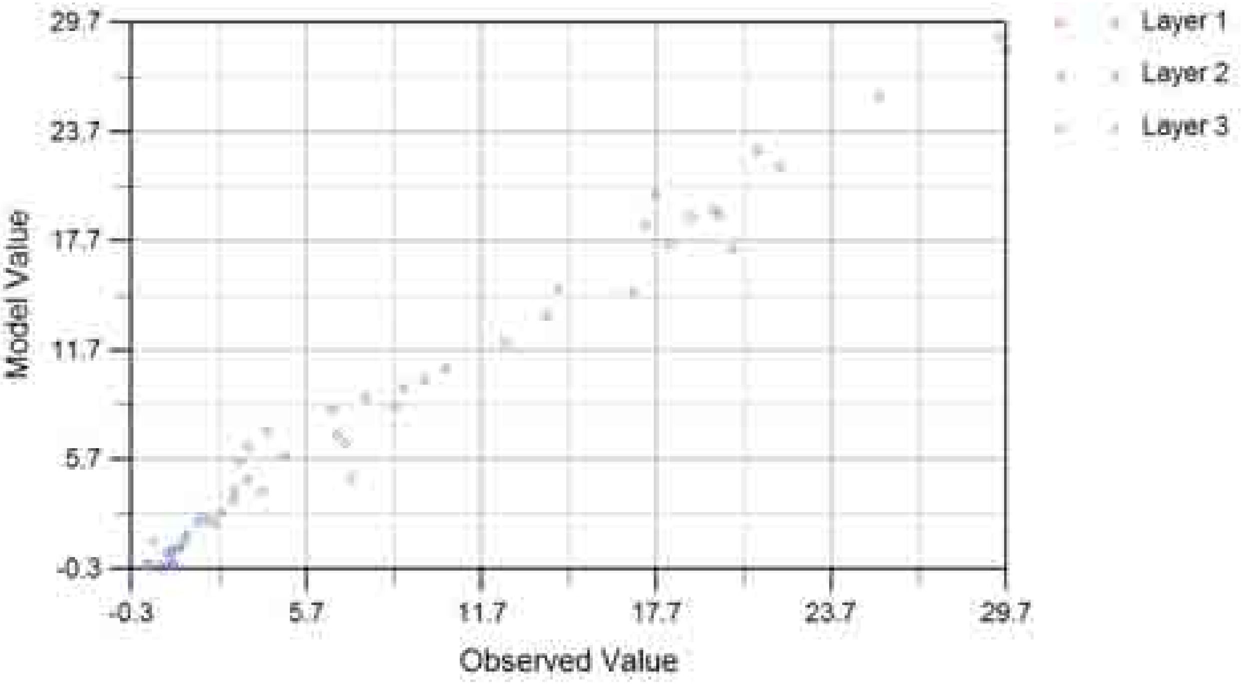

Figure D. 7 Plot of observed groundwater levels versus modelled levels for steady state simulation

Table D. 3 Calibration output data from steady-state simulation

Name	X	Y	Layer	Observed	Computed	Weight	Group	Residual
I44/0835 Donnellys P6	2306120	5480005	1	21.137	22.66793	1	1	-1.53093
I44/0842 Harley P6	2305319	5479065	1	18.137	17.56503	1	1	0.57197
I44/0847 Janefield	2306135	5479197	2	18.857	19.02851	1	1	-0.17151
I44/0790 Woollen Mills	2304700	5478400	3	14.315	15.13034	1	1	-0.81534
I44/0848 Momona	2295681	5472450	2	0.446	1.192761	1	1	-0.74676
I44/0838 Outram	2295000	5479400	1	3.657	4.552478	1	1	-0.89548
I45/0007 Waipori-99 P3	2290100	5467700	2	0.285	-0.08619	1	1	0.371193
I45/0007 Waipori-99 P1	2290100	5467700	3	0.149	-0.07378	1	1	0.222784
H44/0007	2288709	5473692	2	7.02	6.580091	1	1	0.439909
H44/0010	2289100	5470900	2	0.71	-0.3098	1	1	1.019804
H45/0292	2289700	5467800	2	0.67	-0.12832	1	1	0.798324
H45/0293	2289700	5467800	2	0.19	-0.12832	1	1	0.318324
H45/0294	2285700	5469900	2	1.06	0.717926	1	1	0.342074
H45/0295	2286900	5469200	2	0.93	-0.16188	1	1	1.091881
I44/0020	2305900	5478500	2	20.28	17.27177	1	1	3.008226
I44/0024	2292300	5476100	2	2.31	2.296204	1	1	0.013796
I44/0042	2295700	5476300	2	2.53	2.205971	1	1	0.324029
I44/0043	2294300	5475900	2	1.6	1.564874	1	1	0.035126
I44/0066	2297900	5474800	2	3.15	3.451449	1	1	-0.30145
I44/0067	2295400	5477700	2	2.75	2.75484	1	1	-0.00484
I44/0084	2293200	5471400	2	1.09	0.525684	1	1	0.564316
I44/0094	2292104	5470187	2	1.02	0.201117	1	1	0.818883
I44/0215	2296394	5475260	2	1.94	2.197941	1	1	-0.25794
I44/0217	2290700	5473900	2	0.89	0.601064	1	1	0.288936
I44/0218	2302100	5478100	2	9.01	9.626503	1	1	-0.6165
I44/0227	2291600	5474200	2	1.26	0.825347	1	1	0.434653

Name	X	Y	Layer	Observed	Computed	Weight	Group	Residual
I44/0295	2296600	5479700	2	3.4	5.562523	1	1	-2.16252
I44/0328	2295255	5473921	2	1.49	1.330896	1	1	0.159104
I44/0347	2298200	5475900	2	4.14	3.92774	1	1	0.21226
I44/0385	2301900	5475900	2	6.58	8.433994	1	1	-1.85399
I44/0399	2307000	5481200	2	29.42	28.91015	1	1	0.509847
I44/0422	2297742	5477148	2	3.22	3.970312	1	1	-0.75031
I44/0427	2290500	5475600	2	10.43	10.6502	1	1	-0.2202
I44/0439	2298200	5479200	2	3.68	6.403328	1	1	-2.72333
I44/0441	2302500	5476800	2	9.75	10.06996	1	1	-0.31996
I44/0452	2303300	5479200	2	13.94	13.51474	1	1	0.425256
I44/0476	2305700	5479500	2	19.66	19.43487	1	1	0.225127
I44/0478	2306800	5480000	2	25.31	25.64359	1	1	-0.33359
I44/0495	2302054	5479873	2	12.45	12.15174	1	1	0.298263
I44/0517	2299107	5480247	2	8.71	8.598074	1	1	0.111926
I44/0519	2302500	5481238	2	19.79	19.07408	1	1	0.715917
I44/0535	2292200	5479700	2	17.29	18.52447	1	1	-1.23447
I44/0548	2293800	5477300	2	2.11	2.593155	1	1	-0.48316
I44/0562	2299900	5479200	2	4.32	7.277796	1	1	-2.9578
I44/0580	2303900	5480500	2	17.61	20.17463	1	1	-2.56463
I44/0595	2301400	5478700	2	7.74	9.044109	1	1	-1.30411
I44/0610	2296900	5479000	2	7.23	4.718157	1	1	2.511843
I44/0626	2299801	5476361	2	4.94	5.874037	1	1	-0.93404
I44/0651	2304800	5480600	2	21.91	21.78279	1	1	0.127212
I44/0686	2293500	5474500	2	1.4	0.851696	1	1	0.548304
I44/0714	2290400	5470300	2	1.07	-0.12968	1	1	1.199681
I44/0717	2290400	5470300	2	1.11	-0.12968	1	1	1.239681
I44/0724	2300600	5477300	2	6.71	7.05861	1	1	-0.34861
I44/0801	2304300	5481700	2	29.67	28.16185	1	1	1.50815

Name	X	Y	Layer	Observed	Computed	Weight	Group	Residual
I44/0802	2304600	5478400	2	16.87	14.92501	1	1	1.944986
I44/0217	2290700	5473900	2	0.89	0.601064	1	1	0.288936
I44/0218	2302100	5478100	2	9.01	9.626503	1	1	-0.6165
Residual Mean								-0.02054
Res. Std. Dev.								1.144901
Sum of Squares								72.1171
Abs. Res. Mean								0.83515
Min. Residual								-2.9578
Max. Residual								3.008226
Range in Target Values								29.521
Std. Dev./Range								0.038783

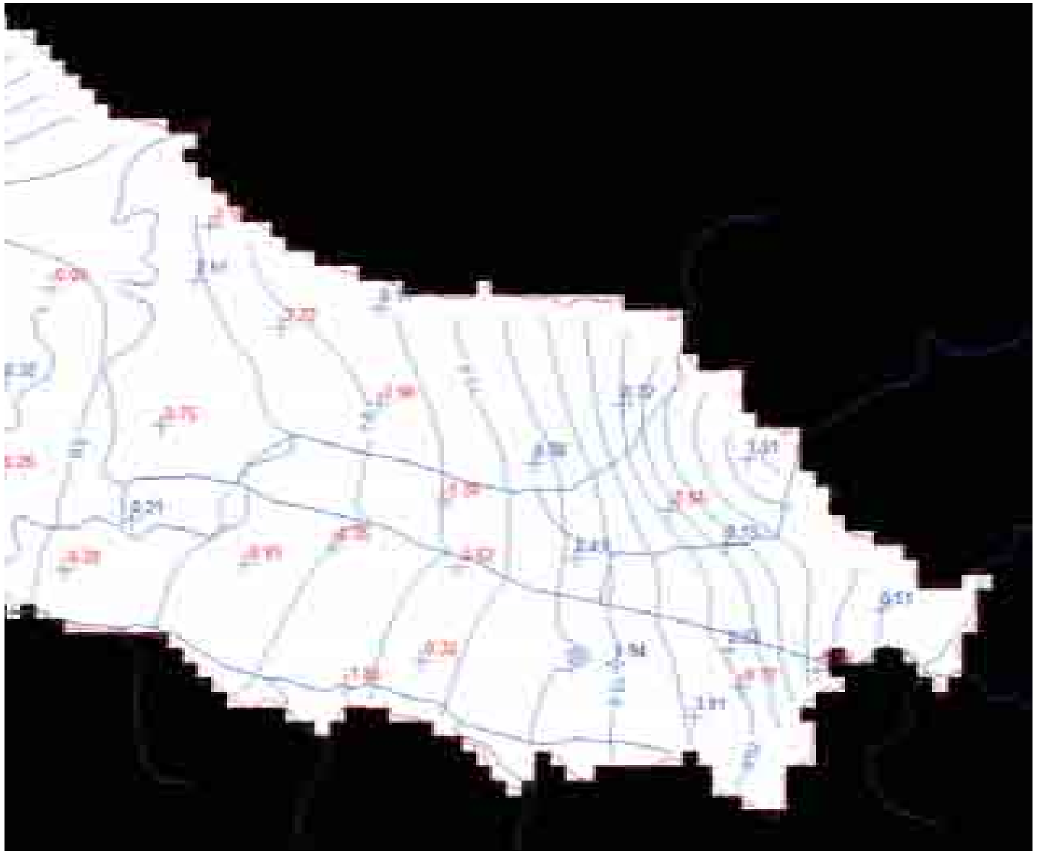

Figure D. 8 Steady-state modelled head distribution (Layer 2) for the East Taieri

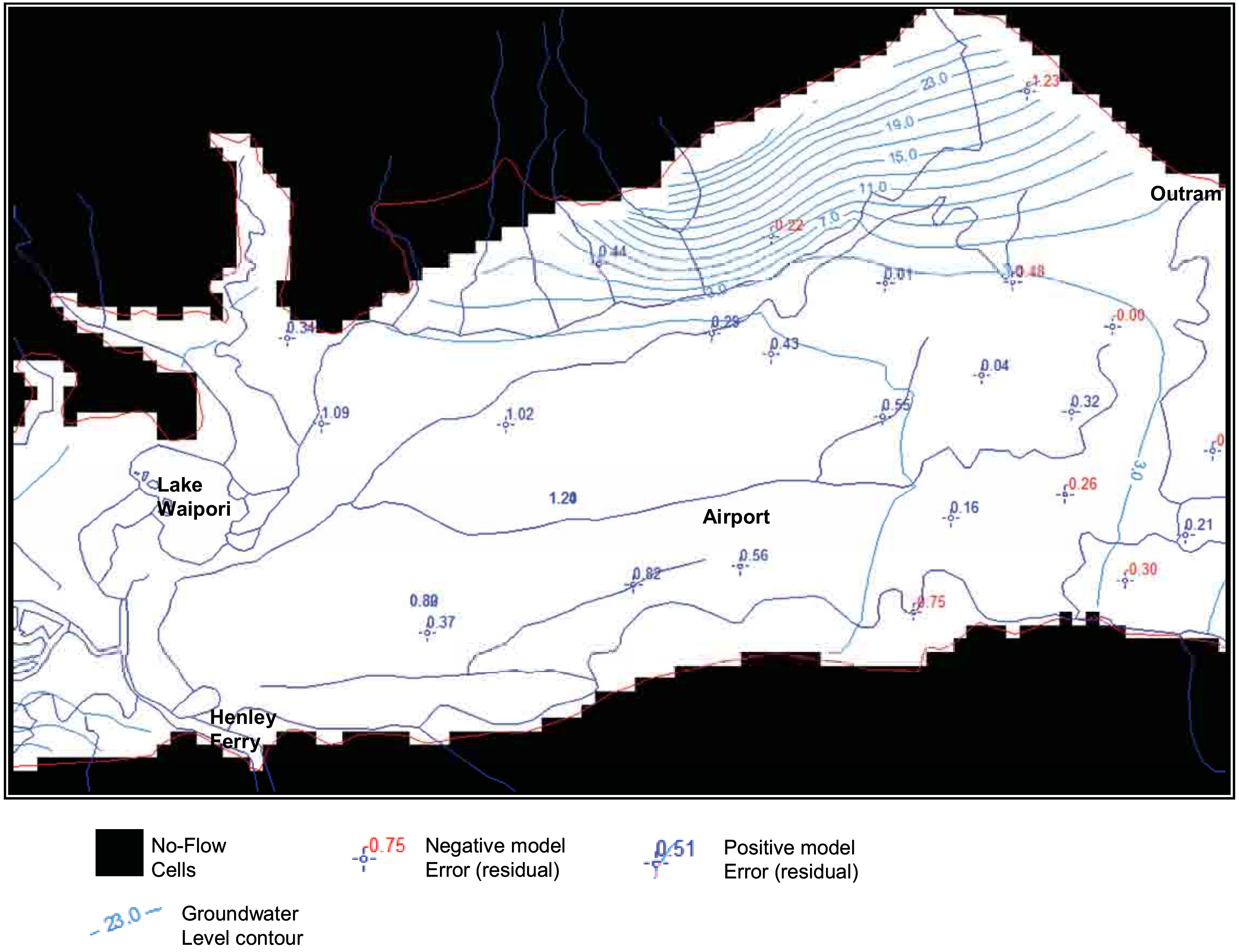

Figure D. 9 Steady state modelled head distribution (Layer 2) for the West Taieri

Steady-state mass balance

The steady-state mass balance is shown in Table D4. Inflows are solely rainfall recharge and outflow is dominated by discharge to rivers. The predominant outflows are to 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. 4 Steady-state mass balance (March 2008 calibration)

Flow component	Inflows (m^3/d)	Outflows (m^3/day)
Rivers: Taieri d/s Outram, Silver Stream d/s Invermay, Waipori d/s Gorge	9,650	19,024
Drains: (School Swamp, West Taieri Drainage Scheme)		34,391
Constant head to lakes	397	4,871
Rainfall recharge	52,232	
Wells: Mosgiel water supply		4,000
Totals	62,279	62,286

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 shown in Figure D10. Parameters have been multiplied by factors of between 0.1 and 2.0 in 0.1 increments. The results of these sensitivity simulations are plotted in Figure D10. For simplicity, only the best result from each sensitivity run specific to a parameter zone is plotted. The result is expressed as the sum of squares calibration statistic. The lower the result, the better the change to the parameter within its zones has been to model calibration. Significant shifts in the sum of squares results between parameter-zones indicate relatively high sensitivity. The sum of squares result is shown as columns, the best change ratio is indicated by points on the secondary axis.

The model is most sensitive to changes in vertical hydraulic conductivity, particularly in the permeability Zone 3, which coincides with the Waihola Silt-Sand. Horizontal hydraulic conductivity is the parameter of least sensitivity to the model result. Of the horizontal hydraulic conductivity Zones, Zone 2 imparts the most sensitivity to the model. Horizontal hydraulic conductivity Zone 2 is found in Layer 1 as a strip Wingatui-Mosgiel-Outram. Recharge imparted the most sensitivity for Zones 1, 5 and (to a lesser extent) Zone 2.

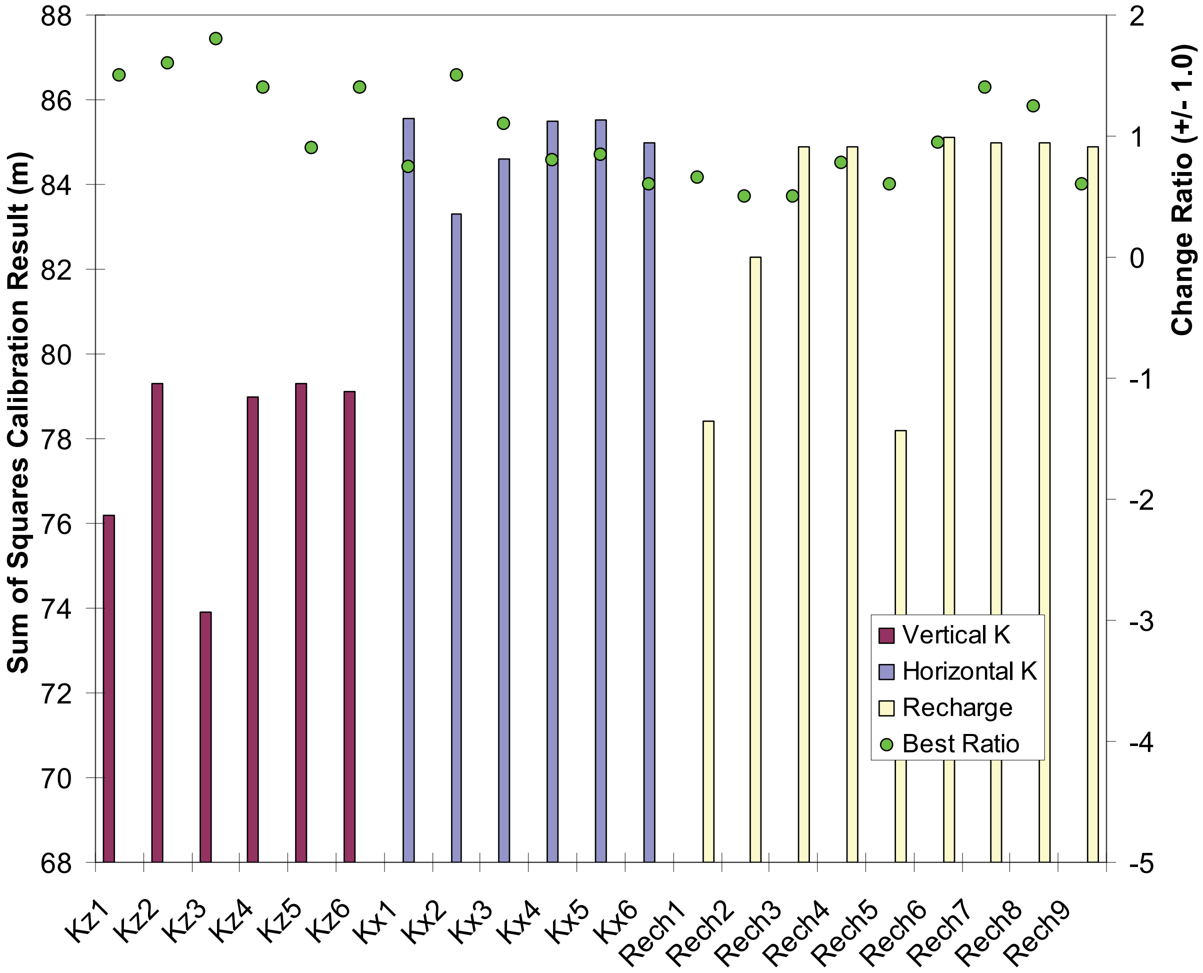

Figure D. 10 Plot of sum of squares sensitivity results for the best result. The change ratio of the best result is plotted on the secondary (right hand) axis

The steady-state sensitivity analysis pointed to the benefits of concentrating trial-and-error calibration on a few parameter zones for the rest of the calibration process. When trial and error calibration with the steady-state model and ‘pseudo’ steady-state calibration comparators (mean and snapshot surveys of groundwater levels) began to give diminishing returns of improved calibration statistics, the calibration process was turned over to transient calibration. Table D3 lists the results of the ultimate steady-state calibration. The ultimate sum of squares statistic achieved was 72.11m, which integrated many of the most plausible high sensitivity changes to model parameters.

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 optimising 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 procedures and use of automated parameter optimisation (PEST).

Transient model design and initial inputs

The transient model structure is largely the same as the steady-state model, except that additional hydraulic conductivity zones have been introduced, particularly around the Taieri River course. Recharge estimation methodology and model inputs are described in detail in Appendix B. To prepare for the transient modelling, the transient recharge files were altered in direct proportion to the ultimate steady-state calibrated recharge.

Groundwater abstractions were incorporated in the transient model calibration and were assumed to be pumping at 60% of their annual consented rates either over the full year in the case of public water supply or industry, or a 150-day period for irrigation. In the case of the Mosgiel water supply bores, the total annual supply production was recorded and simulated by splitting the total in reasonable proportion across them. After 2004 actual daily production data was available and this was lumped for input within the seven-day pumping periods used in the transient model.

Because continuous aquifer head observations have been available from April 1996-March 2008, this period was chosen for transient model calibration. 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 662 seven-day stress periods and runs for 4,354 days.

Starting head conditions were not thought to be critical for successful transient calibration in the Lower Taieri Basin model. Monitoring well hydrographs (Figures 7.1 and 7.2) show that the groundwater levels follow regular patterns of recharge and discharge over-printed in longer-term trends of groundwater accumulation or depletion as a function of climate, although the Harley Bore (I44/0842) was strongly affected by nearby water supply bores. Initial starting conditions for groundwater levels were specified as the steady-state solution, which was calibrated to average groundwater levels from monitoring bores and May 1994 conditions in the water level survey bores.

Calibration targets

There are several long-term groundwater level monitoring sites within the Lower Taieri Basin, including three multi-level piezometers. These have been outlined in Section 5.3.1, which describes the current continuous monitoring sites. The continuous record was reduced from 15 minute frequency to daily values for use in calibration, which was particularly important for filtering the record of the Harley Bore, P2 piezometer.

Transient calibration

Optimised values for hydraulic conductivity, specific yield and specific storage are shown in Table D5. The calibration process involved an initial auto-sensitivity analysis to identify parameters with higher sensitivity. Subsequently, trial-and-error calibration runs were used to optimise the model transient output with the calibration records.

Table D. 5 Optimised aquifer parameters

Hydraulic conductivity zone	Formation	Kx,y m/day	Kv m/day	Specific yield/ specific storage
1	Waihola Silt-Sand	3 x 10-8	0.015	0.25
2	Mosgiel – Outram Gravel	0.5	1	0.25
3	Layer 2 aquifer	2.1	0.7	1 x 10-5
4	Silver Stream and gravels and Layer 3 gravel	10	4.2	0.25
5	Outram Bridge	1000	100	0.25
6	Tirohanga – Woodside colluvium	0.95	0.0095	0.25

Calibrated aquifer properties generally fall lower than those determined in aquifer tests and extrapolated from derived transmissivities (Section 3.3). The specific yield values agree with assessed values of about 20%.

Some emphasis has been placed on matching simulated head to observed heads, specifically at the long-term monitoring wells [Harley Bore (I44/0842), Outram Bore (I44/00838), Momona Bore (I44/0848) and Waipori 99-1 Bore (I45/0007)]. Figure D11 stacks modelled versus observed transient calibration plots, and illustrates the ultimate calibration success achieved at Harley Bore (shallow piezometer), Momona Bore (Layer 2 semi-confined) and Outram Bore (shallow).

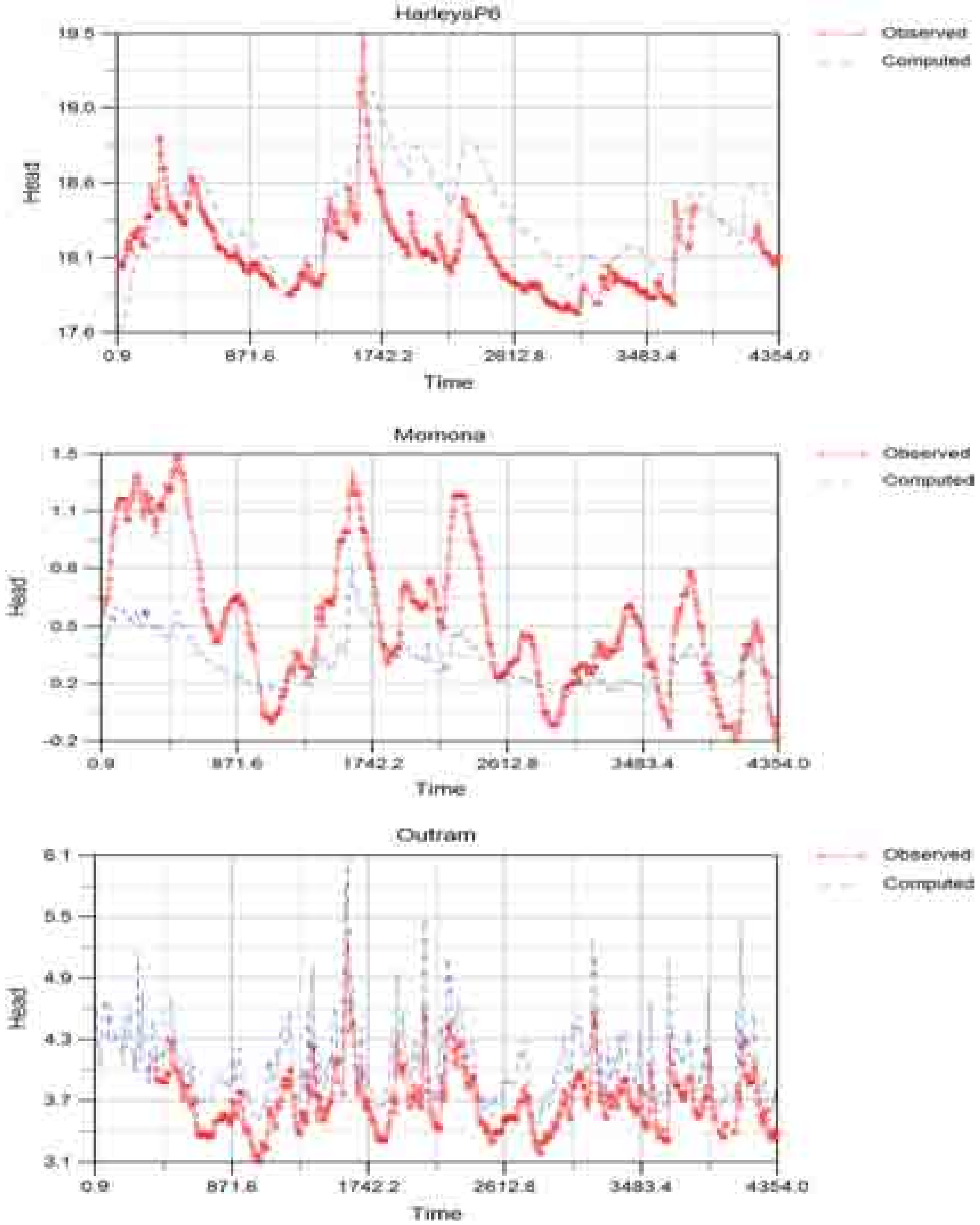

Figure D. 11 Transient calibration plots for the Harley Bore piezometer P6 (I44/0842), the Momona Bore (I44/0848) and the Outram Bore (I44/0838)

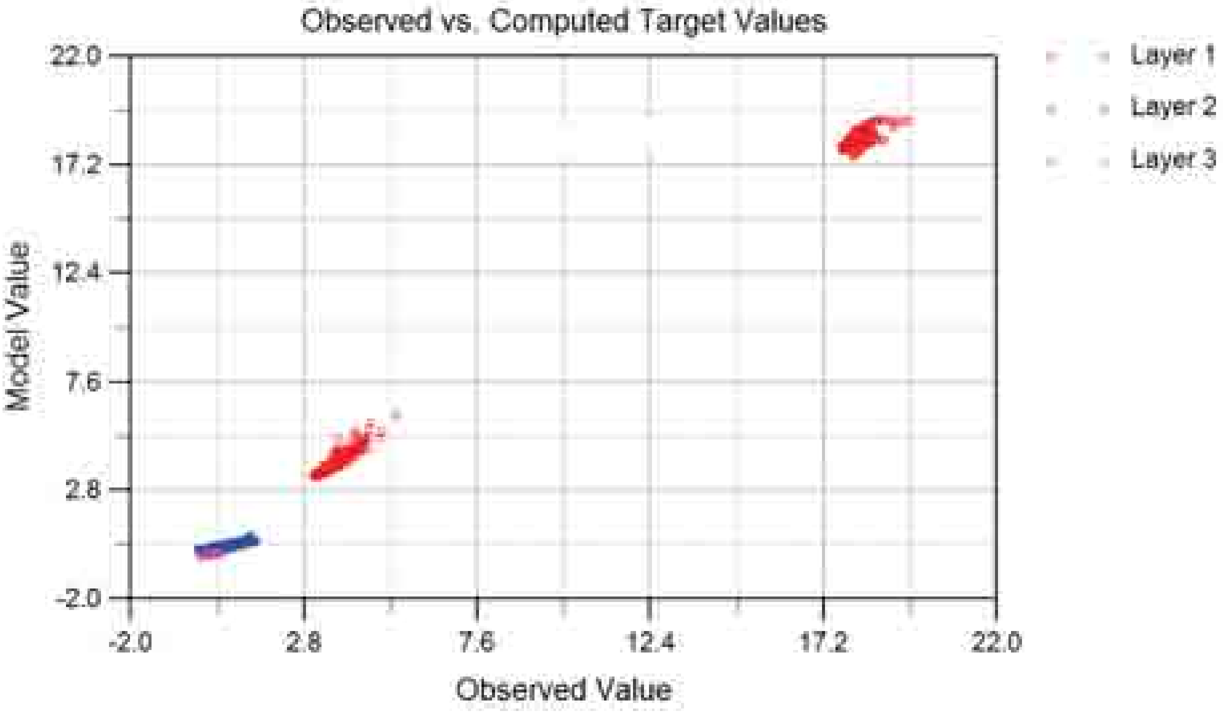

Figure D. 12 Transient calibration scatter plot and calibration statistics. Calibration bore clusters are labelled

Table D. 6 Transient calibration statistics

Residual mean	-0.0933
Res. std. dev.	0.345
Sum of squares	228.40
Abs. res. mean	0.3068
Min. residual	-1.3430
Max. residual	0.892
Range in target values	62.79
Std. dev./range	0.0175

When the sum of squares and standard deviation/range ratio are considered, the impression can be gained of good correspondence between observed and modelled groundwater levels.

Limitations of model

All models are a simplification of reality and subject to uncertainty and inaccuracy. The key to the appropriate use of numerical models for the prediction of future groundwater behaviour is to simplify the elements of the conceptual model sufficiently for inclusion in the numerical model architecture. The goal should be to simplify sufficiently in order to bring the numerical model complexity within achievable limits. The management of uncertainty begins with the inherent error in field data used in the formulation of the conceptual model, but includes underlying assumptions, the setting of various boundaries and the manipulation of various parameters. Uncertainty is greatly diminished by a critical approach to model formulation, and various quality assurance practices such as sensitivity analysis, calibration, parameter optimisation and verification. It has been an underlying goal to follow these practices throughout the modelling process, but it should be recognised that all models have degrees of uncertainty attached to them.

The Lower Taieri Basin model shares these limitations with all other models. However, it is worthwhile explicitly stating the specific limitations to which the numerical model developed in the course of this investigation was subject. Various primary sources of uncertainty are known to be present in the model:

Model grid and layering
The assumption made in model development of three model layers represented a balancing of actual system complexity and model simplification. In the Mosgiel area in particular, the intense layering of silty and gravelly lenses contributes to a very steep vertical gradient manifesting as significant head differences (e.g. Harley Bore P6 and P2 piezometers). In the model, the pattern was simulated by three model layers segregated only by vertical hydraulic conductivity. Such an arrangement is incapable of simulating the degree of vertical gradient observed in nature, which is a limitation of the Lower Taieri Basin model. Future modelling investigations might consider using Telescopic Mesh Refinement to produce a sub-model of the Mosgiel area within the larger basin model. The sub-model could be refined with a multitude of model layers to attempt replication of the vertical gradient effect.

Boundaries
The setting of no-flow boundaries implies impermeability of the basement margins. In fact, the permeability contrast is more gradational than the no-flow boundaries imply. The application of RIV river boundaries includes a significant degree of uncertainty in the bed conductance used. The conductance values were tested in sensitivity analysis, but calibration is a blunt instrument with which to sharpen the accuracy of these values in the model.

Parameters
The principal model parameter with significant sensitivity was found to be vertical hydraulic conductivity. The available aquifer tests were clustered around Mosgiel and generally only give an estimate of the horizontal hydraulic conductivity. There is also a bias towards high hydraulic conductivity since the well drillers would select for the highest yielding water-bearing-layers and bores. Low yielding bores do not tend to be pump tested. In addition, the sole determinations of vertical hydraulic conductivity were indirect. A coefficient of vertical flow resistance derived from a Dunedin International Airport aquifer test was converted to vertical hydraulic conductivity using an estimate of the thickness of the aquitard. The vertical hydraulic conductivities of other zones of the groundwater system were estimated using rules of thumb as to typical horizontal-vertical conductivity contrasts. The lack of direct measurements of vertical hydraulic conductivity is a limitation in the model and a source of uncertainty.

Calibration and verification data-sets
Calibration is the process of matching the model with observed groundwater behaviour. Verification is the process of comparing model predictions against relevant observations of phenomena in the same groundwater system to test for the possibility of non-uniqueness and equivalence problems developing in the calibration process. The calibration and sensitivity analysis of the Lower Taieri Basin was hampered by the fact that only groundwater level measurements were available as transient calibration data. It strengthens the calibration process for independent sources of calibration data to be

used. For example, if measurements of spring flow through time from the aquifer are available, these should be used to calibrate the model well. In the case of the Lower Taieri Basin, the fact that the lower catchment is essentially flooded by tidal water means that measurement of groundwater discharge is not feasible. This lack places a limitation on the confidence that can be applied to the calibrated model. The Lower Taieri Basin also lacked a verification data-set. Typically, a verification data-set would involve observations of groundwater flow rate and groundwater level trends that had not formed part of the calibration data-set. One candidate for the verification data-set was the 1922 to 1947 shallow groundwater level record from the Mosgiel Woollen Mills well. However, it was considered that the lack of a concurrent evapotranspiration data-set for the same period precluded the use of the use of the recharge model to provide a transient recharge record, and thus the verification was not attempted.

Recharge modelling and calibration of recharge

The soil moisture and soil drainage process of the Lower Taieri Basin are quite variable spatially. In areas with a deep water table, the recharge processes are simple and result in drainage to the water table. However, significant parts of the basin are, either:

- drained with mole drains and drainage ditches
- or, contain limiting horizons in the sub-soil impeding vertical drainage to the water table
- or, have a high water table that result in refused recharge and the potential for evapotranspiration of groundwater.

During the calibration process, it was found that recharge rates indicated by recharge modelling needed to be changed in some zones to account for differences in recharge implied by calibration results. This resulted, in some instances, in the departures from typical recharge processes as described above.

Transient mass balance

Figure D13 shows the modelled mass balance plots for principal flow components as a function of time covering the entire 12-year model period. Table D7 contrasts the external mass balance flows modelled in the base transient simulation.

Table D. 7 Transient mass balances for two stress periods (11 June 1999 and 5 Nov 2000)

Units: m^3/d	Stress period 167 11-Jul-1999 Low GWL*	Stress period 236 5-Nov-2000 GWL peak
River inflow	9,503	1,055
Lake inflow	568	408
Aquifer Storage inflows	18,536	105,742
Recharge inflow	56,462	117
River outflow	17,614	54,188
Lake outflow	3,508	4,219
Aquifer storage outflow	37,079	10,425
West Taieri Drainage Scheme outflow	23,958	34,988
Well pumping	2,933	3,527
Percentage error (inflow – outflow)	0.006%	0.006%
Period totals	170,160	214,669
Silver Stream interchanges in Reach 11 (Invermay to Taieri Depot)	Silver Stream lost 1,555 net	Silver Stream gained 6,330 net

Note:
* GWL = Groundwater level

Table D7 lists the global groundwater system water exchanges with the surface water system for two contrasting model stress periods. The first stress period, which began on 11 July 1999, corresponds with a period of low groundwater level, following sustained depletion of system. The second began on 5 November 2000, during a period of very high groundwater level.

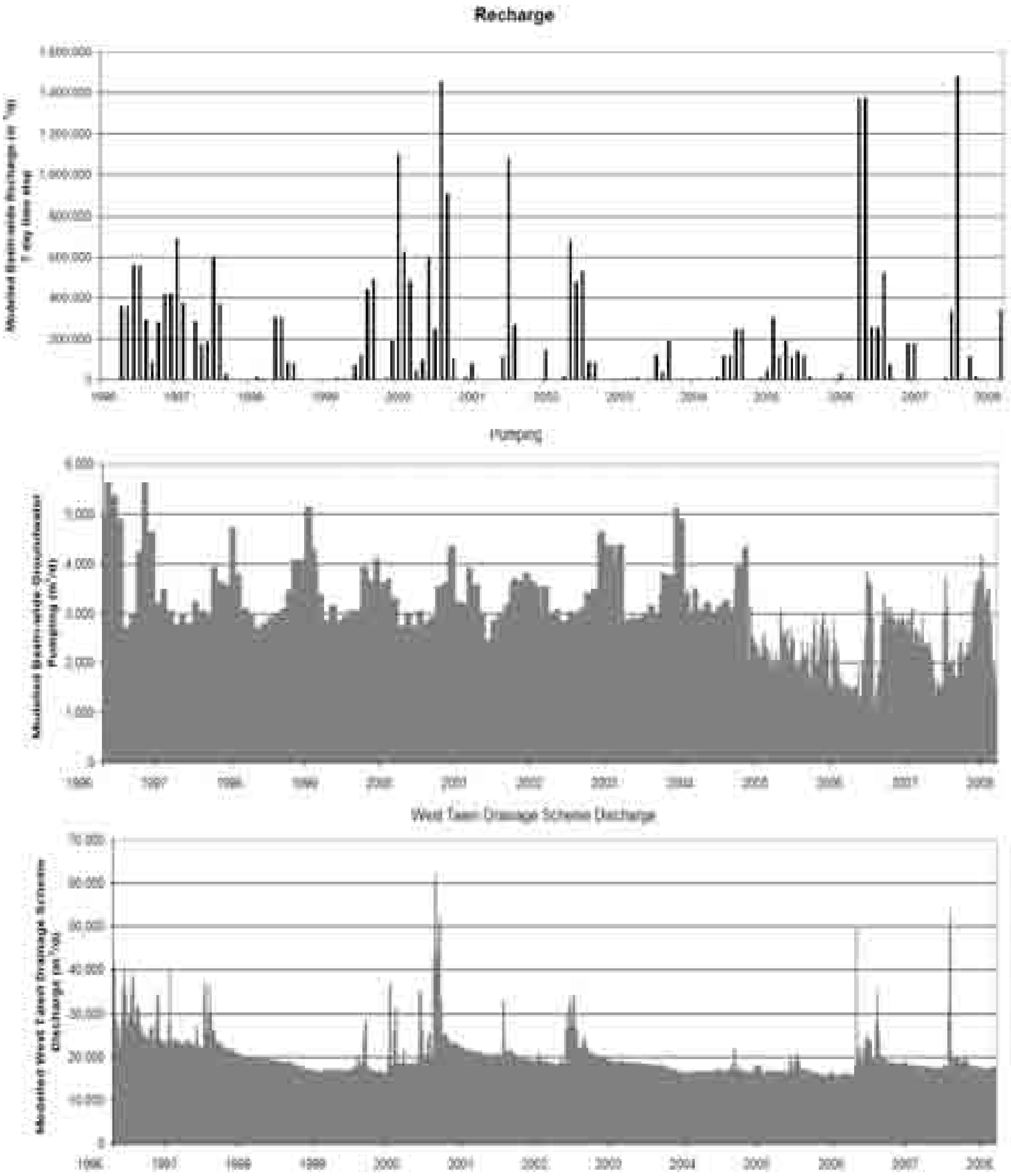

Figure D. 13 Transient calibration mass balance plots. The plots of exchanges with the groundwater system follow from recharge, pumping and West Taieri Drainage Scheme discharge

Figure D13 illustrates the intense variation in groundwater model exchanges made between the various compartments or boundary conditions simulated. Groundwater recharge has significant variability within each season and from year to year. Groundwater pumping tends to peak in the summer months but maintains a strong base rate throughout the year. The discharge from groundwater into the West Taieri Drainage Scheme is less volatile than, say, recharge. However, the drainage discharge tends to respond to accumulating recharge and peaks in the Taieri River.

The rivers play a significant role in balancing the groundwater model. Changes in groundwater level immediately change the polarity and intensity of interchange between the surface water and groundwater systems. Equally, transient surface water changes were included in the simulation of the Silver Stream and Taieri River as it crossed the Lower Taieri Basin. These variabilities have a knock-on effect for adjoining groundwater levels. Indeed, the quite different hydrographs within the calibration process (displayed in Figure D11) hint at the effects of historic surface water level variations on monitoring sites at a variety of proximities to surface water and the depth of the screened interval. Ultimately, the groundwater resource condition of the Lower Taieri Basin, especially in the West Taieri area, is underpinned by the surface water interchanges. Significant dips in groundwater levels are readily augmented by drawing from aquifer storage, but more importantly from the nearest surface water body.

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Appendix E Consented groundwater takes within the Lower Taieri Basin groundwater system

Well number	Consent number	Water take restriction zone	Depth (m)	Easting	Northing	Annual Allocation (m^3/yr)	Irrigation Area (ha)	Maximum Daily Quantity (m^3)	Maximum Monthly volume (m^3)	Use
I44/0747	2000.456	East Taieri	37	2304814	5478942	1,825,000	N/A	1,296	161,200	DCC Mosgiel Water Supply
I44/0742	2001.372	East Taieri	31.1	2304151	5477852			720		
I44/0744	2001.373	East Taieri	40.3	2303568	5477558			1,296		
I44/0753	2002.248	East Taieri	37.1	2304809	5478922			1,344		
I44/0749	2002.249	East Taieri	33.45	2303623	5478771			1,296		
I44/0751	2002.250.	East Taieri	50.9	2305110	5478751			530		
I44/0750	2002.251	East Taieri	34.5	2303171	5478203			2,200		
I44/0748	2002.317	East Taieri	39.65	2305015	5478917			750		
I44/0746	2002.318	East Taieri	34.2	2304151	5478389			750		
I44/0747	2000.456	East Taieri	37	2304814	5478942			1,296		
I44/0352	2001.850	East Taieri	30.5	2305000	5480200	288,000	N/A	800	24,000	Industrial
I44/0964	2002.341	East Taieri	40.5	2302300	5477800	14,930	7	60.2	1,866	Irrigation
I44/0684	2000.438	East Taieri	35.5	2,302,900	5,477,100	19,980	N/S	222		Irrigation
I44/0441	2000.222	East Taieri	26.4	2302500	5476800	14,976	3	156	1,872	Irr/Dom.
I44/0806	2002.374	West Taieri	23.8	2,291,700	5,475,600	118,010	30	-	14,690	Irrigation
I44/0958	2005.233	West Taieri	40	2293000	5475200	47,888	N/S	162	4,931	Irrigation
I44/1001	2004.632	West Taieri	27.15	2290600	5473700	31,104	N/A	85	2,592	Irrigation
Several	2004.971	West Taieri	30 - 60	-	-	N/A	N/A	-	-	Heat Exchanger Fluid
			Total annual allocation =			2,359,887				

Note: N/A = Not applicable, N/S = Not specified, Irr = Irrigation, Dom. = Domestic
Consent 2004.971 at Dunedin International Airport authorises the circulation of groundwater as a heat exchanger fluid; water extracted is then re-injected to the aquifer.

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