

Groundwater and salt fluxes through sediments, weathered and fractured granite at the Baldry site, NSW, Australia.

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Abstract

Water and salt fluxes through clayey sediments and weathered and fractured granite are being quantified at the Baldry trial forest site, a salinity hotspot in the Murray Darling Basin. Granites and granodiorites are fractured and deeply weathered, outcropping in the upper areas, and overlain by granite derived sands and saline clayey sediments elsewhere. Groundwater levels were typically 2-6 m below ground and occasionally above the surface indicating a potential upwards flow gradient. Groundwater salinity was relatively high within clayey sediments, and within the fractured granite in the upper areas. Granite was a significant source of Mg, Mn and Sr, but could not account for saline NaCl type groundwater. Stable isotopes (δO^{18} and δH^2) indicated groundwater was of meteoric origin with no evidence of evaporative concentration. Although there was evidence for geochemical reactions along groundwater flow paths, some sites within fractured granite appeared to be isolated from flow.

Key Words

Fractured rock, salinity, clay, hydrochemistry, recharge, isotopes

INTRODUCTION

A hydrogeological investigation is in progress to quantify water and salt fluxes through clayey sediments and weathered and fractured granite to help assess salinity issues. The Baldry site is located in the Little River catchment, a tributary of the Macquarie River, in Australia's Murray Darling Basin (Fig. 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, a known salinity hotspot. The Baldry Site is one of 7 Key Sites that are a part of the NSW DPI salinity investigation strategy.

Surface water, groundwater, soil water and meteorological conditions have been monitored at the site, a ~50 hectare sub-catchment, since 2004 along with associated studies on tree water use to identify the factors controlling groundwater recharge. 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.

Average annual rainfall in the Baldry area is 596 mm per annum (Yeoval station). 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.

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 (Fig. 2). 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. Further details of the site, field and laboratory techniques and full datasets are provided by Acworth et al. (2009).

RESULTS AND DISCUSSION

Geology and Hydrogeology

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 (up to 8 m thick) overlying the weathered granite in the mid to lower areas of the site. To the east of the creek an extensive development of a red podsollic 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.

Subsurface conditions were described by EM31 mapping, resistivity cross-sections (Fig. 3), stratigraphic logs from bores and test pits and geophysical bore logs as shown in Fig. 4 (natural gamma and bulk electrical conductivity). 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 ~2m below surface, and in October 2003 were recorded above the surface indicating a potential upwards flow gradient from fractured granite into clayey sediments. Water levels have been monitored in all bores on an hourly basis. The reduced levels for the deep and shallow bores at site 2 are shown in Fig. 5. 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 indicated a very low hydraulic conductivity, as indicated by the very long recovery time required to return to the regional trend. There is a lateral hydraulic gradient of ~8 m over a distance of ~400 m (dh/dL 0.02) to drive groundwater flow through the fractured granite.

A scaled cross-section showing groundwater levels relative to geology and intake intervals is shown in Fig. 6. 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 was 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 downwards 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 \times 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.

Hydrochemistry and Isotopes

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 (δO^{18} and δH^2 , 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. 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, but there was no consistent spatial trend with freshening observed at some sites.

Groundwater in fractured granite was a significant source of Mg, Mn and Sr, but could not account for saline groundwater, or NaCl type groundwater. Groundwater pH averaged 7.2, with significant spatial variation from pH 5.8 to 8.5 at fractured granite sites only ~100 m apart. Groundwater was oxidising (Eh-NHE ~300 mV average) and field spectrophotometer analysis indicated very low Fe^{2+} , and S^{2-} below detection limit. A piper diagram shows distinct hydrochemical types for deep and shallow groundwater and an evolution along deep groundwater flow paths (Fig. 7). Although there was evidence for geochemical reactions along groundwater flow paths within sediments and rock, some sites within fractured granite appeared to be isolated from flow.

Groundwater was of meteoric origin (δO^{18} and δH^2 values similar to average local rainfall) with no evidence of evaporative concentration (Figs. 8 and 9). Studies are continuing to determine whether or not significant differences in recharge can be identified between the pasture and forested areas, and how salt fluxes may impact on stream loads in the future.

Salinisation of groundwater

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. Spatial variability in groundwater chemistry was of greater significance than changes over time.

Groundwater salinity was attributed to dissolution of salts from localised areas of saline clay. A 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 10). 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. It is possible that Na is gained (bores 1S, 2S, 2D, 3S, 4D, 7S, 7D, 8D) due to weathering of mineral such as albite (sodic plagioclase) in granite. 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. These observations are 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. 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 reflect 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 1). There was no correlation between high groundwater salinity and thicker clay overburden or depth to hard granite. There was no significant correlation between high groundwater salinity and the peak bulk salinity measured by bore logging (EM39).

The highest correlation (limited r^2 of 0.24) occurred for the EM31, although even this low r^2 value would suggest it is not the primary factor related to groundwater salinity. However, it is clear that it is the presence of saline clay, not clay deposits per se, that is related to high groundwater salinity. 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.

Evidence of recharge

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, a 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 (BE) 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). For example, the BE of groundwater level response in bores 2S and 2D was 0.35 and 0.98 respectively, after correction for the effects of earth tide (Fig. 5 inset). Unconfined conditions can be defined by the observation that atmospheric pressure impacts directly on the watertable surface. The presence of a BE response ($BE>0$) can then be used to indicate partially confined conditions in the aquifer at bore 2S and fully confined conditions at bore 2D, meaning

that recharge cannot occur. It is of interest that a BE of 0.99 was observed for Site 5 with fractured rock at the surface and a relatively fresh groundwater salinity that may have otherwise suggested recharge in this area. There is insufficient discrimination in stable isotope data to determine whether the freshening may instead be due to upwards movement of groundwater from deeper fractured granite.

Table 1. Possible factors related to groundwater salinity

Bore ID	Landuse	Groundwater EC in 2008 (mS/cm)	Depth to hard granite (m)	Thickness of clay (m)	EM39 max (mS/m)	EM39 max dpth (m bg)	EM31 [^] Approx. (mS/m)
2S	forest	6.79	6	4.9	170 [#]	4.2 [#]	30
2D	forest	2.95	6	4.9			30
3S	forest	3.49	12.5	6	180	4	20
3D	forest	4.41	12.5	6			20
5D	forest	4.01	0.5	0	-	-	50
6D	forest	5.82	10.5	2	70	2	120
10D	forest	7.38	10	2.5	60	4	60
11D	forest	5.08	1.8	-	-	-	100
12D	forest	5.37	2	-	-	-	30
1D	pasture	3.75	4	1.3	80	2	30
4D	pasture	3.67	4	1.5	180	1	20
7D	pasture	3.79	6	3	100	3	25
8S	pasture	9.67	8	4	240	3	25
8D	pasture	3.17	8	4			25
9D	pasture	6.28	4.5	2	270	3	35
Correlation with groundwater salinity r^2			-0.014	<<0.01	0.14	0.13	0.24*

*without three shallow sites [#]See Fig. 4 [^]See Fig. 3

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 stabilised 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.

Acknowledgements

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REFERENCES

- Acworth RI, Timms WA, Bernadi T (2009). Hydrogeological study of the Baldry Site. University of New South Wales Water Research Laboratory Research Report No. 235. April, 2009.
- Acworth, RI (1999). Investigation of dryland salinity using the electrical image method. *Australian Journal of Soil Research*, 37(4):623–636.
- Acworth RI and T. Brain (2008) Calculation of barometric efficiency in shallow piezometers using water levels, atmospheric and earth tide data. *Hydrogeology Journal*, 16: 1469–1481.
- Rančić, A, Salas G, Kathuria A, Acworth I, Johnston W, Smithson A, and Beal G. (2009). Climatic influences on shallow fractured-rock groundwater system in the Murray-Darling Basin. Technical report, Department of Environment and Climate Change, NSW, ISBN 9781 1 74122 8717.

Fig. 1 Location of the Baldry site in Macquarie catchment of the Murray-Darling Basin

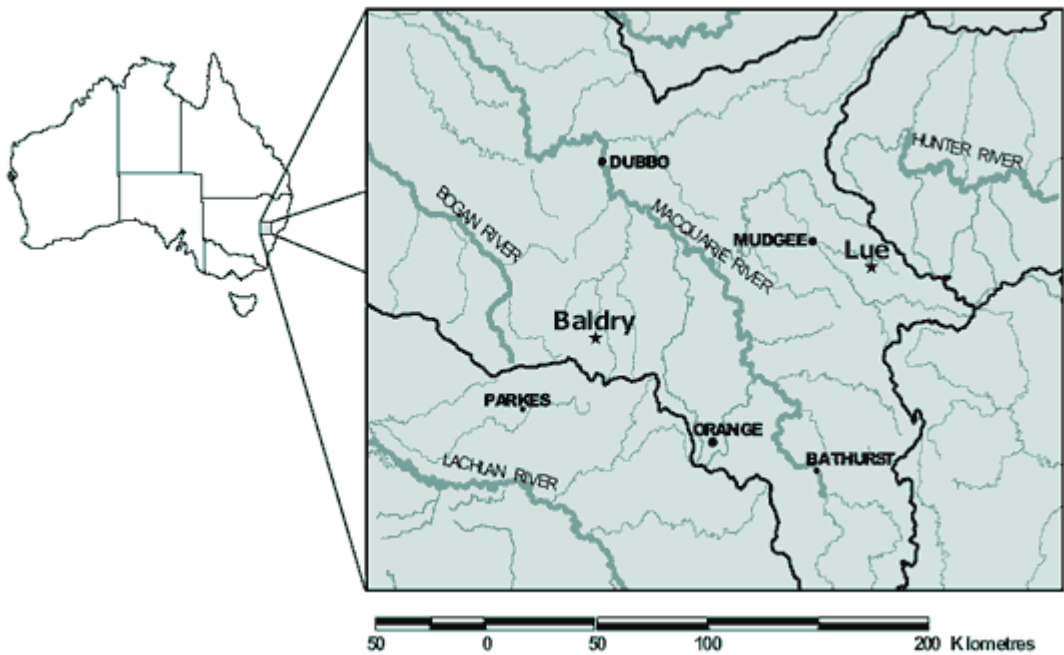


Fig. 2 Bores and piezometers at the Baldry site

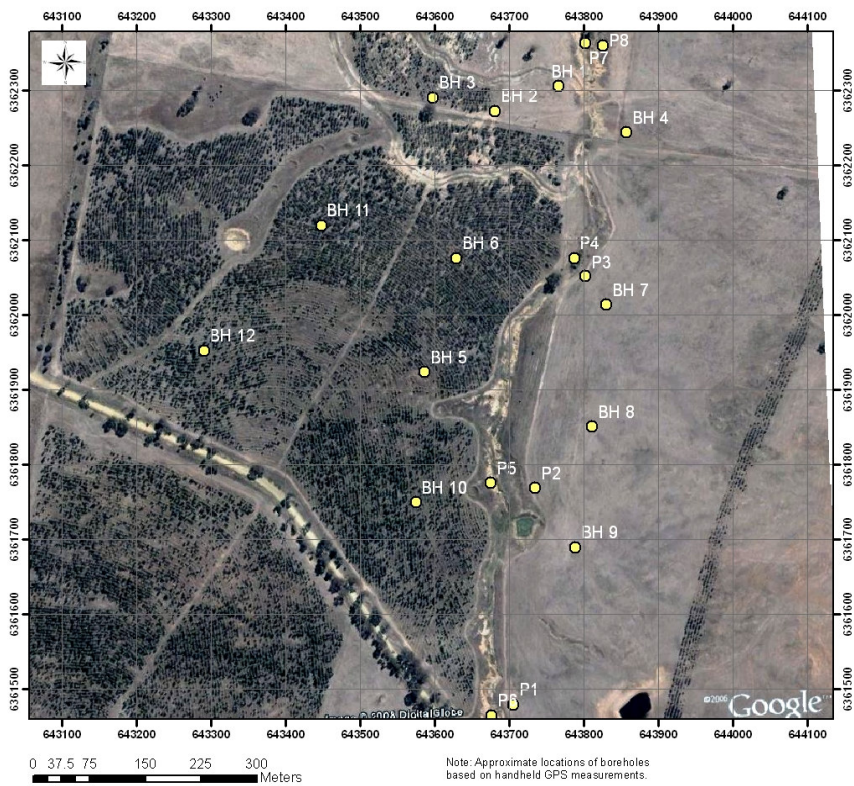


Fig. 3 Example of resistivity image through Sites 2, 3 and 4

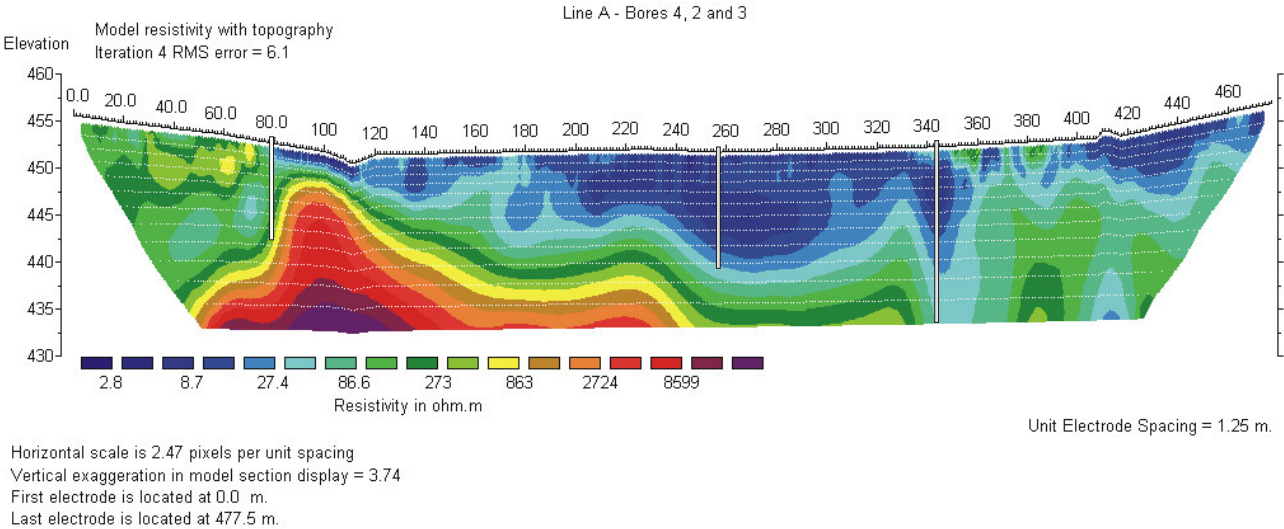


Fig. 4 Example of stratigraphic log and downhole geophysical logs for Site 2.

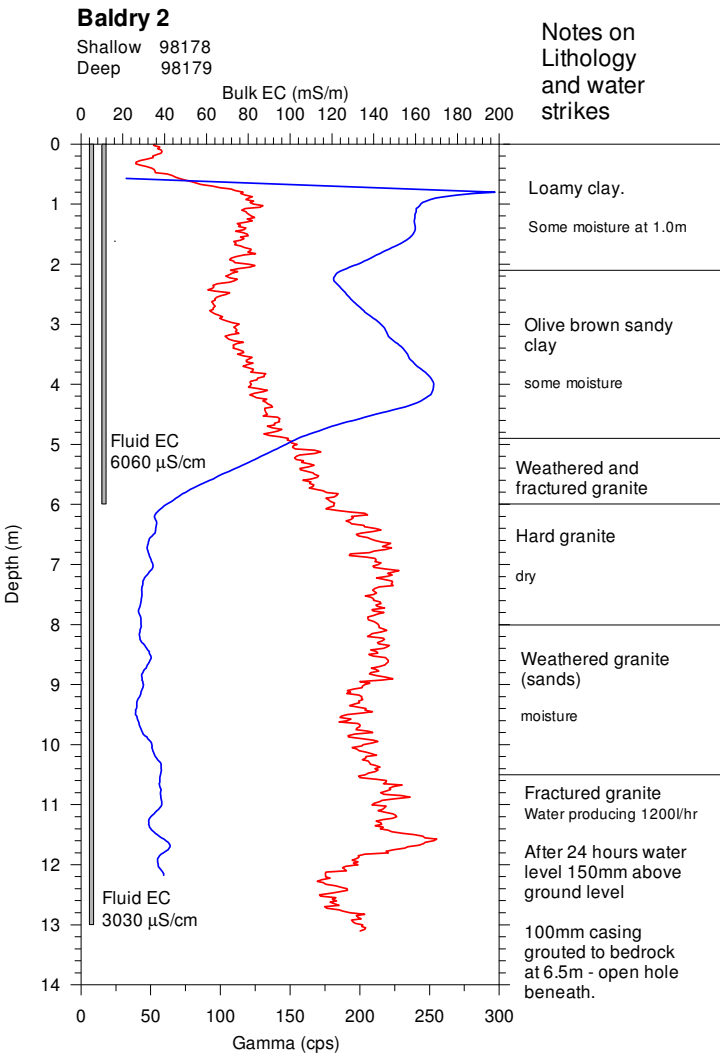


Fig. 5 Shallow and deep water levels (hourly data) and rainfall for Site 2. Insets show barometric pressure calculation .

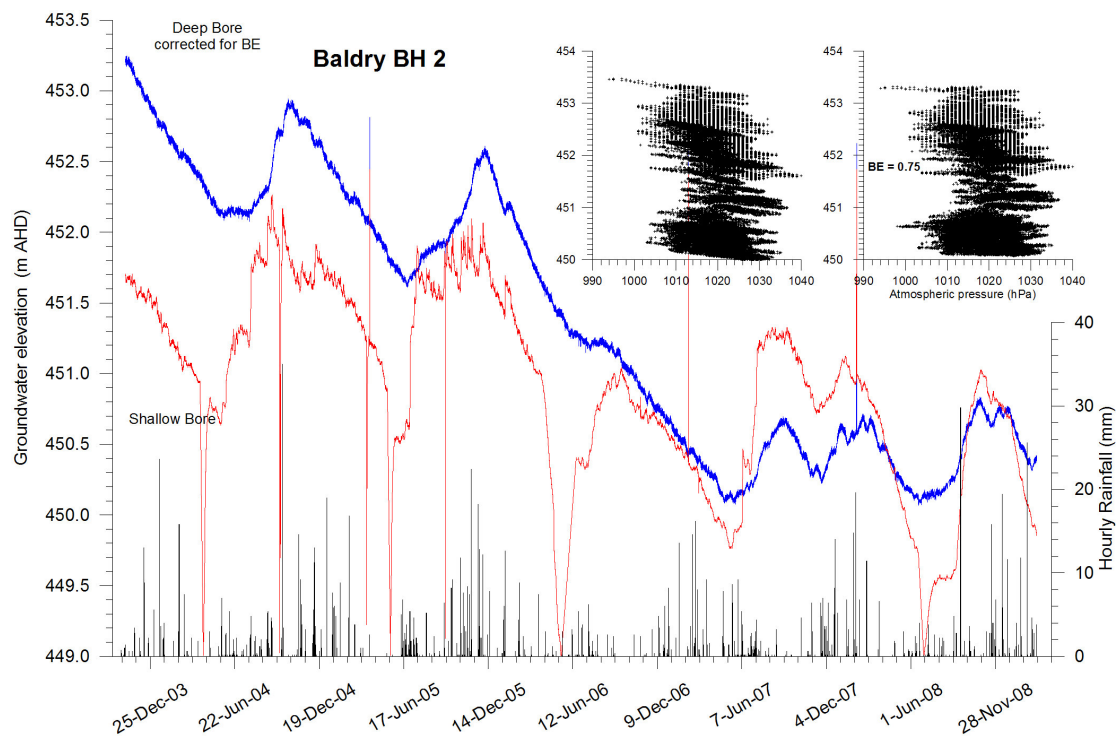


Fig. 6 Cross sections showing groundwater conditions at Baldry, June 2008.

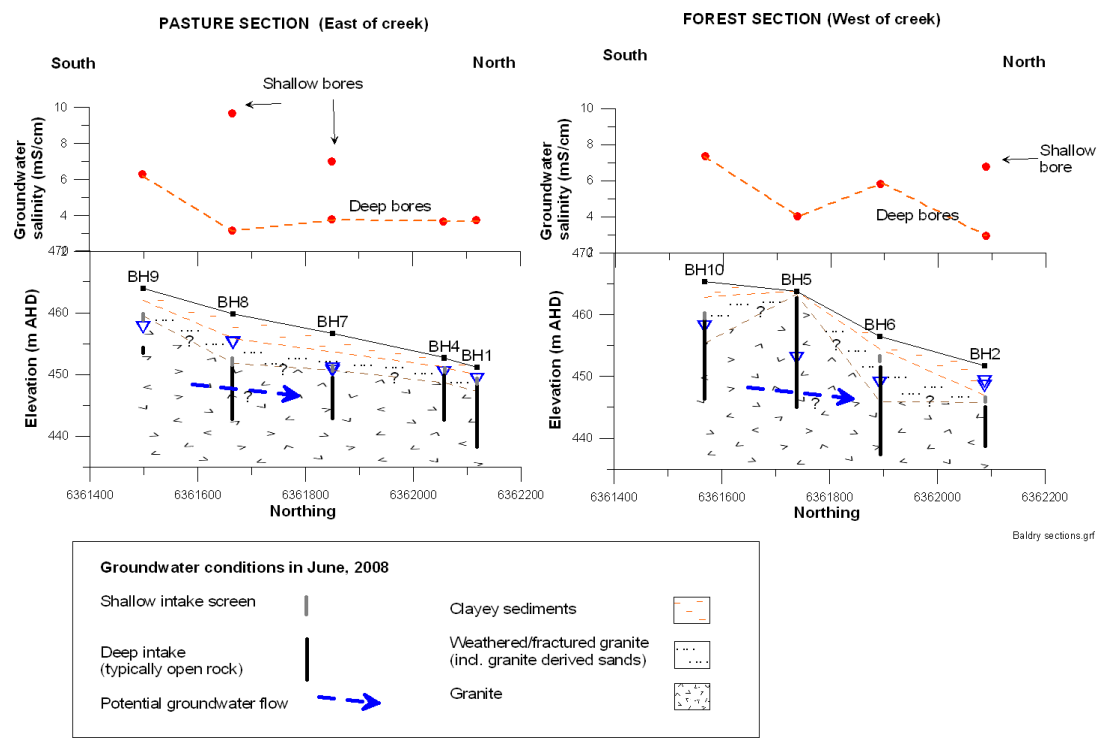


Fig. 7 Piper diagram showing geochemical relationships of deep groundwater

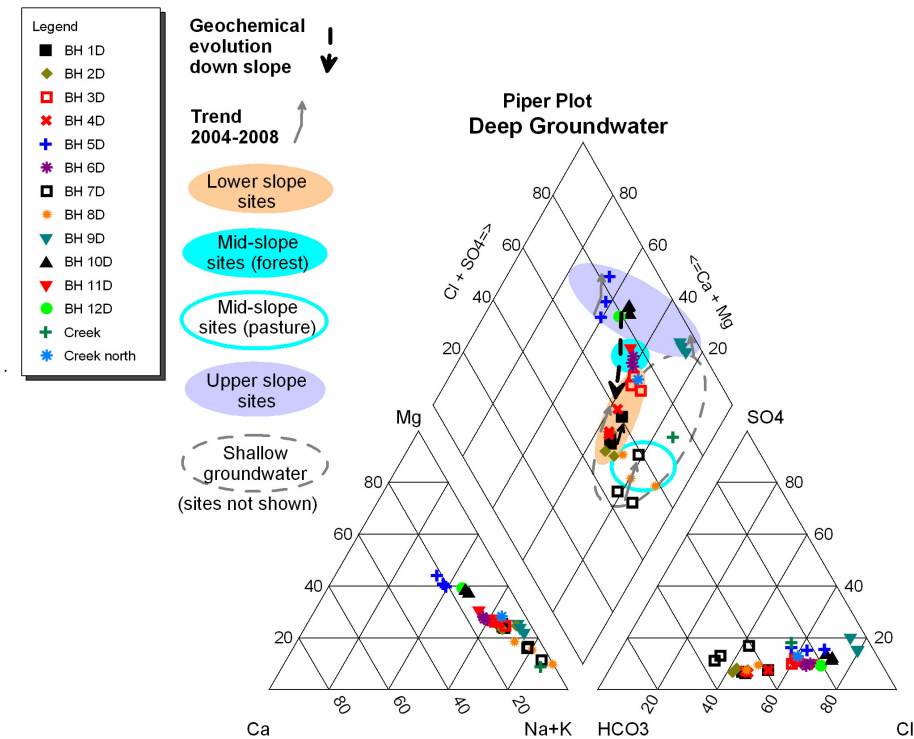


Fig. 8 Oxygen-18 and deuterium data - groundwater relative to Baldry rainfall and Local Meteoric Water Line (LMWL)

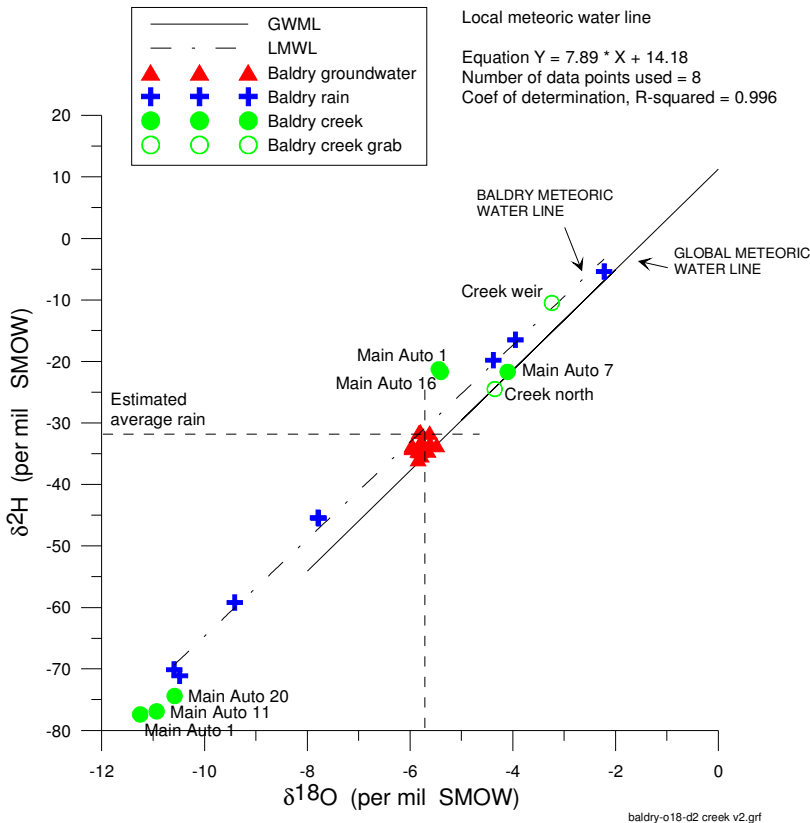


Fig. 9 Oxygen-18 and deuterium isotope values compared with groundwater salinity

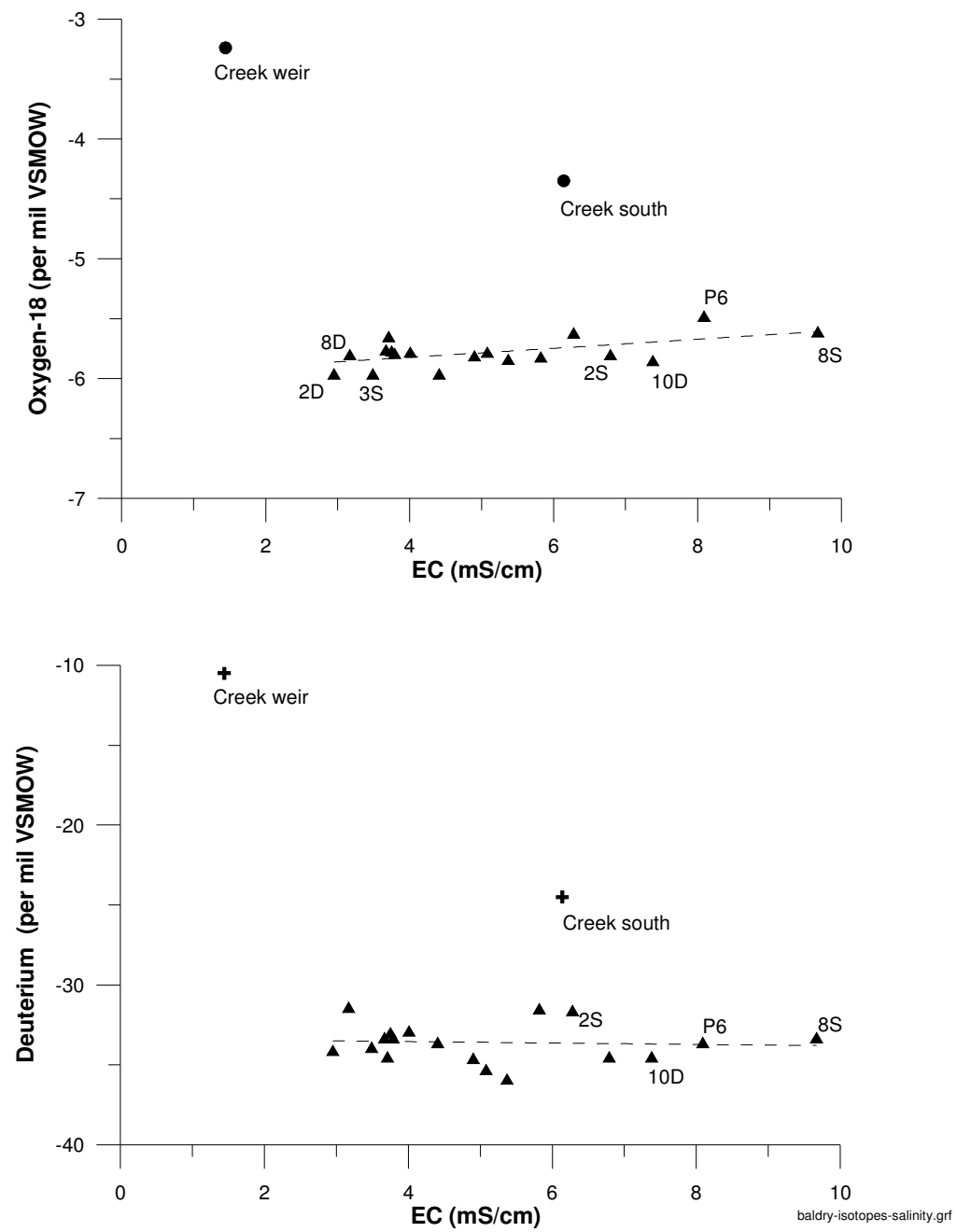


Fig. 10 Relationships between Na, Cl concentrations and Total Dissolved Salts.

