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WRL Research Report 235
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Water Research Laboratory
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Hydrogeological Study of the Baldry Site

WATER RESEARCH LABORATORY
RESEARCH REPORT
No. 235

Prepared by

R I Acworth, W A Timms and T Bernardi

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April 2014

EXECUTIVE SUMMARY

A hydrogeological investigation is in progress to quantify water and salt fluxes through clayey sediments and weathered and fractured granite in a sub-catchment of the Little River, a salinity hotspot in the Murray Darling Basin. Surfacewater, groundwater, soil water and meteorological conditions have been monitored at the Baldry research site, a ~50 hectare sub-catchment, since 2004 along with associated studies on tree water use to identify the factors controlling groundwater recharge. Two stream gauging weirs and a network of 8 shallow piezometers and 12 nested monitoring bores were established in pasture areas on the eastern side of the catchment and trial forest areas on the western side of the catchment. The deepest monitoring bores were completed to about 20 m depth and were open hole within granite, while shallower monitoring bores and piezometers were completed with PVC casing and screen inlets.

Fine-grained granites and granodiorites are well fractured and deeply weathered, outcropping in the upper parts of the site, and overlain by approximately 8 m of clayey sediments in the mid to lower areas of the site. Subsurface conditions were described by stratigraphic logs from bores and test pits, geophysical bore logs (natural gamma and bulk electrical conductivity), EM31 mapping, resistivity cross-sections. Highly saline sediments were evident near an historic salt scald, and as patches within clayey sediments. Granite derived sands occurred above weathered granite, with the upper surface of hard granite located at up to 13 m below ground. The granite was mostly dry, with water bearing fractures that become a pathway for tree roots that tend to block open boreholes.

Groundwater levels in deep bores were typically 4-6 m below surface in the upper areas (elevation ~464 m AHD). However in the lower areas (elevation ~452 m AHD), groundwater levels in deep bores were generally only ~2 m below surface, and in October 2003 were recorded above the surface indicating a potential upwards flow gradient from factured granite into clayey sediments. At most multi-level piezometer sites, the shallow piezometer was either dry, or indicated an upwards hydraulic gradient to the deeper aquifer, except at bore 7 where an downwards hydraulic gradient was observed.

There is a lateral hydraulic gradient of about 8 m over a distance of 400 m (dh/dL 0.02) to drive groundwater flow through the weathered and fractured granite. The permeability of the weathered granite is limited by angular, poorly sorted materials, while the permeability of fractured granite is likely to vary. The rate of groundwater flow is likely to be very slow and stagnant in disconnected fractures. The interpretation of groundwater hydraulics is consistent with hydrochemical and isotopic evidence.

Water samples were obtained in April 2004, March 2005 and June 2008 for hydrochemical analysis (n=59 groundwater, n=24 surface water) and stable isotope analysis ($\delta^{18}O$ and $\delta^{2}H$, n = 35). In June 2008, groundwater EC varied between 1.0-9.7 mS/cm (n=21), compared with surface water 0.4-1.4 mS/cm (n=2), and EC 6.1 mS/cm at a creek pond where groundwater appeared to be discharging. Salts loads generated by this sub-catchment appear to depend on the degree to which salt patches in clayey surface sediments are flushed into shallow groundwater and discharged to the creek.

Groundwater salinity was relatively high within clayey sediments, and groundwater salinity within the fractured granite was highest in the upper areas and typically decreased downslope. Between 2004 and drier conditions in 2008, groundwater salinity increased significantly at several bores in the lower and mid sub-catchment, but freshening observed at one site near the top of the forested area.

Groundwater pH averaged 7.2, with spatial variation from pH 5.8 to 8.5. The site with highest pH was likely due to effects of cement grout used during bore construction at a site with very low flow rates. Groundwater was oxidising (Eh-NHE ~300 mV average) and field spectrophotometer analysis indicated very low Fe^{2+}, and S^{2-} below detection limit. Groundwater in fractured granite was a significant source of Mg, Mn and Sr, but could not account for saline groundwater, or NaCl type groundwater. There was evidence for geochemical evolution of groundwater chemistry along flow paths from higher to lower elevations within the sub-catchment. Groundwater is generally of a Na-Cl type at higher elevations, with a higher proportion of Mg. However, despite generally decreasing salinity, groundwater is of Na-HCO3 type at mid to lower elevations with relatively high proportions of Na.

Spatial variability in groundwater chemistry was of greater significance than changes over time. No evidence of recharge was observed during the study period, although the decrease in salinity of deep groundwater down-slope may be attributed to areas in the mid-catchment that allow steady downwards percolation of water through non-saline soil and sediments. Alternatively, groundwater freshening trend down-slope may be due to discharge of very deep fresh groundwater, although there is no evidence available to test this possibility. The lack of evidence for recharge is consistent with detailed studies of barometric efficiency within three of the monitoring bores which indicate confined aquifer conditions, even at sites with thin clay overburden and shallow fractured rock (Acworth and Brain, 2008).

Groundwater was of meteoric origin ($\delta^{18}O$ and $\delta^{2}H$ values similar to average local rainfall) with no evidence of evaporative concentration, or of significant recharge during the study period. Highly saline groundwaters are not the result of evaporative concentration processes. Groundwater is generally more depleted in stable isotopes relative to the estimated average isotope values of local rainfall, indicating that aquifers in weathered and fractured granite may have been recharged primarily during periods of wetter and cooler climatic that observed during the study.

There does not appear to be a significant difference in groundwater conditions on the western forested side of the sub-catchment, compared with the eastern side of the sub-catchment where pastures remain the predominant landuse. On both sides of the sub-catchment, the horizontal hydraulic gradient that drives groundwater flow is similar. Groundwater salinity of granite aquifers is highest at the top of the catchment and of similar magnitude beneath the forest and pasture areas.

The detailed hydrogeological investigation at the Baldry site between 2004 and 2008 has not identified a connection between surface conditions and groundwater. There was no significant recharge to groundwater during the study period. There was no evidence that surface water, soil water or associated salts reach the watertable, or that changing landuse had an influence on groundwater levels or groundwater salinity. The possibility that minor fluxes of water and salt pass through the vadose zone to groundwater cannot be ruled out, particularly if minor fluxes occur episodically through localised areas of the hillslope.

Heavy clay deposits near the surface may act as an effective flow barrier. The heavy clay deposits, with associated salt patches are not derived from the underlying weathered granite, and have effectively disconnected groundwater within those zones from surface processes. Available evidence suggests that planting trees may not have a direct influence on groundwater by limiting recharge. However, it is possible that tree roots extracting groundwater may contribute to lowered groundwater levels and that salt scalds can be stablised by limiting soil erosion. Although the concept of recharge control through tree planting has not been validated for the Baldry site, it is probable that tree planting will act to decrease the total salt load in downstream surface waters surface waters by stabilising and preventing soil erosion.

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Chapter 1

Introduction

The Baldry site is located in the Little River catchment, a tributary of the Macquarie River, in Central West NSW (Figure 1.1). The site is located near the catchment divide, and is upstream of the inland city of Dubbo and the Macquarie Marshes. The Baldry sub-catchment has an area of 111,134 ha or 43% of the Little River catchment.

The Baldry Site is one of 7 Key Sites that are a part of the NSW DPI salinity investigation strategy. The hydrogeological component of the research project at Baldry has been undertaken by UNSW (Connected Waters Initiative at the Water Research Laboratory) and included a drilling program, associated geophysical investigation using electrical imaging and borehole geophysical methods, analysis of water level records and a hydrochemical monitoring and investigation program.

1.1 Climate

A long term record of daily rainfall exists for Cummnock and Yeoval. The cummulative departure from the mean for the Yeoval data is shown in Fig. 1.2. This figure also shows annual rainfall as a bar chart with dry years (less than 1 standard deviation below the mean) and wet years (more than 1 standard deviation above the mean) separately. It is clear that a significant change occurred in 1948, with the onset of a wetter period. This trend has been reported throughout the eastern part of NSW by Rančić et al. [2009] and is now considered to have been fundamental in the onset of dryland salinity in the latter part of the 20th Century..

Average maximum and minimum temperatures, potential evaporation and rainfall are given monthly in Table1.1 for Molong (40 km south east of Baldry) and Wellington (50 km south west of Baldry).

The water balance (Eto - Rainfall) in Table 1.1 illustrates the significance of the possibility of winter recharge when the Eto term is much reduced.

1.2 Topography

The site has appreciable topography with a relief of approximately 50 m. The site slopes in a northerly direction and is drained by a northward running ephemeral creek that runs into the Little River.

A very approximate contour model of the surface topography is shown in Figure 1.3 based upon the DEM provided with the electromagnetic survey carried out by the Department of Infrastructure Planning and Natural Resources (DIPNA).

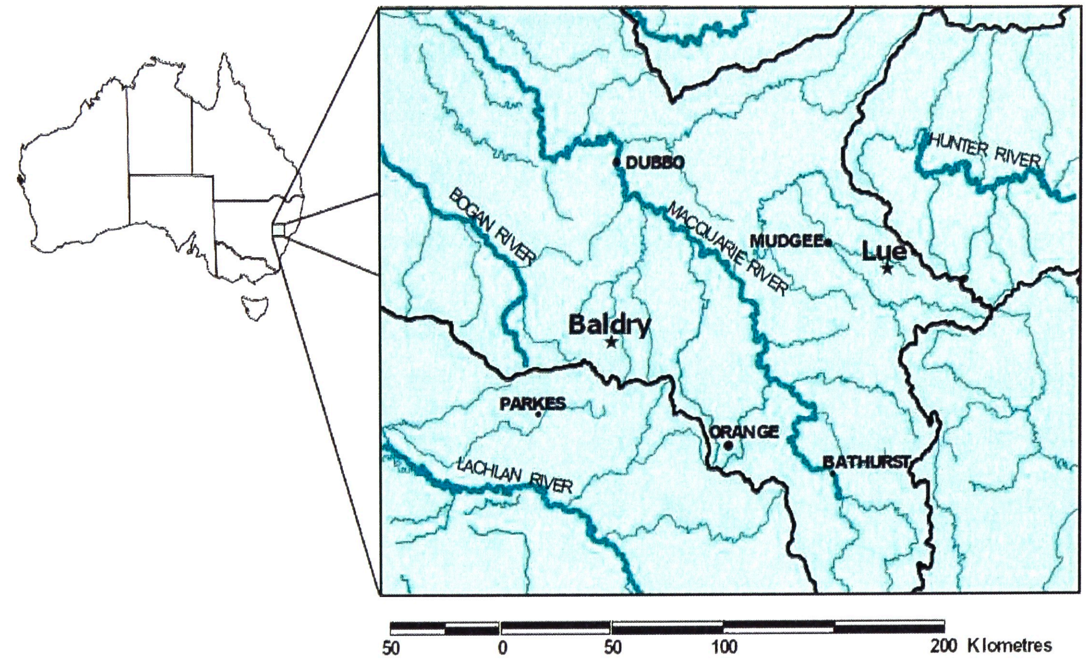

Figure 1.1: Location of Baldry site in the Macquarie Catchment (Walsh, 2003)

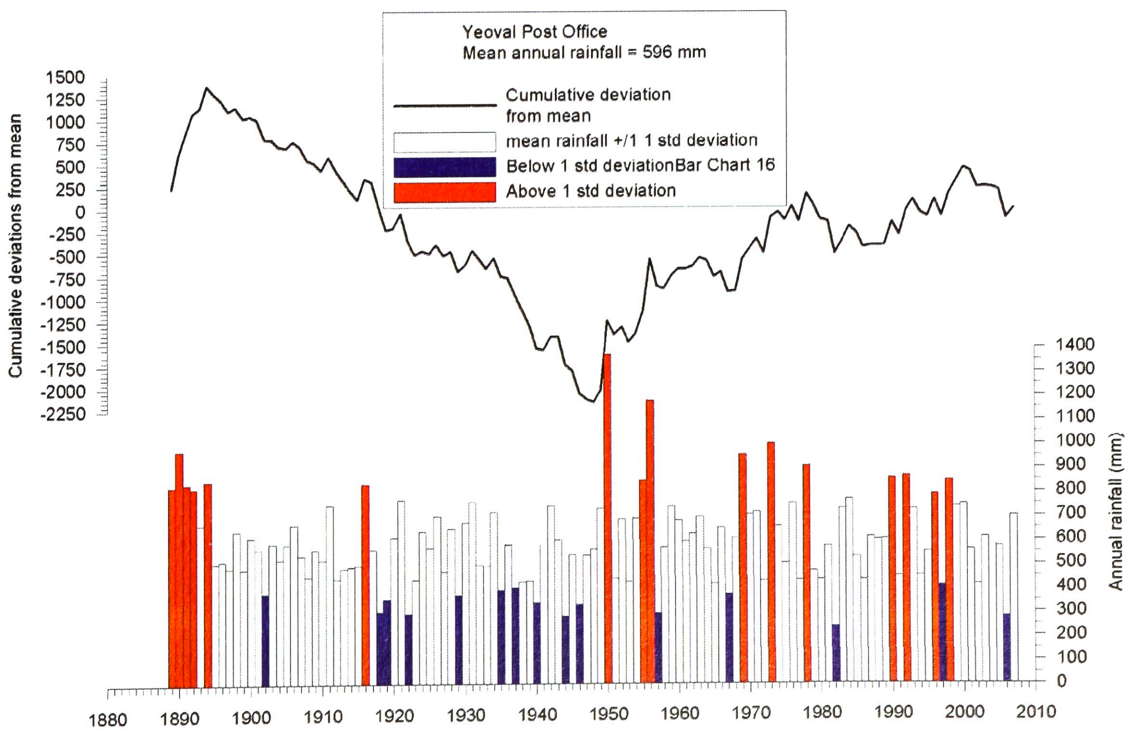

Figure 1.2: Cummulative departure from mean rainfall for Yeoval

Table 1.1: Monthly climate data for Molong and Wellington (source BoM (2003)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Wellington											
Daily max temp (°C)	31.0	30.1	27.4	23.0	18.4	14.7	14.0	15.6	18.8	22.6	26.2	29.9
Daily min temp (°C)	17.5	17.4	15.0	10.9	7.6	4.5	3.5	4.2	6.6	9.9	12.6	15.9
Evaporation (mm)	267	216	192	126	78	51	53	74	102	155	204	267
Rainfall (mm)	66.4	59.1	52.0	44.4	49.3	40.0	47.2	49.0	45.4	64.4	57.2	50.7
Rain-Etp	-200.1	-156.9	-140.0	-81.6	-28.7	-1.0	-5.8	-25.0	-56.6	-90.6	-146.8	-216.3
	Molong											
Daily max temp (°C)	31.0	30.1	27.5	22.5	17.4	14.0	12.9	14.7	18.6	22.6	26.4	29.5
Daily min temp (°C)	13.3	13.2	10.4	6.0	2.7	0.9	-0.1	0.6	2.4	5.4	8.4	11.5
Rainfall (mm)	69.8	56.7	55.6	50.6	55.0	60.7	59.9	62.6	54.3	60.7	58.6	62.3

The front piece to this report is a photograph taken from the western boundary of the site in November, 2003 looking east towards the plantation. The plot slopes in a northerly direction with a pronounced drainage channel running through the centre.

1.3 Hydrology

A climate station (Fig. 1.8) was established at the site and a network of 5(?) rain gauges. A weir (Fig. 1.4) was constructed at the bottom of the investigation site to monitor flow leaving the area. An ephemeral creek line runs to the east down to the Little River and has been subject to gully erosion in the past.

1.4 Geology

The geology of the site consists of fine-grained Silurian to Devonian age granites and granodiorites that are a part of the Yeoval Batholith intruded into the Silurian and Devonian metasediments of the Cowra trough. The fine-grained granites crop out in several parts of the catchment and are not limited to the hill tops. The granites appear to be well fractured and deeply weathered - at least in parts.

There is evidence of significant clay deposits overlying the weathered granite.

1.5 Soils

Weathered granite crops out in many areas of the site but particularly in the area to the north of the public road. Bore 5 has been located on an area where rock crops out at the surface as shown in Figure 1.7.

To the east of the creek an extensive development of a red podsolic soil occurs that is currently under cultivation. On the western side of the creek and towards the base of the hill, extensive dispersion of a saline soil has occurred. Tree growth in this area has been stunted. Past land management has included forming several contour banks to delay runoff and inhibit the development of gullying.

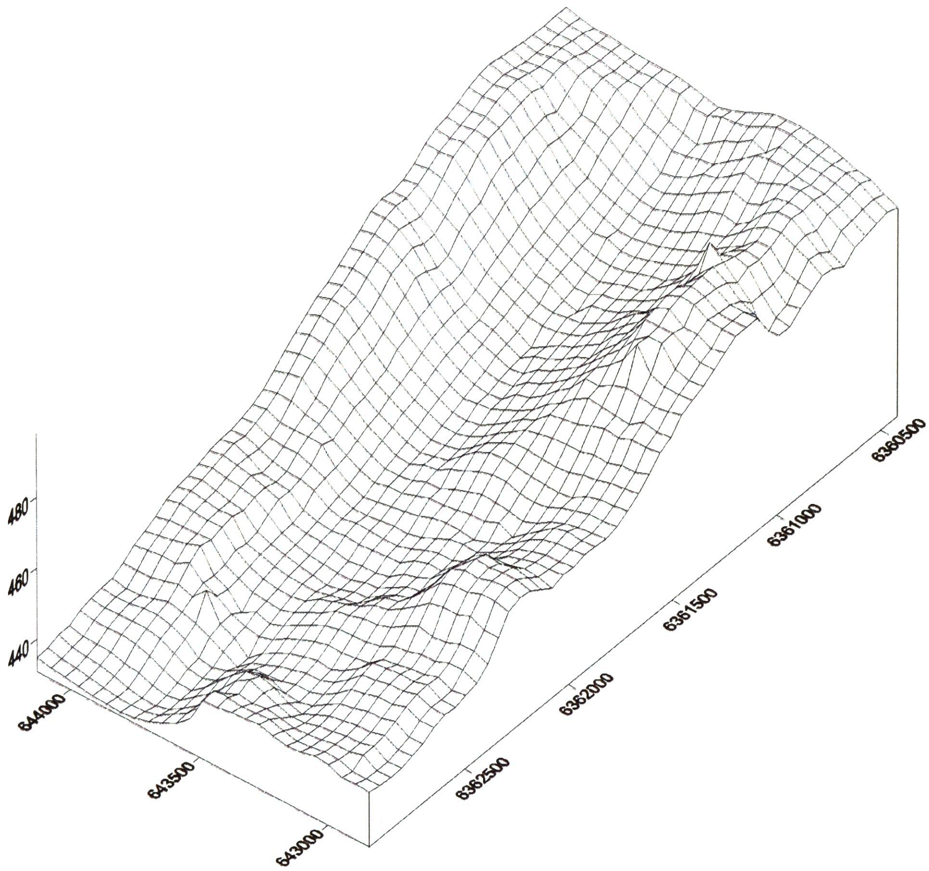

Figure 1.3: Wireframe model of the surface elevation at the Baldry Site

Figure 1.4: Construction of the main weir and a subsidiary weir on a contributing channel

Figure 1.5: Little River at the junction of the ephemeral drainage line leaving the site

Figure 1.6: Typical profile along the drainage channel

Figure 1.7: Bore 5 location showing shallow fractured rock with almost no soil development

Figure 1.8: The climate station at Baldry

Figure 1.9: Shallow soil profile white salt deposits on top of silt

Chapter 2

Description of methods used

2.1 EM31 Survey

The EM31 survey was carried out by DIPNA and the output was used to site the bore locations in the drilling program. A QUADCYCLE equipped with a data logger, GPS and an EM31 was driven over the site collecting data at approximately 20 m line widths.

2.2 Electrical Imaging

Electrical images Acworth [1999] were carried out along 4 profiles joining the bore sites and generally aligned east - west. A 2.5 m spacing between electrodes was used and data collected using an ABEM4000 resistivity system and a LUND ES464 multi-electrode switching system. Data was collected in August 2003 when ground conditions were dry. Interpreted ground resistivities were developed for a 20 m depth along the lines of investigation using the RES2DINV software package Loke [2001].

2.3 Drilling

An air-hammer rig was used to drill the piezometers. A shallow piezometer was installed to the top of the weathered rock and a casing and screen set and sealed. A deeper hole was then drilled alongside to encounter the first fractures in the granite that carry water. This hole was drilled at a diameter of 100 mm to the base of the weathered zone and a casing cemented in. Drilling was then continued through the casing to leave an open hole for sampling and monitoring. Unstable formation was encountered at Bore 3 and an 80 mm casing was installed to the total depth of 19 m.

2.4 Level monitoring

A variety of logging systems was deployed at the site including loggers manufactured by GREENSPAN, SCHLUMBERGER (Diver) and OTT.

Data loggers have been installed in all bores and set to monitor at hourly intervals. The loggers have been downloaded every few weeks and a dipping round conducted to ensure tha t the accuracy of the logging was maintained. All data has been entered onto an ACCESS data base maintained by Tony Bernardi.

2.5 Borehole Logging

GEONICS EM39 logs of apparent conductivity and gamma-ray activity were run in all the bores. A GEOVISTA system was used to measure gamma-ray spectroscopy, caliper (bore diameter) and fluid properties (temperature, fluid electrical conductivity, dissolved oxygen, pH and Eh) in all the deeper bores.

2.6 Hydrochemistry

A mobile chemical laboratory was taken to site in mid April 2004 and again at the end of March 2005. Samples were taken from all the piezometers that contained water. Field measurements were restricted to pH and fluid EC as the complete bore profile was sampled using the HYDROLAB sonde attached to the GEOVISTA logging unit.

A battery operated sampling pump was used on all bores whee the standing water level was less than 5 m deep. A GRUNDFOS submersible pump was used to sample the remainder of the bores.

2.7 Field sampling techniques

Sampling and on-site analysis of unstable parameters was undertaken according to standard groundwater sampling procedures. A battery operated sampling pump was used on all bores where the standing water level was less than 5 m deep. A GRUNDFOS or BENNETT submersible pump was used to sample the remainder of the bores.

Prior to sampling, stagnant groundwater was purged for at least one bore volume and until field parameters stabilised. For some sites, sampling was undertaken after the bore was pumped dry and allowed to partially recover. Samples were taken from all the piezometers that contained water.

Water samples were obtained in April 2004, March 2005 and June 2008 for hydrochemical analysis (n=59 groundwater, n=24 surface water) and stable isotope analysis ($\delta^{18}O$ and $\delta^{2}H$, n = 35). A mobile chemical laboratory was taken to site on each occasion to facilitate on-site analysis of unstable parameters. Field water quality parameters were analysed on-site with calibrated water quality meters and electrodes. Parameters measured in the field include temperature, conductivity (EC), pH and dissolved oxygen. Field measurements in 2004 and 2005 were restricted to pH and fluid EC as the complete bore profile was sampled using the HYDROLAB sonde attached to the GEOVISTA logging unit. All field parameters for groundwater samples were measured within a flow cell to avoid contact with oxygen prior to sampling. Ferrous iron Fe^{2+} and sulphide S^{2-} (reduced species) were measured in June 2008 on selected bores using a field spectrophotometer.

2.8 Water analysis and QA/QC

Samples were obtained for analysis by the UNSW Analytical Centre which follows standard analytical QA and QC procedures. Analysis included major and minor ions, metals and nutrients as detailed below. Water samples were analysed for the following parameters:

- pH, EC, temperature and dissolved oxygen - measured in the field with calibrated meters and sondes
- Alkalinity, a measure of water hardness - measured in the field by titration
- Ferrous iron and sulphide - measured in the field for selected samples (June 2008)

- Major ions - calcium, sodium, potassium, magnesium, chloride and sulphate.
- Nutrients - nitrate, nitrite and total phosphorous.
- Minor ions and metals fluoride, manganese, sulphur, strontium, silicon, boron, bromide and barium.

Analytical accuracy was verified by analysis of blind duplicate samples, selected duplicates of field measurements and checking that ion charge balance errors (CBE). One analysis from bore 2S (June 2008) with CBE >10% was not considered in the assessment. Bicarbonate alkalinity for surface water samples was determined by difference to maintain a zero CBE. Blind duplicate samples of bore 2D demonstrated that results were repeatable with an insignificant analytical error.

Chapter 3

Results

3.1 EM31 Survey Data

The results of the EM31 survey are presented in Figure 3.1. There is a clear area of elevated apparent electrical conductivity associated with the valley seen in the topographic plot (Fig. 1.3). Sharp changes in apparent resistivity are also seen.

3.2 Surface water monitoring

Monitoring results for water level and fluid electrical conductivity at the weir site are shown in Fig. 3.2 for the period May to December 2005.

A shorter part (2 months) of the record is shown in Fig. 3.3 to allow detail to be better presented.

3.3 Drilling and Borehole Logging

Thirteen borehole locations were selected with the intention of installing a deep and shallow piezometer at each site. 25 piezometers were installed. The site selected on the conductivity low (Bore 5) encountered very shallow solid rock and there was therefore no point in installing a shallow piezometer at this location.

Locations of the monitoring bores are shown in Figure 3.4. Table 3.1 provides installation details for bores, including the lithology at intake depth.

The geophysical logging results for 10 of the sites are presented in Figs. 3.5 to 3.14 below. Construction notes and observations have been added to these figures.

3.4 Electrical Images

Line A ran along the northern margin of the site from east of Bore 4 to beyond the saline ground at the base of the tree planting. The line was 480 m long and ran along the access track and passed Bore 4, Bore 2 and Bore 3. The front piece to the report shows the orientation of the image line along the fence, with Bore 3 located close to the large tree shown in the middle distance beside the fence line. The interpreted results are shown in Figure 3.15. The high resistivity ground (red) represents granite that has not been

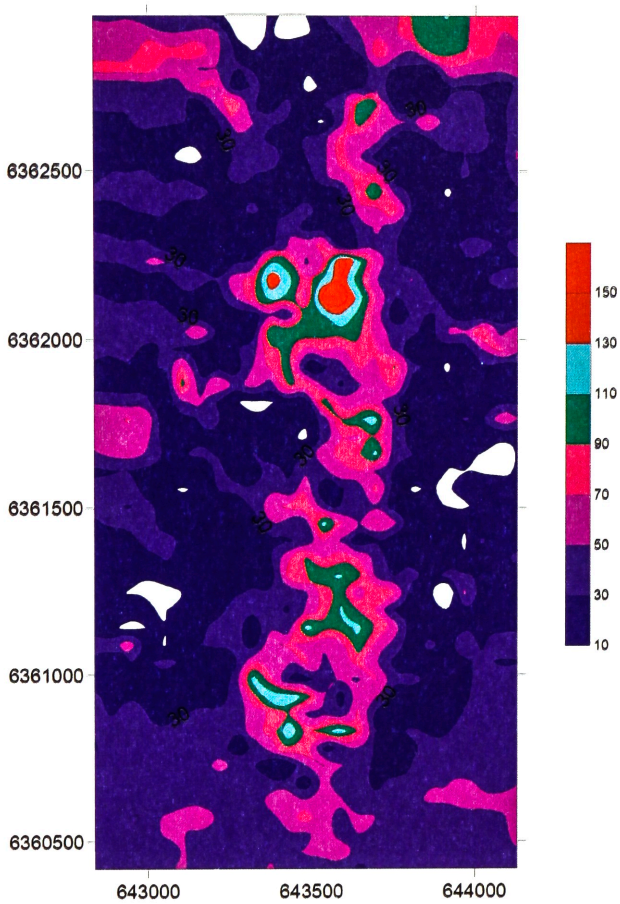

Figure 3.1: EM31 Survey data over the Baldry catchment

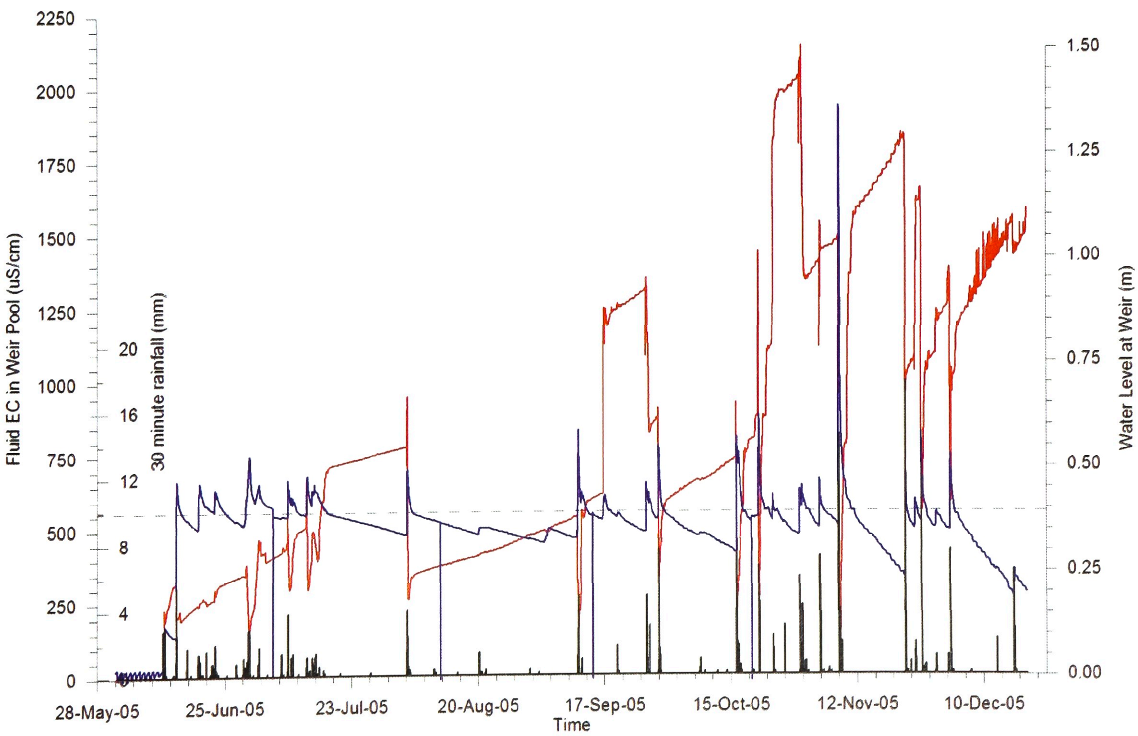

Figure 3.2: The record of weir water level, rainfall and fluid EC - June to December 2005

Table 3.1: Installation details for monitoring bores. Bore co-ordinates were determined with Garmin hand-held GPS (UTM WGS 84, Zone 55)

ID	Easting	Northing	Elevation (m AHD)	Casing Stickup (m)	Depth (m)	Screen Interval (m)	Lithology at intake depth
1D	643691	6362118	451.24	0.96	13	Open from 2.6	Granite
1S	643691	6362118	451.21	0.60	2.9	1.9-2.9	Granite
2D	643573	6362088	451.79	0.91	13	Open from 6.5	Granite
2S	643573	6362088	451.78	x	6	5-6	W granite
3D	643489	6362103	452.42	0.94	19	18-19	Granite
3S	643489	6362103	452.35	0.54	10.8	9.8-10.8	W granite
4D	643745	6362057	452.71	0.91	10	Open from 2.5	Granite
4S	643745	6362057	452.65	0.57	2.5	1.5-2.5	Loamy clay
5	643472	6361738	463.84	0.64	19	Open from 0.5	Granite
6D	643519	6361893	456.46		19	Open from 4.5	Granite
6S	643519	6361893	456.47	0.54	4	3-4	Granite sands
7D	643775	6361850	456.67	0.58	19	Open from 7	
7S	643775	6361850	456.66	0.61	6	5-6	Granite sands/ W granite
8D	643696	6361665	459.86	0.55	17.5	Open from 8.5	Granite
8S	643696	6361665	459.81	0.60	8	7-8	W granite
9D	643676	6361498	463.99	0.54	10.5	9.5-10.5	Granite
9S	643676	6361498	463.96	0.48	5	4-5	W granite
10D	643457	6361567	465.37	0.62	19	Open from 6m	Granite
10S	643457	6361567	465.36	0.55	6	5-6	Granite Sands
11D	643455	6362115		1.1	15.75	Open	Frc granite
11S	643455	6362115		0.54	3.84	2.88-3.33	W granite
12D	643289	6361945		0.975	17.275	Open	Frc granite
12S	643289	6361945		0.69	7.16	6.15-6.66	W granite
13D	643259	6361651		1	20.8	Open	Frc granite
13S	643259	6361651		3.82		2.93-3.44	W granite

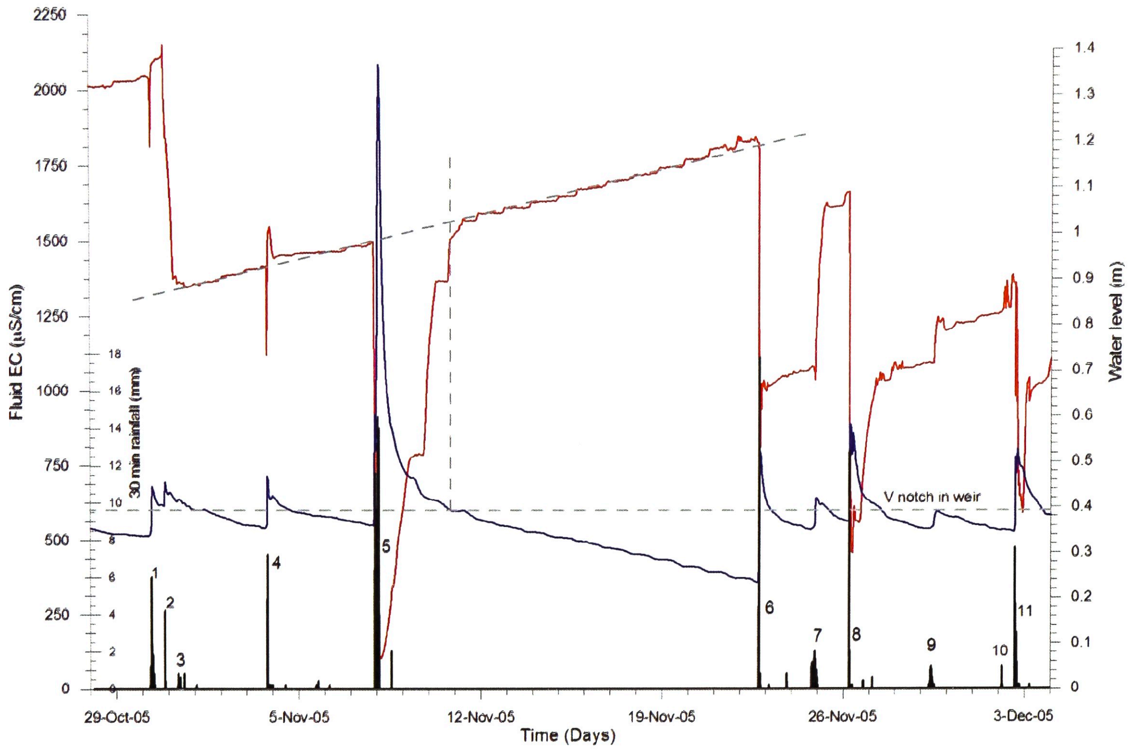

Figure 3.3: Detail of the weir water level response

deeply weathered. The low resistivity material represents clayey-silt material that overlies the granite. Field evidence indicates that the clayey-silt is not a weathering product of the granite.

Water levels in Bores 2 and 3 were close to or slightly above ground level initially. Clay is recorded in the drill logs and this is clearly also seen in the low resistivity material above bedrock in the electrical image (Fig. 3.15).

Bore 3 appears to be located close to a fracture zone in the granite. An alternative exoplanation for this liear anomaly would be the effect of the tree.

Line B runs from 80 m east of Bore 7 through cropping land and then over the creek and into the tree plantation to the west (Fig. 3.16). There does not seem to be the same thick development of clayey-silt along line B as occurs along Line A. This is confirmed by the drilling results and the borehole logs.

Line C runs from 80 m east of Bore 8 to the bare rock outcrop around Bore 5 (Fig. 3.17). The electrical image indicates a significant development of clayey-silt terminating against solid rock (granite crops out at the western edge of the line). The fluid EC in the top part of Bore 8 is 10,000 μS/cm.

Line D runs from 40 m east of Bore 9 towards Bore 10 (Fig. 3.18). The lithology is not well separated on the electrical image along this line, certainly when compared to the previous line. Bore 10 is close to an area of low resistivity and the fluid EC of the piezometer at this location was 14,350 μS/cm. Lower resistivity material appears around Bore 9 but the lithological log indicates a small depth of clayey-silt overlying weathered granite material (sands).

3.5 Groundwater levels and potential flow gradients

Groundwater levels in deep bores were typically 4-6 m below surface in the upper areas (elevation ~464 m AHD). However in the lower areas (elevation ~452 m AHD), groundwater levels in deep bores were generally only ~2 m below surface. Groundwater levels were lower in June 2008, than when first recorded in 2004. Many shallow monitoring bores were dry in June 2008 (bores 1S, 4S, 6S, 9S, 10S, 11S and 12S).

Figure 3.4: Bores and piezometers at the Baldry site

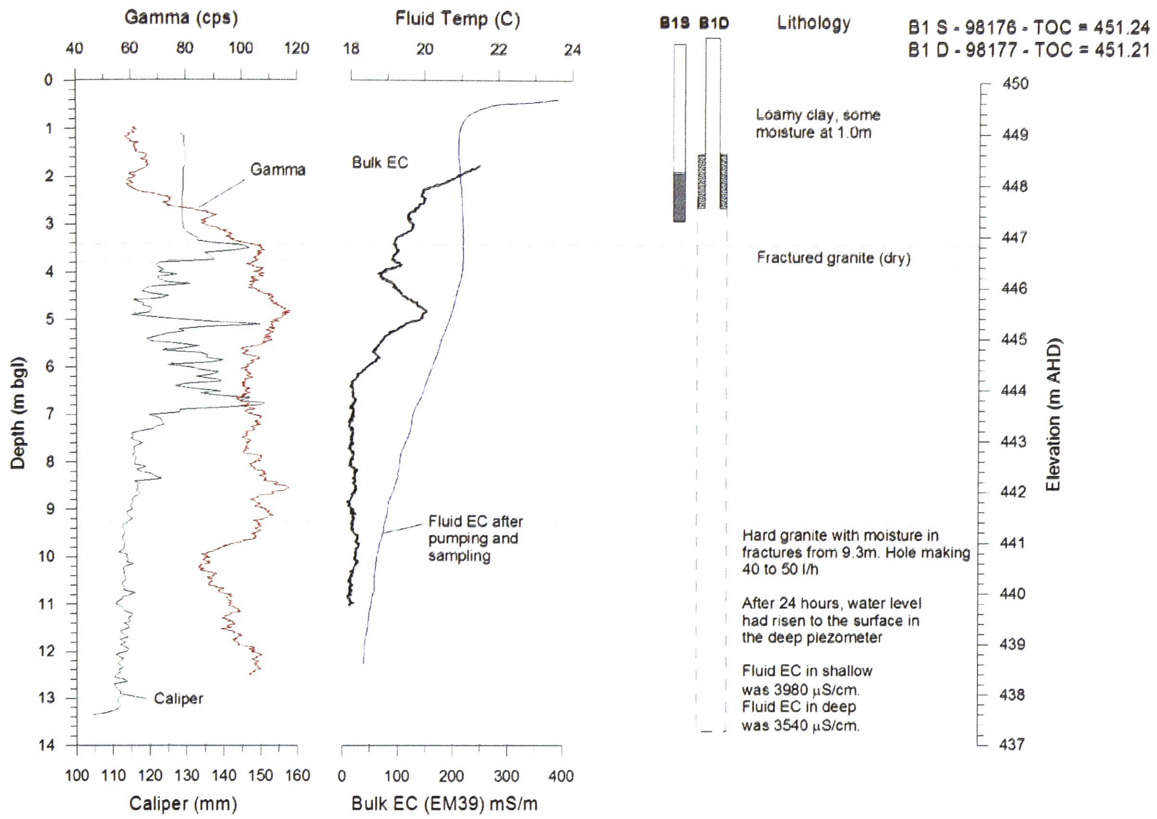

Figure 3.5: Geophysical logs and construction data for Site 1

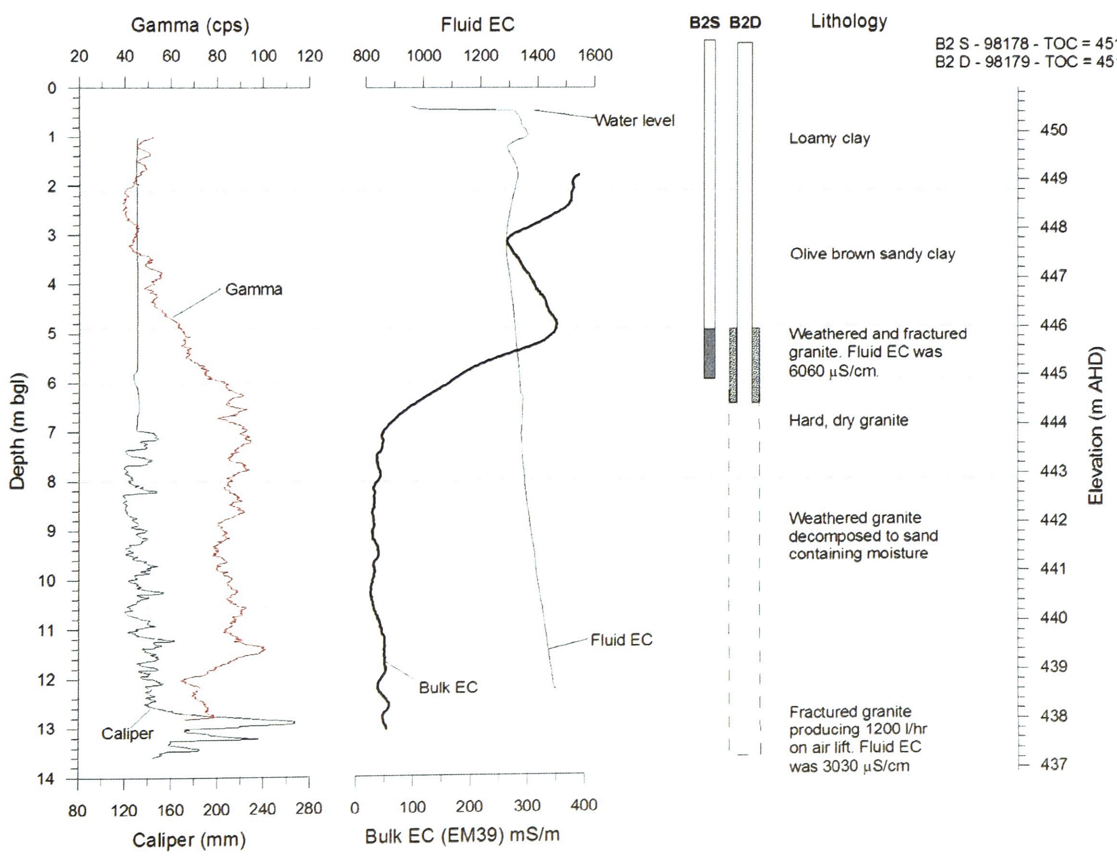

Figure 3.6: Geophysical logs and construction data for Site 2

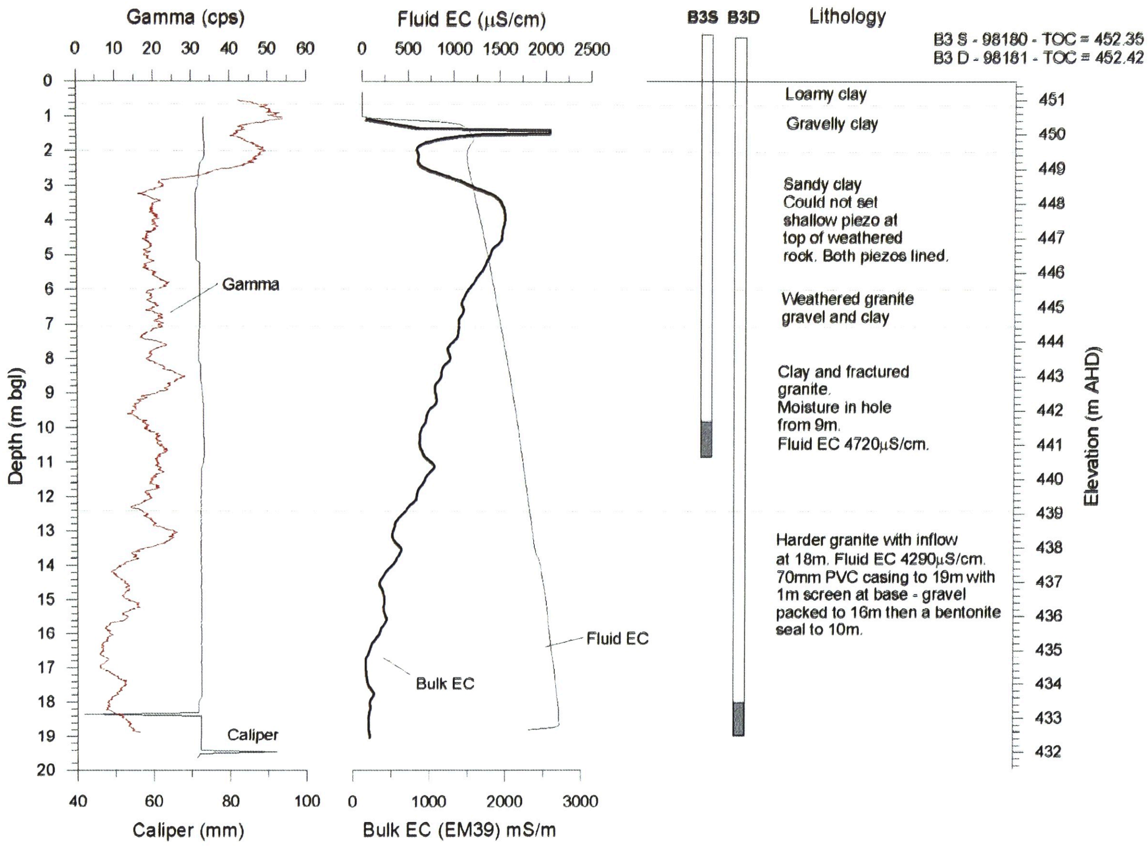

Figure 3.7: Geophysical logs and construction data for Site 3

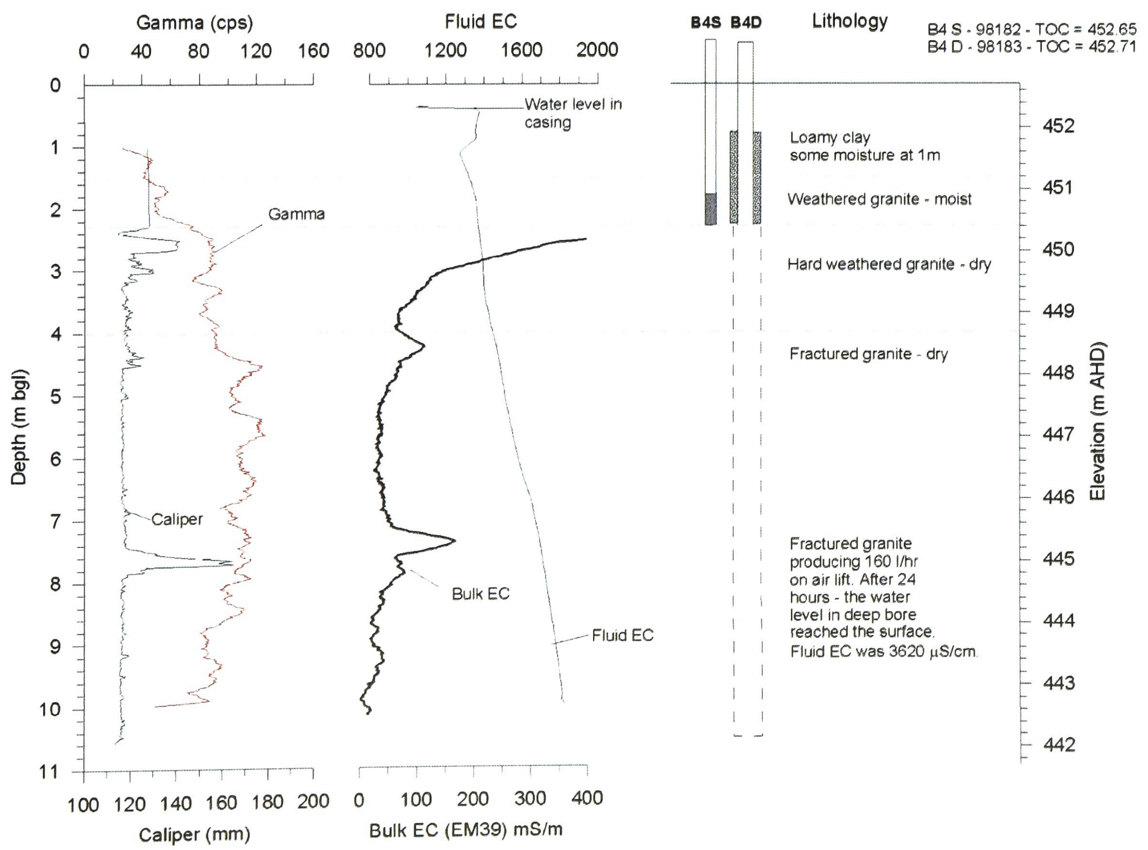

Figure 3.8: Geophysical logs and construction data for Site 4

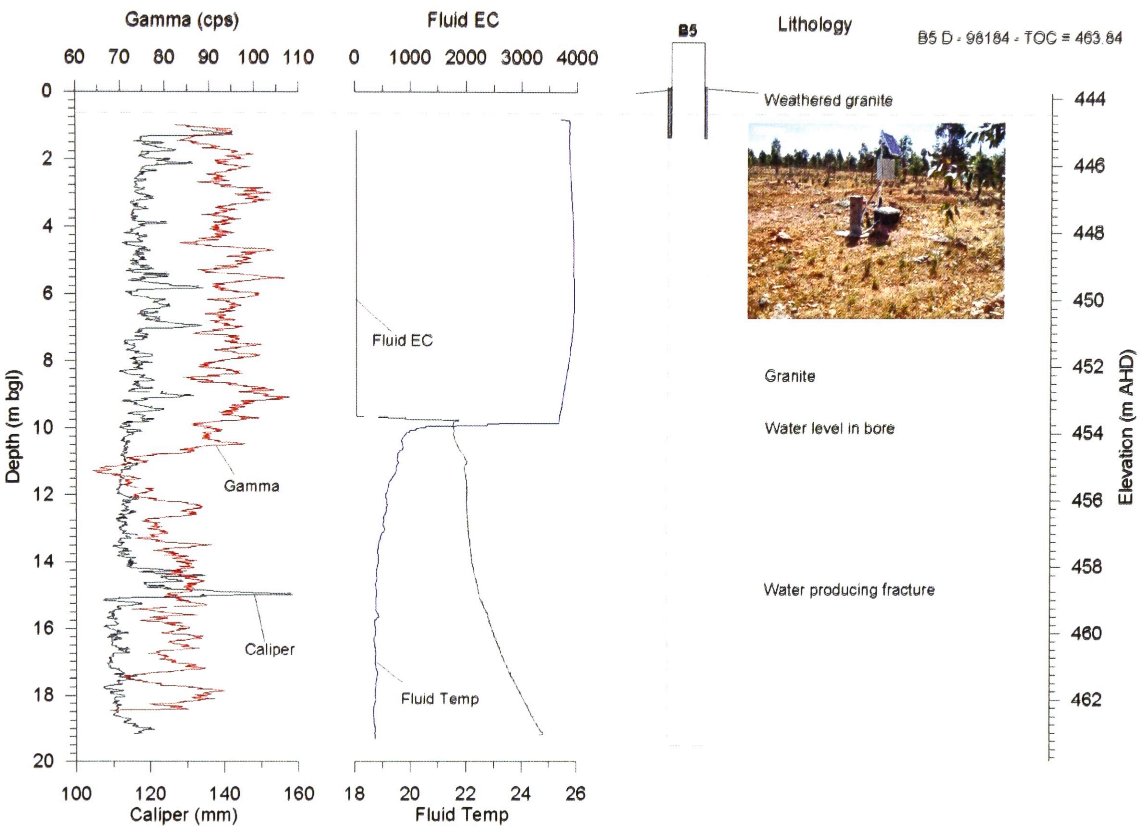

Figure 3.9: Geophysical logs and construction data for Site 5

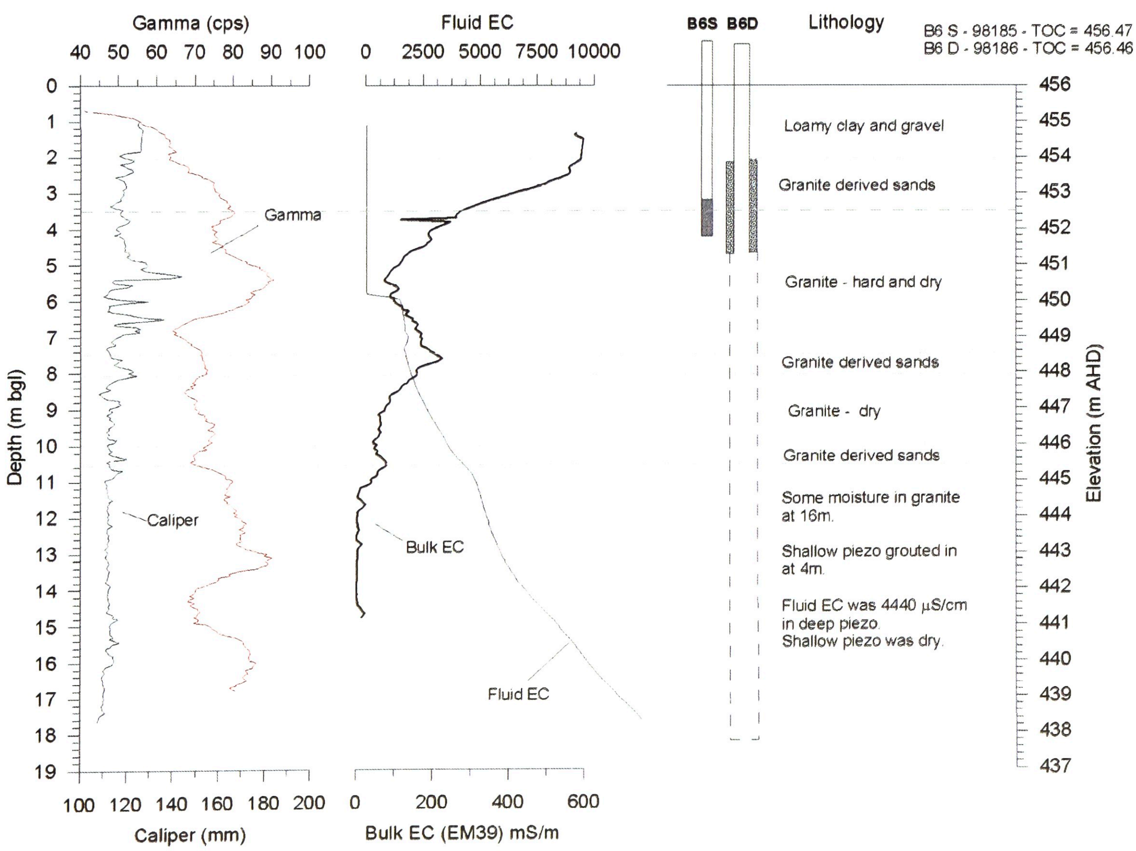

Figure 3.10: Geophysical logs and construction data for Site 6

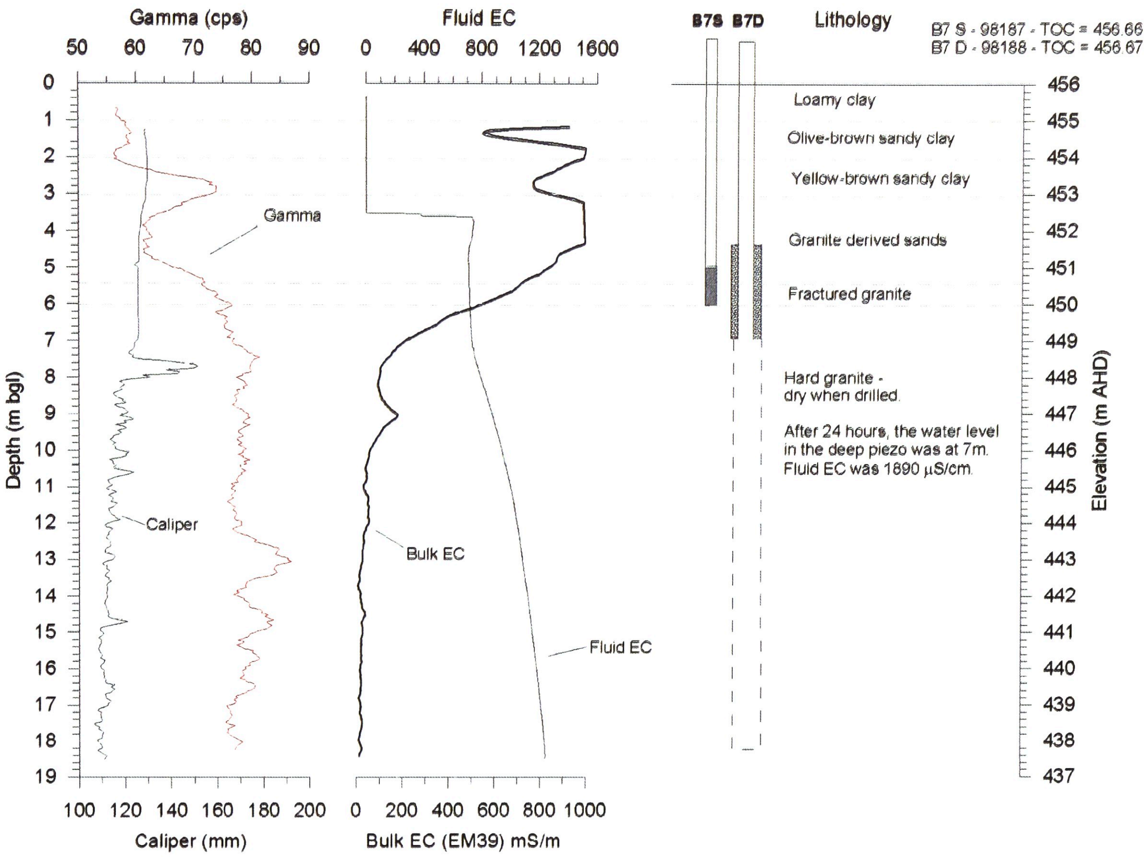

Figure 3.11: Geophysical logs and construction data for Site 7

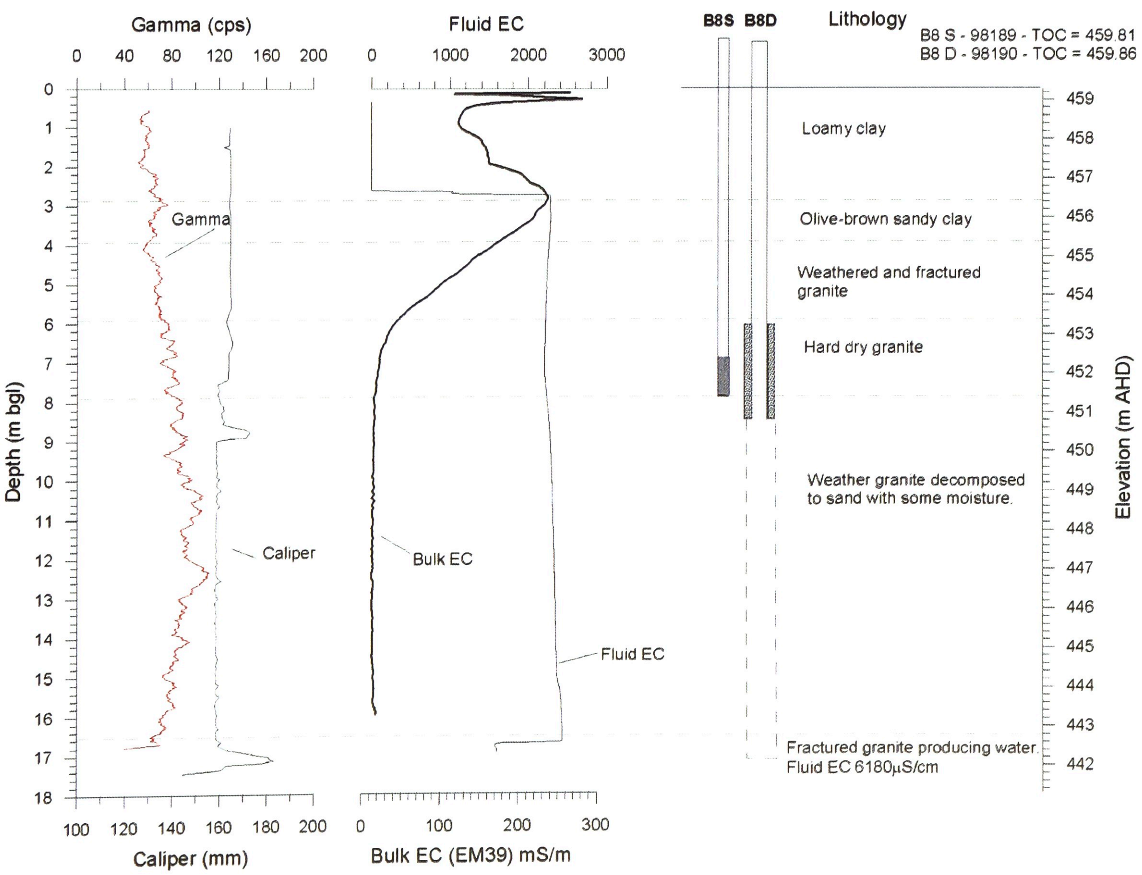

Figure 3.12: Geophysical logs and construction data for Site 8

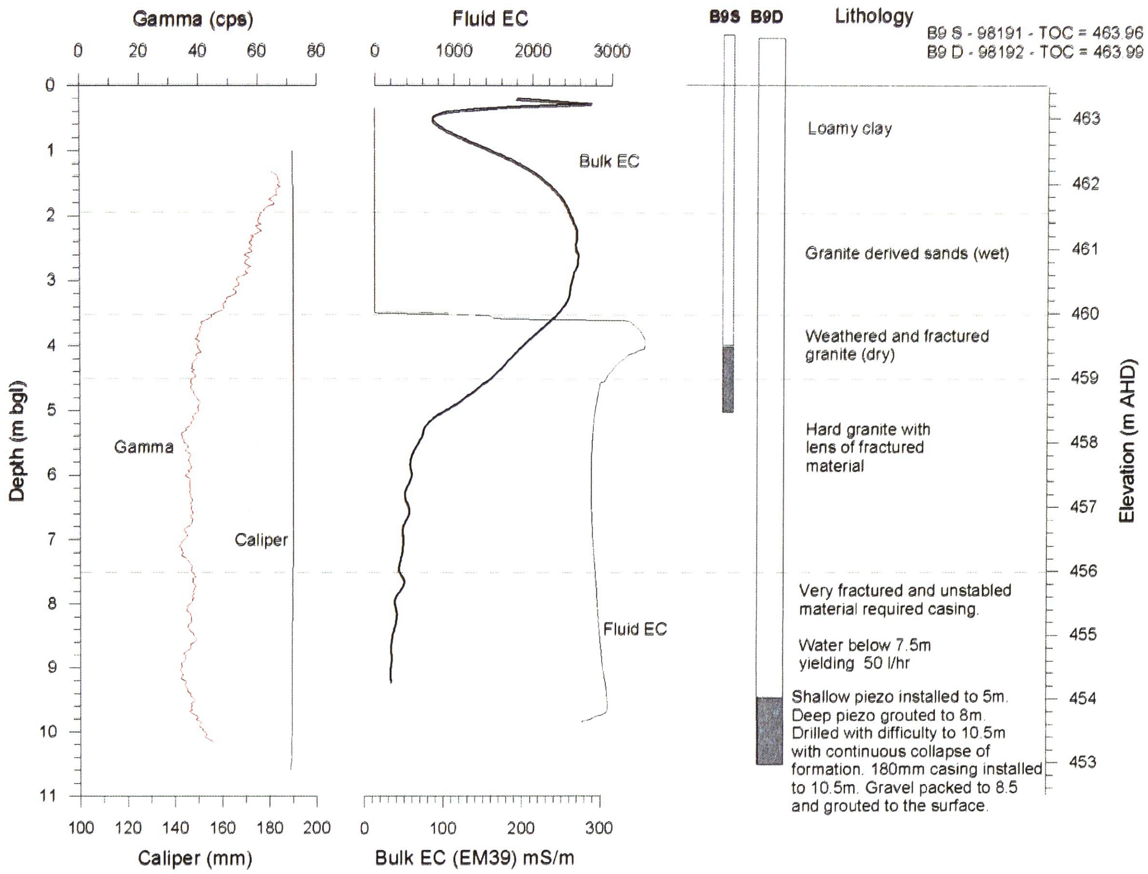

Figure 3.13: Geophysical logs and construction data for Site 9

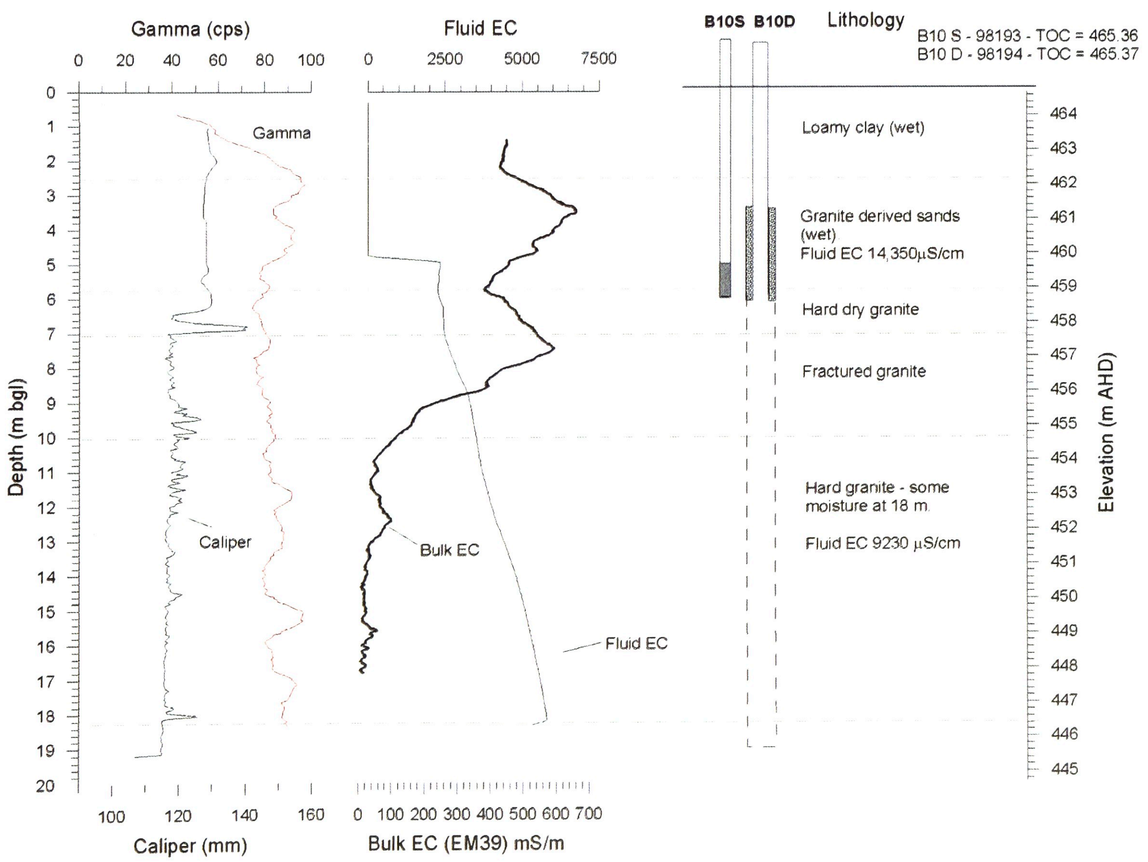

Figure 3.14: Geophysical logs and construction data for Site 10

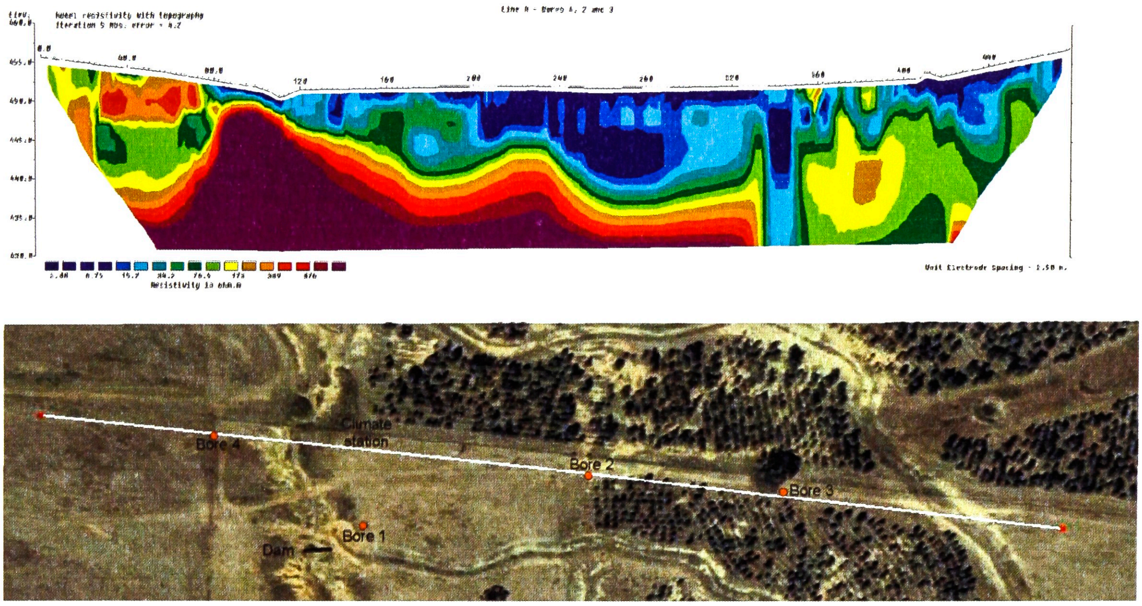

Figure 3.15: Electrical image line through bores 4,2 and 3. The google image is shown below indicating the line location.

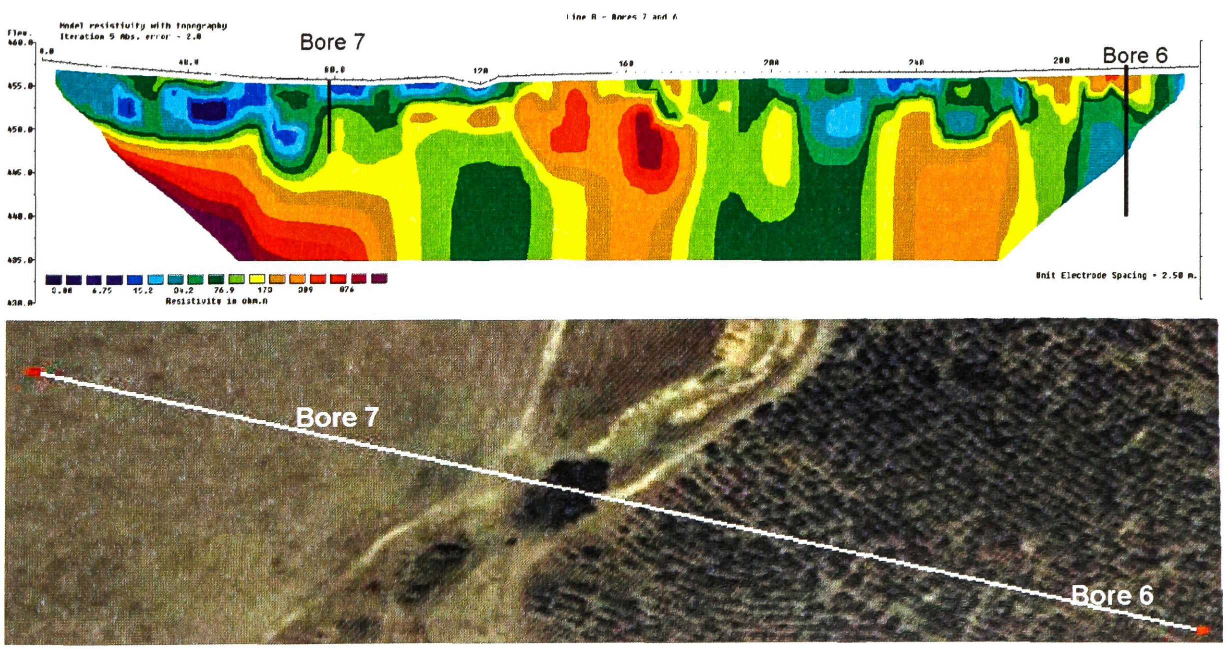

Figure 3.16: Electrical image line through bores 7 and 6. The google image is shown below indicating the line location.

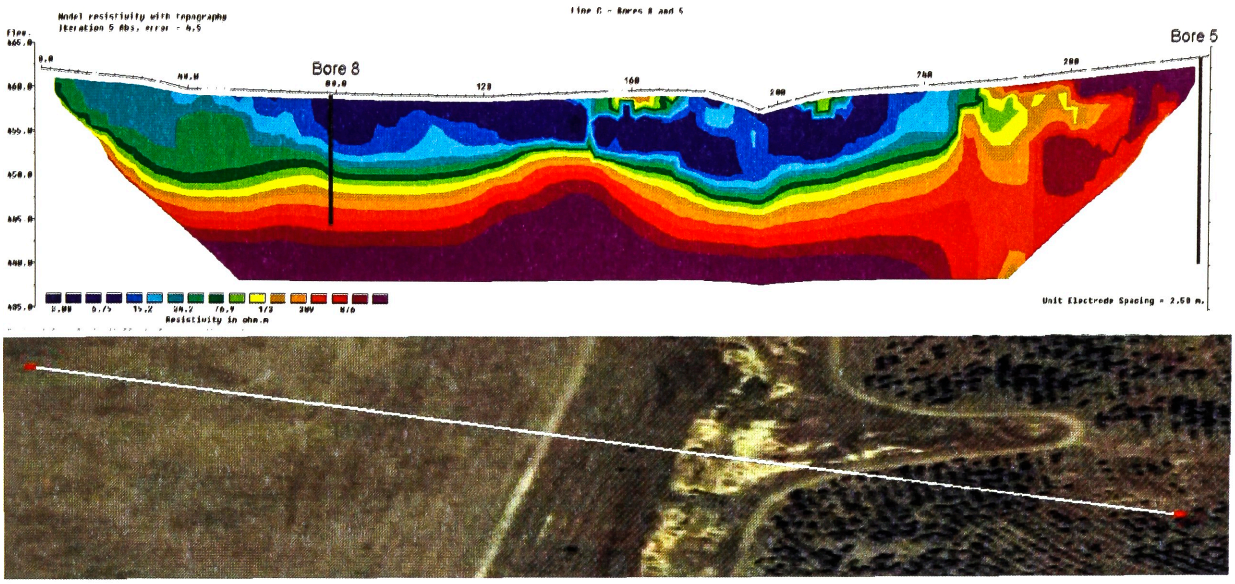

Figure 3.17: Electrical image line through bores 8 and 5. The google image is shown below indicating the line location.

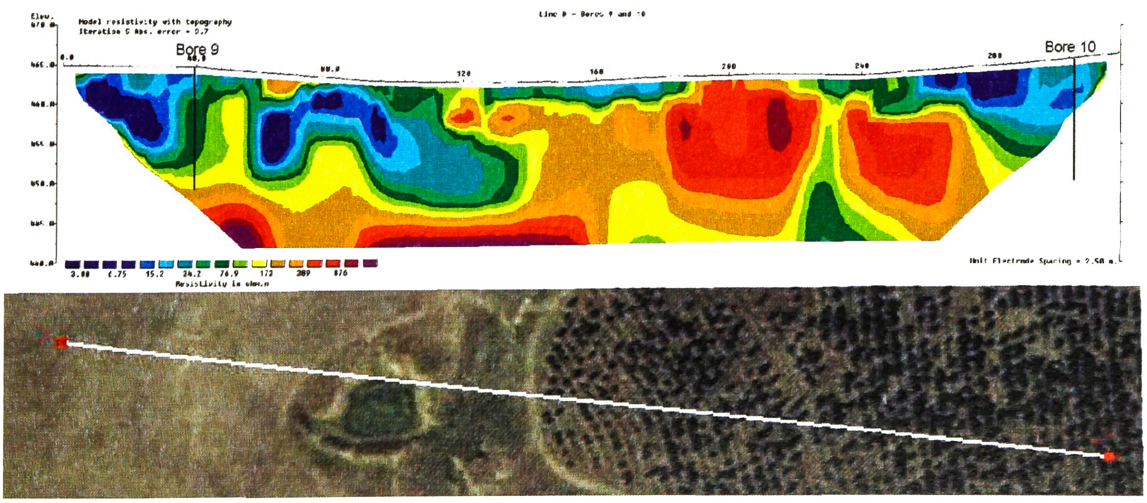

Figure 3.18: Electrical image line through bores 9 and 10. The google image is shown below indicating the line location.

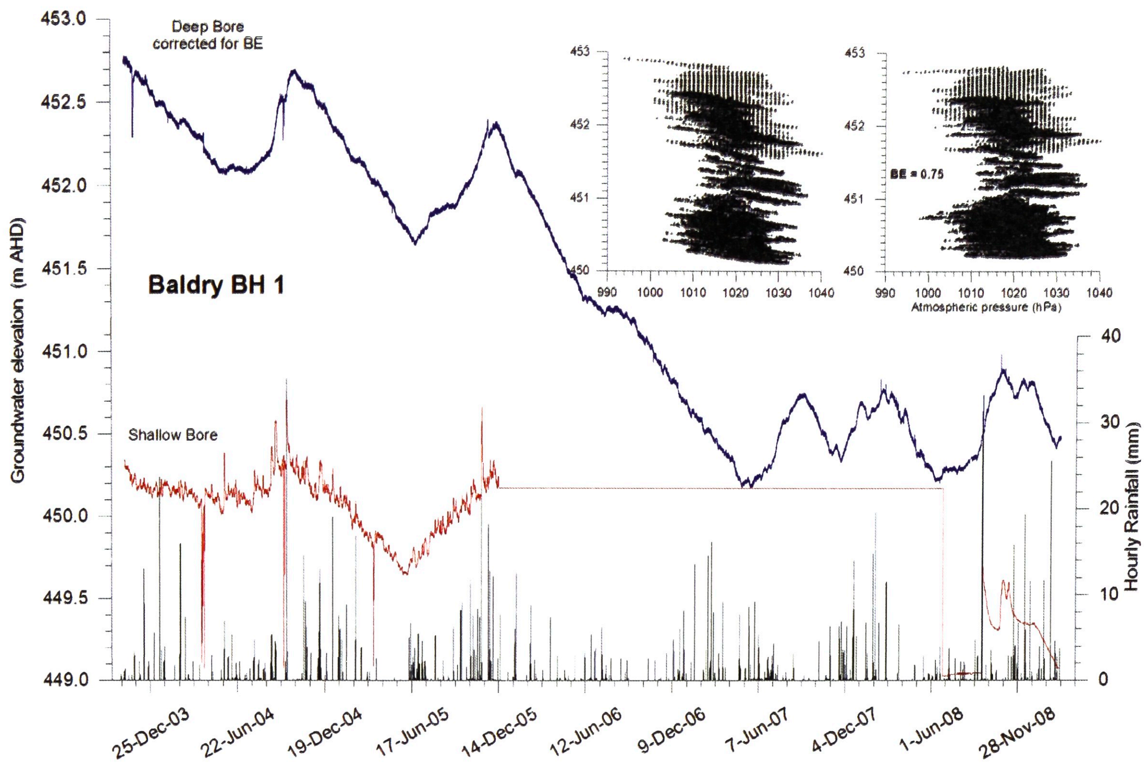

Figure 3.19: Shallow and deep water levels (hourly data) and rainfall for Site 1. Insets show barometric efficiency calculation

Water levels have been monitored in all bores on an hourly basis. The reduced levels for the deep bores are shown in Fig. ??. The large departures from the major trends are due to chemical sampling events where all the water has been removed from the bore. In this respect, Bore 8D is shown to clearly have a very low hydraulic conductivity, as indicated by the very long recovery time required to return to the regional trend.

Water level records for each site are shown in Figs. 3.19 to 3.26. Note that there is no shallow piezometer at Site 5. The shallow piezometers at Sites 6 and 10 were dry.

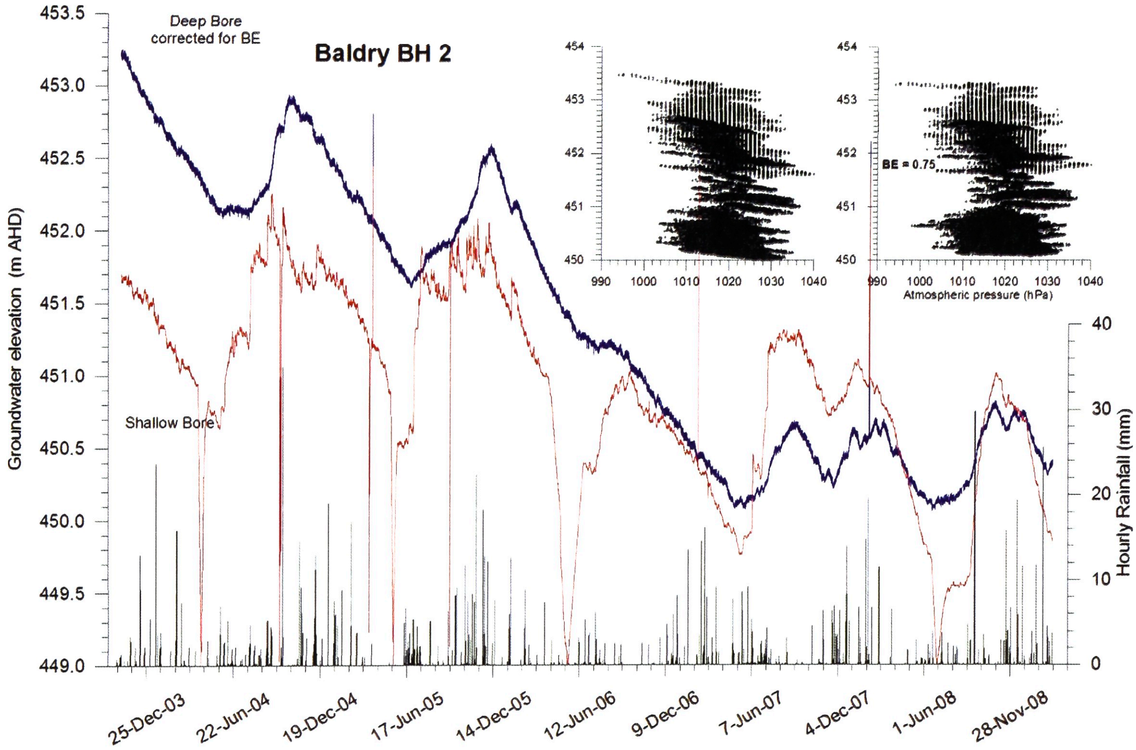

Figure 3.20: Shallow and deep water levels (hourly data) and rainfall for Site 2. Insets show barometric efficiency calculation

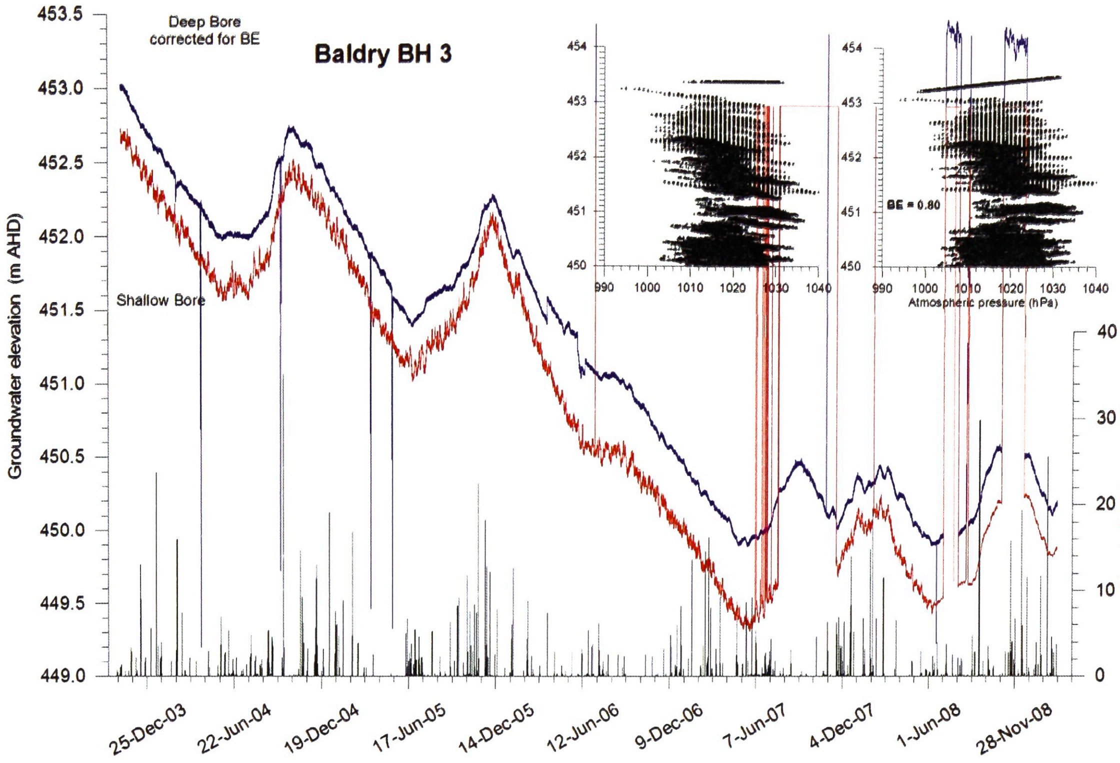

Figure 3.21: Shallow and deep water levels (hourly data) and rainfall for Site 3. Insets show barometric efficiency calculation

A scaled cross-section showing groundwater levels relative to geology and intake intervals is shown in Figure 3.27. Semi-confined or confined conditions are evident at most sites, with groundwater levels rising above the top of the intake screen or open rock section of boreholes. However, at bore 5, the groundwater level is mid-way in the open rock interval, yet shows a consistent hydraulic gradient with bores positioned higher and lower on the slope.

At most multi-level piezometer sites, the shallow piezometer was either dry, or indicated an upwards hydraulic gradient to the deeper aquifer, except at bore 7 where an upwards hydraulic gradient was observed. In October 2003, groundwater was recorded above the surface indicating a potential upwards flow gradient from fractured granite into clayey sediments.

A lateral hydraulic gradient of about 8 m over a distance of 400 m (dh/dL 0.02) could potentially drive groundwater flow through the weathered and fractured granite. Darcy's Law (groundwater flow = hydraulic gradient x hydraulic conductivity) could be used to estimate groundwater flow, however the hydraulic conductivity or permeability is unknown. The permeability of the weathered granite is limited by angular, poorly sorted materials, while the permeability of fractured granite is likely to vary. Therefore the rate of groundwater flow is likely to be very slow and stagnant in disconnected fractures.

3.6 Hydrochemistry

Water samples were obtained for hydrochemical analysis in April 2004, May 2005 and June 2008. The results are shown in Table 3.2 for field parameters including groundwater level and Table 3.3 provides major ion results for groundwater including charge balance errors. Table 3.4 provides minor ion results for groundwater.

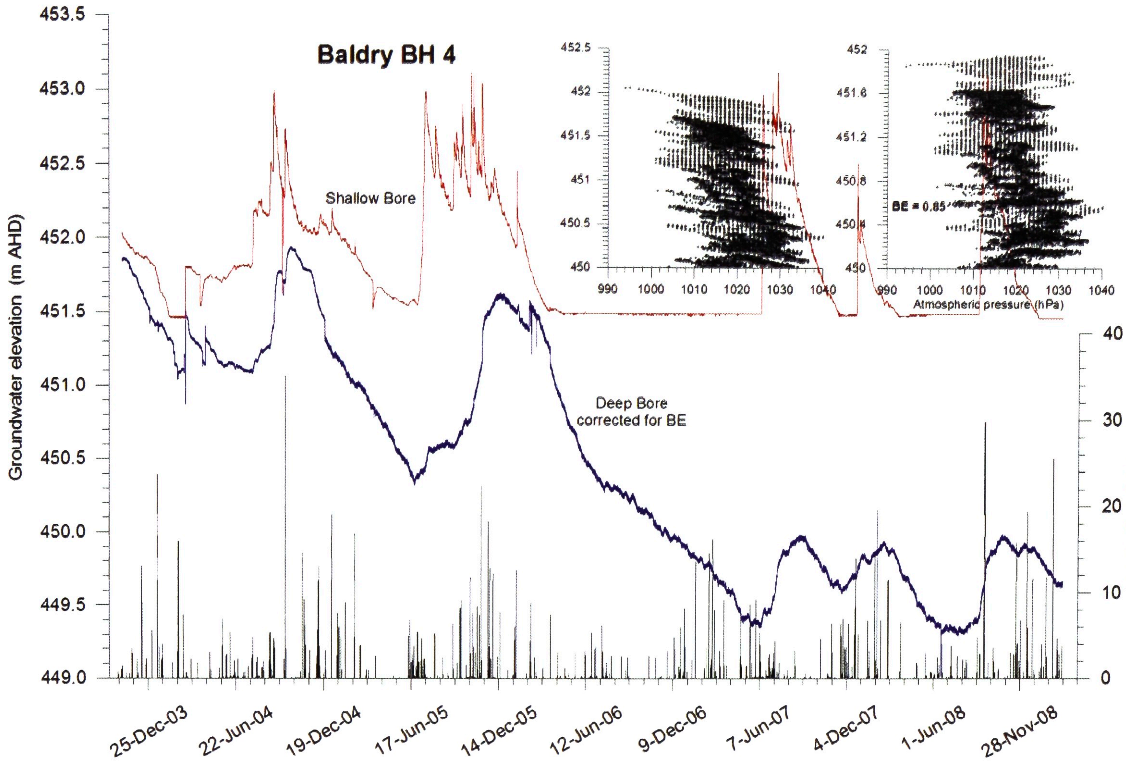

Figure 3.22: Shallow and deep water levels (hourly data) and rainfall for Site 4. Insets show barometric efficiency calculation

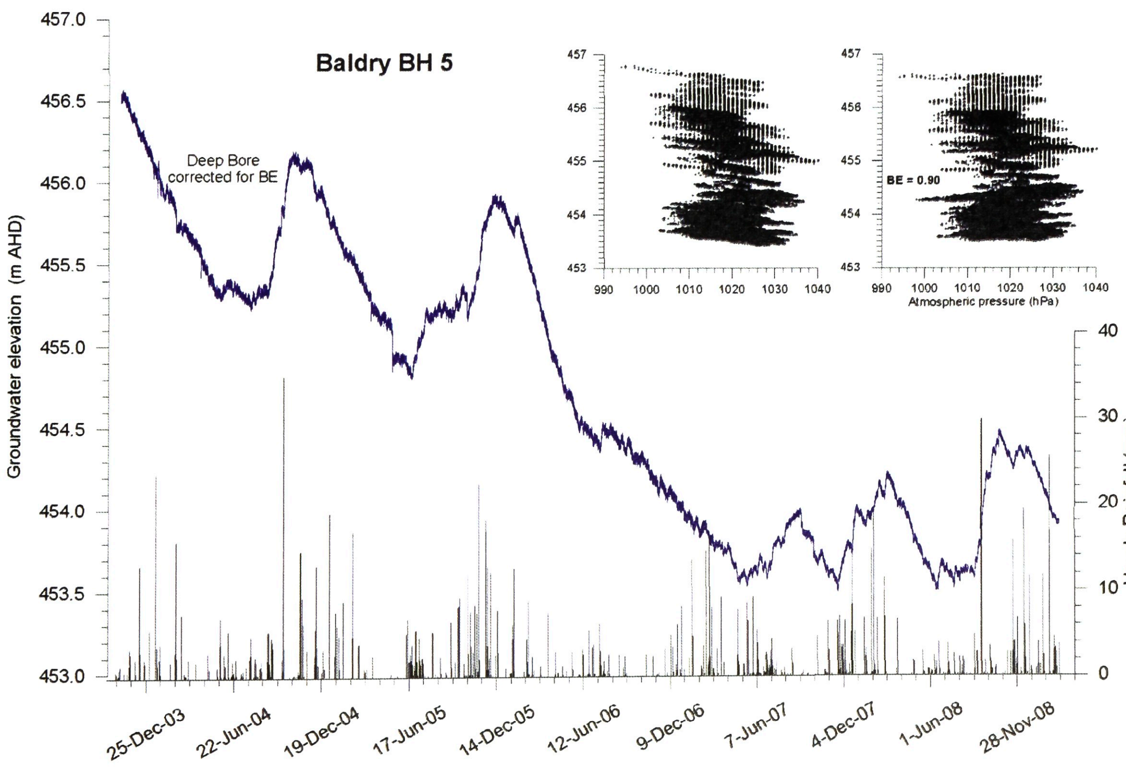

Figure 3.23: Deep water level (hourly data) and rainfall for Site 5. Insets show barometric efficiency calculation

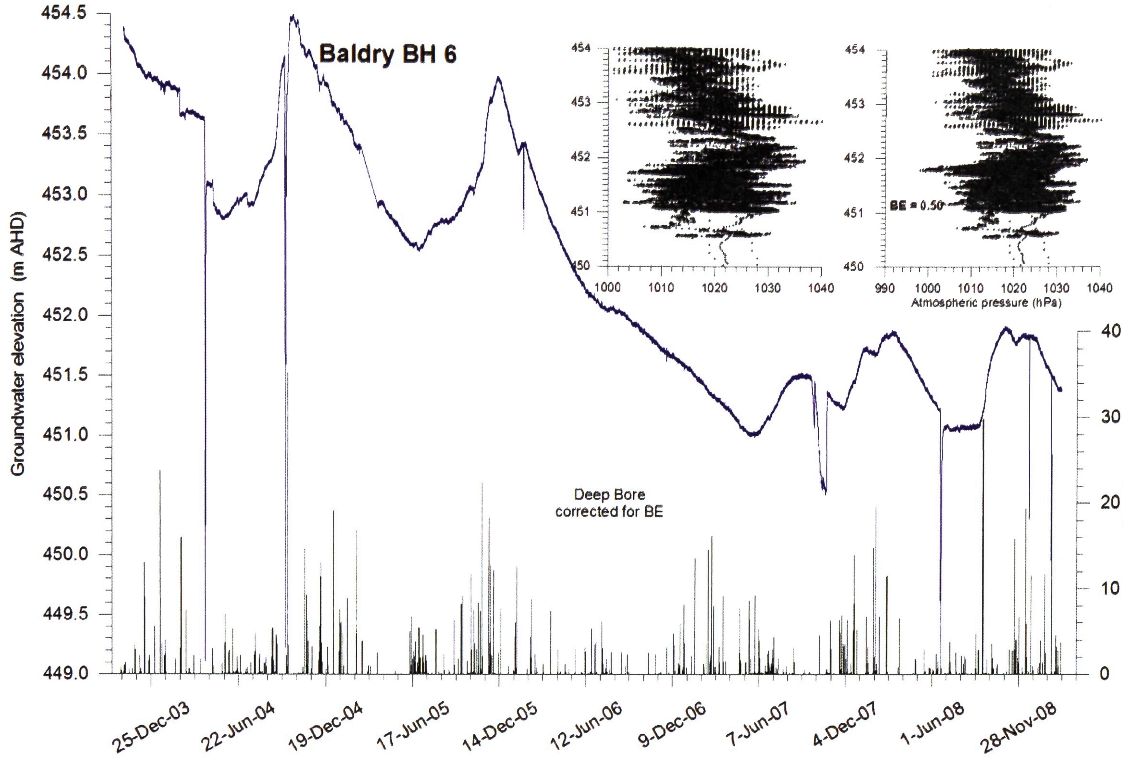

Figure 3.24: Deep water levels (hourly data) and rainfall for Site 6. Insets show barometric efficiency calculation

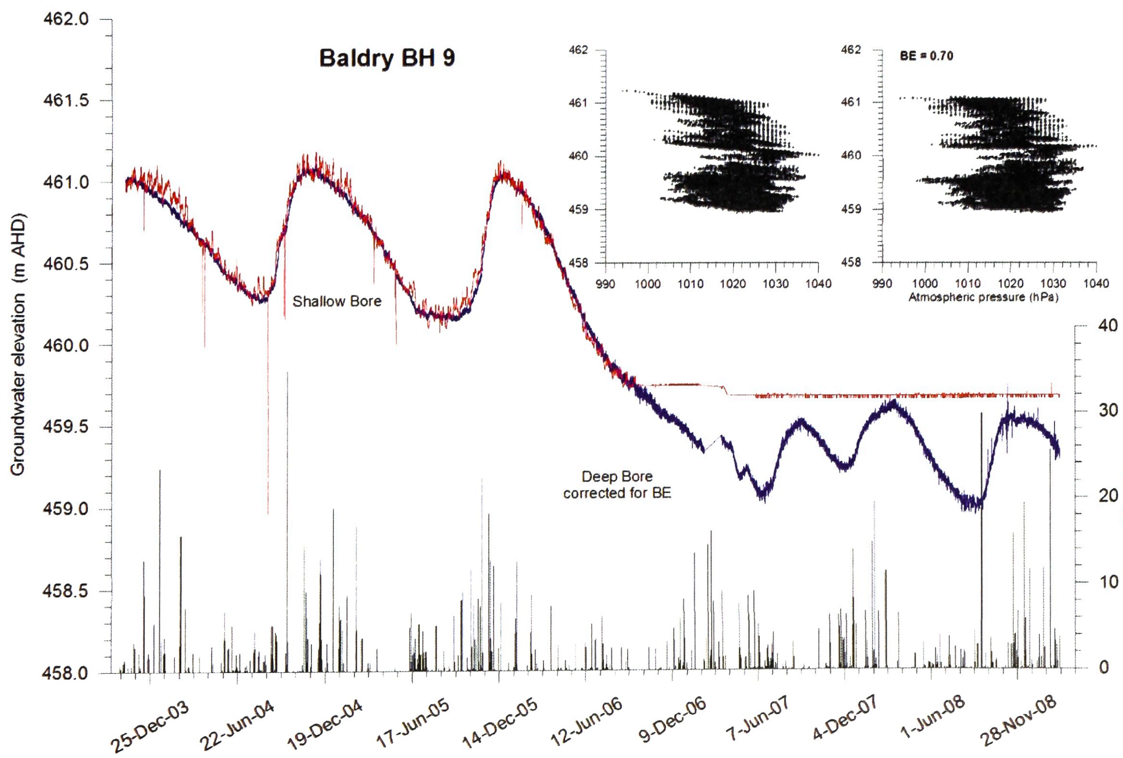

Figure 3.25: Shallow and deep water levels (hourly data) and rainfall for Site 9. Insets show barometric efficiency calculation

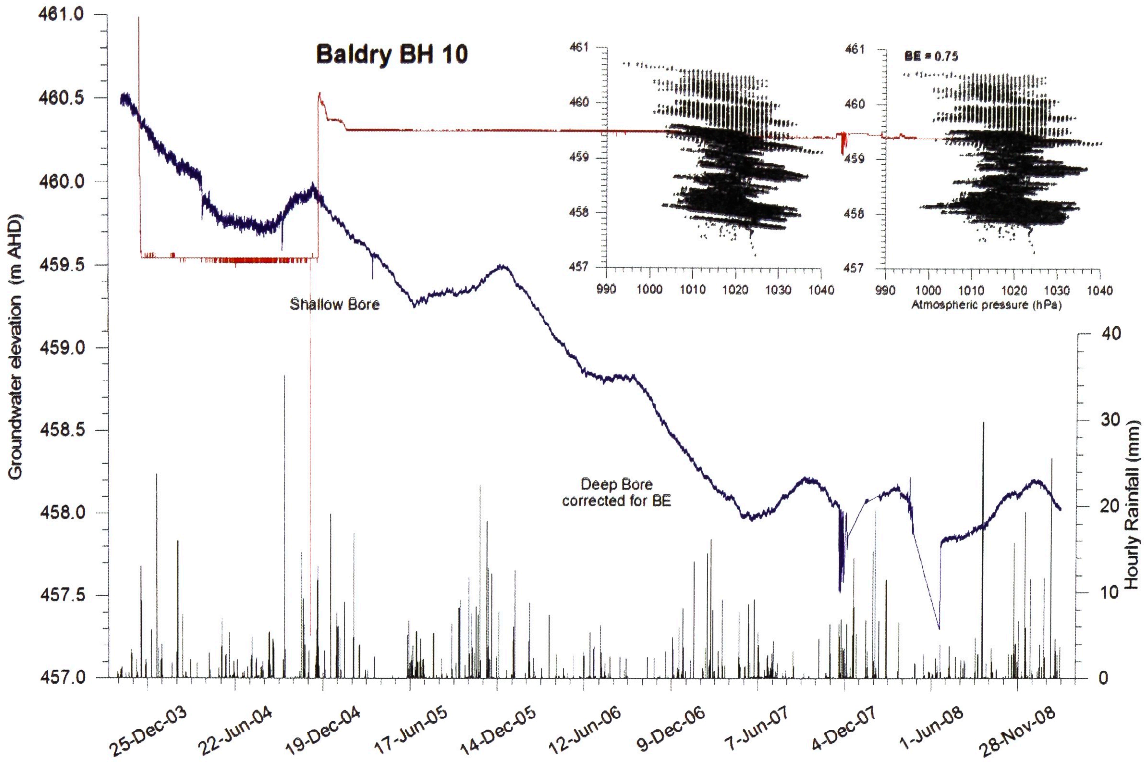

Figure 3.26: Shallow and deep water levels (hourly data) and rainfall for Site 10. Insets show barometric efficiency calculation

Table 3.2: Field chemistry including groundwater levels 2004 to 2008

Piezo	Sample Date	SWL (m below casing)	SWL (m AHD)	EC (mS/cm at 25 °C)	Temp (°C)	pH	DO (mg/L)	Eh NHE (mV)
1S	14-Apr-04	2.34	449.47	3.86	x	7.6	x	
	29-Mar-05			3.6	x	7.43	6.6	
	18-Jun-08	dry						
1D	13-Apr-04	0.95	451.25	3.37	20	7.58	2.4	
	31-Mar-05			3.49	19.8	6.88	x	
	16-Jun-08	2.98	449.22	3.75	19.3	7.27	3.23	402
2S	13-Apr-04	3.95	447.83	4.97	22.5	8.23	3.68	
	29-Mar-05	1.815	449.96	6.82	21.5	7.61	4.15	579
	16-Jun-08	3.33	448.45	6.79	20.4	7.44	1.34	292
2D	13-Apr-04	1.27	451.43	2.54	19.8	7.4	1.92	
	29-Mar-05			2.7	x	7.05	3.67	
	30-Mar-05			2.88	19.5	6.97	2.79	290
	16-Jun-08	3.52	449.18	2.95	19.4	7.05	1.47	337
3S	14-Apr-04	1.62	451.27	2.56	18.9	7.18	5.7	
	29-Mar-05			4.6	18.4	7.04	0.49	299
	16-Jun-08	3.81	449.08	3.49	19	6.99	0.04	321
3D	14-Apr-04	2.16	451.19	4.47	21.1	7.74	7.55	
	30-Mar-05			4.62	21.3	6.94	2.18	283
	16-Jun-08	4.35	449.00	4.41	19.7	6.9	0.2	285
4S	14-Apr-04	dry						
	29-Mar-05			4.8	21	7.84	x	
	16-Jun-08	dry						
4D	14-Apr-04	1.17	452.45	3.42	22.3	7.15	0.78	
	31-Mar-05			3.81	21.7	7.13	x	
	16-Jun-08	3.31	450.31	3.67	19.5	7	0.69	637
5D	15-Apr-04	9.48	455.01	3.05	20.4	6.64	2	
	30-Mar-05			2.91	20.3	6.56	1.95	316

continued on next page

Table 3.2: Field chemistry including groundwater levels 2004 to 2008

Piezo	Sample Date	SWL (m below casing)	SWL (m AHD)	EC (mS/cm at 25 °C)	Temp (°C)	pH	DO (mg/L)	Eh NHE (mV)
	18-Jun-08	11.58	452.91	4.01	18.9	6.4	1.08	356
6S	15-Apr-04	dry						
	18-Jun-08	dry						
6D	15-Apr-04	5.5	450.96	5.42	20	6.87	3.85	
	30-Mar-05			5.62	19.4	6.88	0.4	304
	18-Jun-08	7.55	448.91	5.82	19	7.01	0.32	254
7S	14-Apr-04			6.01	20.7	7.75	6.56	
	30-Mar-05			5.78	19.1	7.26	2.18	248
	17-Jun-08	6.29	450.98	7.01	16.8	7.65		
7D	14-Apr-04	4.57	452.68	2.17	19.6	8.98	1.42	
	31-Mar-05			2.775	20.8	7.71	x	
	17-Jun-08	6.73	450.52	3.79	19.5	8.2	4.6	290
8S	14-Apr-04	3.75	456.65	12.82	19.5	7.6	3.06	
	30-Mar-05			13.54	18.6	6.61	1.82	256
	17-Jun-08	5.35	455.05	9.67	22.1	6.31	2.76	195
8D	14-Apr-04	3.42	456.99	3.05	19.4	9.7	5.1	
	31-Mar-05			3.68	x	7.44	x	
	17-Jun-08	5.19	455.22	3.17	19.6	8.53	2.79	117
9S	14-Apr-04	4.25	460.19	6.53	22.8	5.57	6.82	
	30-Mar-05			5.83	18.8	5.06	x	337
	17-Jun-08	dry						
9D	14-Apr-04	4.44	460.09	6.24	19.9	5.82	0.74	
	31-Mar-05			6.44	18.3	5.83	x	
	17-Jun-08	6.87	457.66	6.28	19.4	5.87	0.22	358
10S	15-Apr-04	8.15	457.77	15.76	27.1	6.5	2.8	
	18-Jun-08	dry						
10D	15-Apr-04	5.67	460.32	10.5	19.9	6.65	1.51	
	30-Mar-05			9.24	19.8	6.62	0.35	197
	18-Jun-08	7.87	458.12	7.38	18.9	6.73	0.16	138
11S	18-Jun-08	dry						
11D	18-Jun-08	8.97		5.08	19	6.57	0.09	360
12S	18-Jun-08	dry						
12D	18-Jun-08	11.76		5.37	19.9	6.78	0.19	327
P1	18-Jun-08	dry						
P2	18-Jun-08	dry						
P3	18-Jun-08	2.07		0.997	17.5	6.82		
P4	18-Jun-08	dry						
P5	18-Jun-08	5.19		4.9	18.7	8.12		
P6	18-Jun-08	3.72		8.09	18.3	7.56		
P7	18-Jun-08	almost dry		5.31	18.6	8.21		
P8	18-Jun-08	3.41		3.71	19.6	7.31	4.89	369
PT1	18-Jun-08	2.38						
Creek	16-Jun-08	x		1.442	13.7	8.94	13.79	
Creek north	18-Jun-08	x		6.14	18	8.02		
Puddle	16-Jun-08	x		0.397	14.3	7.73	8.36	

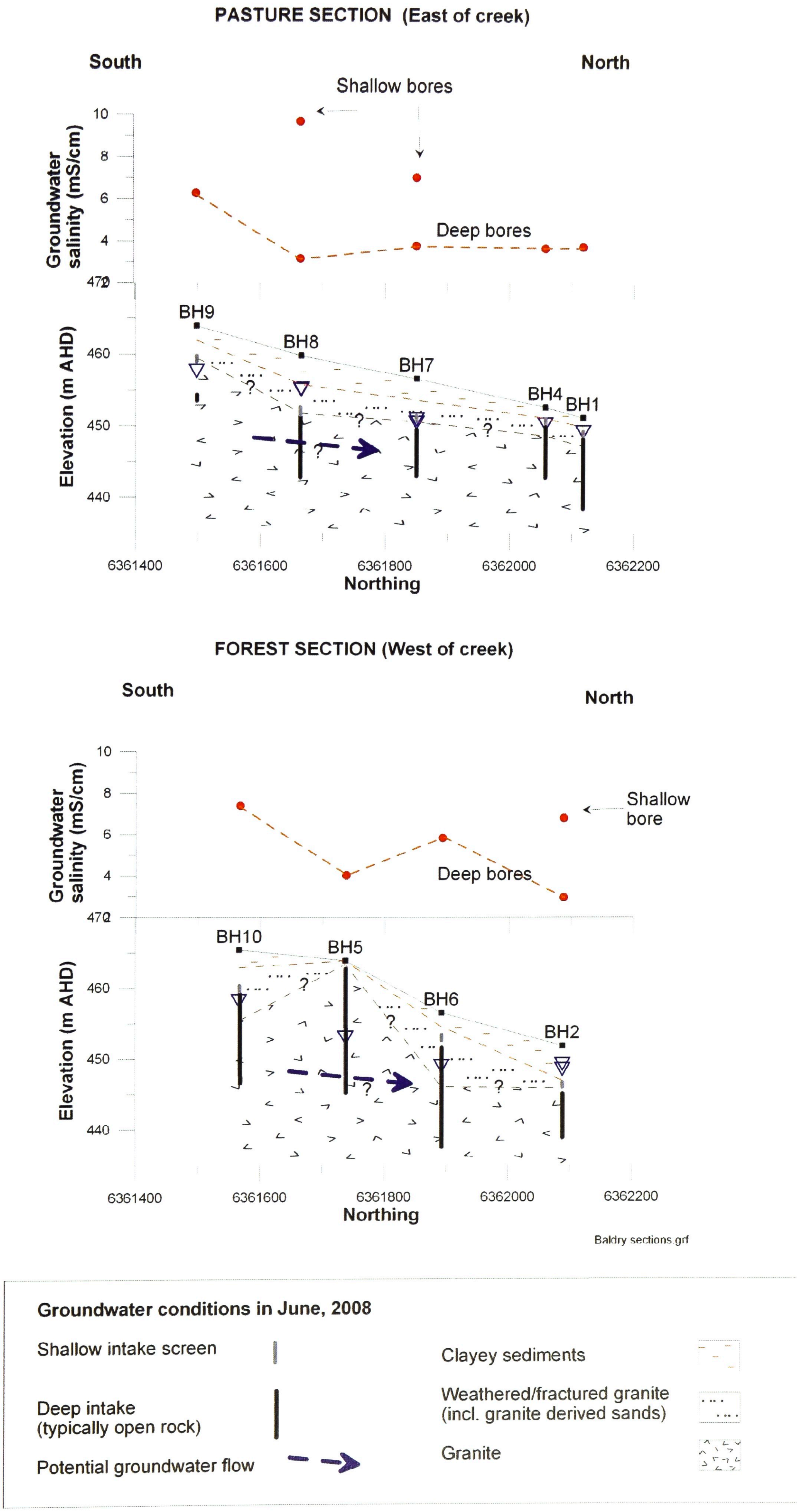

Figure 3.27: Cross sections showing groundwater conditions at Baldry site, June 2008

Table 3.3: Major ion results for groundwater 2004-2008

Sample ID	Date	Ca	K	Mg	Na	SO_4	HCO_3	Cl	TDS	CBE %
		mg/L								
1S	14/04/2004	69.0	2.9	90.6	665.1	135.6	1171.2	714.7	2852.9	-2.8
	29/03/2005	64.0	2.7	83.7	643.9	114.5	1207.8	630.7	2751.9	-2.3
1D	13/04/2004	68.6	2.1	105.9	567.0	123.6	1122.4	614.4	2606.4	-1.9
	31/03/2005	71.7		108.6	561.9	114.4	1104.1	629.3	2603.0	-1.6
	16/06/2008	74.9	3.0	123.1	603.4	152.7	1028.0	817.5	2819.6	-3.5
2S	13/04/2004	24.0	1.3	55.3	1059.6	193.3	1632.0	847.4	3817.2	-2.7
	29/03/2005	26.2	0.8	64.5	1154.9	217.2	1579.9	1065.7	4113.5	-3.1
	16/06/2008	18.6	1.0	48.4	674.4	375.9	1486.0	1602.0	4209.6	-38.6
2D	13/04/2004	32.4	1.3	93.6	508.0	122.3	947.9	468.9	2176.2	0.2
	29/03/2005	63.0	1.0	84.5	456.6	97.8	976.0	457.5	2139.4	-1.6
	16/06/2008	68.0	1.6	93.9	470.5	121.2	947.0	554.0	2273.3	-3.1
2D*	29/03/2005	62.8	1.0	84.6	457.9	117.9				
	30/03/2005	67.5	1.2	86.8	455.2	102.3	982.1			
3S	14/04/2004	78.8	0.8	137.7	744.9	247.9	1030.9	929.4	3171.0	-0.6
	29/03/2005	76.1	0.8	131.8	748.6	226.7	1034.0	960.1	3183.8	-1.6
	16/06/2008	51.9	0.9	93.6	622.8	181.1	1098.2	678.8	2742.8	-4.5
3D	14/04/2004	80.2	7.1	135.4	690.1	263.6	786.9	980.2	2954.6	-0.8
	30/03/2005	106.2	2.5	146.4	662.2	226.8	890.6	1027.7	3068.7	-2.2
	16/06/2008	113.8	2.4	154.5	672.7	263.8	858.5	1103.0	3176.1	-3.0
4S	29/03/2005	59.0	2.2	147.0	798.1	143.0	1052.3	1081.2	3286.5	-0.9
4D	14/04/2004	73.7	2.3	115.4	547.0	127.3	1085.8	613.0	2573.0	-1.0
	31/03/2005	80.5	2.0	117.3	556.0	116.6	1076.7	636.3	2596.9	-0.2
	16/06/2008	84.9	2.4	129.9	570.8	151.5	1022.6	811.2	2791.6	-3.6
5D	15/04/2004	114.9	3.2	131.9	246.2	218.3	463.6	570.6	1756.4	-1.6
	30/03/2005	130.0	3.3	151.0	264.7	229.1	430.1	706.0	1914.8	-2.0
	18/06/2008	248.9	4.0	305.2	448.6	457.1	613.4	1509.7	3596.4	-4.2
6D	15/04/2004	179.4	6.0	209.7	813.0	300.3	908.9	1460.4	3900.9	-0.5
	30/03/2005	172.2	4.1	195.0	787.7	262.7	948.6	1393.7	3776.5	-1.1
	18/06/2008	197.0	6.4	233.7	974.9	353.1	1201.8	1729.6	4697.6	-2.9
7S	14/04/2004	79.9	2.6	167.1	1121.2	436.4	1415.2	1209.4	4437.1	0.1
	30/03/2005	70.0	1.7	140.2	986.8	396.4	1226.1	1115.7	3965.6	-1.6
7D	14/04/2004	14.3	3.6	30.1	428.6	138.3	707.6	269.8	1594.9	-0.4
	31/03/2005	30.6	3.5	52.0	480.8	143.9	906.5	319.6	1945.8	-0.1
	17/06/2008	42.4	4.3	81.5	731.2	356.3	1110.4	662.0	2994.0	-4.2
8S	14/04/2004	72.5	1.9	150.0	2601.4	608.4	460.6	3855.9	7756.8	0.1
	30/03/2005	82.8	1.7	187.6	2570.2	637.1	756.4	4033.4	8272.0	-3.0
	17/06/2008	23.3	1.8	98.1	1932.0	356.9	392.7	2950.2	5755.7	-2.0
8D	14/04/2004	3.4	22.4	36.2	618.6	138.0	786.9	533.9	2145.7	-0.3
	31/03/2005	58.3	5.5	72.7	542.3	126.0	1003.5	574.4	2384.8	-3.9
	17/06/2008	30.1	5.2	59.8	590.8	97.9	806.1	425.3	2018.8	8.4
9S	14/04/2004	12.0	1.1	159.0	1130.7	496.1	9.8	2014.1	3833.6	-3.4
	30/03/2005	13.7	1.0	129.9	974.8	479.1	38.4	1597.9	3236.0	-1.7
9D	14/04/2004	48.0	1.8	167.9	1082.8	489.7	219.6	1884.1	3897.0	-2.8
	31/03/2005	52.3	1.1	178.6	1030.8	463.4	219.6	1840.7	3790.6	-2.4
	17/06/2008	52.4	1.5	197.6	1045.0	646.9	221.3	1797.6	3963.8	.6
10S	15/04/2004	35.5	3.2	530.3	2079.0	456.3	902.8	4265.4	8278.4	-3.1
10D	15/04/2004	311.2	7.6	490.8	1107.9	646.5	985.2	2718.9	6274.5	-1.0
	30/03/2005	305.6	6.1	478.3	1074.5	605.8	1024.8	2741.7	6239.5	-2.5
	18/06/2008	265.3	6.9	420.7	1011.0	639.4	967.7	2348.7	5665.6	-1.8
11D	18/06/2008	170.5	3.1	217.6	744.0	308.2	907.3	1526.1	3883.5	-4.5
12D	18/06/2008	205.8	5.2	306.0	665.4	302.3	872.6	1701.4	4065.1	-3.1
P3	18/06/2008	10.7	2.4	13.2	129.5	37.9	109.1	143.3	450.9	5.0
P5	18/06/2008	72.1	2.7	188.2	798.2	312.5	1177.4	1136.9	3689.3	-3.6
P6	18/06/2008	63.3	1.4	188.7	1618.0	407.2	1214.6	2473.5	5966.7	-4.8
P8	18/06/2008	43.3	5.6	131.9	688.7	164.1	1204.3	840.1	3078.0	-4.2

Continued on next page

Table 3.3: Major ion results for groundwater 2004-2008

Sample ID	Date	Ca	K	Mg	Na	SO_4	HCO_3	Cl	TDS	CBE %
		mg/L								
PT 1	18/06/2008	66.6	3.6	181.0	1040.0	395.6	782.9	1673.2	4146.5	-3.6
* Duplicate samples										

Table 3.4: Minor ion results for groundwater 2004-2008

Sample ID	Date	P	NO_3	F	Mn	Al	Sr	Si	B	Br	Ba	Fe
		mg/L										
1S	14/04/2004	3.76					0.61	10.92	0.03			
	29/03/2005	4.6				1.2		12.4	0.0			
1D	13/04/2004	2.20					0.40	14.69	0.04			
	31/03/2005	10.9					1.0	11.2	0.0			
	16/06/2008	n.a.	15.8	1.0	0.0	0.0	1.2	14.7	0.0	n.a.	0.0	0.5
2S	13/04/2004	4.26					1.36	15.81	0.03			
	29/03/2005	4.3					0.8	9.6	0.0			
	16/06/2008	n.a.	n.a.	3.3	0.1	0.0	0.6	5.4	0.0	5.2	0.0	1.6
2D	13/04/2004	1.81					3.96	20.53	0.04			
	29/03/2005	3.0					0.9	13.5	0.0			
	16/06/2008	n.a.	15.8	1.4	0.0	0.0	1.0	16.6	0.0	n.a.	0.0	3.4
2D dup	29/03/2005	3.2					0.9	13.3	0.0			3.2
	30/03/2005	6.3					0.9	13.0	0.0			
3S	14/04/2004	0.56					1.13	22.87	0.03			
	29/03/2005	5.7					1.3	15.6	0.0			
	16/06/2008	n.a.	14.3	1.3	0.0	0.0	1.0	19.3	0.0	n.a.	0.0	0.0
3D	14/04/2004	10.99					0.72	12.84	0.02			
	30/03/2005	6.4					1.4	12.8	0.0			
	16/06/2008	n.a.	7.2	n.a.	0.0	0.0	1.6	16.0	0.0	3.2	0.0	0.0033
4S	29/03/2005	3.7					1.4	12.1	0.0			
4D	14/04/2004	8.57					5.88	17.75	0.03			
	31/03/2005	11.5					0.8	12.5	0.0			
	16/06/2008	n.a.	18.3	n.a.	0.0	0.0	0.9	15.1	0.0	n.a.	0.0	0.0
5D	15/04/2004	7.74					2.51	13.75	0.02			
	30/03/2005	0.6					1.3	24.2	0.0			
	18/06/2008	n.a.	9.4	n.a.	0.0	0.0	2.8	27.2	0.0	4.5	0.0	0.9
6D	15/04/2004	23.18					1.62	26.10	0.03			
	30/03/2005	12.5					2.0	16.7	0.0			
	18/06/2008	n.a.	n.a.	n.a.	1.1	0.0	2.4	24.5	0.0	5.6	0.1	0.0009
7S	14/04/2004	5.35					1.20	14.97	0.02			
	30/03/2005	28.7					1.5	27.8	0.0			
7D	14/04/2004	2.62					0.03	5.81	0.03			
	31/03/2005	8.9					0.4	15.6	0.0			
	17/06/2008	n.a.	4.7	0.9	0.4	0.0	0.7	17.8	0.0	2.8	0.1	0.0003
8S	14/04/2004	6.11					0.77	45.93	0.01			
	30/03/2005	2.9					1.5	14.6	0.0			
	17/06/2008	n.a.	n.a.	n.a.	0.6	0.0	0.7	23.3	0.0	10.6	0.1	0.2252
8D	14/04/2004	6.22					1.05	35.32	0.01			
	31/03/2005	2.2					0.6	14.9	0.0			
	17/06/2008	n.a.	n.a.	3.0	0.6	0.0	0.3	12.6	0.0	n.a.	0.0	0.0
9S	14/04/2004	10.87					0.80	18.79	0.02			
	30/03/2005	1.2					0.7	40.4	0.0			
9D	14/04/2004	3.15					3.39	17.34	0.04			
	31/03/2005	4.2					1.0	38.7	0.0			
	17/06/2008	n.a.	n.a.	n.a.	1.4	0.1	1.1	45.4	0.0	6.7	0.0	15.0
10S	15/04/2004	5.90					1.30	11.72	0.02			
10D	15/04/2004	6.47					3.11	11.47	0.03			

Continued on next page

Table 3.5: Stable Isotope Data for Rainfall and Creek

Sample site	Date	$\delta^{18}O$	$\delta^{2}H$
Rain centre M/R/G	24/1/07	-3.95	-16.5
Manual rain centre	8/3/07	-2.22	-5.4
Manual rain W/S	18/5/07	-10.59	-70.1
Rain sample centre	18/5/07	-10.48	-71.1
Rain crop	6/7/07	-9.41	-59.2
Rain sample weather station	11/7/07	-7.78	-45.5
Weather station rain gauge 68.6	26/3/08	-4.38	-19.8
Rain S/E	11/7/07	-7.79	-45.4
Main, Auto 1	17/5/07	-4.1	-21.7
Main, Auto 7	18/5/07	-5.44	-21.3
Main, Auto 16	18/5/07	-5.4	-21.7
Main, Auto 1	18/5/07	-11.25	-77.4
Main, Auto 11	18/5/08	-10.93	-76.9
Main, Auto 20	19/5/07	-10.58	-74.4
Creek	16/6/08	-3.24	-10.5
Creek North	18/6/08	-4.35	-24.5

Table 3.4: Minor ion results for groundwater 2004-2008

Sample ID	**Date**	**P**	**NO_3**	**F**	**Mn**	**Al**	**Sr**	**Si**	**B**	**Br**	**Ba**	**Fe**
		mg/L										
	30/03/2005	2.8					3.5	16.8	0.0			
	18/06/2008	n.a.	4.6	1.0	0.4	0.0	3.3	19.9	0.0	9.0	0.0	0.4313
11D	18/06/2008	n.a.	5.7	0.9	0.0	0.0	1.5	21.6	0.0	4.4	0.0	0.0024
12D	18/06/2008	n.a.	5.2	1.4	0.0	-0.1	1.7	18.8	0.0	5.0	0.0	1.5
P3	18/06/2008	n.a.	4.8	n.a.	0.0	0.0	0.2	12.6	0.0	n.a.	0.0	
P5	18/06/2008	n.a.	n.a.	1.1	0.1	0.0	2.2	19.7	0.0	3.7	0.2	
P6	18/06/2008	n.a.	n.a.	n.a.	0.0	0.0	1.8	18.4	0.0	6.7	0.1	
P8	18/06/2008	n.a.	n.a.	n.a.	0.0	0.0	1.1	12.8	0.0	n.a.	0.1	
PT 1	18/06/2008	n.a.	2.8	0.8	0.0	0.0	1.7	8.0	0.0	5.2	0.1	
Creek	16/06/2008	n.a.	n.a.	0.8	0.0	0.2	0.2	4.9	0.0	n.a.	0.0	
Creek north	18/06/2008	n.a.	n.a.	n.a.	0.5	0.0	1.5	9.6	0.0	3.7	0.2	

3.7 Stable isotopes

Environmental isotopes, elements with varying atomic mass, now routinely contribute to groundwater investigations, providing a unique insight into recharge processes, groundwater quality, rock-water interaction, and the origin of salinity Clarke and Fritz [1997]. Stable isotopes such as carbon-13 ($\delta^{13}C$), deuterium ($\delta^{2}H$) and oxygen-18 ($\delta^{18}O$), which are used in this study, provide a natural signature tracer for groundwater origin.

Isotope data for the Baldry site are presented in Tables 3.5 and 3.6

Table 3.6: Stable Isotope Data for Groundwater

Sample site	**April 2004**		**June 2008**	
	$\delta^{18}O$	$\delta^{2}H$	$\delta^{18}O$	$\delta^{2}H$
1S	-5.42	-32.2	-	-
1D	-5.46	-33.0	-5.77	-33.0
2S	-5.41	-33.1	-5.8	-34.5
2D	-4.95	-29.4	-5.96	-34.1
3S	-5.54	-32.7	-5.96	-33.9
3D	-5.39	-31.6	-5.96	-33.6
4S	-	-	-	-
4D	-	-	-5.76	-33.3
5D	-5.35	-34.3	-5.78	-32.9
6S	-	-	-	-
6D	-5.51	-31.6	-5.82	-31.5
7S	-5.16	-31.9	-	-
7D	-5.80	-33.4	-5.79	-33.3
8S	-4.8	-30.9	-5.61	-33.3
8D	-5.43	-34.4	-5.8	-31.4
9S	-5.04	-32.2	-	-
9D	-5.35	-33.2	-5.62	-31.6
10S	-4.37	-28.8	-	-
10D	-5.5	-30.9	-5.85	-34.5
11D	-	-	-5.85	-34.5
12D	-	-	-5.84	-35.9
P5	-	-	-5.81	-34.6
P6	-	-	-5.48	-33.6
P8	-	-	-5.65	-34.5
P1	-	-	-5.82	-34.2

Chapter 4

Interpretation and discussion

4.1 Climate data

The cumulative departure from the mean long-term rainfall record for Yeoval (Fig. ??) shows that the early part of the 20th Century was drier than average and that there was a change to wetter than average conditions about 1947. This change has been noted across eastern NSW [Rančić et al., 2009]. The rainfall through the latter part of the 20th Century is wetter, with a change back to drier conditions in 2000. This latter change is not as pronounced for the Yeoval record as for other stations further east.

Cumulative departures from the mean for the 4 seasons in the Yeoval record are shown in Fig. 4.1. This data shows that the autumn and winter rainfall has not varied significantly over the 130 years of record. However, the spring and summer rainfall were significantly reduced. Further work is required to investigate the probably long-term impacts on groundwater recharge. The lower spring rainfall would possibly significantly reduce recharge.

4.2 Geology and geophysics

4.3 Hydrogeology

4.3.1 Water levels

The barometric efficiency has been calculated for all deep bores and has been used to correct the observed data. Acworth and Brain [2008] reported on a methodology for this correction that has been developed using the Baldry data set. Fig. 4.2 demonstrates that the water levels in the ground respond to both diurnal and semi-diurnal tides in atmospheric pressure and to longer frequency variations in atmospheric pressure caused by mesoscale disturbances. The barometric efficiency at this site is 0.98.

4.4 Hydrochemistry

4.4.1 Spatial variability

Spatial variability in groundwater salinity was of greater significance than changes over time, although minor changes were observed at some sites as discussed in Section 4.4.6. The following discussion focuses

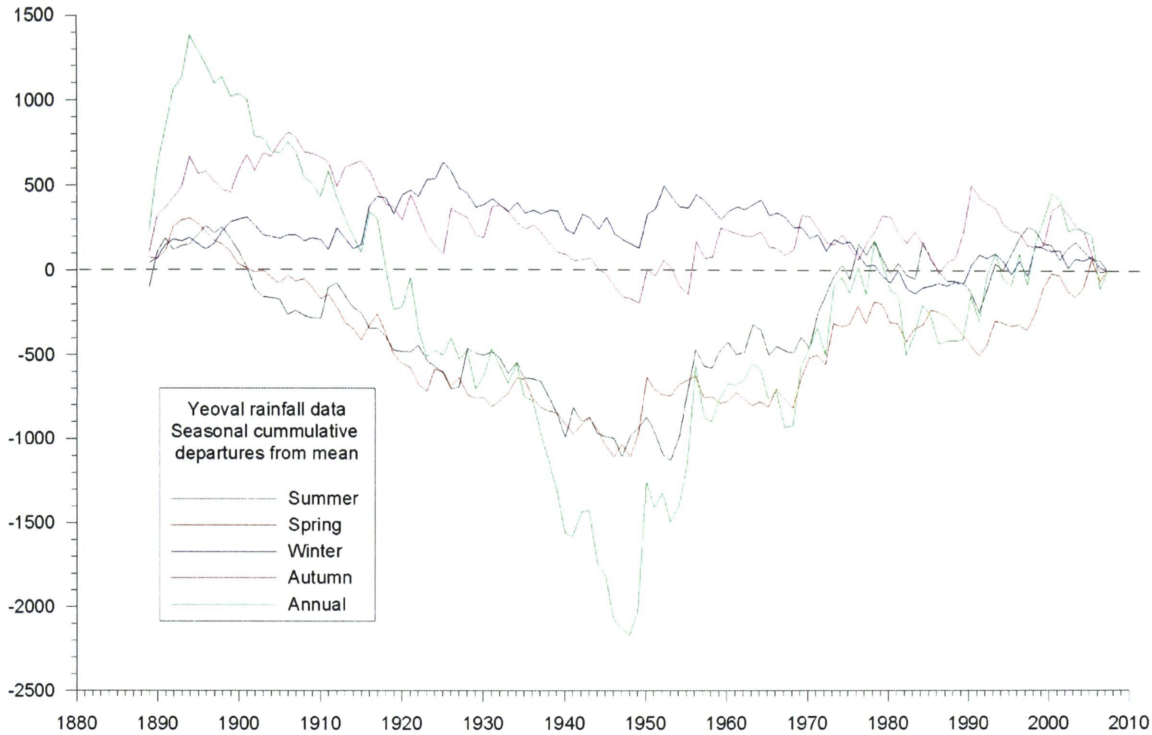

Figure 4.1: Seasonal variation in rainfall

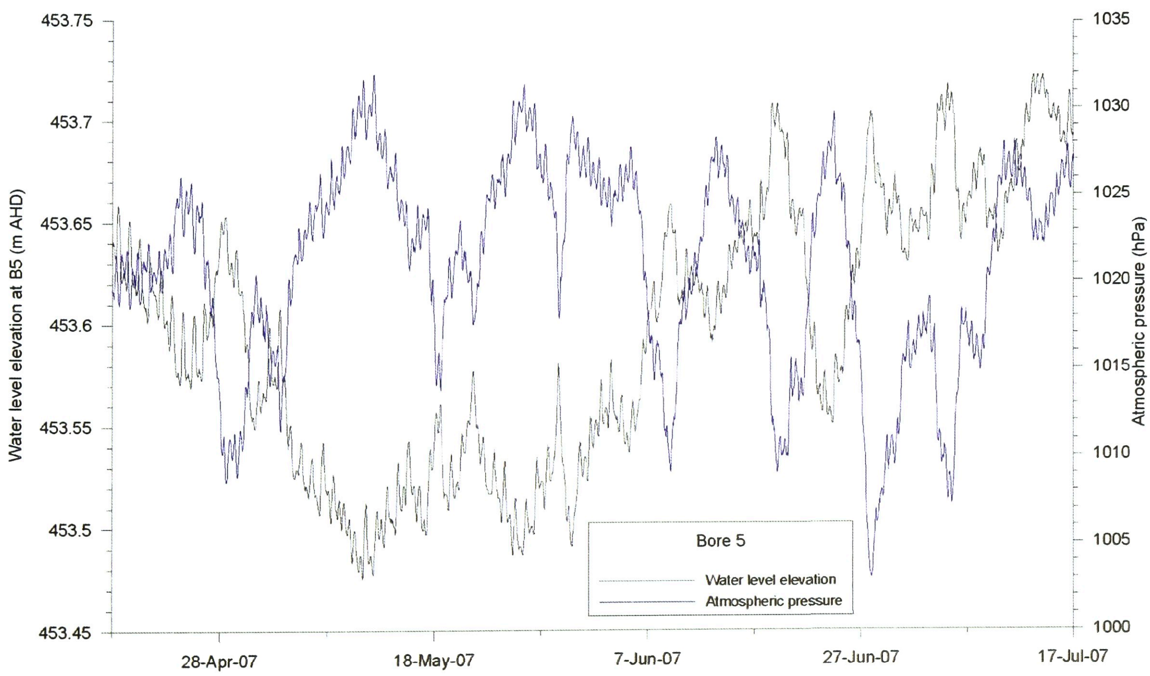

Figure 4.2: Plot to show the inverse response of water levels to change in barometric pressure

mainly on spatial variability observed in June 2008. This period is considered representative of site conditions during a dry period. Some of the samples prior to June 2008 had artifacts due to incomplete flushing of installation grouting.

4.4.2 Field water quality parameters

In June 2008, groundwater EC varied between 1.0-9.7 mS/cm (n=21), compared with surface water 0.4-1.4 mS/cm (n=2), and EC 6.1 mS/cm at a creek pond (south of the weir) where groundwater appeared to be discharging. A maximum EC of 9.7 mS/cm was recorded at bore 8S. Generally lower conductivities were measured in bores at the base of the hill (bores 1, 2, 3 and 4) while higher conductivities were measured in the higher parts of the catchment especially at monitoring bores 9 and 10 and P6. Bores 6, 11 and 12 in the middle of the catchment showed higher conductivities (around 5 mS/cm) than the bores in the lower catchment. The difference between shallow and deep monitoring bores was not significant except at monitoring bores 7 and 8 where higher salinity water was observed at shallower depths (3.7 and 6.58 mS/cm respectively).

Groundwater pH averaged 7.2, with spatial variation from pH 5.8 to 8.5. In June 2008, the lowest pH was measured at monitoring bore 9D and the highest at bore 8D. The site with highest pH was likely due to effects of cement grout used during bore construction at a site with very low flow rates. The pH was between 7 and 8 for bores located in the pasture areas except for bore 9 where the pH was below 6. Groundwater temperature was lowest (18.9 degrees C) at the deep monitoring bores 5D and 10D and the highest at the shallow bore 8S.

Groundwater was generally oxidizing, with dissolved oxygen between 0.04 mg/L at bore 3S and 4.89 mg/L at piezometer P8. Redox values (Eh-NHE) showed a wide range from -88 mV at bore 8D to 197 mV at bore 1D (Eh-NHE ~300 mV average). Oxidizing groundwater was consistent with field spectrophotometer analysis results of very low Fe^{2+}, and S^{2-} (below detection limit).

4.4.3 Major ions and TDS

Majon ion concentrations and TDS varied significantly across the site. Sodium concentrations ranged between 448.6 and 1932.0 mg/L at bores 5D and 8S respectively. Potassium concentrations ranged between 0.9 and 6.9 mg/L at bores 3S and 10D respectively. Potassium varied with depth below ground at bores 3, 8 and 10 where concentrations were lower in the shallow bores than the deeper bores. Sodium concentrations were also relatively high in shallow bores 2, 8 and 10. Higher potassium concentrations and lower sodium concentrations were observed in fresher, deeper groundwater within the granite.

The lowest calcium concentration measured was 18.6 mg/L at bore 2S while the highest was measured at bore 10D with 265.3 mg/L. Differences in calcium concentrations in shallow and deep bores was not observed, but concentrations tended to be higher in the the southern sub-catchment. Magnesium varied between 48.4 mg/L at bore 2S and 420.7 mg/L at bore 10D. There was more variability spatially than with depth, with higher concentrations in the western and southern part of the area (bores 5, 9, 10, 11, 12).

The lowest chloride concentration was found at bore 8D with 425.3 mg/L while the highest concentration was found at bore 8S with 2950.2 mg/L. At a few locations (bores 2, 3 and 8) chloride concentrations were higher in shallow bores than the deep bores. Chloride concentration was highest at bores located in the middle and southern part of the site especially at bores 9, 10 and P6. Bicarbonate concentrations were lowest at bore 9S with 38.4 mg/L and highest at bore 2S with 1486 mg/L. Bicarbonate was generally higher at bores in the northern or lower subcatchment (bores 1, 2, 3, 6, 8D) where salinity was generally lower. Sulphate concentration was lowest at bore 8D with 97.9 mg/L and the highest at bore 9D with 649.9 mg/L. No difference in sulphate with depth was observed. Sulphate was generally higher in bores in the south-eastern and middle part of the area than the northern (bores 1, 2, 3 & 4) and western bores (bores 11 & 12).

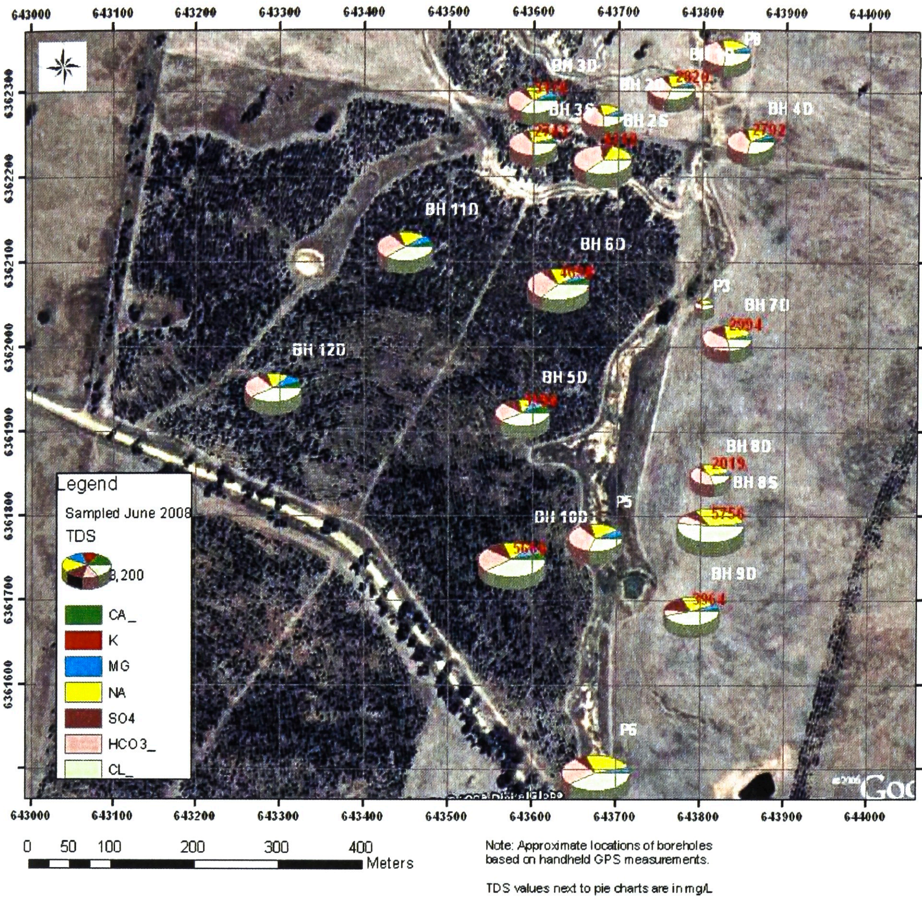

Figure 4.3: Distribution of major ions and TDS values, June 2008

The highest TDS value was observed at bore 8S with 5755.7 mg/L and the lowest at bore 8D with 2018.8 mg/L. Higher TDS values were measured at the shallow bores 2, 8 and 10 than in the deeper bores. Spatial distribution was observed in high TDS values of 3596.4 mg/L (bore 5D) and more found in the southern and western part (bores 6, 9, 10, 11 and 12).

Figure 4.3 shows major ion results for June 2008 as pie charts. The size of the circle is proportional to total dissolved solids. The TDS values are slightly lower at the northern end of the site, while the southern, upland part of the site is generally more saline, especially at bores 10D, 8S and P6.

4.4.4 Minor ions

Minor ions phosphorous, strontium, silicon and boron were analysed in 2004, 2005 and 2008. In addition to these parameters, nitrate, flouride, manganese, aluminimum, bromide and barium were also analysed in 2008. Many results were below the analytical detection limit of 0.05 mg/L (listed in the table as n.a.), particularly for flouride, manganese, aluminium, boron and barium.

- Iron concentrations ranged from 0 to 15.0 mg/L (average 1.5 mg/L, n=17)
- Sulphide was measured at a concentration of 0.034 and 0.013 mg/L in one sample at bore 10D.
- Nitrate concentrations ranged from 0 to 18.3 mg/L (average 9 mg/L, n=12)
- Phosphorous concentrations ranged from 0 to 28.7 mg/L (average 6.5 mg/L, n=36)
- Strontium concentrations ranged from 0 to 5.9 mg/L (average 1.4 mg/L, n=59)
- Bromide concentrations ranged from 0 to 10.6 mg/L (average 5.5, n=14)

- Silicon concentrations ranged from 0 to 45.9 mg/L (average 17.7 mg/L, n=59)

Iron was not detected at bores 3S, 4D and 8D. Low iron concentrations between 0.5 and 3.4 mg/L were measured at bores 1D, 2S, 2D, 5D and 12D. The highest iron concentration was measured at bore 9D with 15 mg/L and 11 mg/L in a repeat measurement. At this bore manganese and silicon reached much higher concentrations compared to the other bores with silicon 2 to 3 times higher and manganese 2 times higher. Oxygen was low (0.22 mg/L) and Eh was positive (358 mV as NHE).

Sulphide was not analysed at most of the bores as waters were oxidizing and no odour was observed during sampling. At bore 10D a concentration of 0.034 mg/L and 0.013 mg/L in a repeat measurement was recorded.

Table 4.1: Summary of major and minor ions for groundwater and creek, June 2008

	Average concentration			Maximum concentration			Creek	
	Shallow ground water	Deep ground water	Piezos	Shallow ground water	Deep ground water	Piezos	Weir	North
N	18	34	5	18	34	5	1	1
Major species (mg/L)								
Ca	47.9	**108.3**	51.2	82.8	**311.2**	72.1	9.294	103.4
K	1.8	**4.0**	3.1	3.3	22.4	**5.6**	3.245	4.102
Mg	134.6	**164.6**	140.6	**530.3**	490.8	188.7	10.4	216.6
Na	**1144.0**	660.8	854.9	**2601.4**	1107.9	1618.0	195.5	920.7
SO4	**317.1**	265.4	263.5	**637.1**	**646.9**	407.2	95.5	425.6
HCO3	**795.1**	532.6	0.0	**1632.0**	1122.4	0.0	0	0
Cl	**1646.4**	1107.1	1253.4	**4265.4**	2741.7	2473.5	220.3	1477.1
Minor species (mg/L)								
P	**6.3**	**6.6**		**28.7**	23.2	0.00	n.a.	n.a.
NO3	**14.3**	9.6	3.79	14.3	**18.3**	4.82	n.a.	n.a.
F	**2.3**	1.4	0.98	**3.3**	3.0	1.12	0.754	n.a.
Mn	0.20	**0.33**	0.03	0.6	**1.4**	0.11	0.003	0.46
Al	**0.2**	0.0	0.00	**0.9**	0.1	0.02	0.176	0.01
S	**114.2**	78.6		**212.8**	**215.9**	0.00		
Sr	1.0	**1.6**	1.42	1.5	**5.9**	2.23	0.162	1.45
Si	**18.3**	**18.5**	14.30	**45.9**	**45.4**	19.73	4.9	9.6
B	0.0	0.0	0.02	0.0	0.0	0.02	0.012	0.012
Br	**7.9**	5.1	5.22	**10.6**	9.0	6.72	n.a.	3.7
Ba	**0.1**	0.0	**0.11**	0.1	0.1	**0.20**	0.05	0.15
Values in bold show highest average and so on								

There appeared to be no spatial pattern in the high concentrations of nutrients. bores with high nitrate (1D, 2D and 4D) were at the northern part of the site, while bores with high phosphorous (3D, 6D, 7S, and 9S) were scattered in the middle part of the site. The average nitrate concentration was higher in shallow groundwater compared with deep groundwater, however in contrast, average phosphorous concentrations were generally similar in shallow and deep groundwater.

There was limited correlation of high salinity with Sr and Br. The highest strontium concentrations occurred at bore 4D (2004), 2D (2004), 9D (2004) and 10D (2005). The highest bromide concentrations were at bore 8S, 10D and 9D (in decreasing order).

Very high silicon concentrations occurred at bores 8 and 9, however the values varied substantially between 2004, 2005 and 2008 and no clear trend could be discerned. Silicon concentrations were similar in deep and shallow groundwater.

Deep groundwater was characterised by relatively high concentrations of Mg, Mn and Sr. This could be associated with a source of ions from weathered granite.

4.4.5 Watertype and geochemical evolution down-slope

Groundwater in fractured granite was a significant source of magnesium and potasssium (and manganese and strontium as discussed in Section 4.4.4, but could not account for saline groundwater, or NaCl type groundwater.

All sites were NaCl type water in June 2008, except for 8D and P3 which were NaHCO3 type. Bores 1D, 2D, 2S, 4D, and 7D were initially of NaHCO3 type water (in 2004) and gradually became NaCl type water. These changes may be at least partially attributed to contamination by grout after bore installation which took some time to flush.

Groundwater was generally of a Na-Cl type at higher elevations, with a higher proportion of Mg. However, despite generally decreasing salinity, groundwater was of Na-Cl type at mid to lower elevations with relatively high proportions of Na.

Water types are shown in Piper diagrams for the deep and shallow groundwater systems Figure 4.4 and Figure 4.5. There was evidence for evolution of groundwater chemistry along flow paths from higher to lower elevations within the sub-catchment. Groundwater in the mid-catchment beneath the forested area was consistent with geochemical evolution down the slope. However, groundwater in the mid-catchment beneath the pasture area was relatively high in sodium and did not fit a simple mixing or geochemical evolution down the slope.

It is also evident from the piper diagrams that shallow groundwater tends to be higher in sodium and is of similar watertype to deep groundwater below the mid slope and lower slope. Creek water collected from a site north of the weir is similar to deep groundwater below the mid slope, whereas creek water collected south of the weir is very distinctive from deep groundwater. However, the creek water south of the weir is more similar to shallow groundwater composition.

4.4.6 Variability over time

Changes over time were of less significance that spatial variation. Between 2004 and drier conditions in 2008, groundwater salinity increased significantly at several bores in the lower and mid sub-catchment, but freshening observed at one site near the top of the forested area. The following table lists parameters which have changed over time for all sample locations.

Figure 4.6 shows the variation in goundwater salinity, expressed as EC, over time. Samples that are likely contaminated by grout during bore installation are marked. These sites also had relatively high pH, and over time appeared to be adequately flushed. There is a general trend of converging groundwater salinty over time, with values tending to be more stable, and more similar.

There appears to be a mixing of different salinity waters within bores screened in across both sand and fractured granite.

Between 2004 and 2008, major ion concentrations increased at most of the bores, especially chloride and sulphate. Over time, most species decreased in concentration in bores 8, 9 and 10. Figure 4.7 compares chloride values from 2004 to 2008. At bores 8, 9 and 3S a decrease in concentration was observed, while chloride at all other bores increased, especially at bores 5 and 10.

Freshening occurred at bore 8S and 8D with a change of water type from Na-Cl to Na-HCO3 water. Also most water quality parameters decreased over time. At bore 8, shallow groundwater was characterised

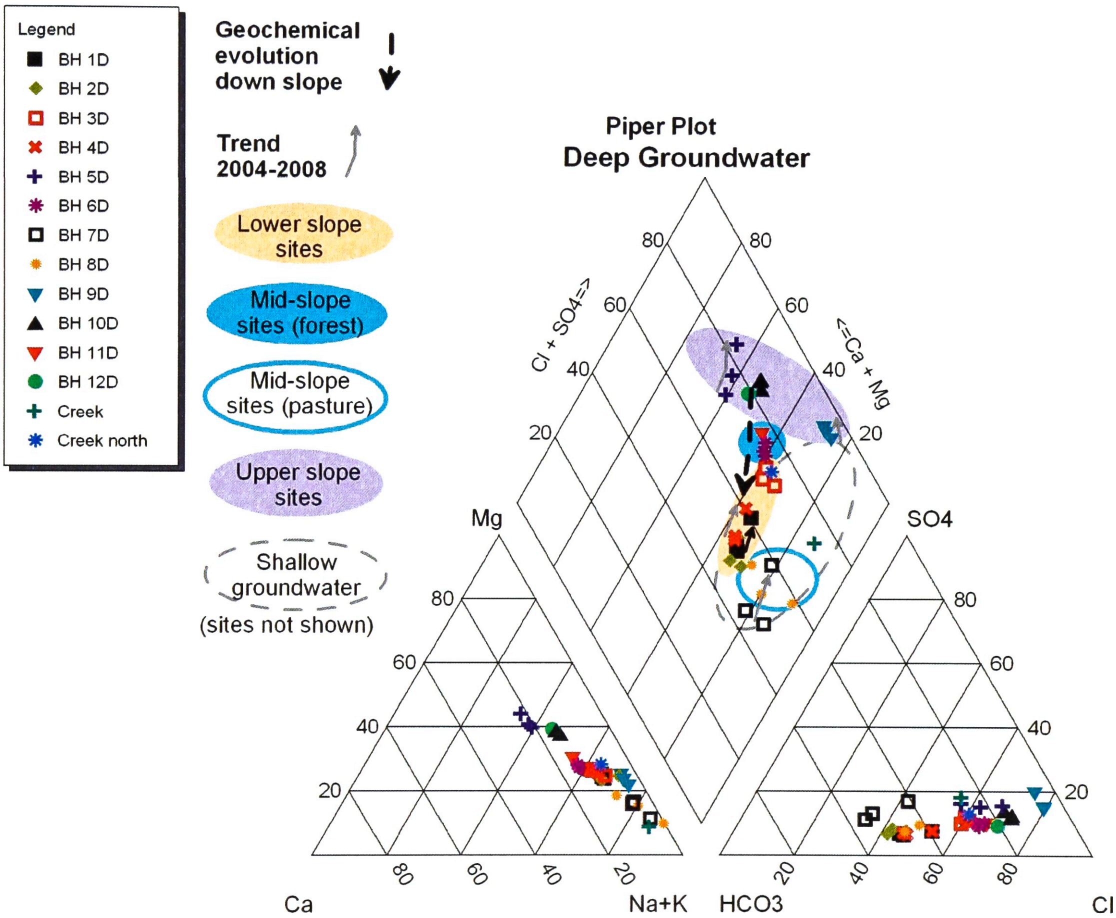

Figure 4.4: Piper diagram showing geochemical relationships of deep groundwater

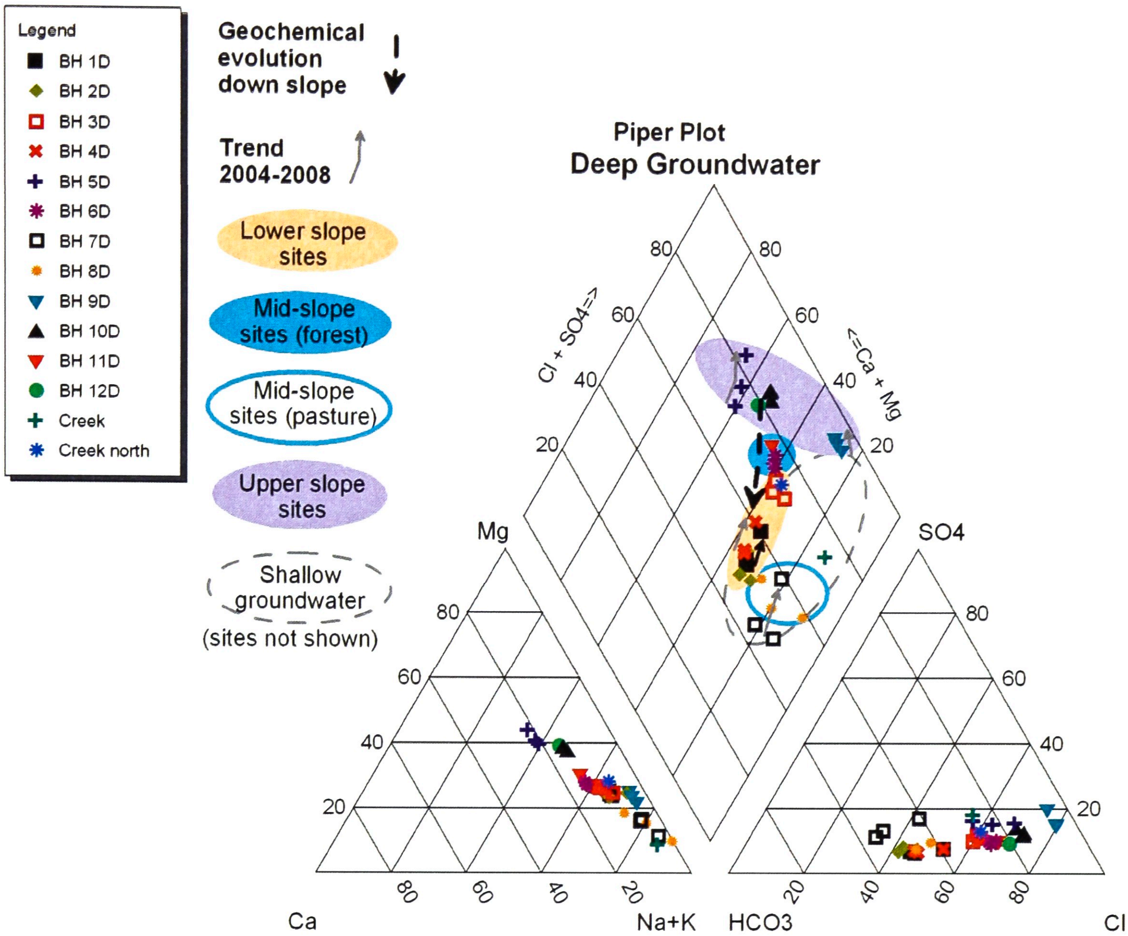

Figure 4.5: Piper diagram showing geochemical relationships of shallow groundwater ***need to revise

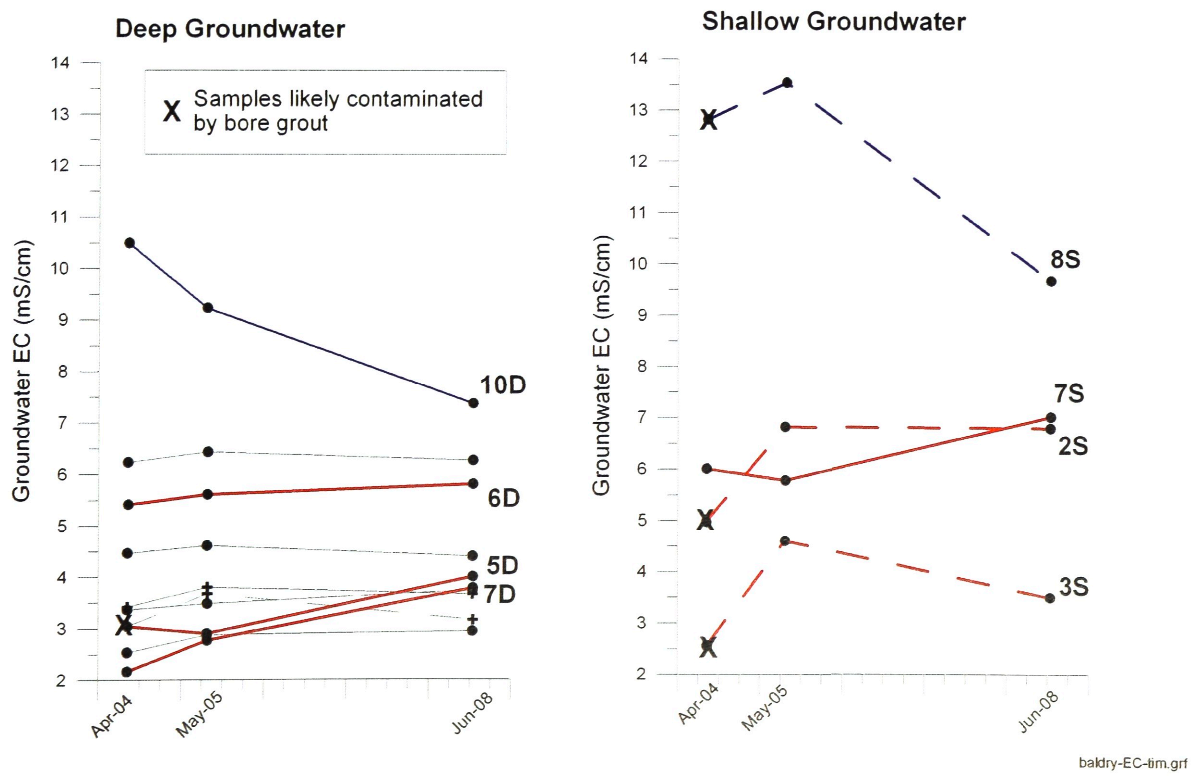

Figure 4.6: Groundwater salinity (EC) over time

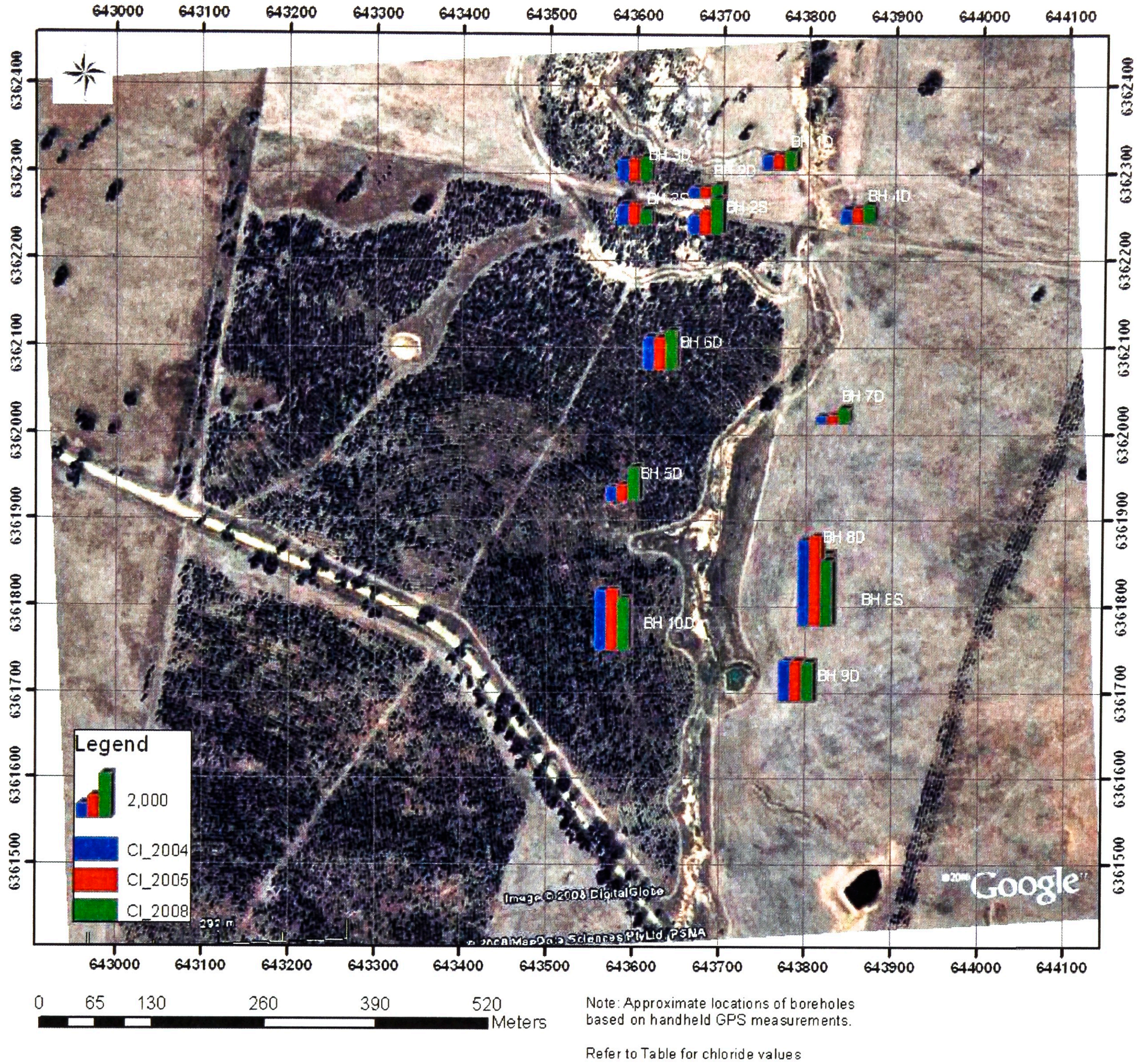

Figure 4.7: Distribution of changes in chloride concentrations, 2004-2008

by high chloride (4̃,000 mg/L)compared with 5̃00 mg/L at depth.

4.5 Stable isotopes

4.5.1 Establishing a local meteoric water line

A local meteoric water line (LMWL) was established for Baldry (Figure 4.8). Determining a LMWL was important to understanding the values of ^{18}O and ^{2}H observed in ground and surface waters, relative to modern rainfall. For instance, some of these samples plot to the left of the GMWL, but to the right of the Baldry LMWL. This distinction is important in interpreting the effects of mixing versus other geochemical processes such as silicate hydration.

The Baldry LMWL was defined as follows:

$$\delta^2 H = 7.9\delta^{18}O + 14.2 \quad (4.1)$$

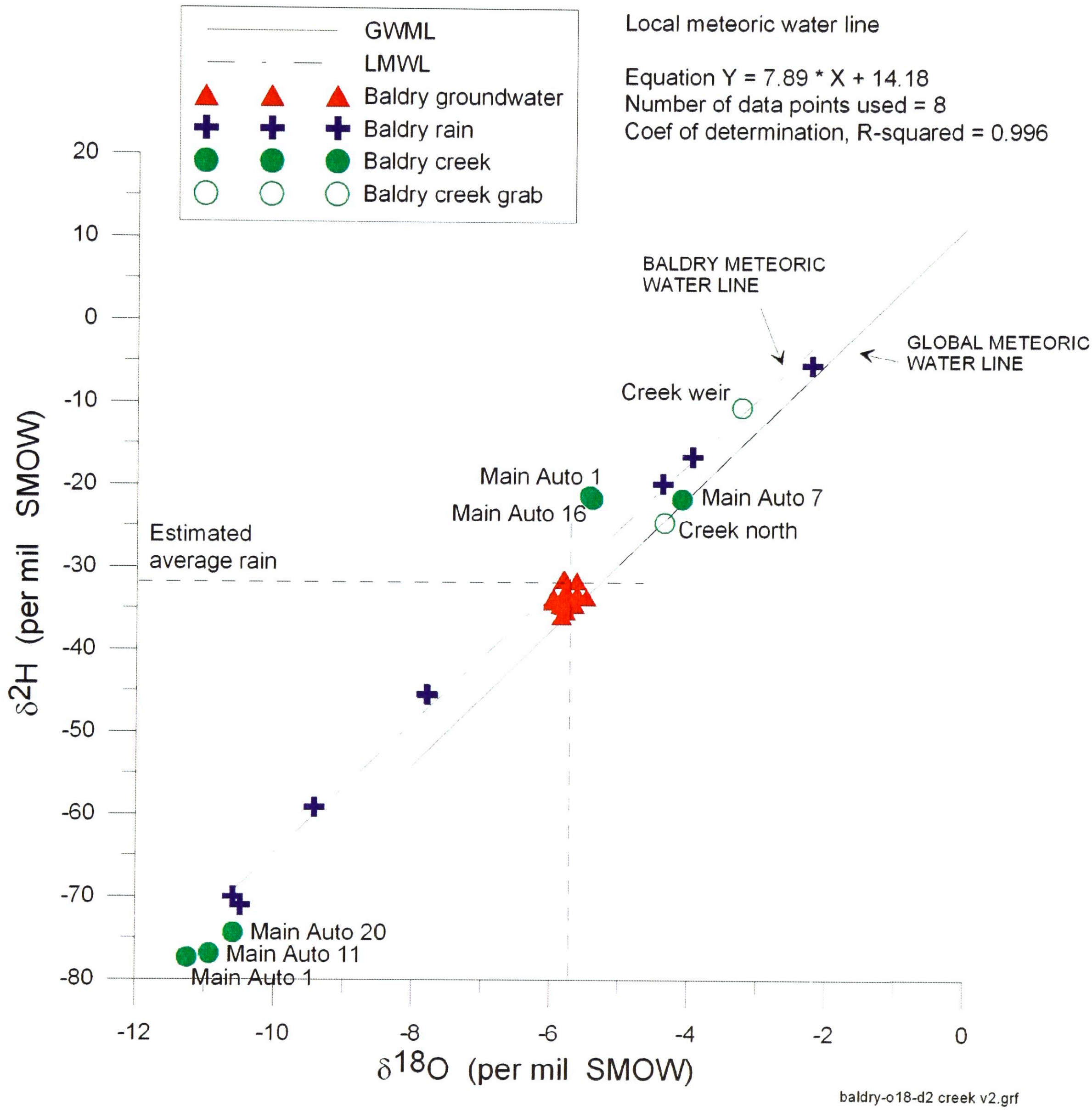

Figure 4.8: Oxygen-18 and deuterium data - groundwater relative to Baldry rainfall and LMWL

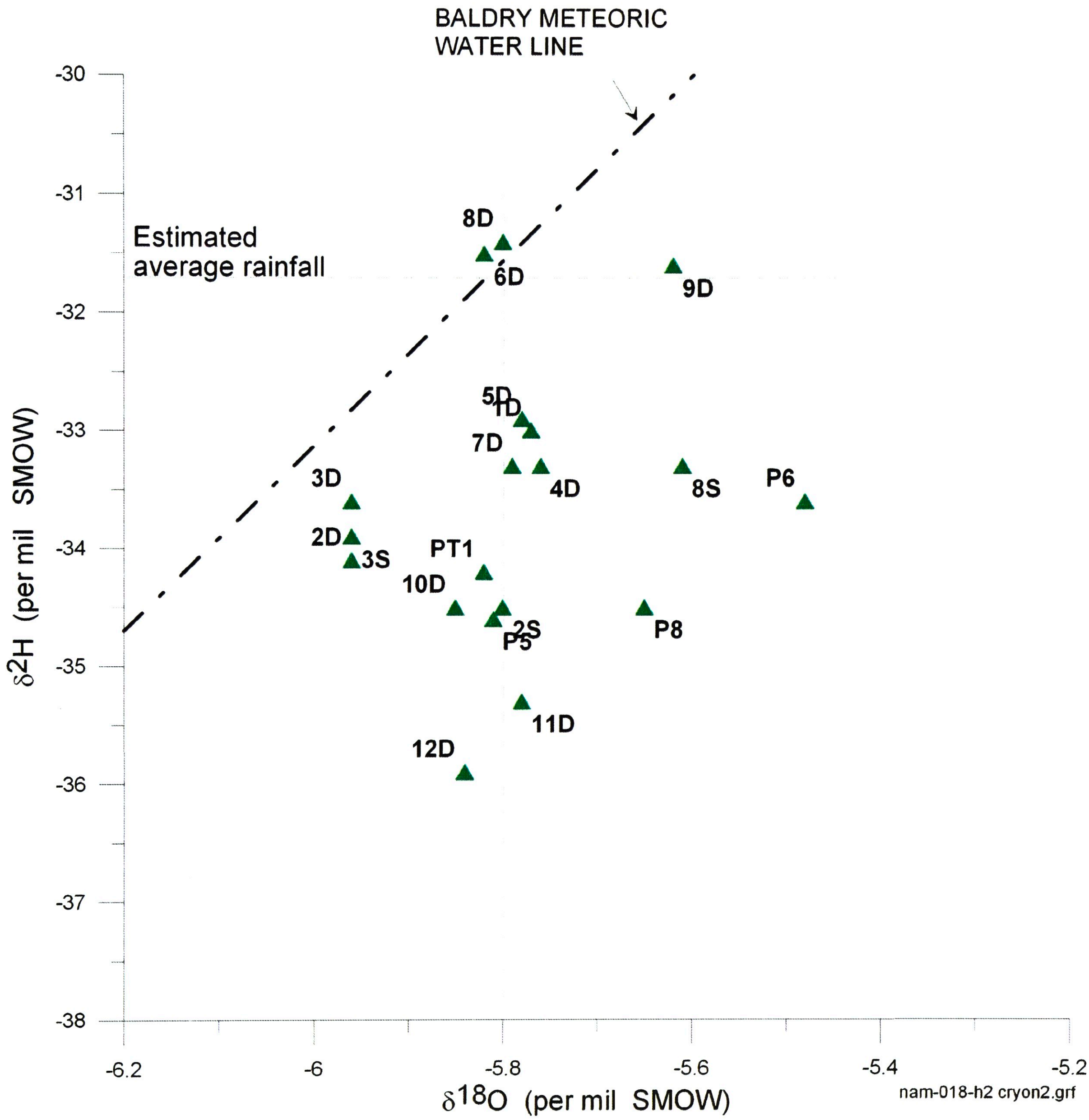

Figure 4.9: Oxygen-18 and deuterium data - Baldry groundwater samples

Table 4.2: Slope and deuterium excess for Australian rainfall isotope monitoring stations.

Location	LMWL slope	LMWL ^{2}H intercept	No. of data points
Brisbane * 0	7.76	12.89	227
Alice Springs *	7.56	9.3	75
Melbourne *	7.44	8.48	224
Adelaide *	8.08	12.17	89
Ballimore 1	7.76	15.56	4 (2 from Gunnedah)
Gunnedah 2	7.9	16	2?
Gunnedah 3	8.4	15.99	17
Leeton 4	7.3	11.3	10
Baldry	7.9		8

The LMWL was based on 8 samples collected from rainfall events between 24/1/07 and 26/3/08 (T. Bernadi, pers. com.) at the Baldry site. Samples were collected from weather stations and manually, and were from either the centre of site or the crop site (check with Tony).

The LMWL for Baldry is similar to the global meteoric water line (GMWL), that was first defined by

The lower slope may be attributed to evaporation during rainfall. Identical ^{2}H intercept is a coincidence which is controlled by primary evaporation in the source region of water vapour

The estimated mean $\delta^2 H$ was -31.7 ‰ and the mean δ^{18}O -5.8 ‰. These values were determined from 5 samples, not including duplicate samples of the same event. There is considerable uncertainty in these estimates, given limited number of samples, sampling technique and lack of information on rain volumes during these events.

$$\delta^2 H = 8.17\, \delta^{18} O + 11.3 \qquad (4.2)$$

The LMWL established may be compared with other monitoring stations and LWML that have been established (Table 4.2). Baldry LMWL has a lower slope and a deuterium excess that lies between the values for Melbourne and Brisbane, the two closest official stations. The slope and intercept values also lie between the LWML that have been established for Gunnedah, to the north, and for Leeton, to the south. These differences are to be expected, but do suggest that the Baldry rainfall samples are likely to be representative of the long term average for that part of the Macquarie catchment. Furthermore, the sampling period was one of slightly above average (check with Tony B) rainfall and was of over 12 months duration, capturing both summer and winter rainfall events.

4.5.2 Isotope signatures of surface and groundwater

The distribution of groundwater isotope values are tightly clustered around the meteoric waterline. This finding shows that groundwater is of meteoric (rainfall recharge) origin, as expected for sediments overlying weathered and fractured granite. It was not possible to determine a mean weighted isotope values for rainfall that could identify whether or not there is similarity with average groundwater isotope values. It is possible that groundwater is generally more depleted in stable isotopes relative to the estimated average isotope values of local rainfall. If confirmed, this indicates that aquifers in weathered and fractured granite may have been recharged primarily during periods of wetter and cooler climate than that observed during the study.

It is significant that at this site, there are relatively small differences between maximum and minimum ^{18}O and ^{2}H values, with no evidence of enrichment or depletion due to secondary processes. There is no relationship apparent between groundwater salinity and isotope enrichment (Figure 4.10), meaning that salinity cannot be attributed to evaporative concentration.

Creek waters sampled in June 2008 were either directly rainfall derived (sampled at the weir), or a mixture of groundwater and rainwater (sampled south of the weir), without any significant evaporative concentration. The values of ^{18}O and ^{2}H were similar to rainwater at the weir. At a pool within the creek south of the weir both ^{18}O and ^{2}H values are mid-way between the creek at the weir and groundwater in bores 8S or P6. Groundwater discharge could account for roughly half of the creek water at this location.

Isotope data from 2004 is subject to some uncertainty due to contamination by bore grout. However, in general there were trends between 2004 and 2008 towards the LMWL or towards more depleted groundwater. Insignificant isotope changes were observed at one bore (7D). Bores 1D, 5D, 6D, 8D and 9D became more similar to the LMWL over time, with relatively similar, or enriched ^{2}H values, and relatively depleted ^{18}O values. Increasingly depleted groundwater in both O18 and ^{2}H was observed at bores 2S, 2D, 3S, 3D, 8S and 10D. The magnitude of variability in these stable isotope values over time is unexpected and cannot be explained at this time.

** Add this to isotope tables (‰VSMOW) **

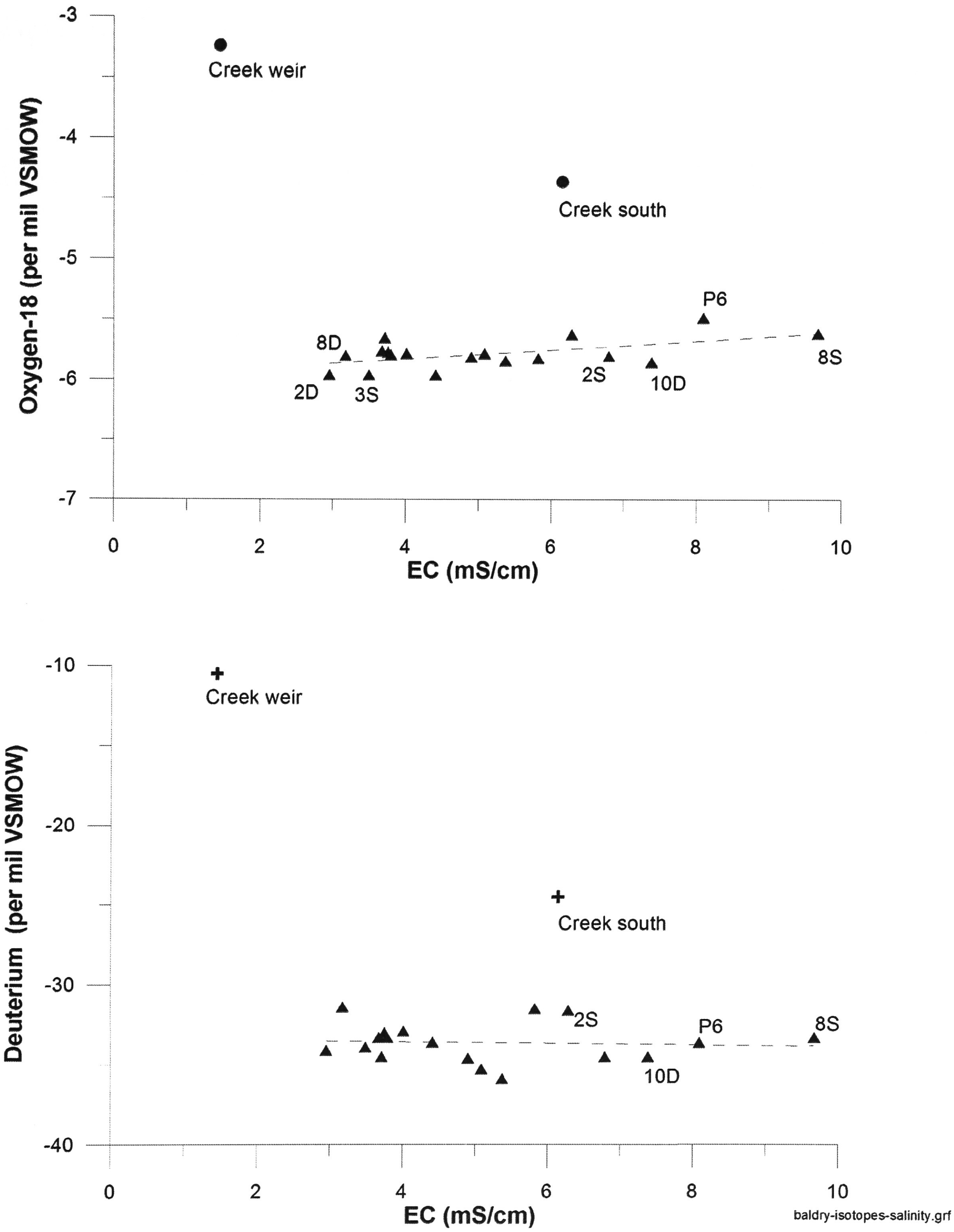

Figure 4.10: Isotope values vs. salinity

Chapter 5

Conclusions and recommendations

5.1 Salinisation of groundwater

Groundwater salinity is attributed to dissolution of salts from localised areas of saline clay. As demonstrated in Section 4.5, the lack of enriched stable isotope values in groundwater mean that salinity cannot be due to evaporative concentration of salts.

The ratio between Na and Cl (expressed as meq/L) provided evidence for NaCl dissolution, with many samples plotting on the 1:1 line (Figure 5.1). Samples below the 1:1 line indicate Na gained from sediments due to ion exchange, a process which tends to occur at relatively low to moderate salinity, as indicated by the relationship between Na/Cl versus TDS. Those samples above the 1:1 line, indicated that Na is lost from groundwater due to reverse ion exchange.

Generally, reverse ion exchange occurs at higher salinity where Na concentrations in solution are higher than exchangeable-Na. However, at the Baldry site, reverse ion exchange is evident over a range of salinities and appears to occur only at sites below the forest (bores 5, 6, 10, 11 and 12). In the TDS range of ~2000 to 5000 mg/L, Na appears to be either lost or gained by exchange processes. This observation is yet to be explained. Further hydrogeochemical assessment is required, including equilibrium modelling using a code such as PHREEQC.

There was no relationship evident between groundwater salinity, thickness of clay and landuse. Figure 5.2 shows a wide scatter of groundwater salinity versus thickness of clay. Bore 8S recorded the highest groundwater salinity with a moderate overlying thickness of clay. Both forest and pasture site exhibited a similar range in groundwater salinity. However, this graph does not indicate the salt content of the clay overburden.

The sites in the northern and eastern part of the area are characterised by more significant clay and sands deposits (Table 5.1). There was no correlation between high groundwater salinity and thicker clay overburden or depth to hard granite. There was no correlation between high goundwater salinity and the peak bulk salinity measured by bore logging (EM39).

There was a possible correlation between high groundwater salinity and localised areas of saline clay sediments.

Salts loads generated by this sub-catchment appear to depend on the degree to which salt patches in clayey surface sediments are flushed into shallow groundwater and discharged to the creek. In June 2008, groundwater EC varied between 1.0-9.7 mS/cm (n=21), compared with surface water 0.4-1.4 mS/cm (n=2), and EC 6.1 mS/cm at a creek pond where groundwater appeared to be discharging.

Groundwater salinity was relatively high within clayey sediments, and groundwater salinity within the fractured granite was highest in the upper areas and typically decreased downslope. Between 2004 and

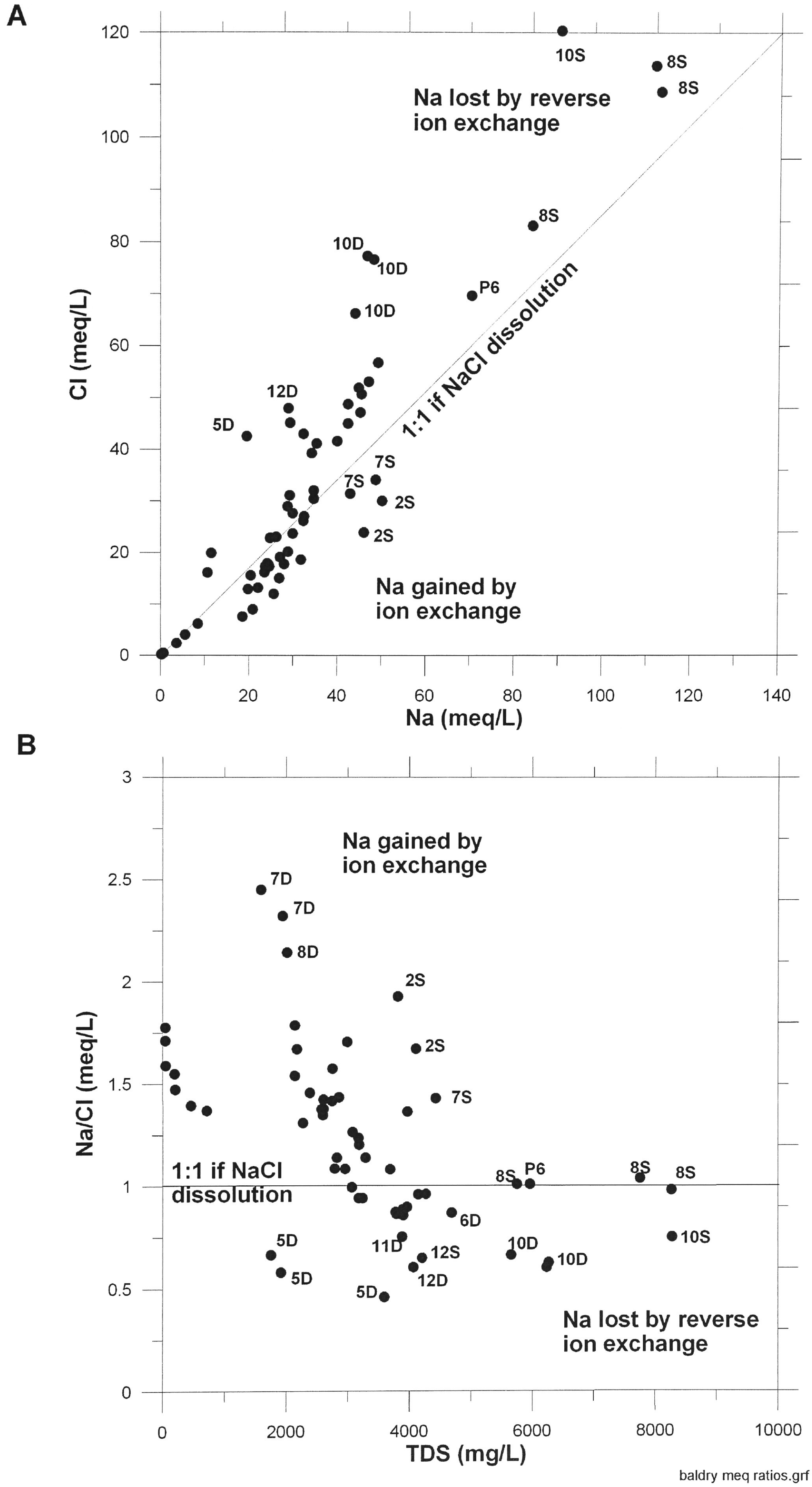

Figure 5.1: Relationships between Na, Cl and TDS

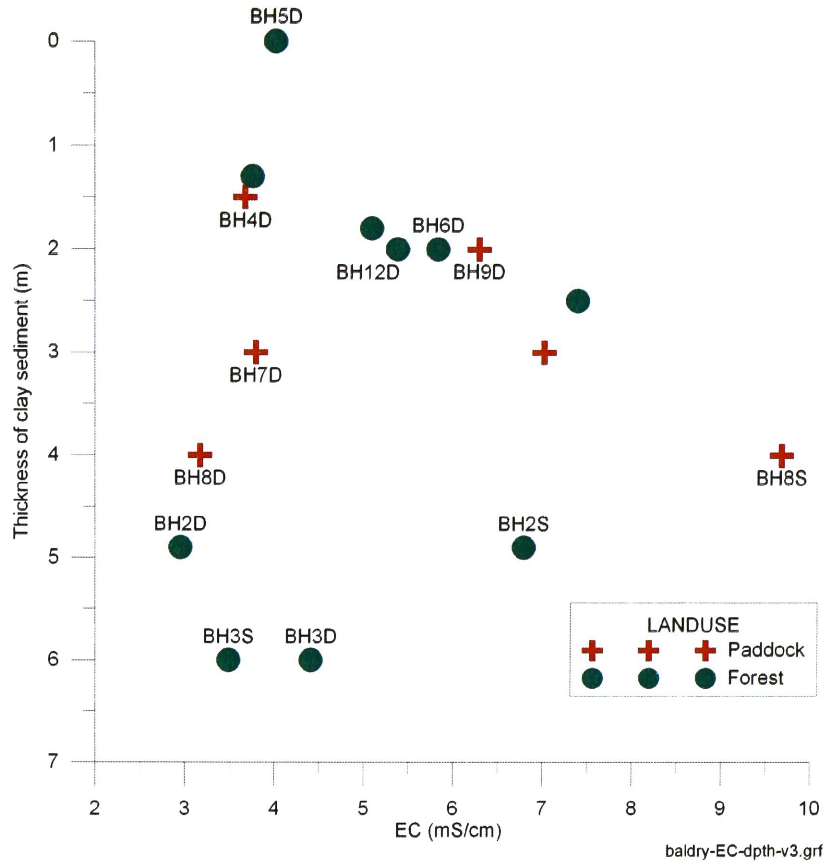

Figure 5.2: Relationship between groundwater salinity, thickness of clay and landuse

Bore	Land use	Depth to hard granite (m)	Thickness of clay (m)	Groundwater EC in 2008 (mS/cm)	EM39 max (mS/m)	EM39 max dpth (m bg)	EM31 (mS/m)
2S	F	6	4.9	6.79	170	4.2	
2D	F	6	4.9	2.95			
3S	F	12.5	6	3.49	180	4	
3D	F	12.5	6	4.41			
5D	F	0.5	0	4.01			
6D	F	10.5	2	5.82	70	2	
10D	F	10	2.5	7.38	60	4	
11D	F	1.8		5.08			
12D	F	2		5.37			
1D	P	4	1.3	3.75	80	2	
4D	P	4	1.5	3.67	180	1	
7D	P	6	3	3.79	100	3	
8S	P	8	4	9.67	240	3	
8D	P	8	4	3.17			
9D	P	4.5	2	6.28	270	3	

Table 5.1: Possible factors related to groundwater salinity

drier conditions in 2008, groundwater salinity increased significantly at several bores in the lower and mid sub-catchment, but freshening observed at one site near the top of the forested area.

Spatial variability in groundwater chemistry was of greater significance than changes over time. No evidence of recharge was observed during the study period, although the decrease in salinity of deep groundwater down-slope may be attributed to areas in the mid-catchment that allow steady downwards percolation of water through non-saline soil and sediments. Alternatively, groundwater freshening trend down-slope may be due to discharge of very deep fresh groundwater, although there is no evidence available to test this possibility. The lack of evidence for recharge is consistent with detailed studies of barometric efficiency within three of the monitoring bores which indicate confined aquifer conditions, even at sites with thin clay overburden and shallow fractured rock (Acworth and Brain, 2008).

5.2 Implications for catchment management

There does not appear to be a significant difference in groundwater conditions on the western forested side of the sub-catchment, compared with the eastern side of the sub-catchment where pastures remain the predominant landuse. On both sides of the sub-catchment, the horizontal hydraulic gradient that drives groundwater flow is similar. Groundwater salinity of granite aquifers is highest at the top of the catchment and of similar magnitude beneath the forest and pasture areas.

The detailed hydrogeological investigation at the Baldry site between 2004 and 2008 has not identified a connection between surface conditions and groundwater. There was no significant recharge to groundwater during the study period. There was no evidence that surface water, soil water or associated salts reach the watertable, or that changing landuse had an influence on groundwater levels or groundwater salinity. The possibility that minor fluxes of water and salt pass through the vadose zone to groundwater cannot be ruled out, particularly if minor fluxes occur episodically through localised areas of the hillslope.

Heavy clay deposits near the surface may act as an effective flow barrier. The heavy clay deposits, with associated salt patches are not derived from the underlying weathered granite, and have effectively disconnected groundwater within those zones from surface processes. Available evidence suggests that planting trees may not have a direct influence on groundwater by limiting recharge. However, it is possible that tree roots extracting groundwater may contribute to lowered groundwater levels and that salt scalds can be stablised by limiting soil erosion. Although the concept of recharge control through tree planting has not been validated for the Baldry site, it is possible that tree planting may act to decrease the total salt load in surface waters.

5.3 Recommendations

The possible links between surface processes, including water use by trees and potential impacts on groundwater and catchment salt export could be explored in more detail. The recommendations outlined below follow up on issues which have been identified during the current study, and address important knowledge gaps that have emerged:

- Assess relationship between tree water use and groundwater level fluctuations
- Assess hydrochemical mixing using chloride balance and/or hydrochemical equilibrium codes such as PHREEQC.
- Repeat groundwater hydrochemical and stable isotope analyses after a major rainfall event (>100 mm) to confirm the lack of signicant recharge
- Utilize advanced techniques such as soil water stable isotope analysis to identify water fluxes through the vadose zone. Complimented with existing soil moisture information, this data might establish why no significant groundwater recharge has been detected

- Permeability testing using air-slug test where there is sufficient water in cased and screened bores, and packer testing of open rock bores. There are various geophysical and tracer testing techniques available to assess the significance of flow within fractured rock bore sections.

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