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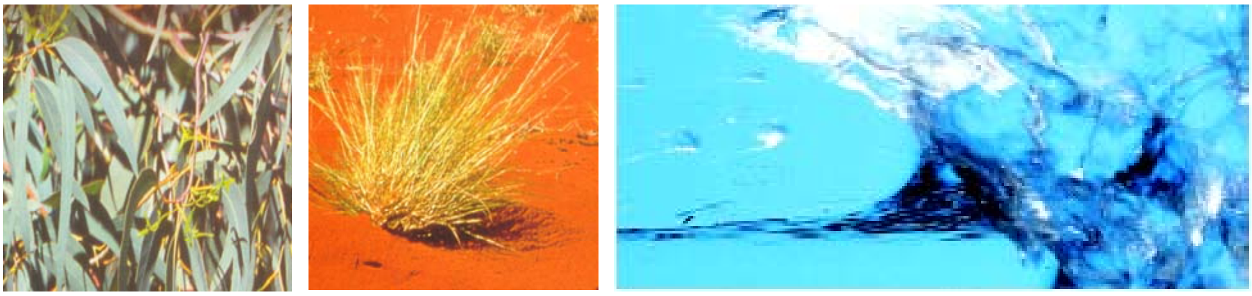

# Investigation into the precipitation of Al-hydroxide during pumping of bores at Bookpurnong (Western's Highland Site) in relation to groundwater quality in the Loxton Sands Aquifer

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Report DWLBC 2004/40

Government
of South Australia

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# FOREWORD

South Australia's natural resources are fundamental to the economic and social well-being of the State. One of the State's most precious natural resources, water is a basic requirement of all living organisms and is one of the essential elements ensuring biological diversity of life at all levels. In pristine or undeveloped situations, the condition of water resources reflects the equilibrium between, rainfall, vegetation and other physical parameters. Development of these resources changes the natural balance and may cause degradation. If degradation is small, and the resource retains its utility, the community may assess these changes as being acceptable. However, significant stress will impact on the ability of the resource to continue to meet the needs of users and the environment. Understanding the cause and effect relationship between the various atresses imposed on the natural resources is paramount to developing effective management strategies. Reports of investigations into the availability and quality of water supplies throughout the State aim to build upon the existing knowledge base enabling the community to make informed decisions concerning the future management of the natural resources thus ensuring conservation of biological diversity.

**Bryan Harris**

*Director, Knowledge and Information Division*

*Department of Water, Land and Biodiversity Conservation*

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# SI UNITS COMMONLY USED WITHIN TEXT

| Name of unit | Symbol | Definition in terms of other metric units | |
|---|---|---|---|
| Millimetre | mm | $10^{-3}$ m | length |
| Metre | m | | length |
| Kilometre | km | $10^{3}$ m | length |
| Hectare | ha | $10^{4}$ $m^{2}$ | area |
| Microlitre | µL | $10^{-9}$ $m^{3}$ | volume |
| Millilitre | mL | $10^{-6}$ $m^{3}$ | volume |
| Litre | L | $10^{-3}$ $m^{3}$ | volume |
| Kilolitre | kL | 1 $m^{3}$ | volume |
| Megalitre | ML | $10^{3}$ $m^{3}$ | volume |
| Gigalitres | GL | $10^{6}$ $m^{3}$ | volume |
| Microgram | µg | $10^{-6}$ g | mass |
| Milligram | mg | $10^{-3}$ g | mass |
| Gram | g | | mass |
| Kilogram | kg | $10^{3}$ g | Mass |

# Abbreviations Commonly Used Within Text

| Abbreviation | | Name | Units of measure |
|---|---|---|---|
| AHD | = | Australian Height Datum | |
| TDS | = | Total Dissolved Solids *(milligrams per litre)* | mg/L |
| EC | = | Electrical Conductivity *(micro Siemens per centimetre)* | µS/cm |
| pH | = | Acidity | |
| | | | |
| $\delta D$ | = | Hydrogen isotope composition | **$^{o}/_{oo}$** |
| CFC | = | Chlorofluorocarbon *(parts per trillion volume)* | pptv |
| $\delta^{18}O$ | = | Oxygen isotope composition | **$^{o}/_{oo}$** |
| $^{14}C$ | = | Carbon-14 isotope *(percent modern Carbon)* | pmC |
| | | | |
| Ppm | = | Parts per million | |
| Ppb | = | Parts per billion | |

# EXECUTIVE SUMMARY

## Statement of the Problem

Clogging of pump impellers and delivery hoses with an amorphous white precipitate has been observed during aquifer tests on the Loxton Sands trial salt interception production bore BHP1, at Western's highland in the Bookpurnong region. This clogging caused a decline in the pumping rate from 4.4 L/s to 2.7 L/s over the duration of a 7-day pump test (AWE, 2002). The formation of the precipitate was accompanied by the discharge of unusually low pH (< 5.5) groundwater from the delivery hose. Chemical and mineralogical analyses of the precipitate revealed that it comprised predominantly aluminium-oxyhydroxide with trace amounts of Al-silicate and some Ca and Mg (AWE, 2002, 2003a).

The objective of the current study was to determine (1) the hydrogeochemical conditions and processes leading to the formation of the aluminium precipitate, and (2) whether this occurs on a regional scale, as this could cause significant problems for the highland salt interception scheme planned for the region. At commencement of the study, the aluminium precipitate and low pH groundwater had not been observed at observation well BHO1ls, located 30 m away from BHP1 and screened over approximately the same interval. Hence, the precipitate was believed to be restricted to the immediate vicinity of BHP1, although such localization of a phenomenon like this would be unusual.

## Aluminium and Iron Mobilisation and Precipitation

Water quality versus depth profiles of the production bore, BHP1, showed that low pH (< 5) groundwater, which can allow aluminium to occur as a dissolved phase, occurs in the Upper Loxton Sands (ULS; above 44 m depth). In contrast, the pH in the Lower Loxton Sands (LLS) is between 5 and 6.5. These pH values correspond to EC values of 45 mS/cm in the ULS and 95 mS/cm in the LLS. Discrete sampling of groundwater from the ULS and LLS confirmed that high aluminium concentrations (25 mg/L) coincide with the low pH groundwater in the ULS at BHP1.

Results of the series of pump tests conducted at Western's Highland suggest that two threshold pH values govern the formation of the aluminium precipitate on pumping from the ULS. $Al^{3+}$ is most likely to be present in the ULS as an exchange phase on aquifer minerals or organic matter. Changes in groundwater pH can then cause the release of this $Al^{3+}$ from exchange sites. Further studies would be required to confirm this. The exact values of the pH thresholds would therefore depend on the aquifer minerals present as well as the transient pH and $Al^{3+}$ concentrations that occur as the reactions proceed, being approximately as follows:

1) At pH < 5.5 $Al^{3+}$ is released from exchange sites on various aquifer minerals or organic matter.

2) At pH < 4.5 $Al^{3+}$ can remain dissolved in groundwater.

If the groundwater pH is originally reduced below 4.5, $Al^{3+}$ would be released into solution. However, it would only precipitate as Al-hydroxide if the pH is then increased above this value, for example by mixing with a higher pH groundwater. However, if the groundwater pH is only reduced to between 4.5 and 5.5, $Al^{3+}$ will still be released from exchange sites, but will begin to precipitate out of solution immediately in the form of Al-hydroxide. Results of the pump tests on BHP1, BHO1ls and BHP6 suggest that the magnitude of the decrease in groundwater pH, and, in fact, of the amount of precipitate formed, may be proportional to the rate at which the bore is pumped.

The conclusions of this study are that the most likely mechanism for the lowering of groundwater pH in the ULS around BHP1 is the oxidation of ferrous iron ($Fe^{2+}$). Oxygenation of previously anoxic groundwater can occur as a result of drawdown and turbulent flow around a well caused by high pumping rates (> 2 L/s), such as those imposed during the pump tests. Dissolved $Fe^{2+}$ is then oxidised to $Fe^{3+}$, which is precipitated as Fe-oxide, presumably around the well and in the surrounding aquifer. The overall reaction produces acidic conditions within the aquifer. The presence of large amounts of dissolved $Fe^{2+}$ in the ULS in the Loxton-Bookpurnong region is suggested by high degrees of ferruginization observed in the ULS. The measurement of negligible concentrations of $Fe^{2+}$ in the ULS groundwater at BHP1 may be the result of removal by precipitation as Fe-oxide during pumping. Pumping of the nearby observation well, BHO1ls at $\approx 1$ L/s produced low pH groundwater, with high dissolved Al concentrations and negligible Fe concentrations in the ULS, as well as the white precipitate in the discharge water after approximately 6 hours of pumping. Prior to the pump test, this borehole had only been pumped at < 0.2 L/s and groundwater in the ULS had a pH of approximately 6 (similar to that of the LLS), with high $Fe^{2+}$ and negligible $Al^{3+}$ concentrations.

## Scale of the Problem

The following natural conditions are required for the formation of the Al-precipitate:

1) High dissolved $Fe^{2+}$ concentrations (e.g. $\geq 25$ mg/L).

2) Low concentrations of buffering species (i.e. alkalinity), allowing pH to drop below approximately 5.5.

3) Aluminium in some available form (e.g. sorbed to minerals or organic matter).

Although such high groundwater $Fe^{2+}$ concentrations have not been observed anywhere else in the Loxton-Bookpurnong region, few bores known to be screened in the Upper Loxton Sands have been available for sampling. The high degree of ferruginization of the ULS suggests that there is potential for large amounts of dissolved $Fe^{2+}$ in this aquifer throughout the area. Condition 1 should therefore be considered to be satisfied throughout the region, particularly in the ULS, in the absence of further data to refute this. As $Al^{3+}$ is a weathering product of silicate minerals, it is ubiquitous in the natural environment. However, it is only mobile at low pH (< approx. 4.5). Condition 3 could therefore also be considered to be satisfied throughout the region.

The potential for the Al precipitate to occur at any given location therefore depends on Condition 2 being satisfied. This occurs at Western's Highland due to the low initial pH of 6 and low alkalinity of the ambient ULS groundwater and the lack of any carbonate material in the sediments to buffer the decrease in acidity. In areas with high ambient groundwater pH and alkalinity, for example where irrigation water, carbonate aquifer material or both are present, even if $Fe^{2+}$ oxidation occurs, the resulting drop in pH will probably not be great enough mobilize $Al^{3+}$. The regional geochemical sampling program has shown that the Loxton Sands groundwaters in the Loxton-Bookpurnong region generally have pHs >7 and alkalinity >4 mEq/L. However, conditions similar to those at Western's Highland (i.e. pH <7 and alkalinity <4 mEq/L) have been observed in piezometer IA3 and bore EES4 in the Bookpurnong region. Additional down-hole water quality profiles have also identified a low groundwater pH of 5 in piezometer IA2, which may be due to reducing conditions in the well, but does indicate a lack of buffering against acidity production at that location. Water quality profiles at EES1, EES2, EES6, BKP1, BKP2, BHP2 and BHP3 indicated groundwater pHs between 7 and 8.5. These results suggest that the potential for the Al precipitate to occur in the Bookpurnong region may be limited to the north and east of the groundwater mound (i.e. north of EES2 and east of EES2 and BKP1). A lack of data in that region prevents the risk area from being more clearly defined than this.

In the Loxton region, bores L22, L24A and L14, to the east of the groundwater mound, are the only Loxton Sands bores observed to intersect groundwater with pH values below 7. However the groundwater alkalinities at these locations are greater than 10 mEq/L suggesting that this area represents only a minor risk of Al-hydroxide precipitation. The floodplain Monoman Formation observation well LFO3A to the north of Loxton has a comparatively low groundwater pH of 6.6 and a relatively low alkalinity of 4.8 mEq/L, conditions representative of a mild risk for the formation of the Al-hydroxide precipitate.

## *Recommendations*

If it is necessary to pump from the ULS in areas where the Al-hydroxide precipitate is likely to occur, a potential management approach may be to ensure that the groundwater pH is lower than approximately 4.5 and prevent mixing between this water and water with a higher pH in areas where the Al precipitate would cause clogging. However, as the reactions discussed above have not been observed over time scales greater than a week, this would not be recommended until further study is carried out. The best approach would be to avoid installing production bores in identified high risk areas unless preliminary testing for the occurrence of the precipitate has been carried out. As a cautious approach, it is recommended that such testing be carried out at all locations of proposed Loxton Sands borefields.

Pumping from the LLS only may be an alternative option in areas where the Al precipitate is produced from the ULS. However, mixing with substantial amounts of ULS groundwater must be prevented and the long-term effects of this approach have also not been adequately assessed. The presence of abundant shell fragments and carbonate material in the LLS appears to maintain generally high alkalinities, which can buffer any production of acidity. However, complete dissolution of this material over long time scales may, for example, allow pHs to drop below the threshold of approximately 5.5 in the future and allow the onset of Al-hydroxide precipitation.

The conditions identified through this study to be required for the onset of the aluminium hydroxide precipitate at Bookpurnong are known to, and could easily, exist in many other parts of the Murray Basin. A cursory review of Loxton Sands obswell data in the region surrounding Loxton has identified bores with groundwater pH <6.5. Low pH groundwaters in the Upper Loxton-Parilla Sand have been identified in Victoria and attributed to $Fe^{2+}$ oxidation (Macumber, 1991), and a similar amorphous white precipitate has been observed to occur under similar hydrogeochemical conditions in the Mineral Reserve Basin on the floodplain of the Avoca River in Victoria (McLaughlan et al., 1993). This highlights the potential for aluminium clogging to occur in other regions of the Murray Basin and that it should be considered during any preliminary investigations for proposed future groundwater pumping schemes in the Murray Basin.

# 1 INTRODUCTION

## 1.1 Background and Objectives

During a 7-day aquifer test conducted on the Loxton Sands trial salt interception production bore BHP1, at Western's highland in the Bookpurnong region, it was observed that the pump impeller and delivery hoses became clogged with a white precipitate (AWE, 2002). This precipitate caused a decline in the pumping rate from 4.4 L/s to 2.7 L/s over the duration of the test. Chemical analysis of the precipitate revealed that it contained a very high concentration of Al, with lesser amounts of Ca and Mg (AWE, 2002). Subsequent XRD analysis suggested that it is predominantly Al-oxyhydroxide with trace amounts of Al-silicate (AWE, 2003a). A 7-day chlorination trial on the bore failed to prevent the onset of the white precipitate (AWE, 2003a), eliminating the possibility that it is biologically produced. Observation of the soil core from the Western's Highland site and the results of the two 7-day tests led to the hypothesis that the precipitate may be caused by mixing between two different water types in the bore, i.e. water from the Upper and Lower Loxton Sands.

If the hydrogeochemical conditions leading to clogging of pumps and delivery pipes with a precipitate such as that observed at BHP1 occur on a regional scale at Bookpurnong, this could cause significant problems for the highland salt interception scheme planned for the region. The objectives of the following study were therefore to determine:

- The hydrogeochemical conditions (geological setting, chemical composition of aquifer material and ambient groundwater) and processes leading to the formation of the white precipitate.
- Whether these hydrochemical conditions occur on a regional scale in the Loxton Sands or are localized at BHP1.

## 1.2 Site Description

The production bore, BHP1, is located on Brian Western's property, upstream from River Murray Lock 4 in the Bookpurnong Irrigation District (Fig. 1). There is no floodplain between the cliff and the river at this location, and the water table is well above river level due to the occurrence of irrigation inland of the site. Both of these factors have made the Western's Highland site a desirable location for a borefield designed to intercept saline groundwater as it flows from the centre of the Bookpurnong Groundwater Mound towards the River Murray. Figure 2 shows the local hydrogeology. The predominantly coarse-grained sands of the Upper Loxton Sands (ULS) are by far the best target aquifer for saline groundwater interception. However, the saturated thickness of this aquifer is only 6 m at Western's highland, diminishing southward towards Loxton, where it is unsaturated. This limited saturated thickness makes it desirable to screen production bores across both the Upper and Lower Loxton Sands (LLS) despite the significantly smaller grain size and poorer aquifer properties of the latter. Hence, BHP1 is screened across approximately 6 m of saturated ULS and 10 m of the LLS.

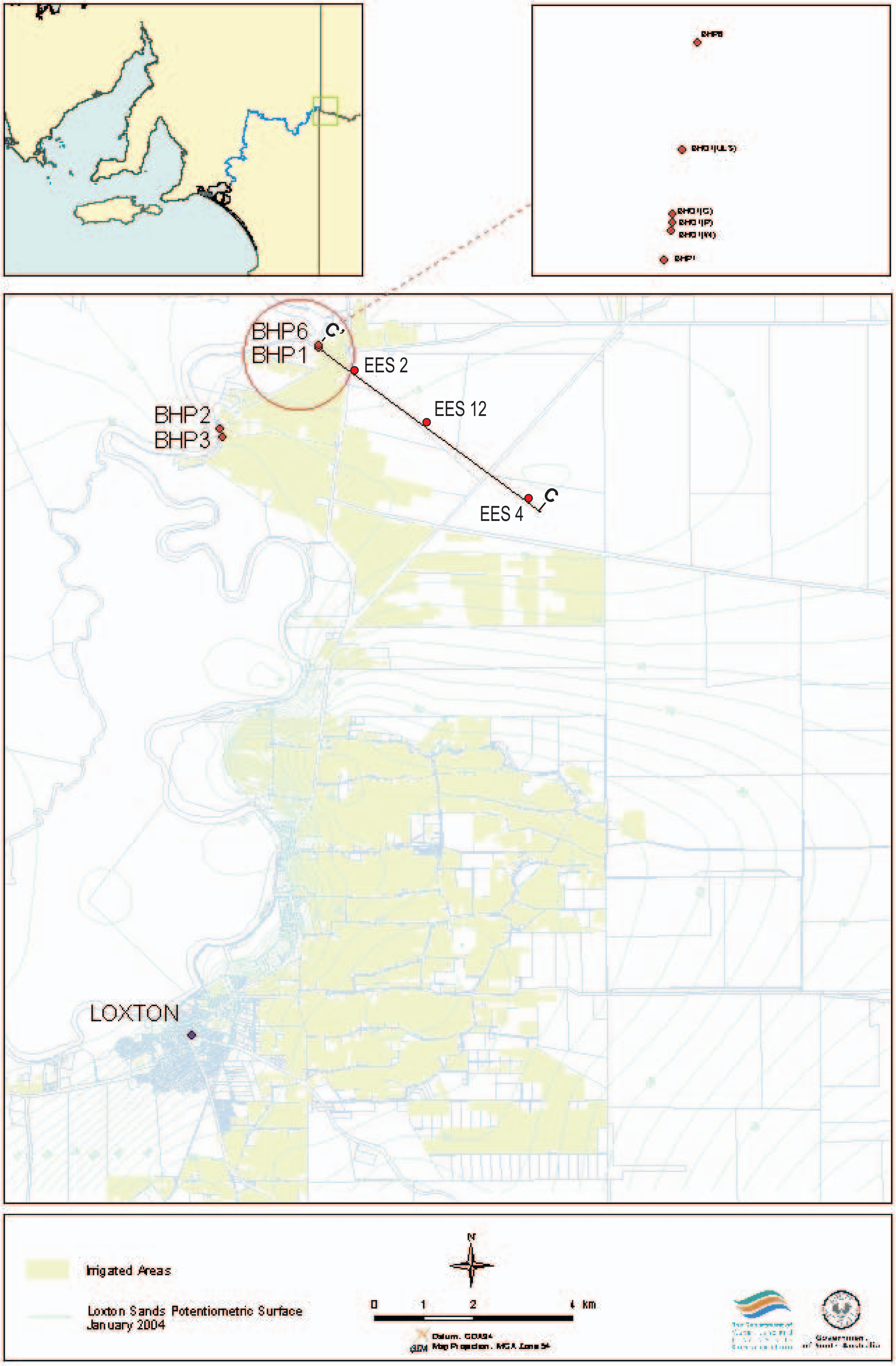

**Figure 1:** Loxton - Bookpurnong area site map, showing locations of bores on Western's Property (inset) and the location of Transect AA'.

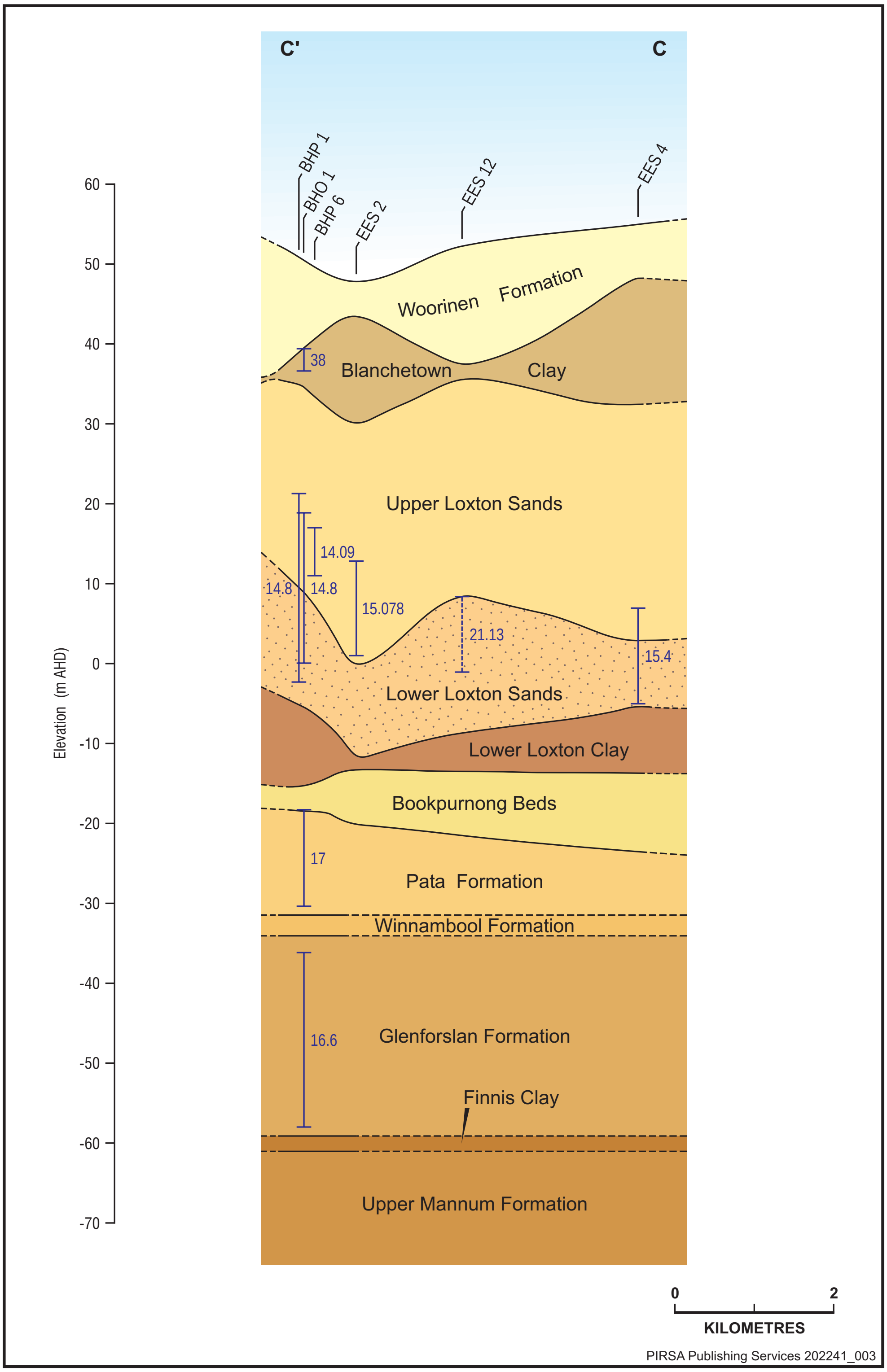

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**Figure 2. Bookpurnong cross section, showing screened intervals of bores (including BHP6), fresh water hydraulic heads and TDS values adjacent the screens.**

A nest of observation wells is located adjacent production bore BHP1, with screens in the ULS/LLS, Pata Limestone and Glenforslan Formation, as well as in a perched aquifer in the surficial Woorinen Formation (BHO1ls, BHO1P, BHO1G and BHO1W respectively; Fig. 2). Figure 2 shows that observation well BHO1ls, located approximately 30 m away from BHP1, screens approximately the same saturated interval of Loxton Sands.

## *1.3 Review of Previous Work at BHP1*

AWE (2002) provides the details of the original bore development and the 7-day pump test carried out on BHP1. AWE (2003a and b) describes the subsequent chlorination trial and 22-hour packer test carried out on the bore using a single packer to pack off the LLS and limit flow to that from the ULS. The relevant observations and results from each of these tests are discussed below.

### 1.3.1 BORE DEVELOPMENT (AWE, 2002)

Subsequent to drilling and installation, BHP1 was airlifted for approximately 6 hours. Major ion compositions of water samples collected from BHP1 and the adjacent Loxton Sands observation well BHO1ls during airlifting were quite different, despite their proximity to each other and their similar screened intervals (Table 1). The overall salinity of groundwater airlifted from the production bore was approximately twice that from the observation well. Other notable differences were the much higher Al concentration at BHO1ls (7.74 mg/L) than that at BHP1 (0.6 mg/L), as well as the higher $NO_2$+$NO_3$ (0.018 mg/L (as N) at BHO1ls compared with <0.005 mg/L (as N) at BHP1) (Table 2). The white precipitate was not observed during development of either bore. pHs measured in the laboratory were 7.1 and 7.6 for BHO1ls and BHP1 respectively (Table 2).

### 1.3.2 7-DAY PUMP TEST (AWE, 2002)

During the 7-day pump test of BHP1, a pump was set at 53 m below ground level (9 m below the ULS/LLS boundary), with approximately 15 m of water above the pump. The flow rate was set at 4.3 L/s. The following observations were made:

- A decline in flow rate commenced within several hours of starting the test and continued steadily throughout the test, with the final flow rate being 2.7 L/s.
- The decline was caused by clogging of the pump impellers by a white, gel-like precipitate.
- The drawdown in the production bore during pumping was approximately 5 m (i.e. the water table was drawn down to the base of the Upper Loxton Sand).
- There was no decline in the head of water over the pump following the initial drawdown.
- The maximum drawdown in the Loxton Sands observation well 28 m away (BHO1ls) was 30 cm.

**Table 1.** **Construction details and standing water levels (SWLs) for the bores and piezometers located at Western's Highland, as well as other Bookpurnong production bores, BHP2 and BHP3.**

| | **BHP1** | **BHO1ls** | **BHP6** | **BHO1W** | **BHO1P** | **BHO1G** | **BHP2** | **BHP3** |
|---|---|---|---|---|---|---|---|---|
| **Location** | **Western's Highland** | | | | | | **Near Lock 4** | |
| **Aquifer*** | **ULS / LLS** | | **ULS** | **Woorinen** | **Pata** | **GF** | **ULS/LLShells** | |
| **Ground Elev.** (m AHD) | 51.97 | 51.72 | 51.41 | 51.86 | 51.76 | 51.82 | 27.97 | 32.83 |
| **Total Depth** (m) | 62 | 53.34 | 40.4 | 15.21 | 85.0 | 111.15 | 25.5 | 28.0 |
| **Screened Interval** (m bgl**) | 30.5–54.5 | 36.0–54.0 | 34.4–40.4 | 12.0–15.0 | 73.0–85.0 | | 11.5–23.5 | 20.1–26.1 |
| **SWL** (m bgl*) | 38.1 | 38.71 | 37.58 | 13.86 | 36.41 | 35.17 | 14.6 | 20.3 |
| **SWL** (m AHD) | 13.80 | 13.77 | 13.84 | 38.0 | 15.36 | 16.64 | 13.93 | 12.52 |
| **Diameter** (mm) | 177 | 80 | 175 | 80 | 80 | 125 | 200 | 175 |

* ULS = Upper Loxton Sands, LLS = Lower Loxton Sands, GF = Glenforslan Formation, LLShells = Lower Loxton Shells

** m bgl = metres below ground level

**Table 2.** **Comparison of chemical compositions of groundwater sampled from various depths at BHP1 and BHO1ls at various times and under various pumping conditions.**

| | | | | | | | | | | | | | **BHOls Pump test** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Test** | | **Bore Development** | | **7-day test** | **overnight** | **chlorination** | **packer test** | **DWLBC GW Sampling** | | **BHP1 Discrete Sampling** | | | **Pre-pump** | | **Discharge** | | **Post-pump** | |
| **Bore** | | **BHP1** | **BHO1ls** | **BHP1** | **BHP1** | **BHP1** | **BHP1** | **BHP1** | **BHO1ls** | **BHP1** | **BHP1** | **BHP1** | **BHO1ls** | **BHO1ls** | **BHO1ls** | **BHO1ls** | **BHO1ls** | **BHO1ls** |
| **Method** | | jetting | jetting | pump | pump | pump | pump | pump | pump | pump | gas bailer | gas bailer | gas bailer | gas bailer | pumped | pumped | gas bailer | gas bailer |
| **Aquifer** | | ULS/LLS | ULS/LLS | LLS | | | ULS | ULS | LLS | ULS | ULS | LLS | ULS | LLS | LLS | LLS | ULS | LLS |
| **Sample depth** | m | | | 53 | | | 40.5 | 45 | 51 | 40 | 40 | 50 | 40 | 50 | 50 | 50 | 40 | 50 |
| **Date** | | 21/03/2002 | 22/03/2002 | | | | 08/05/2003 | 23/07/2003 | 24/07/2003 | 25/09/2003 | 26/09/2003 | 26/09/2003 | 20/11/2003 | 20/11/2003 | 20/11/2003 | 20/11/2003 | 21/11/2003 | 21/11/2003 |
| **Pump Rate** | L/s | | | 2.7–4.3 | | | 1.15–1.25 | 0.06–0.1 | 0.2 | 0.22 | – | – | – | – | 1 | 1 | – | – |
| **pH** | | 7.1 | 7.6 | 5.7 | 5.4 | 5.4–5.8 | 4.6 | 6.4 | 6.5 | 4.1 | | | 6.6 | 7.1 | 6 | 6 | 5.1 | 6.2 |
| **EC** | mS/cm | 92.6 | 55.8 | 58.1 | 59.7 | 55–60 | | 64.3 | 65.9 | 40.1 | | | 39.4 | 88.7 | 69.3 | 68.5 | 53.9 | 95.1 |
| **TDS by calc.** | mg/L | 71 900 | 39 600 | 40 400 | | | 32 300 | 62 800 | 62 200 | 32 300 | 28 500 | 77 400 | 38 000 | 78 800 | 56 800 | 57 500 | 38 600 | 81 200 |
| **Ca** | mg/L | 528 | 326 | 249 | | | 161 | 372 | 401 | 142 | 117 | 470 | 200 | 512 | 337 | 331 | 195 | 541 |
| **Mg** | mg/L | 2 160 | 1 150 | 1 150 | | | 912 | 1 610 | 1 660 | 824 | 705 | 2 060 | 884 | 3 730 | 1 620 | 1 730 | 1 130 | 2 530 |
| **K** | mg/L | 312 | 169 | 191 | | | 177 | 267 | 281 | 169 | 154 | 318 | 182 | 357 | 265 | 260 | 189 | 387 |
| **Na** | mg/L | 23 200 | 12 700 | 12 500 | | | 9 950 | 19 400 | 18 600 | 9 960 | 8 840 | 23 300 | 18 100 | 22 300 | 18 000 | 19 200 | 12 900 | 28 800 |
| **Alk (as $HCO_3$)** | mg/L | 435 | 382 | 55 | | | 2 | 329 | 384 | 13.4* | 4.27* | 305* | 210 | 419 | 188 | 166 | 32 | 327 |
| **Cl** | mg/L | 36 600 | 20 300 | 21 600 | | | 17 700 | 32 100 | 31 700 | 17 000 | 15 100 | 39 500 | 15 300 | 35 600 | 29 700 | 28 500 | 20 300 | 37 800 |
| **SO4** | mg/L | 8 860 | 4 780 | 4 660 | | | 3 390 | 6 690 | 7 089 | 3 080 | 2 580 | 8 760 | 3 010 | 15 700 | 6 660 | 7 140 | 3 790 | 10 600 |
| **NO2/3 as N** | mg/L | <0.005 | 0.018 | 0.387 | | | 0.59 | 0.091 | 0.064 | 0.522 | 0.672 | 0.04 | – | – | | – | – | – |
| **$NH_3$ N** | mg/L | | | | | | | 0.235 | 0.269 | 0.012 | 0.079 | 0.465 | – | – | | – | – | – |
| **B** | mg/L | 3.56 | 1.68 | 2.09 | | | 2.75 | 3.09 | 3.01 | 2.57 | 2.47 | 4.8 | – | – | | – | – | – |
| **Si-Reactive** | mg/L | | | | | | | 14 | 15 | 28 | 29 | 10 | 14 | 11 | 20 | 20 | 29 | 11 |
| **Fe-total** | mg/L | 7.33 | | | | | | 2.49 | 4.27 | <0.3 | <0.3 | 0.382 | 25.9 | 4.02 | 2.59 | 2.31 | 4.08 | 3.93 |
| **Al-total** | mg/L | 0.6 | 7.74 | | 12.6 | | | <0.2 | 0.338 | 21.4 | 25.2 | <0.02 | <0.2 | <0.2 | 0.652 | 0.488 | 4.53 | <0.2 |

- Drawdowns in the Murray Group observation wells were less than 5 cm.
- Down-hole camera footage showed that significant clogging of the bore BHP1 was restricted to the bottom metre of the slotted interval (i.e. 53.5 m – 54.5 m).

The chemical composition of the groundwater sampled from the discharge hose at the end of the 7-day pump test was similar to that sampled during jetting of BHO1ls with the following notable exceptions (Table 2):

- The (laboratory measured) pH was much lower (5.7).
- [$HCO_3$] was much lower, presumably due to the lower pH.
- [$NO_2$+$NO_3$] was much higher (0.387 mg/L).

A 48 hour pump test was carried out a month after the 7-day pump test (cf. AWE, 2003a). A thin film of white residue was evident at the discharge point after 5 hours of pumping. This had developed into a thick white gelatinous sludge by the next morning. Groundwater sampled from the discharge point had a similar salinity and pH to the sample collected during the 7-day test (Table 2). The aluminium concentration of the sample was 12.6 mg/L, higher than those observed during jetting of both the observation well and the production bore (Table 2).

### 1.3.3 CHLORINATION TRIAL (AWE, 2003A)

A 7-day chlorination trial was carried out in September, 2002, to determine whether the Al-residue is biologically produced and can hence be prevented by chlorination of the well. The chlorination trial was conducted whilst pumping at the same pumping rate and from the same depth as the 7-day pump test to enable a direct comparison to be made between results. Prior to chlorination, the bore was re-developed by airlifting to remove solids that were clogging the screen adjacent the Lower Loxton Sands, particularly in the bottom 1 m. A series of five chlorination cycles were carried out, ranging from 45 mins to 105 mins in duration.

Electrical conductivity (EC), pH, redox potential (Eh), dissolved oxygen (DO) and temperature were logged continuously throughout the test. During pumping, EC remained fairly constant at 60 mS/cm, with the exception of discrete spikes caused by the chlorination cycles themselves. Redox potential increased steadily from approximately 100 mV to 800 mV, also with spikes induced by the chlorination cycles. Dissolved oxygen concentrations remained fairly constant between 2 ppm and 5 ppm, whilst pH decreased steadily from 5.8 to 5.4 with spikes up to 6.2 during chlorination.

After the chlorination trial had been going for 24 hrs, white sludge was being discharged from the pump outlet and on completion of the trial, the insides of the pump impellers and discharge hoses were found to be coated with a 2 mm crust of a friable white deposit. The flow rate had again decreased from 4.5 L/s to 2.35 L/s over the duration of the test. It was also noted that the white sediment had formed on the outside of the delivery pipe, extending from the pump to approximately 4 m above it, just below the boundary between the Upper and Lower Loxton Sands.

### 1.3.4 PACKER TEST (AWE, 2003B)

Following the previous tests, it was thought that low pH aluminium-bearing groundwater responsible for the white precipitate may exist in the Lower Loxton Sands, and that mixing of this groundwater with higher pH groundwater in the production bore and pump leads to precipitation of the $Al^{3+}$ as a solid. The reasoning behind this hypothesis was that (a) it is known that $Al^{3+}$ can only be stable in solution under low pH conditions (Appelo & Postma, 1999), (b) such conditions are not observed in other Loxton Sands piezometers, which are predominantly screened in the Upper Loxton Sands, and (c) the white precipitate was observed to form on the pump delivery hose adjacent the LLS (AWE, 2003a).

To investigate this hypothesis, and determine whether clogging of the pump could be prevented by pumping from only the Upper Loxton Sands, a 22-hour packer test was conducted on BHP1. An inflatable rubber packer was placed at a depth of 42 m below the top of the casing, above the interpreted ULS/LLS boundary (44 m). The pump intake was set at approximately 41 m below the top of the casing. The flow rate was set at 1.25 L/s.

As in previous tests, a reduction in flow rate through the pump was observed over the 22-hour test. This reduction was greater than had occurred during the first 22 hours of the 7 day test. A white residue was observed on the ground at the discharge point approximately 5 hours after the commencement of pumping and this was much thicker after 22 hours at the end of the test. Groundwater sampled from the bore at completion of the test had the lowest (laboratory measured) pH observed so far (4.6), the lowest salinity (TDS = 32 300 mg/L) and the highest [$NO_3$ + $NO_2$] (0.59 mg/L) (Table 2).

## *1.4 Summary and Preliminary Hypothesis*

The following facts must be considered in relation to the occurrence of the white precipitate in the production bore, BHP1:

- The precipitate has not been observed during pumping of the adjacent Loxton Sands observation well (BHO1ls), despite the fact that it is only approximately 30 m away from BHP1 and screens a similar interval of the aquifer.
- The precipitate has not been observed during pumping of any other production bores or observation wells in the Loxton and Bookpurnong regions.
- The precipitate is associated with extremely low pH water (pH as low as 4.1), which has also not been observed in any other bores in the region.

Based on the results and observations from the previous tests described above, the following hypothesis was developed (Fig. 3):

- The presence of dissolved aluminium in groundwater is caused by a low pH, which allows stability of the dissolved phase.
- Following the reasoning described in Section 1.3.4, this low pH groundwater is most likely to occur in the LLS. The packer test did not conclusively exclude the LLS as the source of the low pH groundwater and Al, as small amounts of vertical flow up the annulus of the bore may occur despite the area inside the casing being packed off. This may still allow mixing between Upper and Lower Loxton Sands groundwater.

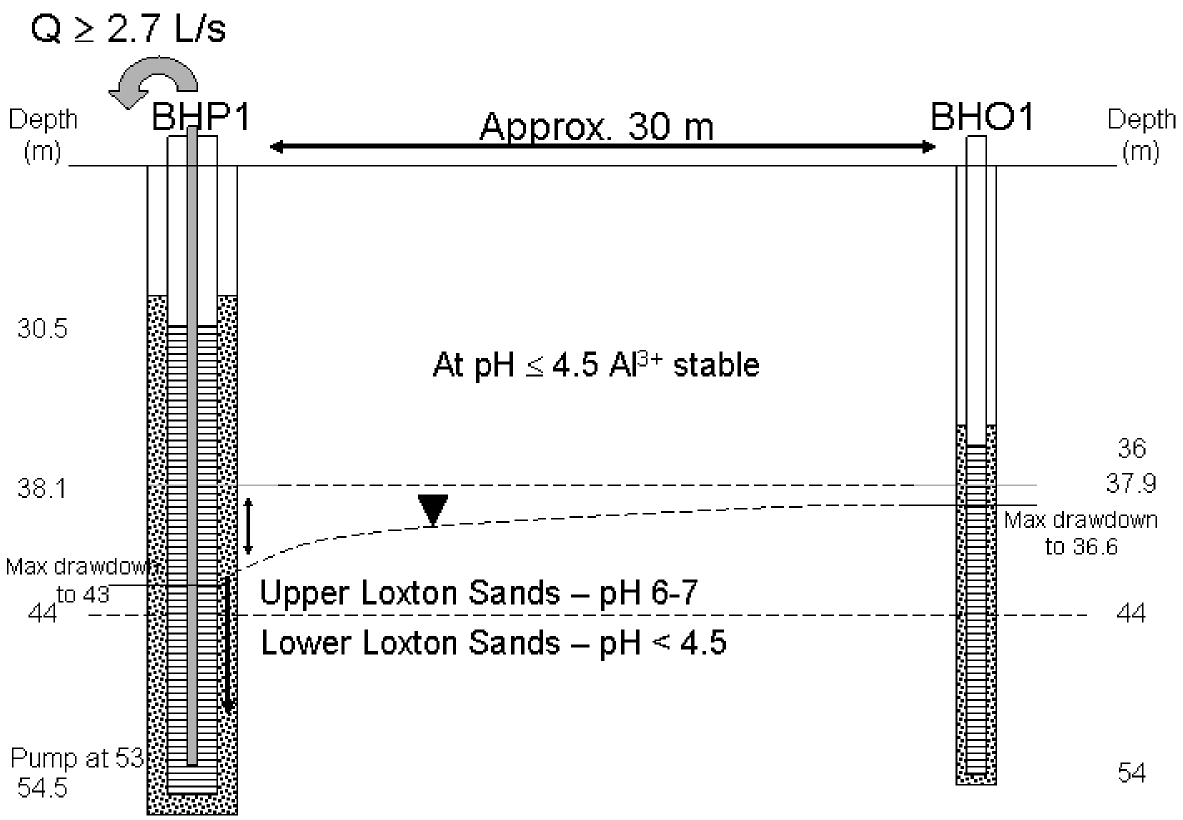

**Figure 3. Preliminary conceptual model for the conditions leading to the formation of the Al precipitate in production bore BHP1 at Western's Highland.**

- Mixing between the low pH water and a higher pH water (presumably from the ULS) during pumping induces precipitation of the Al as an Al-oxyhydroxide.

The results of this study have now shown this preliminary hypothesis to be partially incorrect.

# 2 METHODOLOGY

A joint proposal between DWLBC and AWE was submitted to investigate in more detail the processes leading to the precipitation of the Al-oxyhydroxide sludge. The component carried out by DWLBC supplements a detailed geochemical and isotopic study of the groundwater flow system in the Loxton and Bookpurnong regions, which also includes data from the Loxton Sands aquifer (Harrington et al., in prep.). The investigation of the cause of the Al-hydroxide precipitate was originally carried out in two stages, with the methodology for a third and fourth stage developed based on the results of Stages 1 and 2.

## 2.1 Stage 1 – Chemical and Mineralogical Analysis of Al-Precipitate and Loxton Sands Sediments

Samples of the white sludge, previously collected by AWE, were analysed by Geoscience Australia using a JEOL 6400 Scanning Electron Microscope (energy dispersive system) in order to better identify the structure of the substance and hence its origin. Selected formation samples from the Upper and Lower Loxton Sands from the Bookpurnong Highland Cored Hole (BHC1) were also submitted for X-ray diffraction (XRD) analysis to identify any minerals that may contribute to the low groundwater pH or high concentrations of dissolved aluminium. The analyses were carried out by Geoscience Australia and were eventually extended to include X-ray fluorescence (XRF), bulk chemical analysis via ICP and a short wave Portable Infrared Mineral Analyser (PIMA).

## 2.2 Stage 2 – Down-hole water quality profiling, flow logging and discrete sampling

In order to identify zones of different groundwater quality, particularly the location of any low-pH zones, a YSI 600XLM Multi-Parameter Water Quality Monitor (Sonde) was lowered down the production bore, BHP1, the adjacent Loxton Sands observation well, BHO1ls, and two other Bookpurnong production bores, BHP2 and BHP3 (see Fig. 1 for locations). Measurements of EC, pH, temperature and dissolved oxygen were logged at 1 m depth intervals below the water table in each of these bores.

Review of the down-hole water quality profiles was then used to select target depths for in-bore vertical flow measurements on the production bores using an EM (electromagnetic) flowmeter. Flow meter stations were selected within zones of different groundwater quality and on either side of boundaries between such zones. The flow meter tests were carried out to determine the flow characteristics of the bores under both ambient and pumped conditions and hence identify where the high production zones are. The details of the flow meter tests are provided in Table 3 and bore construction details are shown in Table 1.

Due to observed differences in the chemical characteristics (predominantly pH and EC) of the ULS and LLS groundwaters using the down-hole Sonde (see Section 3.3), groundwater samples were also collected at 40 m (ULS) and 50 m (LLS) using a gas bailer. The objective of this was to investigate whether there are also differences in the

**Table 3. Details of borehole flow meter tests on Bookpurnong production bores BHP1, BHP2 and BHP3.**

| | **BHP1** | **BHP2** | **BHP3** |
|---|---|---|---|
| SWL (m below ground) | 38.1 | 14.6 | 20.3 |
| Pump Depth (m below ground) | 40 | 16 | 21 |
| Pump Rate (L/s) | 0.18 | 0.2 | 0.24 |
| Station 1 (m bgl) | 51 | 22 | 25 |
| Station 2 (m bgl) | 47 | 19.5 | 24 |
| Station 3 (m bgl) | 44 | 18 | 22.5 |
| Station 4 (m bgl) | 43 | 16.5 | 21.5 |
| Station 4 (m bgl) | 40 | – | – |
| Station 4 (m bgl) | 39 | – | – |

dissolved ion compositions of the Upper and Lower Loxton Sands groundwaters and, in particular, dissolved metal concentrations. The bailer used was a Solinst ® Discrete Interval Sampler and helium gas was used to operate the valve due to its inert chemical properties. Nitrogen was not used due to the interest in nitrogen species, and nitrate fertilizers as a potential source of acidity, at this stage of the study. Samples for major ion analyses were filtered through Millipore ® 0.45 μm membrane filters and stored in 1.25 L plastic bottles. Samples to be analysed for metals were filtered through Millipore ® 0.45 μm membrane filters, acidified to pH < 2 with analytical grade $HNO_3$ and stored in 0.5 L acid-washed plastic bottles. Samples to be analysed for $NO_x$ species were neither filtered nor acidified and were stored in 0.5 L plastic bottles. All samples were stored at <4°C until analyses could be carried out. Analyses were carried out at the Australian Water Quality Centre, Bolivar.

## *2.3 Stage 3 – Pump Test on Observation Well BHO1ls*

Review of the results of Stages 1 and 2 suggested that the geochemical reactions leading to the production of the Al-precipitate in BHP1 may have been induced by the large drawdown in the well caused by the high rate of pumping. As neither the large drawdown nor the Al-precipitate had yet been observed in the nearby observation well, BHO1ls, it was considered that pumping of BHO1ls at the highest rate possible may induce in this bore the reactions believed to have occurred at BHP1.

The pump test on BHO1ls commenced at 10:30 am on Nov 20th 2003 and continued until 9:00 am on Nov 21st 2003. The pump was positioned approximately 50 m below ground level (adjacent the Lower Loxton Sands), similarly to the pump tests on BHP1. The following methodology was carried out:

- Measurement of pre-pumping water quality profiles at bores BHO1ls and BHP1 was done, using a down-hole Sonde (YSI Incorporated 600XLM Sonde). This was carried out to identify any changes in basic water quality parameters with pumping via comparison with post-pumping profiles. It was planned to measure these water quality profiles prior to collection of water samples to minimise disturbance of the water column prior to measurement of the water quality profiles. However, this was not the case as technical problems with the Sonde required a replacement to be sent from Adelaide and the water samples were collected whilst waiting for it to arrive in order to reduce the delay. Water quality profiles were then measured immediately before starting the pump the following day.
- Groundwater samples were collected from the ULS and LLS in BHO1ls (40 m and 50 m depths respectively) prior to pumping, using a gas bailer. Chemistry of these groundwater samples were subsequently compared with post-pumping samples to identify any changes as a result of pumping. Sample collection and analysis was carried out as described for Stage 2.
- The observation well (BHO1ls) was pumped at approximately 1 L/s, using an SQ7 submersible pump supplied by SA Water. A 10 minute pause in pumping occurred at approximately 12 pm on the 20th Nov, when a connection in the poly pipe at the top of the bore became disconnected.
- Continuous logging of EC, pH, DO, Eh and temperature was done using a 90FLMV flow-through-cell, as well as periodic measurements of standing water level.
- Samples of the white precipitate were collected for analysis and compared with that collected from BHP1.
- Water quality profiling of both the observation well and production bore was done immediately after the pump was turned off and removed.
- Because the post-pumping water quality profile was different from the pre-pumping profile, and the white precipitate was observed in the discharge water, post-pumping groundwater samples were collected from the upper and lower Loxton Sands in BHO1ls using a gas bailer for major and minor ions and dissolved metals analyses, as described above.

## *2.4 Stage 4 – Construction of and Pump Test on a New Production Well, BHP6 (Upper Loxton Sands Only)*

Because both BHP1 and BHO1ls are constructed across both the ULS and LLS, which were identified to have different chemical characteristics (different EC, as well as different pHs after pumping at high rates – see Section 3.6.3), a new production bore, across the ULS only, was constructed. The objective of this was to determine whether mixing between the ULS and LLS groundwater is a necessary requirement for the Al precipitate to occur. The Upper Loxton Sands was chosen because this was identified to be the source of the dissolved aluminium (see Section 4).

Drilling and construction of the new bore, BHP6, was carried out from 12–14 January, 2004 and was supervised by AWE. The bore log is included in Appendix 1. The hole for BHP6 was drilled using a rotary mud technique to a depth of 42 m below ground level. This collapsed back to 40.4 m before the casing could be installed. The bore was constructed from 175 mm class 12 PVC, with slotted casing between 34.4 m and 40.4 m below ground level. A gravel pack was applied around the casing, from 29.5 m to 40.4 m below ground level, with a 2 m thick bentonite seal above this and cement to 10 m. Immediately after construction, the bore was developed by airlifting for 300 minutes and the final standing water level was 13.87 m below ground level.

The pump test on BHP6 (on 11/02/2004) was conducted in an identical fashion to that on BHO1ls (Section 2.3), with the exception that only the Upper Loxton Sands was targeted. Preliminary water quality profiles of the bore, collected with a down-hole Sonde, showed a layer of low EC water (approximately 6 mS/cm) sitting above higher EC water typical of the Upper Loxton Sands (approximately 40 mS/cm) (see Section 3.7.1). The low EC water was interpreted to be remnant development water and hence, it was decided to pump the well at a low rate (approximately 0.25 L/s) to remove this water prior to commencement of the pump test. It was anticipated that this low rate would not cause sufficient drawdown in the well to initiate the reactions that were expected to occur during the pump test. However, small amounts of the white precipitate began to appear in the discharge water after pumping for approximately 3 hours at this rate. Pumping was continued for a further 3 hours to confirm this and allow any reactions to proceed to a reasonable extent before the test was abandoned.

# 3 RESULTS

## 3.1 Al Sludge Analysis

Analysis of the white sludge retrieved during one of the previous pump tests on BHP1 indicated that it contains halite (NaCl), thenardite ($Na_2SO_4$) and amorphous aluminium hydroxide ($Al(OH)_3$). Excess oxygen recorded on all samples was believed to be an artefact of the analytical technique rather than a natural phenomenon. Likewise, use of an epoxy resin in the analysis process resulted in carbon being detected (KP Tan, Geoscience Australia, pers. comm., Nov 2003).

Halite commonly occurred in the sample as cubes, or rectangular crystals, whilst thenardite occurred as platy 'rhombs' or needle-like crystals. These evaporite minerals were probably precipitated from the groundwater upon drying of the sample. The amorphous aluminium hydroxide were sub-micron particles that made up the bulk of the sample. Small crystals with the same chemical composition are believed to be gibbsite (KP Tan, Geoscience Australia, pers. comm., Nov 2003).

## 3.2 Loxton Sands Mineralogical Analyses

Interpretation of the bulk XRD analyses of the Loxton Sands (ULS and LLS) samples indicated the following (KP Tan, pers. comm., 21st Oct 2003):

- All samples consist predominantly of quartz.
- Muscovite is also present.
- The Upper Loxton Sands contain some feldspars.
- Glauconite ($(K,Na)(Al,Fe,Mg)_2(Al,Si)_4O_{10}(OH)_2$) is present in the Lower Loxton Sands.

Detailed analysis of the diagnostic peaks that were identified via XRD, using a Portable Infrared Mineral Analyser (PIMA), showed a general lack of Al-silicate minerals in the samples. The results of quantitative analyses using X-Ray Fluorescence (XRF), and bulk geochemical analyses of the core samples are shown in Tables 4 and 5 respectively. The XRF data confirmed that the samples are predominantly composed of quartz ($SiO_2$). They also showed that Al-silicates (identified as $Al_2O_3$) make up less than 1% of the sample in the Upper Loxton Sands, increasing to just over 2 % near the bottom of the screened interval of BHP1. Likewise, the concentration of iron in the samples ($Fe_2O_3$) increases from approximately 0.1 % near the water table to approximately 2 % near the bottom of the BHP1 screen, corresponding with the identification of glauconite in the Lower Loxton Sands from the XRD analyses. As well as an increase in Al-silicates with depth is an increase in the concentrations of the rare earth elements (Table 5).

**Table 4. Results of X-Ray Flourescence analyses of Western's Highland core, BHC1.**

**Results are in % wt.**

| Depth (m) | Al2O3 | CaO | Cl | Cr | Cu | F | Fe2O3T | K2O | MgO | MnO | Na2O | Ni | P2O5 | Sc | SiO2 | SO3 | TiO2 | V | Zn | Total Oxides (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 37.5 | 0.799 | 0.019 | 1799 | -2 | -1 | 892 | 0.137 | 0.205 | 0.044 | -0.005 | 0.015 | -2 | 0.017 | -2 | 98.596 | 0.051 | 0.036 | 7 | 20 | 96.933 |
| 40.6 | 0.971 | 0.028 | 626 | -2 | 2 | 1058 | 0.834 | 0.289 | 0.062 | -0.005 | 0.042 | 3 | 0.028 | 5 | 97.555 | 0.035 | 0.056 | 17 | 54 | 99.923 |
| 44.55 | 1.355 | 0.038 | -5 | 8 | -1 | 471 | 0.906 | 0.448 | 0.094 | -0.005 | 0.191 | -2 | 0.019 | 4 | 94.492 | 0.927 | 0.116 | 20 | 237 | 105.619 |
| 52.5 | 2.149 | 0.082 | -5 | 5 | -1 | -50 | 1.936 | 0.538 | 0.29 | 0.007 | 0.359 | 11 | 0.025 | 7 | 91.4 | 1.366 | 0.188 | 44 | 103 | 102.422 |

**Table 5. Chemical composition of core samples from the Western's Highland core, BHC1.**

**Concentrations are in ppm.**

| | silver | arsenic | barium | beryllium | bismuth | cadmium | cerium | cesium | dysprosium | erbium | europium | gallium | gadolinium | germanium | lutetium | hafnium | holmium | lanthanum | lutetium | molybdenum | niobium | neodymium | lead | praseodymium | rubidium | samarium | tin | strontium | tantalum | terbium | thorium | uranium | yttrium | ytterbium | zirconium |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Depth (m) | Ag | As | Ba | Be | Bi | Cd | Ce | Cs | Dy | Er | Eu | Ga | Gd | Ge | Lu | Hf | Ho | La | Lu | Mo | Nb | Nd | Pb | Pr | Rb | Sm | Sn | Sr | Ta | Tb | Th | U | Y | Yb | Zr |
| 37.5 | 0.1 | 3 | 58 | 0.1 | -0.1 | -0.1 | 6.35 | 0.37 | 0.53 | 0.37 | 65 | 0.9 | 0.43 | 2.4 | 0.07 | 0.9 | 0.14 | 2.88 | 0.07 | 1 | 0.9 | 2.36 | 2.4 | 0.69 | 20.3 | 0.48 | -0.5 | 14.8 | 0.9 | 0.71 | 1.4 | 0.37 | 3.8 | 0.37 | 31 |
| 40.6 | 0.08 | 6.5 | 79 | 0.7 | -0.1 | -0.1 | 7.83 | 0.42 | 0.88 | 0.57 | 157 | 1.1 | 0.83 | 2.4 | 0.09 | 1 | 0.22 | 3.47 | 0.09 | 1.4 | 1.1 | 3.67 | 3.7 | 0.98 | 22.2 | 0.79 | -0.5 | 15.3 | 0.8 | 0.11 | 1.5 | 0.47 | 5.3 | 0.56 | 32.4 |
| 44.55 | 0.09 | 10.8 | 100 | 0.5 | -0.1 | -0.1 | 9.33 | 0.56 | 0.87 | 0.58 | 165 | 1.6 | 0.77 | 2.2 | 0.1 | 2 | 0.22 | 4.64 | 0.1 | 1.8 | 2.7 | 3.76 | 4.4 | 1.09 | 27.9 | 0.73 | 0.8 | 17.1 | 1.4 | 0.13 | 1.9 | 1.17 | 6.3 | 0.57 | 72.4 |
| 52.5 | 0.13 | 21.4 | 111 | 0.7 | -0.1 | -0.1 | 11.78 | 0.94 | 0.89 | 0.57 | 235 | 2.8 | 1.01 | 2.4 | 0.1 | 1.2 | 0.21 | 5.48 | 0.1 | 1.8 | 4.1 | 5.13 | 5.6 | 1.39 | 33.4 | 1.03 | 0.9 | 21.7 | 0.6 | 0.15 | 2.4 | 1.62 | 5.6 | 0.57 | 45.9 |

## 3.3 Down-Hole Water Quality Profiling

The down-hole water quality profiles (temperature, EC and pH) for BHP1, BHO1ls, BHP2 and BHP3, as recorded in September 2003, are shown in Figures 4a, 4b, 4c and 4d respectively. Water quality profiles were collected at BHP1 at three different times in September: (1) during the initial Sonde program, (2) immediately prior to the borehole flowmeter test, and (3) immediately after the borehole flowmeter test.

The BHP1 water quality profiles show a distinct difference between the chemistry of groundwater in the Upper and Lower Loxton Sands at that location (Fig. 4a). Upper Loxton Sands groundwater has a lower EC (approx. 40 mS/cm) than the Lower Loxton Sands (approx. 95 mS/cm) and a lower pH (ranging between 4 and 6, compared with approximately 6 in the Lower Loxton Sands). A similar EC stratification is observed in the adjacent observation bore, BHO1ls (Fig. 4b), however pH is fairly uniform with depth at approximately 6.

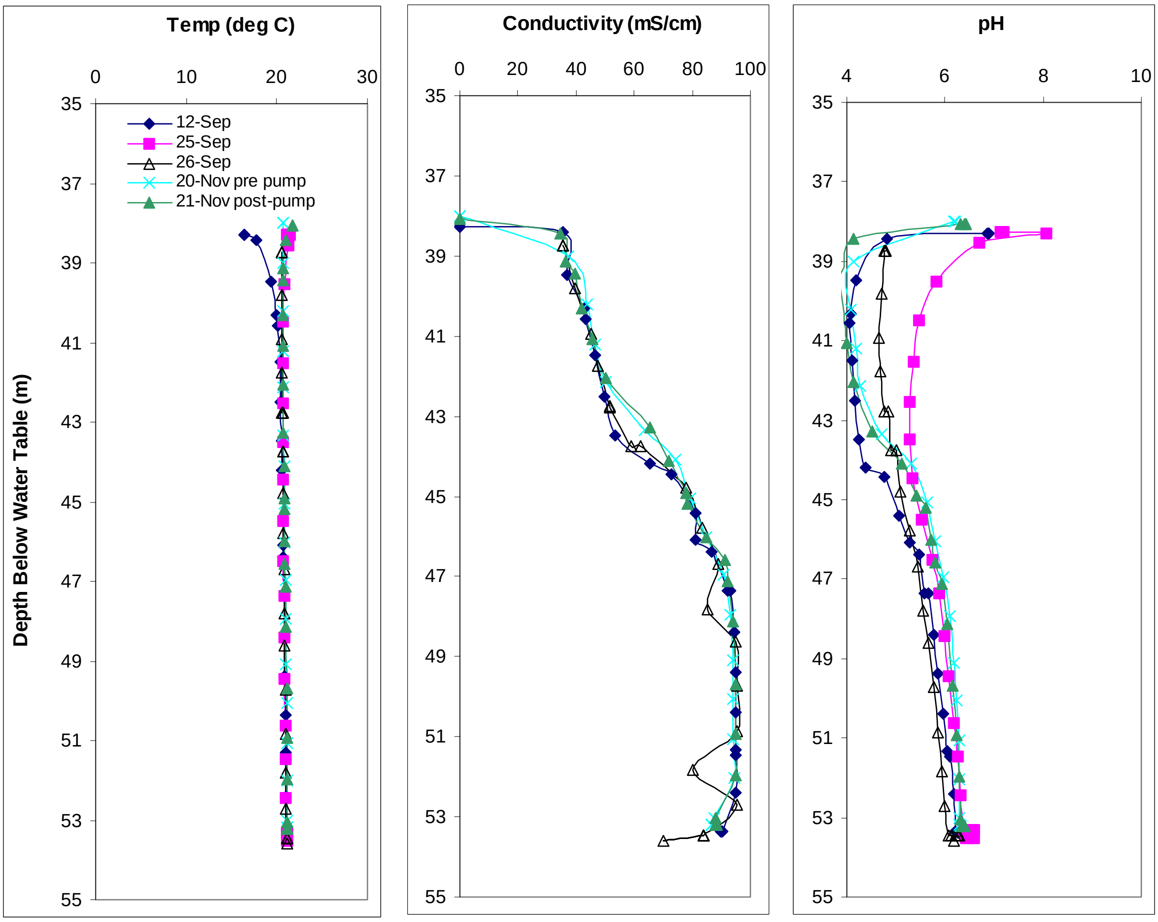

**Figure 4a. Temperature, conductivity (EC) and pH versus depth profiles for bore BHP1, recorded at different times during Sept. and Nov. 2003, including before and after the flow meter test (25 Sept and 26 Sept respectively) and before and after the pump test on BHO1ls (Nov 20 pre-pump and Nov 21 post-pump respectively).**

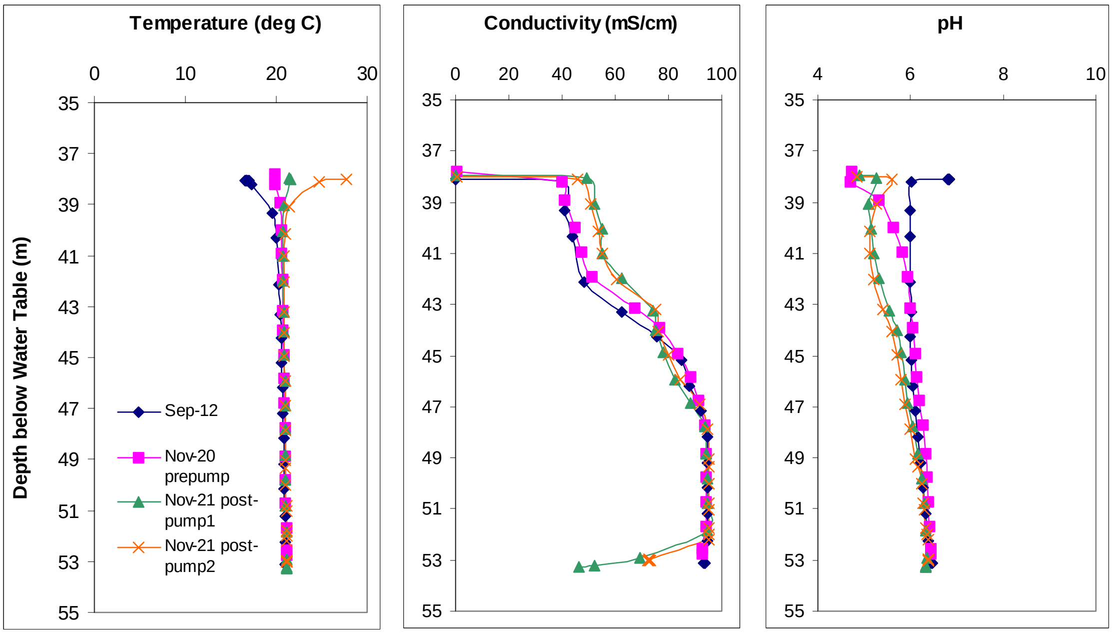

**Figure 4b.** **Temperature, conductivity (EC) and pH versus depth profiles for bore BHO1ls.**

**The graphs show profiles recorded at different times during 2003: During the first round of profile collection (Sept 12), immediately before the pump test on the well (Nov 20 pre-pump), 2.5 hrs after the pump test (Nov 21 post-pump) and 3.5 hrs after the pump test (Nov 21 post-pump2).**

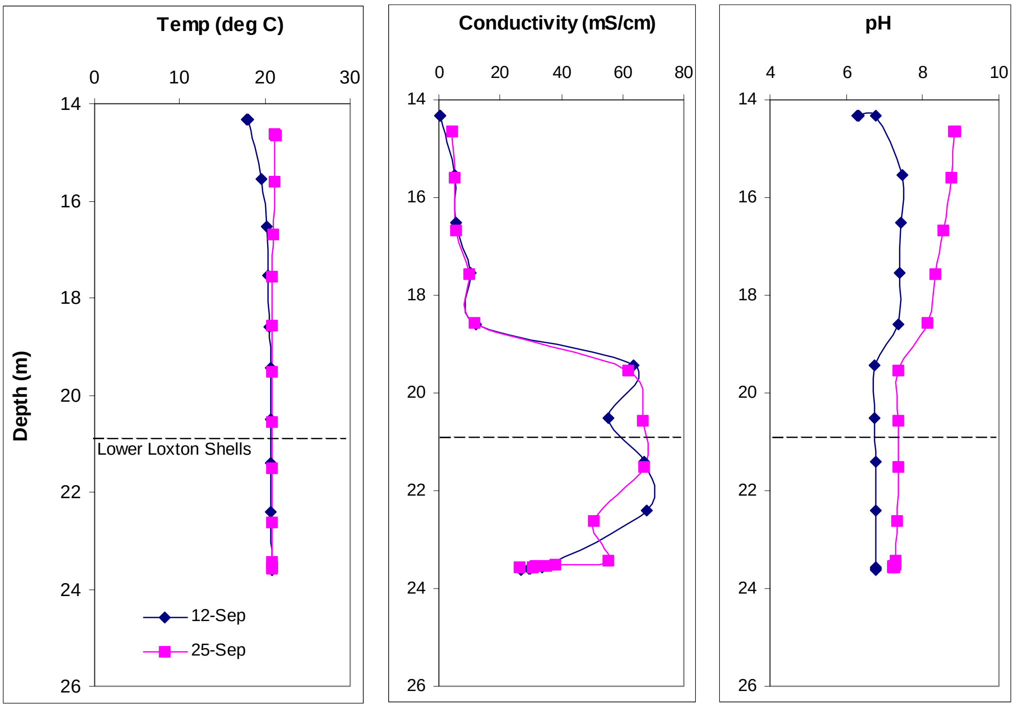

**Figure 4c.** **Temperature, conductivity (EC) and pH versus depth profiles collected from bore BHP2 at two different times.**

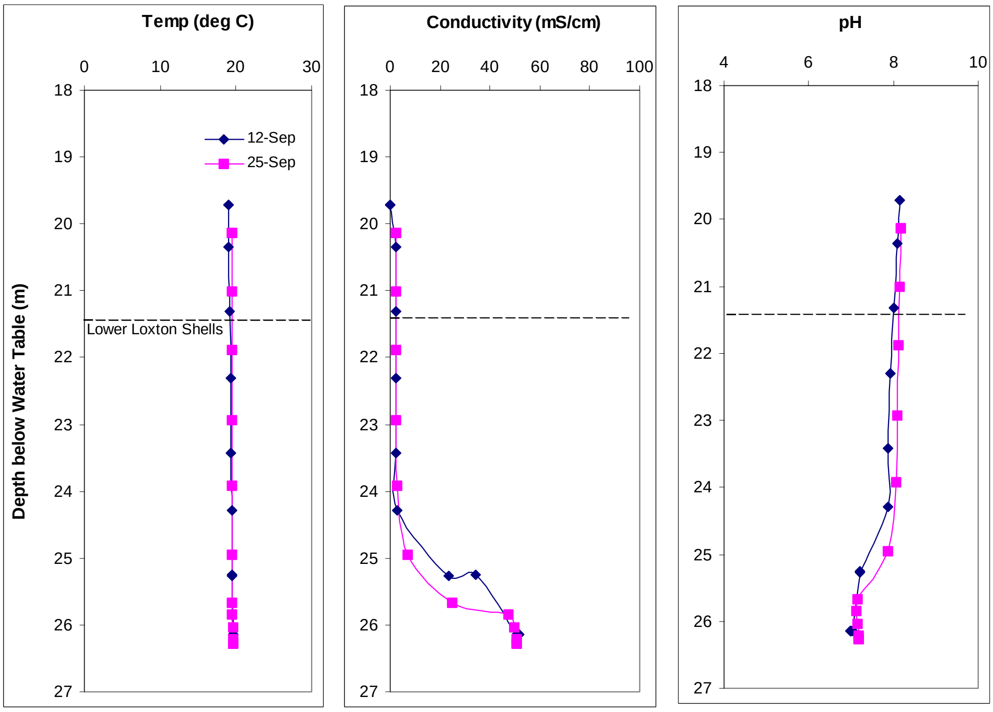

Figure 4d. Temperature, conductivity (EC) and pH versus depth profiles for bore BHP3 collected at two different times.

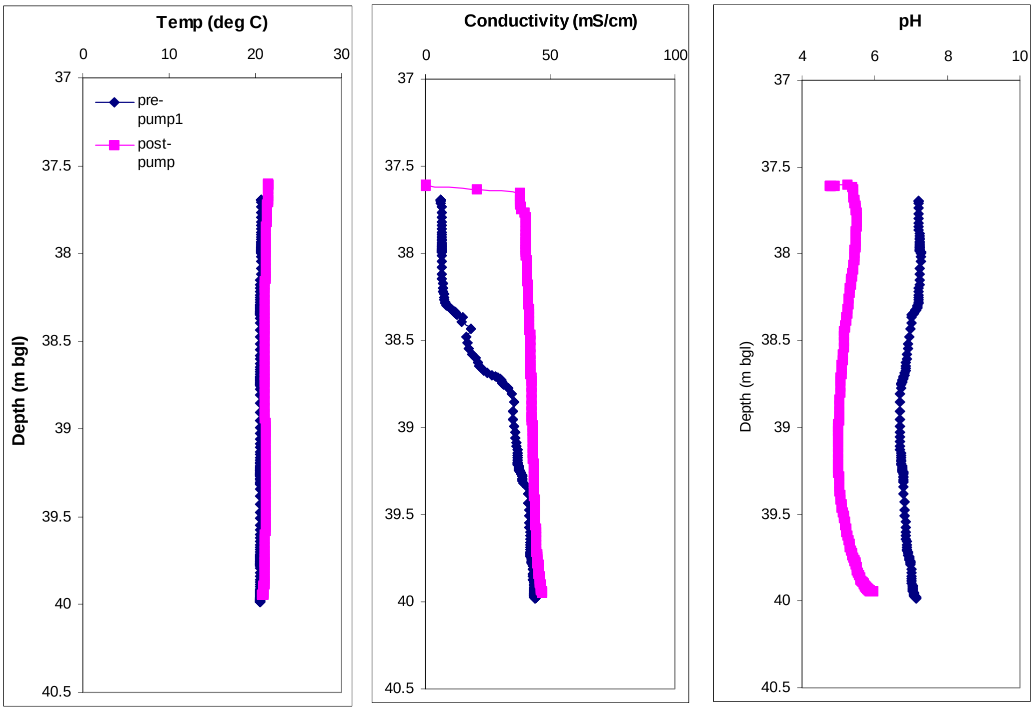

Figure 4e. Temperature, conductivity (EC) and pH vs depth profiles for the entirely Upper Loxton Sands bore BHP6, collected before and after pumping the well for 6 hrs at 0.25 L/s.

The water quality versus depth profiles collected at different times at BHP1 show little variation in salinity with time. However, large variations in pH of the Upper Loxton Sands groundwater are evident over time, with pH varying between approximately 4.1 and 5.5 (Fig. 4a).

The profiles at BHP2 and BHP3 (Figs 4c and 4d), located near Lock 4 (Fig. 1) are considerably different from those at Western's Highland (BHP1 and BHO1ls; Figs 4a and 4b). This is not surprising considering that they are located in a slightly different hydrogeological setting, being screened in the Lower Loxton Sands and Lower Loxton Shells, whilst the Upper Loxton Sands is unsaturated (see Appendix A for well construction details). The Lower Loxton Shells, which is found below the Lower Loxton Sands in some locations in the Loxton – Bookpurnong region, is an informal unit up to 5 meters thick comprising grey, silty clay with shells and shell fragments that underlies Lower Loxton Sands. The unit reflects the transition from high energy beach and upper shoreface sands of the Loxton sands to lower shoreface clays and silts of the Bookpurnong Formation (Hill, et al 2004).

The Loxton Sands groundwaters at both BHP2 and BHP3 are characterized by comparatively low EC water (< 10 mS/cm) sitting above higher EC water (50–70 mS/cm) (Figs 4c and 4d). The low EC of this upper-profile groundwater suggests that it is irrigation water.

## 3.4 Flow Meter Tests

The results of the flow meter tests at BHP1, BHP2 and BHP3 are shown in Figure 5. The measurements made under ambient flow conditions do not indicate any vertical flow occurring in the bores, with the exception of a small upward flow between the depths of 18 and 22 m in bore BHP2. This is recorded as an upward flow of 228 ml/min (0.004 L/s) at a depth of 19.5 m, with zero flow occurring on either side at 18 m and 22 m. This suggests that groundwater occurs under semi-confined conditions between 19.5 m and 22 m, possibly with a high permeability layer conducting this groundwater into the well. The well then forms a preferential vertical flow path. A layer of coarse well- to moderately well- sorted sand containing shell fragments is recorded in the geological log, between the depths of 21 m and 22 m (Appendix A). This may provide such a conduit for groundwater flow.

The fact that the groundwater exits the well between 18 m and 19.5 m also suggests the presence of a high permeability zone occurring between these depths, although such a layer was not recorded in the geological log.

The flow meter tests under pumped conditions were carried out with the pump located 1 to 2 m below the water table, pumping at a rate of approximately 0.2 L/s. In all cases, the uppermost flow meter station was located just below the pump. Under pumped conditions, there was a gradual increase in upward flow towards the pump. However, at both BHP1 and BHP2, less than 50% of the total flow that was discharged by the pump came from below the pump depth. The remaining 50% was therefore derived from the aquifer adjacent to or above the pump, or flowed along the annulus of the bore.

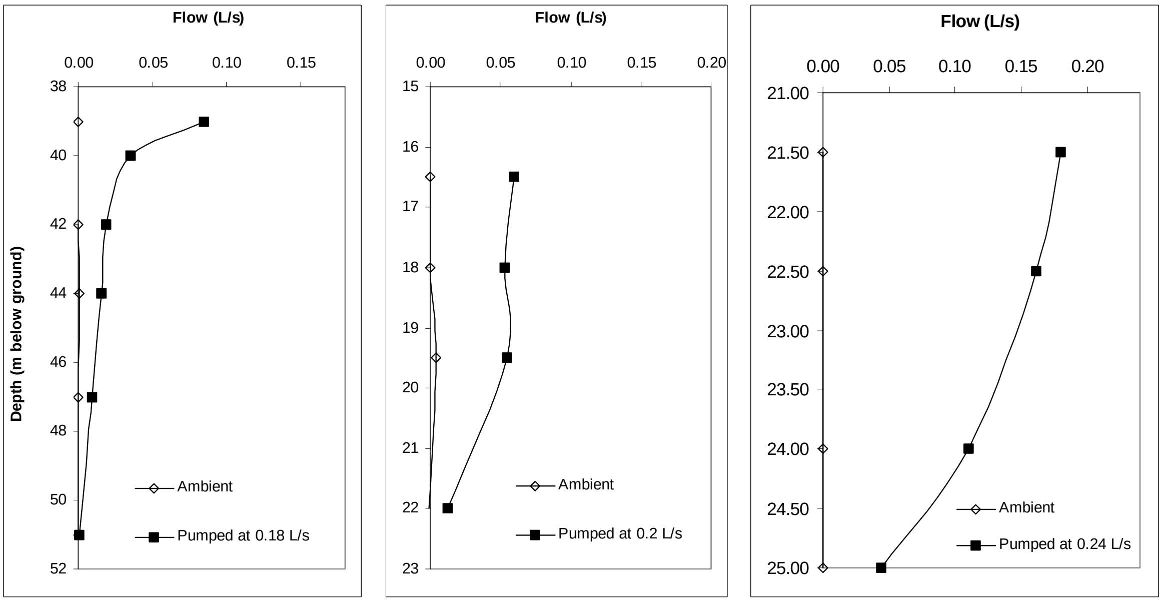

**Figure 5. Vertical flow (L/S) vs depth (m bgl) in boreholes BHP1, BHP2 and BHP3 measured using an electromagnetic (EM). Measurements were made under both ambient and pumped conditions.**

A gradual but steady increase in flow up the bore occurs below 40 m depth at BHP1 under pumped conditions. This is consistent with the observation that the aquifer material below 40 m depth has fairly uniform hydraulic properties, but is low yielding, described as silty and clayey sands (Appendix A). The greatest increase in flow occurs above 40 m depth, where the sediments become more coarse-grained according to the geological log (Appendix A). At bore BHP2, a large increase in flow under pumped conditions occurs between 22 m and 19.5 m, consistent with the results of the ambient test on this bore that suggest preferential flow along a high permeability zone between these depths. There is very little change in flow between 19.5 m and the base of the pump at 16.5 m, suggesting little contribution from the aquifer in this depth interval. However, the flow recorded just below the pump at this site was still less than 25% of the total flow and hence the majority of flow is derived from between the depths of 16 m and the water table (14.6 m).

## *3.5 Discrete Sampling of the Upper and Lower Loxton Sands in Production Bore BHP1*

The results of the chemical analyses of groundwater from the Upper and Lower Loxton Sands, collected from the production bore BHP1, using a gas bailer, as well as of the groundwater pumped from the Upper Loxton Sands (at 40 m depth) during the flow meter test (flow rate = 0.18 L/s) are shown in Table 2. The TDS concentrations of both bailed samples were consistent with the EC versus depth profiles from BHP1 (Fig. 4a). Groundwater from the Lower Loxton Sands generally has higher TDS than that from the

Upper Loxton Sands. Some other striking differences between the analyses are (a) the high concentration of dissolved aluminium (25 mg/L) in the Upper Loxton Sands, compared with negligible concentrations in the Lower Loxton Sands, and (b) a low alkalinity in the Upper Loxton Sands compared with the Lower Loxton Sands.

The groundwater pumped from 40 m depth in the Upper Loxton Sands had a pH of 4.1 and a slightly higher TDS than that collected from the same depth using the gas bailer. This suggests that this pumped sample consists predominantly of the lower salinity Upper Loxton Sands groundwater, with a small contribution of higher salinity groundwater from the Lower Loxton Sands.

## *3.6 Pump Test on BHO1ls*

### 3.6.1 PRE-PUMPING WATER QUALITY PROFILES

The pre- and post-pumping water quality profiles collected on the 20th and 21st November from BHP1 and BHO1ls are shown in Figures 4a and 4b respectively. The pre-pumping profiles at BHP1 were similar to those observed on earlier occasions in that bore, although smearing of the pH and EC profiles around the Upper and Lower Loxton Sands boundary (44 m) appears to have occurred due to sampling with the gas bailer and repeated raising and lowering the Sonde whilst attempting to fix the technical problems. A similar process may have occurred at BHO1ls, where low pH groundwater was recorded just below the water table, possibly due to intrusion of oxygen as the bailer was raised and lowered in the well. Besides this, the pre-pumping pH and EC vs depth profiles for BHO1ls were similar to those recorded previously in September 2003 (Fig. 4b). Similarly to BHP1, EC shows the same stratification between low EC water in the Upper Loxton Sands and higher EC water in the Lower Loxton Sands, whilst in contrast to BHP1, pH is fairly constant with depth at approximately 6 (Fig. 4b).

### 3.6.2 OBSERVATIONS MADE DURING PUMPING

Water levels measured in BHO1ls within the first hour of pumping indicated a water level drop of approximately 2.5 m. Unfortunately, the PVC conduit used for taking water level measurements had to be removed from the bore and could not be replaced when the join in the poly pipe at the surface became disconnected. Hence, subsequent water level measurements were not possible, although it is reasonable to assume that they would have remained fairly stable during the remainder of the test as there was no drop in flow rate and bore BHP1 has previously been observed to reach a stable water level very quickly during pumping.

EC, dissolved oxygen (DO), alkalinity, pH and redox potential (Eh) of the discharge water are plotted versus time in Figure 6 for the entire pumping period. pH of the outflow water remained constant at approximately 6. Eh increased from –123 mV to –98 mV in the first 4 hrs of pumping, signifying increasingly oxidised conditions within the aquifer.

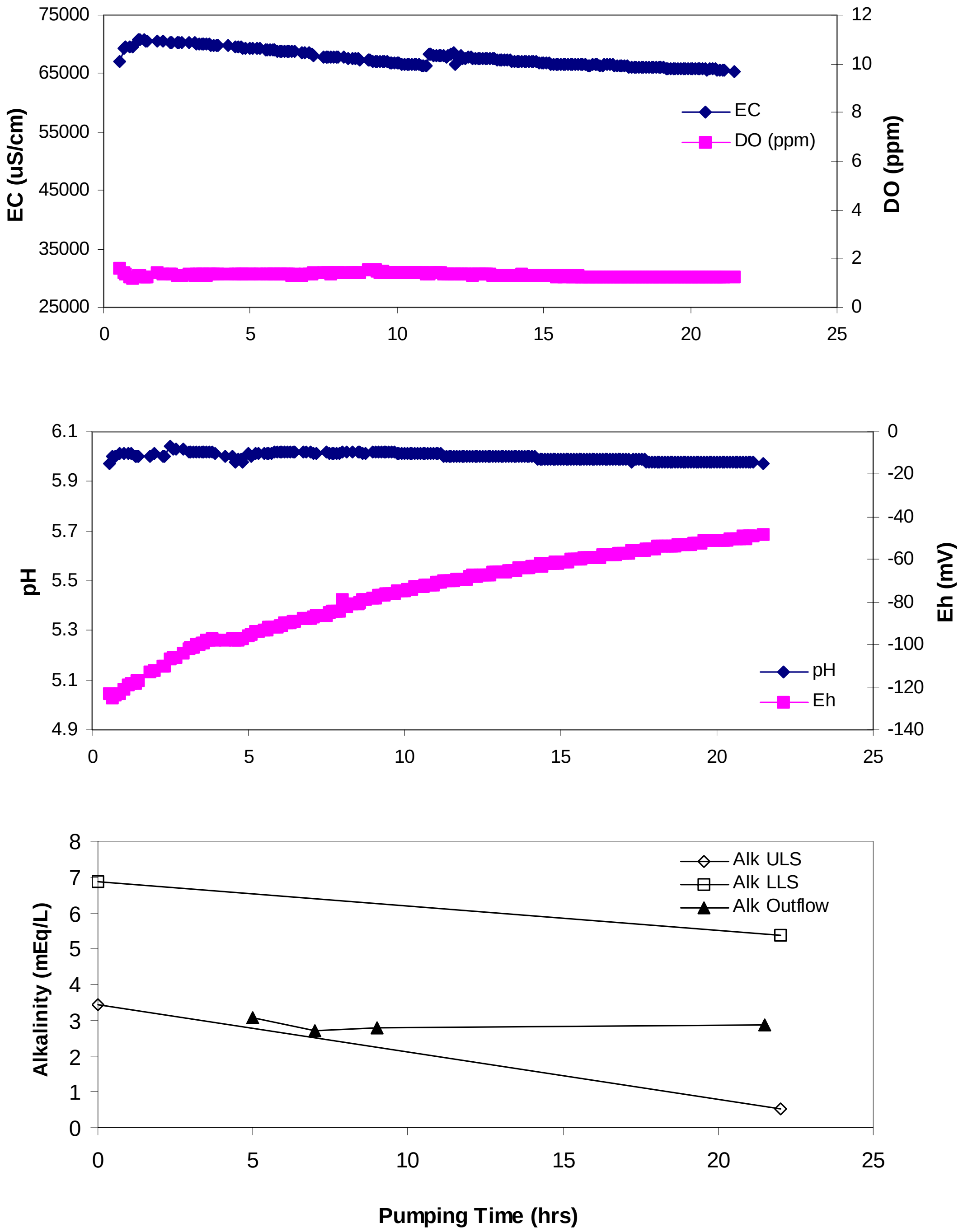

**Figure 6.** **Plots of alkalinity, pH and Eh of outflow water vs time for the November 20th / 21st pump test on BHO1ls. Pre- and post-pump alkalinities of groundwater extracted from the Upper and Lower Loxton sands using a gas bailer are also shown for reference.**

After 4 hrs, Eh remained fairly constant for approximately 1 hr and then increased steadily again for the remainder of the pump test (although overnight data was not recorded), reaching –43 mV after 21 hrs of pumping.

There was an initial decrease in the alkalinity of the discharging water over the first several hours of the test, after which it became stable at approximately 2.8 mEq/L (Fig. 6). This decrease was also reflected in a large decrease in alkalinity, from 3.4 mEq/L to 0.5 mEq/L, of the Upper Loxton Sands groundwater sampled with the gas bailer before and after the test (Fig. 6). A significant alkalinity decrease, from 6.9 mEq/L to 5.4 mEq/L, also occurred in the Lower Loxton Sands.

The white precipitate was observed in the discharge water approximately 6 hrs after commencement of pumping, first as just a white tinge of material settled out in the pond of discharge water. This “film” gradually built up and became more obvious, but remained less that 1 mm thick (Figs 7a and 7b). When the pump was turned off, the inside of the poly pipe was also covered in a thin film of the white gelatinous precipitate and dismantling of the pump revealed a similar layer inside the pump impellers (Fig. 7c). The onset of the precipitate coincided approximately with the stabilization of the alkalinity of the discharge water at 2.8 mEq/L and the brief plateau in Eh at –98 mV.

### 3.6.3 POST-PUMPING WATER QUALITY PROFILES

There was virtually no change in the water quality profiles at BHP1 as a result of the pumping activity at BHO1ls (Fig. 4a). In contrast, the pre-pumping pH and EC profiles in the Upper Loxton Sands at BHO1ls were considerably different from the post-pumping profiles (Fig. 4b). Groundwater pH in the Upper Loxton Sands had decreased from approximately 6 to 5.1 and EC had increased from approximately 47 mS/cm to 55 mS/cm (Fig. 4b). The magnitude of the pH decrease was not as large as that observed at BHP1 after previous pump tests on that bore. However, some mixing of the water column in the well during removal of the pump was suspected to be the reason that the low pH was not observed when the water quality profile was taken. The slightly higher post-pumping groundwater EC in the Upper Loxton Sand at BHO1ls supports this as previous profiles of BHP1 showed no change in the EC of the Upper Loxton Sands after pumping.

### 3.6.4 PRE- AND POST-PUMPING GROUNDWATER QUALITY IN THE UPPER AND LOWER LOXTON SANDS AT BHO1LS

The results of chemical analyses of groundwater samples collected, using a gas bailer, from the Upper and Lower Loxton Sands (40 m and 50 m depths respectively) at BHO1ls, both before and after pumping, are shown in Table 2. In addition to the reduction in pH and slight increase in EC of the Upper Loxton Sands groundwater observed in the groundwater quality profiles after pumping, the following changes in Upper Loxton Sands groundwater chemistry are observed (Table 2):

**Figure 7a.** White precipitate on ground after pumping from BHO1ls had stopped and discharge water had drained away.

**Figure 7b.** White precipitate on ground where discharge water had ponded during pumping of BHO1ls.

**Figure 7c. White precipitate coating on inside of pump after pumping BHO1ls.**

- The Mg concentration increased from 884 mg/L to 1 130 mg/L.
- The Cl concentration increased from 15 300 mg/L to 20 300 mg/L.
- The $SO_4$ concentration increased from 3 010 mg/L to 3 790 mg/L.
- The reactive Si concentration increased from 14 mg/L to 29 mg/L.
- The Al concentration increased from < 0.2mg/L to 4.53 mg/L.
- The Na concentration decreased from 18 100 mg/L to 12 900 mg/L.
- The alkalinity (as $HCO_3$) decreased from 210 mg/L to 32 mg/L.
- The Fe concentration decreased from 25.9 mg/L to 4.08 mg/L.

These changes resulted in slight a net increase in TDS, from 38 000 mg/L to 38 600mg/L.

## *3.7 Pump Test on BHP6 (Upper Loxton Sands Only)*

### 3.7.1 PRE-PUMPING WATER QUALITY PROFILES

The pre-pumping water quality profiles from the newly constructed ULS production bore BHP6 showed a stratification in groundwater salinity in the screened interval (Fig. 4e). Groundwater between the water table (37.53 m below ground level) and 38.3 m had a comparatively low EC of 6 500 uS/cm. Below this, a transition zone occurred between 38.3 m and 38.8 m, with higher EC water (43 600 uS/cm – 44 000 uS/cm) below this. The fact that the low EC water had not been observed at either BHP1 or BHO1ls led to the belief that this water may be residual drilling fluid. The pH of the low salinity water was approximately 7.2, dropping to approximately 6.8 in the higher EC zone (Fig. 4e). The dissolved oxygen concentration of the groundwater ranged from 28% at the water table to 2.5% at the base of the screened interval.

### 3.7.2 OBSERVATIONS MADE DURING PUMPING

The maximum observed drawdown in the water level in the well was 1.94 m, from 37.53 m to 39.47 m below ground level, reaching this level very quickly after the pump was started and remaining constant throughout the test. This level is approximately 1 m above the bottom of the screened interval (40.4 m) and 50 cm above the pump depth (40 m). Similarly to the pump test on BHO1ls, the EC, DO, pH and Eh of the discharge water were logged continuously during the pump test on BHP6. Plots of these parameters versus time are shown in Figure 8. Groundwater samples were not collected during pumping as it was believed, based on previous pumping of BHP1, that the pump rate should be low enough to prevent the iron oxidation reaction from occurring (see Section 4.1 below).

Figure 8 shows that the EC of the discharge water remained at approximately 40 000 uS/cm, with numerous sharp decreases to between 28 000 uS/cm and 30 000 uS/cm. The dissolved oxygen concentration of the water also fluctuated between 4 ppm and 12 ppm. The pH decreased steadily from approximately 5.7 to 4.9 whilst the redox potential (Eh) increased from 100 mV to 200 mV.

An additional observation was that the discharge water alternated during pumping between being quite clear to highly aerated, with an effervescent appearance.

### 3.7.3 POST-PUMPING WATER QUALITY PROFILES

The water quality profiles recorded after the pump was stopped and removed from the well are shown in Figure 4e, with the pre-pumping profiles for comparison. The profiles show that the low EC water had been removed from the top of the profile by pumping. The EC profile had become constant with depth at approximately 40 mS/cm, similar to that observed in the top of the Upper Loxton Sands at BHP1 and BHO1ls (Figs 4a and 4b). The pH had decreased from between 6.8 and 7.2 to between 5 and 5.5.

### 3.7.4 POST-PUMPING GROUNDWATER SAMPLING

A sample of discharge water collected immediately prior to the pump being turned off has been submitted to the Australian Water Quality Centre for analysis results will be reported in a future communication.

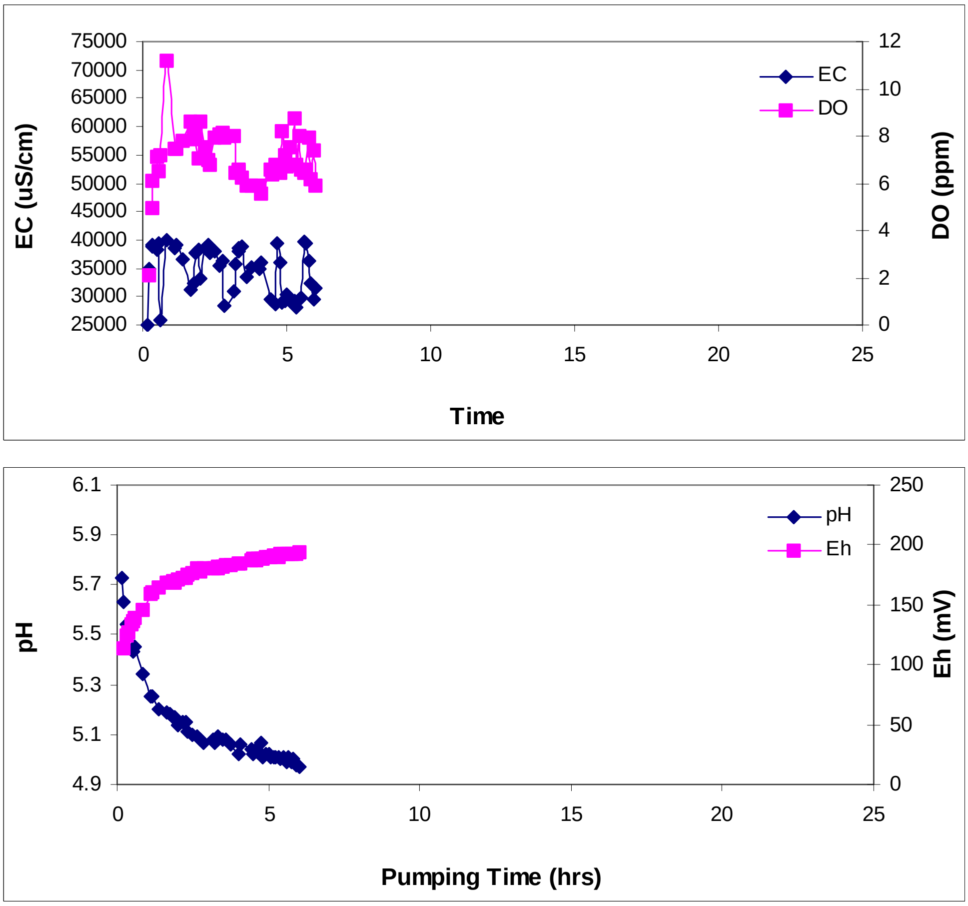

**Figure 8. Plots of EC, DO, pH and Eh of outflow water vs time for the pump test on BHP6.**

# 4 DISCUSSION

## 4.1 The Origin of Low pH Groundwater in the Upper Loxton Sands at Western's Highland

The importance of low pH in the mobility and speciation of Al will be discussed in the following sections. A relationship between unusually low pH groundwater and the occurrence of the white Al precipitate at BHP1 was identified early in this study. A reduction in pH of the Upper Loxton Sands groundwater, where the original pH was between 6 and 7, the same as that of the Lower Loxton Sands groundwater, occurred after pumping observation well BHO1ls and production bore BHP6 (Figs 4b and 4e). This suggests that such low pH groundwater does not occur naturally in the aquifer, and that the low pH observed at BHP1 was also probably a result of pumping that bore. The geochemical reactions that may lead to such a reduction in groundwater pH are discussed below.

Common causes of low pH in groundwater include (Appelo, 1999):

- $CO_2$ production in the soil via organic matter decay and root respiration.
- Infiltration of acid rain.
- Excessive use of ammonia and manure as fertilizers.
- Oxidation of pyrite.

Even in the absence of significant buffering processes within an aquifer, the natural production of $CO_2$ in the soil zone cannot cause pH below about 4.6, and unpolluted rainwater that dissolves $CO_2$ in the soil zone will generally obtain only a slightly acid pH of about 5.6 (Appelo, 1999). Buffering by the dissolution of carbonate species in the soil zone generally causes even higher pHs. In addition to this, low pH groundwater produced by this reaction would have been obvious in BHP1, BHO1ls and BHP6 over the entire sampling period and hence this is not believed to be responsible for the low pH groundwater observed at BHP1 and now at BHO1ls and BHP6. The effects of acid rain are also not applicable to this study. Low nitrate concentrations (< 1 mg/L; Table 2) in the Upper Loxton sands at BHP1 indicate that the oxidation of ammonia is not a source of acidity to groundwater at this site, and the fact that significant amounts of pyrite have not been observed also suggests that pyrite oxidation is probably not (directly) the mechanism responsible.

An alternative explanation for the development of low pH groundwaters at Western's Highland is provided by Macumber (1991), who describes the occurrence of acid groundwaters in the Parilla Sand (the Victorian equivalent of the Loxton Sands) of the Tyrrell Basin in the Mallee region of north-western Victoria. Macumber (1991) also states that such groundwaters, ranging in pH from 3.5 to 4.5 occur extensively in the Parilla Sand throughout north-western Victoria and are also commonly found in the Palaeozoic bedrock aquifers of central Victoria. Low pH in the Tyrrell Basin was restricted to the upper 25 m of the saturated zone and this pH zonation was co-incident with a redox zonation, the acid groundwaters being more oxidized than the underlying more neutral pH groundwaters. The mechanism suggested by Macumber (1992) for the formation of these low pH waters follows that of White (1965), who suggested that the oxidation of ferrous iron is responsible for low laboratory-measured pH values of oil-field brines with low alkalinities (low concentrations of buffering species). In this way, hydrogen ions (acidity) are produced via the reaction:

$$Fe^{2+} + 2H_2O + 1/2O_2 + e^- \Leftrightarrow Fe(OH)_3 + H^+ \qquad (1)$$

The source of ferrous iron in the Parilla Sands groundwater is believed to be dissolution by infiltrating rainwater of iron oxides and hydroxides in the ferruginized Karoonda Surface that caps the Loxton-Parilla Sand, as well as pyrite oxidation. Large amounts of ferruginization in the Upper Loxton Sands in the Loxton - Bookpurnong region suggest that iron may also be an important geochemical agent there and the oxidation of this iron is proposed as the reaction producing low pH water around BHP1 and BHO1ls.

The pre- and post-pumping analyses of the Upper Loxton Sands groundwater from BHO1ls support this hypothesis, as the total Fe concentration before pumping of 25.9 mg/L is reduced to 4.08 mg/L after pumping of the bore (Table 2). This is consistent with removal of $Fe^{2+}$ from solution via oxidation and precipitation as $Fe(OH)_3$, as shown in Reaction 1. The occurrence of this was observed visually in the field, as the high dissolved Fe concentration caused a rust-coloured Fe oxyhydroxide precipitate to form in the pre-pumping Upper Loxton Sands groundwater sample within 6 hrs of collection, whereas the post-pumping sample remained clear (Fig. 9). The proposed mechanism for oxidation of $Fe^{2+}$ around bores BHP1 and BHO1ls is that described by Appelo and Postma (1999) (Fig. 10). Pumping the wells at sufficiently high rates causes cones of drawdown and turbulence around the wells that can draw oxygen into the saturated zone and allow oxidation reactions to occur.

**Figure 9. A rust coloured precipitate formed in the pre-pumping Upper Loxton Sands groundwater sample from BHO1ls, whilst the post-pumping sample remained clear. This is consistent with high dissolved iron concentrations in the Upper Loxton Sands prior to pumping, whilst this has all been oxidised to $Fe^{3+}$ and precipitated out as $Fe(OH)_3$ after pumping.**

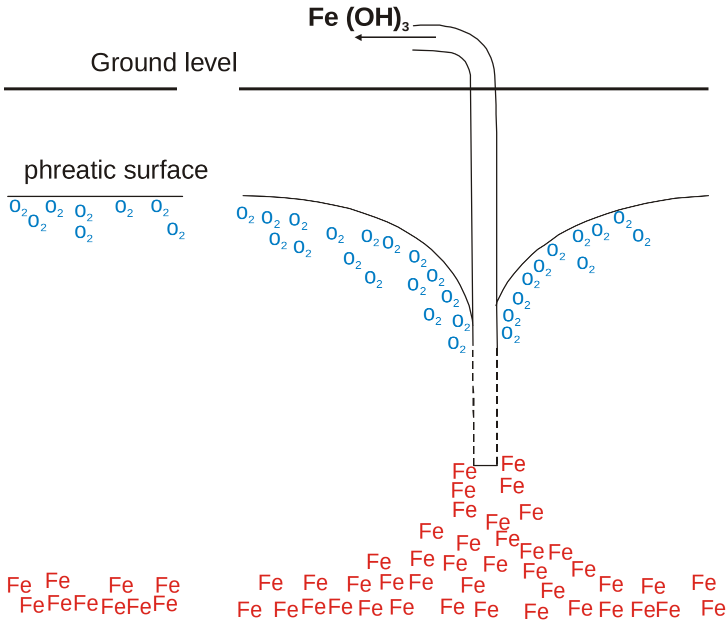

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**Figure 10. Oxidation of groundwater containing dissolved Fe around a well by pumping (From Appelo and Postma, 1999).**

## *4.2 Sources of Aluminium in Groundwater*

Aluminium may be naturally present in available forms (i.e. available to become dissolved in solution) in aquifer systems as weathering products of silicate minerals (Appelo & Postma, 1999). Such weathering products include gibbsite ($Al(OH)_3$) and clay minerals, such as kaolinite. These products have relatively fast dissolution kinetics under low pH conditions, although probably not on the time scale of hours, which is the time scale of the appearance of the Al-hydroxide precipitate in BHP1.

Aluminium that is released into groundwater over longer time scales via dissolution of these weathering products is strongly adsorbed to surfaces of clay particles, organic matter and oxide minerals, for example Fe-oxides. The surface charge and hence cation exchange capacity of these minerals is also dependent on the pH of the solution in which they are immersed (i.e. the groundwater). The pH at which the net charge of a mineral is zero is known as the Point of Zero Charge ($pH_{PZC}$). At pHs above its $pH_{PZC}$, a mineral has the capacity for cation exchange (e.g. to adsorb $Al^{3+}$ or positive Al complexes), and for anion exchange below this pH. For example, if the positively charged aluminium species (predominantly $Al^{3+}$) in groundwater are adsorbed to a particular aquifer mineral, a decrease in groundwater pH below the $pH_{PZC}$ for that mineral will cause the aluminium species to be released from the exchange sites. Table 6 shows the $pH_{PZC}$ of clay minerals and common soil oxides and hydroxides.

**Table 6. Table 6. Points of zero charge ($pH_{PZC}$) of clay minerals and common soil oxides and hydroxides (Parks, 1967; Stumm & Morgan, 1981; Davis & Kent, 1990) (After Appelo and Postma, 1999).**

| | $pH_{PZC}$ |
|---|---|
| Kaolinite | 4.6 |
| Montmorillonite | < 2.5 |
| Corundum ($\alpha$-$Al_2O_3$) | 9.1 |
| $\gamma$-$Al_2O_3$ | 8.5 |
| $\alpha$-$Al(OH)_3$ | 5.0 |
| Hematite ($\alpha$-$Fe_2O_3$) | 8.5 |
| Goethite ($\alpha$-FeOOH) | 7.3 |
| $Fe(OH)_3$ | 8.5 |
| Birnessite ($\delta$-$MnO_2$) | 2.2 |
| Rutile ($TiO_2$) | 5.8 |
| Quartz ($SiO_2$) | 2.9 |
| Calcite ($CaCO_3$) | 9.5 |
| Hydroxyapatite ($Ca_5OH(PO_4)_3$ | 7.6 |

Table 6 shows that, if ambient groundwater has a pH between 6 and 7, any positively charged Al species released by weathering may become adsorbed to minerals such as kaolinite, montmorillonite, Al-hydroxides, Mn-oxides, rutile and quartz. If the pH then drops to 5 or below, as observed in the Upper Loxton Sands at BHP1, any aluminium that is sorbed to kaolinite, Al-hydroxide and rutile will be released back into solution. Hence, any kaolinite, Al-hydroxide or rutile present in the Upper Loxton Sands may be a potential source of dissolved Al under conditions of a groundwater pH reduction from near-neutral to 5 or less, as seen at BHP1.

Organic matter, either forming coatings on the coarser grains in sediments, or suspended in groundwater as colloidal material, also has the ability to adsorb metals, such as aluminium. The cation exchange capacity (CEC) of organic matter is also pH dependent, according to the relationship:

$$\text{CEC (mEq/100g)} = 51 \cdot \text{pH} - 59. \qquad (2)$$

Hence, at a pH of 6, the CEC of organic matter is approximately 250 mEq/100g, whilst this drops to 150 mEq/100g at a pH of 4.

As clays, Al-hydroxide and rutile are only very minor components of the sediments at BHP1, organic matter may also be a source of available aluminium at this site, although no analyses have been carried out to date to confirm this.

## 4.3 The pH Dependence of Aluminium Precipitation from Upper Loxton Sands Groundwater at Western's Highland

The dependence of aluminium speciation on groundwater pH is shown in Figure 11. Significant amounts of aluminium can only occur in solution in groundwaters in the low pH range. For example, for aluminium concentrations of 25 mg/L (9.3 x $10^{-4}$ mmol/L), as observed in the groundwater sample from the Upper Loxton sands in BHP1 (Table 2), stability of the dissolved phase is at pH < 4, and dissolved aluminium is predominantly in the form of $Al^{3+}$. For aluminium concentrations of 4.5 mg/L (1.7 x $10^{-4}$ mol/L), as observed after pumping in the Upper Loxton Sands at BHO1ls, dissolved aluminium stability is at pH < 4.4. A pH above these threshold values will cause any dissolved aluminium to precipitate out of solution as $Al(OH)_3$, as observed in and around the pumps and discharge hoses when these bores are pumped. Hence, one of two things may occur when the pH of the Upper Loxton Sands groundwater drops as a result of $Fe^{2+}$ oxidation (Reaction 1) and $Al^{3+}$ is released from exchange sites on aquifer minerals or organic matter:

a) pH < 4.5. Here, the pH drops below the threshold for stability of dissolved $Al^{3+}$ described above. The released $Al^{3+}$ will remain in solution until the pH increases above this threshold. Such a pH increase may occur via mixing with a higher pH groundwater, for example, groundwater from the Lower Loxton Sands.

b) 4.5 < pH < 5.5. Here, the pH drops below the threshold to release Al from exchange sites, but not low enough to maintain $Al^{3+}$ in solution. In this case, the released Al will immediately begin to precipitate out as $Al(OH)_3$.

Note that the threshold pH values described above are approximate only as they depend on the minerals to which the aluminium is originally adsorbed and the dissolved aluminium concentration that results from the release of this aluminium.

The observations at BHP1 suggest that scenario (a) may have occurred at this bore. The groundwater pH appears to have dropped low enough (to approximately 4) for the released aluminium to remain in solution. A slight increase in pH, for example by mixing with higher pH groundwater from the Lower Loxton Sand then causes this aluminium to precipitate out. As the pH drop at BHO1ls was not as great (to approximately 5.1), scenario (b) may have occurred during pumping of this bore. That is, the Al precipitate would have occurred regardless of any mixing with Lower Loxton Sands groundwater and may, in fact, have precipitated out more extensively in the aquifer than in the pump and discharge hose. Scenario (b) also explains why the aluminium precipitate was observed on pumping of BHP6 (albeit in barely visible quantities), despite the fact that this bore is screened in the Upper Loxton Sands only and hence, mixing between the low pH Upper Loxton Sands water and the higher pH Lower Loxton Sands water was prevented.

Based on the results of the tests, it appears that the extent of the pH decrease in the Upper Loxton Sands may be directly related to the pumping rate and hence the drawdown in the well, although this requires further investigation.

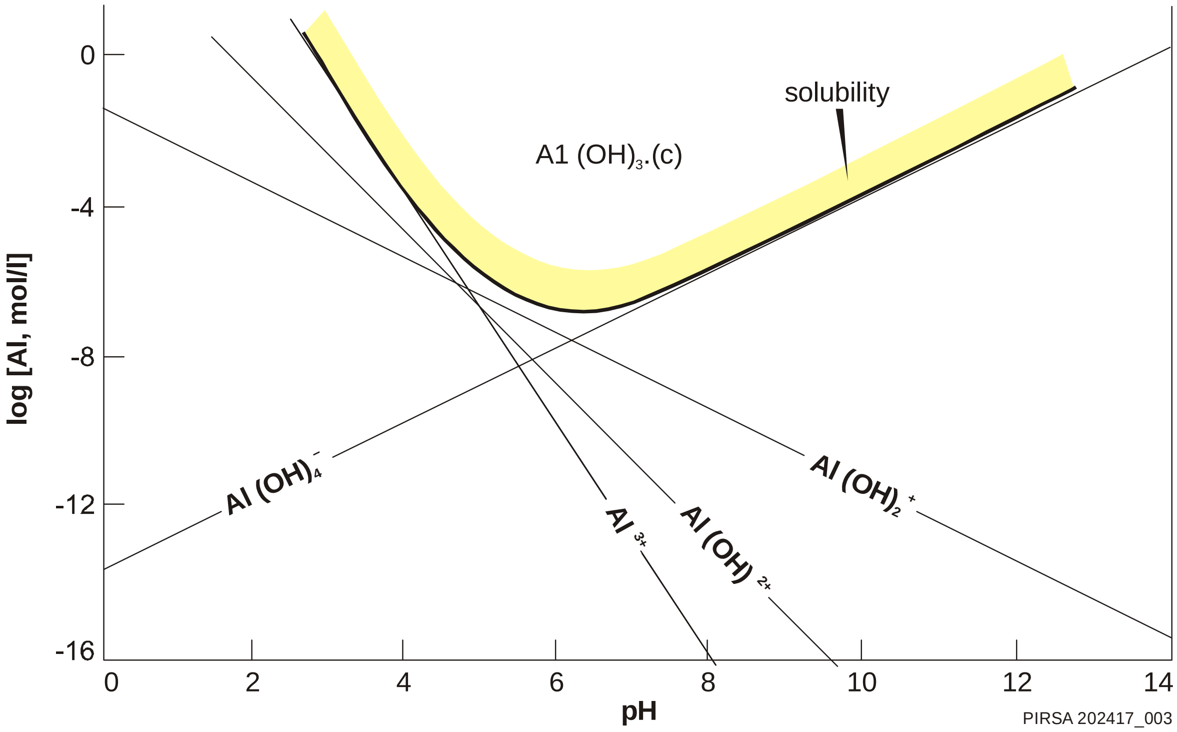

**Figure 11. Solubility constraints on total dissolved aluminium by gibbsite (Al(OH)$_3$) and aqueous Al-hydroxide complexes (after Appelo & Postma, 1999, Figure 6.7). The speciation of Al in groundwater depends on the logarithm of the initial concentration of dissolved Al and the pH of the solution (groundwater). Aluminium dissolved in groundwater samples that plot on the hatched side of the solubility curve for Al(OH)$_3$ (heavy line) will precipitate out of solution as Al(OH)$_3$. This diagram shows that the threshold pH for precipitation of dissolved aluminium at the Western's site BHO1ls ([Al] = 4.5 mg/L) is approximately 4.4 and approximately 4 at BHP1 ([Al] = 25 mg/L).**

## 4.4 Summary of the Processes Leading to the Formation of the Al-Hydroxide Precipitate in Groundwater Pumped From the Loxton Sands

Based on the above discussion, a hypothesis for the processes leading to the formation of the Al-hydroxide precipitate has been formed. This hypothesis explains (a) the geochemical processes leading to the production of groundwater acidity, (b) the precipitation of the Al precipitate, and (c) why these were originally observed at the production bore BHP1 and not in the observation well BHO1ls 30 m away, which screens approximately the same interval of aquifer.

The hypothesis is as follows (Fig. 12):

- The pre-pumping chemistry of Upper Loxton Sands groundwater at BHO1ls is representative of ambient conditions within the aquifer.
- Under ambient conditions, the Upper Loxton Sands groundwater is anoxic with a pH of approximately 6 and contains high (at least 25 mg/L) concentrations of dissolved $Fe^{2+}$, as well as aluminium in some as yet unconfirmed available form, e.g. adsorbed to aquifer minerals or organic material.
- Pumping from the production bore, BHP1, at high rates (e.g. > 2.7 L/s during the 7-day pump test) caused a cone of drawdown around the well (up to 5 m drawdown) and oxygenation of the groundwater around the well.
- As the maximum drawdown in the nearby observation well, BHO1ls, was only 30 cm during pumping of BHP1, oxygenation of the groundwater around this well did not occur to such an extent as at the production bore.
- Oxygenation of the groundwater around BHP1 caused oxidation of Fe2+ and precipitation of the resulting Fe3+ as Fe(OH)3, following reaction (1) above. This reaction produces H+ ions and causes the pH of the groundwater in the zone of oxygenation to drop from 6 to as low as 4.
- The reduction in pH caused aluminium to come into solution (probably released from cation exchange sites). This pH reduction at BHP1 was great enough for the aluminium to remain dissolved in solution.
- Mixing between the low pH, aluminium-bearing water from the Upper Loxton Sands and the higher pH groundwater from the Lower Loxton Sands (not affected by oxygenation) occurred around the pump, which was set adjacent the Lower Loxton Sands (at 53 m).
- Mixing between these two groundwater types resulted in a pH > 4.5 and the aluminium precipitated out around the pump and in the discharge water.
- Subsequent pumping of BHO1ls and BHP6 at lower rates ($\leq$ 1 L/s) caused the pH of the Upper Loxton Sands groundwater to decrease via Reaction 1 described above. This pH decrease was not as great as that observed at BHP1, being great enough to release aluminium from cation exchange but not to maintain it in a soluble form. The released aluminium then precipitated out as $Al(OH)_3$. Hence, mixing with the Lower Loxton Sands groundwater was *not* required for the precipitate to form in this case.

Even though the pump has been set adjacent the Lower Loxton Sands during the test on BHP1, appreciable volumes of low pH aluminium-bearing water can be obtained from the Upper Loxton Sands if the pump rate is high enough. This is due to the comparatively high permeability of the sediments in the top of the Upper Loxton Sands, as seen in the results of the flow meter test (Section 3.4). This enables mixing between the Upper and Lower Loxton Sands groundwaters and the onset of the Al-oxyhydroxide precipitation reaction. This is supported by the salinity of the discharge water, which was intermediate, between those of the Upper and Lower Loxton Sands groundwaters (Table 2).

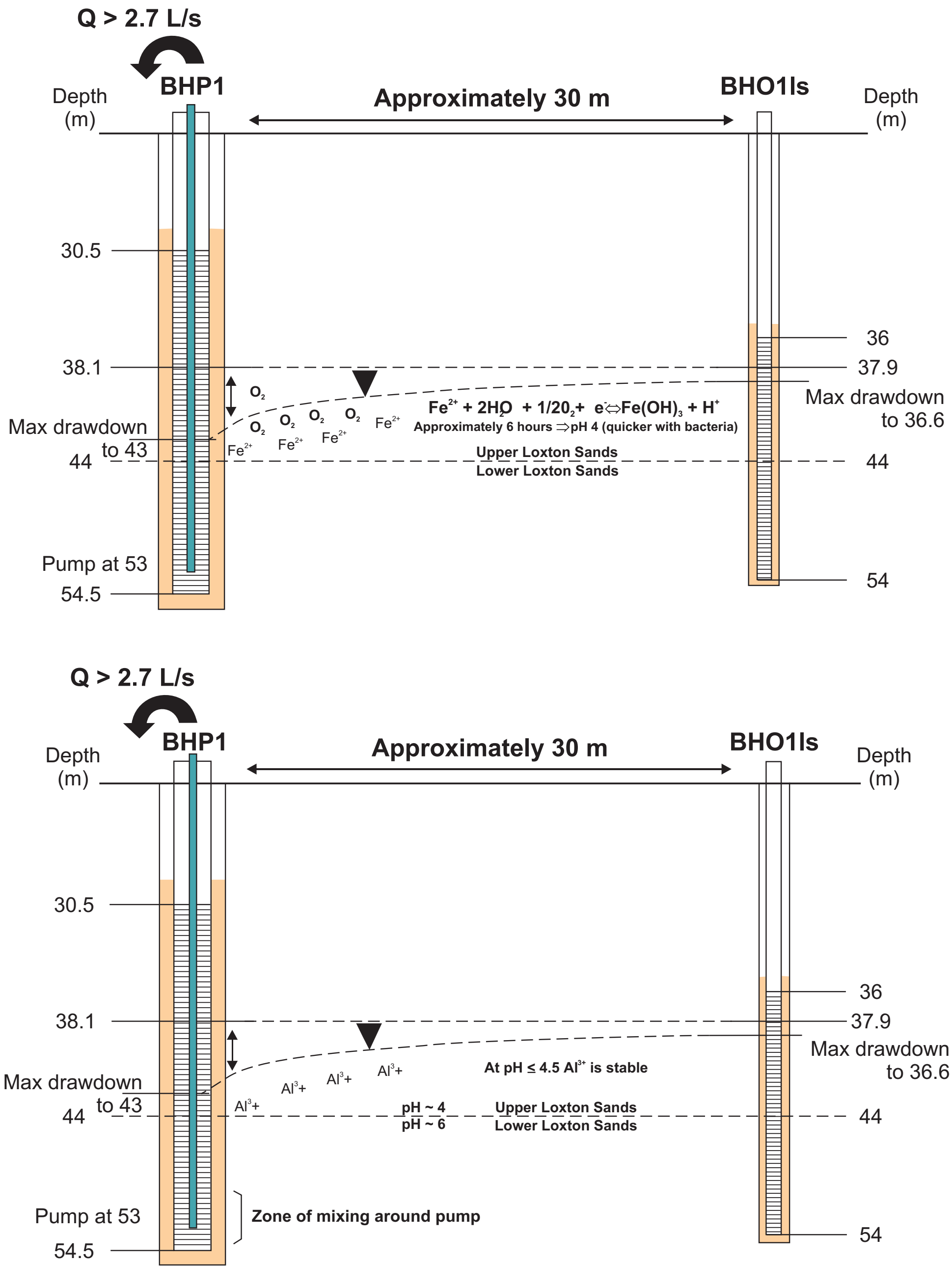

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**Figure 12.** Schematic diagram of final hypothesis for Al-precipitate formation.

## 4.5 Spatial Extent of the Problem

Of major importance to the development of the Loxton and Bookpurnong Salt Interception Schemes is the spatial extent of the conditions that lead to the precipitation of Al-hydroxide in bores screened in the Loxton Sands. Based on the above results and discussion, the following conditions are required for the formation of the precipitate:

1. High dissolved iron concentrations (e.g. $\geq$ 25 mg/L).
2. Low concentrations of buffering species (i.e. alkalinity), allowing pH to drop below approximately 5.5.
3. Aluminium present in some available form (e.g. sorbed to minerals or organic matter).

Such high dissolved iron concentrations as that observed in the pre-pumping Upper Loxton Sands groundwater sample from BHO1ls (25.9 mg/L) have not been observed elsewhere in the Loxton Sands of the Loxton – Bookpurnong region (Harrington et al., 2004, in prep.). However, there are few bores available that are known to be screened in the Upper Loxton Sands and the high degree of ferruginization suggests that there is potential for large amounts of dissolved Fe in this aquifer throughout the area. Condition 1 should therefore be considered to be satisfied throughout the region, particularly in the ULS, in the absence of further data to refute this. As aluminium is a weathering product of alumino-silicate minerals, it is ubiquitous in the natural environment, although generally not mobile due to the dependence of its soluble form on low pH conditions. Condition 3 could therefore also be considered to be satisfied throughout the region.

The potential for the Al precipitate to occur at a particular location therefore depends on Condition 2 being satisfied. This occurs at Western's Highland due to the low initial groundwater pH of 6 and low alkalinity of the ambient ULS groundwater and the lack of any carbonate material in the sediments to buffer the decrease in acidity. In areas with high ambient groundwater pH and alkalinity, for example where irrigation water, carbonate aquifer material or both are present, even if iron oxidation occurs, the resulting drop in pH will probably not be great enough to bring $Al^{3+}$ into solution. The regional geochemical sampling program has shown that the Loxton Sands groundwaters in the Loxton-Bookpurnong region generally have pHs greater than 7 and alkalinity greater than 4 mEq/L (Harrington et al., in prep.). However, conditions similar to those at Western's Highland (i.e. pH < 7 and alkalinity < 4 mEq/L) have been observed in piezometer IA3 and bore EES4 in the Bookpurnong region. Additional down-hole water quality profiles have also identified a low groundwater pH of 5 in piezometer IA2. However, a subsequent attempt at collecting a groundwater sample from this bore identified that the water is black and cloudy with a strong $H_2S$ smell. The reducing conditions implied by this may therefore also be responsible for the low pH in this bore, although the result indicates the lack of buffering against acidity production at that location. Bore IA2 must be re-developed before a representative groundwater sample can be obtained from it. Water quality profiles at EES1, EES2, EES6, BKP1, BKP2, BHP2 and BHP3 indicated groundwater pHs between 7 and 8.5 (Harrington et al., 2004). These results suggest that the potential for the aluminium precipitate to occur in the Bookpurnong region may be limited to the north and east of the groundwater mound (i.e. north of EES2 and east of EES2 and BKP1). A lack of data in that region prevents the risk area from being more clearly defined than this.

In the Loxton region, bores L22, L24A and L14, to the east of the groundwater mound, are the only Loxton Sands bores observed to intersect groundwater with pH values below 7. However the groundwater alkalinities at these locations are greater than 10 mEq/L suggesting that this area represents only a minor risk of Al-hydroxide precipitation. The floodplain Monoman Formation observation well LFO3A to the north of Loxton has a comparatively low groundwater pH of 6.6 and a relatively low alkalinity of 4.8 mEq/L, which are conditions representative of a mild risk for the formation of the Al-hydroxide precipitate. However the potential for the occurrence of this process on the floodplain has not been adequately assessed for substantial conclusions to be drawn from this.

## 4.6 Possible Management Approaches

If it is necessary to pump from the ULS in areas where the Al-hydroxide precipitate is likely to occur, a potential management approach may be to ensure that the groundwater pH is reduced below approximately 4.5 (the limited results suggest that this may be possible by pumping at rates greater than 2.7 L/s, for example, although this is yet to be confirmed) and prevent mixing between this water and water with a higher pH in areas where the aluminium precipitate would cause clogging. However, as the reactions discussed above have not been observed over time scales greater than a week, this would not be recommended until further study is carried out. The best approach would be to avoid installing production bores in identified high risk areas unless preliminary testing for the occurrence of the precipitate has been carried out. As a cautious approach, it is recommended that such testing be carried out at all locations of proposed Loxton Sands borefields.

Pumping from the LLS only may be an alternative option in areas where the Al precipitate is produced from the ULS. However, mixing with substantial amounts of ULS groundwater must be prevented and the long-term effects of this approach have also not been adequately assessed. Although the presence of abundant shell fragments and carbonate material in the LLS appears to maintain generally high alkalinities, and dissolution of this material can buffer any production of acidity, complete dissolution of this material over long time scales may, for example, allow pHs to drop below the threshold in the future and allow the onset of Al-hydroxide precipitation.

# 5 CONCLUSIONS AND RECOMMENDATIONS

- The Al-oxyhydroxide precipitate is a product of:
    - Ambient geochemical conditions in the Upper Loxton Sands, i.e. high concentrations of dissolved $Fe^{2+}$, a low buffering capability of the aquifer and the presence of available aluminium (probably adsorbed).
    - Oxidation of $Fe^{2+}$ by pumping, causing a reduction in groundwater pH to below approximately 4.5 at which the available Al comes into solution.
    - Mixing of resulting water with more neutral water from the Lower Loxton Sands.
    - Alternatively, if the pH only decreases to between 4.5 and 5.5 (approximately) as a result of the $Fe^{2+}$ oxidation reaction, the Al released from cation exchange sites will immediately begin to precipitate as $Al(OH)_3$.
- Therefore, the areas at greatest risk for the production of the Al precipitate are those where there are large concentrations of dissolved Fe (this appears to be predominantly in the Upper Loxton Sands), where the aquifer material does not contain carbonaceous material and ambient groundwater pH is < 7, i.e. north and east of the groundwater mound at Bookpurnong (north of EES2 and east of EES2 and BKP1).
- Regional geochemical data suggests a minor risk of Al-hydroxide precipitation in the region to the east of the irrigation mound at Loxton, and potentially in the Monoman Formation on the floodplain in the vicinity of observation well LFO3A to the north of Loxton.
- As a cautious approach, it is recommended that preliminary drilling and testing of observation wells for the aluminium precipitate be carried out in all locations where production bores are proposed to be screened in the Loxton Sands aquifer and that areas where the precipitate is known to occur be avoided as sites for a production borefield unless proper investigation of alternative management approaches is carried out.
- In the case of the occurrence of low pH, Al-bearing water, a possible management approach may be pumping from the Lower Loxton Sands only, although the long term processes associated with this should be investigated.

# 6 REFERENCES

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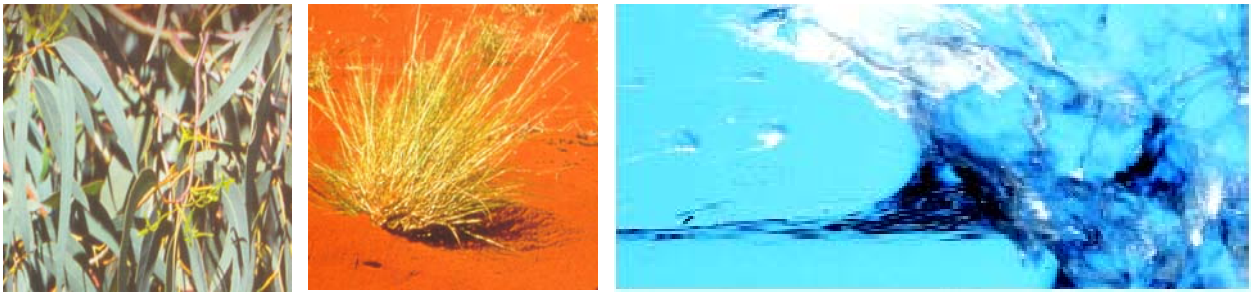
# 7 APPENDIX A



## BORE LOGS

Australian WATER Environments
Level 1, 68 The Parade Norwood SA 5067
PO Box 171 Kent Town SA 5071
Telephone: (08) 8363 7050  Facsimile: (08) 8363 7049

| | |
|---|---|
| ***Project:*** | Bookpurnong SIS |
| ***Job No.*** | 42441.211 |

## Bore data

| | |
|---|---|
| **Permit No.** | 63469 |
| **Unit No.** | |
| **Obs. No.** | |
| **AWE Name** | BHP6 |
| **Purpose** | Production Bore |

## Location Data

| | |
|---|---|
| **Hundred** | Gordon |
| **Section No.** | 199 189 |
| **Easting (m)** | 463212 |
| **Northing (m)** | 6201486 |
| **Datum** | GDA |

## Elevation data

| | **(m)** |
|---|---|
| **Ground Surface** | 51.412 |
| **Ref. Point above Ground** | 51.943 |
| **Ref. Point** | 0.531 |
| **Top of open interval** | 17.0 |
| **Bottom of open interval** | 11.0 |

## Drilling data

| | |
|---|---|
| **Start date** | 12/01/2004 |
| **Finish date** | 14/01/2004 |
| **Driller** | Underdale Drillers |
| **Drilling Method** | Rotary |
| **Circulation** | Mud |
| **Maximum drilled depth (m)** | 42.0 |
| **Completed bore depth (m)** | 40.4 |
| **Samples logged by** | Michael Wall |

## Post-development data

| | |
|---|---|
| **Date** | 14/01/2004 |
| **Development duration (min)** | 300 |
| **Depth to SWL below Ref. Pt. (m)** | 38.11 |
| **Depth to SWL below GL (m)** | -13.84 |
| **RSWL (m AHD)** | -37.58 |
| **EC Field (uS/cm)** | 38000 |
| **EC Lab (uS/cm)** | |
| **Yield (L/s)** | 0.5 |
| **Method** | Jetting |

## Completion data

| **Hole Diameter** | | **mm** | **From** | **To** | **Bit** |
|---|---|---|---|---|---|
| | Pilot Hole | 146 | 0.0 | 33.8 | 5 3/4" Blade |
| | | 127 | 33.8 | 42.0 | 5" Rock Roller |
| | Reaming | 342.9 | 0.0 | 42.0 | 13.5" Blade |
| **Backfilled** | | | **From** | **To** | **Material** |
| | | | | | |
| **Casing Diameter** | | **mm** | **From** | **To** | **Material** |
| | | 175 | 0.0 | 34.4 | Class 12 PVC |
| **Screen Diameter** | | **mm** | **From** | **To** | **Material** |
| | | 175 | 34.4 | 40.4 | 12 PVC Slotted PVC |
| | | | **From** | **To** | **Type** |
| **Grout** | | | 10.0 | 27.5 | 4 bags |
| **Bentonite Seal** | | | 27.5 | 29.5 | 2 Buckets |
| **Gravel Pack** | | | 29.5 | 40.4 | |

## Chemistry

| **Chemistry** | | **Units** |
|---|---|---|
| **pH** | | |
| **TDS by EC** | | mg/L |
| **EC** | | uS/cm |
| **TDS by calc.** | | mg/L |
| **Ca** | | mg/L |
| **Mg** | | mg/L |
| **K** | | mg/L |
| **Na** | | mg/L |
| **HCO3** | | mg/L |
| **F** | | mg/L |
| **Cl** | | mg/L |
| **SO4** | | mg/L |
| **NO2/3 as N** | | mg/L |
| **NO2/3 as NO3** | | mg/L |
| **Boron** | | mg/L |
| **Fe - Total** | | mg/L |

## Geophysics

| | |
|---|---|
| **Job No.** | **N/A** |

## Geology

| Depth (m) | Stratigraphy | Bore Diagram | Material | Description / Notes |
|---|---|---|---|---|
| 0-5 | Woorinen Formation | | SAND | Fine red brown quartz rich sand, minor calcrete |
| 5-7 | Woorinen Formation | | CALCRETE | Hard pink calcrete |
| 7-9 | Blanchetown Clay | | SAND | Fine white quartz sand |
| 9-13 | Blanchetown Clay | | SAND | Clean, fine white sand, finest between 10-11m, increasing grain size with depth from 11-13m |
| 13-17 | Blanchetown Clay | | SAND | Very clean medium grained quartz sand, white, sub angular- sub rounded |
| 17-18 | Blanchetown Clay | | SAND | Red, fine quartz sand, minor clay content |
| 18-20 | Blanchetown Clay | | SANDY CLAY | Very sandy clay, fine red quartz |
| 20-24 | Upper Loxton Sands | | SAND | Well cemented chips, fine, sandy, dull yellow |
| 24-28 | Upper Loxton Sands | | SAND | Very fine quartz, yellow sand, very well sorted |
| 28-29 | Upper Loxton Sands | | CLAYEY SAND | Becoming clayey and silty, darker colour, greenish |
| 29-32 | Upper Loxton Sands | | CLAYEY SAND | Clayey sand, fine, greenish yellow brown, some medium sized quartz grains |
| 32-35 | Upper Loxton Sands | | SAND | Orange brown, quartz, medium grained, sub angular |
| 35-36 | Upper Loxton Sands | | SAND | Medium grained well sorted quartz sand |
| 36-37 | Upper Loxton Sands | | SAND | Clean, yellow-white medium grained well sorted quartz sand |
| 37-40 | Upper Loxton Sands | | SAND | Clean, medium grained, well sorted quartz sand, white |
| 40-41 | Upper Loxton Sands | | SAND | Becoming silty medium grained, quartz sand, sub angular - sub rounded |
| 41-42 | Upper Loxton Sands | | SILTY SAND | Increasing fines, as above. |

## Drilling Flow and Salinity Data

| Depth (m) | Volume (L) | Time (sec) | Yield (L/s) | Salinity (EC) |
|---|---|---|---|---|
| | | | | |

Pit losing water at 27-30m

Hard band from 33.7-34.5m

Rock roller put on at 33.8m (very slow with blade)
>42m very minor grey silty clay lumps (<1% of sample, bit must be almost touching grey layer
4 bags cement

**BHP6**

| | |
|---|---|
| **Project** | BL4EA |
| **Job No.** | 41313 (H) |

## Bore data

| | |
|---|---|
| **Permit No.** | 57458 |
| **Unit No.** | N/A |
| **Obs. No.** | BHP1 (uls) |
| **Purpose** | Piezometer |

## Location Data

| | |
|---|---|
| **Hundred** | Gordon |
| **Section No.** | 198 |
| **Easting (m AMG)** | 463204 |
| **Northing (m AMG)** | 6201432 |
| **Datum** | GDA94 |

## Elevation data

| | (m) |
|---|---|
| **Ground Surface** | 51.97 |
| **Ref. Point above Ground** | 0.49 |
| **Ref. Point** | 52.46 |
| **Top of open interval** | 21.5 |
| **Bottom of open interval** | -2.5 |

## Drilling data

| | |
|---|---|
| **Start date** | 19/03/2002 |
| **Finish date** | 21/03/2002 |
| **Driller** | Underdale Drillers |
| **Drilling Method** | Mud Rotary |
| **Circulation** | mud |
| **Maximum depth (m)** | 62.0 |
| **Completed depth (m)** | 62.0 |
| **Samples logged by** | Geoff White |

## Post-development data

| | |
|---|---|
| **Date** | 14-Jun-02 |
| **Depth to SWL below Ref. Pt. (m)** | 38.62 |
| **Depth to SWL below GL (m)** | 38.13 |
| **RSWL (m AHD)** | 13.84 |
| **EC Field (uS/cm)** | - |
| **EC Lab (uS/cm)** | 58100 |
| **Yield (L/s)** | >4L/s |
| **Method** | Jet (6hrs at least) |

## Completion data

| **Hole Diameter** | **mm** | **From** | **To** | **Bit** |
|---|---|---|---|---|
| | 356 | 0.0 | 62.0 | Blade |
| **Backfilled** | | | | **Material** |
| | | | | |
| **Casing Diameter** | | | | **Material** |
| | 177 | 0.0 | 30.5 | Class 12 PVC |
| **Screen Diameter** | | | | **Material** |
| | 177 | 30.5 | 54.5 | Class 12 PVC 2mm slots |
| | | | | **Type** |
| **Grout** | | 26.0 | 0.0 | |
| **Bentonite Seal** | | 26.0 | 27.0 | 1/4 inch pellets |
| **Gravel Pack** | | 27.0 | 37.0 | 1/4 by 1/8 gravel |
| | | 37 | 62 | 6/8 gravel |

## Chemistry

| | | **Sediment** | **Units** |
|---|---|---|---|
| **pH** | 5.7 | | |
| **TDS by EC** | 39000 | | mg/L |
| **EC** | 58100 | | uS/cm |
| **TDS by calc.** | 40400 | | mg/L |
| **Ca** | 249 | 3380 | mg/L |
| **Mg** | 1150 | 4250 | mg/L |
| **K** | 191 | | mg/L |
| **Na** | 12500 | | mg/L |
| **HCO3** | 55 | | mg/L |
| **Al** | | 193000 | mg/L dry |
| **Cl** | 21600 | | mg/L |
| **SO4** | 4660 | | mg/L |
| **NO2/3 as N** | 0.387 | | mg/L |
| **NO2/3 as NO3** | 1.72 | | mg/L |
| **Boron** | 2.09 | | mg/L |
| **Fe - Total** | | | mg/L |

## Geophysics

| | | |
|---|---|---|
| **Job No.** | | Not logged |

## Geology

| **Depth (m)** | **Stratigraphy** | | **Material** | **Description** |
|---|---|---|---|---|
| 0 - 7.0 | Woorinen Fm | 🟫 | sand and calcrete | no samples |
| 7.0 - 8.2 | Woorinen Fm | 🟫 | sand and calcrete | pink to red fine quartz sand. Minor clay, some calcrete nodules. |
| 8.2 - 9.0 | Woorinen Fm | 🟫 | sand | no samples |
| 9.0 - 12.2 | Unnamed Sand | 🟨 | sand | fine white quartz sand (9.2-11.9 no sample but sample from mud gives evidence) |
| 12.2 - 13.7 | Unnamed Sand | 🟨 | sand | no samples |
| 13.7 - 13.8 | Blanchetown Clay | 🟩 | sandy clay | light green sandy clay and white/pink quartz sand mod well sorted, subrounded. |
| 13.8 - 16.2 | Blanchetown Clay | 🟩 | sandy clay | no samples |
| 16.2 - 21.5 | Upper Loxton Sands | ▨ | clayey sand | fine white and orange slightly clayey quartz sand with evidence of pisolites at 16.2m. Core losses between18.0-18.1,18.6-18.8,20.6-20.8 |
| 21.5 - 25.3 | Upper Loxton Sands | ▨ | clayey sand | no samples |
| 25.3 - 25.5 | Upper Loxton Sands | ▨ | sand | orange med quartz sand sub-rounded mod well sorted. |
| 25.5 - 26.2 | Upper Loxton Sands | ▨ | sand | no samples |
| 26.2 - 27.5 | Upper Loxton Sands | ▨ | clayey sand | orange to red med/fine sand and clay less well sorted than above. |
| 27.5 - 30.5 | Upper Loxton Sands | ▨ | sand | fine orange/yellow quartz sand (contains coarser sand inclusions) poorly sorted sub angular |
| 30.5 - 33.1 | Upper Loxton Sands | ▨ | sand | no samples |
| 33.1 - 34.7 | Upper Loxton Sands | ▨ | sand | coarse well cemented (hard) quartz sand purple and orange coloured. Sub rounded. core loss from 32.7-33.05,33.7-34.6 |
| 34.7 - 35.5 | Upper Loxton Sands | ▨ | sand | no samples (hard drilling). |
| 35.5 - 41.6 | Upper Loxton Sands | ▨ | clayey sand | quartz sands poorly sorted with minor clay subangular grains. core loss from 35.7-39.7, 35.7-41.6 |
| 41.6 - 41.7 | Upper Loxton Sands | ▨ | silty sand | grey silty quartz sand slightly micaceous |
| 41.7 - 44.0 | Upper Loxton Sands | ▨ | silty sand | no samples but colour change in cuttings at 42.7m and minor clay on the bit. |
| 44.0 - 57.7 | Lower Loxton Sands | ▨ | silty sand | fine dark grey silty micaceous sand. Some bands slightly sandier or clayey. Med to fine grained sand with silt matrix. Core losses 44.7-45.5, 45.7-46.5, 46.7-50.2, 50.7-51.7, 51.7-51.9, 52.7-53.7, 54.0-54.4, 54.7-55.3, 55.7-56.7 |
| 57.7 - 62.0 | Lower Loxton Shells | ▨ | clayey silt | fossiliferous (bivalves) clayey silt with very minor mica. Dark green colour. |

**Notes on installation of piezometer:**

All depths are measured below ground level (BGL) unless otherwise stated

Centralizers were used to keep the pvc in the centre of the hole and maintain a constant gravel pack width.

Casing has bulbed joints and were joined using pvc cement and tech screws
External endcap was used.

Depth of gravel found using a fishing line with weights.

A protective standpipe was cemented into position to complete the bore

**Australian Water Environments**

| Bore data | |
|---|---|
| **Permit No.** | 59143 |
| **Unit No.** | N/A |
| **Obs. No.** | BHP2 (uls) |
| **Purpose** | Production |

| Location Data | |
|---|---|
| **Hundred** | Gordon |
| **Section No.** | adj. 117 |
| **Easting (m AMG)** | 461219 |
| **Northing (m AMG)** | 6199826 |
| **Datum** | GDA |

| Elevation data | (m) |
|---|---|
| **Ground Surface** | 27.97 |
| **Ref. Point above Ground** | 0.48 |
| **Ref. Point** | 28.45 |
| **Top of open interval** | 16.5 |
| **Bottom of open interval** | 4.5 |

| Drilling data | |
|---|---|
| **Start date** | 02/09/2002 |
| **Finish date** | 02/09/2002 |
| **Driller** | Underdale Drillers |
| **Drilling Method** | Rotary |
| **Circulation** | Mud |
| **Maximum depth (m)** | 36.0 |
| **Completed depth (m)** | 25.5 |
| **Samples logged by** | Geoffrey White |

| Post-development data | |
|---|---|
| **Date** | 03/09/2002 |
| **Depth to water below Ref. Pt. (m)** | 14.52 |
| **Depth to SWL below GL (m)** | 14.04 |
| **RSWL (m AHD)** | 13.93 |
| **EC Field (uS/cm)** | 37,000 |
| **EC Lab (uS/cm)** | 38,100 |
| **Yield (L/s)** | 1.8 |
| **Method** | Air Jetting |

| Completion data | | | | |
|---|---|---|---|---|
| **Hole Diameter** | **mm** | **From** | **To** | **Bit** |
| | 356 | 0.0 | 26.5 | Blade |
| | 165 | 26.5 | 36.0 | Stepped Blade |
| **Backfilled** | | **From** | **To** | **Material** |
| | | 26.5 | 36.0 | Cuttings |
| **Casing Diameter** | **mm** | **From** | **To** | **Material** |
| | 200 | 0.0 | 11.5 | Class 12 PVC |
| | 200 | 25.5 | 23.5 | Class 12 PVC |
| **Screen Diameter** | **mm** | **From** | **To** | **Material** |
| | 200 | 11.5 | 23.5 | Class 12 PVC 2mm machine slots |
| | | **From** | **To** | **Type** |
| **Grout** | | 0.0 | 8.0 | 8 bag mix, 1 bag of bentonite |
| **Bentonite Seal** | | 8.0 | 10.0 | 1/4inch pellets |
| **Gravel Pack** | | 10.0 | 25.5 | 1/4*1/8 with fines |

| Chemistry | | Units |
|---|---|---|
| **pH** | 7.9 | |
| **TDS by EC** | 24,000 | mg/L |
| **EC** | 38,100 | uS/cm |
| **TDS by calc.** | 26,200 | mg/L |
| **Ca** | 209 | mg/L |
| **Mg** | 683 | mg/L |
| **K** | 120 | mg/L |
| **Na** | 8,710 | mg/L |
| **HCO3** | 755 | mg/L |
| **F** | N/M | mg/L |
| **Cl** | 12,200 | mg/L |
| **SO4** | 3,930 | mg/L |
| **NO2/3 as N** | < 0.005 | mg/L |
| **NO2/3 as NO3** | 0.02 | mg/L |
| **Boron** | 4.55 | mg/L |
| **Al - Total** | 3.25 | mg/L |

| Geophysics | |
|---|---|
| **Job No.** | |

## Geology

| Depth (m) | Stratigraphy | Material | Description |
|---|---|---|---|
| 0 - 2 | Woorinen Formation | Sand | Red brown fine grained quartz sand well sorted. |
| 2 - 3 | Woorinen/Bakara | Sand and Calcrete | Sand as above with pink calcrete chips. Calcrete is hard with white centre. |
| 3 - 8 | Woorinen Formation | Slightly clayey sand | Fine to Med/fine quartz sand, trace clay feel (possibly the drilling Mud) moderately well sorted (some med subrounded quartz grains). No Calcrete. Trace mica. Red grey in colour. |
| 8 - 9 | Unnamed SandUnit | Sand | Very poorly sorted quartz sand fine to coarse sub rounded brown grey in colour. |
| 9 - 11 | Unnamed SandUnit | Sand | Brown grey to red fine very poorly sorted sand to silty sand. Minor mica. Minor coarse quartz grains subrounded. |
| 11 - 12 | Upper Loxton Sands | Sand | 80% coarse to med quartz sand rounded to sub rounded moderately well sorted. 20% fine quartz silty sand with no mica. Red browny grey in colour |
| 12 - 17 | Middle Loxton Sands | Sand | Yellow orange silty poorly sorted sand. Sand is medium to coarse grained sand is subrounded (no mica) 80% sand, 20% silt. Some gravel sized grains. |
| 17 - 20 | Middle Loxton Sands | Silty Sand | Yellow orange silty sand (19 - 20m contains 100mm of hard band) Poorly sorted. 50% sand 50% silt. Sand is sub rounded and becoming fossiliferous. (large bivalve fragments) |
| 20 - 21 | Upper Loxton Sands | Sand | Browny yellow coarse quartz sand. Containing shell fragments to 1cm. Sand well to moderately well sorted. <5%silt and >95% Sand. |
| 21 - 22 | Lower Loxton Shells | Silty Sand | Becoming grey highly fossiliferous silty sand. Very poorly sorted. Silt to very coarse quartz sand. Shell fragments to >1cm. |
| 22 - 25 | Lower Loxton Shells | Silty Sand | Grey poorly sorted silty sand containing large quartz grains subrounded. Large bivalve fragments. Contains mica, no black flecks. Light to medium grey. |
| 25 - 30 | Lower Loxton Shells | Silty Sand | Medium grey slightly clayey silty sand containing large abundant fossils (to 1.5cm) Mollusc and gastropod shells. Quartz grains are dominantly fine but large sub well rounded grains are present. Hard band (150mm) From 27 - 28m. |
| 30 - 35 | Lower Loxton Shells | Clayey Silt | Grey fossiliferous clayey silt containing large fossils to 1cm. Also contains minor mica and Black flecks that are lignitic. Very low plasticity. |
| 35 - 36 | Lower Loxton Clay | Silty Clay | Light grey medium plasticity silty clay. No black flecks and no fossils. |

**Notes on installation of piezometer:**
All depths are measured below ground level (BGL) unless otherwise stated
Bore jetted with air on 3/9/02. Clean flow was obtained after 5.5hrs. Jetting completed after 6hrs. Minor quantity of gravel pack was produced initially and then fine grained formation was slowly reduced to nothing after 5.5 hrs.
Screen planned to be 12 - 24m but collapse of the hole and meant that the casing was installed 0.5m short.
Starter bar used for drilling the 14 inch hole

4 bags of bentonite used in the mud
2L of Liquid polymer used.
8 bags of cement used in the grout along with 1 bag of bentonite.
2 buckets of 1/4 inch bentonite pellets used.
1.25 bulka bags of 1/4 by 1/8 gravel used in the gravel pack. The gravel contained some fine grained material from some (minor) left over 6/8 gravel used in the past.

Casing and screen had bulbed joints and were joined using PVC cement and Stainless Steel Tech Screws.
External Endcap used

Riverland Heritage Committee Aboriginal Supervision provided by Agnes Rigney and Bayden Moore for the top 3m of the hole and the mud pit drilled. (2/9/02)

| | |
|---|---|
| **Project** | Bookpurnong Highland Bores |
| **Job No.** | 42393(i) |

## Bore data

| | |
|---|---|
| **Permit No.** | 61768 |
| **Unit No.** | |
| **Obs. No.** | BHP3 |
| **Purpose** | Production Bore |

## Location Data

| | |
|---|---|
| **Hundred** | Gordon |
| **Section No.** | PT 276 |
| **Easting (m AMG)** | 461261.90 |
| **Northing (m AMG)** | 6199651.77 |
| **Datum** | RTK/GDA |

## Elevation data

| | m AHD |
|---|---|
| **Ground Surface** | 32.830 |
| **Ref. Point above Ground** | |
| **Ref. Point** | |
| **Top of open interval** | 12.7 |
| **Bottom of open interval** | 6.7 |

## Drilling data

| | |
|---|---|
| **Start date** | 29/04/2003 |
| **Finish date** | 30/04/2003 |
| **Driller** | Steve Juett |
| **Drilling Method** | Rotary |
| **Circulation** | Mud |
| **Maximum depth (m)** | 30.0 |
| **Completed depth (m)** | 27.6 |
| **Samples logged by** | Ben Hopkins |

## Post-development data

| | |
|---|---|
| **Date** | 25/06/2003 |
| **Depth to water below Ref. Pt. (m)** | 20.314 |
| **Depth to SWL below GL (m)** | 20.31 |
| **RSWL (m AHD)** | -20.31 |
| **EC Field (uS/cm)** | 13170 |
| **EC Lab (uS/cm)** | 14300 |
| **Yield (L/s)** | 1.0 |
| **Method** | Airlift |

## Completion data

| | mm | From | To | Bit |
|---|---|---|---|---|
| **Hole Diameter** | | | | |
| | 343 | 0.0 | 28.0 | Blade |
| **Backfilled** | | **From** | **To** | **Material** |
| | | | | |
| **Casing Diameter** | **mm** | **From** | **To** | **Material** |
| | 175 | 0.0 | 20.1 | Class 12 PVC |
| | 175 | 26.1 | 27.6 | Class 12 PVC |
| **Screen Diameter** | **mm** | **From** | **To** | **Material** |
| | 175 | 20.1 | 26.1 | 2.0 mm slots |
| | | **From** | **To** | **Type** |
| **Grout** | | 13.0 | 16.0 | Bentonite/cement |
| **Bentonite Seal** | | 16.0 | 17.0 | 1/2 bucket pellets |
| **Gravel Pack** | | 17.0 | 28.0 | 6/8 gravel |

## Chemistry

| | | Units |
|---|---|---|
| **pH** | 7.6 | |
| **TDS by EC** | 8300 | mg/L |
| **EC** | 14300 | uS/cm |
| **TDS by calc.** | 8790 | mg/L |
| **Ca** | 65.4 | mg/L |
| **Mg** | 208 | mg/L |
| **K** | 51.2 | mg/L |
| **Na** | 2840 | mg/L |
| **HCO3** | 802 | mg/L |
| **CO3** | 33 | mg/L |
| **Cl** | 3920 | mg/L |
| **SO4** | 1280 | mg/L |
| **NO2/3 as N** | 3.18 | mg/L |
| **NO2/3 as NO3** | 14.1 | mg/L |
| **Boron** | 4.77 | mg/L |

## Geophysics

| | |
|---|---|
| **Job No.** | |

## Geology

| Depth (m) | Stratigraphy | | Material | Description |
|---|---|---|---|---|
| 0 - 4 | Woorinen Fmn | 🟧 | Sand | red-brown, fine grained, quartz |
| 4 - 10 | Upper Loxton Sands | 🟨 | Sand | yellow and white, fine to medium, quartz |
| 10 - 12 | Upper Loxton Sands | ⬜ | Sand | white, medium to coarse, quartz |
| 12 - 19 | Upper Loxton Sands | 🟨 | Sand | yellow, poorly sorted, fine to coarse, quartz |
| 19 - 24 | Upper Loxton Sands | 🟨 | Sand | orange, fine to medioum, quartz, micaceous |
| 24 - 25 | Upper Loxton Sands | 🟨 | Sand | orange, fine to medium, quartz, micaceous, minor shell fragments |
| 25 - 26.5 | Upper Loxton Sands | 🟧 | Shells | abundant iron-stained fine grained shells, minor silt matrix |
| 26.5 - 27 | Lower Loxton Shells | ▨ | Shells | abundant grey medium grained shells, minor silt matrix, micaceous. Colour change at 26.5 m |
| 27 - 29 | Lower Loxton Shells | ▨ | Shells | grey, silty matrix, minor clay, medium grained shells |
| 29 - 30 | Lower Loxton Shells | ▤ | Silt | grey, silty clay matrix, fewer shells than above. |

**Drilling notes:**
Drilled 7" pilot hole to obtain accurate samples at metre intervals to 30 m, then reamed to 13.5" to 28 m
Not considered worth slotting Lower Loxton Shells because of risk of bleeding silt
Shells at this location dirtier and not as coarse as shells at BHO3

**7 Day Pump Test Info.**
Had trouble when pump first fired up - ran out of water above the pump and bore not recovering quick enough
Pump fired up second time with no problem. Was pumping clean water at 0.5-1L/s easily enough
To play it safe bore was re-jetted with air for an hour to see if any liquid polymer still in gravel pack.
Water came out clear and clean. Did not have the liquid polymer feel.
Bore was then jetted with chlorine and water to make sure there was no problem with gravel pack
Bore produced clean water and a steady flow of about 1L/s
Pump intake at 26m
Pumping at 1L/s

When aquifer test conducted, bore casing was flush with ground level.
DTW before pumping commended was 19.59 below ground level.
After aquifer test, bore was fitted with a PVC standpipe and flanged cap suitable for vaccuum sealing.
Top of flange is adopted as reference point, which is approximately 0.64 m above ground level
Clear PVC plate that covers flange (when pump not installed) is approximately 0.010 m thick

| | |
|---|---|
| **Project** | BL4EA |
| **Job No.** | 41313 (H) |

## Bore data

| | |
|---|---|
| **Permit No.** | 57448 |
| **Unit No.** | N/A |
| **Obs. No.** | BHO1 (g) |
| **Purpose** | Piezometer |

## Location Data

| | |
|---|---|
| **Hundred** | Gordon |
| **Section No.** | 198 |
| **Easting (m AMG)** | 463205 |
| **Northing (m AMG)** | 6201443 |
| **Datum** | GDA94 |

## Elevation data

| | (m) |
|---|---|
| **Ground Surface** | 51.76 |
| **Ref. Point above Ground** | 0.52 |
| **Ref. Point** | 52.29 |
| **Top of open interval** | -69.2 |
| **Bottom of open interval** | -168.2 |

## Drilling data

| | |
|---|---|
| **Start date** | 12/03/2002 |
| **Finish date** | 15/03/2002 |
| **Driller** | Underdale Drillers |
| **Drilling Method** | Mud Rotary |
| **Circulation** | mud |
| **Maximum depth (m)** | 85.0 |
| **Completed depth (m)** | 73.0 |
| **Samples logged by** | Geoff White |

## Post-development data

| | |
|---|---|
| **Date** | 14-Jun-02 |
| **Depth to SWL below Ref. Pt. (m)** | 38.68 |
| **Depth to SWL below GL (m)** | 38.16 |
| **RSWL (m AHD)** | 13.61 |
| **EC Field (uS/cm)** | - |
| **EC Lab (uS/cm)** | 21500 |
| **Yield (L/s)** | - |
| **Method** | airlift |

## Completion data

| | | | | |
|---|---|---|---|---|
| **Hole Diameter** | **mm** | **From** | **To** | **Bit** |
| | 203 | 0.0 | 121.0 | Blade |
| | 102 | 121.0 | 220.0 | Blade |
| | | | | |
| **Backfilled** | | | | **Material** |
| | | | | |
| **Casing Diameter** | **mm** | | | **Material** |
| | 125 | 0.0 | 121.0 | Class 12 PVC |
| | | 121.0 | 220.0 | open hole |
| **Screen Diameter** | **mm** | | | **Material** |
| | | | | |
| | | | | **Type** |
| **Grout** | | 0.0 | 121.0 | |
| **Bentonite Seal** | | | | |
| **Gravel Pack** | | | | |

## Chemistry

| | | Units |
|---|---|---|
| **pH** | 8.4 | |
| **TDS by EC** | 13000 | mg/L |
| **EC** | 21500 | uS/cm |
| **TDS by calc.** | 12800 | mg/L |
| **Ca** | 76.3 | mg/L |
| **Mg** | 129 | mg/L |
| **K** | 88.4 | mg/L |
| **Na** | 4570 | mg/L |
| **HCO3** | 660 | mg/L |
| **F** | - | mg/L |
| **Cl** | 6740 | mg/L |
| **SO4** | 902 | mg/L |
| **NO2/3 as N** | <0.005 | mg/L |
| **NO2/3 as NO3** | 0.02 | mg/L |
| **Boron** | 1.52 | mg/L |
| **Al** | 4.52 | mg/L |

## Geophysics

| | |
|---|---|
| **Job No.** | Not logged |

## Geology

| Depth (m) | Stratigraphy | | Material | Description |
|---|---|---|---|---|
| 0 - 7.0 | Woorinen Fm | 🟫 | sand and calcrete | no samples |
| 7.0 - 8.2 | Woorinen Fm | 🟫 | sand and calcrete | pink to red fine quartz sand. Minor clay, some calcrete nodules. |
| 8.2 - 9.0 | Woorinen Fm | 🟫 | sand | no samples |
| 9.0 - 12.2 | Unnamed Sand | 🟨 | sand | fine white quartz sand (9.2-11.9 no sample but sample from mud gives evidence) |
| 12.2 - 13.7 | Unnamed Sand | 🟨 | sand | no samples |
| 13.7 - 13.8 | Green Blanchetown Clay | 🟩 | sandy clay | light green sandy clay and white/pink quartz sand mod well sorted, subrounded. |
| 13.8 - 16.2 | Green Blanchetown Clay | 🟩 | sandy clay | no samples |
| 16.2 - 21.5 | Upper Loxton Sands | ▨ | clayey sand | fine white and orange slightly clayey quartz sand with evidence of pisolites at 16.2m. Core losses between18.0-18.1,18.6-18.8,20.6-20.8 |
| 21.5 - 25.3 | Upper Loxton Sands | ▨ | clayey sand | no samples |
| 25.3 - 25.5 | Upper Loxton Sands | ▨ | sand | orange med quartz sand sub-rounded mod well sorted. |
| 25.5 - 26.2 | Upper Loxton Sands | ▨ | sand | no samples |
| 26.2 - 27.5 | Upper Loxton Sands | ▨ | clayey sand | orange to red med/fine sand and clay less well sorted than above. |
| 27.5 - 30.5 | Upper Loxton Sands | ▨ | sand | fine orange/yellow quartz sand (contains coarser sand inclusions) poorly sorted sub angular |
| 30.5 - 33.1 | Upper Loxton Sands | ▨ | sand | no samples |
| 33.1 - 34.7 | Upper Loxton Sands | ▨ | sand | coarse well cemented (hard) quartz sand purple and orange coloured. Sub rounded. core loss from 32.7-33.05,33.7-34.6 |
| 34.7 - 35.5 | Upper Loxton Sands | ▨ | sand | no samples (hard drilling). |
| 35.5 - 41.6 | Upper Loxton Sands | ▨ | clayey sand | quartz sands poorly sorted with minor clay subangular grains. core loss from 35.7-39.7, 35.7-41.6 |
| 41.6 - 41.7 | Upper Loxton Sands | ▨ | silty sand | grey silty quartz sand slightly micaceous |
| 41.7 - 44.0 | Upper Loxton Sands | ▨ | silty sand | no samples but colour change in cuttings at 42.7m and minor clay on the bit. |
| 44.0 - 57.7 | Lower Loxton Sands | ▨ | silty sand | fine dark grey silty micaceous sand. Some bands slightly sandier or clayey. Med to fine grained sand with silt matrix. Core losses 44.7-45.5, 45.7-46.5, 46.7-50.2, 50.7-51.7, 51.7-51.9, 52.7-53.7, 54.0-54.4, 54.7-55.3, 55.7-56.7 |
| 57.7 - 61.8 | Lower Loxton Shells | ▨ | clayey silt | fossiliferous (bivalves) clayey silt with very minor mica . Dark green colour. |
| 61.8 - 67.4 | Lower Loxton Clays | ▨ | clayey silt | fine grey to green silty clay with black low flecks (unknown ID) low plasticity with minor fossil content. |
| 67.4 - 69.7 | Bookpurnong Beds | ▨ | clay | olive green shelly clay, med plasticity, glauconitic. Shells are mostly bivalve shells |
| 69.7 - 70.6 | Bookpurnong Beds | ▨ | clay | no samples |
| 70.6 - 86.3 | Pata Fm | ▨ | calcareous sand | fossiliferous calcareous sands and clays- low plasticity. No ID on fossils possible (fine samples) losing sand and becoming silty clay at 82.6. Core losses 70.6-71.25, 72.7-73.55, 73.7-74.25,74.7-75.7(due to no core catcher), 75.8-77.4, 76.7-77.6, 78.7-79.0, 79.8-79.95, |
| 86.3 - 88.7 | Winnambool Fm | ▨ | calcareous clay | calcareous clay, minor fossil content low plasticity 86-87 but med plasticity heavy clay towards the base. Light grey to yellow. |
| 88.7 - 114.0 | Glenforslan Fm | ▨ | calcareous clays and calcarenite | light grey calcareous clay and silt powdery feel. Contains minor light grey fossiliferous limestone and some calcarenite bands. Core losses 91.7-91.8, 102.7-103.05 |
| 114.0 - 115.7 | Finnis Fm equivalent | ▨ | clay | med dark grey calcareous silty low plasticity clay. |

|  |  |  |  |  |
|---|---|---|---|---|
| 115.7 - 140.0 | Upper Mannum Fm | ░ | calcareous clayey sands and Limestone | fossiliferous light grey to white limestone interbedded with some clayey calcareous sands and darker grey calcarenite. Fossils include Turretella. Some of the core loss may be due to cavities. Core Losses: 123.5-123.58, 127.7-128.5, 139.7-139.82. Other minor losses represented by poly pipe inserts in the core. |
|  |  | ▦ | limestone | 115.7-119.2 limestone |
|  |  | ░ | calcareous sand and calcarenite | 119.2-122.7 calcareous sands and calcarenite |
|  |  | ▦ | limestone | 122.7-123.9 limestone |
|  |  | ░ | calcareous sand | 123.9-125.7 calcareous sands |
|  |  | ▦ | limestone | 125.7-128.2 limestone |
|  |  | ▦ | limestone | 128.2-129.4 limestone |
|  |  | ▩ | calcarenite | 129.4-140.0 calcarenite dominated |
| 140.0 - 147.2 | Lower Mannum Fm | ▩ | calcarenite | yellow grey calcareous sands to 145.7m then darker grey fossiliferous calcarenite. Core Losses: 144.2-144.25 |
| 147.2 - 148.7 | Lower Mannum Fm | ▩ | calcarenite | light grey soft friable calcarenite some 0.2m core loss-see poly insert |
| 148.7 - 150.2 | Lower Mannum Fm | ▩ | calcarenite | soft friable calcarenite with coarser bands and echinoid spines |
| 150.2 - 151.7 | Lower Mannum Fm | ░ | calcareous sand and calcarenite | dark grey soft drilling calcarenite and calcareous sand. Core loss from 150.2 150.7 |
| 151.7 - 154.7 | Lower Mannum Fm | ░ | calcareous silt | dark grey calcareous silt with hard cemented layers. Fossils include sponge spicules, echinoid spines, gastropods and bryozoa. Core loss from 153.2-154.7 |
| 154.7 - 156.2 | Lower Mannum Fm | ░ | calcareous silt | soft drilling calcareous silt. Core loss from 155.5-155.77 |
| 156.2 - 157.7 | Lower Mannum Fm | ▦ | limestone and calcareous sand | hard cemented limestone grading to dark grey calcareous sand and silt. Core loss 156.6-157.0 |
| 157.7 - 160.7 | Lower Mannum Fm | ░ | calcareous sand and calcarenite | dark grey calcareous sands and calcarenite, variously soft and friable and hard. Some cavities may be present. Core loss from 159.2-159.3 |
| 160.7 - 162.2 | Lower Mannum Fm | ▦ | limestone and calcareous sand | Light grey hard limestone with light grey calcareous clays and sands. Sponge spicules were contained within the sample. |
| 162.2 - 163.7 | Lower Mannum Fm | ▦ | limestone and calcareous sand | harder drilling hard limestone at top with a band of light and dark grey calcareous sands and silts. Sands have may fossils including bryozoa and echinoid spines. Silts have powdery feel. |
| 163.7 - 165.2 | Lower Mannum Fm | ░ | calcareous silt | Light and dark grey calcareous clays and silts. Core loss 0.1m see poly insert. |
| 165.2 - 168.2 | Lower Mannum Fm | ░ | calcareous silt | hard drilling. Light grey calcareous silt and sand with a hard limestone band. Core loss 166.7-166.8 |
| 168.2 - 169.7 | Lower Mannum Fm | ░ | Calcareous sands and limestone | dark grey calcareous sands and silts with hard limestone bands. Core loss from change of bit 168.2-168.36 |
| 169.7 - 172.7 | Lower Mannum Fm | ▩ | Calcarenite | Crumbly Calcarenite and light grey fine calcareous sand with bryozoa, sponge spicules, echinoid spines and some larger chemically altered bivalves. |
| 172.7 - 174.2 | Lower Mannum Fm | ░ | Calcareous sands and calcarenite | light and dark grey fossiliferous calcareous sands with some clay calcarenite bands |
| 174.2 - 175.7 | Lower Mannum Fm | ▦ | Limestone and Calcareous sands | limestone and calcareous sands with minor clay. Core loss from 174.5-174.7 |
| 175.7 - 177.2 | Lower Mannum Fm | ▦ | Limestone and Calcareous sands | limestone and calcareous sands with minor clay, quite fossiliferous near the top |
| 177.2 - 178.7 | Lower Mannum Fm | ▩ | Calcarenite | calcarenite at the top with a non horizontal boundary with underlying calcareous sands and clays. |
| 178.7 - 181.7 | Lower Mannum Fm | ▩ | Calcarenite | as above with some large recognisable fossils and possible worm tubes. Core Loss 180.2-180.45 |
| 181.7 - 183.2 | Lower Mannum Fm | ▦ | Limestone and Calcareous sands | light and dark grey limestone with calcareous sands and clays. Unusual bedding feature at 182.4m |
| 183.2 - 184.7 | Lower Mannum Fm | ▩ | calcarenite | hard drilling with sample showing a grey fossiliferous calcarenite with large a large bivalve at 183.3. |
| 184.7 - 186.2 | Lower Mannum Fm | ▩ | calcarenite | med grey moderately well cemented calcarenite |
| 186.2 - 187.7 | Lower Mannum Fm | ░ | Calcareous sand and limestone | grey calcareous sand and limestone containing small fossils |
| 187.7 - 189.2 | Lower Mannum Fm | ▦ | Limestone | Well cemented l/stn with worm tubes fossils not identifiable. |
| 189.2 - 192.2 | Lower Mannum Fm | ▦ | Limestone | no samples due ring in triple tube dislodging and preventing sample catching. |
| 192.2 - 193.7 | Lower Mannum Fm | ▦ | limestone and calcarenite | limestone and grey well cemented calcarenite. Core loss 192.2-192.5 |
| 193.7 - 197.5 | Lower Mannum Fm | ▩ | calcarenite | grey well cemented calcarenite core loss 194.6-194.7, 195.7-195.25 |
| 197.5 - 198.2 | Lower Mannum Fm | ░ | Calcareous Sands | well cemented calcareous sands containing minor glauconitic from 197.5 |
| 198.2 - 199.7 | Lower Mannum Fm | ░ | Calcareous sands and clay | banded calcareous sands and clays with some soft patches in the drilling. Still slightly glauconitic and worm tubes now full of dark grey clays. |
| 199.7 - 202.7 | Lower Mannum Fm | ░ | clayey sand | fossiliferous sands and clays becoming increasingly glauconitic. Core loss 201.2-201.3 other see poly pipe inserts |
| 202.7 - 216.2 | Lower Mannum Fm | ░ | clayey sand | Med to dark grey limestone and calcareous sands and clays. Minor Glauconite at 197.5 and increasing content with depth. Fossil content decreasing with depth and the fossils are aragonitic. Fossils becoming less bryozoal/echinoid/sponge and increasing in bivalve content. |
| 216.2 - 223.7 | Ettrick Fm | 🟩 | clay | Becoming increasingly glauconitic and losing fossils content. Fossils that do exist appear to be non altered. Towards the base of the hole the sample becomes a very heavy glauconitic clay with no fossils. There is a minor mineral content. Mineral identified as pyrite due to black streak, hardness and crystal structure. Some core loss from approx 214.7-215.4 |

**Notes on installation of piezometer:**

All depths are measured below ground level (BGL) unless otherwise stated

This hole was first drilled using 75mm triple tube coring and then reamed out to 121m using an 8 inch blade bit. The hole was then grouted back to the surface. The following day the remainder of the hole was reamed out using a 4 inch blade bit.

Casing has bulbed joints and were joined using pvc cement and tech screws

Depth of gravel found using a fishing line with weights.

A protective standpipe was cemented into position to complete the bore

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| | |
|---|---|
| **Project** | BL4EA |
| **Job No.** | 41313 (H) |

## Bore data

| | |
|---|---|
| **Permit No.** | 57457 |
| **Unit No.** | N/A |
| **Obs. No.** | BHO1 (uls) |
| **Purpose** | Piezometer |

## Location Data

| | |
|---|---|
| **Hundred** | Gordon |
| **Section No.** | 198 |
| **Easting (m AMG)** | 463208 |
| **Northing (m AMG)** | 6201459 |
| **Datum** | GDA94 |

## Elevation data

| | (m) |
|---|---|
| **Ground Surface** | 51.72 |
| **Ref. Point above Ground** | 0.76 |
| **Ref. Point** | 52.48 |
| **Top of open interval** | 15.7 |
| **Bottom of open interval** | -2.3 |

## Drilling data

| | |
|---|---|
| **Start date** | 22/03/2002 |
| **Finish date** | 22/03/2002 |
| **Driller** | Underdale Drillers |
| **Drilling Method** | Mud Rotary |
| **Circulation** | mud |
| **Maximum depth (m)** | 60.0 |
| **Completed depth (m)** | 36.0 |
| **Samples logged by** | Geoff White |

## Post-development data

| | |
|---|---|
| **Date** | 14-Jun-02 |
| **Depth to SWL below Ref. Pt. (m)** | 36.84 |
| **Depth to SWL below GL (m)** | 36.08 |
| **RSWL (m AHD)** | 15.64 |
| **EC Field (uS/cm)** | - |
| **EC Lab (uS/cm)** | 55800 |
| **Yield (L/s)** | - |
| **Method** | airlift |

## Completion data

| | | | | |
|---|---|---|---|---|
| **Hole Diameter** | **mm** | **From** | **To** | **Bit** |
| | 152 | 0.0 | 54.0 | Blade |
| **Backfilled** | | **From** | **To** | **Material** |
| | | | | |
| **Casing Diameter** | **mm** | **From** | **To** | **Material** |
| | 80 | 0.0 | 36.0 | Class 12 PVC |
| **Screen Diameter** | **mm** | **From** | **To** | **Material** |
| | 80 | 36.0 | 54.0 | Class 12 PVC 2mm slots |
| | | **From** | **To** | **Type** |
| **Grout** | | 0.0 | 33.0 | |
| **Bentonite Seal** | | 33.0 | 34.0 | 1/4 inch Pellets |
| **Gravel Pack** | | 34.0 | 54.0 | 1/4*1/8 gravel |

## Chemistry

| | | Units |
|---|---|---|
| **pH** | 7.6 | |
| **TDS by EC** | 37000 | mg/L |
| **EC** | 55800 | uS/cm |
| **TDS by calc.** | 39600 | mg/L |
| **Ca** | 326 | mg/L |
| **Mg** | 1150 | mg/L |
| **K** | 169 | mg/L |
| **Na** | 12700 | mg/L |
| **HCO3** | 382 | mg/L |
| **F** | - | mg/L |
| **Cl** | 20300 | mg/L |
| **SO4** | 4780 | mg/L |
| **NO2/3 as N** | 0.018 | mg/L |
| **NO2/3 as NO3** | 0.08 | mg/L |
| **Boron** | 1.68 | mg/L |
| **Al** | 7.74 | mg/L |

## Geophysics

| | |
|---|---|
| **Job No.** | Not logged |

## Geology

| Depth (m) | Stratigraphy | | Material | Description |
|---|---|---|---|---|
| 0 - 6.0 | Woorinen Fm | 🟧 | Clayey Sand | fine red/orange slightly clayey well sorted sand |
| 6.0 - 8.0 | Unnamed Sand | ⬜ | Sand | white fine well sorted sand and carbonate material with minor clay which has slight red colour. |
| 8.0 - 11.0 | Unnamed Sand | ⬜ | Sand | fine white well sorted sand. |
| 11.0 - 16.0 | Blanchetown Clay | ▨ | Sandy Clay | green to white slightly sandy clay. Colour change in mud at 11m hard band at approx 15m |
| 16.0 - 18.0 | Blanchetown Clay | ▨ | Clay | green to red variegated clay with minor sand. Hard band at 17.5m |
| 18.0 - 23.0 | Upper Loxton Sands | ▨ | Sandy Clay | slightly red to green sandy clay. |
| 23.0 - 25.0 | Upper Loxton Sands | ▨ | Sandy Clay | red sandy clay with some iron staining of the sand. Very hard at 23.5m losing lots of mud |
| 25.0 - 27.0 | Upper Loxton Sands | 🟨 | Sand | yellow to orange poorly sorted fine to coarse sand with some ironstaining. |
| 27.0 - 29.5 | Upper Loxton Sands | ⬜ | Sand | fine to med white sand with minor ironstaining flecks |
| 29.5 - 43.0 | Upper Loxton Sands | 🟧 | Sand | Poorly sorted sub rounded coarse qtz sand ironstained grains with some hard bars and some clay contamination. 32.5 - 33m, 35.5-36m hard bands. Losing Mud 39-41m |
| 43.0 - 46.0 | Lower Loxton Sand | ▒ | Sand | grey poorly sorted micaceous fine to coarse sub rounded sand. Colour change at approx 43m |
| 46.0 - 54.0 | Lower Loxton Sand | ▒ | Sand | med well sorted micaceous qtz sand grey to dark grey becoming finer to almost clay at 54m. |

**Notes on installation of piezometer:**

All depths are measured below ground level (BGL) unless otherwise stated

Casing has bulbed joints and were joined using pvc cement and tech screws

External endcap was used.

Depth of gravel found using a fishing line with weights.

A protective standpipe was cemented into position to complete the bore