The Potential Hazard On-Site Wastewater Treatment Systems in Darfield and Kirwee Present to Local Groundwater Quality and Critique of Current Assessment Methods

Prepared as part of a Ministry of Health
contract for scientific services

by

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March 2014

Client Report
FW 14004

The Potential Hazard On-Site Wastewater Treatment Systems in Darfield and Kirwee Present to Local Groundwater Quality and Critique of Current Assessment Methods

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ACKNOWLEDGEMENTS

The author is grateful to Iain Haycock (MacMillan Drilling Services), Fiona Mathis (Fonterra) and staff of Environment Canterbury's Groundwater Investigations and Monitoring Group for provision of hydrogeological data, also to Pattle Delamore Partners for their review of the report.

Table of Contents

List of Figures

List of Tables

EXECUTIVE SUMMARY

Darfield and Kirwee townships are located in the Selwyn District upon the extensive unconfined alluvial gravel aquifer that underlies the central Canterbury Plains. Both townships have experienced considerable population growth since the earthquakes that affected Christchurch in 2011. The population's expansion has revived concerns previously expressed by Community and Public Health regarding the sustainability of on-site wastewater systems in the Darfield-Kirwee area, notably the hazard they present to groundwater quality and the associated risk to public health. To furnish an informed debate on the subject, the Institute of Environmental Science and Research Ltd has reviewed the hydrogeological setting in the Darfield-Kirwee area, assessed the vulnerability of the aquifer underlying the central Canterbury Plains to water quality impacts from the septic tank clusters and analysed the functionality of Selwyn District Council's (SDC's) groundwater quality monitoring well network. A quantitative assessment of public health risk was not included as part of the brief for this work.

Nitrate is the primary groundwater contaminant of concern that is associated with on-site wastewater treatment systems in the Darfield-Kirwee area. On the basis of published literature values, domestic effluent leaching from the septic tank clusters could contain close to 65 mg NO_3-N/L. Conditions in the aquifer are not conducive to any nitrate reaction, yet effluent will be diluted with natural land surface recharge water as it migrates downwards to the water table, which lies around 80 m below ground level (bgl) at Darfield and 65 m bgl at Kirwee, respectively. Localised groundwater nitrate impacts concentrated at the water table beneath the townships are estimated to be closer to 20 mg NO_3-N/L.

The thick vadose zone in the area is likely to prevent most, if not all, microbial contaminants from effluent reaching the saturated zone. Nonetheless, there have been several positive detections of *Escherichia coli* in local groundwater sampled at depths of almost 125 m. This suggests the aquifer is not entirely immune from microbial contamination originating from land-based practices, and preferential vertical transport pathways caused by the installation of water wells are suspected to have contributed to the positive *Escherichia coli* detections. Considering more bores have been drilled in Kirwee than in Darfield, and the vadose zone is shallower at Kirwee, the impression is that the aquifer is most vulnerable to any microbial contamination at Kirwee.

The scale of the nitrate plumes emanating from Darfield and Kirwee cannot be predicted accurately at this stage, because the physical heterogeneity of the alluvial gravel aquifer is difficult to incorporate into predictive mathematical models. Contaminant transport in such groundwater systems is generally characterised by preferential flow pathways, and the strong vertical hydraulic gradients in the region inevitably promote mixing and therefore dilution of point-source pollution impacts, as does lateral spreading. It is anticipated that groundwater nitrate impacts above the drinking-water maximum acceptable value of 50 mg/L nitrate (11.3 mg NO_3-N/L) extend hundreds of metres down-gradient of the septic tank clusters and follow some unmapped convoluted path.

There is no evidence to suggest that the groundwater system underlying Darfield and Kirwee is strongly affected by any river recharge, and the aquifer is heavily impacted by nitrate that derives from the regional agricultural land use onto which impacts from septic tanks are superimposed. Background groundwater nitrate concentrations of up to 16 mg NO_3-N/L near the water table and 9 mg NO_3-N/L in water supply bores screening more than 200 m bgl have been detected up-gradient of Darfield and are unrelated to on-site wastewater treatment practices. This suggests the local aquifer has 'nitrate issues' *before* impacts from the Darfield and Kirwee wastewater disposal fields are even taken into account, with the implication that the regional groundwater system has a limited capacity to dilute nitrate impacts sourced from the clusters of septic tanks in Darfield and Kirwee. Furthermore, the high background nitrate levels and their seasonal variability confound the problem of being able to reliably identify nitrate impacts sourced from septic tank operations.

Nitrogen mass loading rates from on-site wastewater treatment systems are proportional to population densities. The current population densities are approximately 5.7 people/ha in Darfield and 3.7 people/ha in Kirwee. It is estimated that Darfield contributes the equivalent of between 18 kg N/ha/yr and 52 kg N/ha/yr, probably closer to 36 kg N/ha/yr, to the regional groundwater system, of which the net load from wastewater is expected to range from 9 kg N/ha/yr to 36 kg N/ha/yr, more likely to be about 27 kg N/ha/yr. Nitrogen leached from the soils underlying residential allotments makes up a small proportion of the total nitrogen load from the town, but is included in the assessment of effects, because this dilutes effluent impacts and is an integral part of the wastewater treatment process. Nitrogen loads from Kirwee are anticipated to be between 74 percent and 88 percent lower than nitrogen loads from Darfield owing to the lower population density.

Conceptually, on-site wastewater treatment operations in Darfield and Kirwee contribute similar nutrient loads, in terms of nitrogen mass, to the groundwater system as intensive agricultural land uses, notably dairy farming.

The network of wells used by SDC to monitor groundwater quality utilises the majority of the existing well infrastructure in the area. It provides a useful measure of the groundwater quality that is being abstracted for use, but is not fit for the purpose of reliably evaluating the water quality impacts from the clusters of septic tanks in Darfield and Kirwee, particularly in Darfield where the closest monitoring well is located more than 1.8 km from the pollution source. The spatial coverage of the wells means that the quality of the water determined at their locations provides little and in many cases no information about the magnitude of the water quality impacts associated with on-site wastewater treatment practices in the area.

The reliability of the available piezometric contour data is questionable. It would be useful to conduct a local piezometric survey to gain a better appreciation of the directions in which the contamination from the septic tank clusters is likely migrating, and hence where monitoring should be focused.

Establishing whether the objective of SDC's water quality monitoring strategy is to investigate septic tank impacts, or to simply provide some defensive monitoring to secure the health of discrete local domestic water users down-gradient of the townships, will ultimately determine the modifications to be made to the existing network of wells.

Robust monitoring of the impacts of the septic tank clusters would require a significant investment in monitoring well infrastructure. The cost of installing a fit for purpose monitoring well in the area is estimated to be $18,000–26,000, depending on the well’s exact depth. Many wells would need to be installed if the objective is to reliably delineate the extent of the contaminant plumes perceived to emanate from the septic tank clusters. Such an investigative strategy is not advised, because sinking wells in the vicinity of the pollution source could actually exacerbate the problem by involuntarily creating preferential vertical flow pathways for contamination to penetrate deeper, thereby exposing existing drinking-water supply wells to greater risk.

The monitoring network in its current state provides some value in terms of defensively monitoring the water quality for existing water supply bores positioned down-gradient of the townships. The vulnerability of the groundwater as a drinking-water resource in the Darfield-Kirwee area is significantly reduced, because water supply wells in the region are normally screened at depths that are greater than 35 m below the water table, which is far below the core of any contaminant plumes associated with the septic tanks. Defensive monitoring of existing environmental receptors using sentinel observation bores is a more cost-effective way of managing the health risk from groundwater impacts than a broad and generalised monitoring strategy.

Overall, given the extensive and increasingly intensive agricultural land use across the Canterbury Plains, the existing on-site wastewater practices in the Darfield and Kirwee area contribute a relatively minor, albeit locally significant, component to the overall nitrate-nitrogen mass budget. When this is considered along with the perception that groundwater vulnerability to microbial pathogens is likely to be low, because of the thickness of the vadose zone, it is difficult to establish a strong technical argument against a wastewater strategy that focuses on decentralised treatment systems in Darfield and Kirwee, unless the population density was to increase dramatically. No case studies have been published that could be used as reference cases to strongly contest against the continued operation of on-site wastewater treatment practices in Darfield and Kirwee.

It is helpful to recognise that the current practice of multiple discharges distributed over a broad area promotes the mixing and dilution of impacts in the aquifer. Consequently, broad yet relatively short contaminant plumes are currently expected to spread from the towns. If discharges were focussed at a discrete point such as a centralised effluent disposal field, then unless the system offered advanced treatment to reduce concentrations, the contaminant plume, although narrower, would likely extend further.

It is pertinent to note that an objective stated in the Canterbury Land and Water Regional Plan (CLWRP) is that ‘all activities operate at “good practice” or better to protect the region’s fresh water resources from quality and quantity degradation’. Monitored groundwater nitrate levels in the Selwyn-Waihora zone already exceed health indicator targets specified in the CLWRP, and reducing the nitrogen footprints associated with farming practices is a focus of the plan. Any initiative to reduce nitrogen loads from wastewater discharges from the Darfield and Kirwee area would therefore complement the objectives of the CLWRP and would help mitigate any risk to public health.

1. INTRODUCTION

Darfield is the largest population centre in New Zealand (NZ) that does not have a reticulated community wastewater treatment system. The potential for harm to public health that is associated with the large cluster of septic tanks in the area has been a topic of debate by Community and Public Health (CPH) for many years. Of particular concern are the impacts that the numerous on-site waste water treatment systems have on groundwater quality, because the unconfined alluvial gravel aquifer into which the effluent drains also serves as the regional drinking-water supply that is generally untreated.

The earthquake in Christchurch in February 2011 accelerated residential development and population growth in the Selwyn District. Early results from the 2013 census compared with the 2006 population statistics, estimate a 16 percent rise in Darfield's resident population and a 23 percent increase in the population in the Kirwee area. Currently, Darfield's population is estimated to be 1935 (Statistics New Zealand 2013), and based on the areas defined in the NZ census, 3486 people live in the encompassing Kirwee area unit, which covers a larger area than the Kirwee township. This unexpected growth in urban development has refuelled the debate about the sustainability of on-site wastewater treatment systems in the Darfield-Kirwee area.

Wastewater management in the Darfield-Kirwee area is under the authority of Selwyn District Council (SDC). Since 2006, SDC has undertaken near-annual surveys of groundwater quality in the area, aimed at monitoring the potential adverse effects of land-based wastewater disposal practices on the local groundwater system. SDC's survey has often been complemented by groundwater quality surveys also conducted by Environment Canterbury (ECan). So far, seven water quality surveys have been completed in the Darfield-Kirwee area in March 2006, December 2006, May 2007, December 2008, December 2009, January 2011 and January 2012.

Overall, the results of the surveys, which are generally completed using a common set of up to 28 water wells, have not revealed any obvious signs that the groundwater resource is being extensively impacted by septic tank effluent originating from Darfield or Kirwee. So far, any changes in groundwater quality detected in the area have been attributed to general regional agricultural land-use impacts and natural seasonal variations (Liquid Earth 2012).

Recently, SDC commissioned a study to assess the impacts of Darfield and Kirwee's wastewater discharges on groundwater quality (PDP 2011). Nitrate was perceived to be the only contaminant of concern, and a variety of mathematical modelling scenarios were applied to predict the scale of the groundwater quality impacts to which some uncertainty bounds were attached. In terms of the extent of the predicted nitrate impacts from septic tank operations, PDP (2011) estimated that groundwater nitrate concentrations above the drinking-water threshold of 11.3 mg NO_3-N /L would be confined to small plumes extending no further than 15 m down-gradient from Darfield and 70 m down-gradient from Kirwee. The combined effects of dilution and dispersion were predicted to mitigate any impacts from septic tank operations on the groundwater resource underlying the towns that might present a regional public health hazard.

Since 2009, groundwater scientists at the Institute of Environmental Science and Research Ltd (ESR), representing CPH, have repeatedly queried whether the set of wells utilised by SDC and ECan in the annual surveys are fit for the purpose of defensively monitoring the water quality impacts associated with on-site wastewater treatment systems in Darfield and Kirwee. The limitations of the monitoring array have been similarly highlighted by the environmental consultancy commissioned by SDC to report on the latest water quality survey (Liquid Earth 2012). The concern expressed is that the spatial distribution of the wells and the depths at which they are screened bias the water quality results and limits the ability to draw definitive conclusions about the true impact of the on-site wastewater treatment systems on the local environment, which might lead to a misinformed assessment of potential risk presented to public health. In effect, there is a high chance that the current resource management decisions being made by SDC on the basis of their groundwater monitoring strategy are prone to type II (false-negative) errors.

This report provides the necessary technical information that will facilitate informed discussions among CPH, SDC and ECan about the sustainability of on-site wastewater treatment systems in Darfield and Kirwee, and will guide future monitoring of their potential impacts on the receiving groundwater environment. This report does not discuss the technical merits of wastewater treatment options and does not quantify any of the health risks associated with wastewater treatment practices. The report:

1. reviews the groundwater contaminants perceived to be associated with on-site wastewater treatment practices in Darfield and Kirwee
2. describes the hydrogeological environment beneath Darfield and Kirwee, and discusses its condition from the perspective of making a vulnerability assessment of the groundwater system, while at the same time highlighting important knowledge gaps
3. incorporates a review of the literature to determine whether there is evidence of impacts from on-site wastewater treatment systems on similar environments, and to identify monitoring methods and management strategies applied elsewhere
4. critically assesses the usefulness of SDC's current groundwater quality survey methods for monitoring the potential impacts of clusters of on-site wastewater treatment systems on groundwater quality at Darfield and Kirwee, and to identify the scope for technical improvement.

2. GROUNDWATER CONTAMINANTS ASSOCIATED WITH ON-SITE WASTEWATER TREATMENT SYSTEMS

Nitrogen and microbial pathogenic organisms are considered to be the main contaminants of concern in relation to groundwater contamination from on-site wastewater treatment systems and human health (USEPA 2002). The fate and transport of these main contaminants in an alluvial gravel aquifer environment are explained in detail in the report sections that follow. Phosphorus, heavy metals, hormones and pharmaceuticals are contaminants of lesser concern, and are briefly discussed here:

Phosphorus is often perceived to be a contaminant of concern in wastewater, but only from an environmental perspective owing to its ability to cause eutrophication in surface waters. Eutrophication is linked to some public health issues, including toxic cyanobacterial blooms. On its own, however, phosphorus is not a groundwater contaminant of public health significance. Furthermore, it is generally assumed that phosphorus is effectively attenuated by the precipitation and sorption processes that occur in the soil and vadose zone below effluent disposal fields (McCray et al 2005), although this has never been studied under NZ conditions.

Similarly, any hazards posed by heavy metals that might be present in wastewater are mitigated by their abilities to sorb to clay minerals in the alluvial sediments under the circumneutral pH and aerobic redox conditions present in Canterbury’s alluvial gravel aquifer system. Trace compounds that include hormones and pharmaceuticals, are broadly classified as contaminants of emerging concern and have not been studied in NZ. Since the rationale for research into these contaminants tends to be based on environmental rather than health concerns, they are beyond the scope of this work.

Table 1 lists the published concentration ranges of selected determinands within septic tank effluent that are relevant to this study. It includes common assumptions about nitrogen (N) and phosphorus (P) loads, and it is reasonable to assume that wastewater leaching from the effluent drainage fields underlying Darfield and Kirwee has similar a chemical composition to that reported in the literature.

Table 1: Published concentrations of determinands within septic tank effluent.

Nutrients		**Major ions**	
Nitrogen generation[*$~]	6–7 g N/person/d	Calcium[#^]	6–108 mg/L
Phosphorus generation[$~]	1–3 g P/person/d	Magnesium[#^]	4–14 mg/L
Total nitrogen[*$+]	12–170 mg N/L (62.1 mg N/L)	Potassium[#^]	7–35 mg/L
Ammonium[*$+%&]	6–230 mg N/L (61.0 mg N/L)	Sodium[#^]	40–110 mg/L
Nitrites and nitrates[*$+]	<1 mg N/L (0.2 mg N/L)	Bicarbonate[#^]	50–120 mg HCO_3/L
Total phosphorus[*]	18–29 mg P/L	Chloride[*+#^]	53–128 mg/L
Phosphate[*$+]	1.2–24 mg P/L (9.0 mg P/L)	Sulphate[*]	23–48 mg/L
Microbial		**Other**	
Total coliforms[*+#]	10–12 log units/100 mL	pH*[+]	6.6–8.6
Faecal coliforms[*+%]	8–10 log units/100 mL	Alkalinity[*#]	60–775 mg/L
		Iron*	0.26–3 mg/L

*Lowe et al (2004); [$]McCray et al (2005); [+]Hughes (1993); [~]USEPA (2002); [%]Pang et al (2006); [#]Ellis (2004); [&]WERF (2009); [^]unpublished ESR data

Values in brackets indicate the values assumed in mathematical models within the publications, which are generally given as average or median values.

2.1 Nitrogen

Nitrogen, in the form of either nitrate or nitrite, is the main inorganic groundwater contaminant of concern associated with on-site wastewater treatment systems. Nitrogen oxides are potentially harmful chemicals because nitrate can be reduced to nitrite, which is a known human toxin that can cause methaemoglobinaemia (WHO, 2011). To provide a safe level of health protection to bottle-fed infants, the maximum acceptable value (MAV) for nitrate in NZ drinking-water is 50 mg/L (ie, 11.3 mg NO_3-N/L). A short-term exposure limit of 3 mg/L (ie, 0.91 mg NO_2-N/L) and a provisional long-term exposure limit of 0.2 mg/L (ie, 0.06 mg NO_2-N /L) applies to nitrite (MoH 2008). Until a freshwater quality outcome is explicitly set by the Selwyn-Waihora sub-regional zone committee, the Canterbury Land and Water Regional Plan (CLWRP) has specified a provisional target for shallow unconfined aquifers predominantly recharged by drainage that states nitrate levels in the monitored groundwater system should not exceed the drinking-water MAV and that, on average, concentrations should be below 50 percent of the MAV (ie, <5.65 mg NO_3-N /L).

Nitrogen in septic tank effluent is predominantly exported as ammonium and organic-N nitrogen, but in a sandy gravel vadose zone, including that underlying the Canterbury Plains, ammonium is completely converted to nitrate within a relatively short distance after leaving the disposal field (Nokes et al 2012). Hence, it can be assumed that all nitrogen in septic tank leachate contaminates groundwater in the form of nitrate.

Assuming that the average daily per capita production of nitrogen is between 11 g N/day and 16 g N/day (Sedlak 1991; USEPA 2002; McCray et al 2005) and a typical NZ resident on a mains water supply produces 200 L of wastewater per day (ARC

2004), then the average nitrate concentration in undiluted effluent infiltrating to the water table can be predicted to be in the region of 55–80 mg NO_3-N /L. In a recent modelling study of the wastewater impacts from Darfield and Kirwee, PDP (2011) assumed groundwater nitrate inputs of 60 mg NO_3-N/L. Furthermore, Pang et al (2006) assumed groundwater nitrate inputs of 64 mg NO_3-N/L in a similar modelling study performed in the Yaldhurst area of Canterbury. In the Water Environment Research Foundation's (2009) comprehensive characterisation of septic tank effluent that was based on surveys conducted in the USA, the median nitrogen concentration in drainage water was reported to be approximately 60 mg N/L.

The carbon-limited, aerobic hydrogeochemical conditions that exist in the fluvio-glacial sediments that constitute the aquifer underlying Darfield and Kirwee are not conducive to the reduction of nitrate. Nitrogen mass is therefore conserved in the aquifer system and the only way in which nitrate can be assimilated by the aquifer is through mixing with cleaner water. As a consequence, the phrase: 'dilution is the solution to [nitrate] pollution' can be utilised.

2.2 Predicted nitrate loads and source concentrations for Darfield and Kirwee

As mentioned previously, the average concentration of nitrate in septic tank effluent is estimated to be within the range of 55–80 mg NO_3-N/L. It is reasonable to assume that as a worst-case scenario, occasionally, in some areas under the Darfield and Kirwee townships, localised groundwater nitrate impacts ('hotspots') of a potentially similar magnitude might occur at or near the groundwater table.

Some lateral spreading however will occur as the leachate infiltrates the vadose zone, which contributes to the mixing and, therefore, to the dilution of the effluent with natural soil drainage water. If it is assumed that effluent sourced from a septic tank cluster is perfectly mixed with natural soil drainage water within the confines of a township's footprint, then it is estimated that nitrate concentrations in the aquifer on a township scale will more likely be within the ranges of 7–30 mg NO_3-N/L, probably close to 20 mg NO_3-N/L, for Darfield, and 6–25 mg NO_3-N/L, probably close to 16 mg NO_3-N/L, for Kirwee (see Appendix A).

Using the 2006 census statistics, PDP (2011) calculated the mass of nitrogen entering the aquifer from on-site wastewater treatment systems in Darfield and Kirwee. The estimated effective loads of between 26 kg N/ha/yr and 31 kg N/ha/yr are comparable with the loads estimated independently by ESR in 2012 during the preparation of a submission to the CLWRP for CPH (ESR unpublished).

Appendix A contains revised estimates of the nitrate loading rates based on assessments of the current footprints of the towns and using 2013 census statistics. Unlike the aforementioned historic load estimates, these revised figures reflect the total effective loads, that is, septic tank effluent compounded on top of natural soil drainage water that itself carries an unmanageable load of nitrogen, yet ultimately forms an integral part of effective land-based wastewater treatment.

In terms of contaminant mass, the latest estimates of impacts on groundwater quality at Darfield are marginally higher than the historic estimates, and are predicted to range from 18 kg N/ha/yr to 52 kg N/ha/yr, and are probably closer to 36 kg N/ha/yr.

For Kirwee, it is suspected that historic assessments may have potentially overestimated the population density of the town. Using the latest available population information supplied by SDC, effective nitrate loads from on-site wastewater treatment systems at Kirwee are predicted to be within the range of 16–39 kg N/ha/yr, that is, between 74 percent and 88 percent of the magnitude of the loads sourced at Darfield.

To put these nitrogen loading rates into some context, Table 2 lists the nitrogen leaching rates and the groundwater nitrate impacts for different land uses that have been predicted for the soil and climatic conditions at Darfield and Kirwee (Lilburne et al 2010). Clearly, the perceived nitrogen loads from on-site wastewater treatment systems in Darfield are towards the upper end of the scale for intensive agricultural land uses, namely, dairy farming activities. The nitrogen inputs from on-site wastewater systems in Kirwee rank lower, and are comparable to the pollution loads generally associated with less intensive dairy farming or arable land use.

Table 2: Published nitrate-nitrogen leaching rates and expected nitrate concentrations in drainage water reaching the water table.

Land use	Nitrogen mass loading rate (kg N/ha/yr)	Average nitrate concentration in leachate (mg NO_3-N/L)
Septic tank cluster at Darfield	17.9–51.6 (36.0)	7.0–30.2 (19.8)
Dairy at 4 cows/ha (winter on) (winter off)	41.4 31.9	16.3 12.5
Dairy support irrigated	39.8	15.6
Dairy at 3 cows/ha (winter on) (winter off)	31.9 23.9	12.5 9.4
Septic tank cluster at Kirwee	15.7–39.1 (26.5)	6.3–25.0 (15.8)
Pigs	17.5	12.5
Lifestyle/horticulture	16	12.4
Arable seasonal	19.2–19.8	8–13
Arable mixed	8.5–23.6	8
100% sheep	6.3–11.3	6.3
Viticulture	9.0	5.3

Values in brackets are the most probable values. Data are from Lilburne et al (2010). Refer to Appendix A additionally.

It is important to recognise that the nitrate concentrations listed in Table 2 reflect those expected in water draining from the land for the specified land use and are subject to a number of simplifying assumptions as Lilburne et al (2010) point out. The values are presented because they indicate the likely maximum localised impacts on the aquifer at the water table. They do not, however, necessarily represent the impacts on a regional scale or on the water quality that would necessarily be encountered in a water supply well, because they constitute integrals of various recharge waters that are time- and space-specific. Nevertheless, it is evident from the values in Table 2 that groundwater nitrate impacts under Darfield and Kirwee are of similar magnitude to impacts generally associated with dairy farming activities. The high relative nitrate concentration results from the fact that domestic effluent sourced from septic tank drainage fields is not subject to the larger dilution effects that occur under irrigated pasture used for dairy farming.

2.3 Microbial pathogens

The consumption of water contaminated with microbial pathogens can result in illnesses such as vomiting, diarrhoea and in some cases may be fatal. Sewage is a rich source of bacteria, protozoa and viruses. *Escherichia coli* is the microbial indicator organism used in the Drinking-Water Standards for New Zealand (MoH 2008) to assess the potential for recent faecal contamination of water, and it has a MAV of less than one organism per 100 mL water sample. The MAV for total pathogenic protozoa is less than one infectious (oo)cyst per 100 L (MoH 2008). Viruses have no MAV in the Drinking-Water Standards for New Zealand (MoH 2008).

Viruses are particularly hazardous because they are highly infectious and they are environmentally robust. Their long survival times, taken together with their small sizes and biochemical characteristics, enable viruses to be transported over longer distances in the subsurface environment than either bacteria or protozoa. Although no national water quality standard has been established for viruses in drinking-water, guidelines are available for evaluating separation distances between on-site domestic wastewater systems and water wells, based on the transport of viruses (Moore et al 2010).

Microbial contaminants become inactivated over time as effluent infiltrates through the natural subsurface. This is caused by a combination of natural die-off and predation, facilitated by the physical attenuation processes of adsorption, filtration and desiccation, and this provides the fundamental basis for the operation of effluent disposal fields. Microbial attenuation is most effective in the unsaturated zone and in fine-grained sediments, although because effluent is produced almost continuously from on-site wastewater treatment systems associated with households, it is conceivable that unsaturated conditions rarely prevail directly under the septic tank clusters at Darfield and Kirwee.

A comprehensive review of microbial removal rates in natural porous media conducted by Pang (2009) reports removal rates in the order of 10^{-1} log/m in the vadose zone for clay, sand-gravels and coarse gravel media, and removal rates in the order of 10^{-2}–10^{-3} log/m in gravel aquifers, which includes the system underlying the Canterbury Plains. Lower removal rates generally apply in situations where high contaminant loads are sustained, as is the condition at Darfield-Kirwee. This is because inputs of dissolved organic carbon can condition the surface of sediments and steadily reduce their capacity to adsorb certain microorganisms (Weaver 2013). It is important to realise that behind the effective removal rates quoted by Pang (2009) lies some underlying assumption about the velocity at which effluent is travelling through the subsurface, which is naturally a site specific variable. Also, the removal rates Pang (2009) evaluated for vadose zone conditions derive from experiments that examined across a physical scale of less than 10 m. Despite these limitations, the removal rates are useful for making generalised assessments about the vulnerability of water resources. A removal rate value of 10^{-1} log/m effectively implies one log-reduction (ie, 90%) contaminant removal over 10 m and two log-reductions (ie, 99% contaminant removal) over a travel distance of 20 m etc.

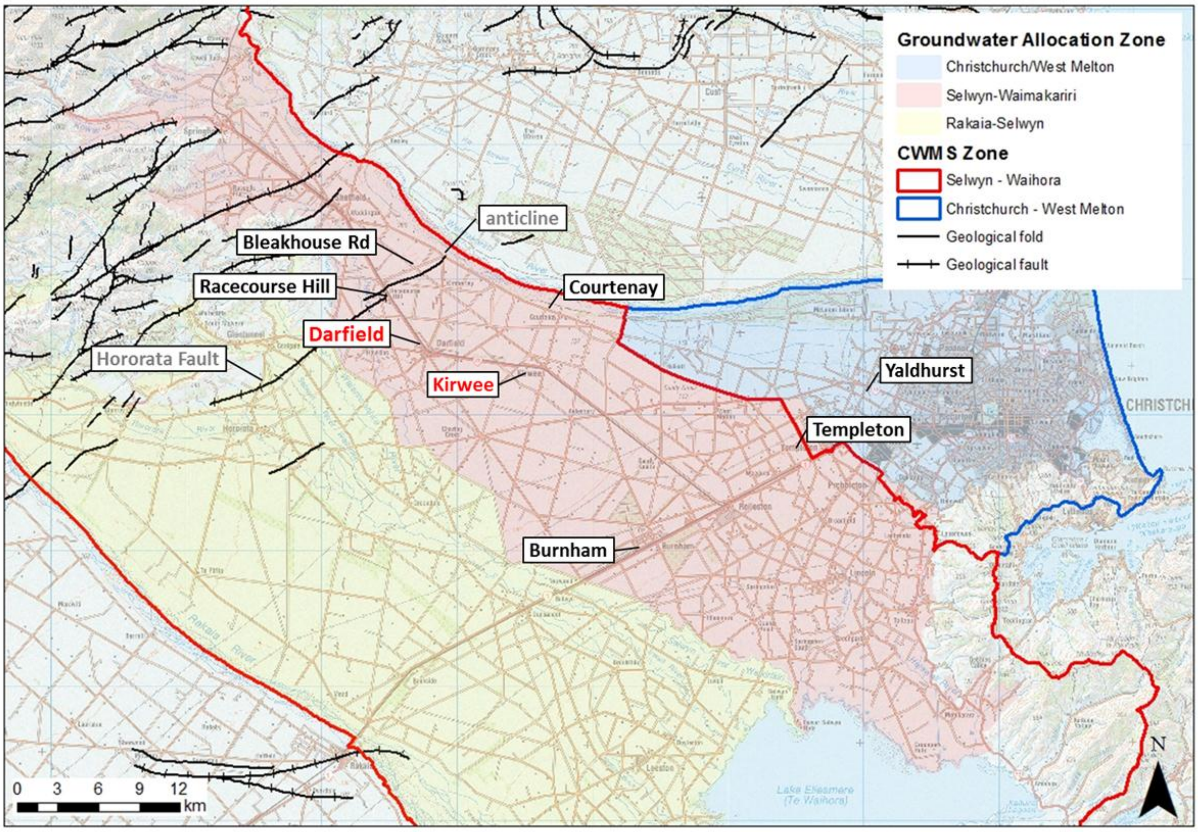

Figure 1: Darfield and Kirwee are located within the Selwyn-Waimakariri groundwater allocation zone, which constitutes part of the Selwyn-Waihora sub-regional zone in the Canterbury Water Management Strategy.
Collectively, Christchurch-West Melton, Selwyn-Waimakariri and Rakaia-Selwyn comprise what is commonly referred to as the central Canterbury Plains. Areas of geographic interest referred to in the text are highlighted.

3. THE HYDROGEOLOGICAL SETTING OF DARFIELD AND KIRWEE

Darfield and Kirwee are located towards the upper end of the Selwyn-Waihora groundwater zone that is managed by ECan and encompasses the central Canterbury Plains sub-region situated between the Waimakariri and Rakaia rivers, the Malvern foothills and the coast (Figure 1). Near Darfield and Kirwee, the central Canterbury Plains are composed of fluvio-glacial outwash deposits of the Quaternary period that are associated with the Waimakariri River, and these deposits coalesce with similar massive outwash deposits from the Rakaia River system and the smaller Selwyn River system to form the regional aquifer (Vincent, 2005). While there has only been a very limited detailed investigation into the local hydrogeology surrounding Darfield to date, ECan plans to investigate the local complexities of the region in the near future (David Poulsen, Hydrogeologist, ECan, personal communication, November 2013).

The conceptual model of the hydrogeology of the alluvial gravel aquifer under Darfield and Kirwee provided in this work has been developed from:

- a review of published technical reports, including those commissioned by SDC
- an analysis of publically available data from ECan’s WELLS and SQUALARC (water quality) databases
- an analysis of data provided by Fonterra
- interviews held with Ian Haycock (McMillan Drilling Services), Carl Hanson (ECan) and Pat Morrison (retired farmer and previous landowner of the Fonterra Darfield milk factory site).

3.1 Aquifer structure and its influence on contaminant transport

Darfield and Kirwee rest upon the abandoned braided-river flood plain of the Waimakariri River, last occupied during the last glacial maximum, approximately 18,000 years ago (Forsyth et al 2008) (Figure 2). SDC’s exploratory water-supply bore L35/1069 is the deepest bore to have been drilled in the Darfield and Kirwee area and it comprises gravel alluvium containing varying amounts of sand, silt or clay, to a depth in excess of 288 m below ground level (bgl) (Appendix B). Overall, the Canterbury Plains represents almost 2 million years of geological deposition and some stratification is to be expected. Unfortunately, the absence of reliable geological markers inland makes it difficult, if not impossible, to differentiate the ages of the materials at depth or to make correlations between potential erosional surface features inferable from the borelog data (Brown and Weeber 2000).

A simplified hydrogeological description of the subsurface environment is that it predominantly comprises a silty sandy gravel matrix that contains relatively small channels or lenses of clast-supported gravels that are the units through which water and contaminants are the most rapidly transmitted. Erosional surfaces relating to episodic glacial events will have some control over the hydrogeological characteristics on a large scale, but aside from the cut and fill valley remnant of the Waimakariri River inferred from seismic refractions made along Bleakhouse Road, 5 km north-west of Darfield town (discussed in section 3.2; see Figure 1 for location), no such large-scale hydrogeological features have been studied for the area in general.

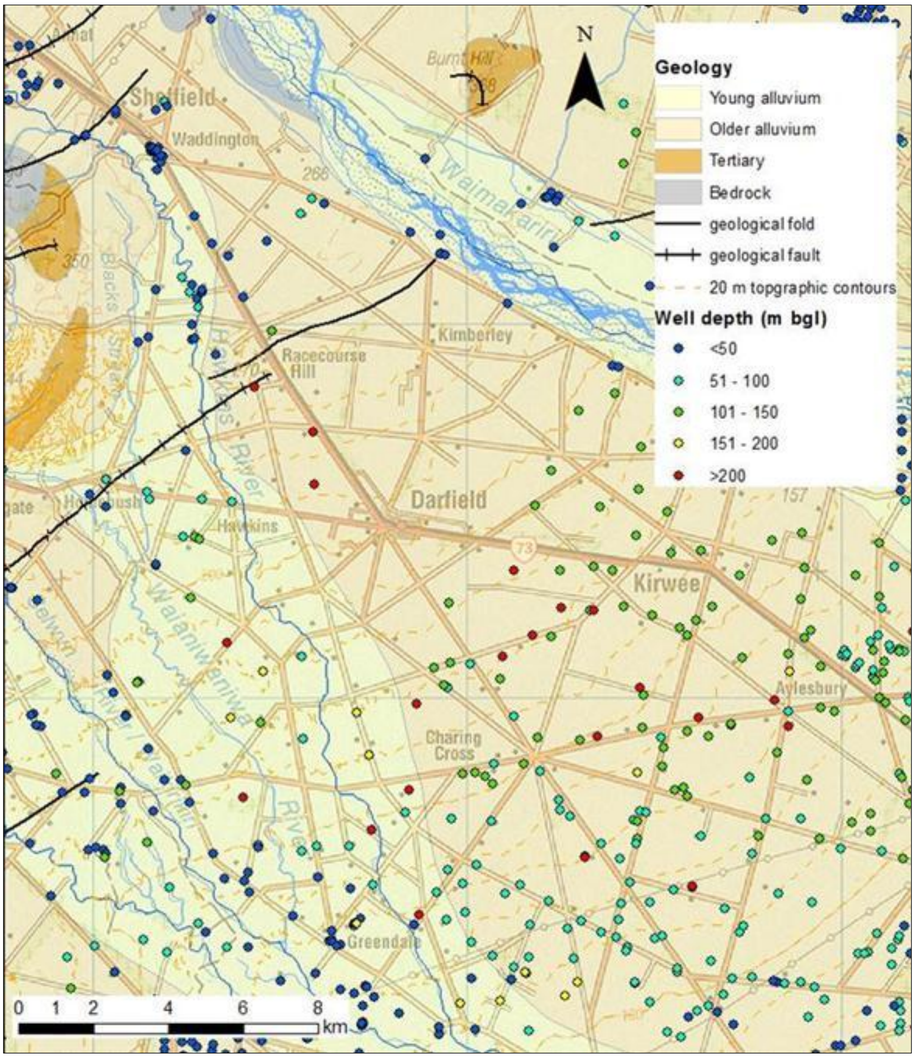

Figure 2: Map of the geology of the Darfield and Kirwee area and active wells.

The alluvial origins of the aquifer determine that the system exhibits significant anisotropy; hence, it is conceivable that the groundwater and its contaminants will tend to move horizontally and in general alignment with the Waimakariri fan extending from the Waimakariri Gorge, that is, roughly north-west to south-east. As a guide to the general magnitude of the anisotropy values associated with NZ gravel outwash aquifers, Thorpe et al (1982) calculated the ratio of horizontal to lateral hydraulic conductivity (K_x/K_y) to be in the range of 2–5 for saturated alluvial gravel material on the Heretaunga Plains. Burbery et al (2012) conducted gas-tracing experiments in open-framework gravel units of the central Canterbury Plains and while a broad range of anisotropy values were estimated, the average ratio of K_x/K_y was 6.

Given the braided characteristics of the gravel outwash sediments, it is perceived that a contaminant plume extending from a point-pollution source in the aquifer beneath Darfield and Kirwee will be asymmetrical in shape and will exhibit substantial fingering, which relates to preferential flow along permeable gravel hydrofacies or paleochannels. Groundwater tracing experiments performed by ESR at an experimental well field at Burnham, located at the lower half of the aquifer underlying the central Canterbury Plains (Figure 1), have demonstrated the rapid transport and non-idealised flow pathways taken by solutes as they travel through alluvial gravel outwash material over distances of tens and hundreds of metres (Pang et al 1998; Dann et al 2008). Across larger distances, for example, at the kilometre scale, it is likely that the significance of such macro-scale heterogeneities is weakened in relation to governing the general shape of a contaminant plume, and a more uniformly distributed plume feature might be assumed for practical purposes, as were the assumptions applied to PDP’s (2011) modelling assessment. The field experiments performed at Burnham highlight the inherent difficulties associated with reliably detecting groundwater contamination derived from a point source in an alluvial gravel aquifer from point-scale observations (ie, monitoring wells), and this has implications for effective groundwater quality monitoring.

Given their location towards the top end of the Waimakariri braid plain and their age, the gravels beneath Darfield and Kirwee could contain a considerable amount of fines, which probably partly explains the profuse ‘claybound gravel’ strata recorded on many of the driller borelogs for the area (see Appendix B). Indeed, the paucity of wells in the Darfield area (Figure 2), influenced by failures to access good yields of groundwater at depths of less than about 200 m, provides anecdotal evidence to support this. Consequently, the bulk permeability of saturated sediments under Darfield and Kirwee could be lower than that characterised for similar material examined closer to the coast, which is likely to have undergone better sorting during deposition. Certainly, the weathered pro-glacial sediments beneath these sites are less permeable than the younger post-glacial river alluvium that marks the surface of the Christchurch-West Melton aquifer (Figures 1 and 2) and incorporates the Christchurch City aquifer system, which is the recipient of significant river recharge from the Waimakariri River.

3.2 Aquifer boundaries and recharge mechanisms

As the alluvial gravels of the aquifer system underlying the central Canterbury Plains are inherently related to the Waimakariri River, it is possible that there is some type of hydraulic connection. This connection is significant and obvious for the Christchurch-West Melton aquifer located down-gradient of Kirwee (Figure 1) where the regional groundwater system conforms with the general Canterbury hydrogeological model assumptions in the CLWRP, that is, water seeping from the alpine rivers providing a continuous through-flow of clean water in the aquifer, superposed on top of which are land surface recharge (LSR) (ie, soil drainage) inputs. The river through-flow component is important for maintaining the overall water quality of the bulk groundwater system, because it acts as a diluent for anthropogenic impacts associated with land use, particularly nitrate inputs. This concept can be visualised in the groundwater quality transects published by Hanson and Abraham (2009) that were generated for the aquifer underlying the central Canterbury Plains between Courtenay and Lake Ellesmere/Te Waihora (see also Bidwell 2009).

Darfield and Kirwee, however, are located upstream of areas where significant Waimakariri River flow losses occur and there is no evidence to suggest that the groundwater system under Darfield and Kirwee is strongly influenced by the Waimakariri River. Indeed, if anything, the Waimakariri River potentially gains flow from the land along its reach past Darfield and Kirwee from the gorge to Courtenay Road (White et al 2012).

The Hawkins River that flows to the west of Darfield (Figure 2) provides another potential river recharge boundary, but it is a relatively small river (mean flow of 742 L/s at Auchenflower Road [Topélen 2007]) that drains the Russell Hills and it is a tributary of the Selwyn River. It is related to the Selwyn gravel outwash deposits that occupy the depression between the major Waimakariri and Rakaia fans (Vincent 2005). The Hawkins River is ephemeral and loses flow to groundwater under normal conditions, downstream of Sheffield. Generally, all flow is lost by the time the river emerges onto the Canterbury Plains, south-west of Racecourse Hill (Figure 2). It is not known precisely how and exactly where the Hawkins River water recharges the aquifer underlying the central Canterbury Plains, but groundwater contour data (Figure 3) tend to signify that the Hawkins River water is unlikely to invoke any direct or major hydraulic influence on the groundwater system up-gradient of Darfield and Kirwee. The general inference from piezometric data when they are combined with anecdotal geological data is that once it has rounded Racecourse Hill, the water from the Hawkins River continues to flow southwards as shallow groundwater moving within its own sediments (Vincent 2005). Pervasive vertical water leakage from the shallow Hawkins River alluvium to the regional aquifer system underlying the central Canterbury Plains may occur, although the available piezometric contour data suggest that recharge to the main aquifer from the rivers draining the foothills is largely focused down-gradient of Darfield (see section 3.3).

The significance of these factors is that recharge of the aquifer system in the vicinity of Darfield and Kirwee appears to be dominated by LSR. This limits the potential driving force of the groundwater flow, and, most importantly, it indicates that in the Darfield and Kirwee area, the aquifer is likely to have a reduced capacity to assimilate nitrate contamination coming from the land, compared with other areas of the aquifer underlying the central Canterbury Plains that are influenced to a greater extent by river recharge inputs.

Another hydrogeological aspect of the Darfield and Kirwee area is the plausible north-eastern extension of the regional Hororata tectonic fault. Seismic studies of this suggest a truncation of the thick Quaternary gravels on the central Canterbury Plains in the vicinity of Racecourse Hill, referred to as FA6 in Dorn et al (2010) (Appendix C). On the geological QMap of the area (Forsyth et al 2008), a marked anticlinal feature tracing south-west to north-east immediately under Racecourse Hill, roughly marks the line of this inferred tectonic feature (Figures 1 and 2). Data from available geological borelog records for the area support the geophysical evidence and notion that the thickness of the aquifer underlying the central Canterbury Plains tapers out north-west of Bleakhouse Road. For example, in the area of Racecourse Hill and on the north-west side of Bleakhouse Road, Quaternary alluvial gravels are relatively thin and Tertiary sediments are typically encountered at a depth of less than 60 m as a consequence of tectonic uplift and erosion (see Appendix B for borelogs for L35/0324, L35/0679 and L35/1105). In contrast, on the south-east side of Bleakhouse Road, close to the inferred buried fault trace (ie, the Darfield side of

Racecourse Hill), Quaternary gravels are over 280 m thick, as can be evidenced in borelogs L35/0325 and L35/0743 (Appendix B).

Racecourse Hill is composed of very old outwash material believed to be have been deposited more than 59 ka before present, which led Dorn et al (2010) to suggest that the area underwent some major tectonic activity between 24 ka and 59 ka before present. Dorn et al (2010) hypothesise that the structure of the Quaternary gravels on the south-eastern side of the Horarata Fault (ie, in the vicinity of Bleakhouse Road) was disrupted over a relatively wide zone as a consequence of local tectonic activity. At the moment, the influence the hidden Hororata fault has on the hydraulic characteristics of the hydrogeological system that extends under Darfield and Kirwee can only be speculated. However, it is conceivable that if the fault functions almost as a no-flow hydraulic boundary for the aquifer underlying the central Canterbury Plains, then groundwater flow paths will have a strong vertical component; hence, contaminants leached from the land in the area will permeate deep below the water table, potentially contaminating the full thickness of the aquifer. Furthermore, the below-horizontal dip of the formation caused by the tectonic deformation, might amplify the vertical transport of contaminants. These factors could explain why nitrate has been detected in relatively deep groundwater up-gradient of Darfield, for example, 6 mg NO_3-N/L in SDC's 245-m deep public water-supply bore, BX22/0006, that screens below a depth of 189 m and 54 m under the water table, and 9 mg NO_3-N/L in Fonterra's 248-m deep bore L35/0884 that draws water from a depth of over 192 m and 33 m below the water table (information provided by SDC and Fonterra, respectively) (Figure 3).

Seismic surveys conducted transverse to the alluvial fan on a transect running along Bleakhouse Road have revealed a possible paleochannel of the Waimakariri River that may occupy the upper 60 m of the Quaternary gravel formation (see Figure 10.2 from Finnemore [2004]; Appendix D). Three shallow groundwater quality monitoring bores (L35/1178, L35/1179 and L35/1181) recently installed by Fonterra as part of their land-use resource consent, screen water that appears to be supported by this erosional surface. The depth to the water table in these wells is in the range of 20–58 m (bgl) and the general hydraulic gradient appears to slope towards the south-east. Two bores (L35/1182 and L35/1183) drilled west of SH1 failed to encounter water within a depth of 69 m. Based on the drill-log records of the few bores drilled below this depth (e.g. L35/0743, L35/0883 and L35/0884), it is difficult to ascertain whether this relatively shallow groundwater is a localised perched aquifer system or not, and what hydrogeological relationships it shares with conditions directly under Darfield and Kirwee. From a groundwater quality perspective, however, this question is academic since the nitrate impacts detected in the deep supply wells (eg, L35/0884 and BX22/0006) screening the series of good water-yielding gravels beds below a depth of 190 m, suggest the shallow and deeper groundwater systems are connected. The mean age of groundwater sampled from Fonterra's supply bore L35/0884 that draws water from a depth range spanning 191–248 m bgl, has been estimated to be in excess of 74 years, although it is important to recognise that this age reflects a mixed composition of old and young water.

3.3 Depth and direction of groundwater flow

3.3.1 Horizontal hydraulic gradient

Figure 3 maps groundwater piezometric levels across the top of the Canterbury Plains, which includes Darfield and Kirwee. The shallow unconfined riparian groundwater systems associated with the Waimakariri and Hawkins Rivers (at least up-gradient of Racecourse Hill) are marked by the blue symbols and contrast with the major (deep) groundwater system that underlies the plains and incorporates Darfield and Kirwee.

The piezometric contours (marked in red) in Figure 3, provided by ECan, reflect a spatial interpolation of averaged groundwater level observations evaluated in 2003, which were made at the regional scale and drew from 20 years of historic monitoring records collated from wells of varying depths. The groundwater level data suggest that a steep hydraulic gradient exists, that is, there is a high-flow potential, up-gradient and in the area of Darfield that declines in the vicinity of Kirwee. Since groundwater flow is perpendicular to the hydraulic gradient, the pattern in the contoured piezometric data also suggests that a contaminant plume migrating from Darfield would follow a south-east-to-easterly course, and a plume emanating from Kirwee would migrate almost due south. Detailed inferences from the published piezometric contours should be made with caution, however, because their accuracy is limited by the kriging method used in their generation from a relatively sparse groundwater level dataset in 2003 (Figure 3), distributed over a large regional scale. The contours shown do not incorporate any compensation for vertical piezometric gradients or physical aquifer constraints (eg, the geological boundaries between young and old alluvium, or anisotropy effects), which will in practice, control the directions in which water will actually flow.

The black contours in Figure 3 denote the topographic gradient (see Figure 2 also) and, hence, the general plane of the Waimakariri fan deposits. Assuming LSR is the main recharge mechanisms for the aquifer in this area and acknowledging the limitations in the water level contouring undertaken by ECan, the actual direction of groundwater flow, and by default the direction of contaminant plume migration, under Darfield and Kirwee might lie somewhere between the general gradient marked by black (topographic) and red (piezometric) contours mapped in Figure 3. For Darfield, this generally aligns with Telegraph Road. A plan of perceived groundwater flow paths is contained in Appendix E.

For an effective defensive groundwater quality strategy, reliable knowledge of the groundwater flow direction is required to permit accurate judgements to be made about where monitoring wells might be suitably placed. It is apparent that a reliable assessment of the groundwater flow direction at the local scale of Darfield and Kirwee is currently hampered by inaccuracies in the existing regional piezometric contour dataset. Some of this uncertainty could be reduced if a local piezometric survey was completed at a resolution commensurate with the water quality management problem being addressed, and by making use of the numerous new wells installed since the region-wide analysis that was undertaken in 2003. Surveying as many wells in the area as is practicable might be something ECan undertakes as part of their future investigation into the area.

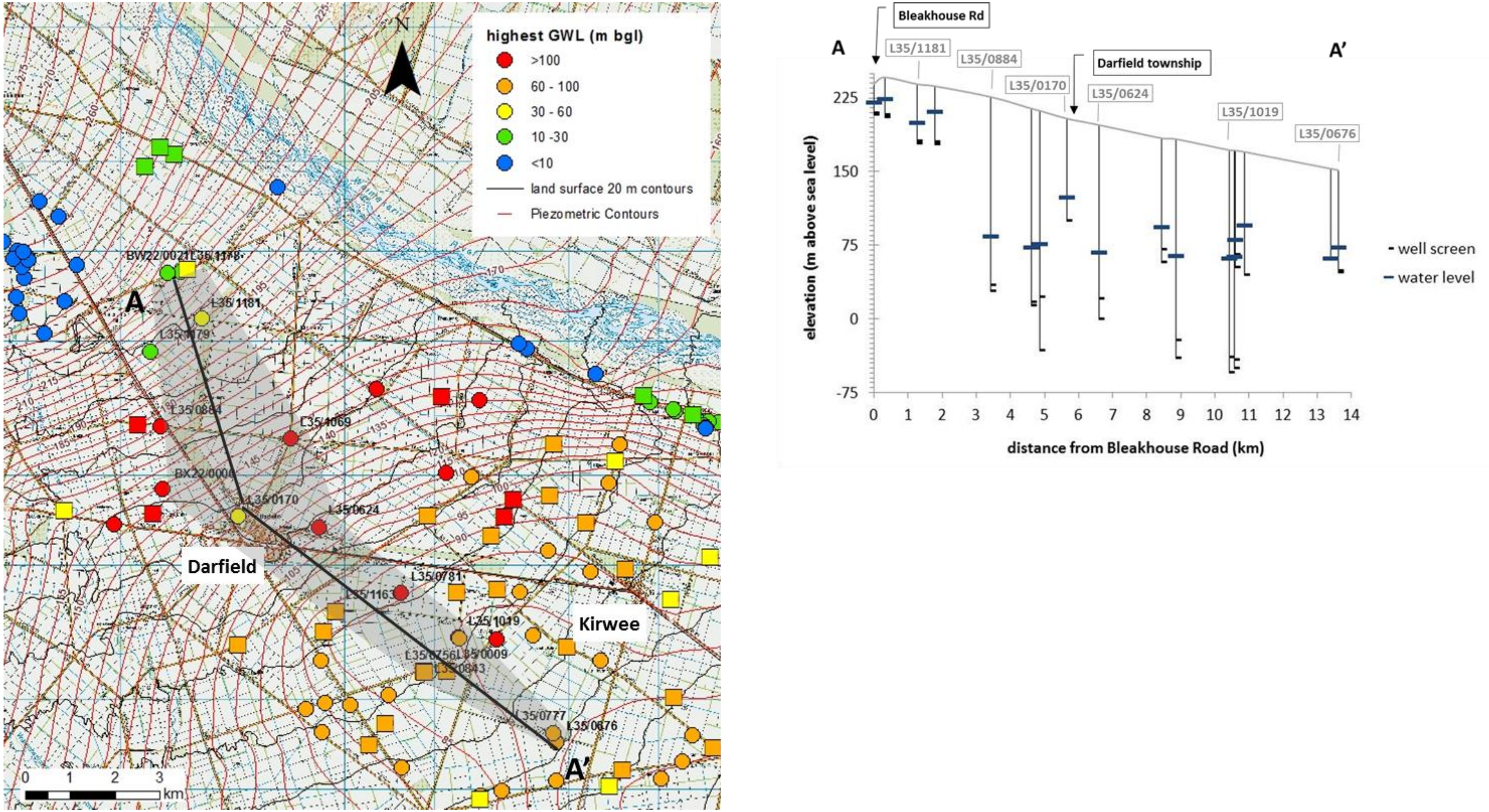

Figure 3: Shallowest groundwater levels recorded for wells in the Darfield-Kirwee area.
Note that not all wells shown are currently active. The piezometric contours are from ECan's 2003 regional dataset; the square symbols denote wells which are recorded to have been drilled and had their water levels measured before 2003.

A crude estimation (see Appendix E for calculations) has determined that the hydraulic gradient driving horizontal flow through the groundwater system under Darfield is between 0.3 percent and 0.7 percent, which is much shallower than the gradient of 1.5 percent that can be estimated from ECan's available piezometric contour data. Since groundwater flows and velocities are directly linked to the hydraulic gradient, this shallower gradient translates to the slower potential movement of groundwater than might be anticipated from references to the piezometric contours in Figure 3. This discrepancy in the potential groundwater flux suggests that the scale of the dilution effects considered by PDP (2011) in its model of the potential nitrate plume at Darfield may have been overestimated. There is little reason to suspect that the assimilative capacity of the aquifer at Darfield should be strikingly different from that at Kirwee. It is worthy to note that the potential discrepancy in hydraulic gradient estimations has no current implications on the existing groundwater monitoring strategy and/or any health risk assessment, since using a shallower gradient in the PDP (2011) contaminant transport model still suggests that that spatial extent of the nitrate plume would be unlikely to extend to the nearest water supply bore down-gradient of Darfield.

3.3.2 Depth to groundwater and vertical transport

Figure 3 includes a profile of the wells for which water level records exist along transect A-A' that starts at Bleakhouse Road and tracks under Darfield. The shallow water table at the top of the plains, as measured from Fonterra's set of water quality monitoring wells, can clearly be seen. A sudden depth change in the piezometric levels, marked by well L35/0884 is also evident. This steep piezometric gradient indicates a strong downward vertical potential for groundwater movement, a characteristic that extends under Darfield.

Based on the water level reported during the drilling of L35/0170 (an exploratory water supply bore that was commissioned by SDC in 1964) and data from bore L35/0340 located 2 km south of the town, it would appear that the water table under Darfield is approximately 80 m bgl. Most active wells in the area, however, screen the aquifer at more than 200 m bgl where better water yields are available (Figure 3; Appendix F). Piezometric levels (ie, water pressures) at that depth are generally more than 135 m bgl. The nature of the hydraulic connection between the groundwater at the shallower depth of 80 m and that associated with an apparent region of high-yielding deep gravel strata is not known and is difficult to predict from the available borelog records. However, it is clear that there is a steep vertical hydraulic gradient and, hence, the potential for contamination (eg, nitrate) entering the aquifer at the water table to permeate fairly deeply and to impact upon the deeper groundwater system. Elevated nitrate levels in water quality data from Fonterra and SDC's deep supply bores tend to suggest some form of active vertical connection.

Exactly where, how and at what rate contamination is transmitted between the shallow groundwater (at a depth of ~80 m) and deeper groundwater (at >135 m deep) is difficult to quantify. From the age of the groundwater in Fonterra's supply well (L35/0884)—the mean age of which has been estimated at 74 years, if not closer to 130 years, and which incorporates vertical transport time through the unsaturated zone—one might presume decades. Similarly, the mean age of water sampled from SDC's bore (L35/0980) screening the aquifer at a depth of between 191.5 m and 243.5 m on Bangor Road has been interpreted as 44 years' old, based on SF_6 isotope analyses, but is more likely to be in the order of 106 years' old if it is judged based on other isotope signatures. It is useful to recognise that the groundwater samples from these wells for which ages have been determined, comprise a mix of groundwater abstracted from different depths and, therefore, of different ages. The inferred mean age for the sampled water has been based on a number of unverified assumptions made about the amount of mixed water in the sample.

The vadose zone under Kirwee is slightly thinner than that encountered at Darfield, but it is still relatively thick and is generally in excess of 65 m. Using data about water levels from records for ECan's closest monitoring well (L35/0163; located 3 km north of Kirwee and closer to the Waimakariri River) that span 61 years, the water table fluctuates +/−20 m about the 65 m mark, approximately, as a response to large-scale seasonal variations. Similar, if not larger fluctuations might be presumed to occur under Darfield, given its position further up the plains. All wells in the Kirwee area screen the aquifer below a depth of 104 m. Isotopic dating analyses have estimated the mean age of groundwater at this depth to be in the region of 115–120 years (Stewart et al 2002).

What does this mean for septic tank contamination emanating from Darfield-Kirwee? Considering all wells active in the Darfield/Kirwee area screen the aquifer below a depth of 100 m and not across the water table, it is reasonable to suspect that the bulk of the water currently being drawn from active wells is of a similar mean age to that which has been dated (ie, in the region of 75–120 years old). If correct, this implies that nitrate impacts detected in the wells largely reflect historic land uses and that they do not necessarily reflect current land-use activities. Furthermore, one can presume, based on simple mass balance considerations that nitrate concentrations in the youngest water concentrated near the water table must be substantially larger than those determined at depth, since inferred groundwater ages reflect average ages based on mixed water samples drawn across a finite depth range that covers an age spectrum.

Given the general age of the water in the aquifer sections from which groundwater is currently pumped in the Darfield-Kirwee area, it could be presumed that there is a low chance of pathogenic microorganisms derived from septic tank wastes impacting on any of the existing water supplies, unless the hydraulic integrity of the aquifer system is breached locally, for example, by the installation of a bore.

Groundwater at the water table will be younger than that sampled via existing active wells, all of which screen at least 35 m beneath the water table. Although no data are available that describe travel times for contaminants to reach the water table, it seems improbable, but not necessarily impossible, given the 65–80 m vertical distance contaminants must navigate through weathered geological strata, that under natural conditions, the time would be less than the order of months, if not years. Certainly, Sinton et al (2005) estimated the vertical transport rate of effluent through alluvial gravels at Templeton to be as high as 15.7 m/d, but this was under conditions of surface flooding. Close (2010) references work in which vertical transport velocities were measured at 20–60 m/d under conditions of continuous flow through similar media on the Heretaunga Plains. These fast drainage velocities were determined over relatively small distances (3–6 m) that are unrepresentative of the large-scale subsurface system under Darfield-Kirwee. The effective vertical transport velocities under Darfield-Kirwee are likely to be much slower owing to the complex lithological strata representing tens of thousands of years of sediment deposition that must be infiltrated.

It should be noted that, sometimes, the boreholes themselves have compromised the hydraulic integrity of the aquifer and reduced the degree of confinement offered by the low-permeable clayey and silty lithofacies that provide the natural hydraulic barrier between shallow and deep water-bearing strata. Although not directly relevant to septic tank operations in Darfield-Kirwee, the records for well L35/0277 (included in Appendix B) illustrate a severe problem where the abandoned well, constructed with multiple screened sections, acts as an open conduit for shallow groundwater draining to deep groundwater.

A more pervasive, but less obvious problem is the potential migration of contaminants down the sidewalls of an installed well via the annulus created from the drilling process—a phenomenon known as skin effects. A high potential exists for skin effects to occur in the Canterbury situation, because the method routinely used to install a modern water well is to drill a borehole using the air-flush rotary method that drives the steel well casing directly into the alluvial gravel aquifer as drilling progresses. Air-flush rotary drilling is an efficient, yet particularly aggressive, drilling method that locally disrupts the aquifer formation, increasing the potential for vertical preferential flow. At the bore termination depth, the well casing is either slotted in situ or a leader pipe that constitutes the well screen is protracted from the open base of the hole. A consequence of using this method is that there is no opportunity to insert grout into any annulus that may have formed along the well walls during the drilling process.

The issue of man-made preferential vertical flow is not perceived to be a major problem for septic tank waste at Darfield, given there are so few bores in the vicinity of the township. Aside from two redundant SDC bores, L35/0170 (103.6 m deep) and L35/0624 (199 m deep), the closest active bore, L35/1163, is over 1 km down-gradient of the town. There are considerably more bores drilled in close vicinity to Kirwee, however, which increases the likelihood of man-made preferential flow pathways arising.

Interestingly, the public water supply well (L35/0191) located in the centre of Kirwee town, which from a health risk perspective is conceivably the most vulnerable well in the area, was installed using cable percussion drilling, which is a less aggressive and invasive method than air-flush rotary drilling. Given the pollution hazard presented from the effluent loads generated by Darfield and Kirwee towns, the risk of involuntarily creating an artificial vertical pathway by installing a well should be considered for any proposed new wells in the area, including any water quality monitoring wells.

The movement of contaminants in the aquifer will potentially be influenced by pumped groundwater abstraction. In the Darfield-Kirwee setting where the groundwater resource is likely governed mainly by LSR and strong vertical pressure gradients that exist naturally, it is conceivable that abstraction of groundwater from deep in the alluvial gravel aquifer system could, over the long term, promote the vertical migration of contamination in the saturated zone. Assuming that the geological anticline at Racecourse Hill effectively represents the upper limit of the aquifer and that there are no river recharge effects from either the Hawkins or Waimakariri River systems, then consented groundwater takes in the Darfield-Kirwee area equate to approximately 75 percent, (and quite possibly over 100 percent, depending upon which LSR estimates are correct) of the total effective annual rainfall (see Appendix G for calculations). This is a relatively large potential hydraulic stress on the natural condition of the groundwater system and aside from steadily drawing water and contaminants down through the saturated water column, water abstraction also slows the passage of groundwater discharging from the aquifer, effectively reducing the effects of dilution upon which a system like that underlying the Canterbury Plains relies for its assimilation of nitrate contamination. In an extreme situation, water could be recycled within the Darfield-Kirwee groundwater system, leading to a progressive increase in nitrate mass in the area.

The effects of pumped abstraction on the disturbance of natural groundwater flowpaths and the migration of land-based contamination have not been studied in the Canterbury region. Mandatory metering of groundwater takes has only started recently in Canterbury, but it will permit an improved assessment of the effective hydraulic stresses imposed on the aquifer underlying the central Canterbury Plains in the future.

3.4 Groundwater quality

Much work has already been published on groundwater quality in the local Darfield-Kirwee area and this information can be found in the general monitoring survey reports commissioned by SDC (SKM 2012; Liquid Earth 2012). These reports and particularly the report by Liquid Earth (2012), which contains the most comprehensive data analysis, describe in detail the groundwater quality determined from SDC's existing array of monitoring wells. The Liquid Earth (2012) report states that on the whole, the surveyed groundwater quality at Darfield-Kirwee is of high quality, although this is a somewhat subjective opinion considering groundwater from almost half the locations sampled had nitrate concentrations that transgressed the 50 percent MAV for drinking-water.

3.4.1 Summary of microbial impacts from Selwyn District Council's survey wells

When ECan's water quality data are collated with SDC's water quality survey results, it is apparent that *E. coli* has been detected at two well locations, L35/0876 and L35/0767, both of which are located on the outskirts of Kirwee and are installed at similar depths of approximately 125 m (Figure 4).

According to SDC's survey reports, the positive *E. coli* detections at L35/0767 have been interpreted as relating to a very localised impact, which appears to be true. Indeed, there are no records of septic tanks within the vicinity of the well, which is used for irrigation and is located on a farm that is situated west of Kirwee. Scrutiny of the water chemistry analysed in January 2012 (Appendix A in Liquid Earth's [2012] report), shows that relative to other well waters sampled, the groundwater drawn from L35/0767 that corresponds to a sample depth of 119.5–125.5 m bgl (ie, >30 m below the water table), has high levels of sodium (12.5 mg/L), chloride (13.3 mg/L), total ions, iron (10.9 mg/L), magnesium (4 mg/L), nitrate (9.9 mg NO_3^-N /L) and zinc (0.23 mg/L), and a trace amount of ammonium that is close to the analytical method detection limit of 0.01 mg NH_4^-N/L. Aerial photographs suggest that the well is located in the centre of a farm yard, surrounded by galvanised buildings. The presence of zinc in the groundwater suggests that stormwater run-off from the numerous buildings might be implicated in the water quality results, although some form of animal waste provides a more likely explanation for the source of the impact, given the elevated ion, nitrate, ammonium and *E. coli* levels in the water. Septic tanks may not be implicated in the water quality results for well L35/0764, but the findings illustrate the fact that the groundwater beneath Kirwee, despite its depth, is vulnerable to contamination from land- and waste-management practices on the surface, including contamination by microbiological organisms.

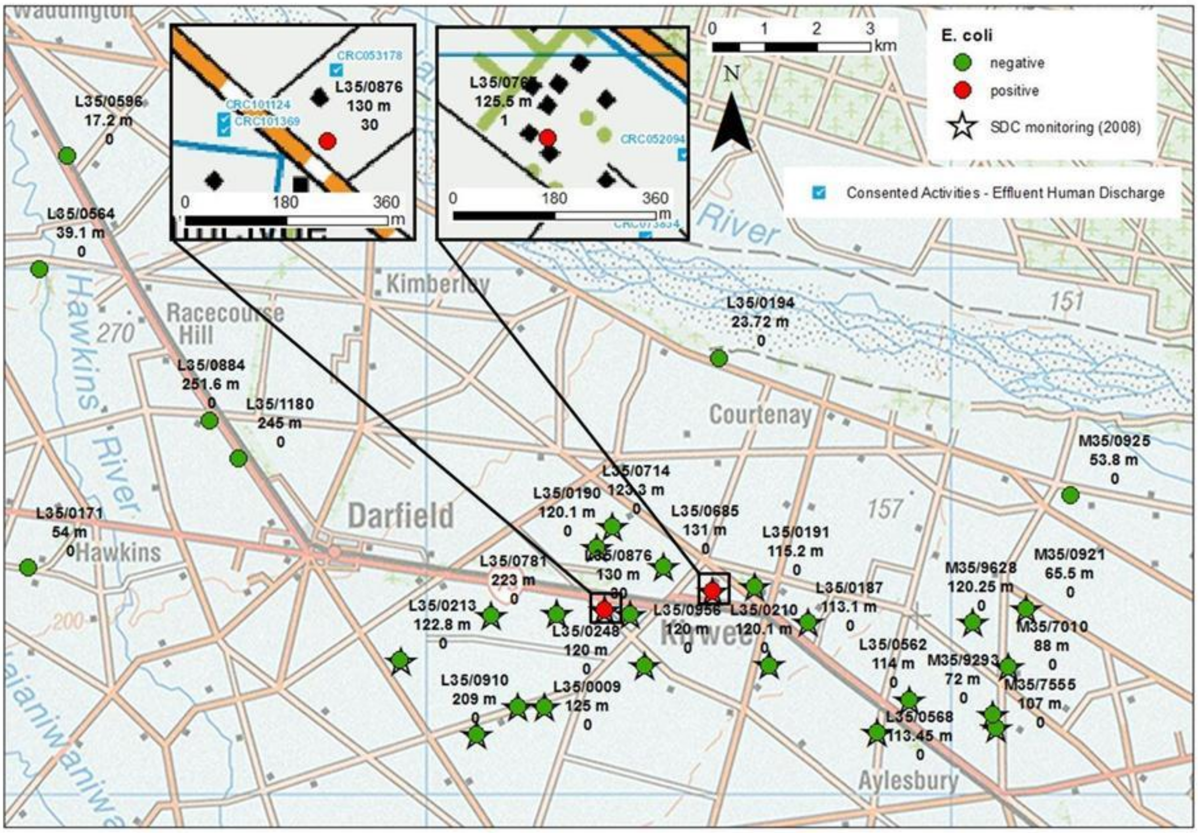

Figure 4: Maximum *Escherichia coli* counts in groundwater samples from the study area.

The labels denote the identification of the wells, the well depths (not screen depths) (m bgl) and the maximum *E. coli* counts (cfu/100 mL). Inset maps show consents to dispose human effluent in the vicinities of wells L35/0876 and L35/0767 where *E. coli* has been detected. The star symbols mark the monitoring wells used in Selwyn District Council’s 2008 water quality survey (SKM 2012). bgl, below ground level; cfu, colony-forming unit.

In relation to well L35/0876, which is a 130-m deep domestic water supply well located 3 km west of Kirwee, *E. coli* was detected only once in December 2008. The well was resampled one week later and no indicator organisms were detected. This result and subsequent non-detections determined in later surveys, suggest that the solitary detection was a consequence of sample contamination or a well-head security issue that has not been repeated. Interestingly, ECan's resource consents database records three consents to discharge human effluent from septic tanks within a distance of 130–185 m of the well, the closest of which is marked as up-gradient of the well (Figure 4 inset).

E. coli has never been detected in water sampled from wells L35/0187 or L35/0210, which of all the wells surveyed for water quality impacts, are the two that are closest to and are down-gradient of the cluster of septic tanks at Kirwee. Each well is over 500 m down-gradient from the nearest possible septic tank pollution source, both screen more than 40 m below the water table and are used for irrigation (Figure 4).

3.4.2 Summary of nitrate impacts from Selwyn District Council's survey wells

Most of the nitrate transgressions in the Darfield-Kirwee groundwater detected during SDC's water quality surveys, have so far been concentrated west and north of Kirwee and directly east of Darfield. Based on perceived groundwater flow paths, one can assume these measured nitrate impacts are not related to the clusters of septic tanks in the area (Figure 5), rather they reflect diffuse agricultural land-use impacts. Nitrogen-15 isotope data collected for the 2007 water quality survey largely support this conclusion (SKM 2012; Liquid Earth 2012).

Between SDC's surveys undertaken in 2008 and 2009, however, nitrate was detected at a level that exceeded the drinking-water MAV (ie, >11.3 mg NO_3-N/L) in one well (L35/0009) that is 125 m deep and located approximately 4.3 km south-west (down-gradient) of Darfield (see Figure 5). Since well-screen data have not been recorded for this well, it is impossible to determine the exact depth from which the impacted groundwater was sampled, yet the water level of 75.2 m bgl measured in this well suggests that it taps a truly unconfined section of the aquifer. More significantly, the nitrate impacts detected in this well in 2007, reported positive for nitrogen sourced from animal or human waste, rather than soil nitrogen mineralisation, based on the $^{15}N\text{-}NO_3$ isotope signature. SDC's most recent water quality monitoring survey undertaken in 2012, showed the concentration of groundwater nitrate sampled from well L35/0009 was 4.7 mg NO_3-N/L, but records in ECan's SQUALARC database suggest it is not uncommon for nitrate at this location to be above or close to the drinking-water MAV. It is not possible to say with any confidence whether the nitrate impacts repeatedly detected at L35/0009 are in any way related to the septic tank operations in Darfield, given the limited data available. Certainly, of the wells SDC use in their survey, L35/009 is on the general path that a contaminant plume emanating from Darfield town may take (see Appendix E), but the well is very far (5 km down-gradient) from the town. Aside from the nitrogen-15 evidence, there is no evidence in the water chemistry data that indicates that the groundwater at L35/0009 is tainted by effluent from septic tanks. The limitations associated with using conventional water quality indicators to ascertain septic tank impacts in the Darfield-Kirwee environment are discussed further in the next section.

Liquid Earth (2012) reports that an increasing trend in nitrate concentrations is detectable in many bores, noticeably in those to the north-west of Kirwee, although a decrease in nitrate levels relative to the previous (2011) survey was largely detected south-east of Darfield. The temporal variance detected in the nitrate data from the Darfield-Kirwee area, to date, is comparable with the scale widely considered to reflect natural seasonal variations.

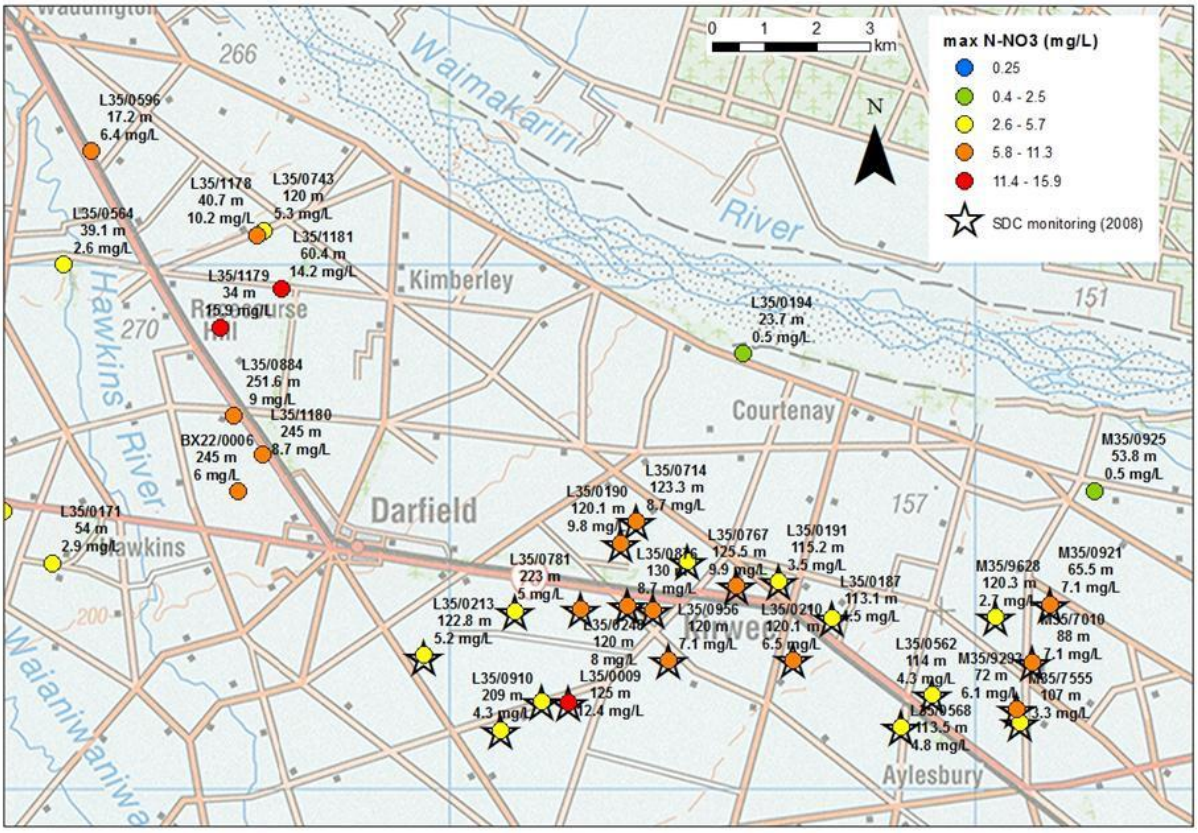

Figure 5: Maximum nitrate concentrations in groundwater samples from the study area.

The labels denote well depths (m bgl) and nitrate concentrations. See Table 3 for the significance of the concentration intervals applied in the legend. The star symbols mark the monitoring wells used in Selwyn District Council's 2008 water quality survey. bgl, below ground level.

3.4.3 Region-wide groundwater quality issues

Having ascertained that the SDC water quality monitoring data do not provide clear evidence of groundwater quality impacts that can be traced back to septic tanks in Darfield and Kirwee, this section presents and discusses the chemical characteristics of the regional groundwater system. This is intended to contextualise the scale of the groundwater-nitrate problem in the Darfield-Kirwee area to which wastewater disposal practices at Darfield and Kirwee contribute, and to highlight limitations in the current water quality analyses applied to detect septic tank effluent impacts, given the nature of the regional water chemistry.

Figure 6 maps the general water type determined from major ion chemistry for the monitoring wells utilised by SDC in their groundwater quality survey, and provides an analysis of the wells in the broader geographic area. The Stiff plots used in Figure 6 contain the same water chemistry information as that contained in the Piper diagrams in SDC's survey reports (SKM 2012; Liquid Earth 2012), but they additionally provide for geospatial representation. The Stiff polygon itself graphs the relative ion composition of water (in units of meq/L), with cations plotted on the left and anions plotted on the right (Figure 6). Although no scale is provided for the Stiff plots shown in Figure 6, the symbols are scaled proportional to their ion content, hence displaying the relative differences in groundwater chemistry across the area.

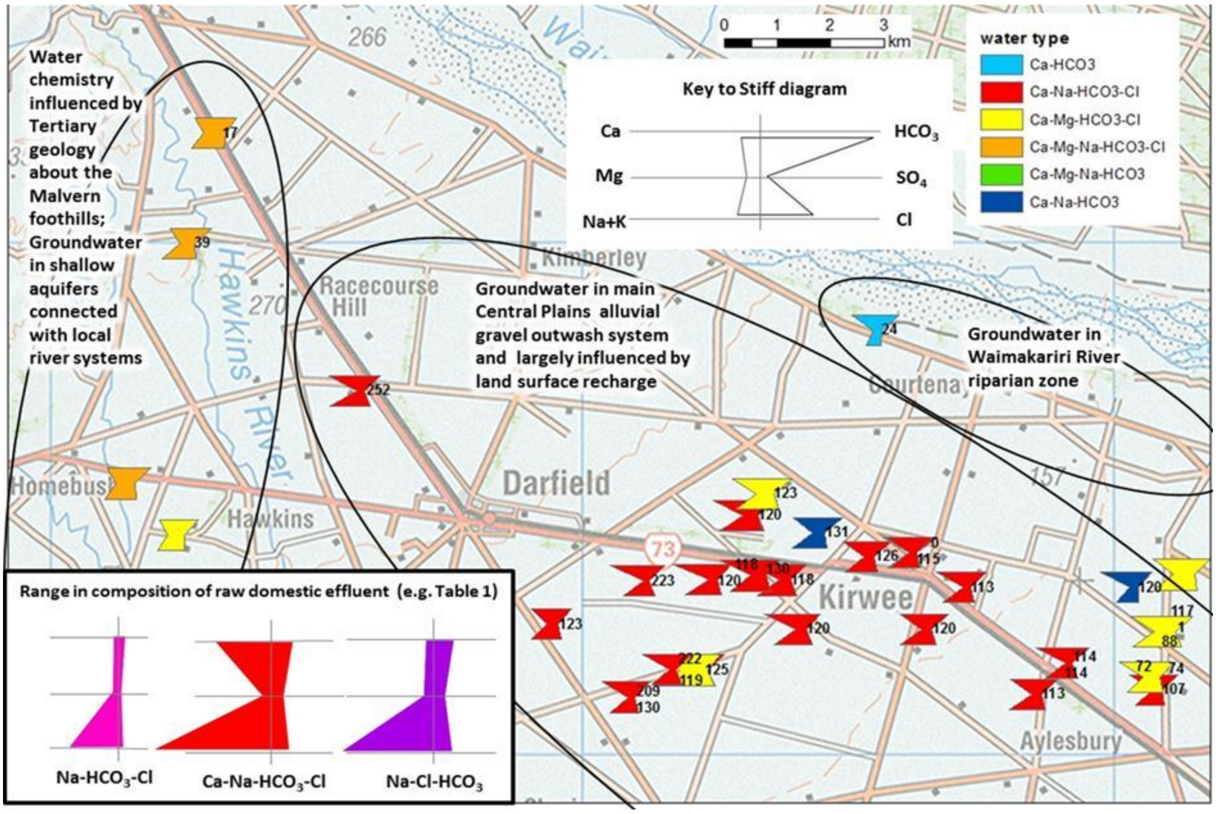

Figure 6: The major ion compositions of groundwater samples from the study area for which basic chemistry data are available.
Numbers denote the well depths (m bgl) from which the samples were collected. bgl, below ground level.

The mineralogy of greywacke geology determines that the ion chemistry of the groundwater underlying the Canterbury Plains is dominated by calcium bicarbonate ($Ca-HCO_3$-type water, denoted by the blue shaded Stiff symbol in Figure 6). Variations from the $Ca-HCO_3$ signature tend to be largely attributed to chemicals that have leached through the soil zone in recharge water or to direct anthropogenic impacts, including waste effluent disposal. The mixed-type $Ca-Na-HCO_3-Cl$ and $Ca-Mg-HCO_3-Cl$ waters are symbolic of the groundwater underlying the Canterbury Plains that is influenced by LSR, with the sodium, magnesium and chloride originating from soil mineralisation processes, effluent and fertilizer applications, and so on.

At the bottom of Figure 6, the Stiff plots for domestic wastewater are shown as a guide and these are based on typical compositions reported in the literature (see Table 1). A consistent feature of all three possible signatures is the high relative sodium and chloride content. A problem encountered when attempting to trace septic tank effluent impacts in Darfield-Kirwee based on basic water chemistry ion composition, arises from the fact that sodium and chloride tend to be the major ions leached from general agricultural land-use practices. It is therefore feasible that beyond the core of an effluent plume, chemical indicators will be unidentifiable from those expressed by the regional groundwater chemistry.

Further research is required to develop a reliable (sensitive) forensic method that can discriminate wastewater-effluent impacts from agricultural land-use impacts, based on the measurement of basic water chemical determinands and multivariate analysis. Work has been carried out to distinguish between different effluent sources such as human, cattle, sheep and birds using a variety of chemical, biochemical and microbial techniques (Devane et al 2006), but the parameters used in these assays tend to be at trace levels in groundwater systems, particularly deep groundwater systems, and often cannot be used for this purpose.

Figures 4, 5 and 6 clearly show that a void in water quality knowledge exists for the Darfield area. This is attributed to the fact that there are few water wells north of Darfield from which groundwater samples can be collected and also due to the influences of general land use activities in the area. The scarcity of water wells reflects the low transmissivity of the outwash gravels aquifer in the first 150 m of the formation. The concentration intervals applied to Figure 5 have some generalised significance at the national scale that is explained in Table 3.

Table 3: Nitrate indicator values.

Groundwater nitrate concentration (mg NO_3-N/L)	Significance	Reference
<0.25	Groundwater recharge prior to the start of low-intensity land use around 1880	Morgenstern and Daughney (2012)
0.25–2.5	Low-intensity land use (1880–1955)	
>2.5	High-intensity land use (post 1955)	
5.65	50% of the drinking-water MAV, which is a drinking-water quality transgression	MoH (2008)
11.3	Drinking-water MAV; do not exceed limit in CLWRP	

MAV, maximum acceptable value; CLWRP, Canterbury Land and Water Regional Plan

The distribution of measured groundwater nitrate concentrations in Figure 5 clearly shows that the regional groundwater system is extensively impacted by nitrate as a consequence of regional land use, regardless of wastewater disposal practices in Darfield and Kirwee. Groundwater nitrate levels are significantly elevated hydraulically up-gradient of Darfield, particularly in the unconfined, relatively shallow groundwater system in the area of Bleakhouse Road, which is monitored by Fonterra, where a maximum nitrate concentration of 15.9 mg NO_3-N/L has been detected in a well screening at 31–34 m bgl. Before Fonterra occupied this land, it was used mainly for crop farming and low-intensity sheep grazing (Pat Morrison, personal communication, December 2013). The significant nitrate impacts at this location are therefore believed to derive from historic crop farming activities. Groundwater nitrate impacts of this magnitude are not unexpected for land used for crop farming (see Table 2), particularly since winter-fallow practices were exercised. The shallow nitrate impacts can be extrapolated to the deep groundwater via the detections made in the supply bores that are over 200 m deep and are operated by Fonterra and SDC, where nitrate levels of up to 9 mg NO_3-N/L breach the NZ drinking-water transgression limit of 5.65 mg NO_3-N/L. Given the hydrogeological conditions at Darfield, it is likely these measured nitrate impacts, which are attributed to diffuse pollution from agricultural land use, extend under Darfield and follow the general flow path sketched in Appendix E. Based on the quality of the water in the regional environment at Darfield-Kirwee, a strong argument can be made for the towns of Darfield and Kirwee to be self-sustainable entities with respect to local assimilation of nitrogen loads by conforming with the housing-density thresholds identified in section 2, since the capacity of the regional groundwater system to assimilate nitrate impacts appears to be limited.

The magnitude of groundwater nitrate impacts from agricultural land uses obfuscates the measurement of nitrate impacts from wastewater effluent at Darfield. Consequently, nitrate is not a good chemical indicator of septic tank impacts in Darfield and Kirwee and it needs to be complemented with nitrogen-15 isotope data and possibly other parameters. The physical limitations in the current groundwater quality monitoring well array that compound the problem are discussed in the next section.

4. CRITIQUE OF SELWYN DISTRICT COUNCIL’S GROUNDWATER QUALITY MONITORING NETWORK

The functional role of the water quality monitoring conducted by SDC should be given some more consideration, and a consensus should be reached about whether the focus of the monitoring is to protect environmental receptors (ie, drinking-water supply wells) or whether its aim is to ascertain the magnitude of the impacts of on-site wastewater operations on the groundwater system. In its current form, the water quality surveillance programme contributes some information to the former objective.

According to the survey reports (SKM 2012; Liquid Earth 2012), the objective of the groundwater monitoring programme operated by SDC is to determine whether existing wastewater disposal practices in Darfield and Kirwee are impacting on down-gradient groundwater quality. Having reviewed the hydrogeological conditions at Darfield-Kirwee, ESR considers that the current network of monitoring wells that SDC relies on to monitor such impacts is unsuitable for this purpose, although it is useful in other aspects.

The main faults with the water quality monitoring network are the spatial location of the wells and the depths from which the wells are sampled in relation to the contaminant sources. There are further limitations to the programme that are associated with the chemical analytical methods currently employed and the lack of knowledge about the true composition of the effluent and its chemical signature relative to the receiving groundwater resource.

The array of wells SDC currently uses for their water quality monitoring utilises most of the existing well infrastructure in the area (see Appendix H). Since these are production wells, none screen at or close to the water table, so the status of the water quality does not represent the worst condition of the aquifer and the position at which any wastewater disposal impacts would be greatest. The water quality monitoring does, however, represent the quality of the groundwater resource that is utilised and to which humans are exposed.

Several wells in the area are not included in the current surveillance programme that despite not screening at the water table, could add value to the dataset if incorporated into the programme, at Darfield these are: L35/1163 (126-m deep irrigation well), L35/1164 (126-m deep irrigation well) and L35/0598 (125-m deep redundant domestic water supply well), and at Kirwee these are: L35/0818 (120-m deep domestic water supply well), L35/0185 (111-m deep irrigation well), L35/0561 (121-m deep irrigation well), L35/0832 (118-m deep irrigation well) and L35/0870 (114-m deep domestic water supply well). These wells are marked in Figures 7 and 8.

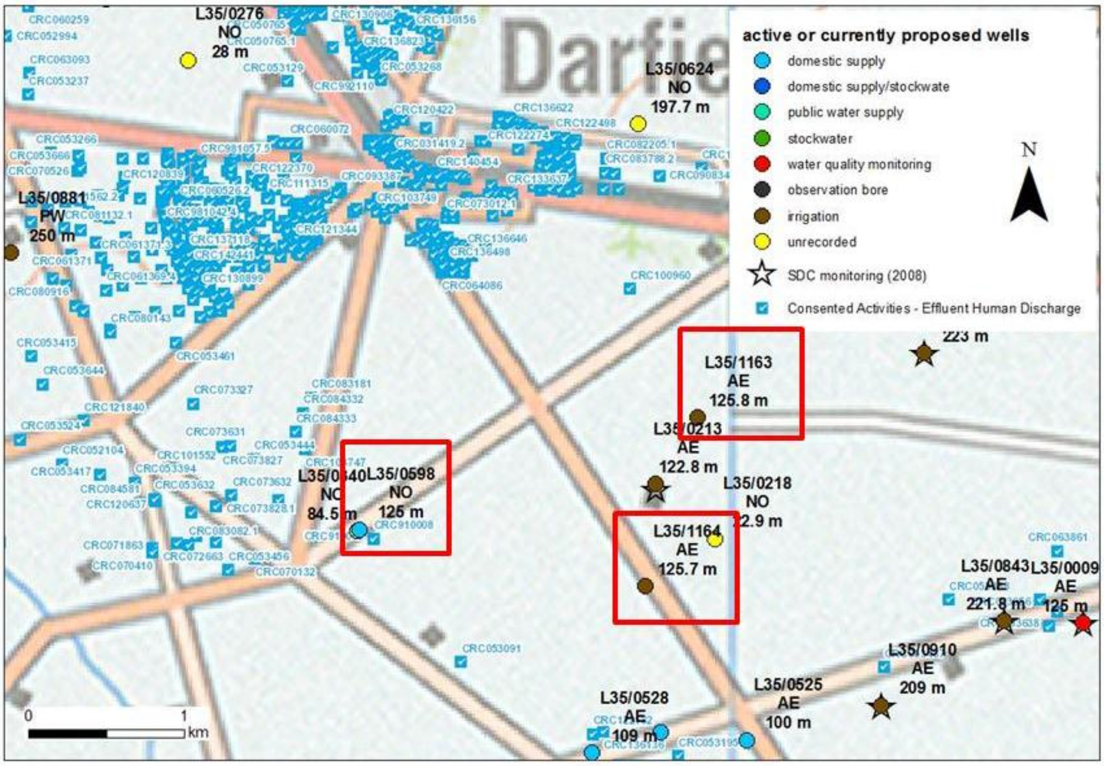

Figure 7: Wells down-gradient of Darfield town.
The red box identifies wells, which, if sampled, could add value to Selwyn District Council's water quality surveillance programme.

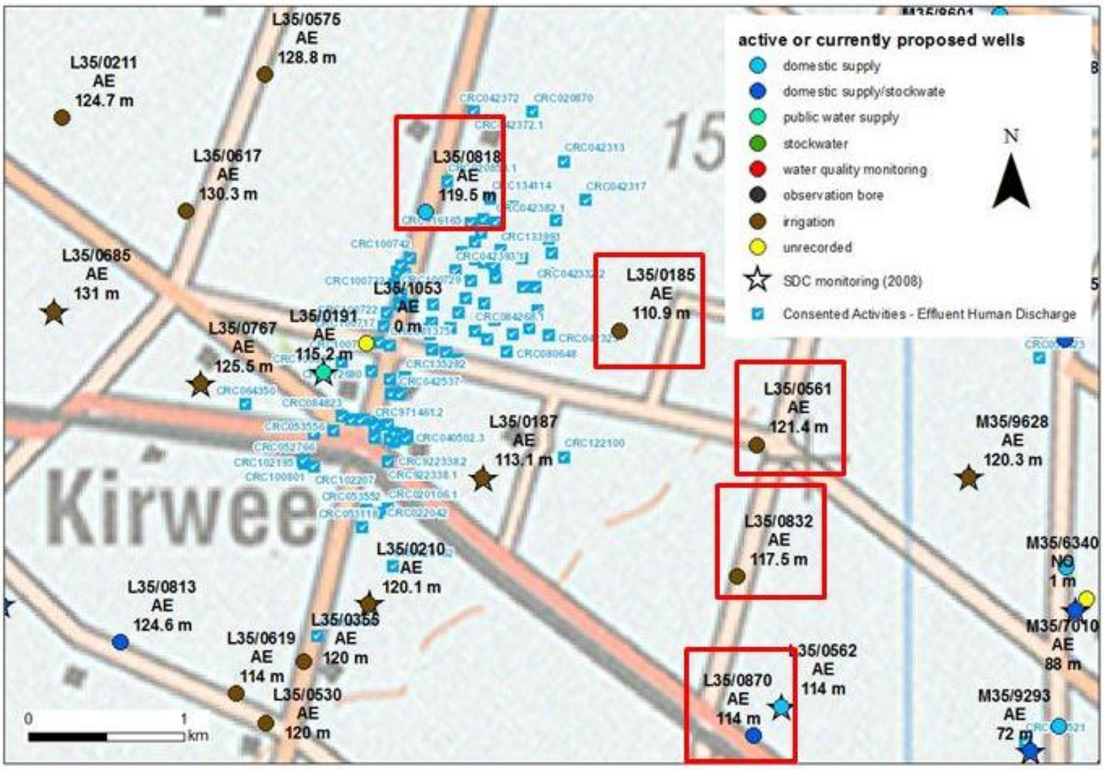

Figure 8: Wells down-gradient of Kirwee town.
The red box identifies wells, which, if sampled, could add value to Selwyn District Council 's water quality survey surveillance programme.

A lot of redundancy exists in the current set of wells surveyed by SDC. It is good practice to survey impacts up-gradient of a point-pollution source to characterise the background condition, yet a disproportionate number of the wells are located either up-gradient of the septic tank clusters at Darfield and Kirwee (eg, L35/0884, L35/0980, L35/1173, L35/0729, L35/0714, L35/0190, L35/0767, L35/0191) or off the general migration paths the effluent is perceived to take from the towns (eg, L35/0876, L35/0528, L35/0248, M35/0921, M35/9628, M35/7010) (see Appendix H). Only a fraction of the aforementioned wells would need be included in surveys characterising impacts from the septic tank clusters at Darfield-Kirwee.

Appendix H ranks the wells used in SDC's water quality monitoring surveys in terms of their perceived use as observation wells for assessing potential groundwater impacts from the septic tank clusters.

A piezometric survey from which more reliable local hydraulic gradients might be determined, would be a useful addition to the current knowledge of the Darfield-Kirwee groundwater environment, and would improve predictions of the directions in which contaminant plumes are thought to travel. This would enable a better technical assessment to be made of the usefulness of the current and future monitoring network and would identify gaps in the monitoring programme.

Currently, no robust observational data are available from which the true composition of the septic tank effluent emanating from the towns can be determined. This complicates the interpretation of the water quality results and is part of the reason why the current water quality assessments rely heavily on hypothesised outcomes.

Obvious technical benefits are to be gained from installing fit for purpose monitoring wells at strategic locations and depths, for example, closer to the septic tank clusters than the current wells are positioned. However, any advantages would be strongly offset by the cost of installing the wells and by the risk posed by drilling boreholes close to the pollutant source that would further compromise the aquifer system's hydraulic integrity, and potentially introduce new preferential vertical flow pathways by which contaminants can migrate. A pragmatic approach would be to focus on securing the protection of the existing groundwater users, rather than investing resources to investigate the exact spatial distribution of contamination emanating from the townships. Furthermore, given the temporal variability of the nitrate impacts and groundwater hydraulics, a monitoring network of fewer wells sampled more frequently than the current annual survey may serve this purpose.

As mentioned previously, information about the true chemical composition of the septic tank effluent discharged from Darfield and Kirwee would help to refine the interpretation of the water quality data generated by the surveys. The standard suite of chemical analyses currently performed for SDC's water quality survey is a pragmatic and cost-effective means of screening for effluent impacts, albeit relatively insensitive and subject to many limitations.

Nitrogen-15 isotope analysis is useful for distinguishing between nitrate impacts sourced from effluent from those derived from soil mineralisation processes. More meaningful interpretations can be achieved when nitrogen-15 and oxygen-18 analyses are applied together. An evaluation of the nitrogen-15 isotope signatures for groundwater under Darfield and Kirwee was completed as part of the water quality survey in 2007. Although a relatively expensive analytical test and unable to verify whether the effluent originated from human or animal waste, it is believed that adding nitrogen-15 isotope analysis, preferably in conjunction with oxygen-18 analysis, as a routine test to future Darfield-Kirwee water quality monitoring programmes would add significant value to the data.

Where isotope results indicate potential effluent impacts, it is suggested that it would be good practice to constrain interpretations with other lines of evidence of wastewater effluent pollution. This might include fluorescent whitening agent analysis and caffeine analysis, which are analytes that have been used with mixed success in groundwater investigations (Close et al 1989; Seiler et al 1999). The presence of either of these tracers in groundwater would unequivocally prove domestic wastewater effluent impacts, but given that fluorescent whitening agents and caffeine are organic compounds that are susceptible to microbial degradation, neither are particularly robust tracers and it would be surprising if they persisted in the Darfield-Kirwee setting. Where *E. coli* is positively detected, molecular faecal source tracking methods should be employed to identify whether the impacts relate to human effluent or animal wastes.

A useful addition to SDC’s survey data would be to determine the age of the groundwater at the sampling points. Where feasible, an evaluation of groundwater age close to the water table would be very informative and would allow for some understanding of the time scale for contaminant transport through the vadose zone in the Darfield-Kirwee area. Ideally, wells with long-screened intervals should be omitted from the monitoring network since they provide dilute, ambiguous water quality data. Any wells used in water quality surveillance for which no well screen information is available, should be physically inspected using a down-hole camera to determine the depth from which the well draws water.

5. SUMMARY

5.1 The current situation

The resident populations of Darfield and Kirwee have increased significantly since the Christchurch earthquakes in 2011. The changes in the towns' population densities, however, are less dramatic and the best estimates are that the current densities are 5.7 people/ha in Darfield and 3.7 people/ha in Kirwee. Darfield and Kirwee do not have reticulated sewage systems, instead the towns contain clusters of on-site wastewater treatment systems. These present a potential environmental hazard to the underlying unconfined aquifer and, by default, they pose a potential human health hazard, since the regional groundwater is heavily utilised by the agricultural industry and as a potable drinking-water supply.

The long-term sustainability of on-site wastewater treatment operations in the Darfield-Kirwee area has been the topic of a long-running debate between CPH and SDC. To inform the debate, ESR has technically assessed the vulnerability of the groundwater to impacts from the clusters of septic tanks in the Darfield and Kirwee townships. The work complements a previous water quality assessment undertaken by PDP (2011) for SDC, and it critiques the usefulness of the existing groundwater quality monitoring surveys performed by SDC.

5.2 Contaminants of concern

Nitrate-nitrogen and microbial pathogens are the main contaminants of concern pertaining to on-site wastewater treatment operations at Darfield and Kirwee. All of the nitrogen in the effluent discharged from Darfield and Kirwee is effectively converted to nitrate that is not susceptible to any natural attenuation in the carbon-limited, aerobic, alluvial gravel outwash aquifer. The MAV for nitrate in drinking-water is 50 mg/L (ie, 11.3 mg NO_3-N/L), which also serves as the target, 'nowhere will exceed', groundwater nitrate concentration prescribed in the proposed CLWRP. Furthermore, the CLWRP anticipates that average nitrate concentrations in the Canterbury aquifers will be sustained at 50 percent of the drinking-water MAV.

To limit the risk of microbial pathogenic disease, the CLWRP proposes that *E. coli* will not exceed 1 cfu/100 mL in Canterbury's groundwater, which is consistent with the MAV for *E. coli* in the Drinking-Water Standards for New Zealand (MoH 2008). A common presumption has been that microbial contaminants will be effectively attenuated as the septic tank effluent infiltrates through the thick vadose zone to the water table beneath Darfield and Kirwee. Although this perception is likely to hold true, *E. coli* has been detected in more than one well, screening more than 30 m below the water table in the Kirwee area. These observations, taken together with recently published research results from the USA that report rapid virus transport in a supposedly confined sandstone aquifer system (Bradbury et al 2013), suggest the groundwater underlying Darfield and Kirwee is more susceptible to microbial pathogenic impacts sourced from septic effluent than might have previously been considered. It is important to recognise, however, that the risk to human health depends on the contaminant impacts experienced at drinking-water supply wells, rather than their impacts on the aquifer in general.

5.3 Hydrogeological setting and groundwater vulnerability at Darfield and Kirwee

The groundwater resource in the Darfield-Kirwee area comprises the upper portion of the regional aquifer system underlying the central Canterbury Plains. River recharge is a major component of the aquifer's water balance, yet there are no obvious signs that a significant flux of water from either the Waimakariri or Hawkins Rivers occurs up-gradient of Darfield and Kirwee. Instead, it appears that the groundwater system under Darfield and Kirwee is mainly driven by LSR. The absence of any significant local river recharge inputs has implications for water quality, because it restricts the aquifer's natural capacity to assimilate contaminants, notably nitrate, from land-based activities through dilution.

Hydrogeological conditions under Darfield and Kirwee are characterised by a strong natural vertical downward hydraulic gradient. Tectonic deformation of the alluvial gravel aquifer associated with an extension of the Hororata geological fault could promote vertical flow in the aquifer north of Darfield. It is also possible that consented groundwater abstractions from deep wells pumping water from more than 200 m bgl will contribute to the steady drawdown of surface-derived contaminants through the saturated thickness of the aquifer. Furthermore, it is suspected that the potential hydraulic stresses from pumped abstractions (which are estimated to be close to 75% of the natural LSR) may be large enough to upset the natural water balance of the system. Of concern is that if the natural groundwater discharge is reduced by pumped abstractions, there is a risk that the mass of nitrate in the aquifer system will accumulate with time as water within the system is effectively recycled. Whether this situation is actually occurring remains to be investigated, but recent advancements in water metering standards will assist in evaluating the actual hydraulic stresses on the aquifer.

The shallowest depth to groundwater is approximately 80 m at Darfield and 65 m at Kirwee. Groundwater is generally not abstracted from these depths, rather all active wells in the area screen at depths of more than 110 m bgl at Kirwee and 120 m bgl at Darfield, that is, more than 40 m below the water table (the water table being where impacts on water quality from effluent disposal fields will be most concentrated).

There is an inherent risk that bores drilled in the area have comprised the structural integrity of the natural aquifer and have produced localised preferential flow pathways that increase the risk of vertical transport. To mitigate the risk of the problem worsening, consideration might be given to imposing some special regulatory control measures on the drilling of bores/installation of new wells in close proximity to the septic tank clusters, irrespective of their use.

The average nitrate concentration in septic tank effluent is predicted to be about 65 mg NO_3-N/L. By the time this has reached the water table and mixed with natural soil drainage water, it is estimated nitrate concentrations might be closer to 20 mg NO_3-N/L. Groundwater nitrate impacts of this magnitude are to be expected at the water table in the immediate vicinity of the Darfield and Kirwee townships. Further dilution of the nitrate impacts will occur in the saturated zone as the contaminant plumes mix with background groundwater via advection and dispersion processes.

In 2011, PDP used a variety of mathematical modelling approaches to predict the scale of groundwater nitrate plumes emanating from the septic tank clusters at Darfield and Kirwee (PDP 2011). Their quantitative assessments revealed that groundwater nitrate impacts above the drinking-water MAV would likely be confined to short plumes less than 40-m long at Darfield and 225-m long at Kirwee. Following further analysis of the hydraulic gradients, it is possible that the nitrate plume at Darfield may have been underestimated. Although no quantitative reassessment has been completed, we suggest it would be reasonable to assume that the nitrate plume migrating downstream from Darfield will be of a similar length to that predicted for Kirwee by PDP (2011).

Despite uncertainties in the presumed scales and distributions of groundwater nitrate contamination sourced from the septic tank clusters in the towns, resource consent records indicate there are no active wells utilised for potable water within a distance that is any less than 1.7-km down-gradient of the septic tank clusters. There are, however, two wells (L35/0191 and L35/0818) in Kirwee itself that supply water for public and domestic uses, respectively. Both are located on the fringe, but up-gradient, of the main cluster of septic tanks. These are perceived to be the most vulnerable water wells in the area, although there has been no evidence to date of impacts on water quality in the public supply bore, which is regularly monitored.

Groundwater in the Darfield-Kirwee area is impacted by nitrate as a consequence of agricultural land use to which the on-site wastewater treatment systems contribute more nitrate mass. Nitrate concentrations as high as 16 mg NO_3-N/L have been recorded in groundwater up-gradient of the septic tank systems in Darfield, and these high levels are believed to be attributed to historic crop farming activities. Nitrate impacts extend deep into the aquifer up-stream of Darfield and sometimes 9 mg NO_3-N/L has been detected in water abstracted from a supply bore drawing from a depth of over 200 m. This plume of diffuse nitrate pollution is suspected to extend under Darfield town and to compromise the ability of the groundwater system to assimilate nitrate sourced from the numerous on-site wastewater disposal fields.

Total nitrogen loads from the cluster of septic tanks in operation in Darfield are estimated to range between 17.9 N/ha/yr and 51.6 kg N/ha/yr, probably closer to 36.0 kg N/ha/yr, of which the net load from wastewater itself is expected to range between 9.1 N/ha/yr and 35.6 kg N/ha/yr. These loads are comparable with nitrogen loads commonly associated with intensive dairy farming.

Groundwater nitrate impacts under Kirwee town are estimated to be between 74 percent and 88 percent lower than Darfield’s nitrate impacts owing to the lower population density. It is suspected that previous attempts to evaluate nitrate impacts from Kirwee’s wastewater treatment operations may have overestimated the population density. Provided the average population densities of the towns remain constant, the magnitude of the nitrate impacts from on-site wastewater treatment operations on groundwater quality will not change substantially. As the towns expand, however, the areal extent of the impacts will expand in unison.

5.4 On-site wastewater treatment policies and monitoring

A search was conducted of the accessible scientific literature and reports from various regulatory authorities, mainly in the USA and UK. However, no published case studies were identified that described septic tanks operating under conditions that are comparable with those at Darfield-Kirwee and from which lessons could be learned about septic tank management rules in such hydrogeological settings. The point of difference between the situation at Darfield-Kirwee and most reported case studies on the control of septic tank effluent is the considerable thickness of the vadose zone at Darfield-Kirwee.

In terms of the management and control of groundwater contamination by microbial pathogens sourced from on-site wastewater treatment systems, the general approach taken overseas is to focus on the proper installation, operation and maintenance of the septic tank treatment systems, which includes the performance of the disposal field where microbial removal is concentrated. This is complemented by policies that rule on acceptable septic tank-water well separation distances to manage health risks.

With respect to the assessment and control of nitrate impacts, the simplified mass balance and groundwater modelling approaches applied by PDP (2011), some of which were revised in this work, are consistent with the methods described in the literature. It is unlikely that any valuable knowledge would be gained by using advanced physically-based groundwater modelling to simulate conditions at Darfield-Kirwee at this stage, because the observational data required to calibrate such a model are not available.

5.5 Critique of current monitoring at Darfield and Kirwee

The purpose of the groundwater quality surveillance conducted by SDC on a near-annual basis needs to be re-examined. In its current format, the monitoring strategy provides little information about the scale of the impacts septic tank systems are having on the groundwater environment underlying Darfield and Kirwee, primarily because the wells used by SDC are positioned outside of the area where the impacts are perceived to be measurable. The surveillance does however provide a measure of the quality of water that is being abstracted for use.

Substantial redundancy exists in the array of wells from which SDC monitors groundwater quality, thus the number of wells used in the survey could be reduced. Appendix H ranks the wells in relation to their value to the groundwater quality monitoring network. The current monitoring programme makes use of most of the existing well infrastructure, yet there are several wells down-gradient of Darfield and Kirwee towns that, if sampled, would likely add value to the monitoring programme.

The area should subjected to a piezometric survey, from which improved knowledge might be gained about the likely migration directions being taken by the contamination sourced from the clusters of septic tanks at Darfield and Kirwee. This information will enable an evaluation of where monitoring should be focused.

None of the existing wells in the area screen across the water table, which is where the contamination will be most concentrated. Rather, the wells provide information about groundwater quality at least 30 m below the water table, thereby reflecting water quality at the point of human exposure. Hence, the groundwater quality monitoring programme based on sampling existing wells in the area has some technical merit.

Although having monitor wells placed within the two perceived plumes of contamination would directly measure the impacts on groundwater quality from the septic tank operations at Darfield and Kirwee, the benefits of accruing this knowledge are offset by the financial costs and the risk that drilling boreholes close to the contaminant source may actually weaken the natural attenuation capacity of the aquifer. The cost of installing a 70-m deep monitoring well in the Darfield and Kirwee area is about $18,000, and about $200 for every extra metre beyond that (Iain Haycock, McMillan Drilling Services, personal communication, February 2014).

It would be prudent for the regulatory authorities to consider imposing restrictions on bore drilling in the vicinities of the Darfield and Kirwee townships to control the risk of creating preferential vertical transport pathways that enable septic tank pollution to impact upon the aquifer at depth.

The ability to identify septic tank impacts on groundwater that are above the background regional impacts associated with diffuse agricultural pollution presents a technical challenge. More research could be conducted to characterise the exact chemical signature of the domestic wastewater discharged from Darfield and Kirwee relative to the chemistry of LSR water from which some discriminant analyses might be performed and a reliable detection methodology determined. Nitrogen-15 and oxygen-18 isotope analyses, and faecal source tracking are useful and well established tests that could constrain interpretations about impacts on water quality in the Darfield-Kirwee area.

6. CONCLUSION

The purpose of this work was to provide a baseline technical understanding of the vulnerability of groundwater at Darfield and Kirwee and to highlight limitations in SDC's current water quality monitoring strategy. The report provides a technical reference document upon which an informed debate can be held among SDC, CPH and ECan about the future of wastewater treatment practices in Darfield and Kirwee and the usefulness of the water quality investigation work commissioned by SDC in the form of the near-annual water quality surveys. Designing a fit for purpose groundwater quality monitoring network was beyond the scope of this work. Instead, modifications to the monitoring SDC undertakes are expected to form a topic of discussion after the parties have become familiar with the issues detailed in this document.

It is good practice that where design specifications are not recorded for wells used in the monitoring, work is completed to ascertain the areas in the aquifer's profile from which the wells draw water. It is helpful to note that one objective stated in the CLWRP is that '*all activities operate at "good practice" or better to protect the region's fresh water resources from quality and quantity degradation*'. Monitored groundwater nitrate levels in the Selwyn-Waihora zone already exceed the health indicator target outcomes currently specified in the CLWRP, and reducing the nitrogen footprints associated with farming practices is a focus of the plan. Any initiative to reduce nitrogen loads from Darfield and Kirwee's wastewater discharges would therefore complement the objectives of the CLWRP and help mitigate any risk to public health.

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8. APPENDICES

Appendix A: Revision of estimated nitrate impacts

Present day impacts

According to the 2013 census statistics results, the current resident population in Darfield is 1935, and this population lives within a unit area of 337 ha. This represents an increase from 1671 people living within an area of 247 ha, evaluated in 2006. A simple visual inspection of the current distribution of septic tanks with active discharge consents in Darfield and a survey of recent satellite imagery on Google maps, suggest that that the area to which the 2013 census population statistics applies might be larger than that recorded by Statistics New Zealand, and could be closer to 464 ha (Figure A1). The population density in Darfield is thus estimated to be within the realm of 4.2–5.7 people/ha. In this study, the higher value reported by Statistics New Zealand is assumed to be the more reliable estimate.

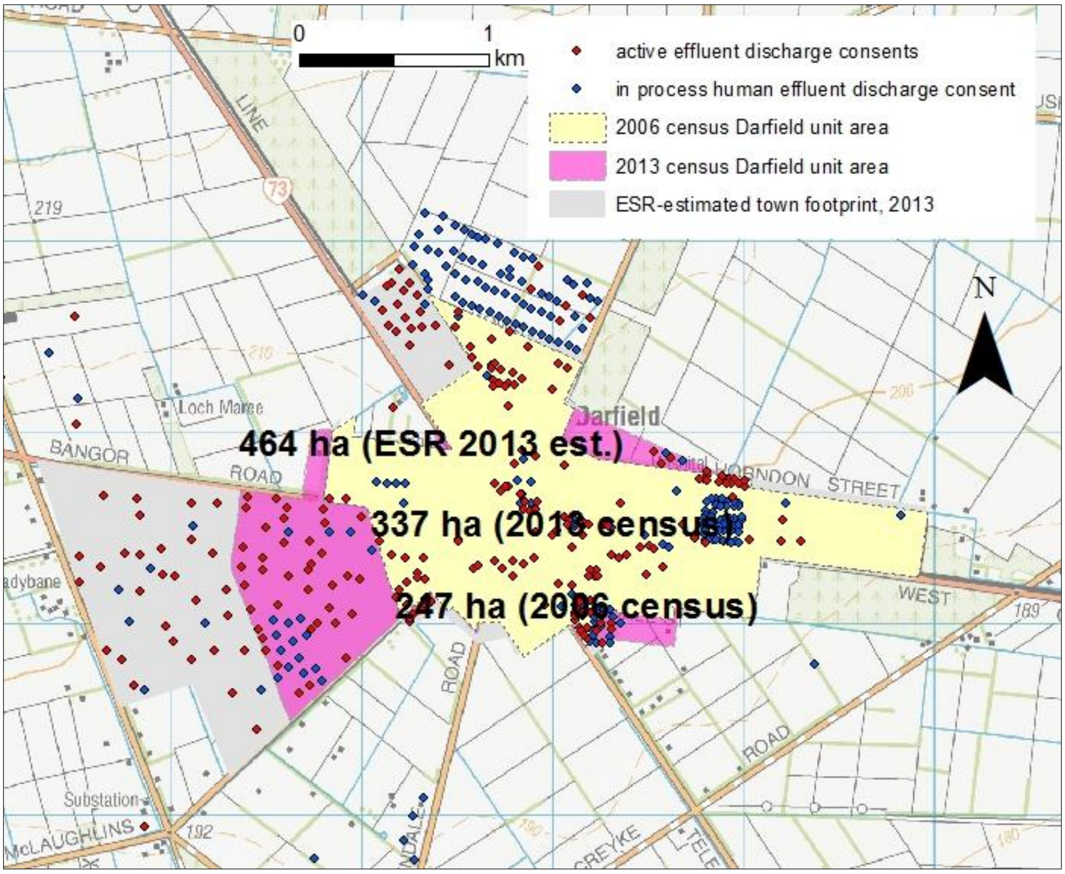


Figure A1. Darfield town unit area as reported in the 2006 and 2013 censuses, and in ESR's independent estimate based on 2013 satellite imagery.
Active resource consents to discharge human effluent are shown together with consents listed on ECan's database as 'inactive', which includes consents being processed.

Population statistics are not reported by Statistics New Zealand for Kirwee town per se, but are reported for a broader rural unit area covering 46,739 ha. Hence, the resident population of the town has to be estimated. SDC is currently refining their estimate of the town's size based on the Living Zone area, rates and building consents data, and the best estimate of Kirwee's township size is currently 1081 people living within an area of 290 ha (Cameron Wood, Strategic Policy Planner, SDC, personal communication, December 2013). ESR attempted an independent estimate based on a count of the 247 properties that feature on the 2013 Google maps satellite imagery within an area of 218 ha (See Figure A2), multiplied by the 2006 NZ census household occupancy rate of 2.8 people/residence. Based on these figures, the population density in Kirwee is estimated to be in the range of 3.2–3.7 people/ha, which is notably less dense than Darfield's population density.

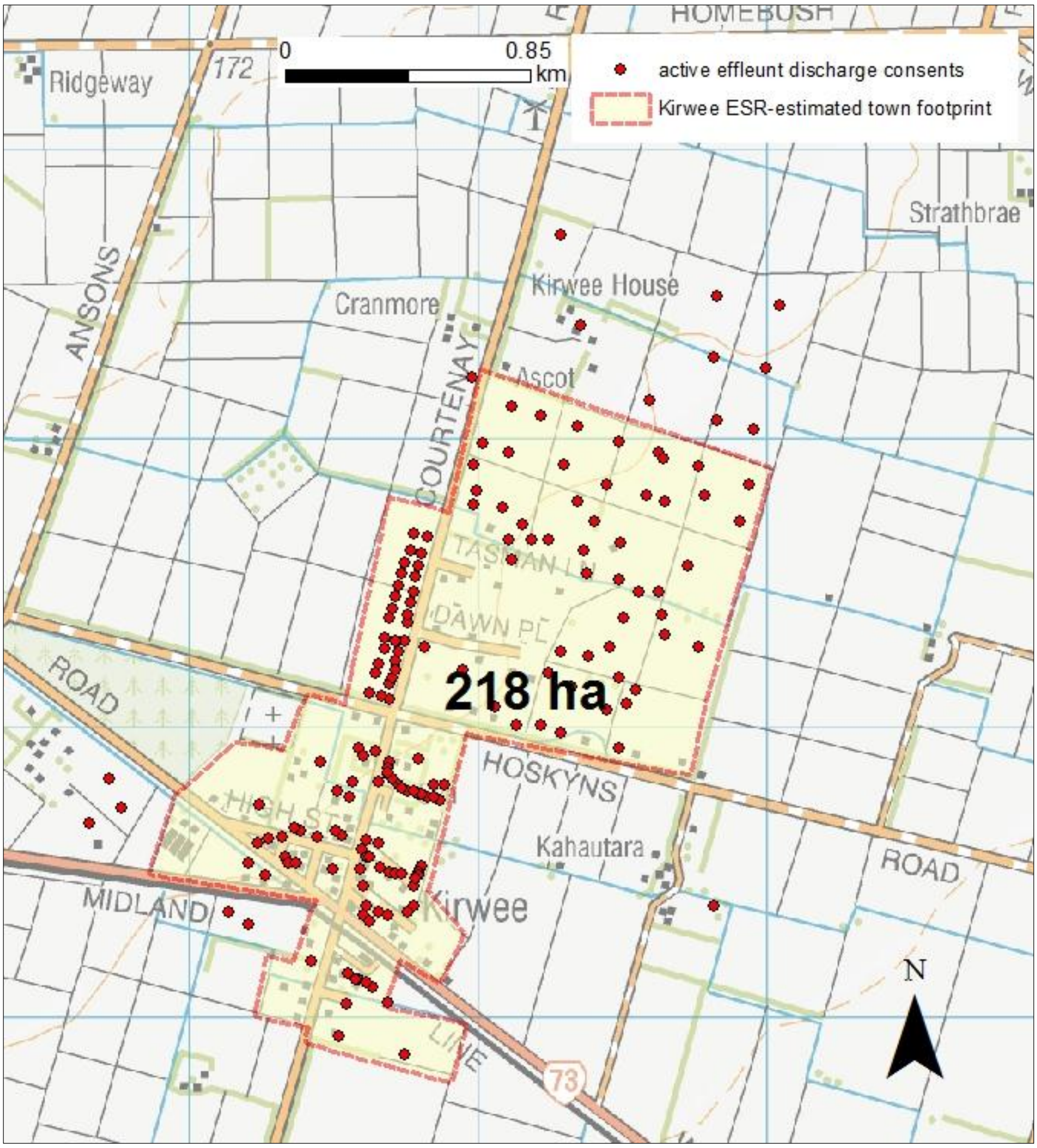


Figure A2: The Kirwee town area that was assumed for this work, bounding the cluster of resource management consents to discharge human effluent (data from ECan's CONSENTS database).

Interestingly, in their previous impact assessment work PDP (2011) had to make similar estimates about the size of the resident population in Kirwee town. They counted 350 dwellings in a supposed area of just 129 ha and, hence, assumed a population density of 7 people/ha. This is almost twice the population density estimated by SDC and ESR. Furthermore, it is inconsistent with SDC's town plans that provide for higher density living in Darfield than in Kirwee. It is suspected that

PDP's (2011) population density estimate was grossly overestimated, hence their predictions about nitrogen impacts associated with Kirwee town were also overestimated. PDP's (2011) results are provided in this work for the purposes of comparison.

Considering the townships as isolated entities, a measure of their nitrate environmental footprint can be determined from a simple mass balance equation, which assumes all contamination released from the town is perfectly mixed and diluted with drainage water from the same finite area (Hantzsche and Finnemore 1992). Dividing the sum of nitrogen sourced from human effluent discharges and that leaches from the land contained within the town boundary by the sum of (artificial and natural) drainage water within the same boundary estimates the average nitrate concentration for the town, C_i:

$$C_i = \frac{(P_i \times N_{eff}) + N_{land}}{V_{eff} + (LSR \times A_i)} \qquad \text{(A1)}$$

where P_i is the population of the town i, N_{eff} is the rate of nitrogen waste production per person and discharged via a septic system; N_{land} is the nitrogen mass leached from land in the town, V_{eff} is the volume of wastewater a person generates each day, LSR is the land surface recharge rate and A_i is the area of the town footprint.

Such 'lumped' models are simplistic, because they do not mimic the spatial distribution of the contamination or route it takes in the subsurface system. At the regional scale such complete mixing assumptions are valid. Furthermore, based on the results of water-tracing experiments ESR conducted in a 10-m deep vadose zone in the Canterbury alluvial aquifer (Burbery et al 2012), one can infer that point-source pollution, including effluent from a septic tank, will undergo significant lateral spreading as it infiltrates over a vertical depth of over 65 m to reach the water table, as is the situation at Darfield and Kirwee. This lateral spreading associated with vertical transport under gravitational flow tends towards a complete mixing model assumption that underpins the use of Equation A1. The same methods were applied by PDP (2011) in their earlier assessment of the nitrate impacts from septic tanks systems at Darfield and Kirwee, but PDP (2011) did not factor in the background nitrate loading from the land that provides the diluent (background nitrate concentrations were, however, accounted for in a separate mass-mixing model assessment).

Table A1 lists the predictions of the spatially- and temporally-averaged nitrate contamination that can be perceived to be associated with the cluster of septic waste systems currently at Darfield, whereby impacts from septic tank wastes are diluted by local land surface recharge (LSR) sourced within the constraints of the town footprint. The 'low' estimate provides a lower bound, whereas the 'high' estimate implies a probable worst-case scenario. The 'more probable' value (shaded grey) can be considered as the best educated guess, and is based on the range of mass loading rates and recharge estimates published in the literature. PDP's (2011) assessment is provided for comparison, although it is important to realise the nitrate concentration value estimated by PDP (2011) assumes effluent dilution with LSR water free of any residual nitrate, which in reality is not possible. Table A2 shows the results for Kirwee.

Table A1: Estimate of the general nitrate footprint Darfield town imposes on the groundwater system underlying the town as a consequence of wastewater discharges diluted with local soil drainage.

Variable	Units	High	Low	More probable	PDP (2011)
Darfield population[$]	people	1935	1935	1935	1482
Darfield area	ha	464	337	337	248.4
Darfield population density	people/ha	4.2	5.7	5.7	6.0[*]
N production: effluent	g N /person/d	6	17	13	12
	tonnes N/yr (town)	4.2	12.0	9.2	6.5
	kg N/ha/yr	9.1	35.6	27.2	26.2
Wastewater production	L/person/day	200	200	200	200
	m^3/person/yr	73	73	73	73
	milllion m^3/yr (town)	0.14	0.14	0.14	0.11
N concentration: effluent	mg NO_3-N/L	30	85	65	60
N mass leached from land[%]	kg N/ha /yr	8.8	16	8.8	0
	tonnes N/yr (town)	4.08	5.39	2.97	0.00
LSR	mm/yr	227	129	140	135
	million m^3/yr (town)	1.05	0.43	0.47	0.34
N concentration: LSR	mg NO_3-N/L	3.88	12.40	6.29	0.00
N concentration under town	mg NO_3-N/L	7.0	30.2	19.8	14.7

N, nitrogen; LSR, land surface recharge

[$] Population from the 2013 national census or 2006 census in the case of the PDP (2011) data.

* PDP (2011)-determined population density from: 2.3 septic systems/ha x 2.6 people/system/town area, not census population statistic.

[%] Dryland sheep farming land use assumed representative of nitrogen leaching rates for gardens and so on within Darfield town ('low' and 'more probable' estimates); lifestyle block land use assumed representative of nitrogen leaching rates for 'high' assessment. All soil leaching rates taken from Lilburne et al (2010).

Note: The nitrate-leaching tables generated by Lilburne et al (2010), which have become the standard reference dataset for land-use impact assessments in Canterbury, were used in the current evaluations. For the 'low' and 'more probable' estimates, all land within the townships (eg, gardens, verges) were assigned nitrogen-leaching rates that are comparable to dryland sheep farming and not lifestyle blocks, which Lilburne et al (2010) predicted to have a larger nitrogen impact than low-intensity land used for sheep grazing. Nitrogen loads from lifestyle blocks were used in the 'high' assessment.

Rainwater run-off from impermeable roads and roof tops in the towns constitutes an effective nitrate-free diluent that it is often discharged direct to ground via boulder pits. The net effect of this stormwater component, for every 5 percent land coverage of this type, is estimated to equate to a 16 percent reduction in the total nitrate concentration sourced from Darfield and 24 percent reduction in nitrate sourced from Kirwee.

Table A2: Estimate of the general nitrate footprint Kirwee town imposes on the groundwater system underlying the town as a consequence of wastewater discharges diluted with local soil drainage.

Variable	Units	Low	High	More probable	PDP (2011)
Kirwee population	people	692	1081	1081	906*
Kirwee area	ha	218	290	290	129
Kirwee population density	people/ha	3.2	3.7	3.7	7.0
N production from effluent	g N /person/d	6	17	13	12
	tonnes N/yr (town)	1.5	6.7	5.1	4.0
	kg N/ha/yr	6.9	23.1	17.7	30.7
Wastewater production	L/person/day	200	200	200	200
	m^3/person/yr	73	73	73	73
	million m^3/yr (town)	0.05	0.08	0.08	0.07
N concentration: effluent	mg NO_3-N/L	30	85	65	60
N mass leached from land$	kg N/ha /yr	8.8	16	8.8	0
	tonnes N/yr (town)	1.92	4.64	2.55	0.00
LSR	mm/yr	227	129	140	135
	million m^3/yr (town)	0.49	0.37	0.41	0.17
N concentration: LSR	mg NO_3-N/L	3.88	12.40	6.29	0.00
N concentration under town	mg NO_3-N/L	6.3	25.0	15.8	16.5

N, nitrogen; LSR, land surface recharge

* PDP (2011) population calculated from density statistics reported by PDP (2011), ie, 2.7 septic systems/ha x 2.6 people/system x town area.

$ Dryland sheep farming land use assumed representative of nitrogen leaching rates for gardens and so on within Kirwee town (‘low’ and ‘more probable’ estimates); lifestyle block land use assumed representative of nitrogen leaching rates for ‘high’ assessment. All soil-leaching rates are from Lilburne et al (2010).

The concentration of nitrate in undiluted septic effluent is predicted to be within the range of 30–85 mg NO_3-N /L, most likely closer to 65 mg NO_3-N/L, and groundwater impacts could be of this magnitude on a local scale at the water table, in the absence of any dilution effects. The nitrogen mass load from the septic tanks in operation at Darfield is predicted to be in the range of 9.1–35.6 kg N/ha/yr, probably closer 27.2 kg N/ha/yr. Nitrogen loads attributed to effluent generated in Kirwee are predicted to be in the range of 6.9–23.1 kg N/ha/yr, more likely 17.7 kg N/ha/yr, because of the lower population density. PDP (2011) previously estimated a substantially higher nutrient load coming from Kirwee that was equivalent to 30.7 kg N/ha/yr, but as discussed previously, it is strongly suspected that an erroneous judgement was made about the population density.

When nutrient loads from the septic tanks are compounded with the unmanageable loads sourced from soils associated with general rural residential land use, the actual estimates of nitrogen loads coming from the two towns are more likely to amount to

36.0 kg N/ha/yr and 26.5 kg N/ha/yr from Darfield and Kirwee, respectively. If one were able to assume LSR (the diluent) were free of nitrate then the net areal averaged groundwater nitrate impacts from effluent disposal would lie in the range of 7.0–30.2 mg NO_3-N/L for Darfield and 6.3–25.0 mg NO_3-N/L for Kirwee.

Population density threshold for sustainable on-site waste-water disposal practice

In an effort to answer the question: 'at what point do on-site wastewater treatment systems become unsustainable?', equation A1 can be applied to determine a population density threshold, assuming of course that nitrogen is the contaminant of critical concern. If the drinking-water MAV for nitrate is set as a desirable outcome for groundwater quality and the protection of public health then, based on the same range of assumptions about nitrogen loads in effluent and dilution potential in the Darfield-Kirwee setting as above, the critical capacity of septic tank systems can be determined. Figure A3 plots groundwater nitrate impacts against population density, with the boundary between the light ('high') and dark ('low') shaded regions marking the 'most probable' outcome.

Considering the cumulative nitrate impact of nitrogen leached from the land and septic tank effluent, it is predicted that a 'sustainable' human population density in Darfield-Kirwee might be just 1.8 people/ha. Based on the 2006 census, the Kirwee housing occupancy density of 2.8 people/dwelling equates to an average housing allotment minimum size threshold of 1.56 ha. Figure A3 also highlights that within the bounds of uncertainty that currently apply to current knowledge about nitrate-leaching rates in the Canterbury environment, one should not reject the possibility that the nitrate drinking-water MAV will ultimately be exceeded in groundwater as a consequence of standard land use on lifestyle sections, even in the absence of any nitrogen load from human effluent.

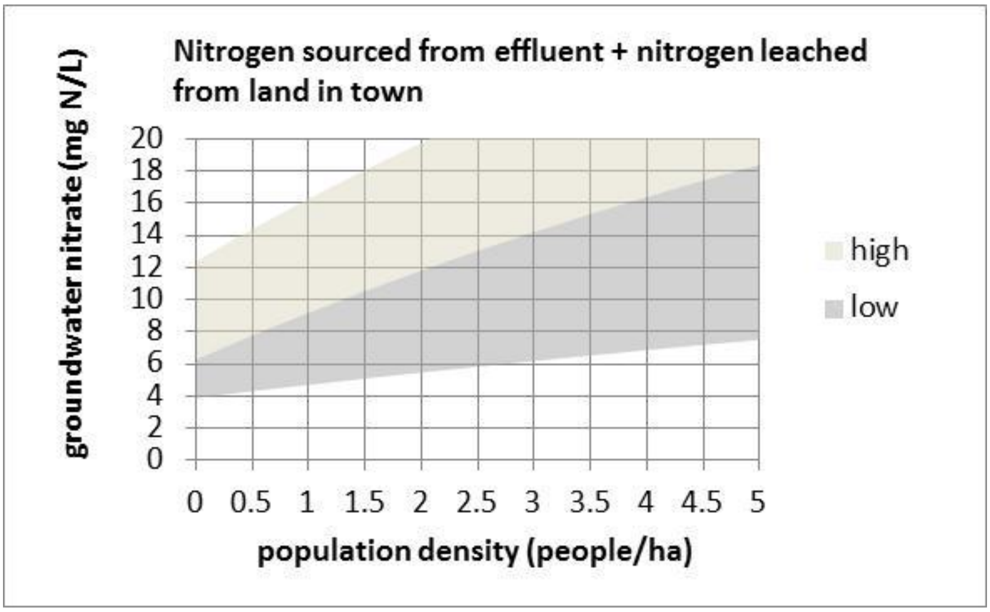


Figure A3: Population density plot against predicted groundwater nitrate impacts at the water table for the Darfield-Kirwee setting.

Note that the drinking-water maximum acceptable value corresponds to 11.3 mg NO_3-N /L. The most probable estimate lies between the high and the low estimates.

If one were to ignore the unmanageable background nitrate load associated with rural residential land use and consider the septic tank effluent in isolation, then a population density of 4.0 people/ha, or an average 0.69-ha allotment size would be suitable, but it should be recognised that the town will have an effective nitrate footprint larger than its territorial border at this density (Figure A4). According to Lilburne et al (2010), the only land uses that dilute groundwater nitrate impacts from septic tank effluent to meet the drinking-water quality standards are forestry (0.01–4.42 mg NO_3-N/L), fruit growing (5.7–8.2 mg NO_3-N/L), viticulture (5.3 mg NO_3-N/L), sheep (6.3 mg NO_3-N/L), deer (7.5 mg NO_3-N/L) and low-intensity dairying at 3 cows/ha (9.4 mg NO_3-N/L), where the bracketed numbers represent the hypothesised nitrate impact of the land uses. The benefit of nitrate-free alpine river inputs for maintaining groundwater nitrate levels below the MAV is obvious, but as suggested, river dilution is likely to only really be effective in the Selwyn-Waimakariri aquifer system down-gradient of Darfield and Kirwee.

For reference, the smallest allotment sizes prescribed in SDC's residential plans are for Living Zone 1 land and these are 650 m^2 for Darfield and 800 m^2 for Kirwee. Living Zone 2 land parcels are required to be no smaller than 5000 m^2 in Darfield and 1 ha in Kirwee. Assuming an average residential occupancy rate of 2.8 people/house and if all of Darfield was to be developed as Living Zone 1 land, then at the worst the population density might reach 43 people/ha. This is 10-times the sustainable population density required to comply with the drinking-water nitrate MAV in groundwater that was predicted in this work.

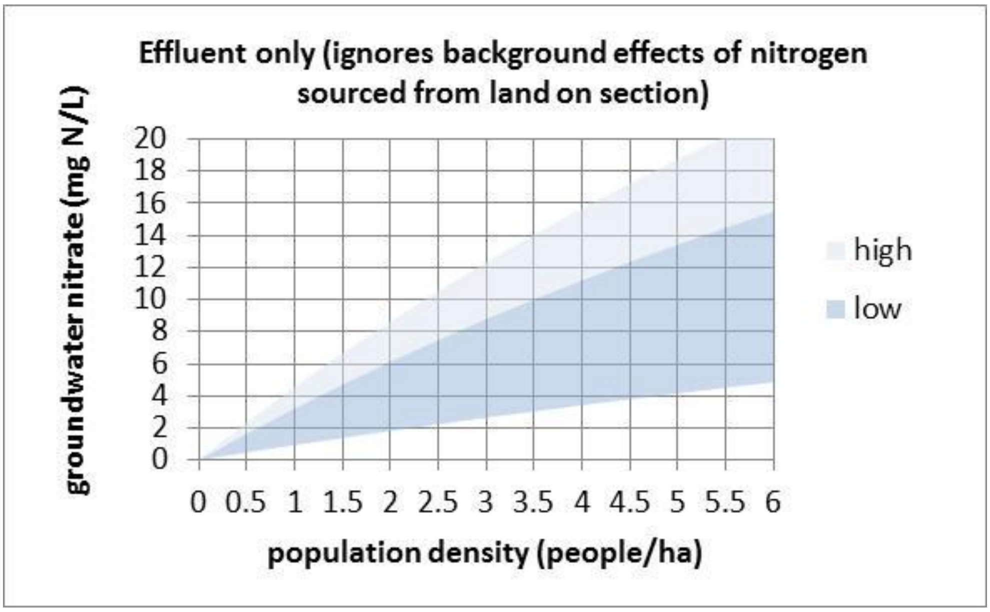


Figure A4: Population density plot against predicted groundwater nitrate impacts at the water table for the Darfield-Kirwee setting, ignoring unmanageable nitrogen loads from rural land uses.

Note that the drinking-water maximum acceptable value corresponds to 11.3 mg NO_3-N /L.

Appendix B: Selected borelogs from the Darfield area

Advanced datasets are accessible online, please replace XXXX for a four-digit well number suffix in following link: http://ecan.govt.nz/services/online-services/tools-calculators/pages/well-detail.aspx?WellNo=L35%2fXXXX

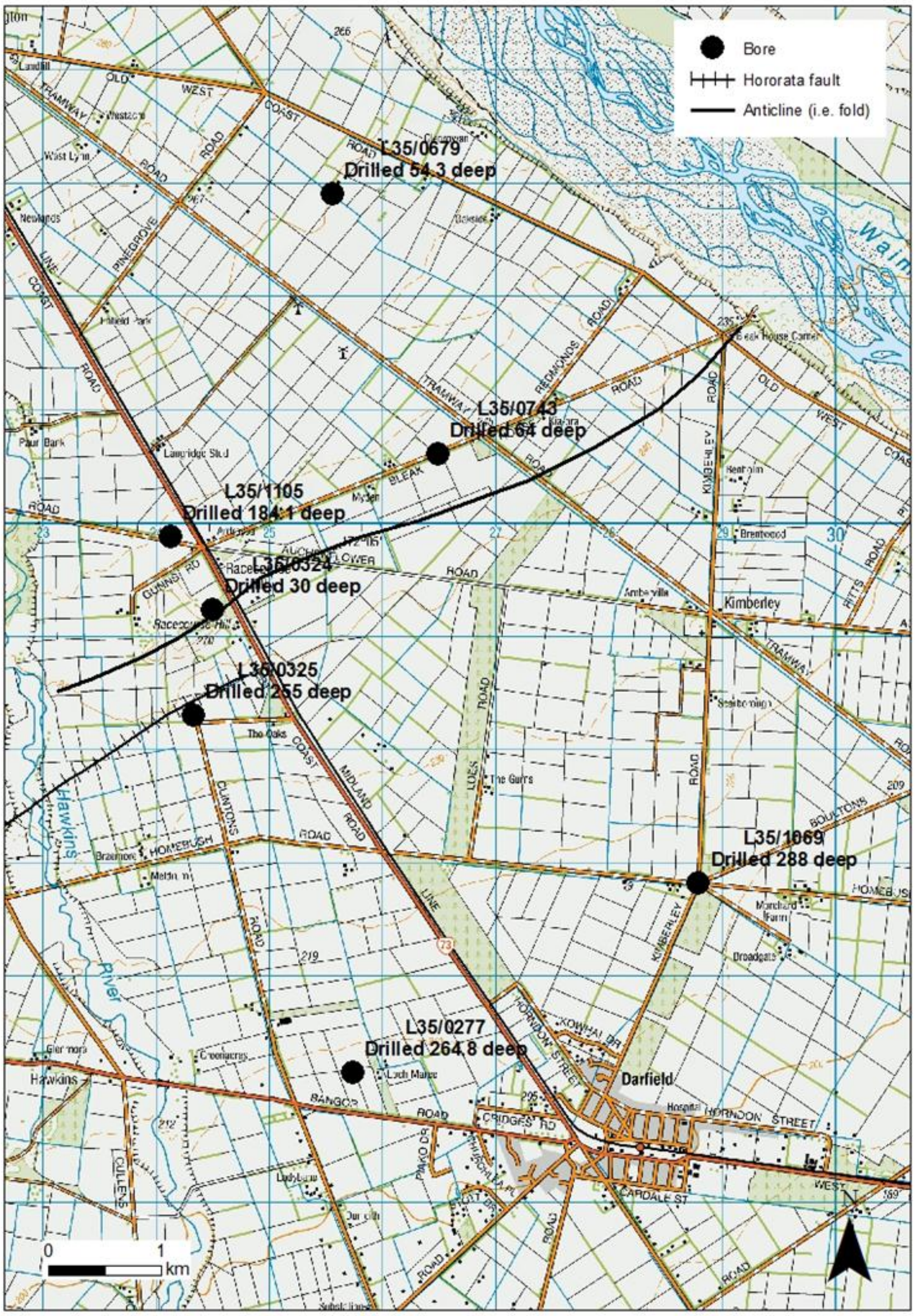
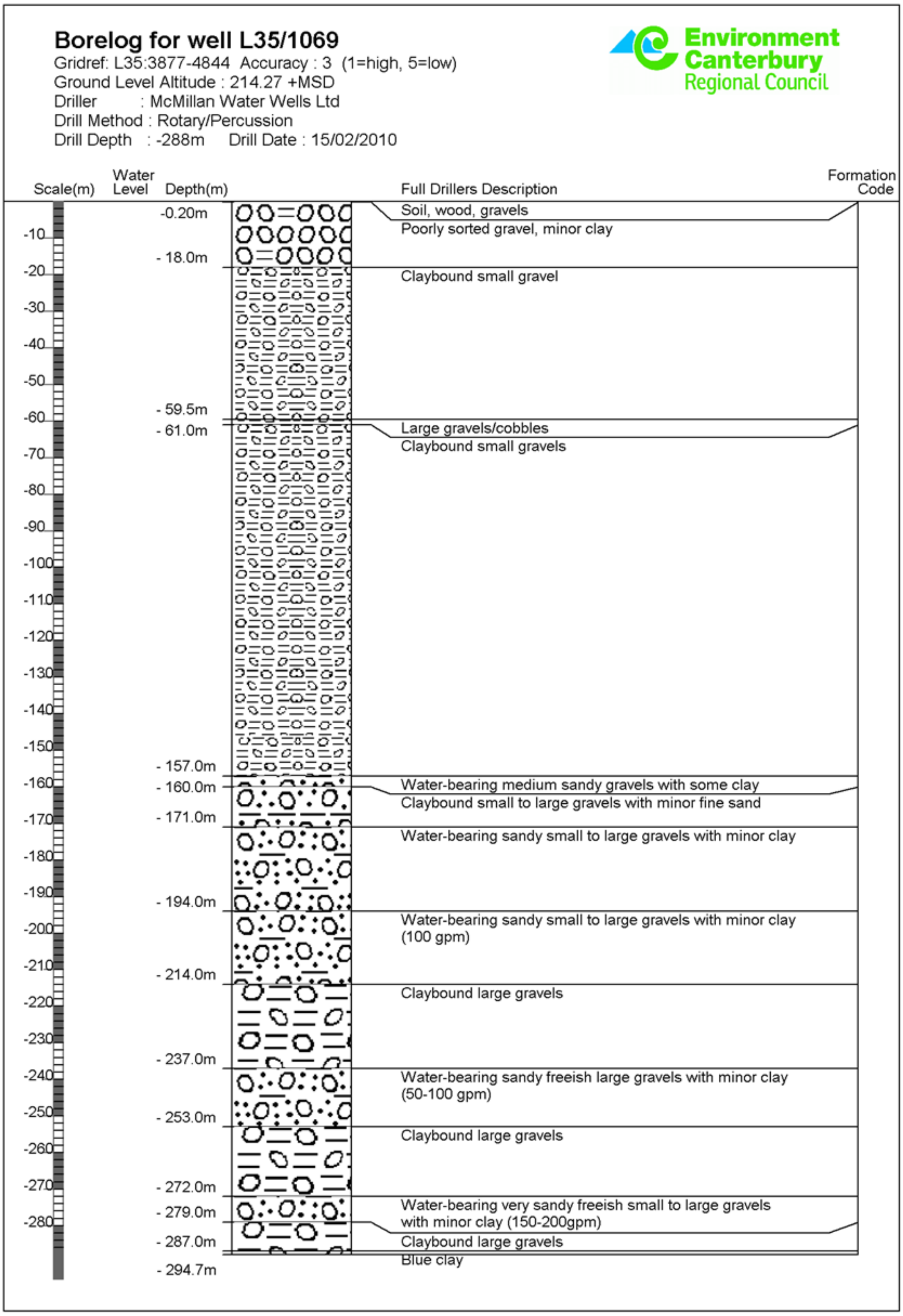


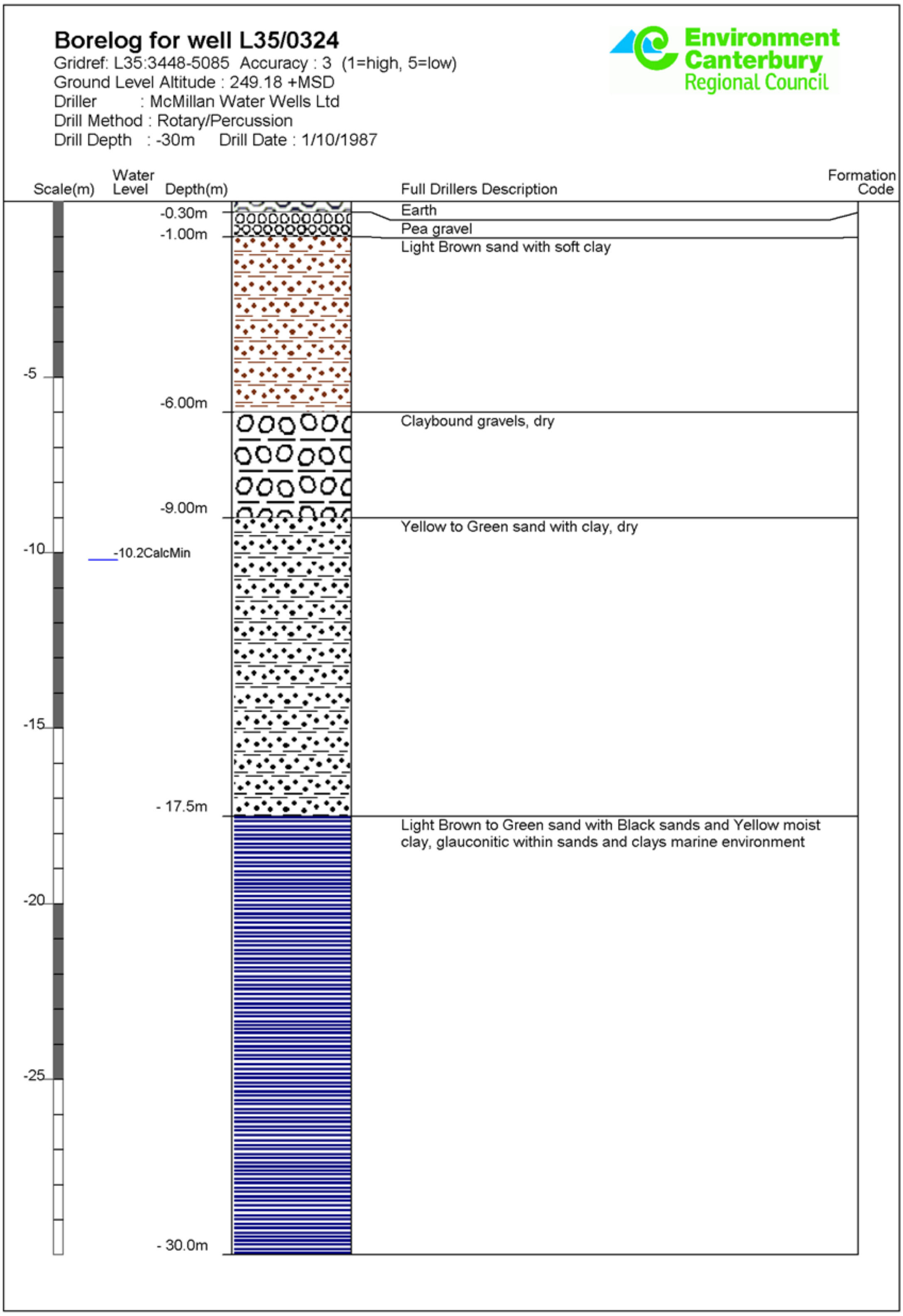
Figure B1: Location map for select bores for which borelog data are provided.



Borelog for well L35/1069

Gridref: L35:3877-4844 Accuracy : 3 (1=high, 5=low)
Ground Level Altitude : 214.27 +MSD
Driller : McMillan Water Wells Ltd
Drill Method : Rotary/Percussion
Drill Depth : -288m Drill Date : 15/02/2010

Depth(m)	Full Drillers Description	Formation Code
-0.20m	Soil, wood, gravels	
	Poorly sorted gravel, minor clay	
- 18.0m	Claybound small gravel	
- 59.5m	Large gravels/cobbles	
- 61.0m	Claybound small gravels	
- 157.0m	Water-bearing medium sandy gravels with some clay	
- 160.0m	Claybound small to large gravels with minor fine sand	
- 171.0m	Water-bearing sandy small to large gravels with minor clay	
- 194.0m	Water-bearing sandy small to large gravels with minor clay (100 gpm)	
- 214.0m	Claybound large gravels	
- 237.0m	Water-bearing sandy freeish large gravels with minor clay (50-100 gpm)	
- 253.0m	Claybound large gravels	
- 272.0m	Water-bearing very sandy freeish small to large gravels with minor clay (150-200gpm)	
- 279.0m	Claybound large gravels	
- 287.0m	Blue clay	
- 294.7m		



Borelog for well L35/0324

Gridref: L35:3448-5085 Accuracy : 3 (1=high, 5=low)
Ground Level Altitude : 249.18 +MSD
Driller : McMillan Water Wells Ltd
Drill Method : Rotary/Percussion
Drill Depth : -30m Drill Date : 1/10/1987

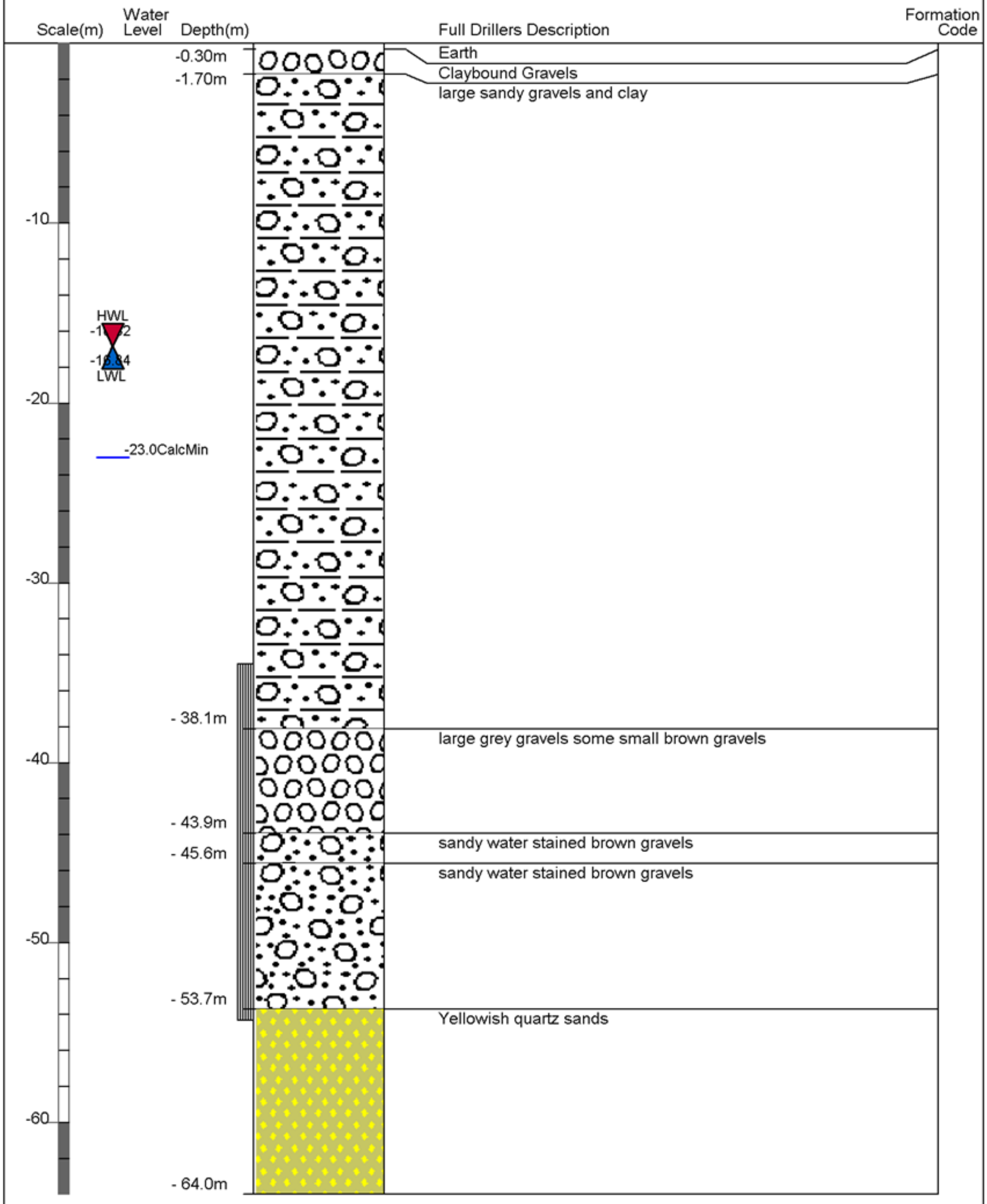
Environment Canterbury Regional Council

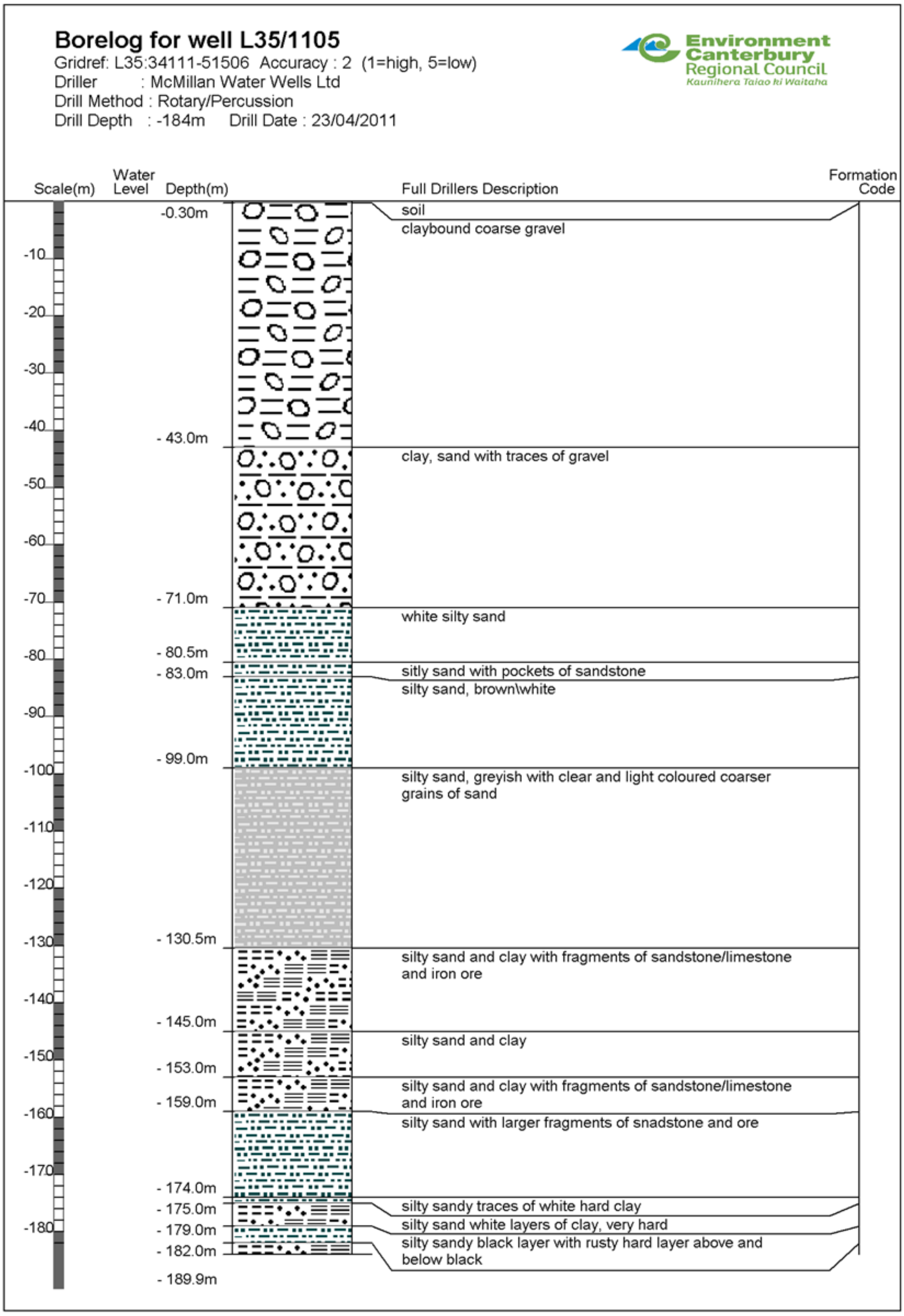
Depth(m)	Full Drillers Description	Formation Code
-0.30m	Earth	
-1.00m	Pea gravel	
-6.00m	Light Brown sand with soft clay	
-9.00m	Claybound gravels, dry	
- 17.5m	Yellow to Green sand with clay, dry	
- 30.0m	Light Brown to Green sand with Black sands and Yellow moist clay, glauconitic within sands and clays marine environment	

Borelog for well L35/0679

Gridref: L35:35538-54532 Accuracy : 1 (1=high, 5=low)
Ground Level Altitude : 259.84 +MSD
Driller : McMillan Water Wells Ltd
Drill Method : Rotary/Percussion
Drill Depth : -64m Drill Date : 25/05/2001

Environment Canterbury
Regional Council

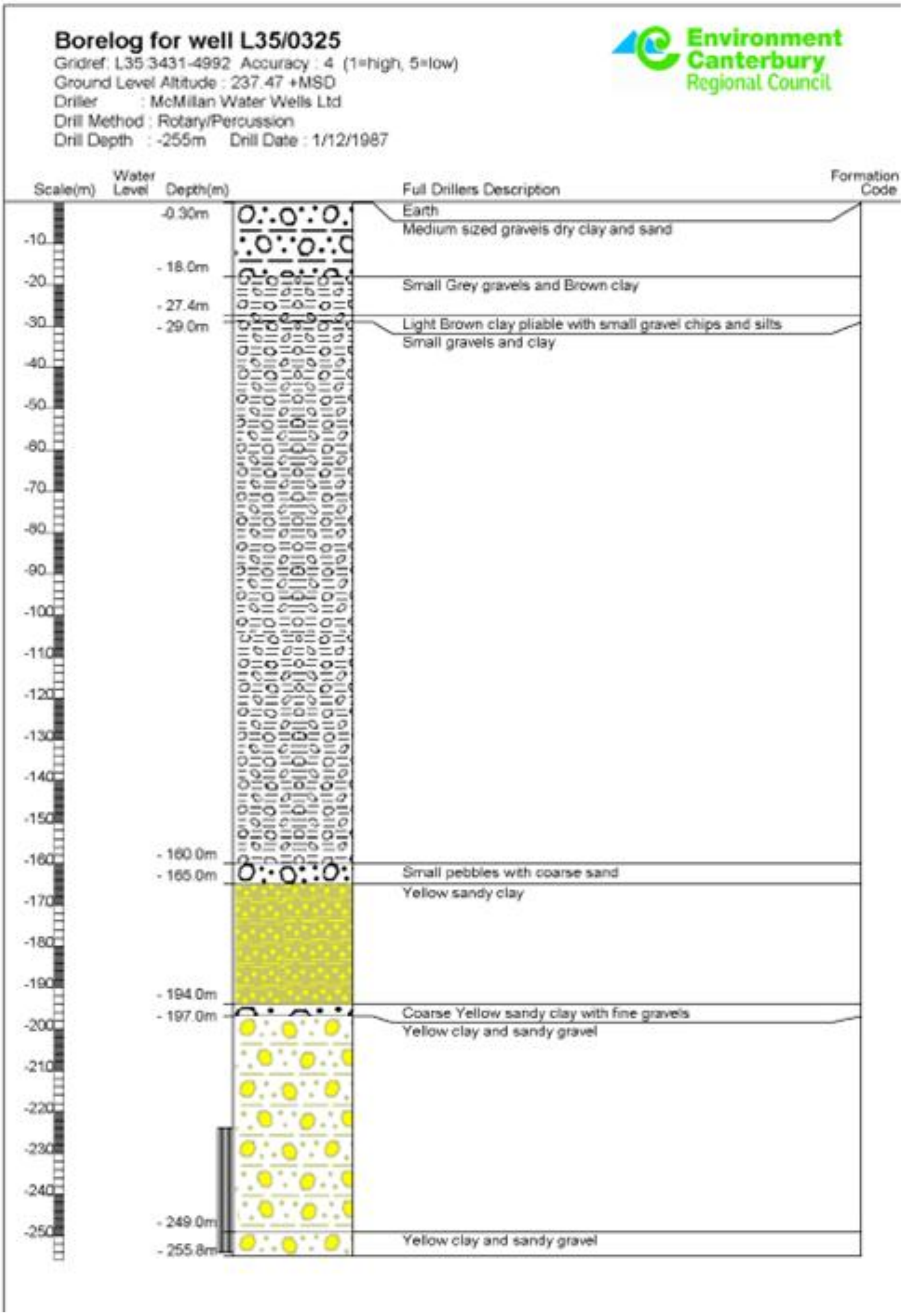




Borelog for well L35/1105
Gridref: L35:34111-51506 Accuracy : 2 (1=high, 5=low)
Driller : McMillan Water Wells Ltd
Drill Method : Rotary/Percussion
Drill Depth : -184m Drill Date : 23/04/2011

Full Drillers Description

soil
claybound coarse gravel
clay, sand with traces of gravel
white silty sand
sitly sand with pockets of sandstone
silty sand, brown\white
silty sand, greyish with clear and light coloured coarser grains of sand
silty sand and clay with fragments of sandstone/limestone and iron ore
silty sand and clay
silty sand and clay with fragments of sandstone/limestone and iron ore
silty sand with larger fragments of snadstone and ore
silty sandy traces of white hard clay
silty sand white layers of clay, very hard
silty sandy black layer with rusty hard layer above and below black



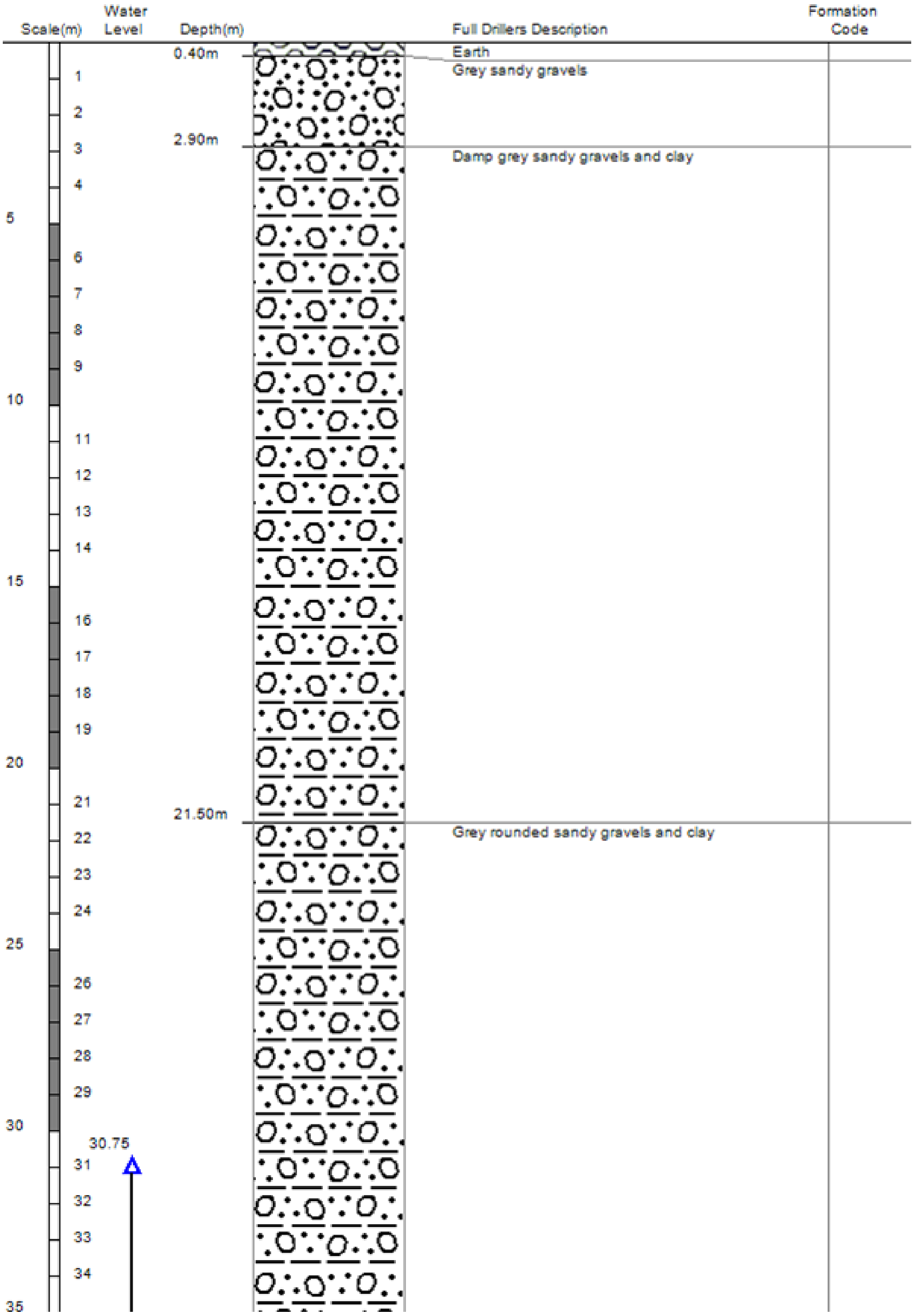
Borelog for well L35/0325

Gridref: L35:3431-4992 Accuracy : 4 (1=high, 5=low)
Ground Level Altitude : 237.47 +MSD
Driller : McMillan Water Wells Ltd
Drill Method : Rotary/Percussion
Drill Depth : -255m Drill Date : 1/12/1987

Depth(m)	Full Drillers Description	Formation Code
-0.30m	Earth	
- 18.0m	Medium sized gravels dry clay and sand	
- 27.4m	Small Grey gravels and Brown clay	
- 29.0m	Light Brown clay pliable with small gravel chips and silts	
- 160.0m	Small gravels and clay	
- 165.0m	Small pebbles with coarse sand	
- 194.0m	Yellow sandy clay	
- 197.0m	Coarse Yellow sandy clay with fine gravels	
- 249.0m	Yellow clay and sandy gravel	
- 255.8m	Yellow clay and sandy gravel	

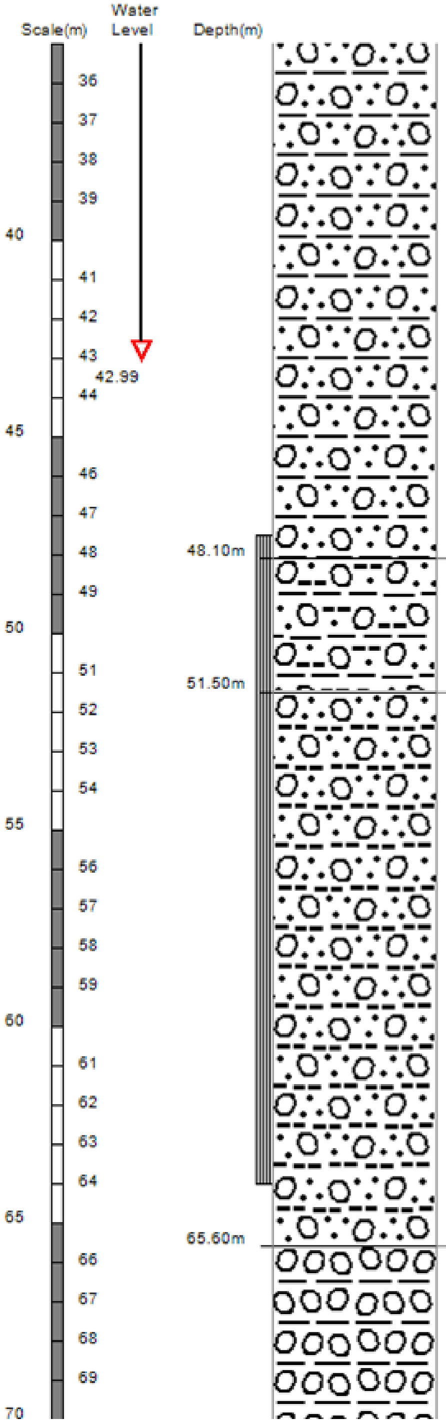
Borelog for well L35/0743 page 1 of 9

Map Reference (NZMG): 2436470 mN, 5752232 mE
QAR Accuracy: 2
Ground Level Altitude: 246.8 +MSD
Driller: McMillan Water Wells Ltd
Drill Method: Rotary/Percussion
Well Depth: 282.809997558594m Drill Date: 12/12/2002



Depth(m)	Full Drillers Description	Formation Code
	Earth	
0.40m	Grey sandy gravels	
2.90m	Damp grey sandy gravels and clay	
21.50m	Grey rounded sandy gravels and clay	

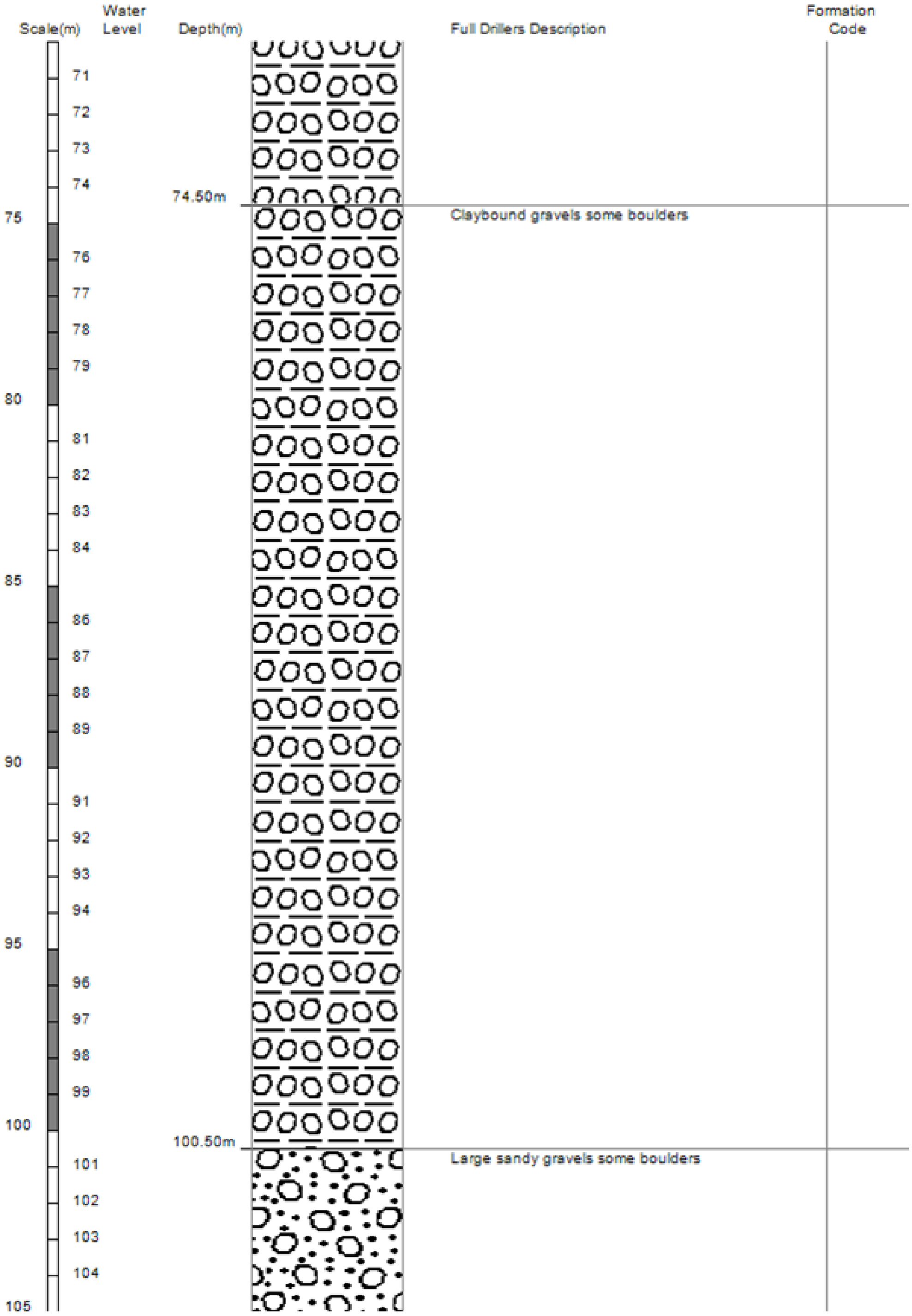
Borelog for well L35/0743 page 2 of 9
Map Reference (NZMG): 2436470 mN, 5752232 mE
QAR Accuracy: 2
Ground Level Altitude: 246.8 +MSD
Driller: McMillan Water Wells Ltd
Drill Method: Rotary/Percussion
Well Depth: 282.809997558594m Drill Date: 12/12/2002



Depth(m)	Full Drillers Description	Formation Code
48.10m	Dark grey and brown gravels clay silt very sandy	
51.50m	Moderately sorted grey and brown sandy gravels some stained silt	
65.60m	Claybound gravels	

Borelog for well L35/0743 page 3 of 9

Map Reference (NZMG): 2436470 mN, 5752232 mE
QAR Accuracy: 2
Ground Level Altitude: 246.8 +MSD
Driller: McMillan Water Wells Ltd
Drill Method: Rotary/Percussion
Well Depth: 282.809997558594m Drill Date: 12/12/2002



Depth(m)	Full Drillers Description	Formation Code
74.50m	Claybound gravels some boulders	
100.50m	Large sandy gravels some boulders	

Borelog for well L35/0743 page 4 of 9

Map Reference (NZMG): 2436470 mN, 5752232 mE
QAR Accuracy: 2
Ground Level Altitude: 246.8 +MSD
Driller: McMillan Water Wells Ltd
Drill Method: Rotary/Percussion
Well Depth: 282.809997558594m Drill Date: 12/12/2002

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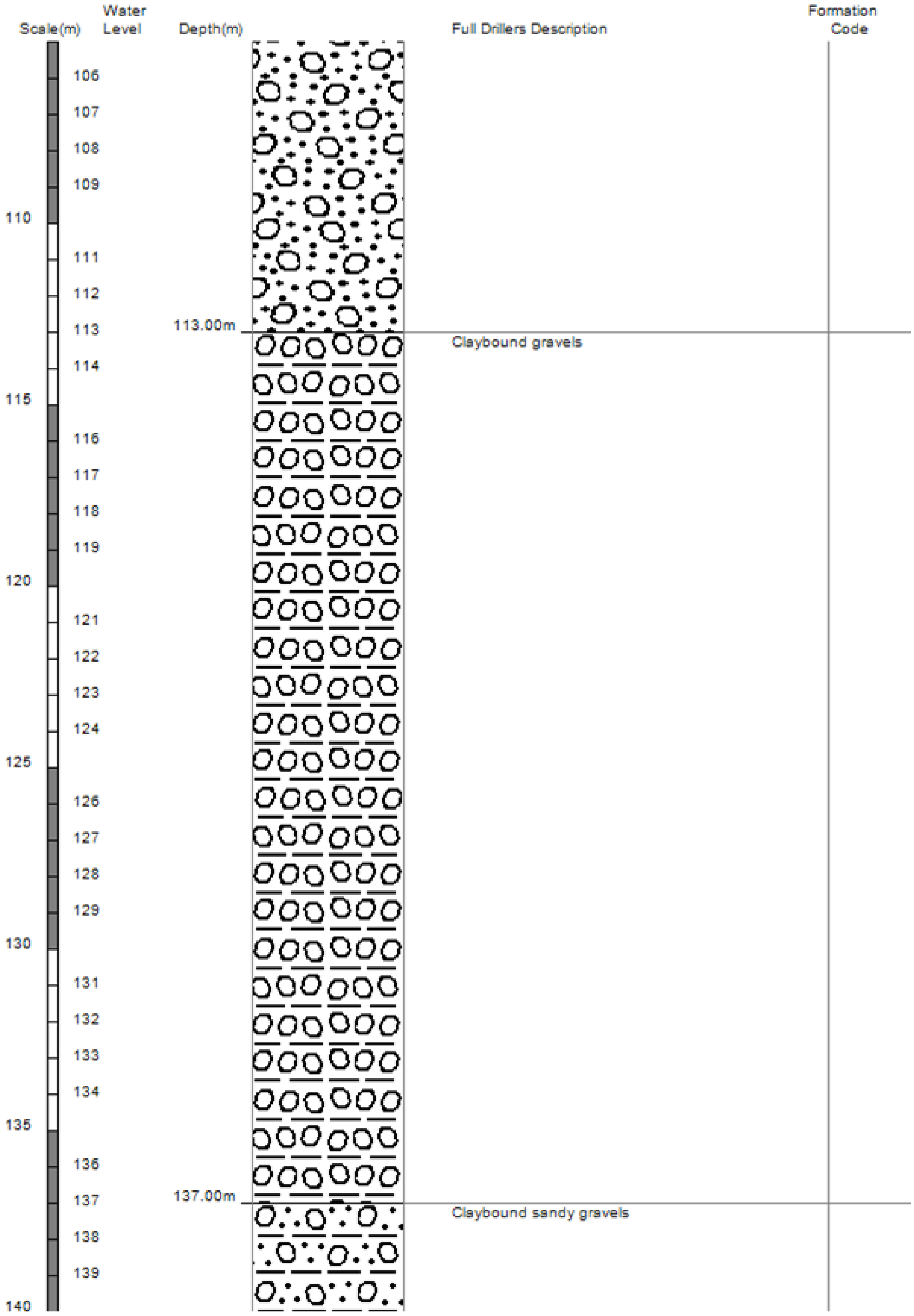
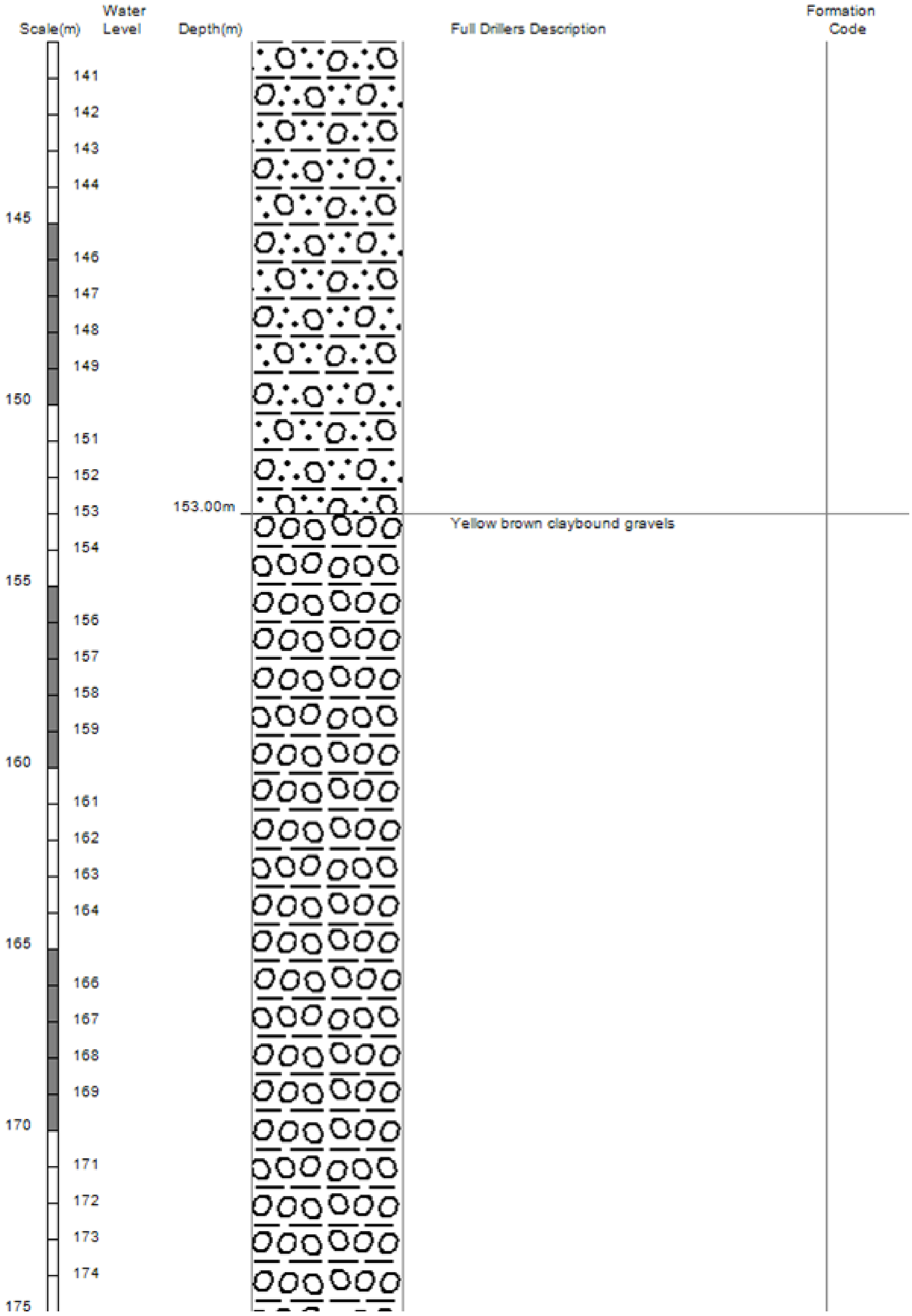
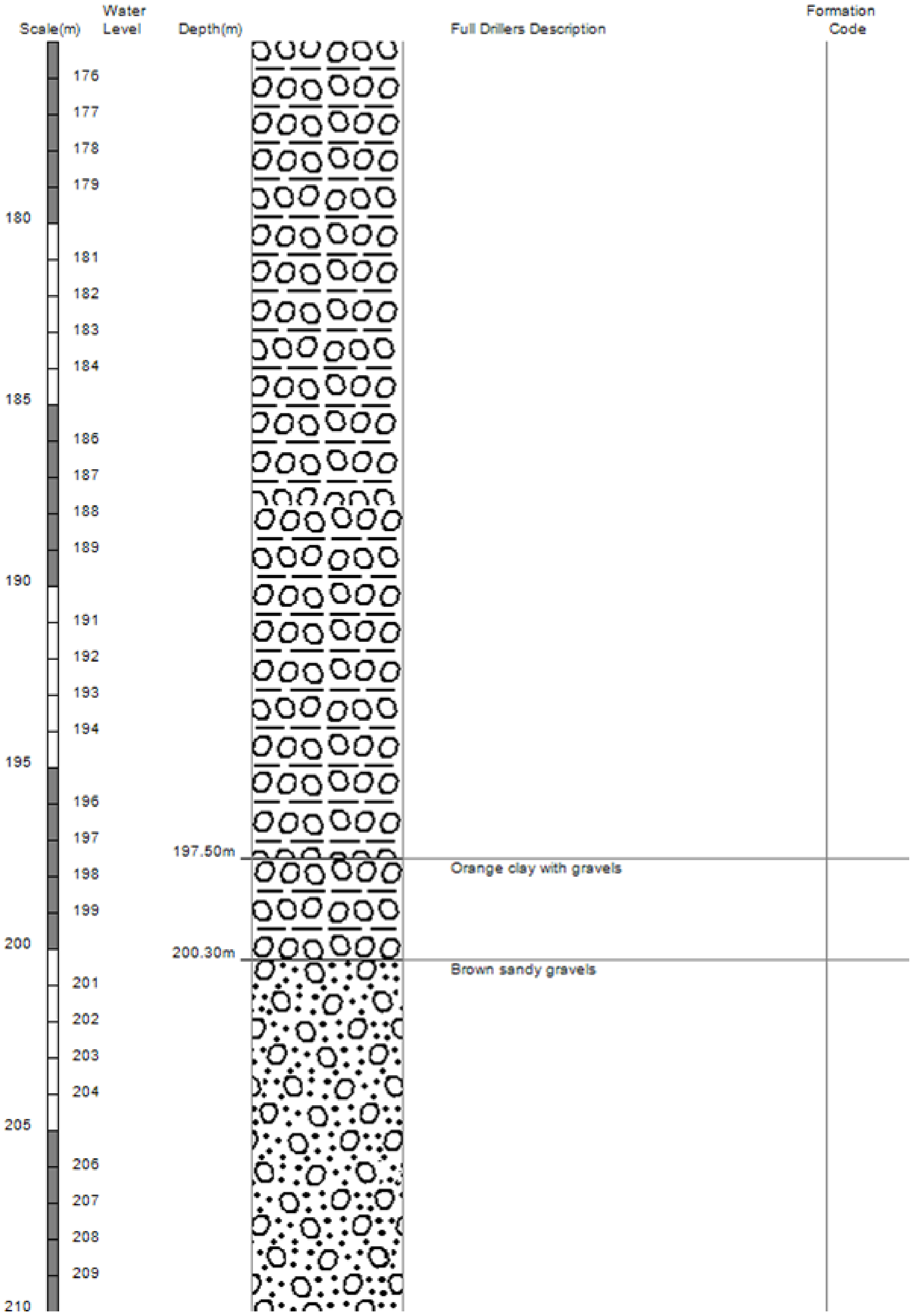


Borelog for well L35/0743 page 5 of 9

Map Reference (NZMG): 2436470 mN, 5752232 mE
QAR Accuracy: 2
Ground Level Altitude: 246.8 +MSD
Driller: McMillan Water Wells Ltd
Drill Method: Rotary/Percussion
Well Depth: 282.809997558594m Drill Date: 12/12/2002



Borelog for well L35/0743 page 6 of 9
Map Reference (NZMG): 2436470 mN, 5752232 mE
QAR Accuracy: 2
Ground Level Altitude: 246.8 +MSD
Driller: McMillan Water Wells Ltd
Drill Method: Rotary/Percussion
Well Depth: 282.809997558594m Drill Date: 12/12/2002

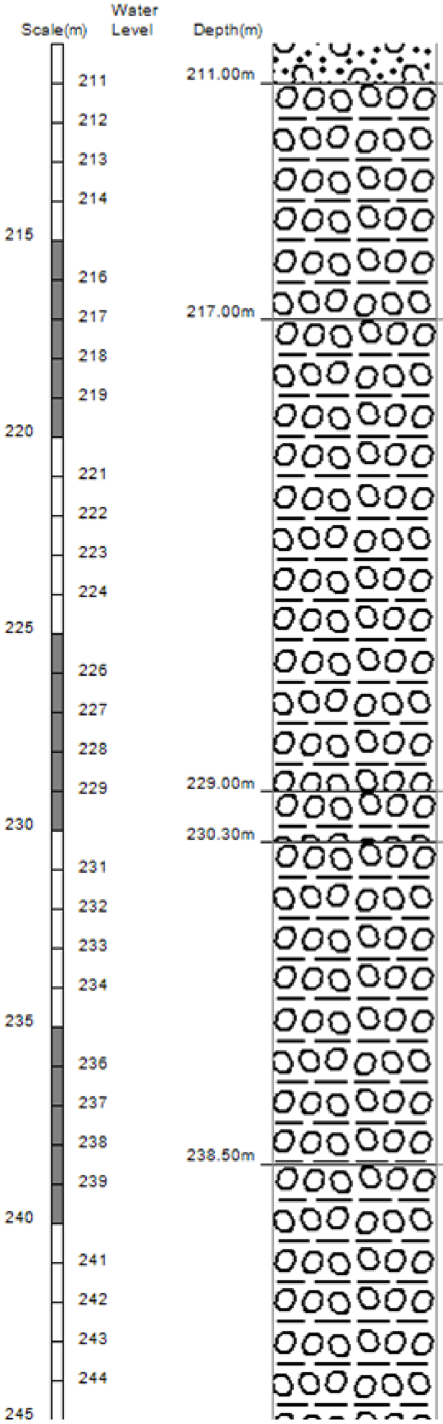


Depth(m)	Full Drillers Description	Formation Code
197.50m	Orange clay with gravels	
200.30m	Brown sandy gravels	

Borelog for well L35/0743 page 7 of 9

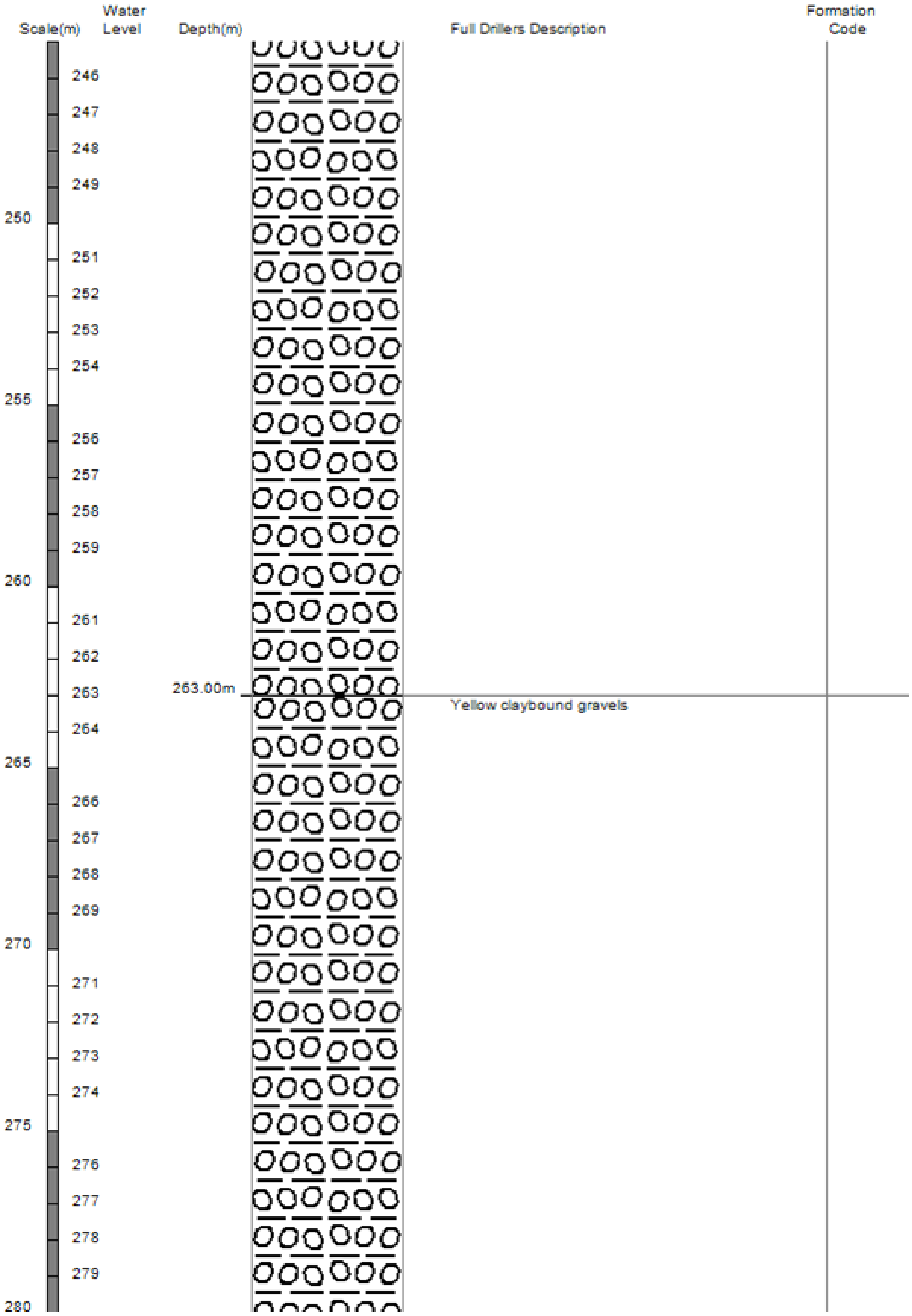
Environment Canterbury
Regional Council
Kaunihera Taiao ki Waitaha

Map Reference (NZMG): 2436470 mN, 5752232 mE
QAR Accuracy: 2
Ground Level Altitude: 246.8 +MSD
Driller: McMillan Water Wells Ltd
Drill Method: Rotary/Percussion
Well Depth: 282.809997558594m Drill Date: 12/12/2002



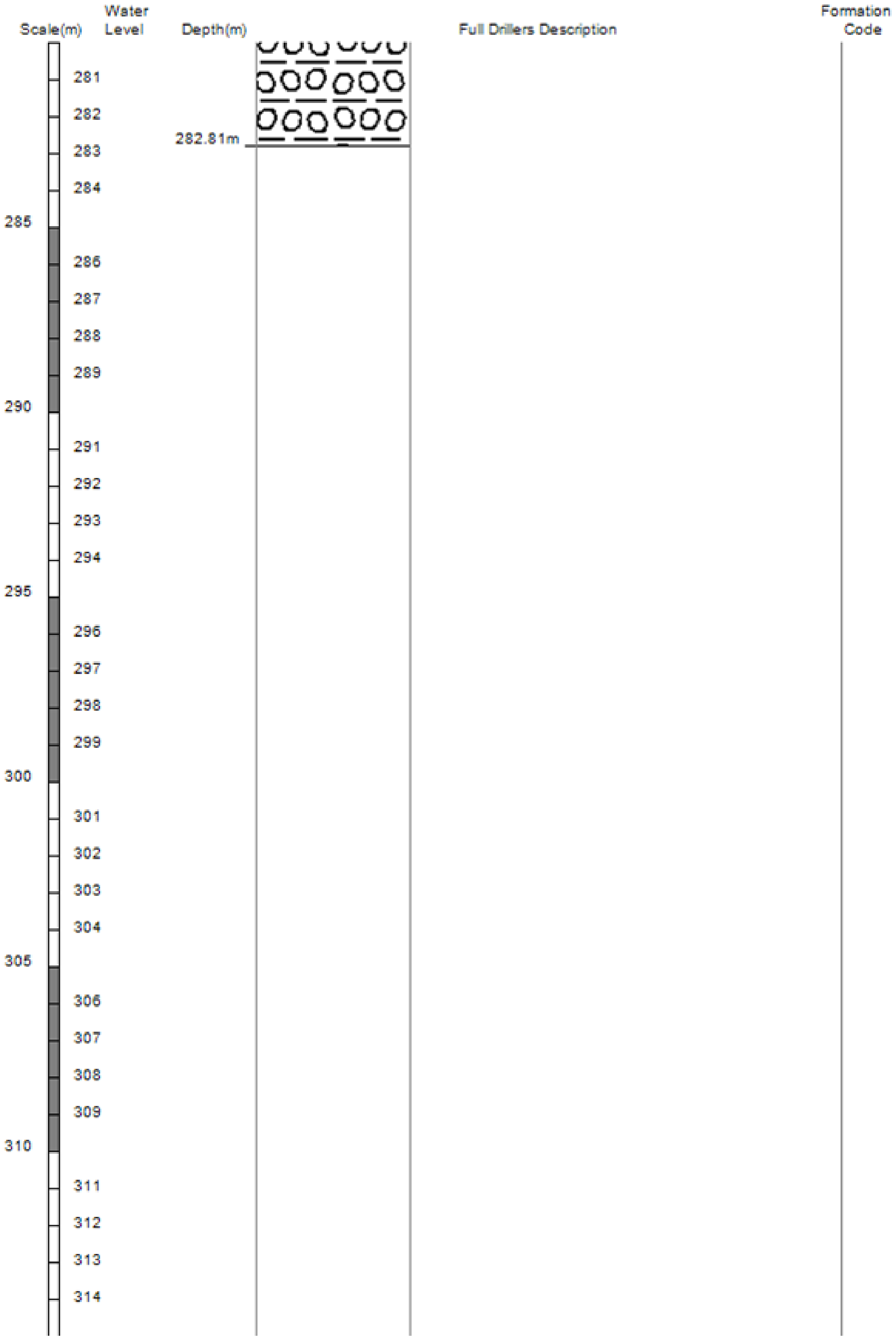
Depth(m)	Full Drillers Description	Formation Code
211.00m	Yellow claybound gravels	
217.00m	Brown red clay with gravels	
229.00m	Yellow claybound gravels	
230.30m	Yellow soft claybound gravels	
238.50m	Brown soft claybound gravels	

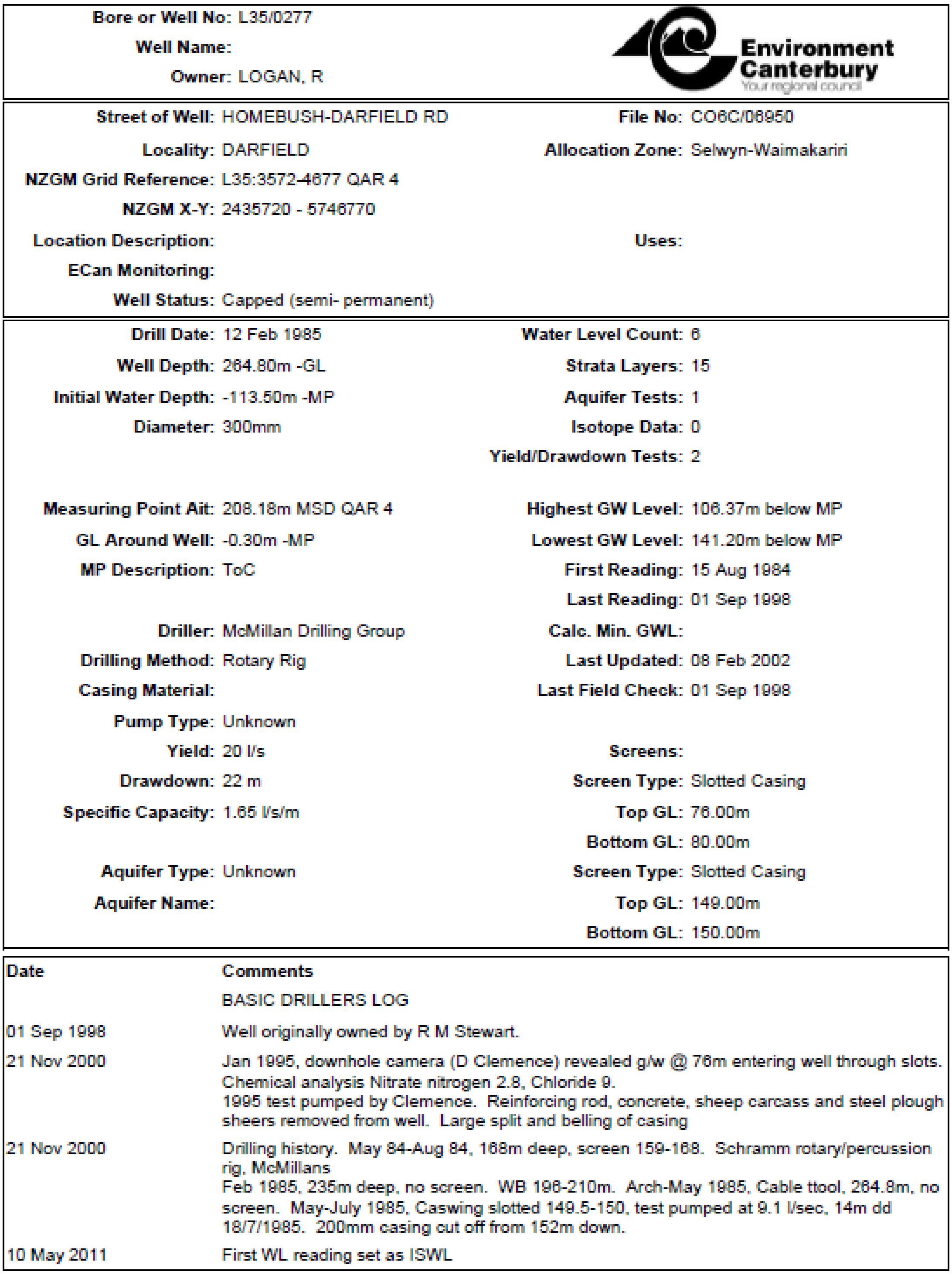
Borelog for well L35/0743 page 8 of 9
Map Reference (NZMG): 2436470 mN, 5752232 mE
QAR Accuracy: 2
Ground Level Altitude: 246.8 +MSD
Driller: McMillan Water Wells Ltd
Drill Method: Rotary/Percussion
Well Depth: 282.809997558594m Drill Date: 12/12/2002



Borelog for well L35/0743 page 9 of 9

Map Reference (NZMG): 2436470 mN, 5752232 mE
QAR Accuracy: 2
Ground Level Altitude: 246.8 +MSD
Driller: McMillan Water Wells Ltd
Drill Method: Rotary/Percussion
Well Depth: 282.809997558594m Drill Date: 12/12/2002





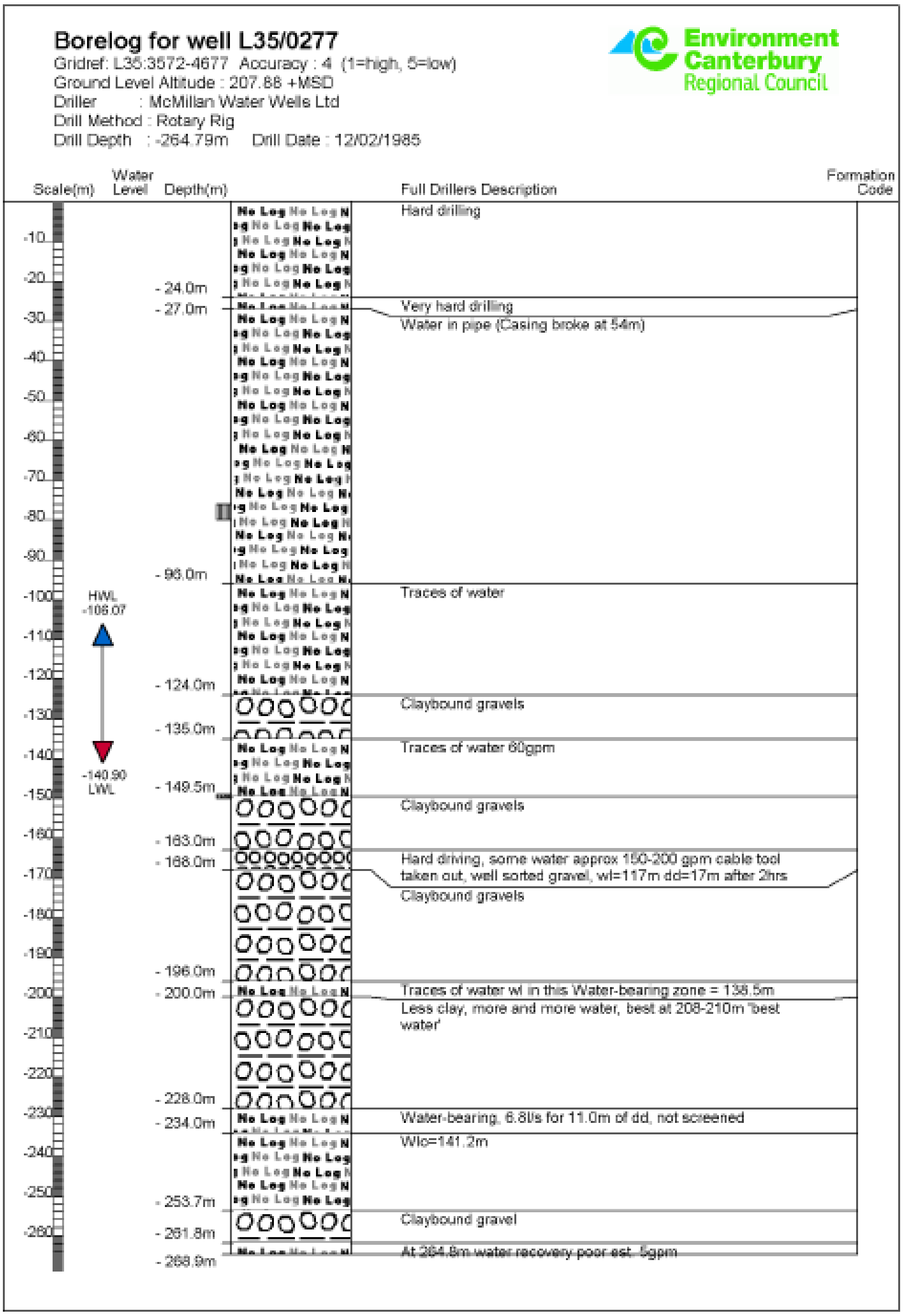
Bore or Well No: L35/0277
Well Name:
Owner: LOGAN, R

Environment Canterbury
Your regional council

Street of Well:	HOMEBUSH-DARFIELD RD	**File No:**	CO6C/06950
Locality:	DARFIELD	**Allocation Zone:**	Selwyn-Waimakariri
NZGM Grid Reference:	L35:3572-4677 QAR 4		
NZGM X-Y:	2435720 - 5746770		
Location Description:		**Uses:**	
ECan Monitoring:			
Well Status:	Capped (semi- permanent)		

Drill Date:	12 Feb 1985	**Water Level Count:**	6
Well Depth:	264.80m -GL	**Strata Layers:**	15
Initial Water Depth:	-113.50m -MP	**Aquifer Tests:**	1
Diameter:	300mm	**Isotope Data:**	0
		Yield/Drawdown Tests:	2
Measuring Point Alt:	208.18m MSD QAR 4	**Highest GW Level:**	106.37m below MP
GL Around Well:	-0.30m -MP	**Lowest GW Level:**	141.20m below MP
MP Description:	ToC	**First Reading:**	15 Aug 1984
		Last Reading:	01 Sep 1998
Driller:	McMillan Drilling Group	**Calc. Min. GWL:**	
Drilling Method:	Rotary Rig	**Last Updated:**	08 Feb 2002
Casing Material:		**Last Field Check:**	01 Sep 1998
Pump Type:	Unknown		
Yield:	20 l/s	**Screens:**	
Drawdown:	22 m	**Screen Type:**	Slotted Casing
Specific Capacity:	1.65 l/s/m	**Top GL:**	76.00m
		Bottom GL:	80.00m
Aquifer Type:	Unknown	**Screen Type:**	Slotted Casing
Aquifer Name:		**Top GL:**	149.00m
		Bottom GL:	150.00m

Date	**Comments**
	BASIC DRILLERS LOG
01 Sep 1998	Well originally owned by R M Stewart.
21 Nov 2000	Jan 1995, downhole camera (D Clemence) revealed g/w @ 76m entering well through slots. Chemical analysis Nitrate nitrogen 2.8, Chloride 9. 1995 test pumped by Clemence. Reinforcing rod, concrete, sheep carcass and steel plough sheers removed from well. Large split and belling of casing
21 Nov 2000	Drilling history. May 84-Aug 84, 168m deep, screen 159-168. Schramm rotary/percussion rig, McMillans Feb 1985, 235m deep, no screen. WB 196-210m. Arch-May 1985, Cable ttool, 264.8m, no screen. May-July 1985, Caswing slotted 149.5-150, test pumped at 9.1 l/sec, 14m dd 18/7/1985. 200mm casing cut off from 152m down.
10 May 2011	First WL reading set as ISWL



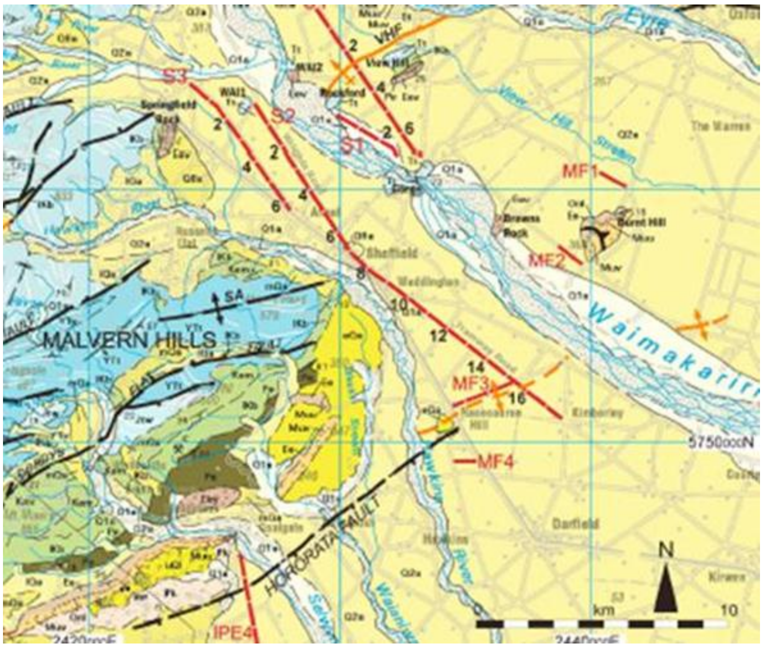
Borelog for well L35/0277

Gridref: L35:3572-4677 Accuracy : 4 (1=high, 5=low)
Ground Level Altitude : 207.88 +MSD
Driller : McMillan Water Wells Ltd
Drill Method : Rotary Rig
Drill Depth : -264.79m Drill Date : 12/02/1985

Depth(m)	Full Drillers Description	Formation Code
- 24.0m	Hard drilling	
- 27.0m	Very hard drilling	
- 96.0m	Water in pipe (Casing broke at 54m)	
- 124.0m	Traces of water	
- 135.0m	Claybound gravels	
- 149.5m	Traces of water 60gpm	
- 163.0m	Claybound gravels	
- 168.0m	Hard driving, some water approx 150-200 gpm cable tool taken out, well sorted gravel, wl=117m dd=17m after 2hrs	
- 196.0m	Claybound gravels	
- 200.0m	Traces of water wl in this Water-bearing zone = 138.5m	
- 228.0m	Less clay, more and more water, best at 208-210m 'best water'	
- 234.0m	Water-bearing, 6.8l/s for 11.0m of dd, not screened	
- 253.7m	Wlo=141.2m	
- 261.8m	Claybound gravel	
- 268.9m	At 264.8m water recovery poor est. 5gpm	

Appendix C: Dorn et al (2010)

Extracts from Dorn et al (2010) showing the interpretation of seismic reflections recorded along transect S2. Dorn et al (2010) suggest that the lack of reflections east of FA6, 16 km along the seismic line (coincident with Bleakhouse Road), likely indicates strong fault-related disruption of expected Late Cretaceous-Tertiary geological units and Quaternary gravels.



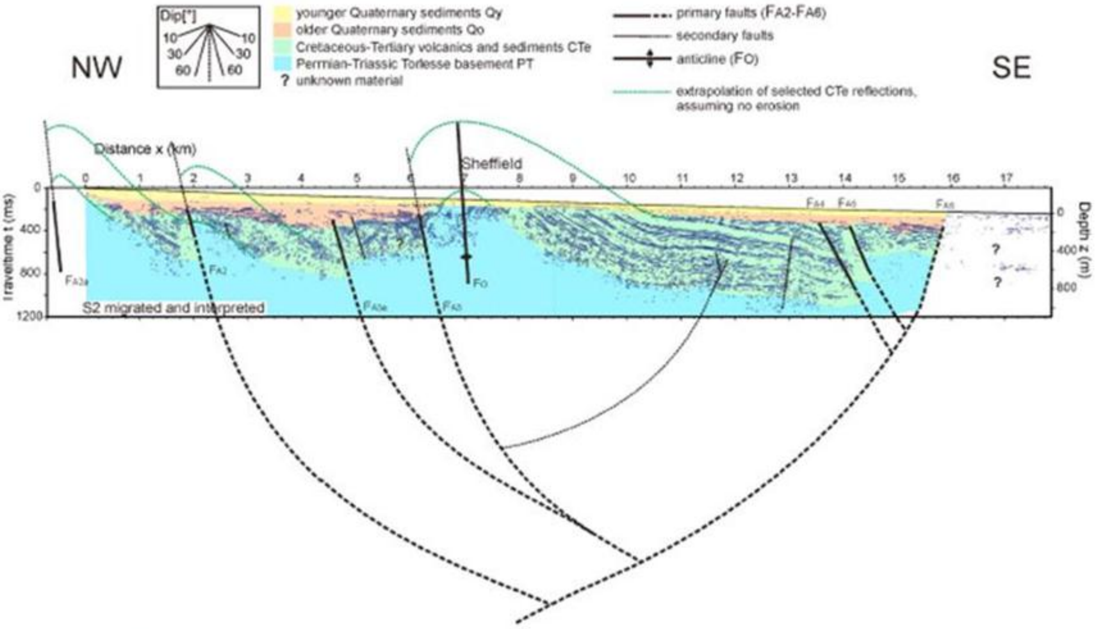


Figure 10. Sketch of interpreted geology superimposed on fully processed seismic section S2 (as in Figure 8) plus speculative extrapolation of some structural features.

Appendix D: Finnemore (2004)

Extracts from Finnemore (2004) showing the results of a seismic survey (Racecourse Hill-2 seismic line) conducted along Bleakhouse Road that runs between Racecourse Hill and the Waimakariri River.

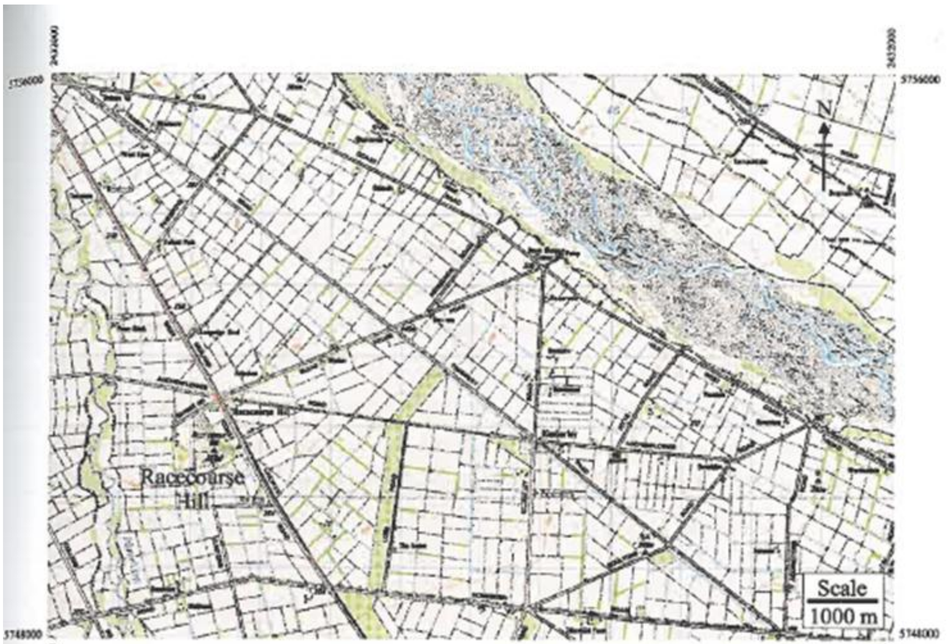


Figure 9.1: Map showing the location of roads where differential G.P.S. measurements were taken near Racecourse Hill.

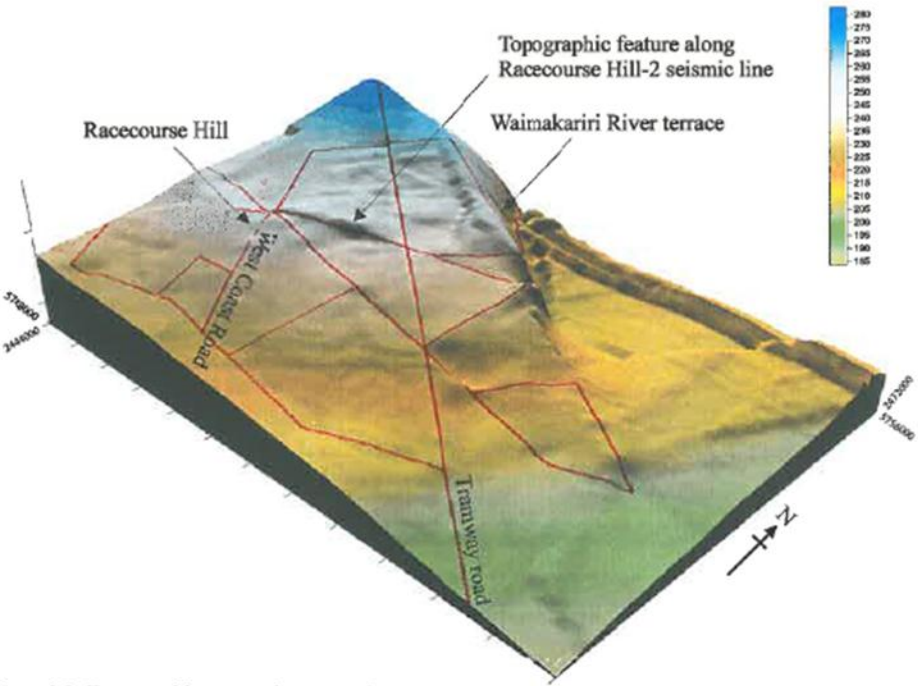


Figure 9.2: Topographic expression around Racecourse Hill. The topography is determined using P-code differential G.P.S. with an accuracy of +/- 1. A 70 x 70 m grid spacing using Kring gridding algorithms was used to produce the topographic model. Red lines show G.P.S. track.

143

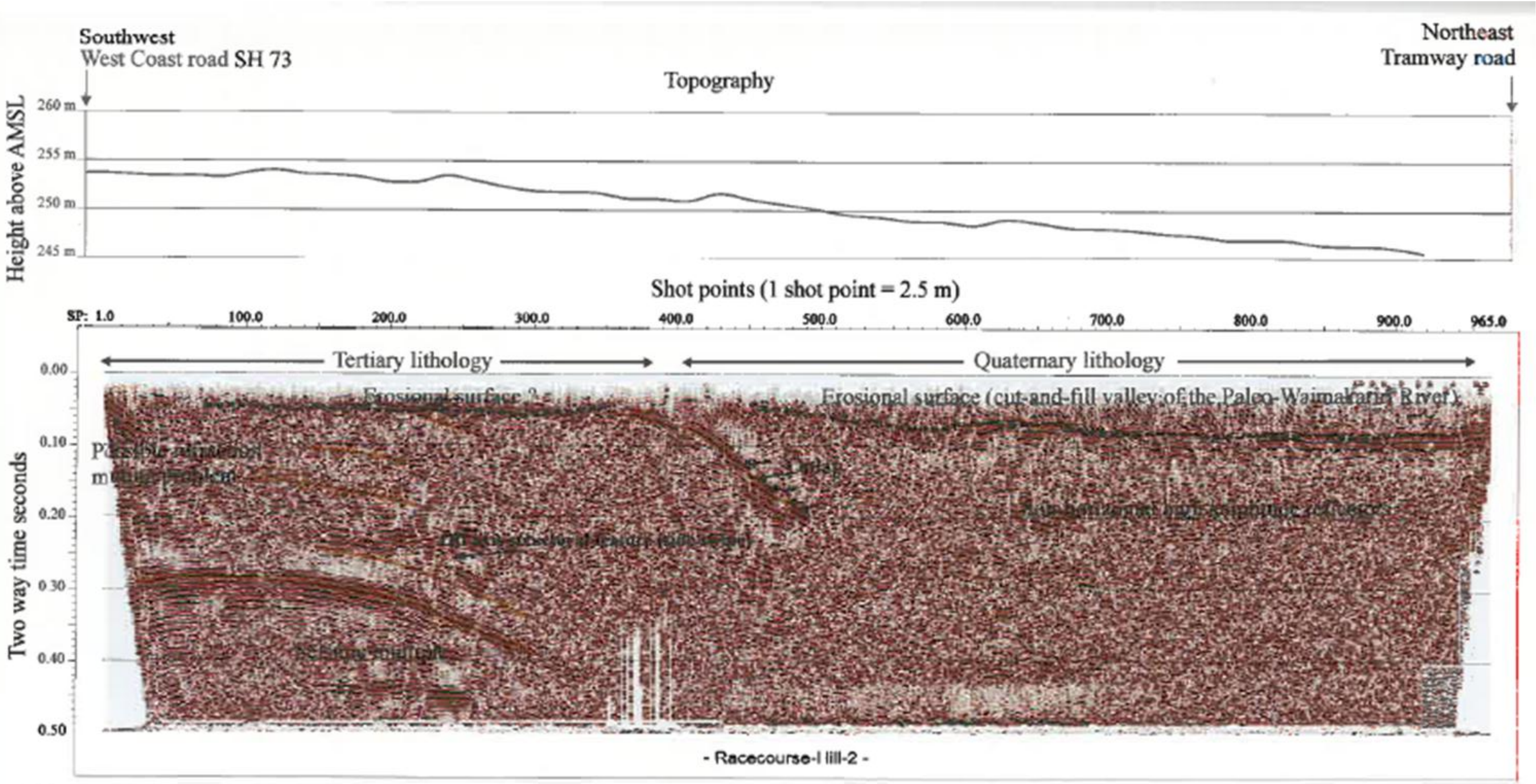


Figure 10.2: Final seismic section Racecourse Hill-2. Intepretation of the seismic section is shown on the overlay . Vertical exaggeration 1.5:1.

Appendix E: Interpretation of the available piezometric data

1. Estimation of the local hydraulic gradient

Methods

Piezometric data from wells along transect A-A’ (see Figure 3) have been divided into three separate datasets in an effort to filter the vertical flow gradient from the horizontal flow gradient.

i) Shallow unconfined groundwater in possible Waimakariri paleochannel inferred by Finnemore (2004) (see Appendix D), labelled here as ‘perched’.

ii) Assumed water table under Darfield town, labelled here as ‘phreatic’.

iii) Piezometric levels associated with deep wells mostly screening >200 m below ground level (bgl).

The hydraulic gradient for each depth group was subsequently estimated from linear regression (Figure E1).

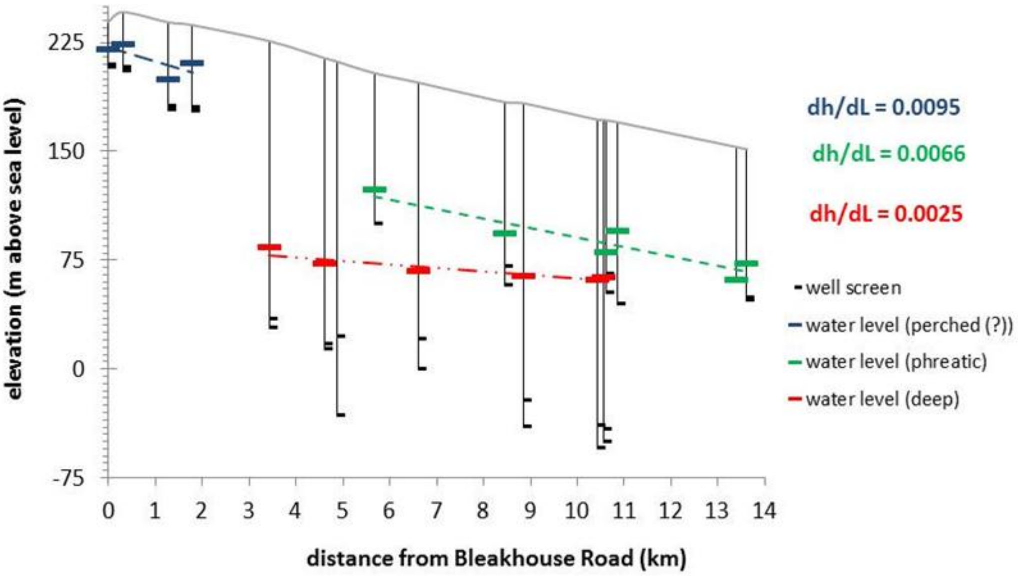


Figure E1: Piezometric gradient estimates based on water levels recorded in a set of wells under the Darfield area (see Figure 3 in the main text for the location plan).

Limitations

- The horizontal distance is that measured from origin of transect A-A’, that is, well BW22/0021 on Bleakhouse Road, not necessarily the true horizontal distance along the assumed flow vector.
- Groundwater levels are the highest levels recorded.
- Most data were sourced from ECan’s public WELLS database queried on 21 October 2013 and do not reflect measurements on any common date. Water levels for the ‘perched’ set of wells were provided by Fonterra, the shallowest levels for which were recorded in July and August 2013.

2. Prediction of groundwater flow direction

Note that all vectors shown in this analysis are estimates, marked by a visual inspection of the data, and not using any rigorous mathematical techniques.

- The red arrows in Figure E2 plot the general direction a contaminant plume emanating from Darfield or Kirwee would be presumed to take if inferred from ECan's regional piezometric contour dataset (the red contours). The length of the arrows roughly reflects the relative velocity assuming that the gradient is proportional to groundwater velocity.
- The black arrows mark the general topographic gradient, that is, the surface of the abandoned Waimakariri River fan and, hence, the assumed orientation of the main axis for the hydraulic conductivity tensor of an alluvial gravel aquifer.
- The green arrows denote an informed best guess of the true migration direction a contaminant plume emanating from Darfield or Kirwee would probably take.
- In effect, the red and black arrows mark the degree of uncertainty in the piezometric contour data available for analysis at present.

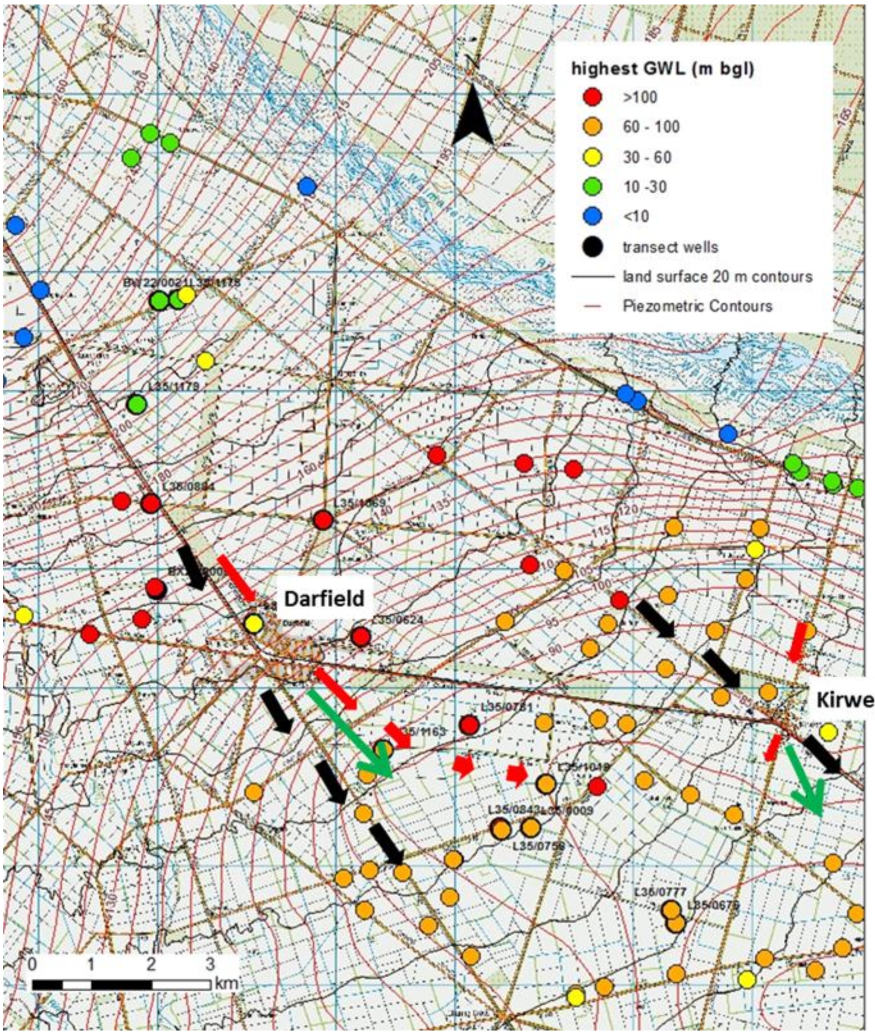


Figure E2: Predicted direction of contaminant transport from Darfield and Kirwee

Appendix F: Depths at which wells screen

A query of ECan's WELLS database in October 2013 records 23 bores drilled within an arbitrary 3-km radius of Darfield and four that are proposed for drilling. Of the existing bores, 16 are reported as either abandoned or unused. Information about the depths from which water is drawn is available for 13 wells, the distribution of which is shown in Figure F1. The wells screening at approximately 77 m bgl in Figure F1 relate to L35/0277 and L35/0340 and are reportedly 'not used' and 'capped/semi-permanent', respectively.

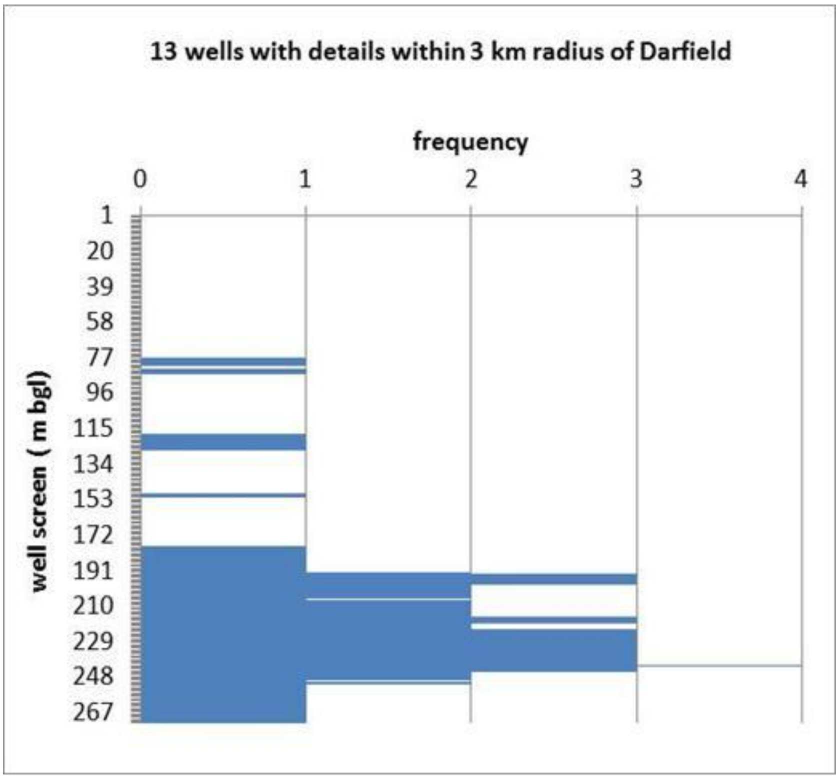


Figure F1: Frequency distribution plot for the depths at which wells screen the aquifer within a 3-km search radius of Darfield.
The data were exported from ECan's WELLS database during July 2013.

Thirty-three bores have been reportedly drilled within a 3-km radius of Kirwee and two more are proposed. Information about the depths at which wells are screened is available for 32 of the bores, with four of the bores reported as either abandoned or not used. The depth distribution of screened well intervals is shown in Figure F2.

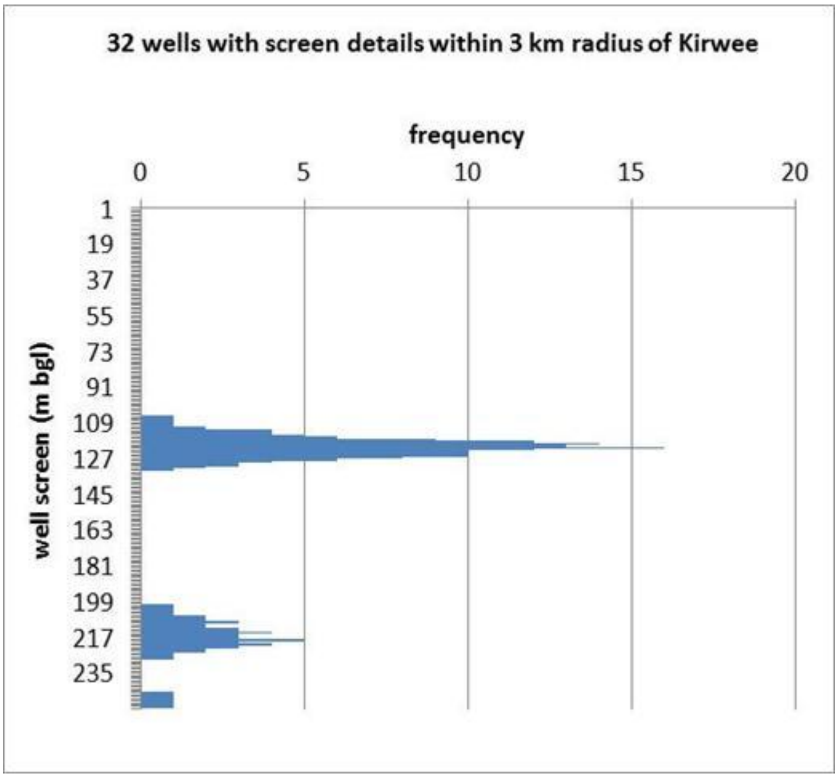


Figure F2: Frequency distribution plot for the depths at which wells screen the aquifer within a 3-km search radius of Kirwee.

The data were exported from ECan's WELLS database during July 2013.

Appendix G: Assessment of groundwater stresses in the Darfield-Kirwee area

A simple water balance has been calculated for a nominal 14,210 ha area that is marked in Figure G1, and largely covers the Darfield-Kirwee area, to gauge the relative hydraulic stresses induced by water abstraction on the groundwater system. The projected extension of the Hororata geological fault (assumed in this case to underlie Bleakhouse Road) defines the top boundary of the sub-regional aquifer studied here.

It is assumed that the groundwater system has effectively no connection with the Hawkins or Waimakariri Rivers, hence, the groundwater resource is completely dependent on LSR. This is a gross simplification yet conservative assumption, the potential errors in which are examined below.

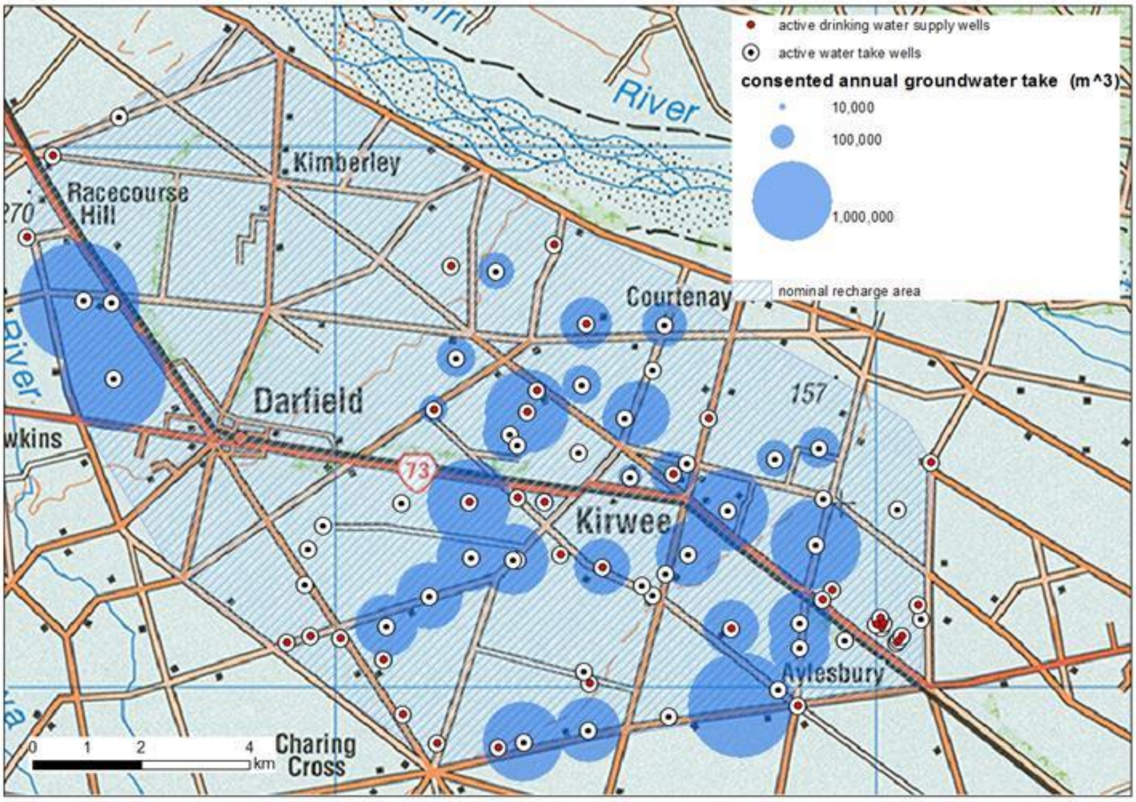


Figure G1: Location of active water take consents in the Darfield-Kirwee area. Wells recorded as potable water supply wells, for which no formal groundwater take consent is required if the daily take is <10,000 L, are marked in red. Other wells marked on the map are active and used for irrigation, industrial or stockwater uses.

The water balance has been computed assuming the aquifer can be treated as a simple closed system (ie, a bucket) for the sub-region of interest, marked by blue hatching in Figure G1. ECan provided information on all of the active groundwater take consents in the marked area (42 in total see Table G1; see Figure G1 for locations). The 'full effective annual' volume of groundwater consented for abstraction is 24,320,251 m^3/yr. Dividing this by the sub-regional area of 14,210 ha equates to an effective depth of abstraction of 171 mm/yr.

Table G1: Active groundwater take consents in the Darfield-Kirwee sub-region marked in Figure G1.

Data were provided by ECan's CONSENTS database queried on 17 October 2013.

Consent no.	Full effective annual volume (m^3)	Water use
CRC000502	237,610	Irrigation
CRC001888	540,660	Irrigation
CRC001889.2	729,960	Irrigation
CRC002098	290,850	Irrigation
CRC002099.2	1,195,950	Irrigation
CRC010861.3	715,340	Irrigation
CRC010890	313,800	Public Water Supply (Municipal/Community)
CRC010945.2	494,570	Irrigation
CRC010982.2	271,911	Irrigation
CRC011081.2	472,640	Irrigation
CRC020319.3	852,350	Irrigation
CRC022119.3	67,667	Irrigation
CRC030266	628,350	Irrigation
CRC030440	267,840	Irrigation
CRC030991	1,219,080	Irrigation
CRC031193.1	789,912	Irrigation
CRC031798.1	812,287	Irrigation
CRC032114	147,260	Irrigation
CRC040323	102,780	Irrigation
CRC041959.3	1,133,324	Irrigation
CRC042659.1	363,750	Irrigation
CRC042689.2	1,903,900	Irrigation
CRC042752.1	563,573	Irrigation
CRC042753	726,165	Irrigation
CRC042798	1,392,000	Irrigation
CRC060458.3	2,599,000	Irrigation
CRC101670	1,171,497	Irrigation
CRC135842	67,720	Irrigation
CRC136768	46,090	Irrigation
CRC951149.6	33,860	Irrigation
CRC951150.2	33,860	Irrigation
CRC951714.3	46,090	Irrigation
CRC951722.2	46,090	Irrigation
CRC981464.6	46,360	Irrigation
CRC982160	671,910	Irrigation
CRC982178.1	46,090	Irrigation
CRC991897	228,345	Irrigation
CRC992125	668,450	Irrigation
CRC992490.2	34,460	Irrigation
CRC061232	294,540	Irrigation
CRC093539.1	1,679,000	Public Water Supply (Municipal/Community)
CRC992345	373,360	Irrigation
TOTAL (m^3)	**24,320,251**	

The average annual rainfall for the Darfield-Kirwee area based on 30-years' historic virtual rainfall records sourced from the national climate database (CLIFLO) is 758 mm/yr. Assuming 30 percent of the annual rainfall actively recharges the groundwater system (ie, 70% is lost by evapotranspiration, which has been the general assumption of most LSR estimates for the region [David Scott, Hydrogeologist, ECan, personal communication, December 2013]), then it is estimated that the groundwater resource under Darfield and Kirwee is the recipient of 227 mm/yr of rainfall recharge. Note that in the nitrogen-leaching rate ‘look-up tables’ in Lilburne et al (2010), soil drainage estimates for the light soils in the Darfield-Kirwee area under dryland conditions are reportedly just 140 mm/year. This disparity in LSR estimates has recently been recognised by ECan and serves to highlight the uncertainty in the general knowledge about the Canterbury hydrological system (Lisa Scott, Groundwater Quality Scientist, ECan, personal communication, November 2013).

Depending upon which LSR estimate is believed, the consented groundwater abstraction in the area equates to between 75 percent (171/227) and >100 percent (171/140) of the net aquifer recharge, should the system be dominated by LSR. All but two of the groundwater take consents are for irrigation water, for which it is generally acknowledged that the actual water usage is less than the consented water usage (Glubb and Durney 2014). Metering of actual water use would reduce this uncertainty. The effects of return irrigation water have not been factored in and could be significant.

Comment on uncertainty of the water balance

The relative scale of the consented groundwater takes evaluated previously represents a conservative estimation based on our conceptualised model of the Darfield-Kirwee groundwater system that assumes no river recharge inputs to the system from either the Hawkins or Waimakariri Rivers.

At the other end of the scale, one could argue that some undetectable volume of water from both the Waimakariri River and the Hawkins River leaks into the aquifer underlying the central Canterbury Plains along the river reaches bordering the Darfield-Kirwee area and that this provides continuous recharge to the system. The calculations that follow involve a raft of arbitrary assumptions regarding river leakage rates. The aim is to provide some understanding of the scale of uncertainty in the water balance computed for Darfield and Kirwee.

Although no significant flow losses are reported for the Waimakariri River between the Waimakariri Gorge and Courtenay (White et al 2011), it remains that some leakage may occur from the river bed undetected, and within the range of flow gauging errors. Considering the seven-day mean annual low flow for the Waimakariri River is around 44 m^3/s, a river low-flow gauging error of 5 percent equates to about 2200 L/s. If one assumes this potential measurement error equates to immeasurable flow losses from the river between the gorge and SH1 flow recorder sites and the losses are distributed evenly along this 49 km reach, then the 8 km of the Darfield-Kirwee aquifer that borders the Waimakariri River (see Figure G1) might be the recipient of 8/49 x 2200 = 359 L/s (or 180 L/s if one were to assume these speculative losses are split 50:50 to each side of the river).

The mean flow statistic for the Hawkins River is 742 L/s at Auchenflower Road (ie, upstream of Racecourse Hill). As mentioned in the main report, essentially all flow from the Hawkins River infiltrates to groundwater. Assuming half of this leakage to the central Canterbury Plains were to occur upstream of Darfield, then one could roughly estimate that the Hawkins and Waimakariri Rivers collectively provide a continuous input of 551 L/s of water to the Darfield-Kirwee area. If distributed evenly over the nominal 14,210 ha area marked in Figure G1, then the river inputs equate to 122 mm/yr. This recharge value is almost half that estimated for LSR (227 mm/yr). For this scenario, the consented groundwater abstractions in the Darfield-Kirwee area equate to 49 percent (171 mm/349 mm) of the annual water budget, which is a relatively significant portion of the water balance.

The water balance calculations in this Appendix are fraught with gross uncertainty, because the true hydraulic influence of the rivers on the aquifer at Darfield-Kirwee remains to be properly characterised. As stated in the main report, the general impression from the regional water quality data is that the aquifer at Darfield-Kirwee is largely insensitive to any river recharge inputs, thus from a water quality management perspective the uncertainties in the water balance are not of major importance. A precautionary approach to water quality management in the region would assume no river recharge inputs.

Appendix H: Existing wells in the Darfield-Kirwee area

Figure H1 shows the distribution of bores/wells in the Darfield-Kirwee area according to ECan's WELLS database (queried on October 2013). Status codes are as follows: AE = active; NO = not operational; PL = planned/proposed; PW = water permit proposed. Reported usage is also indicated.

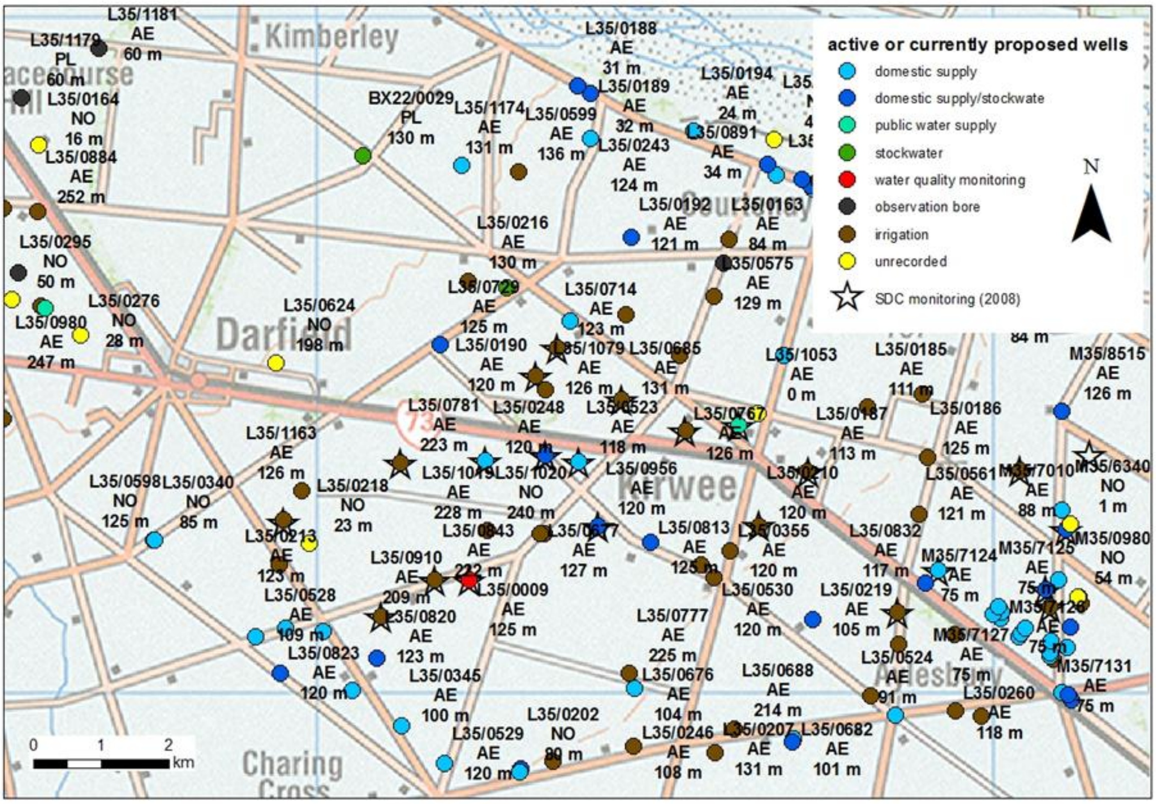


Figure H1: Wells in the Darfield-Kirwee area. Stars indicate wells used in SDC's 2008 survey.

Tables H1 and H2 contain lists of the wells surveyed by SDC over the years. The well construction details are provided, as is a well ranking, which is the perceived use of the well for any future water quality monitoring of potential impacts from septic tanks. The score system is as follows: 1 = useful, retain the well; 2 = some use, retain; 3 = not informative, abandon.

The colour formatting applied to the different physical parameters is green = good; red = bad.

Table H1: Details of SDC survey wells in Darfield.

Well No	Depth	Documented use	Top of well screen (m bgl)	Bottom of well screen (m bgl)	Screened length (m)	Water level above screen height (m)	Distance from Darfield (km)	For	Against	Rank
L35/0213	122.8	irrigation	113	122.8	9.8	21.44	3.05	Down-gradient of Darfield;		1
L35/0009	125	water quality	no information				4.82	Down-gradient of Darfield;	No screen info	2
L35/0528	109	irrigation/ domestic supply	106	109	3	28	1.58	Down-gradient of Darfield;		2
L35/0876	130	irrigation/ domestic supply	no information				6.63	Impacted by animal waste	No screen info	2
L35/0781	223	irrigation	205	223	18	86.15	4.84		Deep	3
L35/0843	221.84	irrigation/ dairy	212.84	221.84	9	104.14	4.35	Down-gradient	Deep; distant	3
L35/0884	251.6	irrigation	191.25	197.24	39.01	48.65	7.24		Up-stream of Darfield;deep; long stream	3
L35/0910	209	irrigation	185	209	24	79	3.43	Down-gradient of Darfield	Deep	3
L35/0980	246.8	irrigation	191.5	203.5	44.5	40.65	5.89		Up-gradient of Darfield;deep; long screen	3

Table H2: Details of SDC survey wells in Kirwee.

Well No	Depth	Documented use	Top of well screen (m bgl)	Bottom of well screen (m bgl)	Screened length (m)	Water level above screen height (m)	Distance from Kirwee (km)	For	Against	Rank
L35/0523	118.2	irrigation/ public water supply	115.2	118.2	3	42.9	1.65	Background well	Cross-gradient	1
L35/0187	113.1	irrigation	109.4	113.1	3.7	54.73	1.91	Down-gradient of Kirwee	Cross-gradient	1
L35/0191	115.2	public water supply	112.2	115.2	3	47.53	0.79	Central to Kirwee		1
L35/0210	120.1	irrigation	118	120.1	2.1		1.78	Down-gradient of Kirwee		1
L35/0562	114	domestic supply	111	114	3		4.27		Distant	2
L35/0568	113.45	irrigation	106.5	113.45	6.95		4.13		Distant	2
L35/0685	131	irrigation/ dairy	118.38	131.1	12.72	32.08	1.05		Up-gradient	2
L35/0767	125.5	irrigation	119.5	125.5	6	36.5	0.00	Historic E.coli impact	Up-gradient	2
L35/0870	114	domestic/ stockwater	111	114	3	35.9	4.21	Down-gradient of Kirwee; potable supply	Distant	2
L35/0248	120	irrigation/ domestic supply	117	120	3	39.54	3.00		Cross-gradient	3
L35/0729	125	irrigation/ domestic supply	117	123	6	20.68	3.85		Cross-gradient	3
L35/0956	120	domestic/ stockwater	117	120	3	34.5	1.92		Up-gradient	3
L35/0190	120.1	irrigation/dairy	117.1	120.1	3	43.58	2.35	Up-gradient of Kirwee		3
L35/0714	123.3	irrigation/ domestic supply	116.3	123.3	7	22.2	2.27		Up-gradient	3
L35/1173	250.83	domestic/ public water supply	242.6	250.6	8	131.89	2.36		cross-gradient; Distant; deep	3
M35/7555	107	irrigation	102	107	5	56	5.99		Distant	3
M35/0921	65.5	irrigation/ domestic supply	60.4	65.5	5.1	35.53	5.98		cross-gradient; Distant	3
M35/7010	88	irrigation/ domestic supply	82	88	6	82	5.81		cross-gradient; Distant	3
M35/9293	72	domestic/ stockwater	66	72	6	10.2	5.83		Distant	3
M35/9628	120.25	irrigation	114.25	120.25	6	55.7	4.97		Cross-gradient; Distant	3
L35/0194	23.7	domestic supply	no information				4.42		Waimakariri River	3