Groundwater Exploration in the Ida Valley

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Foreword

Groundwater in Otago is frequently the sole or major source of water to supply basic water needs to communities and stock watering. Currently groundwater only supplies a small proportion of irrigation needs, however there is increasing pressure for people to turn to groundwater because surface water supplies are heavily allocated.

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

The Ida Valley is in one of the driest parts of the region and new groundwater sources would be a valuable asset. This report provides an assessment of the likely availability of sustainable sources of groundwater, based on geological data, geophysical surveying and drilling exploratory bores. The results will assist the community make better informed decisions in selecting future sites for potential groundwater abstraction.

Executive summary

Exploration for groundwater resources was carried out in the Ida Valley during 2011. In the valley, existing water supplies are mostly sourced from the water races, and there is a great deal of pressure placed on surface water resources. In contrast, there is little use of groundwater, mainly because previous drilling has had limited success. The availability of aerial geophysical survey data has given the Otago Regional Council (ORC) the opportunity to locate potential groundwater sources with greater confidence.

This study has successfully used the aerial geophysical data to delineate groundwater drilling targets in the Ida Valley. Exploratory drilling into the Tertiary sediments has shown the existence of productive groundwater-bearing horizons in the south-western part of the Poolburn catchment.

Productive sediments comprise medium to coarse grained sand derived from schist fragments. These sediments represent fan deposits of colluvium and alluvium sourced from the Raggedy Range. The fans of coarser material lie as lenses up to 3m thick within reworked Bannockburn Formation silty sands and are typically confined.

Pumping tests were carried out on all of the bores drilled in the Tertiary sediments. These tests varied from simple recovery tests following bore development, to a comprehensive 24-hour pumping test at Meade Road. Transmissivity values range from 10-40 m^2/d for the reworked silty sand. Coarser sand horizons in the fan deposits have transmissivity values of up to 80 m^2/d. Greywacke gravel, presumably of reworked Hawkdun Formation, intercepted in a bore at Idavale, gave a transmissivity value of 324 m^2/d.

All the Tertiary sediment exploration boreholes are capable of providing farmers with at least a domestic and stock water supply. A small-scale irrigation supply is possible from the higher yielding boreholes. Specific capacity values measured after 100 minutes pumping ranged from 16 to 41 l/min per meter of drawdown.

Water quality results show that recharge and groundwater circulation is occurring in this part of the valley. Discharge for the Ida Valley is limited by the elevation of the Poolburn Gorge, which is around 395m. Water quality is expected to deteriorate rapidly in groundwater below this elevation.

Two exploratory bores were also drilled into structural targets in the schist bedrock. The rock was highly fractured, but wireline packer testing showed that the permeability of the schist is low. The upper 20-30m of the schist is likely to provide up to 5 l/min/m, which is sufficient for domestic or stock water supply. The high metamorphic grade of the schist renders it an unlikely source for significant volumes of water.

This study has identified areas where there is potential for higher yielding groundwater resources in the Ida and Manuherikia valleys. We believe that groundwater for stock and domestic supply can also be sourced from finer grained areas of reworked Tertiary sediments. However, access to groundwater in these finer gained deposits depends on careful screen selection and the installation of a sand-filter pack.

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1 Introduction

The Ida Valley is one of the most water-short catchments in Otago. Median annual rainfall is 500mm, and only 12% of this is estimated to infiltrate below the soil profile (Wilson & Lu, 2011). All the surface water resources are currently fully allocated, with highland storage reservoirs supplying water races that are tightly rationed. Future water use is expected to be subject to residual and minimum flows in the Poolburn Stream. Furthermore, as farmers use more efficient spray irrigation, there is likely to be less shallow water available for stock ponds in down gradient properties, especially in the Poolburn catchment.

Access to groundwater resources has the potential to provide a robust water resource during times of surface water deficiency. This is particularly important in the light of future climate variability. A groundwater resource can also provide stock water in areas where surface water is scarce. We hope that, by developing a conceptual model for locating groundwater resources in the Ida Valley in this study, groundwater exploration will become more successful in the future in other water-short areas of Central Otago.

This report focuses on exploration drilling for groundwater in the southern Poolburn catchment. Airborne geophysical surveys carried out by Glass Earth identified an area of higher permeability sediments in the south-western corner of the catchment. Drilling for groundwater in these sediments was carried out in the Ida Valley by McNeill Drilling from mid-June to mid-July 2011. Experimental drilling was also carried out on two structural targets in the schist basement.

The report provides a background of the geology of the Ida Valley. Interpretations of the Glass Earth geophysical data are presented along with the rationale for selecting drilling targets. The results of drilling are also presented along with a geological deposition model to help the location of groundwater in similar structural settings. The report includes many technical terms, so a glossary is included to assist the reader.

2 Physiography

The Ida Valley lies between the Raggedy Range and North Rough Ridge. These schist ranges are oriented south-west – north-east and form part of the basin and range topography found in much of Central Otago (McSaveney & Stirling, 1992).

The Ida Valley's surface hydrology comprises the Idaburn catchment, which drains the Ida Range in the north, and the Poolburn catchment, which drains the South Rough Ridge in the south. These water courses meet at the Poolburn Gorge, where the Idaburn has down-cut through the Raggedy Range in response to tectonic uplift of the schist basement during the Quaternary period.

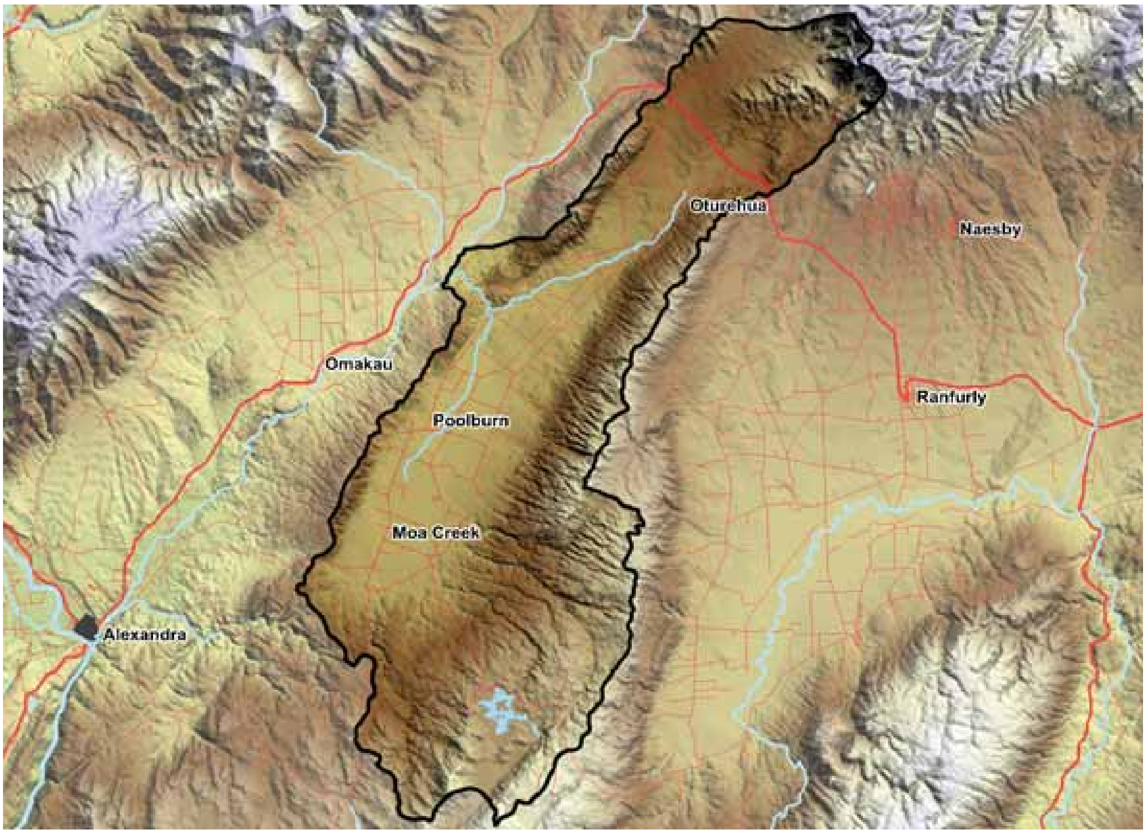

Figure 1. Location map.

3 The geology of the Ida Valley

The Ida Valley's regional surface geology is well known from earlier geological reports and maps. Many reports have been written about specific areas or aspects of Central Otago's geology, and these are summarised in Youngson *et al*. (1998). The most detailed report written on sediments in the Ida Valley was written by Barry Douglas (1986), as part of an investigation into coal and lignite deposits in the area. Two regional scale geological maps also cover the Ida Valley and beyond (Turnbull, 2000; Forsyth, 2001).

These investigations are useful sources of geological information in the Ida Valley, given the lack of material in the ORC database. Table 1 lists the information available about boreholes for the Poolburn catchment. However, of the fourteen listed, seven are too shallow to provide any useful information. Eight of the bores have geological logs, and five of these are of an informative depth. Only three boreholes have been tested for the hydraulic properties of the sediments encountered.

Table 1. Available drilling information for the Poolburn catchment.

Bore Number	Easting	Northing	Depth	Screen	Specific Capacity ($m^3/d/m$)	Log?
C-2016	1347150	5000446	245	-	-	Y
C-2017	1341198	4990987	166	-	-	Y
G42/0131	1337196	4990683	35.5	33.9	6.9	Y
G42/0132	1336991	4995185	33	14.5	2.7	Y
G42/0617	1339996	4991887	4.3	3.1-4.3	-	Y
G42/0618	1337701	4997717	13	7.9-9.5	-	N
G42/0641	1337293	4993485	6.5	-	-	N
G42/0649	1336591	4994585	28.5	-	-	N
G42/0670	1337091	4995085	35	-	-	N
G42/0701	1336891	4995535	6.4	-	-	N
G42/0744	1337463	4992847	9.4	6.5-9.4	4.2	Y
H41/0152	1342390	4998693	5.0	-	-	N
H42/0183	1341092	4996190	138	-	-	Y
H42/0184	1342094	4995291	144	-	-	Y

The bore logs consistently show a sequence of sand, silt and clay. Low permeability water-bearing horizons have been encountered during drilling. However, because of the limited information available in the bore logs, the location of these horizons is not predictable.

To find water-bearing layers, we need to understand the geological processes that formed the host sediments. This requires the development of theories about how the geology of the area has evolved over time. Any uncertainties can be reduced by combining geological knowledge with information gained from drilling, geological mapping and geophysical surveys. A model can then be developed, which can be used to identify areas of more permeable sediments.

3.1 Structural geology

The Ida Basin is part of the basin and range type of topography that covers much of Central Otago (McSaveney & Stirling, 1992). Compression of the earth's crust along the Alpine Fault has folded the schist bedrock into a series of domed ridges and corresponding depressions. This deformation began during the Late Pliocene, and continues to the present day (Markley & Norris, 1999). On a regional scale, the resulting basin and range topography is like a ruffled carpet. The depressions or basins contain Tertiary period sediments, while these same sediments have been eroded from the ridges to expose the underlying schist bedrock.

The Ida Valley is bounded by asymmetrical fault-propagated anticlines along the Raggedy Range and Rough Ridge (Markley & Norris, 1999). These folds have warped the fabric of the schist rock (foliation) and the bedding of the overlying Tertiary sediments, which were originally horizontal.

The folds are asymmetrical because the axial planes of the folds have been tilted, making them steeper on one side than the other. The folds are also faulted along the basin margins because of the pinching of the folded crust in the positions of maximum flexure. The fault displacements[1] are not large, compared to the geometric changes wrought by folding.

The axis of the Ida Valley syncline trends parallel to the axis of the valley at 035º. Exposure of the Blackstone Fault, which bounds the western margin of the valley (1334435E 4990460N), shows a shear orientation of 035/60W. This orientation is consistent with regional observations of fold asymmetry, and it is likely that the fold axes also dip 60º to the west.

3.2 Lithology

Basement geology of the Ida Valley consists of schist that has been metamorphosed (recrystallised) to a high grade (biotite greenschist facies, textural zone IIIB-IV). The surface of the schist forms a nearly planar regional unconformity (Landis *et al*., 2008).

The top few meters of the schist beneath this unconformity have been extensively altered to a pale-green colour by water-rock interaction. Under anoxic (reduced) conditions, the schist mineralogy was altered from mica to kaolinite and smectite clay (Craw, 1994). This alteration occurred as the schist became progressively buried by overlying sediments, and the upper surface of the schist was subject to diagenesis.

The schist is overlain by Tertiary period sediments of the Manuherikia Group. The Manuherikia Group consists of terrestrial meandering flood plain, lake and lake delta sediments dating from the early to middle Miocene age. These sediments pre-date the tectonic stresses that gave rise to the folding of the crust into basin and range terrain. This means that the Manuherikia Group was deposited on a regionally flat schist surface in a low energy environment.

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[1] The distance that movement of the fault has offset rocks between one side of the fault plane and the other

The thickness of Tertiary sediments within the Ida Valley can be determined from boreholes drilled through the sediments into the schist basement. The greatest depth to the basement is 256m, which was found in the Ministry of Energy lignite resource investigation drill hole C-2014, at Oturehua. At Poolburn, the schist has been intercepted in two boreholes on the eastern limb of the syncline at C-2017 (147m) and H42/0184 (144m). Gravity surveys have shown that the sediments are about 600m thick at the syncline axis in the vicinity of Boundary Road (Markley & Tikoff, 2003).

In the Poolburn catchment, Manuherikia Group sediments mostly consist of Bannockburn Formation. This unit consists of interbedded clay, silt and sand, originally deposited into Lake Manuherikia 19-16 million years ago (Mildenhall & Pocknall, 1989). Bannockburn Formation sediments are extensive throughout Central Otago, as Lake Manuherikia extended from northern Southland to mid-Canterbury. This lake is known to have been the home of freshwater crocodiles and was fringed by beech and podocarp forest.

Drilling for this study has shown that the Bannockburn Formation is overlain by at least 40m of reworked Tertiary sediments and schist detritus. While these reworked deposits appear to be the same as that of Bannockburn Formation, the presence of oxidised angular schist fragments helps to distinguish the two in the field. These reworked sediments were deposited as colluvium or fluvial fans during the uplift of the schist ranges from the Late Pliocene (5.3 million years) onwards.

The fan deposits are in turn overlain by a thin veneer of Pleistocene river gravel terraces, the oldest being 340,000 years old (Q10, Forsyth, 2001). The older Pleistocene terrace deposits tend to be found on the edges of the basin or in elevated remnants within the core of the basin. The most recent alluvial gravels are generally associated with modern stream and river drainages.

3.3 Hydrogeology

The water table lies within a few metres of the surface across much of the Ida Valley. Groundwater-fed ponds and wetlands pepper the floor of the valley, particularly in the Poolburn-Moa Creek area. The abundance of these ponds indicates that the basin has a shallow unconfined water table and is fully saturated.

Drilling has shown that the thin veneer of Pleistocene gravels is typically underlain by a shallow clay pan, which acts as a barrier to groundwater drainage. The pools are probably formed in areas where there are large permeability contrasts in the Pleistocene terrace sediments, or where surface gravel deposits are thinner.

Drilling for groundwater in the Ida Valley has limited success, despite numerous attempts by residents after extended dry periods (*pers. comm.*, Graeme Stewart, McNeill Drilling & Pumping Ltd, 12 April, 2010). Given the shortage of water, and that irrigation races are the only other form of communal water supply, the lack of water bores is indicative of how low the groundwater yield is in the valley. There have been few measurements of permeability carried out in the Ida Valley (Table 1); however, the data that does exist suggests that the

Tertiary sediments have low permeability. The Quaternary alluvium has a more moderate permeability, due to recent alluvial reworking and the presence of schist gravels.

Schist permeability consists of primary pore-space and secondary fracture porosities. Primary porosity is generated by spaces in foliation, which is negligible in schist. Secondary or enhanced porosity is formed from fracturing (jointing) and shearing. Regions of interlinked secondary porosity are considered expected to contribute the most to schist permeability.

Water bores have difficulty in producing groundwater unless their position and depth coincides with intense jointing or fracturing, which substantially increases bore yield. Bore development in schist rock is, therefore, often ‘hit-and-miss’.

4 Geophysical prospecting

This section describes how geophysical data was used to identify targets for groundwater exploration drilling in the Ida Valley.

In 1997, ORC formed a partnership with gold explorer, Glass Earth Gold Limited (Glass Earth), to share the costs of conducting an airborne geophysical survey covering about half of Otago's landmass. The technologies used were airborne electromagnetic resistivity traversing and magnetic susceptibility remote sensing. In 2007 an airborne geophysical survey was flown on flight lines oriented north-east, at spacings of 300m. A total of 50,000km of survey lines were flown during the seven-month campaign.

Since completing the survey in August 2007, Glass Earth has undertaken extensive processing of the raw and processed data in a Geographic Information System (GIS) format. The ORC received the processed contour grids of geophysical data in two distinct formats:

- contoured maps of resistivity for four different frequency domains
- profiles of conductivity (conductivity - depth inversions) that are projected along every tenth flight lines (i.e. 3km apart).

The ability to separate resistivity data into different frequency classes provides an opportunity to map cumulative resistivity at specific depths. High electromagnetic frequencies tend to highlight shallow strata resistivity returns, while low frequencies highlight deeper returns. The different frequency domains correspond to the following approximate depths:

140 kHz	18m
40 kHz	21m
8,200 Hz	25m
1,800 Hz	30m

4.1 Interpretation of geophysical data

The geophysical surveys carried out by Glass Earth were used to target areas of higher groundwater permeability. The detection of groundwater targets is based on 'rule-of-thumb' relationships between geophysical and hydrogeological properties of different sediments. These relationships have been constructed from previous surveys conducted throughout New Zealand (e.g. White, 1985). This prior knowledge allows the following assumptions to be made for saturated sediments in Central Otago:

- Saturated sediments will display high resistivity when relatively 'clean' (i.e. free of silts and clays), and low resistivity when the overall silt and clay content is high.
- Fresh schist rock will display moderate to high resistivity values.
- The altered schist unconformity will display low resistivity values.
- Lignite seams within some of the Tertiary terrestrial sediments have a high resistivity that would imitate the signature of clean sandy gravel alluvium. However, the thickness and extent of coal seams is not significant in the Ida Valley lignite measures.

Electromagnetic techniques have a resolution constraint that needs to be taken into account when interpreting the results of surveys for groundwater sources. Survey resolution tends to decrease with depth because the signal return is a composite (cumulative) value of all the overlying material. Thus, layers that are thick or have a high or low resistivity tend to soak up the electromagnetic signal. Consequently, the technique has difficulty detecting aquifers sandwiched between low permeability materials, and its ability to do so decreases with depth.

Take, for instance, a 5m thick sandy gravel layer with a resistivity of 400 Ωm embedded within silty gravels or siltstone of 40 Ωm resistivity at 60m depth. The sandy gravel without the silt matrix would be a useful aquifer after drilling, but the difficulty of resolving such a thin resistive layer within thicker conductive layers would mean that the aquifer was almost invisible (Nobes, 1999).

Despite the technique's inability to detect individual water-bearing horizons, the results are still useful for identifying areas where resistivity is higher in the overall profile. These areas typically indicate that the sediments were deposited in a higher energy environment, and therefore tend to contain coarser material. It is safe to assume that drilling in these areas is more likely to intercept permeable horizons than elsewhere.

4.2 Prospectivity of the Tertiary sediments

We produced contoured resistivity maps of the electromagnetic survey results for the Ida Valley to identify groundwater targets. Figure 2 shows the resulting resistivity colour flood in the 8200 Hz frequency domain, which corresponds to a penetration depth of about 25m. Purple and blue hues have low resistivity and are indicative of low permeability sediments overall. These sediments are probably dominated by clay and silt deposited in a passive depositional environment.

In Figure 2, the higher resistivity areas are represented by red and yellow hues. Pliocene gravels of the Hawkdun Formation show as concentrations of red hues at the northern end of the valley. Low permeability sediments dominate the remainder of the Ida Basin, except for two anomalies at Auripo and Moa Creek (circled in Figure 2). These sediments are expected to be of higher permeability overall and were probably deposited in a higher energy depositional environment. Drilling in these areas is more likely to result in the interception of coarser sediments.

Despite the impression that the range of resistivities contoured in Figure 2 is wide, in fact, it is low, when considered relative to the full range of water-bearing sediments found elsewhere in the region. The highest resistivity value represented in Figure 2 is 100 Ωm, which is barely equivalent to silty sand in terms of grain size. Typical resistivity in the Ida Basin for the 8,200 Hz frequency domain ranges from 10 Ωm to 40 Ωm, which is equivalent to clay and silt.

The geological assessment of the Ida Valley supports the idea that the basin is primarily filled with clay, silt and silty sand. Available bore logs show that coarser sediments, such as sands and gravels, tend to be mixed with significant silt and clay components. Cleaner horizons also tend to be very thin, which suppresses overall groundwater permeability.

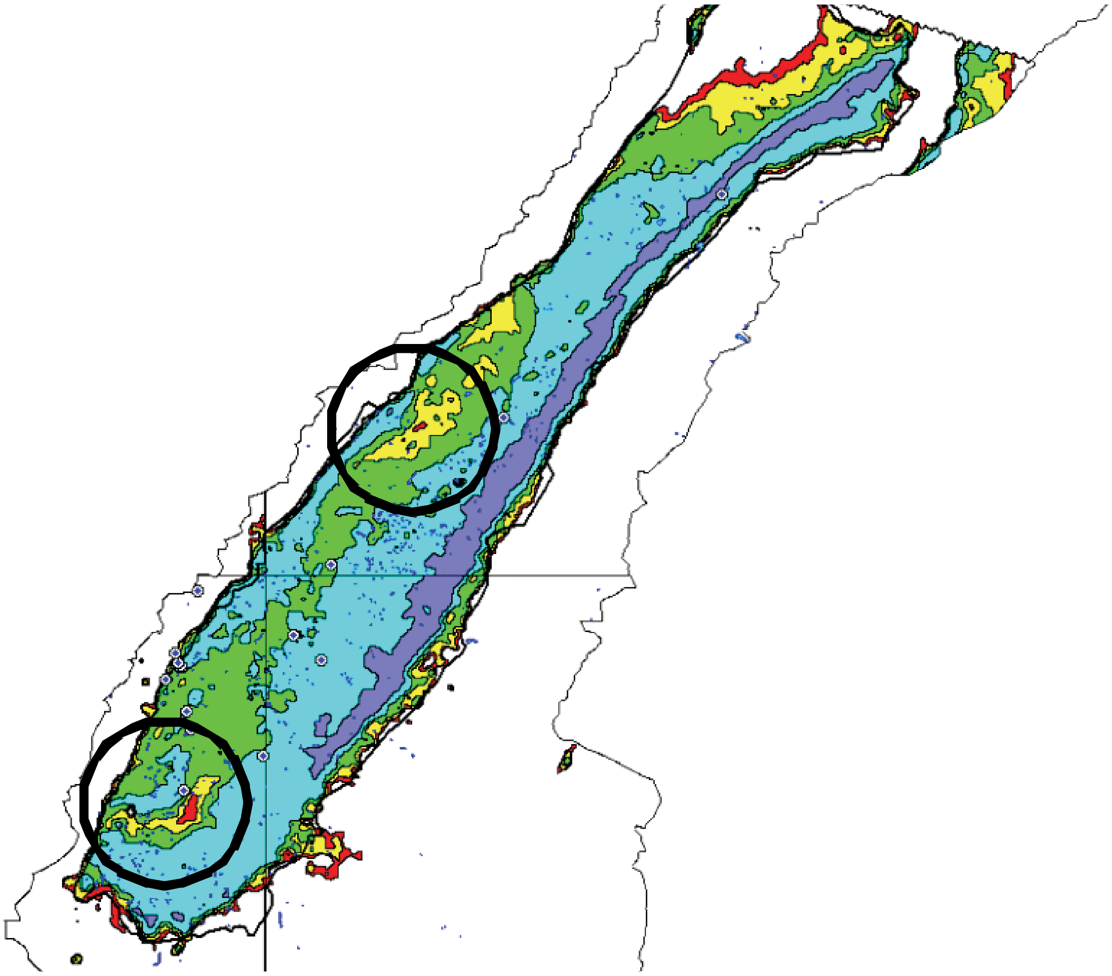

Figure 2. Resistivity contours for the Ida Basin, highlighting two areas with anomalously elevated resistivity.

Moa Creek anomaly

Figure 3 focuses on the southern-most of the two Ida Valley resistivity anomalies in the Moa Creek area. The dashed black lines give an interpretation of formational bedding lines suggested by the resistivity pattern. The solid arrowed black lines represent mapped Miocene river-channel alignments.

This figure also shows the presence of elevated resistivity (yellow and red hues) surrounded by a groundmass of purple and blue hues, which indicate low resistivity. Given that the water table in the Moa Creek area is very shallow and that all the high-lighted materials would be saturated, the elevation in resistivity probably reflects a contrast in lithology. This is likely to indicate an increase in the coarseness and decrease in silt or clay content.

The sedimentary structure lines in Figure 3 were originally considered to reveal a synclinal-fold structure in the basin. This interpretation is consistent with the contrast in resistivity seen across the Ida Valley from east to west.

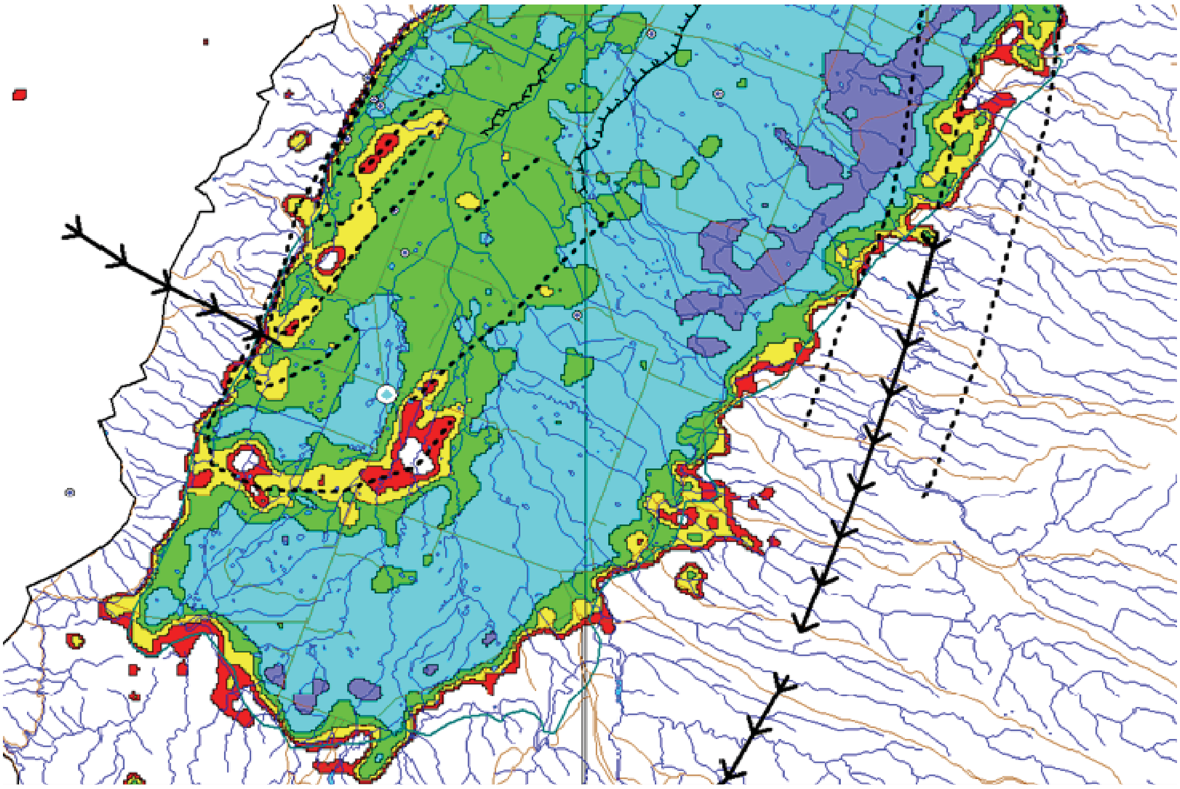

Figure 3. **Expanded map view of the Moa Creek area showing the zone of higher resistivity.**

The Moa Creek target shows the best prospectivity for groundwater in the Ida Valley. There are two main aspects of the resistivity results that make this target attractive for drilling. Firstly, bulk resistivity values are elevated in the area. Secondly, the identification of a fold-type structure suggests some predictability of the sediments, such as continuous coarser horizons.

A map of each of the four frequency domains is shown for the same area in Figure 4 to illustrate how resistivity in this area changes with depth. Higher resolution can be seen in the uppermost maps, and a decrease is seen with depth.

The maps show the presence of higher resistivity within the upper 20-25m of the sedimentary pile. Resistivity below this depth retains some influence of the overlying sediments, but is typically less resistive than the shallower high frequency domains. This indicates that drilling would have the best chance of success in the upper 25m of the sedimentary sequence.

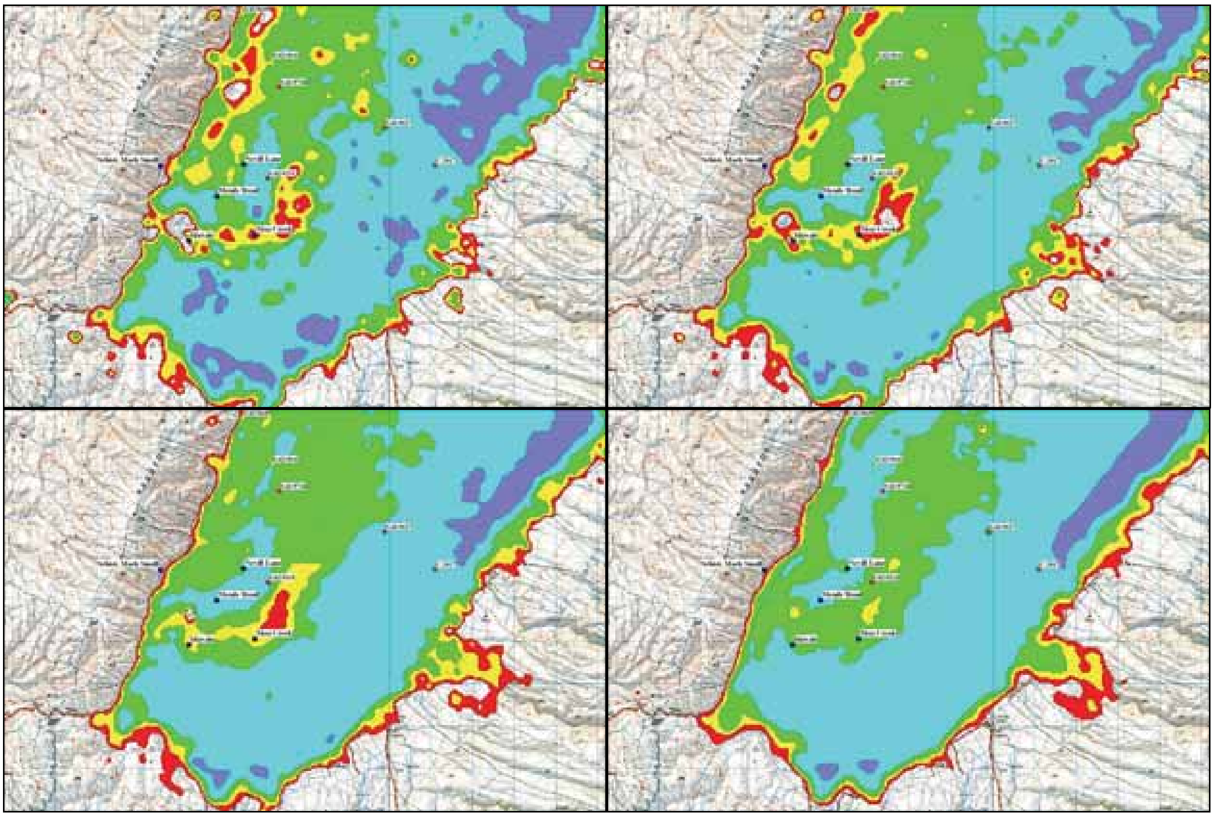

Figure 4. Resistivity contour maps of Moa Creek area. The maps represent increasing depth from left to right, the lower right being the deepest profile (~28m depth).

4.3 Prospectivity of the schist

Given the poor indications of groundwater potential in the sedimentary basins, we considered it worthwhile to delineate structural targets in the schist basement. While generally unproductive for groundwater exploitation, schist rock does provide groundwater in some instances. Favourable settings require an interconnected series of high density fractures to provide both groundwater storage and permeability.

Typical specific capacities for bores installed in schist range from 1.8 l/min/m to 4.2 l/min/m; consequently, vertical bores into the schist usually require the bore to be of sufficient depth to:

- allow significant drawdown above the submersible pump intake
- expose a large area of bore screen to the schist to maximise access to groundwater bearing joints and fractures. Bores in the schist are often uncased or only partially cased to maximise the exposed area for groundwater inflow.

Another limitation of schist rock groundwater resources, even if a water bore is feasible in drawdown terms, is long-term replenishment. Fractured rock groundwater sources have a tendency to deliver steady yields of groundwater for several months, followed by sudden depletion. This phenomenon is usually caused by the rate of extraction exceeding the rate at which the fracture porosity can be recharged.

The factors that characterise a pervasively fractured aquifer are not readily distinguished by geophysical surveys. Targeting groundwater sources in schist requires some knowledge of structural geology. In general, fracture density is expected to increase near major fault zones.

5 Schist drilling

5.1 Introduction

Two exploratory boreholes were drilled into the schist basement in the Ida Valley, at Cresslea and at the end of Meade Road. Figure 5 is a simplified geological map showing the location of these bores. Appendix 1 gives the geological logs for the boreholes, and Appendix 5 provides the wireline packer testing results.

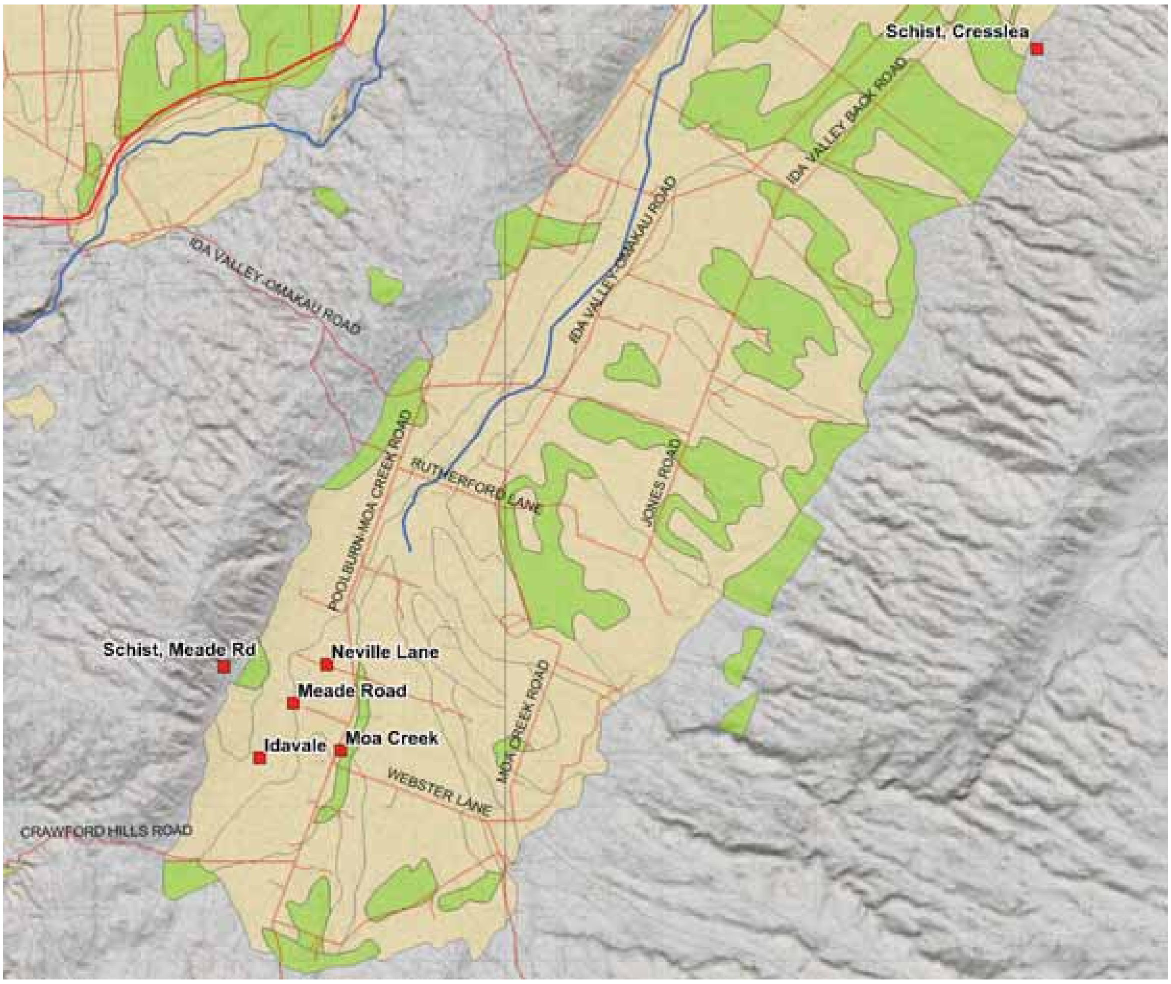

Figure 5. Simplified surface geology map showing drilling locations.
Map key: yellow: Quaternary; green: Manuherikia Group; grey: schist

The locations of the two targets were chosen in order to drill close to the faults that bound the valley margins. We considered that there was a greater likelihood of intercepting areas of increased fracture density if drilling was conducted beside the faults.

Boreholes for groundwater supply from schist bedrock had already been drilled in the McIntosh Road area. These boreholes provide enough water for stock and domestic supply. The bore log for G42/0132 shows a specific capacity of 2.1 l/min/day. That this borehole is located near the Blackstone Fault gave some assurance of success for the two exploratory boreholes.

5.2 Cresslea

Site selection

This site was chosen because of its access to schist basement on the eastern side of the valley. The objective was to drill into fractured rock along the fault that runs along the margin of Rough Ridge. The Cresslea farm is distinctive for its lack of deeply incised gullies, which suggests that water may be infiltrating into more permeable bedrock. The drilling rig was moved as far up the hillside as possible to 1350445E 5002970N.

Drilling results

Drilling was initiated using the percussion bit with air compression. The top 8m consisted of weathered, oxidised schist colluvium, followed by a metre of altered basement rock, obvious because of its distinctive green-grey colour. Drilling continued with the percussion bit through green schist, until water was found at a depth of 18m, with a static water level of 8.06m. The rig was then reconfigured to carry out diamond-core drilling.

The schist was highly fractured and numerous brittle shear zones were evident throughout the drill core. A fault zone was encountered from 19.7-25.1, with a dip of 65º. This zone had very low permeability, due to the abundance of puggy saturated plastic grey clay.

Drilling continued into the footwall of the fault, which was densely fractured. Numerous brittle shear zones were revealed within alternating pelitic and psammitic schist. With no obvious signs of improvement in permeability, drilling was ceased at a depth of 41m.

Despite the promising sheared and fractured nature of the drill core, very little water was lost during the drilling process. While the footwall of the fault contained occasional brittle shears, these were not found to be particularly water bearing. It is possible that drilling would be more successful in the hanging wall of the fault. However, a track mounted drilling rig would be needed to access higher elevations on the ridge.

Wireline packer tests

Where possible, as drilling proceeded, lugeon tests[2] were carried out (Figure 6). Recorded flow loss was lower than expected in all tests, and the response curves indicate that the fractures are tight. The results show that the bore would only yield up to 60 l/min.

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[2] Water is injected into the bore at a known pressure and the rate of water loss is recorded

Figure 6. Installing the wireline packer at Cresslea.

Table 2 provides a summary of the lugeon test results. The faulted section gives the lowest yield overall, and the clays within sheared zones appear to have had a negative impact on permeability.

Test 2 covers the section straddling the fault, and did not provide an adequate seal for the inflated packer due to the brittle nature of the rock. Values for this section have been estimated from tests on the upper and lower sections by using a weighted average approach.

Table 2. Summary of packer-testing results from the Cresslea bore.

Test	Top	Bottom	Length	Lugeon Units (l/m/min)	K (m/d)	T (m^2/d)
1	18.6	23.1	4.5	2.5	0.026	0.12
2 (Estimated)	*23.1*	*31.1*	*8.0*	*1.5*	*0.032*	*0.26*
3	31.1	41.1	10.0	2.6	0.032	0.32
4 (Total)	**18.6**	**41.1**	**22.5**	**2.2**	**0.031**	**0.69**
Post fraccing	**31.1**	**41.1**	**10.0**	**0.9**	**0.011**	**0.11**

Hydrofraccing

The Cresslea bore was forcefully hydraulically fractured (‘hydrofracturing’ or ‘hydrofraccing’) to try to improve its yield. Hydrofraccing is often carried out in rock aquifers overseas to improve borehole yield. The equipment used to hydrofracture is not readily available in New Zealand outside of the petroleum industry. To carry out the hydrofraccing required some improvisation and the sacrifice of the borehole.

The hydrofracturing process involved installing a 50mm galvanised steel pipe into the borehole, with a rubber flange set at a depth of 31m. The borehole was sealed with a layer of sand and bentonite and backfilled with cement grouting. The sealed borehole was left to set for a month before the hydrofraccing was started.

To fracture the rock, the bore was hydraulically pressurised at 1380 KPa (200 Psi). At this pressure, the bore was losing 165 l/min, which showed that fracturing had occurred.

A packer test was carried out after the hydrofraccing to determine the change in well yield. The test showed an actual decrease in yield by a third (Table 2). So, although the rock had been hydraulically fractured, there was negligible interconnected porosity around the bore to sustain any improvement in yield. The injection of water filled the spaces generated by the hydrofraccing process, and the bore had become artesian by the end of the test. This was confirmed by the response curve for the packer test, which showed a drop in discharge over the course of the test.

5.3 Meade Road

Site selection

The Meade Road area was selected as ideal for drilling because of the ease of access into incised gullies along the base of the ridge. Also, the position of the Blackstone Fault can be located quite accurately in this area. The drilling site was chosen because of the ability to access the area immediately west of the fault, where it was possible to drill into fractured rock in the hanging wall. The borehole was located about 120m west of the fault at 1334621E 4990965N (Figure 7).

The Blackstone Fault appears to have had considerable vertical movement in this area, and the foliation of the schist is quite steep (048/60E), compared to the areas next to the range. A nearby outcrop of sheared schist at 2244340 5552180 shows that the fault is oriented 035/60W and cuts across the fabric of the schist. The Meade Road site is also interesting as the hillside above the fault is very steep, and the fault appears to step across in a sinistral-dilational jog. These characteristics suggest intensive fracturing of the rock. The possibility of dilation increases the potential for space to be created within the fractures.

Figure 7. Schist drilling site at Meade Road.

Drilling results

The Meade Road borehole went through 3m of schist colluvium before intercepting weathered schist bedrock at a depth of 7m. Fresh rock below this depth showed that the schist was altered through to a depth of 12m. The drill rig was reconfigured from percussion to diamond core at a depth of 9m.

Drilling intercepted alternating layers of psammitic and pelitic schist. The core was densely fractured overall and contained numerous brittle shear zones. Brittle shearing was pronounced from 30-53m depth in both the pelitic and psammitic schist. Most shear zones and secondary fractures were filled with grey puggy clay. Carbonate veining was commonly associated with shearing and fracturing below 40m depth.

Like the Cresslea bore, the intense fracturing and shearing showed great promise in the drill core. However, very little water was lost during the coring process, and drilling ceased at 61.3m depth.

Wireline packer testing

Lugeon tests were carried out at the end of each 6m length of casing. Only half the tests were successful because intense shearing in the schist made it difficult for the inflated packer to provide an adequate seal. Table 3 gives a summary of the test results.

The top 23m proved to be the most permeable. The yield for this section was slightly better than those measured in the Cresslea and G42/0132 boreholes; as Table 3 shows, the lugeon values decrease below 23m and increase again from 53m onwards. Interestingly, the zone of more intense shearing and fracturing shows the poorest hydraulic response.

Table 3. Summary of packer-testing results from the Meade Road bore.

Test	Top	Bottom	Length	Lugeon Units (l/m/min)	K (m/d)	T (m^2/d)
1	11.1	17.1	6.0	4.8	0.053	0.32
2	17.1	23.1	6.0	2.8	0.031	0.19
3 (Estimated)	*23.1*	*26.0*	*2.9*	*0.1*	*0.001*	*0.00*
4 (Incomplete)	*26.0*	*32.0*	*6.0*	*0.4*	*0.004*	*0.03*
5	32.1	38.1	6.0	1.5	0.016	0.10
6 (Estimated)	*38.1*	53.1	*15.0*	*0.1*	*0.004*	*0.05*
7	53.1	61.3	8.2	3.3	0.039	0.32
8	32.1	61.3	29.2	1.1	0.016	0.47
9 (Incomplete)	*17.1*	*61.3*	*44.2*	*0.7*	*0.011*	*0.47*
		Total	**50.2**	**0.2**	**0.02**	**1.0**

The lugeon test response curves show a very poor response to injection. The first test (11.1-17.1 m) returned the highest value, but responded with a decreasing permeability over the course of the test. This response indicates that partial blocking of fractures is occurring.

After completing the borehole, a decision was made to ream the bore with the 6-inch percussion drill bit to remove any clay smeared down the borehole by the drilling process. The percussion bit also has the capacity to clean fractures with air development. This technique was preferred to hydrofraccing, as the schist was considered to be fractured enough already.

The reamed borehole was subsequently developed for an hour, but the bore showed little improvement in yield. Furthermore, the clarity of the ejected water remained poor, with considerable suspended grey clay, and showed little sign of improving. Monitoring of the recovery after development indicated a specific capacity of 1.5 l/min/m. This yield is only a marginal improvement on the packer test results and is at the lower end of the expected range for schist in Otago.

5.4 Conclusions of schist drilling

The wireline packer testing has indicated that yields from the schist are very poor. Overall lugeon values derived from the two bores were 2.2 and 0.2 l/min/m at the Cresslea and Meade Road sites, respectively. Higher yielding sections within the upper 20m of these boreholes would only provide enough water for stock or domestic supply. The highest observed schist yields are similar to that measured in G42/0132 (2.1 l/min/m), which is currently being used for domestic supply.

As a measure of bore productivity, it is useful to compare these yields with those obtained from the Tertiary sediments. Lugeon units are roughly equivalent to specific capacities obtained via pumping methods. So, exploration bores targeting higher permeability strata in the Tertiary sediments returned specific capacities of 16 to 41 l/min/m, which is an order of magnitude greater than that yielded by the schist.

Densely fractured and sheared sections of the schist showed a decrease in permeability in both boreholes. The low yields within highly fractured rock are probably due to the abundance of powdered mica or clay. To some extent, this is a function of the high grade of metamorphism, and hence mineral segregation, found in the schist. A similar degree of shearing and fracturing might produce more water in a lower grade of metamorphic rock. However, it is unlikely that schist would provide a practical source of water in the Ida Valley, unless a high fracture density was intercepted within a substantial body of psammitic schist.

Figure 8. Defrosting while coring in schist at Meade Road.

6 Tertiary sediments

6.1 Drilling summary

Four exploration boreholes and a piezometer were drilled into the Tertiary sediments in the south-western Poolburn catchment. As outlined in Section 3.2, the target for drilling was an elevated resistivity anomaly in the south-western part of the catchment. Aerial geophysics indicated the presence of coarser sediments held within a synclinal fold in this area.

Table 3 summarises the exploration drilling results, and Appendix 2 provides the geological logs.

Table 4. Summary of boreholes drilled in the Tertiary sediments.

Site	Easting	Northing	Elevation (approx)	Depth (m)	Screen (m)	Static WL (mbgl)	Specific Cap (l/min/m)
Idavale	1335310	4989200	440	36.0	26.5-29.5	16.6	33
Meade Road	1335967	4990257	430	47.0	11.8-12.8	0.0	34
Meade Rd (Piezo)	1335939	4990242	430	12.0	10.0-12.0	0.4	-
Moa Creek	1336882	4989340	427	30.0	12.0-15.0	4.0	41
Nevill Lane	1336610	4991015	418	30.0	17.5-20.5	-0.6[a]	16

a-The Nevill Lane bore is flowing artesian

Borehole yields

The bores intercepted groundwater of sufficient yield to provide stock and domestic supply. There is even the potential to run a small k-line or sprinkler irrigation system from these bores. The exception is the Moa Creek bore, which proved difficult to clean during development. This bore would have benefited significantly from a finer screen or even a sand-filter pack.

Note that because these were exploration bores, little effort was made to source the finest possible screen, or to fit the available screen over the correct interval. For a purpose-drilled production bore, the correct screen and interval would be used, leading to an improved borehole performance.

Specific capacities ranged from 16 l/min/m to 41 l/min/m. These values are higher than those obtained from the other Poolburn catchment bores, as recorded in the ORC database. Boreholes G42/0744 and G42/0131 returned specific capacities of 2.9 and 4.8 l/min/m, respectively. While these boreholes are within the same target area used in this study, they returned low yields similar to those obtained from the upper 20m of the schist.

G42/0131 was drilled and screened to a depth below that indicated in the geophysical surveys as being more permeable. A higher yield could possibly have been obtained from one of the shallower horizons of sandy quartz gravels indicated on the log. G42/0744 is a shallow bore, so it would be expected to be more productive that the bore log shows. Its yield was possibly hindered by the installation of slotted PVC, rather than a stainless steel screen.

Water levels

Below the near-surface clay pan, the static water level tended to decrease with depth in each bore. This observation indicates that groundwater is being drawn downward to recharge deeper sediments in this part of the valley. The static water levels measured were between 415m and 430m elevation. The Poolburn Gorge is just under 400m elevation, and the base of the alluvial gravels at the catchment outlet is about 395m.

Any groundwater above 395m elevation is probably dynamic as it is driven by a topographic gradient. Groundwater below an elevation of 395m is likely to be static and of poor quality, unless held with lenses of Quaternary gravel. This area of static groundwater would include most of the land area north of the Rutherford Lane.

Sediments encountered

The dominant sediment encountered during drilling was a loose, fine grey sand or silt, accompanied by light-brown clay. This silt is typically water bearing, but the finer fractions of sediment continued to flow from the bore during air injection and pumping development. Silt horizons are interspersed with green plastic clay in the upper 25-30m of the sequence, forming aquitards or aquicludes. These sediments make drilling and development an extremely messy process (Figure 9).

Figure 9. Drilling at the start of the Moa Creek borehole.

There is no clear uniformity to the thickness of clay or silt horizons, and it is not possible to trace individual layers laterally. However, there is an overall pattern to the sequence that mirrors the resistivity maps. The upper layer (5m or less) consists of Pleistocene clay-rich gravel, and is underlain by a brown clay horizon to a depth of about 10m. This horizon forms the clay pan that maintains a high water table throughout the valley. The sequence beneath the clay pan consists of alternating silty sand and green clay horizons through to about a depth of 30-35m. These sequences appear to be graded, fining upwards from medium-coarse sand to fine sandy silt and green clay. The graded beds range from 3m to over 10m thick. Monotonous fine silty sand dominates the sequence below a depth of about 30m.

The four boreholes were screened in coarser horizons within the alternating silty sand and clay horizons, at a depth of 10m to 30m. These horizons were readily identified by an increase in grain size from angular medium to coarse sand and a distinctive change in colour to an oxidised red-brown. It appears that there are two main phases of coarser material within the drilling domain, at around 11m and 18.5-22m.

The coarser oxidised horizons do not belong to the Bannockburn Formation because they consist of reworked material, including angular schist fragments. Closer inspection of the silt at 41m within the Meade Road bore also suggests reworking. The silt is mostly composed of angular quartz and feldspar fragments, and many of these are rodded or foliated. Occasional schist clasts were mixed with biotite and muscovite fragments. Rounded lithic and quartz clasts were also present, which were redeposited from primary Bannockburn Formation sediments.

The source material for the silt appears to be mostly reworked Bannockburn Formation, but even at 41 m depth there is a clear schist component. This indicates that these sediments are Late Pliocene to Early Pleistocene in age, and that the Bannockburn Formation sediment was stripped off the schist ranges as they were uplifted. The schist content of the sediments increases upwards though the sequence. This is, because, as the ranges were progressively uplifted, a larger area of schist was exposed and eroded into the Ida Valley. The altered schist surface was also eroded from the top of the ranges and deposited as distinctive green plastic or sticky clay horizons.

Greywacke gravel anomaly

The Idavale bore appears to be an anomaly within the sequence seen in the surrounding area. This bore contained two distinct horizons of greywacke pebble. No boreholes have intercepted similar gravels elsewhere in the Poolburn catchment.

The greywacke gravels can only have been sourced from the Hawkdun or Ida ranges to the north. However, the Bannockburn Formation is representative of a low-energy environment, which poses the following question: How did lenses of well-rounded greywacke gravels make their way to the southern end of the Poolburn Valley? The most likely answer is that a river paleochannel from the Manuherikia Valley crossed over to the Raggedy Range, and this material was shed into the Ida Valley during the uplift of the ranges. This material would be equivalent to greywacke gravels of the Hawkdun Formation.

6.2 Aquifer tests

Each of the drilled boreholes was subject to a preliminary recovery test after completion and development. These tests were carried out using a surface mounted pump (Figure 10). The pumping rate for preliminary tests was measured by repeatedly recording the time taken to fill a 20 litre bucket.

Figure 10. Preliminary pumping test carried out at Meade Road.

Table 5 summarises the pumping tests results, and Appendix 3 shows the preliminary test values. The results indicate transmissivity values of 10-40 m^2/d for the silty sand that pervades the area. Because of the interception of high permeability greywacke gravels, the Idavale borehole returned the considerably higher transmissivity reading of 324 m^2/d.

Table 5. Summary of pumping test results in the Tertiary sediments.

Site	Screen	Curve	T (m^2/d)	B (m)	K (m/d)	S	Q (l/s)	Drawdown (100 min)	Specific Capacity (m^3/d/m)
Meade Piezo	10.0-12.0	E. dd	80	2.8	29	$5x10^{-4}$	4.0	7.0	49
		L. dd	26	2.8	9				
		L. rec	28	2.8	10				
Moa Creek	12.0-15.0	Rec	40	4.6	9		1.7	2.5	59
Idavale	26.5-29.5	Rec	324	1.0	38		1.7	3.1	48
Nevill Lane	17.5-20.5	E. dd	15	3.7	4		1.8	6.7	23
		L. dd	19	3.7	5				
		L. rec	11	3.7	3				

The Meade Road bore was chosen as a suitable site to carry out a comprehensive 24-hour constant rate pumping test (Figure 11). An observation bore was drilled at a distance of 32.3m to the west and installed with a slotted PVC screen. The primary bore was pumped with a submersible pump at a constant rate of 4l/s. Discharge was measured with a digital flow metre and routed into an adjacent water race.

Figure 11. The 24-hour constant rate pumping test carried out on the Meade Road bore.

Drawdown curves for the two bores are shown in Figure 12. Data for the test is provided in Appendix 4.

The water level in the pumped bore fell to 9.6m during the test, which was just above the pump intake. A rate of 4 l/s is the maximum this bore can be pumped over a 24-hour period because the available drawdown is small relative to the yield.

The early-time portion of the piezometer drawdown curve gives a storativity value of 5×10^{-4}. This value is typical of confined aquifer conditions.

The early-time portions of both curves give transmissivity values of 50-80 m^2/d for the coarse sand around the pumped bore. Two lower permeability boundaries are also evident in the drawdown record for the pumped bore. These boundaries are represented by a change in slope of the drawdown curve and correspond to distances of about 250m and 450m. These boundaries probably represent the pinching out of the coarser sand horizon. The late-time data for the test gives a transmissivity value of about 27m^2/d, which is considered to be representative of the lower permeability of the ubiquitous fine silty sand.

Recovery was slow for both bores, with 0.8m and 0.9m residual drawdown remaining after 24-hours' recovery for the pumped bore and piezometer, respectively. This indicates that, while the pumped bore performs well over short pumping durations, its long-term performance depends on the fine silty sand that hosts the coarse sand horizon. Operation of this bore would require close monitoring to avoid causing a steady decline in water levels over time.

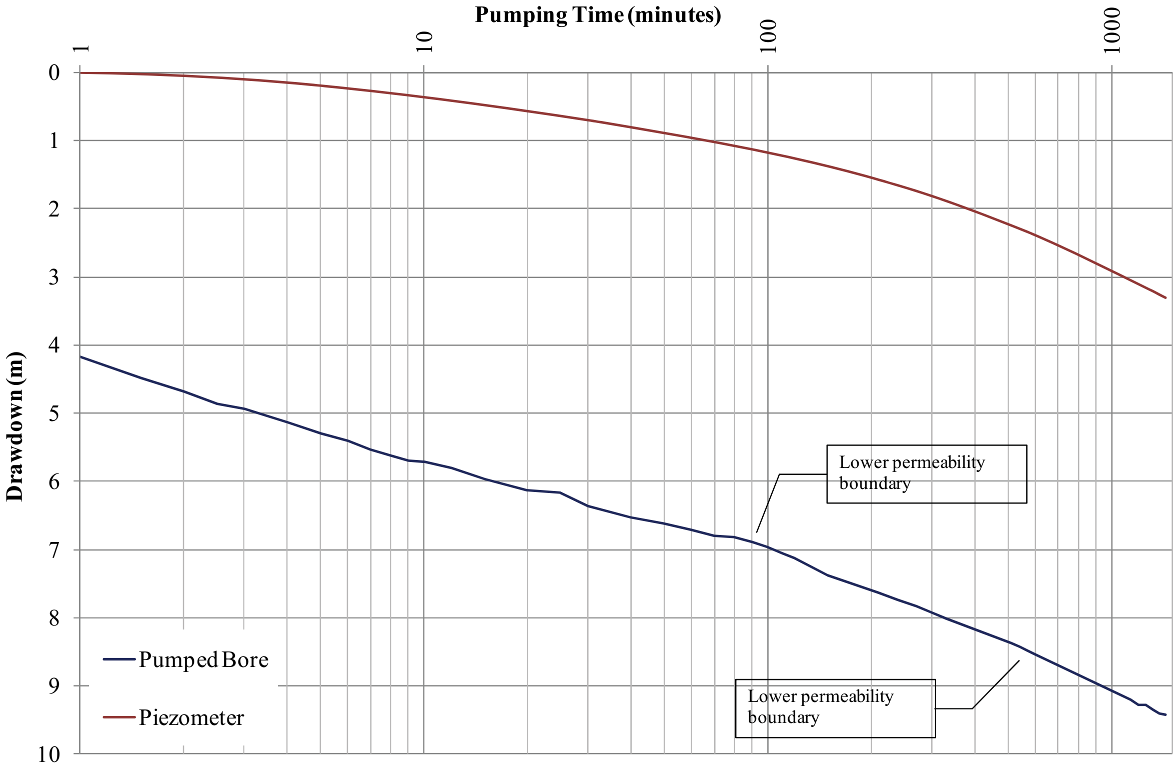


Figure 12. Semi-log drawdown curves for the 24-hour pumping test at Meade Road.

6.3 Groundwater quality

Table 6 summarises major water quality chemistry. Estimated elevations for the bottom of the screen are also given for each borehole.

Table 6. Environmental indicators of water quality (mg/l).

Site	Sample elevation	Conductivity (mS/m)	pH	Cations				Anions		
				Ca	Na	K	Mg	Cl	SO_4	Alkalinity
Moa Creek	412	26	6.9	23.0	22.2	3.1	10.9	20.6	7.1	121
Idavale	410	20	7.2	18.3	19.0	1.1	9.0	15.0	13.6	86
Nevill Lane	398	24	7.4	34.4	26.8	1.5	15.6	52.4	19.6	92
Meade Road	417	39	7.6	44.1	31.3	0.9	15.9	36.3	23.0	164

Groundwater conductivity is quite low in all boreholes, but shows some evidence of water rock interaction. Values of pH are typical either for fresh recharge (Moa Creek, Idavale), or for more confined or leaky conditions with significant through flow (Nevill Lane, Meade Road). These results are encouraging because they suggest that there is significant groundwater circulation above the catchment outlet at Poolburn Gorge (395m). The water quality results confirm that the groundwater system is not blind, but is being recharged on a regular basis.

The Nevill Road bore has Ca-Mg-Cl-type water, while the other three bores have Ca-Mg-HCO_3-type. Sulphate concentrations are elevated at Nevill Lane and Meade Road, which are both artesian. In most groundwater systems, sulphate concentrations decrease with confinement, so it is likely that these two bores are affected by fertiliser use. Magnesium is also unusually elevated compared to other cations, which supports the idea that there is some influence of fertiliser use on groundwater quality.

Table 7 shows the water quality parameters of health significance. All analytes are well below maximum acceptable and guideline values recommended by the Ministry of Health Drinking Water-Standards for New Zealand. The only exception is Nevill Lane, where high iron and manganese may cause precipitation when pumped to the surface. Hardness is in the mid-range, and is not likely to cause problems by forming a lather (below 100mg $CaCO_3$/l) or scale deposition (above 200mg $CaCO_3$/l).

Table 7. Water quality parameters of health significance (mg/l).

Site	Sample depth	Nutrients			Dissolved metals			Hardness
		Nitrate-N	Ammonia-N	DRP	As	Iron	Mn	
Moa Creek	12-15	1.5	<0.01	0.017	<0.001	0.02	0.0041	102
Idavale	26.5-29.5	1.9	<0.01	0.052	0.001	0.02	0.0016	83
Nevill Lane	17.5-20.5	4.5	0.02	<0.005	<0.001	1.31	0.405	150
Meade Road	11-13.8	2.3	<0.01	0.041	<0.001	<0.01	<0.0005	176

Nutrient values indicate that fertiliser use is affecting groundwater quality. Nitrate concentrations in natural groundwaters rarely exceed 1mg/l and values over 3mg/l are almost certainly affected by human activities (Close *et al*., 2001). The samples from the Ida Valley show nitrate-N concentrations over 1mg/l, and the Nevill Lane bore returned a value of 4.5mg/l. DRP values are also surprisingly high in three of the bores. Fairly high DRP concentrations were recorded at Idavale and Meade Road, and the level at Moa Creek was elevated.

In summary, the water quality results show that groundwater quality is good, relative to the Drinking-Water Standards for New Zealand. However, samples from all bores showed evidence of fertiliser contamination, which suggests that nutrients are being leached into groundwater. From the point of view of water availability, this can be viewed as an encouraging observation. Evidence of nutrient leaching confirms that groundwater in the southwest Poolburn area is not stagnant, but is being recharged and is moving down the valley.

6.4 Conclusions of Tertiary sediment drilling

The geophysical surveys successfully targeted an area of reworked higher permeability sediments. Water yields from the drilling program were low, but were higher than bores drilled elsewhere in the Poolburn catchment. The target area provided sufficient good quality water for stock or for domestic supply. The drilling also showed that small supplies for irrigation could be obtained in more favourable geological environments.

Finer silty sediments could provide a source of groundwater if, for example, a sand filter pack was installed around the bore screen. This would allow water to be pumped from finer sediments without drawing silt into the bore. Without a sand pack, the screen would have to be placed in a horizon of medium-grained sand or coarser material.

The installation of a gravel- or sand-filter pack is a standard procedure for water borehole drilling in Australia, but has not been adopted in New Zealand. Probably because most bores in New Zealand are drilled into high permeability gravels, which can readily have the finer fraction removed by development. This would provide an opportunity for drillers to employ sand-filter packing techniques to find successful water sources in the Manuherikia Group sediments in Central Otago.

7 Conceptual model for sediment deposition

The water-bearing sedimentary sequence intercepted in drilling corresponds well to the distribution of high resistivity shown in the geophysical surveys. The asymmetry of the basin and range regime, with its 60º dip to the north-west, means that the eastern side of the ranges is steeper and subject to more uplift that the west.

Erosion of the mountain ranges tends to deposit coarser material along the eastern margins. This is the area where the most uplift has occurred, so there is more erosive energy available to form coarser sedimentary deposits. Because uplift is progressive, the coarser material will be found towards the top of the sequence as more of the Bannockburn Formation is stripped off the ranges and a larger area of schist is exposed.

The original deposition model derived from the geophysics proposed that the coarser sediments would be contained within a syncline. While there is no doubt that Bannockburn Formation sediments are folded into a syncline, drilling has shown that this need not be the case for the reworked sediments. An erosional fan will also produce the same geometry, and the drilling results appear to support this model. It is also possible that the coarser, more recent fan sediments have been deposited along the syncline axial trace where subsidence is greatest.

The erosional fan model has implications for finding water elsewhere in the Tertiary sediments. The combination of factors likely to prove prospective for groundwater sources are:

- Geophysics: Regions where bulk earth resistivity > 50 Ωm at 20-25 m depth
- Topography: adjacent schist ranges are steep and high (greater uplift)
- Geology/geomorphology: identification of colluvium or alluvial fans of eroded schist material.

Figure 13 outlines the areas where these three factors coincide. The highlighted areas are considered to be the most promising areas for groundwater exploration. However, areas of low elevation (close to 395m) are unlikely to provide a high quality of groundwater because there needs to be sufficient hydraulic gradient to maintain groundwater circulation. This is the case for much of the area highlighted at Auripo.

As well as the sites shown in Figure 13, others can be determined by overlaying geophysical, topographical and geological maps. In this way, smaller target areas of coarser fan deposit material can be identified. These targets represent more discrete areas where a catchment of significant size drains from the western margin of the schist ranges. Examples of smaller targets are fan deposits from Dunstan or Donald Stuarts creeks in the north-western Manuherikia.

The main driver for sedimentary deposition is the increased energy associated with tectonic uplift of the mountain ranges. The fold structures resulting from regional deformation are asymmetric. It is this asymmetry that makes the location of coarser water-bearing sediments more predictable. Hence, the same depositional model should apply to other parts of Central Otago which have been subject to the same tectonic stress field. By taking into account the principles underlying the model proposed here, drilling for groundwater in other parts of Central Otago is likely to be more successful.

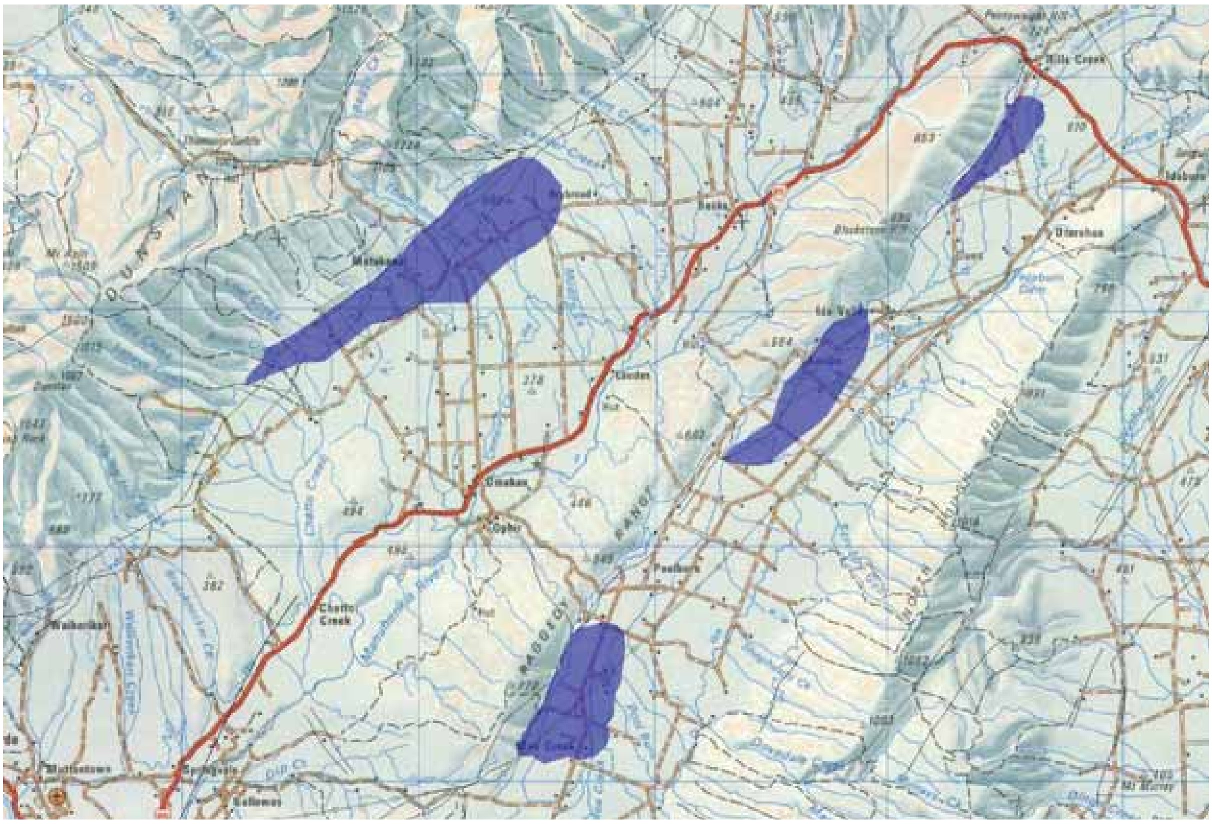


Figure 13. Areas of potential groundwater resources.

8 Conclusions

The Glass Earth geophysical surveys have been invaluable for identifying areas where Tertiary sediments are coarser overall. The resolution of the electromagnetic technique is insufficient to identify individual water-bearing horizons, but it does identify areas where reworking and deposition of coarser material has occurred.

Sediments in the Ida Valley are mainly composed of silty sand. Exploration drilling has shown that at least the upper 40m of the sequence has been eroded from the schist ranges and redeposited in the valley floors. Drilling in the south-western corner of the Poolburn catchment intercepted coarser fan deposits containing schist detritus. These deposits extend to a depth of about 25m.

Study of resistivity, geology and topography maps has revealed subsurface alluvial or colluvial fan deposits in other areas. Areas showing groundwater resource potential were identified at Moa Creek, Auripo, Hills Creek and Mataknui/Thomsons Creek.

Pumping tests have shown that the reworked silty sand has a transmissivity of 10 to 40 m^2/d. Coarser sand horizons in the fan deposits have transmissivity values of up to 80 m^2/d. Higher values can be achieved if greywacke gravels equivalent to Hawkdun Formation can be found. However, we do not expect to find a widespread distribution of such gravels in the Ida Valley.

Drilling in the reworked sediments should return sufficient yields for stock and domestic supply throughout much of the valley. The chances of success can be improved by avoiding areas of low resistivity, selecting an appropriate screen and installing a sand filter pack. Higher yields can be obtained by drilling within areas identified as having groundwater resource potential.

Water chemistry results show that groundwater is of good quality. Recharge and groundwater circulation is also occurring within the target drilling area. Water circulation and, therefore, water quality is expected to deteriorate at elevations below the Poolburn Gorge outlet (around 395m).

Schist has proven to be a poor source of groundwater in Ida Valley. Small volumes for stock and domestic supply might be obtainable from the upper 20-30 m. However, clays associated the high metamorphic grade of the schist appear to limit the permeability of shears and fractures

Glossary

Alluvium
Sediments that have been deposited by a river.

Anticline
A fold that is convex upward. Older rocks are found in the centre of the fold, and the limbs dip away from the axis.

Aquiclude
A low permeability geological unit that will not yield water. An aquiclude impedes groundwater flow, thereby forming boundaries to a groundwater system.

Aquifer
A saturated geological unit, or group of units, that has sufficient storage and permeability to yield economic volumes of water.

Aquitard
A geological unit that holds water in storage, but is not permeable enough to yield significant volumes of water. Aquitards restrict the rate of groundwater flow between aquifers.

Artesian aquifer
A confined aquifer where the potentiometric surface is above ground level. Wells screened in artesian aquifers will free-flow if uncapped.

Basement rock
Solid rock such as schist or greywacke that underlies younger unconsolidated rocks such as gravel.

Colluvium
Loose deposits found at the base of a slope which were deposited by gravity.

Confined aquifer
An aquifer in which water is stored under elastic pressure. The confining pressure causes water levels to rise above the top of the aquifer, forming a potentiometric surface. Storage in confined aquifers is relatively small, and pumping effects can move through the aquifer rapidly. Confined aquifers are generally (but not always) encountered at depth below the ground surface where permeable sediments such as gravels been overlain by low permeability mud, silt, or clay.

Development
The process of increasing the porosity and permeability of sediments around the bore screen. This is usually done by air injection surging.

Diagenesis
Alteration of rock mineralogy resulting from groundwater circulation at low temperatures and pressures.

Drawdown
The lowering of water levels in response to pumping.

Filter pack
A sand or gravel layer placed around the well screen to prevent fine material from entering the screen.

Formation
A distinctive unit of rock that can be mapped.

Greywacke
A general name for hard sandstone rock.

Heterogeneous
Having properties which vary throughout space.

Holocene
The most recent part of the Quaternary geological period, usually referring to the last 12,000 years.

Hydraulic conductivity
The rate at which water can pass through a permeable medium.

Hydraulic gradient
The slope of the water table.

Hydrogeology
The study of aquifers and groundwater.

Leaky aquifer
Aquifers which are partially confined, but when pumped some or all of the water eventually comes from shallower (or deeper) strata into the aquifer being pumped.

Lithic
Sediments composed of rock grains rather than individual minerals.

Lithology
The physical characteristics of sedimentary rocks.

Metamorphic rock
Rocks whose minerals and structure have been changed by high temperatures and/or pressures.

Miocene
A geological period of time representing 23 to 5.3 million years ago.

Pelitic
Hard, fine grained sedimentary rock such as mudstone or siltstone.

Permeability
The ability of a rock or sediment to transmit water. Highly permeable gravel will allow water to flow quite freely.

Piezometer
A small diameter observation well that is used to monitor water levels. Often abbreviated to "Piezo".

Pleistocene
A geological epoch representing 2.6 million to 11,700 years ago. Most of the terrace gravel deposits in New Zealand were formed during this time.

Pliocene
A geological epoch representing 5.3 million to 2.6 million years ago.

Porosity
A measure of the void or pore space within a rock. For example, sand typically consists of 30% pore space, which is a porosity of 0.3.

Psammitic
Hard, coarse grained sedimentary rock such as sandstone.

Quaternary
The most recent geological Period from 2.6 million years ago to the present day. The Quaternary Period includes the Pleistocene and Holocene epochs.

Resistivity
Electrical resistivity is a measure of how strongly a material opposes the flow of electric current. The unit of measurement is ohm-metres (Ωm). The inverse of electrical resistivity is conductivity.

Schist
A type of metamorphic rock in which the individual mineral grains have been elongated or flattened. The fabric of a schist rock is usually planar, or foliated. Schist is the distinctive basement rock found throughout most of Central Otago.

Screen
A filter installed at the end of bore casing to keep sediment from entering a borehole.

Sedimentary rock
Rocks formed by the accumulation of rock particles (sediment).

Shearing
The fabric formed in a rock by shear-stress, which is similar to, and related to faulting.

Sinistral
Movement on the fault is such that an observer would see land on the other side of the fault move to the left. The opposite of sinistral is dextral fault movement.

Specific capacity
A term used to describe well productivity. Specific capacity is determined by pumping a well at a constant rate for a specified duration, usually 30 minutes to two hours. The specific capacity of the pumped well is the rate of discharge divided by the drawdown.

Storativity
This is a measure of the storage characteristic of an aquifer. In confined aquifers it refers to elastic storage (contraction and expansion of water and aquifer matrix). In unconfined aquifers it is a measure of the water released from the pores between grains as a result of flow under gravity (specific yield).

Stratigraphy
The branch of geology that studies rock layers and layering or bedding.

Structure
Structural geology is the study of the faults, folds, fabrics, and bedding of rocks. The term ‘structure’ refers to a particular structural feature, or related series of features within a rock or region.

Syncline
A fold that is convex downward. Younger rocks are found in the centre of the fold, and the limbs dip towards the axis.

Terrace
A flat topographic feature formed by erosion or deposition of sediments by a river.

Tertiary Period
A geological period of time representing 65 to 2.6 million years ago. The Tertiary Period includes the Miocene, and Pliocene epochs of time.

Transmissivity
This is a measure of the permeability of an aquifer i.e. the ease of which water can move through an aquifer. Transmissivity is equivalent to hydraulic conductivity multiplied by the aquifer thickness.

Unconfined aquifer
Unconfined aquifers are typically shallow. They are recharged directly from rainfall infiltration onto the ground surface, or from water flowing from surface water bodies. Streams, lakes and wetlands are usually the surface expression of an unconfined aquifer.

Unconformity
A surface formed by erosion of the underlying rocks.

Water table
The water surface of an unconfined aquifer in which the pressure is atmospheric.

Wireline packer
A wireline packer is an inflatable rubber plug attached to a cable (wireline). The packer is inflated using air pressure so that sections of the bore can be sealed off. For packer tests, water can be pumped into an open-hole bore below the packer depth so that the permeability of that section of rock can be measured.

References

Craw, D. 1994. Contrasting alteration mineralogy at an unconformity beneath auriferous terrestrial sediments, central Otago, New Zealand. *Sedimentary Geology 92*: 17-30.

Close, M.E.; Rosen, M.R.; Smith, V.R., 2001. Fate and transport of nitrates and pesticides in New Zealand's aquifers. *In* "Groundwaters of New Zealand" Rosen, M.R. & White, P.A. (eds). NZ Hydrological Society. p 185 – 220.

Douglas, B. J. 1986: Lignite resources of Central Otago. *New Zealand Energy Research and Development Committee Publication No. PI 04.*

Forsyth, P.J. (compiler), 2001. Geology of the Waitaki area. Institute of Geological & Nuclear Sciences 1:250 000 geological map 19. Lower Hutt, Institute of Geological & Nuclear Sciences Ltd.

Markley, M. & Norris, R.J., 1999. Structure and neotectonics of the Blackstone Hill Antiform, Central Otago, New Zealand. *New Zealand Journal of Geology and Geophysics 42*: 205-218.

Markley, M. & Tikoff, B., 2003. Geometry of the folded Otago peneplain surface beneath Ida Valley, Central Otago, New Zealand from gravity observations. *New Zealand Journal of Geology and Geophysics 46*: 449-456.

McSaveney, M.J. & Stirling, M.W. 1992. Central Otago: basin and range country. p. 482-504 *In*: Soons, J.M.; Selby, M.J. (eds.) Landforms of New Zealand. 2nd ed. Auckland: Longman.

Mildenhall, D.C. & Pocknall, D.P. 1989. Miocene-Pleistocene spores and pollen from Central Otago, South Island, New Zealand. *New Zealand Geological Survey Palaeontological Bulletin 59*, 128 pp.

Nobes, D. 1999: Analysis of proposals submitted for survey and development of groundwater resources in the Waipara Area North of Canterbury. Prepared by David Nobes, Department of Geological Sciences, University of Canterbury for Environment Canterbury and Water of Waipara. ECan Technical Report U99/15, Christchurch, 6 April 1999.

Turnbull, I.M. (compiler), 2000. Geology of the Wakatipu area. Institute of Geological & Nuclear Sciences 1:250 000 geological map 18. Lower Hutt, Institute of Geological & Nuclear Sciences Ltd.

White, P.A., 1985. Handbook on hydro geological applications of earth resistivity measurements, Water and Soils Publication No. 90. Water and Soil Directorate. Ministry of Works and Development, New Zealand p. 41.

Wilson, S. and Lu, X., 2011. Rainfall recharge assessment for Otago groundwater basins. Otago Regional Council resource science report.

Youngson, J. H., Craw, D., Landis, C. A., Schmitt, K. R. 1998. Redefinition and interpretation of late Miocene-Pleistocene terrestrial stratigraphy, Central Otago, New Zealand. *New Zealand Journal of Geology and Geophysics 41*: 51-68.

Appendices

Appendix 1: Schist bore logs

Cresslea

From	To	Length	Colour	Lithology	Structure	SWL
0.0	2.0	2.0	Br	Fine qtz sand & silt w. occ. small angular schist pebbles, clay increases w. depth		
2.0	2.8	0.8	Gy-br	Silty clay		
2.8	6.4	3.6	Red-br	Gritty silty clay, with angular schist frags		
6.4	9.0	2.6	Gn-red	Weathered schist, still clastic		
9.0	13.5	4.5	Gn	Fresh altered schist		
13.5	17.0	3.5	Gy	Schist, unaltered, not much qtz		
17.0	18.8	1.8	Gn-gy	Water-bearing schist, change to HQ core at 17.8m	Several conjugate fracture sets cutting Foln	8.06
18.8	19.7	0.9	Gn-gy	Psammitic gneiss w. strong qtz segregation	Several conjugate fracture sets & shearing // to Foln	
19.7	21.6	2.0	Gy	Clay-rich powdery crush zone	Fault zone hanging wall	
21.6	23.1	1.5	Gy	Fault pug, some coherent but brittle remnants	Fault zone	
23.1	23.8	0.7	Gy	Clay-rich powdery crush zone with qtz frags	Fault zone	
23.8	25.1	1.3	Gy	Sheared schist, becoming more coherent	Fault zone footwall, dip 65°	
25.1	25.8	0.7	Gy	Sheared psammitic & pelitic schist	Mildly sheared & pervasively fractured	
25.8	26.9	1.1	Gy	Highly segregated schist, with carbonate cemented shear zone	Slightly sheared	
26.9	28.9	2.0	Gy	Peilitc schist	Mod. sheared	
28.9	29.2	0.3	Gy	Segregated schist	No shearing	
29.2	29.3	0.2	Gy	Psammitic schist	Mod. sheared	4.92
29.3	29.9	0.6	Gy	Psammitic schist	Thin shear band at 29.8m	
29.9	30.9	0.9	Gy	Segregated schist	Small brittle shear at 30.8m	
30.9	32.1	1.2	Gy	Segregated schist	Minor fracturing	
32.1	33.6	1.5	Gy	Psammitic gneiss w. strong qtz segregation	Minor fracturing	
33.6	35.1	1.5	Gy	Psammitic gneiss w. strong qtz segregation	Moderate fracture density, brittle shear at 34m	
35.1	36.6	1.5	Gy	Gneiss	Zone of brittle shearing & conjugate fracture sets	
36.6	38.1	1.5	Gy	Gneiss, some calcite coating on fracture surface	Moderate fracture density	
38.1	39.6	1.5	Gy	Gneiss	Stronger fracture density	
39.6	41.1	1.5	Gy	Gneiss, brittle shears in more pleitic sections	Thin brittle shears, mild fracturing	4.92

Meade Road

From	To	Length	Colour	Lithology	Structure	SWL
0.0	1.0	1.0	Dk Br	Pea gravel in clay matrix		
1.0	2.0	1.0	Br	Pea gravel in clay matrix, schist boulder		
2.0	3.0	1.0	Br	Pea gravel in clay matrix		
3.0	7.0	4.0	Gn-Br	Weathered altered schist		
7.0	9.0	2.0	Gn-Gy	Fresh altered schist, change to HQ core at 9m		
9.0	12.0	3.0	Gn-Gy	Altered psammitic schist with carbonate wash	Mod. sheared & fractured	
12.0	14.9	2.9	Gn-Gy	Altered pelitic schist	Mod. sheared & fractured, several thin crush zones	2.39
14.9	18.4	3.5	Gn-Gy	Altered psammitic schist, with carbonate fracture coatings	Mod. sheared & fractured	
18.4	19.3	0.9	Gy	Psammisitc schist	Brittle shear zone, mod fractured	
19.3	22.0	2.7	Gy	Weak schist	Brittle shear zone	3.38
22.0	24.2	2.2	Gy	Pelitic schist	Puggy shear zone	
24.2	24.8	0.7	Gy	Altered psammitic schist, with carbonate veins	Mildly sheared, mod. fractured	
24.8	25.9	1.1	Gy	Pelitic schist & qtz veining	Mod. brittle shearing // to Fn	
25.9	28.3	2.3	Gy	Altered psammitic schist, with carbonate veins & sulphides	Mildly sheared & fractured, puggy shear at 26.3m	
28.3	29.4	1.2	Gy	Psammisitc schist	Mod sheared & fractured	
29.4	30.4	1.0	Gy	Psammisitc schist, cohesive	3 thin brittle shears at 29.4m	
30.4	31.9	1.5	Gy	Psammisitc schist	Mod. sheared, shear zones puggy	
31.9	34.0	2.1	Gy	Psammisitc schist, cohesive, fractures, lined with grey clay	Thin puggy shear at 32.8m, minor fracturing	
34.0	37.5	3.6	Gy	Psammisitc schist, shear cuts across Foln	Strong brittle puggy shear zone, densely fractured	3.92
37.5	38.0	0.5	Gy	Psammisitc schist, cohesive	Minor fracturing	
38.0	40.0	2.0	Gy	Psammisitc schist, w. carbonate veins, brittle	Densely shattered, multiple fracture angles	
40.0	41.1	1.1	Gy	Pelitic schist	Puggy shear zone	
41.1	45.0	3.9	Gy	Crumbly schist, pervasive qtz-carb veining	Strongly sheared, densely shattered, multiple fracture angles	
45.0	45.7	0.7	Gy	Psammisitc schist	Shattered zone, puggy	
45.7	46.0	0.3	Gy	Psammisitc schist, cohesive w. carbonate veins	Mod. fractured, various angles	
46.0	47.1	1.1	Gy	Pelitic schist	Puggy shear zone	
47.1	53.2	6.1	Gy	Psammisitc & pelitic schist, vuggy carbonate veining	Brittle shear zone, puggy but open in places	
53.2	53.5	0.3	Gy	Psammisitc schist, cohesive		
53.5	53.9	0.4	Gy	Pelitic schist	Puggy shear zone	
53.9	54.9	1.0	Gy	Psammisitc schist, cohesive w carbonate veins // to Foln	Mildly fractured	
54.9	55.8	0.9	Gy	Psammisitc schist	Shattered zone, puggy	
55.8	57.1	1.4	Gy	Psammisitc schist, cohesive	Fractured at 56.2	
57.1	57.6	0.4	Gy	Psammisitc schist, w. carbonate veins	Puggy shear zone // to Foln	
57.6	58.0	0.5	Gy	Psammisitc schist, fractures lined with carb	Mod. fractured perp to Foln	
58.0	61.3	3.3	Gy	Psammisitc schist, w. carbonate wash & veinlets	Mod. fractured	3.56

Appendix 2: Tertiary sediment bore logs

Meade Road

From	To	Thickness	Colour	Lithology	Water	SWL	Notes
0	4.8	4.8	Br	Quaternary sand & pebbles in clay matrix	WB		
4.8	5.1	0.3	Y-Br	Clay or possibly loess			
5.1	11	5.9	Gy-Br	Plastic clay, hard			
11	13.8	2.8	Red-Br	Fine-coarse qtz-feldspar sand, w. schist fragments	WB	0.14	Sample, T~80
13.8	15.1	1.3	Gn-Br	Plastic clay, hard			
15.1	16.5	1.4	Lt Br-Gy	Loose fine sand and silt			
16.5	20.2	3.7	Gn-Gy-Br	Plastic clay, hard			
20.2	20.8	0.6	Br-Gn	Fine qtz sand & silt w coarse sand and rounded pebbles in silty brown clay matrix	WB	0.4	
20.8	25	4.2	Gn-Br	Plastic clay, hard			
25	25.1	0.1	Dk Br	Organic rich clay			
25.1	26.8	1.7	Lt Br-Gn	Clay			
26.8	35	8.2	Br	Loose silt grading to fine qtz-felspar sand	WB	1.18	
35	36	1	Gn-Br	Fine-med. Sand, w. occ. rounded frags (2-3mm)	WB		
36	45	9	Gn-Br	Fine sand w. 5-10% coarser frags	WB		
45	46	1	Gn-Br	Fine to med. Sand, w. coarser fraction, cleaner	WB		
46	47	1	Gn-Br	Fine sand, w. 5-10% coarser frags	WB		

Meade Road Piezometer

From	To	Thickness	Colour	Lithology	Water	SWL	Notes
0	1.2	1.2	Br	Clay-rich gravel	WB		
1.2	4.1	2.9	Br	Clay, saturated			
4.1	4.4	0.3	Br	Pea gravel (<1cm) in coarse sand & clay matrix			
4.4	6.1	1.7	Y-Br	Sticky clay			
6.1	9.2	3.1	Gn-Gy	Sticky, hard			
9.2	10	0.8	Y-Br	Silty sand			
10	12	2	Red-Br	Fine to coarse sand, w. qtz & schist pebbles <1cm	WB	0.37	T~28

Moa Creek

From	To	Thickness	Colour	Lithology	Water	SWL	Notes
0	1.8	1.8	Dk Br	Qtz pebbles in clay matrix	WB		
1.8	4.3	2.5	Lt Br	Silty clay, w. green sticky horizons			
4.3	8	3.7	Gy Lt Br	V. fine sand to silt, w. clay			
8	12	4	Lt Br	Loose fine sand, w. clay & occ. Gw pebbles <0.5cm	WB		
12	12.6	0.6	Red-Br	Qtz & wx st pebbles (<1cm) & grits in fine to med. Sand, w. clay	WB	3.96	Sample, T~40
12.6	17	4.4	Gn-Br	Clay, hard			
17	17.5	0.5	Red-Br	Ox fine sand or hardpan, hard			
17.5	18	0.5	Br-Gn	Silty clay			
18	19.5	1.5	Br	Fine-med. loose sand w ox sst pebbles	WB	6.65	Too silty to develop
19.5	21.6	2.1	Br-Gn	Fine sand w. clay			
21.6	22.5	0.9	Red-Br	Fine-med sand, w. ox. sst pebbles	WB		
22.5	23.7	1.2	Gn-Br	Silty clay, hard			
23.7	25.8	2.1	Gn-Br	V. fine sand & silt, w. brown clay	PWB		
25.8	26.8	1	Gy	Silty clay, sticky & hard			
26.8	27	0.2	Gn-Br	Silty clay			
27	30	3	Br	V. fine sand, w. qtz grit w. clay			

Nevill Lane

From	To	Thickness	Colour	Lithology	Water	SWL	Notes
0	0.6	0.6	Br	Gravel in clay matrix			
0.6	1.8	1.2	Red-Br	Med. Sand, w. fine qtz & schist pebbles (<0.5cm)	WB		
1.8	2.2	0.4	Wh	Med. qtz sand			
2.2	4.8	2.6	Br	Silty clay w. pebbles			
4.8	5.2	0.4	Br	Silty clay			
5.2	6.8	1.6	Br	Silty clay w. pebbles			
6.8	8.7	1.9	Gn-Br	Clay grading to silty clay			
8.7	9	0.3	Gn	Silty clay, hard			
9	9.4	0.4	Br	Clay-rich silt			
9.4	10	0.6	Gn	Silty clay, hard			
10	10.2	0.2	Red-Br	Coarse sand, w. qtz & schist pebbles & brown clay	WB		
10.2	10.8	0.6	Gn	Silty clay, hard			
10.8	11.7	0.9	Gn	Silt with clay			
11.7	12.6	0.9	Gn	Silt			
12.6	16.5	3.9	Gy	Silty clay, hard			
16.5	18	1.5	Br	Silty clay, hard			
18	19.2	1.2	Br	V. fine silty sand, w. grit and pebbles (<1cm)	WB	-0.61	Sample, T~12
19.2	20	0.8	Gn	Silty fine sand			
20	21.7	1.7	Red-Br	Med.-coarse sand	WB		
21.7	22.3	0.6	Gn	V. fine sand, hard			
22.3	26	3.7	Gn	Silty clay w. qtz grit & organics			
26	27	1	Gy-Br	Fine sand & silt w. brown clay			
27	27.5	0.5	Gn	Silty clay, hard & sticky			
27.5	28	0.5	Br	Silty clay, v. hard			
28	30	2	Gn	Clay, w. v. fine silty sand & rounded pebbles, v. hard			

Idavale

From	To	Thickness	Colour	Lithology	Water	SWL	Notes
0	1.2	1.2	Br	Gravel in clay matrix			
1.2	2.2	1	Br	Clay w. qtz pebbles			
2.2	2.6	0.4	Br	Clay			
2.6	4	1.4	Gy-Br	Clay, hard			
4	5.8	1.8	Gy-Br	Silty clay			
5.8	6	0.2	Gy-Br	V. fine sand to silt			
6	8.8	2.8	Gy-Br	Fine to med. sand & brown clay			
8.8	9.9	1.1	Lt Br	Clay			
9.9	10.5	0.6	Gy-Br	Clay-rich silt			
10.5	12.5	2	Br	Pea gravel in clay matrix	Dry		
12.5	16	3.5	Br	Rounded gw & qtz gravel <3cm in silt matrix	Dry		
16	19	3	Br	Fine sand w. pebbles	Dry		
19	23	4	Gy-Br	Fine sand w. clay			
23	25.2	2.2	Gy-Br	Fine sand w. clay & occ. rounded pebbles and coarse sand	WB		
25.2	27	1.8	Gy-Br	Fine sand w. rounded gravel <2cm	WB		
27	27.5	0.5	Red-Br	Med-coarse sand, w. rounded pebbles in red silty clay	WB	16.61	Sample, T~320
27.5	28	0.5	Red-Br	Fine-med sand & silty clay w. fewer pebbles	WB		
28	30	2	Gy-Br	Fine sand & clay w. occ. pebbles	WB		
30	31.5	1.5	Gy-Br	Qtz & Gw pebbles in fine sand & brown clay matrix	WB		
31.5	32	0.5	Gy-Br	Fine sand & brown clay			
32	32.5	0.5	Gy-Gn-Br	Fine silt & clay			
32.5	32.9	0.4	Gy-Gn-Br	Fine silt & clay w. wx sst pebbles, hard			
32.9	33.2	0.3	Gn	silty clay			
33.2	35.8	2.6	Gn	Fine sand w. less clay	WB		
35.8	36	0.2	Gn-Br	Silt w. brown clay			

Appendix 3: Preliminary pumping test data

Nevill Lane, pumped at 1.8 l/s

Time t	Drawdown	Time t	Recovery time t'	t/t'	Residual drawdown
1	2.51	101	1	101.0	5.96
2	3.56	102	2	51.0	4.61
3	3.82	103	3	34.3	4.10
4	3.99	104	4	26.0	3.79
5	4.26	105	5	21.0	3.55
6	4.45	106	6	17.7	3.37
7	4.54	107	7	15.3	3.22
8	4.63	108	8	13.5	3.10
9	4.72	109	9	12.1	2.98
10	4.80	110	10	11.0	2.89
12	4.95	112	12	9.3	2.72
15	5.13	115	15	7.7	2.52
20	5.39	120	20	6.0	2.29
25	5.57	125	25	5.0	2.12
30	5.73	130	30	4.3	1.96
35	5.85	135	35	3.9	1.84
40	6.02	140	40	3.5	1.74
45	6.12	145	45	3.2	1.65
50	6.20	150	50	3.0	1.58
55	6.30	155	55	2.8	1.51
60	6.35	160	60	2.7	1.46
70	6.48	170	70	2.4	1.36
80	6.57	180	80	2.3	1.28
90	6.63	190	90	2.1	1.21
100	6.69	200	100	2.0	1.15

Idavale, pumped at 1.7 l/s

Time t	Recovery time t'	t/t'	Residual drawdown
71	1	71.0	0.39
72	2	36.0	0.23
73	3	24.3	0.17
74	4	18.5	0.14
75	5	15.0	0.12
76	6	12.7	0.11
77	7	11.0	0.10
78	8	9.8	0.09
79	9	8.8	0.09
80	10	8.0	0.08
82	12	6.8	0.07
84	14	6.0	0.07
86	16	5.4	0.06
88	18	4.9	0.06
90	20	4.5	0.06
92	22	4.2	0.06
94	24	3.9	0.05
96	26	3.7	0.05
98	28	3.5	0.05
100	30	3.3	0.05
105	35	3.0	0.04

Moa Creek, pumped at 1.6 l/s

Time t	Recovery time t'	t/t'	Residual drawdown
201	1	201.0	2.66
202	2	101.0	1.97
203	3	67.7	1.49
204	4	51.0	1.2
205	5	41.0	1.02
206	6	34.3	0.89
207	7	29.6	0.76
208	8	26.0	0.7
209	9	23.2	0.62
210	10	21.0	0.56
212	12	17.7	0.47
215	15	14.3	0.37
220	20	11.0	0.26
225	25	9.0	0.2
230	30	7.7	0.14
235	35	6.7	0.12
240	40	6.0	0.09
245	45	5.4	0.06

Appendix 4: Meade Road 24-hour pumping test

Pumped Bore	Time t	Water depth	Drawdown
7-Jul 12:00	0	0.14	0.00
7-Jul 12:00	0.5	3.63	3.49
7-Jul 12:01	1	4.31	4.17
7-Jul 12:01	1.5	4.63	4.49
7-Jul 12:02	2	4.81	4.67
7-Jul 12:02	2.5	5.00	4.86
7-Jul 12:03	3	5.07	4.93
7-Jul 12:04	4	5.28	5.14
7-Jul 12:05	5	5.44	5.30
7-Jul 12:06	6	5.54	5.40
7-Jul 12:07	7	5.67	5.53
7-Jul 12:08	8	5.76	5.62
7-Jul 12:09	9	5.84	5.70
7-Jul 12:10	10	5.85	5.71
7-Jul 12:12	12	5.95	5.81
7-Jul 12:15	15	6.11	5.97
7-Jul 12:20	20	6.26	6.12
7-Jul 12:25	25	6.30	6.16
7-Jul 12:30	30	6.50	6.36
7-Jul 12:40	40	6.66	6.52
7-Jul 12:50	50	6.76	6.62
7-Jul 13:00	60	6.85	6.71
7-Jul 13:10	70	6.93	6.79
7-Jul 13:20	80	6.96	6.82
7-Jul 13:30	90	7.04	6.90
7-Jul 13:40	100	7.10	6.96
7-Jul 13:50	110	7.19	7.05
7-Jul 14:00	120	7.26	7.12
7-Jul 14:30	150	7.52	7.38
7-Jul 15:30	210	7.77	7.63
7-Jul 16:00	240	7.88	7.74
7-Jul 16:30	270	7.97	7.83
7-Jul 17:00	300	8.07	7.93
7-Jul 17:30	330	8.15	8.01
7-Jul 20:30	510	8.51	8.37
7-Jul 21:00	540	8.57	8.43
7-Jul 21:30	570	8.63	8.49
7-Jul 22:00	600	8.68	8.54
8-Jul 7:00	1140	9.34	9.20
8-Jul 8:00	1200	9.43	9.29
8-Jul 9:00	1260	9.43	9.29
8-Jul 10:00	1320	9.49	9.35
8-Jul 11:00	1380	9.54	9.40
8-Jul 12:00	1440	9.57	9.43

Piezometer	Time t	Water depth	Drawdown
7-Jul 12:00	0	0.37	0.00
7-Jul 12:00	0.5	0.37	0.00
7-Jul 12:01	1	0.38	0.01
7-Jul 12:01	1.5	0.40	0.03
7-Jul 12:02	2	0.43	0.06
7-Jul 12:02	2.5	0.46	0.08
7-Jul 12:03	3	0.48	0.11
7-Jul 12:04	4	0.53	0.16
7-Jul 12:05	5	0.57	0.20
7-Jul 12:06	6	0.61	0.24
7-Jul 12:07	7	0.65	0.28
7-Jul 12:08	8	0.68	0.31
7-Jul 12:09	9	0.71	0.34
7-Jul 12:10	10	0.74	0.37
7-Jul 12:12	12	0.79	0.42
7-Jul 12:15	15	0.86	0.49
7-Jul 12:20	20	0.95	0.57
7-Jul 12:25	25	1.02	0.64
7-Jul 12:30	30	1.08	0.71
7-Jul 12:40	40	1.18	0.81
7-Jul 12:50	50	1.27	0.89
7-Jul 13:00	60	1.34	0.97
7-Jul 13:10	70	1.40	1.03
7-Jul 13:20	80	1.45	1.08
7-Jul 13:30	90	1.50	1.13
7-Jul 13:40	100	1.55	1.18
7-Jul 13:50	110	1.60	1.22
7-Jul 14:00	120	1.64	1.27
7-Jul 14:30	150	1.76	1.38
7-Jul 15:00	180	1.86	1.48
7-Jul 15:30	210	1.95	1.58
7-Jul 16:00	240	2.03	1.66
7-Jul 16:30	270	2.11	1.74
7-Jul 17:00	300	2.19	1.81
7-Jul 17:30	330	2.26	1.89
7-Jul 18:00	360	2.33	1.95
7-Jul 19:00	420	2.45	2.08
7-Jul 20:00	480	2.56	2.19
7-Jul 21:00	540	2.66	2.29
7-Jul 22:00	600	2.76	2.39
7-Jul 23:00	660	2.85	2.48
8-Jul 0:00	720	2.94	2.56
8-Jul 1:00	780	3.02	2.65
8-Jul 2:00	840	3.09	2.72
8-Jul 3:00	900	3.17	2.80
8-Jul 4:00	960	3.24	2.86
8-Jul 5:00	1020	3.30	2.93
8-Jul 6:00	1080	3.37	2.99
8-Jul 7:00	1140	3.42	3.05
8-Jul 8:00	1200	3.48	3.10
8-Jul 9:00	1260	3.53	3.16
8-Jul 10:00	1320	3.58	3.20
8-Jul 11:00	1380	3.63	3.26
8-Jul 12:00	1440	3.68	3.30

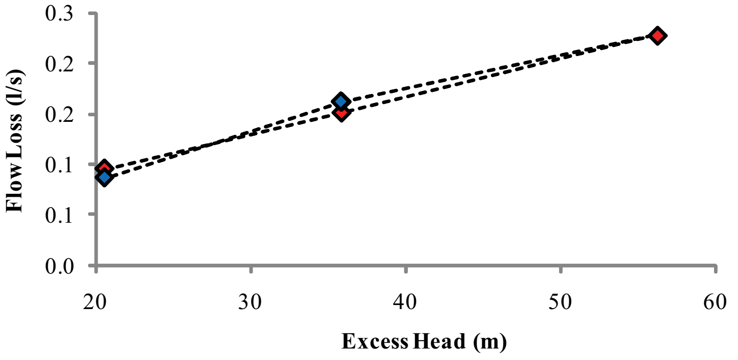
Pumped Bore	Time t	Recovery time t'	Water depth	Residual drawdown
8-Jul 12:00	1440.5	0.5	6.86	6.72
8-Jul 12:01	1441	1	6.01	5.87
8-Jul 12:01	1441.5	1.5	5.55	5.41
8-Jul 12:02	1442	2	5.23	5.09
8-Jul 12:02	1442.5	2.5	5.01	4.87
8-Jul 12:03	1443	3	4.85	4.71
8-Jul 12:04	1444	4	4.63	4.49
8-Jul 12:05	1445	5	4.46	4.32
8-Jul 12:06	1446	6	4.33	4.19
8-Jul 12:07	1447	7	4.22	4.08
8-Jul 12:08	1448	8	4.13	3.99
8-Jul 12:09	1449	9	4.06	3.92
8-Jul 12:10	1450	10	3.98	3.84
8-Jul 12:12	1452	12	3.85	3.71
8-Jul 12:15	1455	15	3.71	3.57
8-Jul 12:20	1460	20	3.53	3.39
8-Jul 12:30	1470	30	3.27	3.13
8-Jul 13:07	1507	67	2.77	2.63
8-Jul 13:25	1525	85	2.62	2.48
8-Jul 14:07	1567	127	2.34	2.20
8-Jul 14:35	1595	155	2.21	2.07
8-Jul 15:05	1625	185	2.08	1.94
8-Jul 15:50	1670	230	1.95	1.81
8-Jul 16:00	1680	240	1.92	1.78
8-Jul 16:30	1710	270	1.84	1.70
8-Jul 17:30	1770	330	1.71	1.57
8-Jul 18:00	1800	360	1.65	1.51
8-Jul 18:30	1830	390	1.60	1.46
8-Jul 19:00	1860	420	1.56	1.42
8-Jul 19:30	1890	450	1.51	1.37
8-Jul 20:00	1920	480	1.47	1.33
8-Jul 20:30	1950	510	1.44	1.30
8-Jul 21:00	1980	540	1.40	1.26
11-Jul 10:25	5665	4225	0.38	0.24

Piezometer	Time t	Recovery time t'	Water depth	Residual drawdown
8-Jul 12:00	1440.5	0.5	3.68	3.30
8-Jul 12:01	1441	1	3.67	3.29
8-Jul 12:01	1441.5	1.5	3.65	3.28
8-Jul 12:02	1442	2	3.63	3.25
8-Jul 12:02	1442.5	2.5	3.60	3.23
8-Jul 12:03	1443	3	3.58	3.21
8-Jul 12:04	1444	4	3.54	3.16
8-Jul 12:05	1445	5	3.49	3.12
8-Jul 12:06	1446	6	3.46	3.08
8-Jul 12:07	1447	7	3.42	3.05
8-Jul 12:08	1448	8	3.39	3.02
8-Jul 12:09	1449	9	3.36	2.99
8-Jul 12:10	1450	10	3.33	2.96
8-Jul 12:12	1452	12	3.29	2.91
8-Jul 12:15	1455	15	3.22	2.85
8-Jul 12:20	1460	20	3.14	2.76
8-Jul 12:25	1465	25	3.07	2.69
8-Jul 12:30	1470	30	3.01	2.63
8-Jul 12:40	1480	40	2.91	2.53
8-Jul 12:50	1490	50	2.83	2.45
8-Jul 13:00	1500	60	2.76	2.39
8-Jul 13:10	1510	70	2.70	2.33
8-Jul 13:20	1520	80	2.65	2.28
8-Jul 13:30	1530	90	2.60	2.23
8-Jul 13:40	1540	100	2.56	2.19
8-Jul 14:00	1560	120	2.48	2.11
8-Jul 14:30	1590	150	2.38	2.01
8-Jul 15:00	1620	180	2.30	1.93
8-Jul 15:30	1650	210	2.23	1.86
8-Jul 16:00	1680	240	2.17	1.80
8-Jul 16:30	1710	270	2.12	1.74
8-Jul 17:00	1740	300	2.07	1.70
8-Jul 17:30	1770	330	2.02	1.65
8-Jul 18:00	1800	360	1.98	1.61
8-Jul 18:30	1830	390	1.94	1.57
8-Jul 19:00	1860	420	1.91	1.53
8-Jul 19:30	1890	450	1.87	1.50
8-Jul 20:00	1920	480	1.84	1.47
8-Jul 20:30	1950	510	1.81	1.44
8-Jul 21:00	1980	540	1.78	1.41
8-Jul 22:00	2040	600	1.73	1.36
8-Jul 23:00	2100	660	1.68	1.31
9-Jul 0:00	2160	720	1.64	1.27
9-Jul 1:00	2220	780	1.60	1.23
9-Jul 2:00	2280	840	1.56	1.19
9-Jul 3:00	2340	900	1.53	1.15
9-Jul 4:00	2400	960	1.49	1.12
9-Jul 6:00	2520	1080	1.43	1.06
9-Jul 8:00	2640	1200	1.37	0.99
9-Jul 10:00	2760	1320	1.32	0.95
9-Jul 12:00	2880	1440	1.25	0.88
9-Jul 18:00	3240	1800	1.12	0.75
10-Jul 0:00	3600	2160	1.06	0.69
10-Jul 6:00	3960	2520	1.01	0.64
10-Jul 12:00	4320	2880	0.99	0.61
11-Jul 12:00	5760	4320	0.81	0.43

Appendix 5: Wireline packer tests

Cresslea Test 3

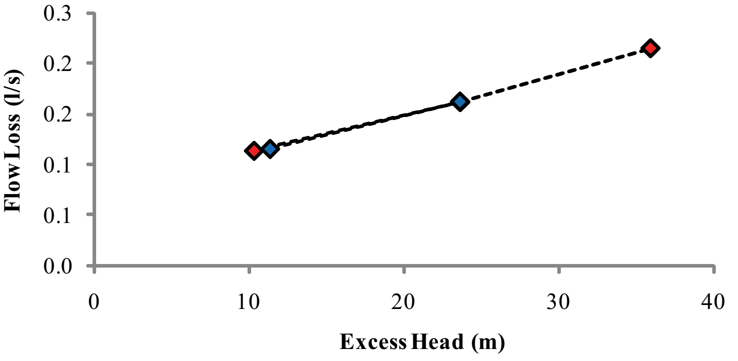
Operator	McNeills	
Date	16-Jun-11	
SWL	-4.92	m
Measuring Point	Ground	
Diameter (m)	0.0965	
Top of packer	31.12	
Bottom	41.12	
Length of section	10	
Hyd Cond	**0.032**	



Time	Pressure (KPa)	Pressure (m)	Excess Head	Avg Head	Water Loss (litres)	Discharge (l/min)	Avg Q (l/s)	LU (m-1)	K (m/d)
5	250	25.5	20.58		29	5.80			
5	250	25.5	20.58	20.58	28	5.60	0.10	2.77	0.03
5	400	40.8	35.88		46.5	9.30			
5	400	40.8	35.88	35.88	44	8.80	0.15	2.52	0.03
5	600	61.2	56.28		62	12.40			
5.5	600	61.2	56.28	56.28	82	14.91	0.23	2.43	0.03
5	400	40.8	35.88		52	10.40			
5	400	40.8	35.88	35.88	45	9.00	0.16	2.70	0.03
5	250	25.5	20.58		24.5	4.90			
5	250	25.5	20.58	20.58	27.5	5.50	0.09	2.53	0.03
						Average	**12.5**	**2.6**	**0.032**

Cresslea Test 4

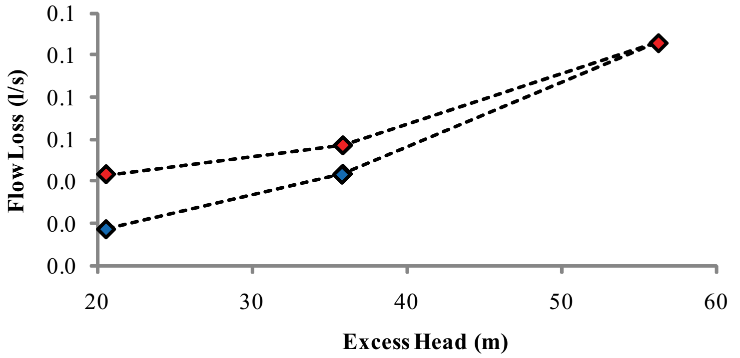
Operator	McNeills	
Date	16-Jun-11	
SWL	-4.92	m
Measuring Point	Ground	
Diameter (m)	0.0965	
Top of packer	18.62	
Bottom	41.12	
Length of section	22.5	
Hyd Cond	**0.031**	



Time	Pressure (KPa)	Pressure (m)	Excess Head	Avg Head	Water Loss (litres)	Discharge (l/min)	Avg Q (l/s)	LU (m-1)	K (m/d)
5	150	15.3	10.38		35	7.00			
5	150	15.3	10.38	10.38	33	6.60	0.11	2.91	0.04
5	280	28.6	23.64		43	8.60			
5	280	28.6	23.64	23.64	54	10.80	0.16	1.82	0.03
5	400	40.8	35.88		67	13.40			
5	400	40.8	35.88	35.88	62	12.40	0.22	1.60	0.02
5	280	28.6	23.64		48	9.60			
5	280	28.6	23.64	23.64	49	9.80	0.16	1.82	0.03
5	160	16.3	11.40		34	6.80			
5	160	16.3	11.40	11.40	35	7.00	0.12	2.69	0.04
						Average	**13.2**	**2.2**	**0.031**

Cresslea Post Hydrofracc Test

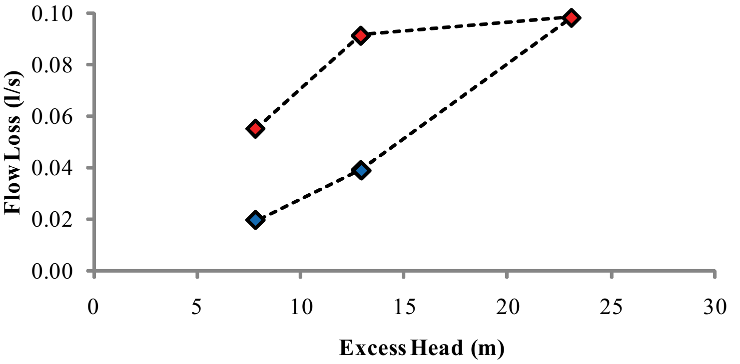
Operator	McNeills	
Date	8-Aug-11	
SWL	-4.92	m
Measuring Point	Ground	
Diameter (m)	0.0965	
Top of packer	31.12	
Bottom	41.12	
Length of section	10	
Hyd Cond	**0.011**	



Time	Pressure (KPa)	Pressure (m)	Excess Head	Avg Head	Water Loss (litres)	Discharge (l/min)	Avg Q (l/s)	LU (m-1)	K (m/d)
5	250	25.5	20.58		10.2	2.04			
5	250	25.5	20.58	20.58	15.7	3.14	0.04	1.26	0.02
5	400	40.8	35.88		23.3	4.66			
5	400	40.8	35.88	35.88	10.9	2.18	0.06	0.95	0.01
5	600	61.2	56.28		35	7.00			
5	600	61.2	56.28	56.28	28.5	5.70	0.11	1.13	0.01
5	400	40.8	35.88		13.2	2.64			
5	400	40.8	35.88	35.88	12.8	2.56	0.04	0.72	0.01
5	250	25.5	20.58		4.6	0.92			
5	250	25.5	20.58	20.58	5.8	1.16	0.02	0.51	0.01
						Average	**4.6**	**0.9**	**0.011**

Meade Road Test 1

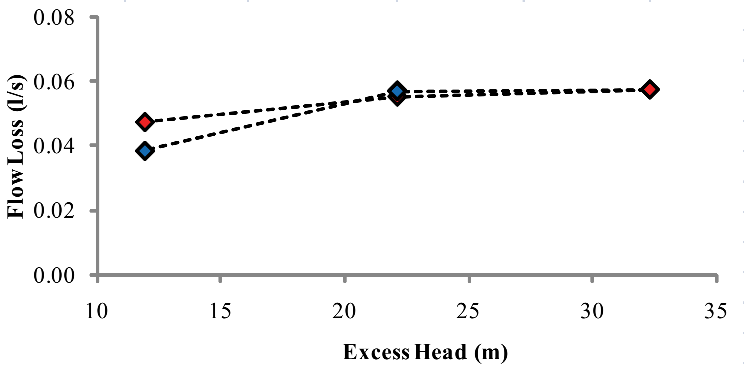
Operator	McNeills	
Date	24-Jun-11	
SWL	-2.39	m
Measuring Point	Ground	
Diameter (m)	0.0965	
Top of packer	11.08	
Bottom	17.08	
Length of section	6	
Hyd Cond	**0.053**	



Time	Pressure (KPa)	Pressure (m)	Excess Head	Avg Head	Water Loss (litres)	Discharge (l/min)	Avg Q (l/s)	LU (m-1)	K (m/d)
5	100	10.2	7.81		19	3.80			
5	100	10.2	7.81	7.81	14	2.80	0.06	7.04	0.08
5	150	15.3	12.91		28	5.60			
5	150	15.3	12.91	12.91	26.8	5.36	0.09	7.07	0.08
5	250	25.5	23.11		29	5.80			
5	250	25.5	23.11	23.11	30	6.00	0.10	4.26	0.05
5	150	15.3	12.91		10.2	2.04			
5	150	15.3	12.91	12.91	13.1	2.62	0.04	3.01	0.03
5	100	10.2	7.81		4.6	0.92			
5	100	10.2	7.81	7.81	7	1.40	0.02	2.48	0.03
						Average	**5.2**	**4.8**	**0.053**

Meade Road Test 2

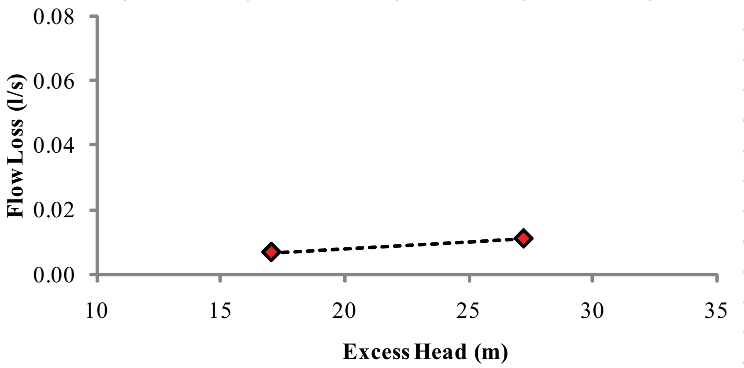
Operator	McNeills	
Date	27-Jun-11	
SWL	-3.38	m
Measuring Point	Ground	
Diameter (m)	0.0965	
Top of packer	17.08	
Bottom	23.08	
Length of section	6	
Hyd Cond	**0.031**	



Time	Pressure (KPa)	Pressure (m)	Excess Head	Avg Head	Water Loss (litres)	Discharge (l/min)	Avg Q (l/s)	LU (m-1)	K (m/d)
5	150	15.3	11.92		14.8	2.96			
5	150	15.3	11.92	11.92	13.5	2.70	0.05	3.96	0.04
5	250	25.5	22.12		16.7	3.34			
5	250	25.5	22.12	22.12	16.3	3.26	0.06	2.49	0.03
5	350	35.7	32.32		18	3.60			
5	350	35.7	32.32	32.32	16.3	3.26	0.06	1.77	0.02
5	250	25.5	22.12		17.3	3.46			
5	250	25.5	22.12	22.12	16.8	3.36	0.06	2.57	0.03
5	150	15.3	11.92		11.3	2.26			
5	150	15.3	11.92	11.92	11.7	2.34	0.04	3.22	0.04
						Average	**4.4**	**2.8**	**0.031**

Meade Road Test 4

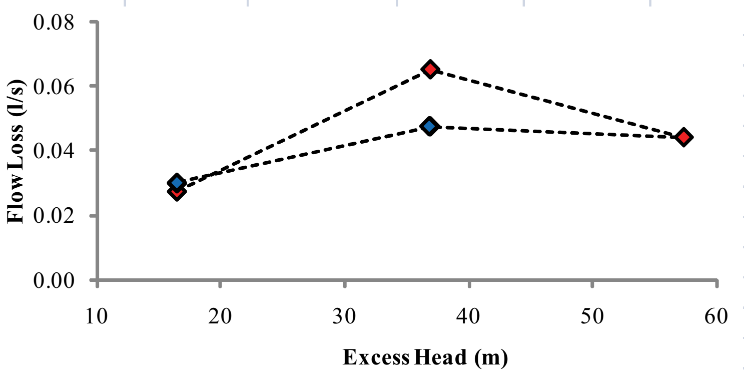
Operator	McNeills	
Date	27-Jun-11	
SWL	-3.38	m
Measuring Point	Ground	
Diameter (m)	0.0965	
Top of packer	25.96	
Bottom	31.96	
Length of section	6	
Hyd Cond	**0.004**	



Time	Pressure (KPa)	Pressure (m)	Excess Head	Avg Head	Water Loss (litres)	Discharge (l/min)	Avg Q (l/s)	LU (m-1)	K (m/d)
5	200	20.4	17.02		1.3	0.26			
5	200	20.4	17.02	17.02	2.7	0.54	0.01	0.39	0.00
5	300	30.6	27.22		3.5	0.70			
5	300	30.6	27.22	27.22	3	0.60	0.01	0.40	0.00
5	500	51.0	47.62						
						Average	**0.8**	**0.4**	**0.004**

Meade Road Test 5

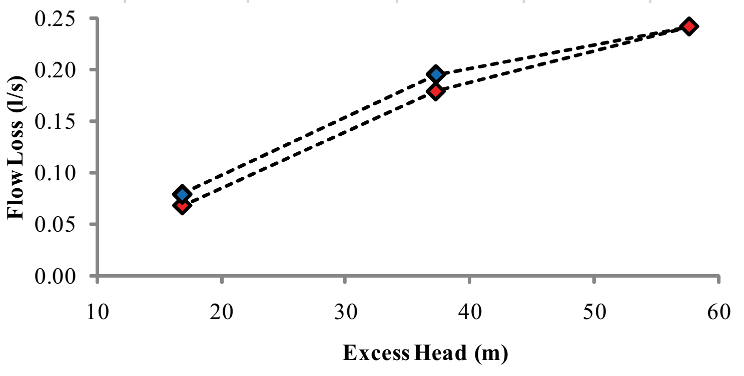
Operator	McNeills	
Date	28-Jun-11	
SWL	-3.92	m
Measuring Point	Ground	
Diameter (m)	0.0965	
Top of packer	32.08	
Bottom	38.08	
Length of section	6	
Hyd Cond	**0.016**	



Time	Pressure (KPa)	Pressure (m)	Excess Head	Avg Head	Water Loss (litres)	Discharge (l/min)	Avg Q (l/s)	LU (m-1)	K (m/d)
5	200	20.4	16.48		11.9	2.38			
5	200	20.4	16.48	16.48	4.6	0.92	0.03	1.67	0.02
5	400	40.8	36.88		19	3.80			
5	400	40.8	36.88	36.88	20	4.00	0.07	1.76	0.02
5	600	61.2	57.28		14	2.80			
5	600	61.2	57.28	57.28	12.5	2.50	0.04	0.77	0.01
5	400	40.8	36.88		12	2.40			
5	400	40.8	36.88	36.88	16.5	3.30	0.05	1.29	0.01
5	200	20.4	16.48		7.5	1.50			
5	200	20.4	16.48	16.48	10.5	2.10	0.03	1.82	0.02
						Average	**3.7**	**1.5**	**0.016**

Meade Road Test 7

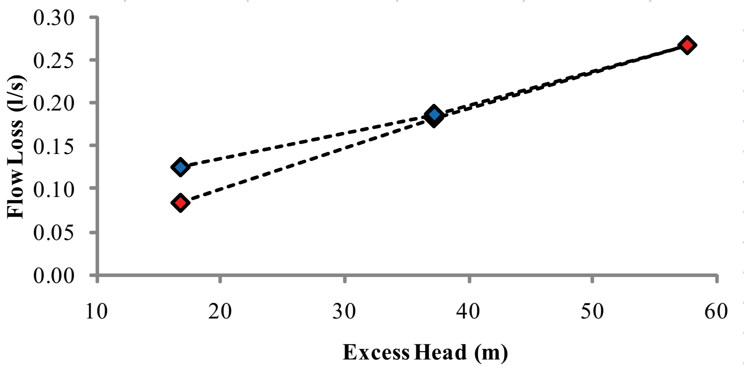
Operator	McNeills	
Date	29-Jun-11	
SWL	-3.56	m
Measuring Point	Ground	
Diameter (m)	0.0965	
Top of packer	53.08	
Bottom	61.32	
Length of section	8.24	
Hyd Cond	**0.039**	



Time	Pressure (KPa)	Pressure (m)	Excess Head	Avg Head	Water Loss (litres)	Discharge (l/min)	Avg Q (l/s)	LU (m-1)	K (m/d)
5	200	20.4	16.84		21.3	4.26			
5	200	20.4	16.84	16.84	19	3.80	0.07	2.90	0.03
5	400	40.8	37.24		62	12.40			
5	400	40.8	37.24	37.24	45	9.00	0.18	3.49	0.04
5	600	61.2	57.64		75	15.00			
5	600	61.2	57.64	57.64	70	14.00	0.24	3.05	0.04
5	400	40.8	37.24		58	11.60			
5	400	40.8	37.24	37.24	59	11.80	0.20	3.81	0.04
5	200	20.4	16.84		23	4.60			
5	200	20.4	16.84	16.84	24	4.80	0.08	3.39	0.04
						Average	**13.1**	**3.3**	**0.039**

Meade Road Test 8

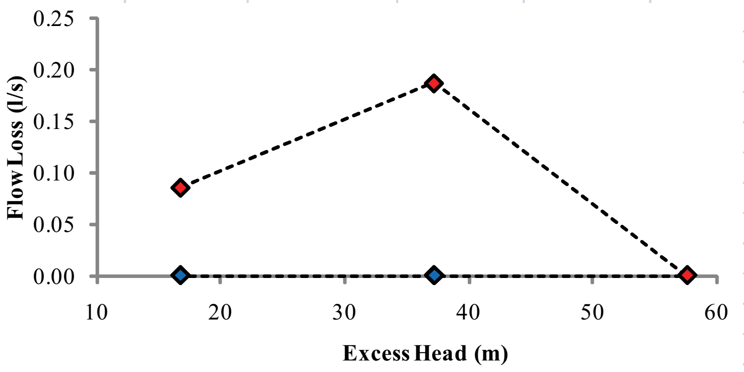
Operator	McNeills	
Date	29-Jun-11	
SWL	-3.56	m
Measuring Point	Ground	
Diameter (m)	0.0965	
Top of packer	32.08	
Bottom	61.32	
Length of section	29.24	
Hyd Cond	**0.016**	



Time	Pressure (KPa)	Pressure (m)	Excess Head	Avg Head	Water Loss (litres)	Discharge (l/min)	Avg Q (l/s)	LU (m-1)	K (m/d)
5	200	20.4	16.84		25	5.00			
5	200	20.4	16.84	16.84	25	5.00	0.08	1.02	0.01
5	400	40.8	37.24		57	11.40			
5	400	40.8	37.24	37.24	52	10.40	0.18	1.00	0.01
5	600	61.2	57.64		80	16.00			
5	600	61.2	57.64	57.64	80	16.00	0.27	0.95	0.01
5	400	40.8	37.24		56	11.20			
5	400	40.8	37.24	37.24	56	11.20	0.19	1.03	0.02
5	200	20.4	16.84		37	7.40			
5	200	20.4	16.84	16.84	38	7.60	0.13	1.52	0.02
						Average	**14.6**	**1.1**	**0.016**

Meade Road Test 9

Operator	McNeills	
Date	29-Jun-11	
SWL	-3.56	m
Measuring Point	Ground	
Diameter (m)	0.0965	
Top of packer	17.08	
Bottom	61.32	
Length of section	44.24	
Hyd Cond	**0.011**	



Time	Pressure (KPa)	Pressure (m)	Excess Head	Avg Head	Water Loss (litres)	Discharge (l/min)	Avg Q (l/s)	LU (m-1)	K (m/d)
5	200	20.4	16.84		26.6	5.32			
5	200	20.4	16.84	16.84	24.4	4.88	0.09	0.68	0.01
5	400	40.8	37.24		56	11.20			
5	400	40.8	37.24	37.24	56	11.20	0.19	0.68	0.01
5	600	61.2	57.64			0.00			
5	600	61.2	57.64	57.64		0.00			
5	400	40.8	37.24			0.00			
5	400	40.8	37.24	37.24		0.00			
5	200	20.4	16.84			0.00			
5	200	20.4	16.84	16.84		0.00			
						Average	**11.7**	**0.7**	**0.011**