DWLBC REPORT

Bookpurnong Living Murray Pilot Project:

Injection of river water into the floodplain aquifer to improve vegetation condition

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Government of South Australia
Department of Water, Land and Biodiversity Conservation

Bookpurnong Living Murray Pilot Project: Injection of river water into the floodplain aquifer to improve vegetation condition

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Science, Monitoring and Information Division
Department of Water, Land and Biodiversity Conservation

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FOREWORD

South Australia's unique and precious natural resources are fundamental to the economic and social wellbeing of the State. It is critical that these resources are managed in a sustainable manner to safeguard them both for current users and for future generations.

The Department of Water, Land and Biodiversity Conservation (DWLBC) strives to ensure that our natural resources are managed so that they are available for all users, including the environment.

In order for us to best manage these natural resources it is imperative that we have a sound knowledge of their condition and how they are likely to respond to management changes. DWLBC scientific and technical staff continues to improve this knowledge through undertaking investigations, technical reviews and resource modelling.

Scott Ashby
CHIEF EXECUTIVE
DEPARTMENT OF WATER, LAND AND BIODIVERSITY CONSERVATION

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- And the members of the Bookpurnong Lock 4 Environmental Association and the Bookpurnong Pilot Project Steering Committee.

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EXECUTIVE SUMMARY

The woodland vegetation communities of South Australia's lower River Murray floodplains are exhibiting signs of severe stress due to floodplain salinisation, a combined result of reduced flooding frequency, river regulation and expansive irrigation on the adjacent highlands. The Bookpurnong floodplain, located downstream of Lock 4 along the River Murray has experienced a decline in vegetation condition with widespread dieback on some parts of the floodplain.

The Living Murray Bookpurnong Pilot Project was undertaken to trial and compare the effectiveness of three floodplain management experiments for rejuvenating vegetation communities. The three trials are investigating: artificial surface watering; groundwater lowering alone; groundwater lowering to induce lateral recharge (bank storage); and injection of fresh river water into a shallow saline aquifer. This report focuses on the injection trial, where river water injection aimed to create a freshwater lens on top of the saline groundwater profile. The intent of this was to improve the root zone condition by decreasing groundwater and soil water salinity to improve vegetation condition.

The injection of fresh river water into the moderately saline floodplain aquifer was delivered via a five point injection array, and the monitoring of groundwater at seven observation wells orientated at two perpendicular transects. Of the three project trials conducted at Clark's Floodplain at Bookpurnong, this trial presented the most uncertainty for success and although technically well implemented and serviced, the trial was not successful at injecting adequate volumes and only created very limited localised freshening.

A total of 4.9 ML of River Murray water was injected over eight weeks commencing on 20 September 2006, with groundwater, soil salinity, geophysics, and visual tree health assessments being monitored both before and after the event. The injection ceased due to injection well and aquifer clogging with biological and particulate matter, resulting in the breaching of the confining clay layer (surface leakage). Injection caused a decrease in osmotic potential in the unsaturated zone immediately after injection around the highest yielding injection well. Across the site, *Eucalyptus camaldulensis* (river red gum) tree condition did not improve after eight weeks of injection, although an improvement was recorded three months post-injection, which corresponded with a high rainfall event.

The outcome of the trial was a very localised and short-lived groundwater freshening that had no observable effect on trees in the freshened zone. The trial encountered significant technical problems associated with aquifer clogging. Overcoming these technical problems would be costly considering the short life of the infrastructure and poor groundwater and vegetation results. Shallow aquifer injection is therefore not recommended as a management technique to promote floodplain health.

1. INTRODUCTION

The River Murray and its floodplains are an integral part of south-eastern Australia's landscape, supporting agriculture, recreation and industry. However over the past 150 years, these floodplains have been progressively alienated from their parent rivers. Floodplains that were once flooded three or four years out of five are often now only inundated once in 10 or 12 years, whilst some have not received any flooding for over two decades (Mussared 1997). In South Australia, the health of these systems are in decline with the dieback of native woodlands attributed to rapid advancement of floodplain (soil) salinisation (Slavich et al. 1999). This escalated salinisation is attributed to river regulation which has decreased the number of high flow events which would typically leach and flush salts from the system. As well the development of irrigation districts adjacent to the river corridor induce groundwater mounding and force naturally saline regional groundwater towards the river via the floodplain. These factors have altered the natural temporal interaction between surface water and groundwater in the Murray Darling Basin.

In response to the decline in health of the river, the Murray-Darling Basin Commission (MDBC) in 2002 established The Living Murray Initiative (Living Murray, 2008). The initial action was to protect and improve the health of the River Murray through the identification of six icon sites along the river. In order to achieve the ecological objectives for the Chowilla Floodplain icon site, The Living Murray Initiative invested in a range of operational 'structural works and measures' to manipulate floodplain and wetland processes. The remoteness of the Chowilla Floodplain does not facilitate straightforward infrastructure installation and investigation, whereas Clark's Floodplain at Bookpurnong (~80km downstream of Chowilla) represents a suitable study site to pilot investigations from which outcomes aim to guide management of the Chowilla Floodplain. Bookpurnong has existing power supply, a groundwater salt interception scheme (SIS) and saline water disposal infrastructure.

The pilot study being carried out on the Bookpurnong floodplain has a number of individual research concepts and sites. The investigations draw on the disciplines of hydrogeology, ecology, hydrology and geophysics to achieve the Living Murray project aims (Living Murray 2008):

- Provide important information/validation of floodplain rehabilitation concepts, which will underpin integrated policy and planning for floodplains on the lower River Murray.
- Provide an opportunity to demonstrate the ecological benefits of manipulated environmental flows in the short to medium term.
- Identify preferred management and rehabilitation regimes to be implemented across salt affected floodplains.

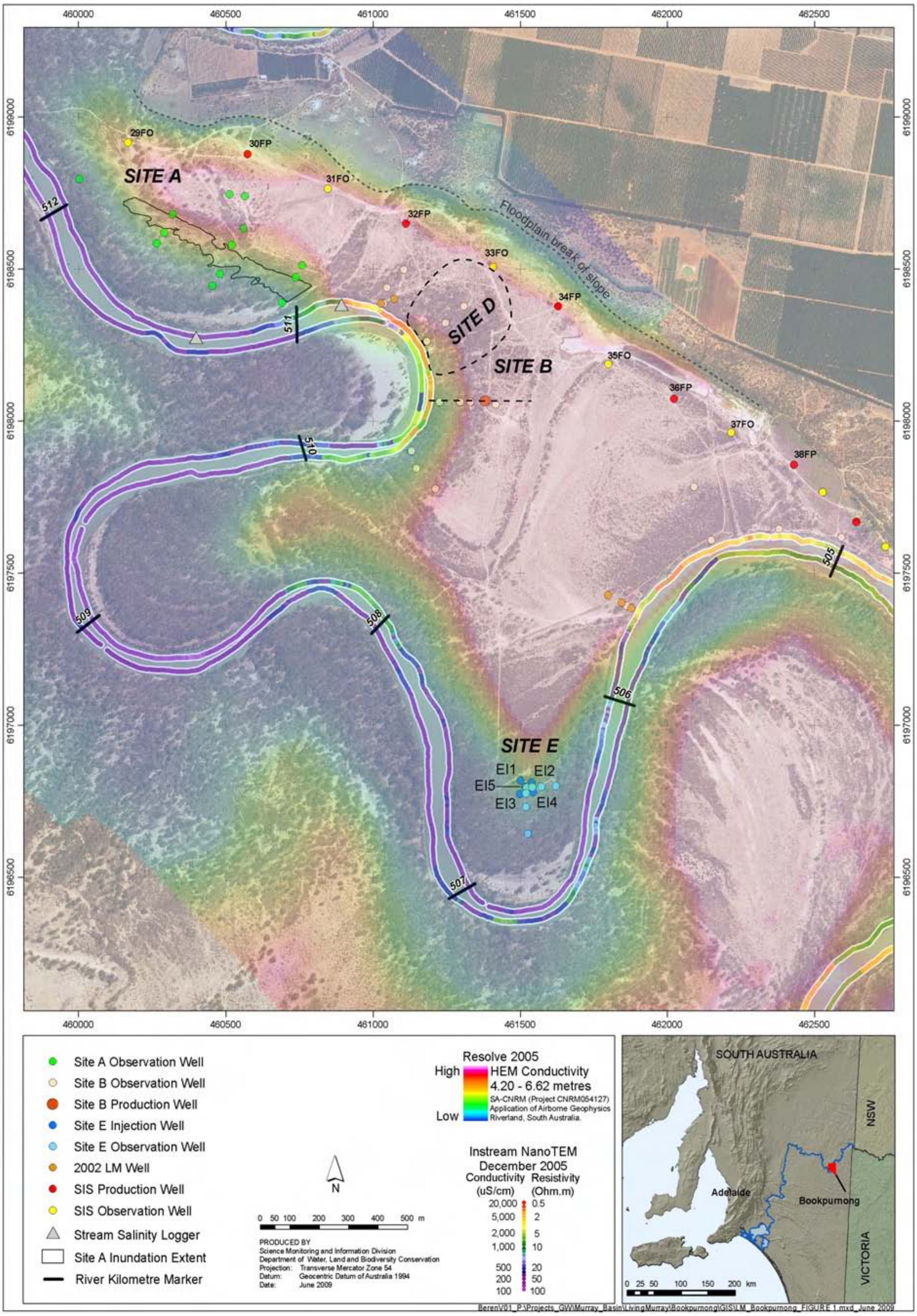

Figure 1. Overview of the manipulation trial sites on Clark's Floodplain, Bookpurnong.

The concepts and sites of the Bookpurnong trials (Figure 1) are summarised below:

Site A – Artificial flooding of a 3.7 ha topographic depression with a focus on improving the health of the river red gum forest. The aim is to leach salt from the soil profile and improve the salinity condition of the root zone and encourage tree rejuvenation and population replacement by providing favourable germination conditions.

Site B – The construction of a purpose designed ‘Living Murray’ groundwater production well to induce the lateral movement of fresh river water through the adjacent floodplain aquifer creating a fresh water lens (enhanced bank storage). Seventeen piezometers were installed in four transects to observe the surface and groundwater interactions across a broader area: Transect 1 capturing SIS only response, Transect 2 to incorporate Site D and the distant SIS and/or LM well response, Transect 3 the LM well transect and Transect 4 as a control.

Site D – Artificial surface flooding of a dried creek system as a comparison with Transect 3 of vegetation response to groundwater freshening. Site D is a small subset area within the larger Site B study area.

Site E – Injection of fresh river water into a moderately saline floodplain aquifer via a five-point injection array, and the monitoring of vegetation health response of a stressed tree community. This trial had the most uncertainty, as success was reliant on the ability to inject a sufficient volume of water for freshening to occur.

Salt Interception Scheme (SIS) – In an effort to reduce the immediate impact of river salt accession, there has been investment into the design and construction of salt interception schemes along the River Murray. These aim to reduce hydraulic gradients and intercept the movement of saline groundwater from the highland to the floodplain and river. The Bookpurnong SIS has seven highland and 16 floodplain interception wells, six of which are on Clark’s Floodplain, within proximity to the Living Murray investigation sites. SIS operation commenced in July 2005 with extraction rates of 2 – 3 L/s per well.

1.1 STUDY AREA

The 500 ha extent of Clark’s Floodplain is adjacent the 1200 ha Bookpurnong irrigation district (Figure 1). The demand on the River Murray to support intensive irrigation in this semi-arid region has increased the hydraulic and salinity pressure on the river and its floodplains. Excess irrigation drainage has led to the development of a localised groundwater mound that is centred within 1.3 km of the river (0.5 km from Clark’s Floodplain) and has a groundwater head almost 10 m above river pool level. The resulting displacement of native regional saline groundwater in excess of 20,000 mg/L has lead to salt accession and salinisation of the floodplain environment. Numerical modelling indicates that prior to salt interception, around 100 tonnes of salt per day discharged to the river along the 18 km Bookpurnong river reach (Yan et al. 2005).

Hydrogeologically, the river is the natural sink for the regional groundwater within the Loxton to Bookpurnong area. The Monoman Sand Formation (~10 m thick) and the overlying Coonambidgal Clay Formation (up to 5 m thick) form the floodplain sedimentary sequence into which the modern channel of the River Murray is incised. The lithology and hydraulic properties of the Monoman aquifer are highly variable, consisting of fine sands to coarse gravels with varying amounts of silts and clays. The Coonambidgal Formation aquitard is typically very stiff consisting of well sorted silts and clays, increasing in sand content with depth. The regional hydro-stratigraphy is schematically represented in Figure 2, which also displays the flow mechanisms that have been enhanced by the presence of highland irrigation.

The floodplain vegetation is dominated by three tree species; river red gum (*Eucalyptus camaldulensis*), black box (*Eucalyptus largiflorens*), and river cooba (*Acacia stenophylla*). The Bookpurnong trials target areas where there is a notable decline in the condition of these tree species, aiming to provide improved conditions for the stressed tree communities.

The lower River Murray has a semi-arid climate with long hot summers and mild winters. Loxton Research Centre (140°60'E, 34°44'S) is located close to Clark's Floodplain recording climate information since 1984. Table 1 describes the climatic information recorded at the station relevant to the injection experiment. Below average rainfall was recorded for the preceding five months prior to the injection trial, with below average rainfall also recorded during the two and half months of the trial. The trial was undertaken in spring when the evaporation rate was increasing. The injection trial was carried out in 2006 when annual rainfall was 165.8 mm, well below average and only 45 mm more than the lowest on record (Bureau of Meteorology, 2008).

Table 1. Climatic information recorded from the Loxton Research Centre from 1984 to present (Bureau of Meteorology 2007).

	Highest	Lowest
Mean daily maximum temperature (°C)	31.4 - January	15.8 - July
Mean daily minimum temperature (°C)	14.4 - January	3.8 - July
Mean daily rainfall (mm)	28.9 - August	11.4 - March
Annual rainfall (mm)	414.1 - 1992	121.0 - 2002
Mean daily evaporation (mm)	9.4 - January	1.7 – June/July

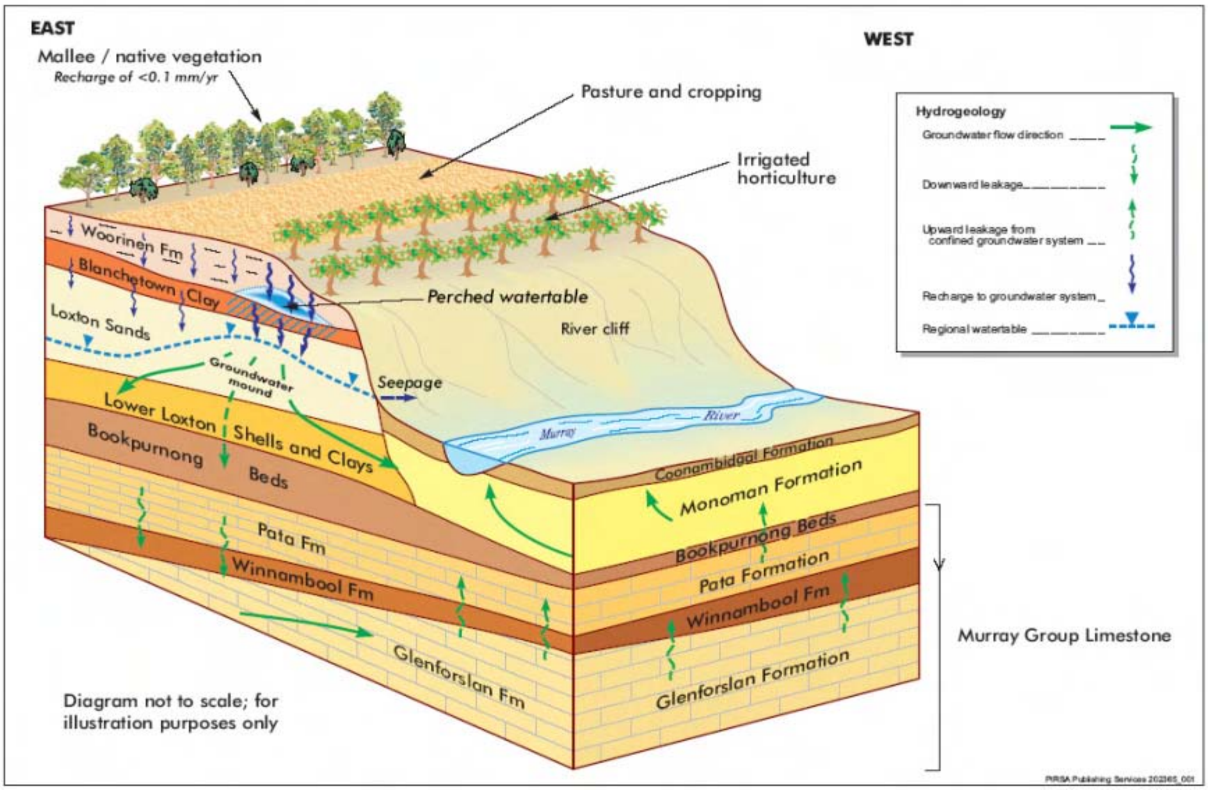

Figure 2. Characteristic hydrogeology of the study area.

1.2 INJECTION SITE

From available information and site visits, five possible injection sites were chosen and assessed. Groundwater depth, vegetation composition and condition, soil salinity (from acquired AEM data where available), soil geology, and accessibility were examined to determine the most appropriate site. The initial site was located on the Ajax – Achilles Floodplain (AWE, 2005) north of Clark's Floodplain, with black box in poor health and river red gums in reasonably good health. Upon further investigation, the site was deemed unsuitable due to its location in the backwaters above Lock 4 and site inaccessibility for drilling rigs. Another four sites were investigated, three on Clark's Floodplain and one site on the Gurra Floodplain.

The chosen site was located on Clark's Floodplain and was selected based on the following attributes:

- Geology; A hand-augured investigation hole indicated a confining clay thickness of around 2 m and approximately 1 m of unsaturated Monoman Sands. The depth to the water table was approximately 3.5 m, and a groundwater salinity of approximately 20,000 EC was recorded. The Aerial Electromagnetic (AEM) data showed the site positioned at the edge of a high conductivity area (Figure 1).
- Vegetation health; the site had a severely degraded open river red gum woodland with a dense lignum (*Muehlenbeckia florulenta*) understorey, most trees had a crown cover of less than 25% and the site hadn't been flooded since 2000. Data from artificial surface-waterings had showed that trees in this canopy class, 11-25% crown extent respond to aquifer freshening via surface recharge (White et al, 2009).

- Site accessibility; this site allowed access for drilling rigs although the clearing of some large stands of lignum was needed and undertaken with Native Vegetation approval.

1.3 AIM AND OBJECTIVES

The initial scope of this trial proposed the installation of an injection bore and surrounding observation bores, with water to be injected for a period of ten to thirty days. The spread and effect of injected fresh river water would be monitored via examinations of water and salt budgets, soil water salinity, groundwater head and salinity, and vegetation changes (AWE, 2005).

The trial was proposed as an alternate methodology to managing the health decline of river red gum and black box communities. The goal was to generate environmental improvement using small amounts of water relative to surface flooding and water extraction techniques, and without the need for water disposal infrastructure.

Since the original site was not suitable, new objectives were needed. The questions to be addressed by the trial were:

- Can river water be injected into the Monoman Sands to form a thin layer of freshwater at the Monoman/Coonambidgal interface?
- Will the freshwater lens improve the soil water salinity of the unsaturated zone?
- Will river red gums at the site respond positively to the freshwater lens?
- Is injection a technique that can easily be transferred to the Chowilla Floodplain?

2. INJECTION DESIGN

2.1 CONCEPTUAL GROUNDWATER MODELLING

Numerical modelling using MODFLOW was adopted to assist in the design of the injection trial, in particular how to maximise the extent of a shallow and thin fresh groundwater lens. It was uncertain whether a single production well screened over the entire aquifer thickness, or a screen of limited length at the top of the aquifer would deliver the best results. Numerical modelling tested the scenarios that would be best for efficient dispersal of the freshwater injected into the brackish aquifer. The scenarios examined injection screen intervals, injection rates and injection well arrays.

An uncomplicated model domain of 1 km x 1 km was discretised into a grid of 5 m x 5 m cells (Figure 3). No flow boundaries were imposed on the top and bottom model extents, and constant head boundaries were assigned to the left and right model domain boundaries. The constant heads were assigned 8 m and 8.2 m creating a 2×10^{-4} hydraulic gradient across the model domain. The model consisted of two layers defined over the entire domain extent: Layer 1 representing the confining Coonambidgal Clay, defined as a layer of inactive cells of 1 m thickness, Layer 2 representing the Monoman Sands, defined as a 12 m thick layer of active cells, with hydraulic parameters based on values typically used for simulations of the Monoman sands in this region (Yan et al. 2005). The initial parameters used for the active Monoman layer are given in Table 2. Figure 3 displays the location of injection and observation points used in the later simulation to test the multiple injection point array.

Table 2. Initial hydraulic properties of active cells in the model domain

Model Parameter	Parameter value
Hydraulic Conductivity (Kx)	10 m/d
Hydraulic Conductivity (Ky)	10 m/d
Hydraulic Conductivity (Kz)	0.1 m/d
Specific Yield (Sy)	0.15
Specific Storage (Ss)	0.0001
Effective Porosity (0.15)	0.15

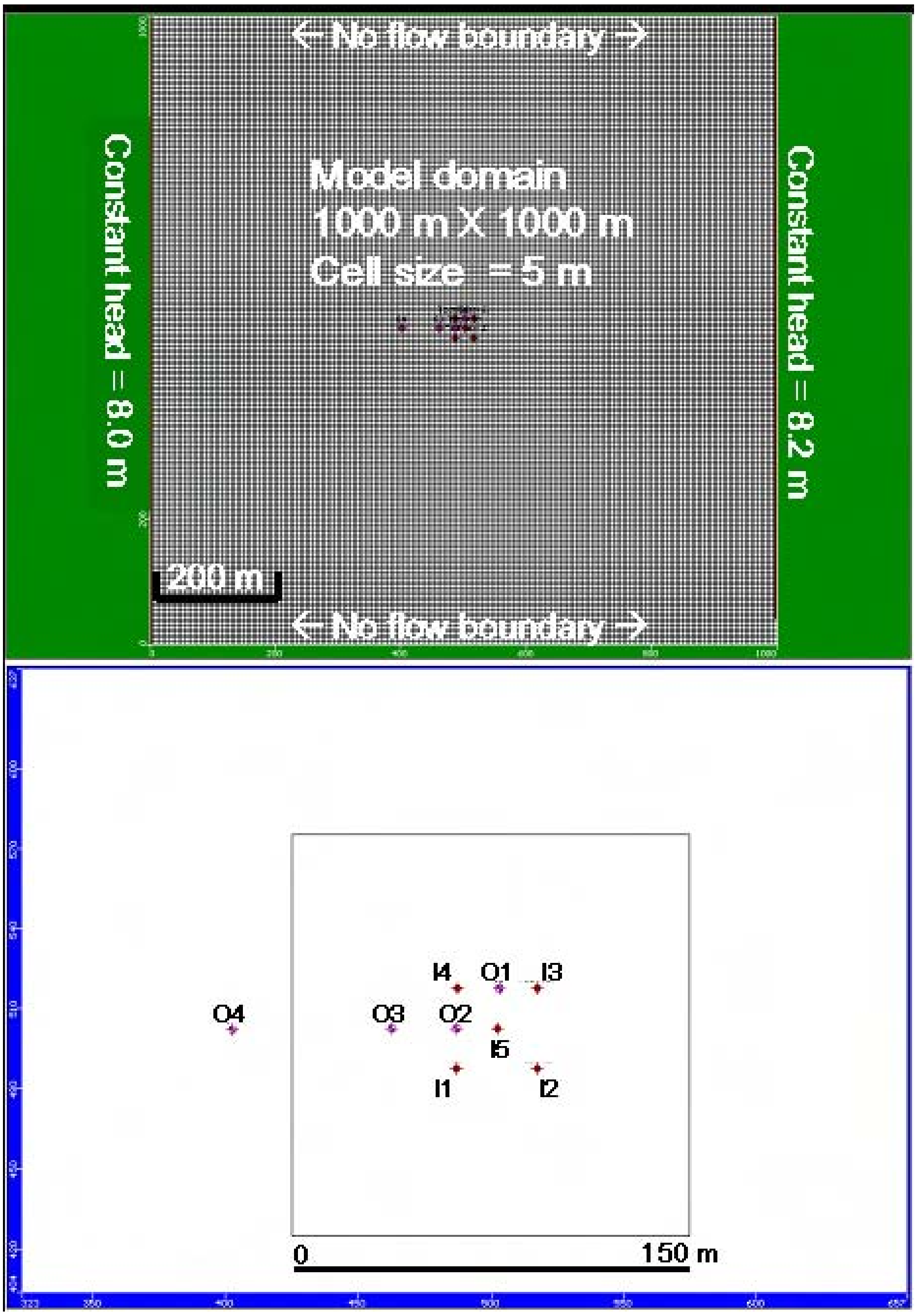

Figure 3. Site E model domain and simulated well configuration

2.1.1 INJECTION SCREEN INTERVAL

The preliminary scenarios tested the sensitivity of the Monoman layer to injection through two different screen lengths, a fully screened aquifer and a shorter 2 m screen, commencing 1 m below the top of the aquifer. Model results indicated that for an injection well screened over the entire Monoman sands aquifer, the fresh water would displace the native groundwater over the entire thickness (Figure 4). Whereas for the top of aquifer 2 m screen scenario, the lesser volume of displaced water remained nearer to the water table (Figure 5). The simulated injection rates were proportioned to match the screen length such that the injection rate per screen length was equal in both scenarios, at 1 litre per metre of screen.

Both these scenarios simulated constant injection for 90 days, representing 15.6 ML in the limited screen scenario and 77.8 ML in the fully screened aquifer scenario. Model outputs were calculated at 1, 30, 60, 90, 120 and 275 days from the start of injection. Figures 4 and 5 shows a selection of time period outputs for both the 2 m and 10 m screen simulation. In consideration of these results, it was thought more pertinent to proceed the modelling based on the 2 m screen scenario. Importance was placed on the near surface (top of aquifer) groundwater displacement and the ability to create a freshwater lens to target the tree root zone, rather than the displacement of water at greater depths of the aquifer. The 2 m screen modelled scenario presented the most efficient way of delivering the required aquifer freshening.

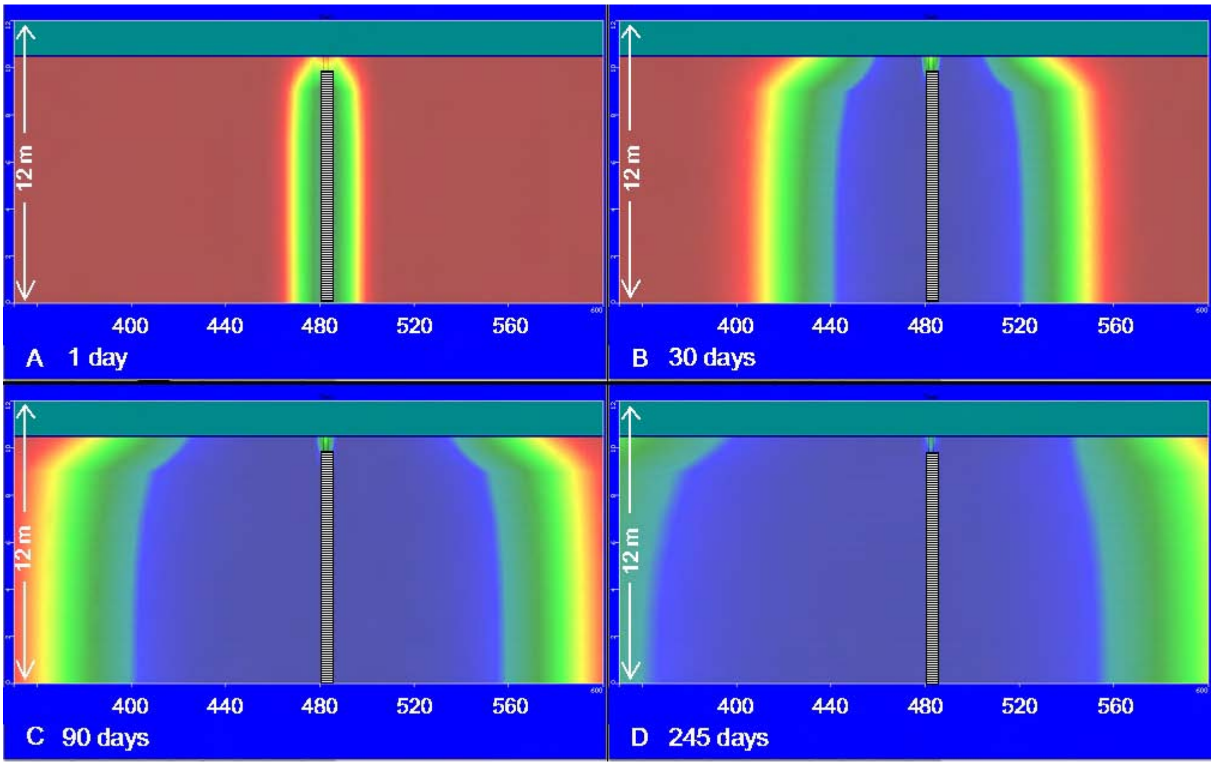

Figure 4. Modelled injection results for 10 m screen at 10 L/s.

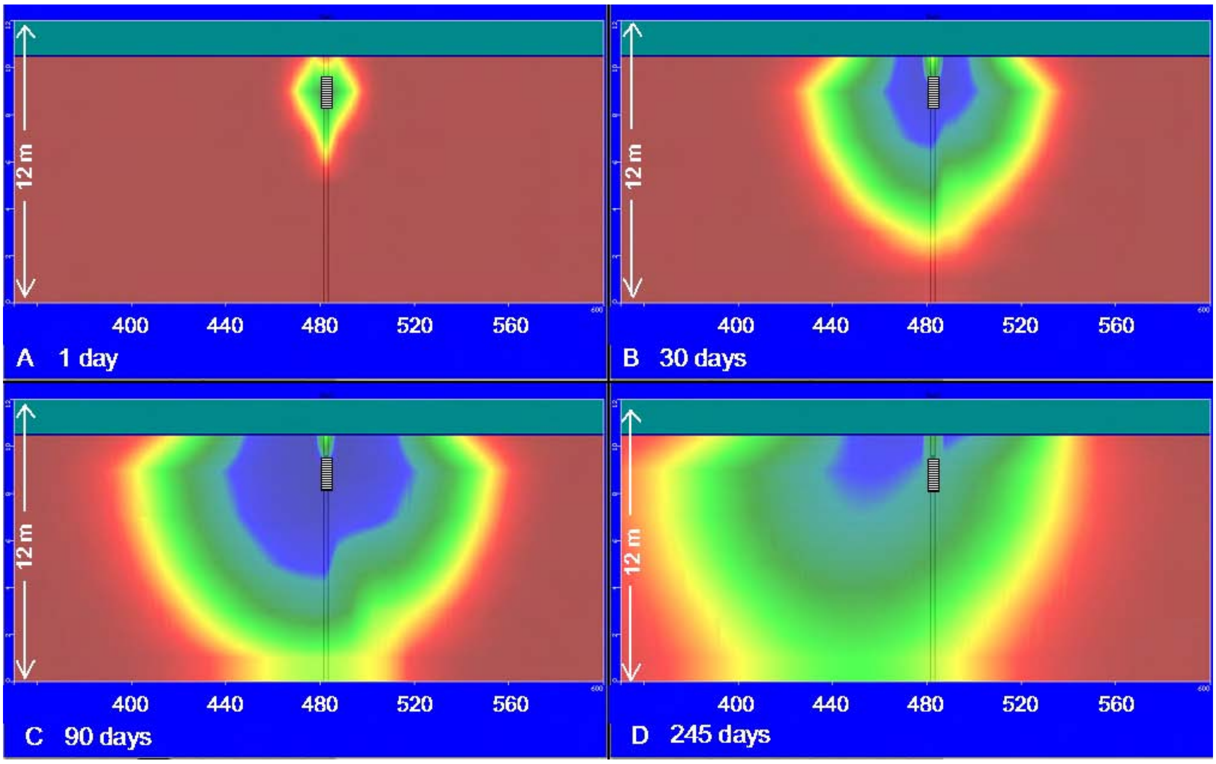

Figure 5. Modelled injection results for 2 m screen at 2 L/s.

2.1.2 INJECTION ARRAY

Further model simulation compared the injectant plume for a ‘single’ injection point design and several scenarios of ‘multiple’ injection points to determine the best potential injection array. Multiple injection point configurations tested include 13-point, 9-point and 5-point arrays, simulated over varying time periods (1, 30 and 90 days), with varying injection rates. These scenarios gave consideration to the desired target area for groundwater freshening and the dispersion of the fresh water injectant. The outcome presented a five-point injection array on a 30 x 30 m grid to be effective in delivering groundwater freshening over a 150 x 150 m extent. This array is depicted in Figure 6. These simulation scenarios assume no evapotranspirative water loses, and a homogenous aquifer of 20,000 mg/L native salinity.

The 5-point array was tested using two injection scenarios; injecting at 2 L/s into each well for 30 days (total of 26 ML), and injecting at 1 L/s into each well for 90 days (total of 39 ML). Predicted drawdown and solute transport outputs were calculated at the 1-day time step, at the end of respective injection period, and for extended periods after the end of the injection stress period. Figure 6 presents a selection of these outputs. The lateral extent of freshening is similar in both scenarios, but the longer-term reduction in the groundwater salinity is greatest in the 1 L/s for 90 days scenario, in which an extra 13 ML of injectant is introduced. Four observation wells were simulated into the model (Figure 3) and allow for simulated observations of temporal groundwater salinity change (Figure 7).

Later simulations were completed using the above five point injection scenario but incorporated individual injection rates for each injection point based on field pumping and pre-injection testing following the construction phase of the project.

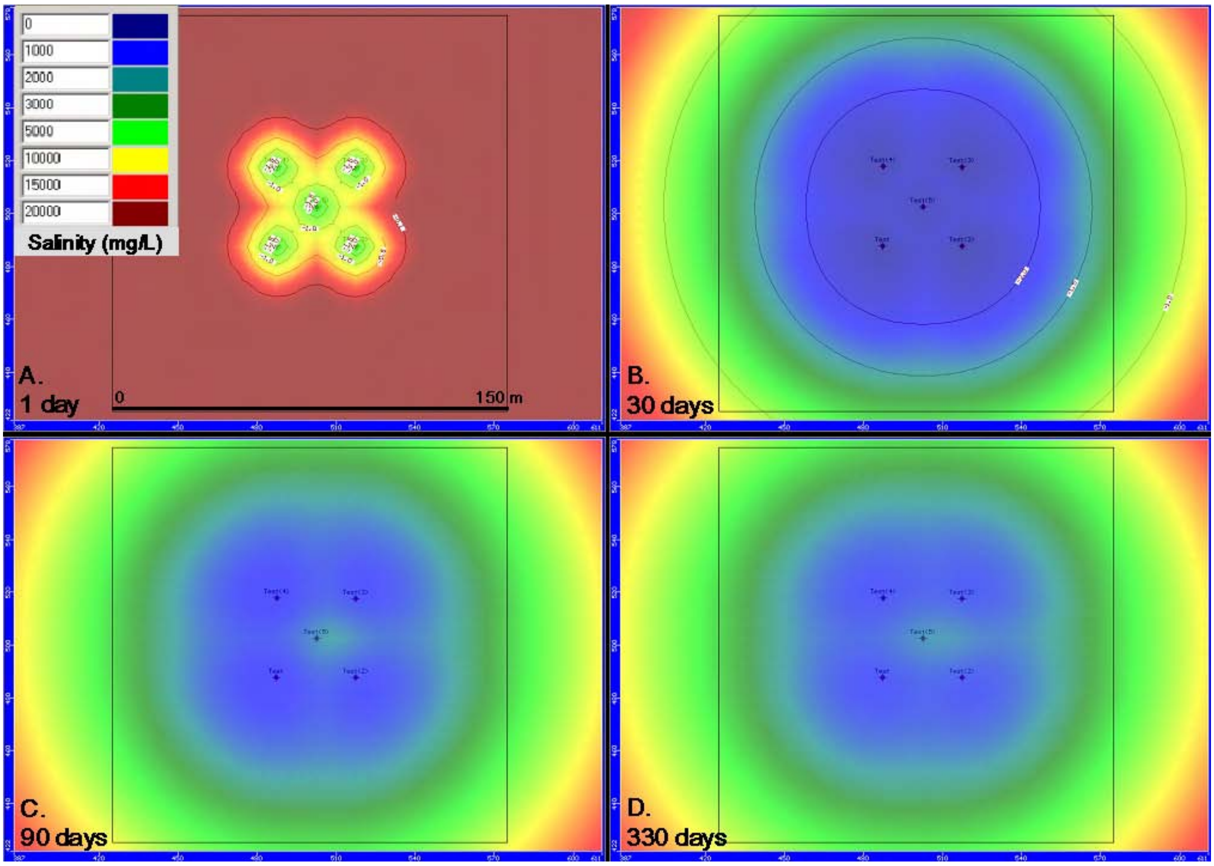

Figure 6. Modelled injection using a five point array through 2 m screens at 2 L/s for 30 days.

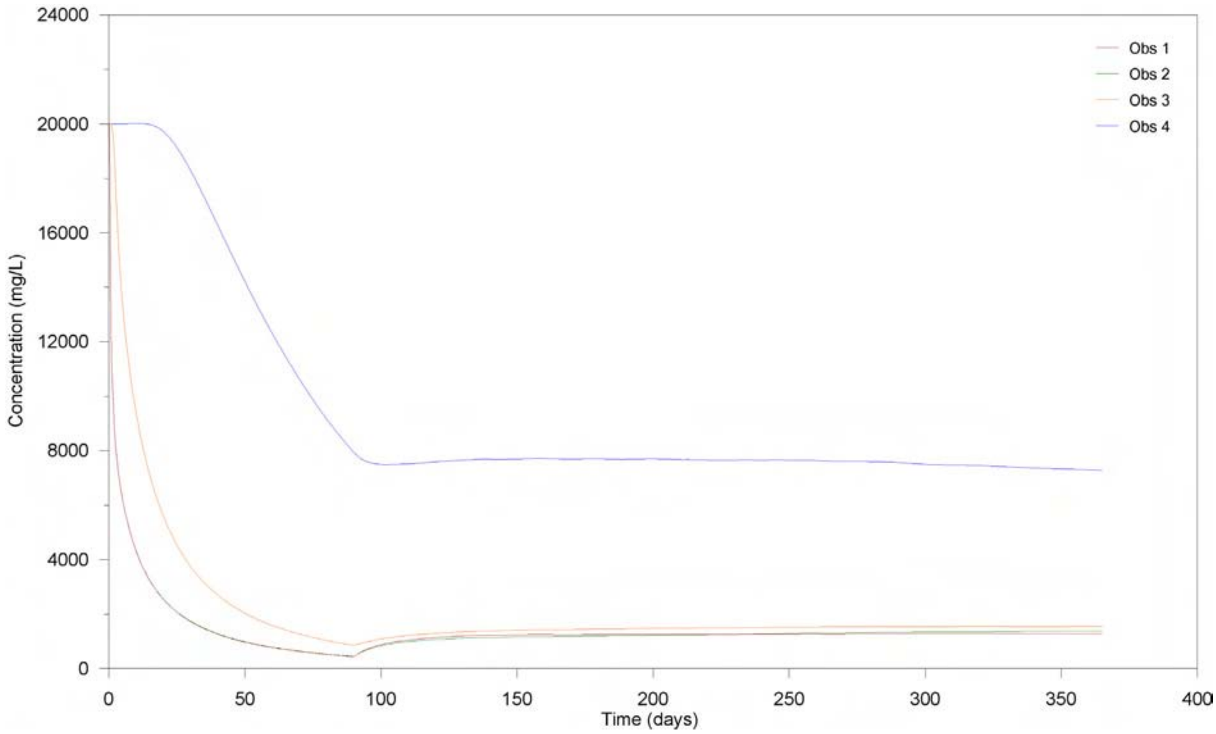

Figure 7. Simulated solute (salinity) response to modelled injection scenario. Five point array through 2 m screens at 1 L/s for 90 days.

2.2 AQUIFER CLOGGING AND WATER QUALITY CONSIDERATIONS

A key consideration in assessing the success of an injection trial is an understanding of the extent of clogging that may occur when introducing one source water with another within the confines of a particular aquifer. The potential for, and the operational activities to manage clogging are influenced by the physical, chemical and biological properties of the source waters and the aquifer.

The potential for the mechanism of physical clogging can be assessed fairly simply by examining a number of indicator parameters including total suspended solids (TSS), membrane filtration index (MFI) and turbidity of the injectant source water. At the inception of the Site E injection, no assessment of the suitability of River Murray (RM) water for injection into the Monoman Sands (MS) aquifer was completed. Although this assessment was highly recommended, the desire to progress the project with a restrictive budget tended towards a very short lead time, thus limiting adequate assessment of injectant and aquifer properties to thoroughly assess the risks of clogging.

Simple calculations were completed to determine the rate of physical pore volume filling. Total suspended solids (TSS) data collected during well development were used to inform the calculation. Additional historical data was sourced from the Environmental Protection Agency environmental data management system for locations ranging between Murray Bridge and Berri and years 1978 to 2005, which provided maximum and minimum TSS values of 86 mg/L and 10 mg/L respectively, with an overall average of 35 mg/L. Water quality parameters of turbidity and TSS are influenced by the amount of flow in the river. During periods of low flow, turbidity units and solid particulate matter would be less than during higher flow periods.

The calculation considers the volume of water containing a specified concentration of suspended solids, required to totally fill an aquifer pore volume over a given distance (diameter) beyond a well screen of length of 3 m. The suspended particulate matter is a physical property that during its movement through the aquifer will be filtered out by the aquifer material. The particulate matter has a mass per unit volume (assumed ~2000 kg/m^3 for wet clay), which can be used to estimate the amount of water required to fill an anticipated aquifer volume. The anticipated aquifer volume is subjective, but influenced by the source water particle size, aquifer grain size and water velocity through the aquifer (influenced by injection rate). This also assumes that all of the pore space is accessible for particle deposition and that all particles are captured within that assumed aquifer pore volume. Table 3 presents a selection of scenarios showing how many megalitres and how many days it would take to physically fill the aquifer pores around the well screen for a single well. For example, scenario 1 considers an aquifer area that extends 25 mm in diameter beyond the well casing at an injection rate of 0.25 L/s. Scenario three considers the amount of time it would take to physically fill the well column over the screened interval if all particulate matter was intercepted by the screen slots.

Table 3. Calculated scenarios to completely physically fill an aquifer volume around the well screen.

Total Suspended Solids (TSS) mg/L	Scenario 1 Aquifer zone diameter of 25 mm at 30% porosity and injection rate 0.25 L/s		Scenario 2 Aquifer zone diameter of 100 mm at 30% porosity and injection rate 1.0 L/s		Scenario 3 200 mm well column at injection rate 0.25 L/s	
	ML to clog	Days to clog	ML to clog	Days to clog	ML to clog	Days to clog
10	3.18	147.3	16.96	196.3	18.85	872.7
100	0.32	14.7	1.7	19.6	1.88	87.3
1000	0.03	1.5	0.17	2	0.19	8.7
35	0.91	42.1	4.85	56.1	5.39	249.3

2.3 VEGETATION SAMPLING DESIGN

The spatial arrangement of the trees was an open woodland across the 150 x 150 m injection area. Sixty river red gums were monitored including all trees near an injection and observation well, which captured ~75% of the trees over the site (Figure 8). Each tree was tagged, assigned a unique code and located using a GPS (Global Positioning System). Trees condition was tracked over time, allowing for direct comparison between assessment dates coinciding with the injection period of April 2006 (pre-injection), November 2006 (immediately post-injection), and February and August 2007 (two and four months post-injection).

The DWLBC tree health assessment method (Souter et al, 2009) is based on a conceptual model of declining tree health due to prevailing environmental conditions and behaviour in response to management intervention e.g. environmental watering. Tree health was measured as a combination of condition and response. Condition is assessed as crown cover and density assessed on a five-category scale (Table 4) although density was eliminated from this analysis as it was only measured on the last two assessment dates. Response is reflected as behavioural reaction to environmental changes e.g. epicormic growth can be a response to fire or rainfall. Six behavioural attributes were measured on a three-category scale (Table 5). Response was measured as the sum of the behaviour scores. Bark condition (cracked or intact) was also recorded.

An ANOVA analysis was undertaken on river red gums directly in the freshening area of the injection wells determined from the post-injection EM31 survey. Six trees were located in this zone, and were compared against six randomly selected control trees well away from the injection area, but with the same starting condition as trees in the injection zone.

Differences in tree condition over time at both the control and injection sites were analysed independently using a Friedman repeated measures ANOVA as the data is categorical. A repeated measures ANOVA examining the effect of the injection and time was performed on river red gum response.

In addition to the visual tree assessments, photo-points were placed at points of interest to provide a good overall representation of the site. The photo-points taken over an 18 month time period show varying degrees of change and were used only as a visual depiction of the sites and hence will not be discussed in this report. Photos taken during the surveys are provided in Appendix A.

Table 4. Crown cover categories used in the tree health assessment

Category	Score	Crown Cover
1	1	Minimal (~1~10%)
2	2	Sparse (~11~25%)
3	3	Moderate (~26~75%)
4	4	Major (~76~90%)
5	5	Maximum (~91~100%)

Table 5. Behavioural response scale. Positive behaviour; epicormic growth; capsule development, flowering, seeding; crown growth. Negative behaviour; crown dieback; leaf damage (eg. insect); mistletoe.

Category	Positive behaviour score	Negative behaviour score	Description
1	0	0	Absent or scare, effect is not seen in a cursory manner
2	1	-1	Common, effect is clearly visible
3	2	-2	Abundant, effect dominates the appearance of the tree

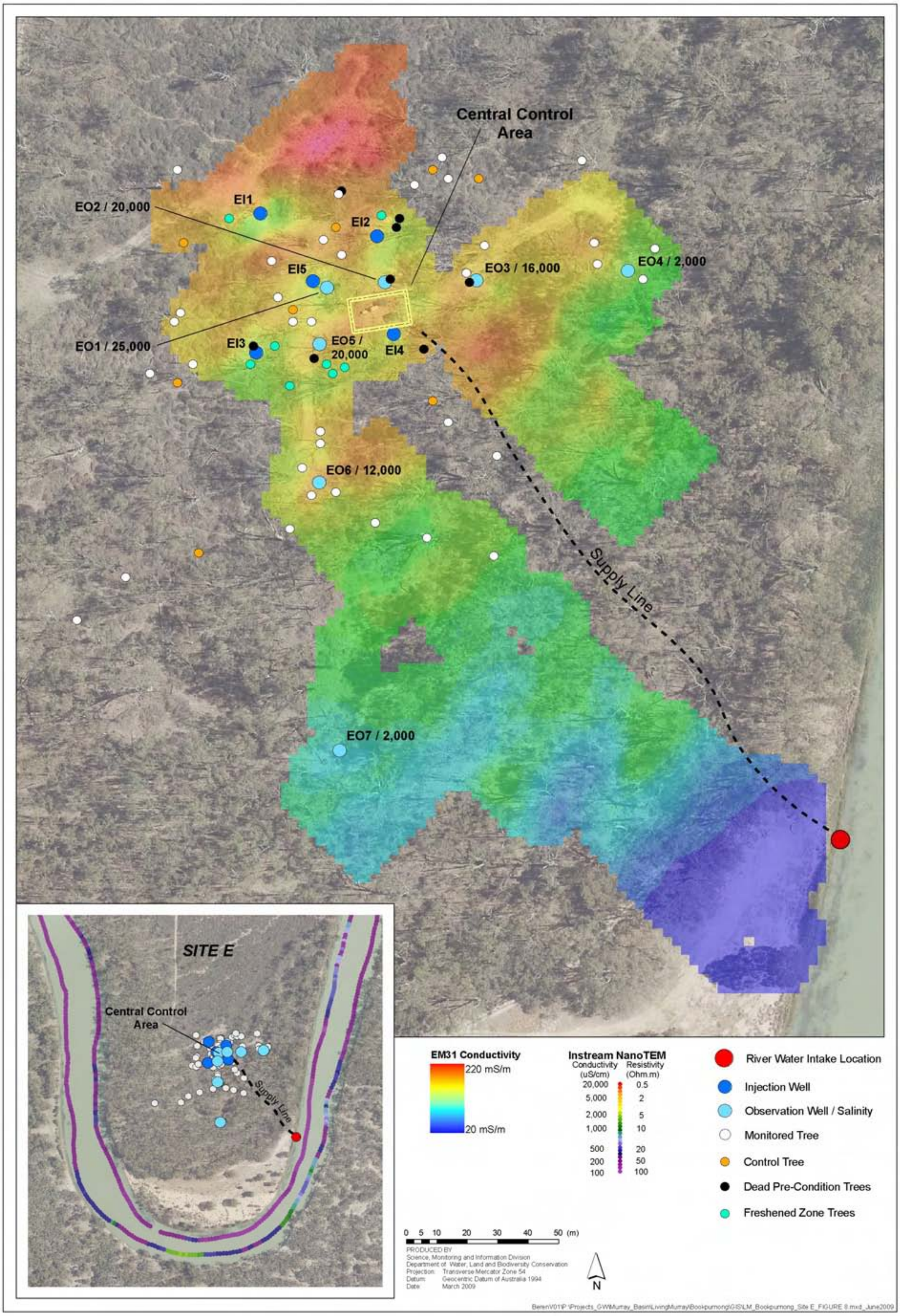

Figure 8. Site E injection trial site map.

3. CONSTRUCTION AND OPERATION

3.1 WELL CONSTRUCTION

The drilling of the observation and injection wells commenced on the 7th April 2006. Installation of the injection wells proceeded on the 11th April 2006. Seven observation wells in two perpendicular transects were completed, six having 5 m screens and one constructed with a longer and deeper 9 m screen. Duel EC and level loggers were installed in EO1, EO2, EO3 and EO5, and additional level only loggers were installed into each of the seven observation wells. A summary of construction details for all injection and observation wells are tabulated in Table 6 and geological logs are provided in Appendix B.

For the construction of the injection wells, a larger 300 mm diameter drill bit was fabricated to provide a suitably large annulus for the emplacement of an adequate cement seal around the 200 mm casing. The drilling contract specified each injection well to be completed with a 3 m PVC screen to be set at approximately 3 to 6 m, and with an additional 1 m sump. The lithology of the material encountered was not ideal over the slotted interval with the upper parts of the screen occurring in silty/clayey material. Attempts were made to deepen the injection wells and screen intervals in order to target better yielding material, however the small drilling rig was operating at full depth capacity whilst using the larger diameter drill bit.

The injection wells were drilled and cased but gravel packing and cementing to surface could not be completed to specification at that same time. Gravel fill was specified to be emplaced 1 m above the top of screen but an insufficient stock of gravel pack was accounted for by the drilling contractor. Distinct verbal and written information was provided to allow the drilling contractors (Underdale Drillers) to return to site and complete the work to specification at a later and convenient date. This work was reported by the supervising driller to be completed on the 26th April 2006. Diagrams of the injection and observation wells are provided Figure 9.

Table 6. Summary of construction details for injection and observation wells

Well Name	Purpose	Unit No.	Drilled Date	Ref Elevation (mAHD)	Gnd Elevation (mAHD)	ID (mm)	Total Depth (m)	Screen interval (m)	Screen Aperture (mm)	Sump (m)
EI1	Injection	70292233	12-Apr-06	13.13	12.35	200	7.0	3.0 - 6.0	1	1.0
EI2	Injection	70292234	11-Apr-06	13.25	12.88	200	7.0	3.0 - 6.0	1	1.0
EI3	Injection	70292235	11-Apr-06	13.63	13.02	200	7.0	3.0-6.0	1	1.0
EI4	Injection	70292236	12-Apr-06	12.97	12.47	200	6.0	2.0-5.0	1	1.0
EI5	Injection	70292237	12-Apr-06	13.53	13.02	200	7.0	3.0-6.0	1	1.0
EO1	Observation	70292238	7-Apr-06	13.82	13.03	80	12.5	2.5-11.5	1	1.0
EO2	Observation	70292239	8-Apr-06	13.37	12.40	80	7.5	2.0-7.0	1	0.5
EO3	Observation	70292240	8-Apr-06	13.35	12.36	80	7.5	2.0-7.0	1	0.5
EO4	Observation	70292241	8-Apr-06	13.45	12.33	80	7.5	2.0-7.0	1	0.5
EO5	Observation	70292242	7-Apr-06	13.18	12.40	80	7.5	2.0-7.0	1	0.5
EO6	Observation	70292243	9-Apr-06	12.88	12.03	80	7.5	2.0-7.0	1	0.5
EO7	Observation	70292244	10-Apr-06	13.64	12.50	80	7.3	1.8 - 6.8	1	0.5

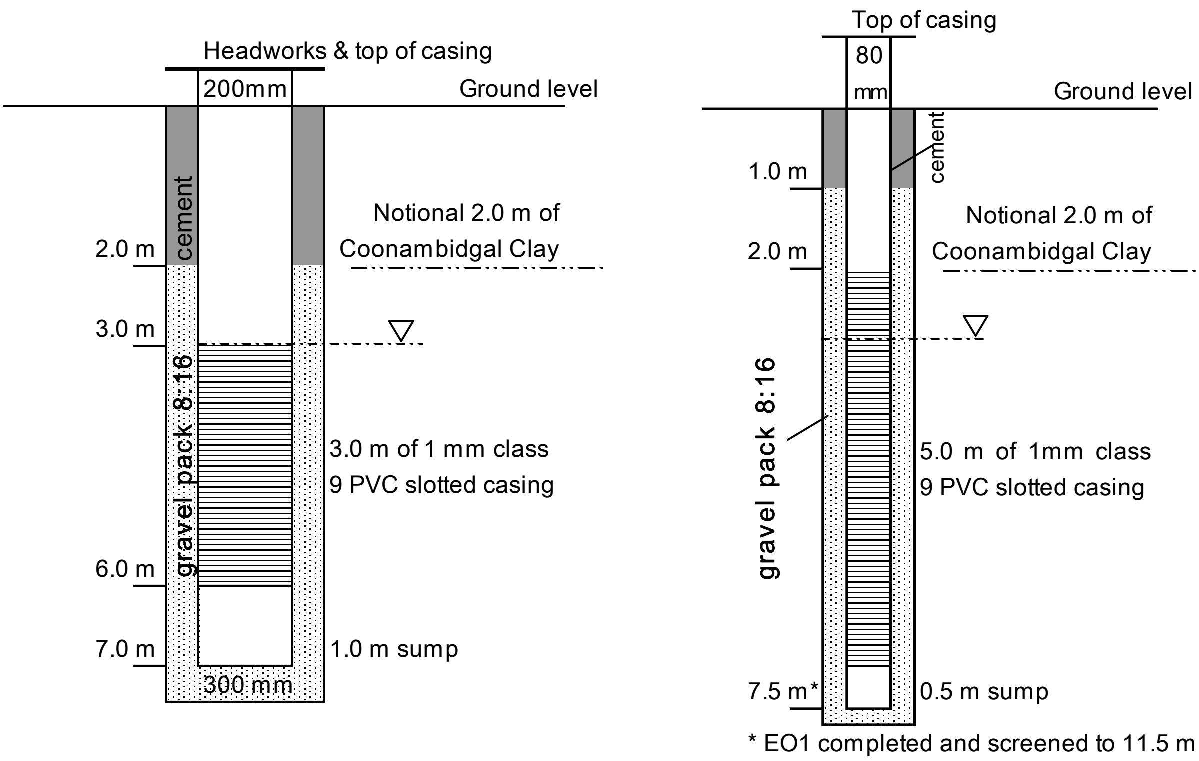

Figure 9. Schematic diagrams of injection and observation well constructions.

3.2 WELL DEVELOPMENT

Upon the completion of the injection wells, the drilling contractors attempted to conventionally airlift and develop the wells. This was not effective due to low yields of the wells and the poor hydraulic connection to the aquifer. DWLBC's Groundwater Technical Services were then deployed to test and develop each injection well. A short injection test was conducted to assess indicative injection rates for each well (results summarised in Table 7). Due to the screen completions in the clayey silt aquifer material, extensive testing could not be conducted and yields much lower than anticipated were recorded. A conservative total injection rate over the 5 wells was set at 1.5 L/s, this value being much lower than the anticipated and scenario-modelled 5 L/s. The measured values (Table 7) were later used as injection parameter variations to a numerical model simulation using the original model domain and hydraulic parameters.

Table 7. Pump test yields and indicative rates for injection into each injection well.

Injection well	Production yield	Expected injection rate
EI 1	0.8 L/s	0.6 L/s
EI 2	0.3 L/s	0.2 L/s
EI 3	0.3 L/s	0.2 L/s
EI 4	0.3 L/s	0.2 L/s
EI 5	0.2 L/s	0.1 L/s

3.3 INJECTION PRE-TRIAL

The injection pre-trial commenced on 2nd June 2006 at an injection rate of 2 L/s. The next day it was found that four of the five injection wells were leaking around the outside edge of the cement seal supporting the casing. The injection pre-trial was abandoned after 16 hours having injected only 0.114 ML (Figure 10). Figure 11 shows visible leakage of the wells at ground surface. Injection well EI1 was the only well not subject to leakage with the pressure head at that well remaining below natural surface (Figure 10).

The leaks occurred at the point when pressure heads in the injection wells reached the natural surface. The integrity of the cement seals were questioned, prompting examination of the construction of the injection wells. Minor excavation works around the annulus of each of the injection wells were carried out on the 22nd June. This revealed that only a limited and unsatisfactory interval of cement was emplaced into the annulus above a greater than specified gravel pack interval. The insufficient cement interval was not completed to specification as documented in the drilling contract (3222-3) and was deemed unacceptable for the purpose of groundwater injection (Figure 12). It was recommended that all five injection wells be considered as 'defective work' under the terms and conditions of drilling contract.

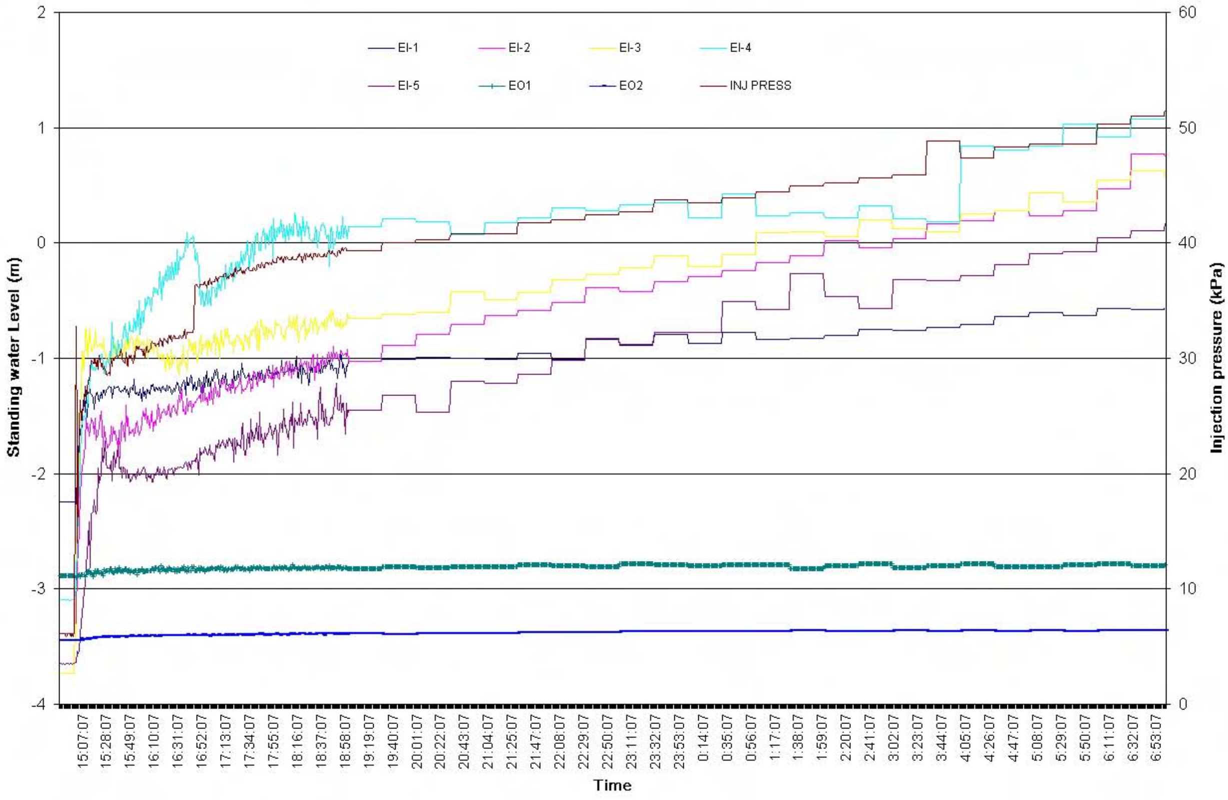

Figure 10. Pressure heads for injection and observation wells during the injection pre-trial.

Figure 11. Photos of water flow at the annulus of the injection wells during the injection pre-trial

Figure 12. Photos post excavation work revealing the insufficient cement seal installed by the drilling contractors.

3.4 RECTIFICATION WORK

From a review of evidence provided to Underdale Drillers by DWLBC, it was agreed by both parties that the drilling of the Site E injection wells were defective and not completed to specification. Underdale Drillers presented a resolution to the satisfaction of DWLBC representatives, with the rectification solution aligned with the original design specification. It involved the re-drilling of a wider annulus by means of hollow stem auger around the existing casing down to a depth such that an appropriate cement seal in line with the original specifications could be emplaced in the new annulus.

The rectification proposal involved the following actions, which were completed on the 21st August 2006:

- Removal of existing flange.
- Hollow stem auguring (406 mm) around the existing casing to a specified depth, and to the satisfaction of the supervising Hydrogeologist, who was present during all rectification work. This widened the annulus to the specified depth from the original 300 mm to 406 mm.
- Filling of the newly drilled annulus with adequate gravel fill and sealing with a 5% bentonite cement seal.
- Installation of a new flange.

3.5 INJECTION TRIAL OPERATIONS

Power for the site was supplied by a 20 kva generator located in a central control area with the power lines run in parallel with the flow pipeline to the pump. Flow delivery was controlled by a Kingfisher Remote Terminal Unit (RTU), programmed to maintain injection flow at a constant rate. Cut-off triggers were integrated to maintain pressure heads at the injection wells threshold values. All injection and observation data was logged by the RTU, a digital display head was fitted into the control cabinet to allow on site visualisation of live data showing water levels, head pressures, flow rate and injection pressures. The RTU connected to a telemetry system allowed for remote data downloads and monitoring of site operations.

The RTU controlled the pump via a Danfos variable speed drive unit with flow measured using an 80 mm Krohne Magflow. Initial total flow to the injection wells was set to 1.25 L/s. To maintain consistent water levels at the individual injection wells, individual flow rates were adjusted manually using 25 mm gate valves fitted to each injection line. As the head pressures rose, the pump speed was adjusted via the variable speed drive to keep the flow at a constant rate. When the pressure in the injection wells reached an assigned threshold (initially set to natural surface), the flow was reduced to maintain the water levels below the preset pressure level.

Injectant water supply was via a Grundfos CR 15 upright submersible pump situated 8 m from the riverbank, fitted with a section of stainless steel bore screen to prevent any large foreign objects from entering the pump. Water to the site was delivered via a 50 mm diameter poly pipeline. At the injection end, the poly pipe was connected to an 80 mm magflow and a distribution manifold. From the manifold, 25 mm poly lines were connected to each of the injection wells.

Figure 13. Injection control area with RTU, power supply, distribution manifold and supply lines.

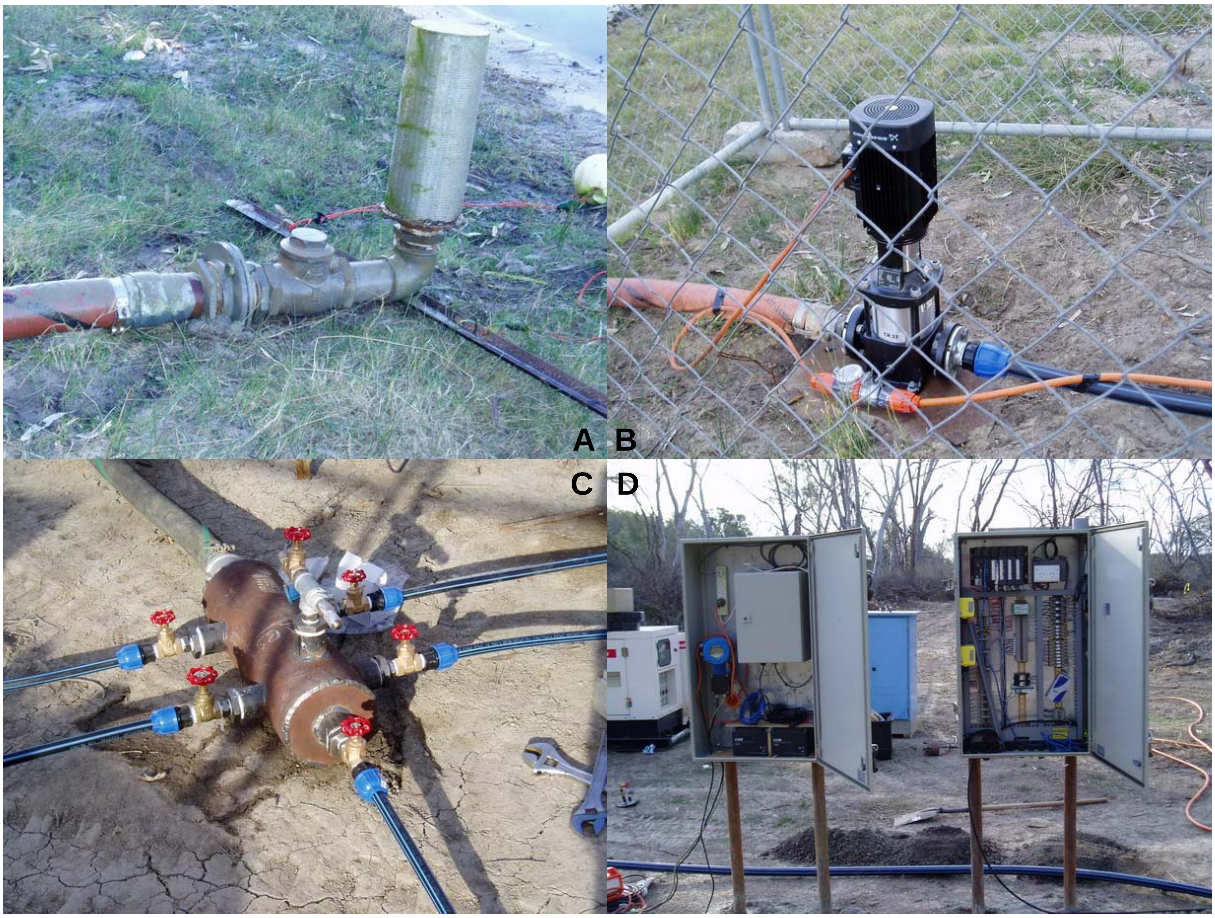

Figure 14. Photographs of (a) River intake, (b) Water pump, (c) Distribution manifold and (d) Remote transmission unit.

3.5.1 INJECTION AND OBSERVATION WELL MONITORING

All wells were fitted with flanges to allow the wells to be sealed. On the injection wells, blank plates were fitted with 50 mm BSP fittings to accommodate installation of the flow line, a 25 mm poly pipe to just below the water level. The plates were also fitted with a 25 mm BSP fitting with a small stand pipe and gate valve to allow for the manual measurement of the water level and an air valve to allow for release of displaced air. Observation wells EO1, EO2, EO3, EO5, EO6 were fitted with air valves/gate valves similar to the injection wells. 0-20 m/h Greenspan level transmitters were fitted to the Injection and observation wells and set approximately 6 m below the top of the casing with data cabling back to the central control area. Due to their more remote distance from the central control area, observation wells EO4 and EO7 were fitted with Innovonics stand alone water level loggers set approximately 6m below the top of the casing. Observation wells EO1, EO2, EO3 and EO5 were also fitted with additional level, EC and temperature data loggers.

Figure 15. Photograph of injection and observation well headwork completion.

4. RESULTS AND DISCUSSION

4.1 INJECTION RATES

Following the initial shortfall in construction and subsequent water seepage at surface, injection rates proceeded cautiously aiming to ensure that pressure heads did not exceed natural surface during early stages of the trial. Total injection rate over the five injection wells commenced at 1.25 L/s on the 20th September 2006 but were adjusted down in a stepwise manner over the first four days to 1 L/s in order to achieve a satisfactory initial pressure level (Figure 16). The rate of 1 L/s was maintained for 31 days during which steady increases in pressure head occurred. Periodic site visits were conducted to check the system whilst manual adjustments were made to the individual gate valves to equalise the pressure across the injection array.

Following the phase of constant injection, a decision was made to increase the injection rate to 1.25 L/s on the 25th October 2006. A decision was made due to the injection trial having already been in operation for 30 days as suggested in the initial project scope (AWE, 2005), significantly less volume than anticipated had been injected (3.2 ML of the allocated 10 ML), and to test the limitations of the injection infrastructure and aquifer. The increased injection rate of 1.25 /s was maintained for 14 days until the groundwater breached the surface at EI3 and EI4 on the 8th November 2006.

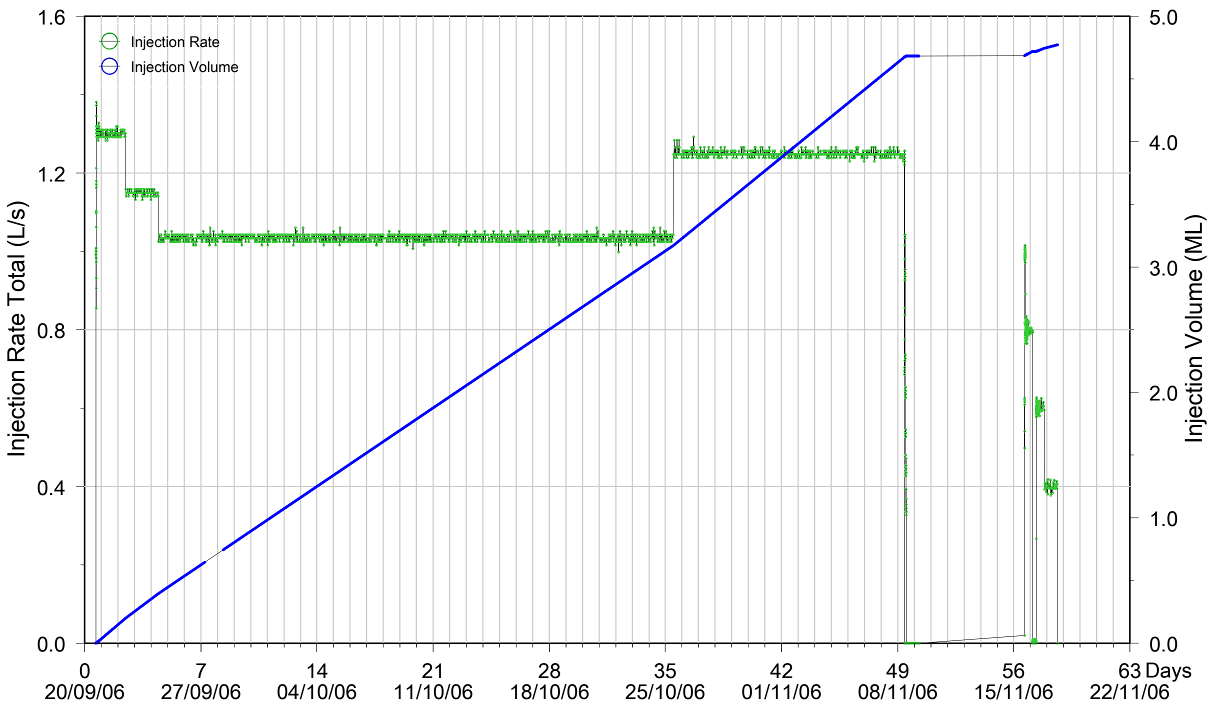

Figure 16. Total injection rates and cumulative injection volume.

During the period of constant and steady injection (1 L/s and 1.25 L/s), the pressure head at each of the injection wells steadily increased (Figure 17). This near linear increase in pressure head level indicated the aquifer and wells reducing ability to receive injectant, an effect characteristic of physical well and aquifer clogging. At the point precluding the increase in injection rate to 1.25 L/s, groundwater heads at the injection wells were around 2 m above natural surface, excluding EI4, which had a pressure head around 1 m above natural surface (Figure 17).

In each case, the breach occurred approximately 1.5 – 2.5 m away from the annulus of the wells (Figure 18). This suggested that the wells cement seal had maintained integrity but the aquifers confining layer had faltered due to the increasing pressure. In an effort to continue the injection, the three remaining intact wells were isolated and the pump restarted at a reduced rate, but the rapid build up of pressure heads could not be avoided. The system was shut down whilst remediation options were undertaken with the aim to continue injection until the environmental watering cut off date on the 5th December 2006, the remaining three injection wells were flushed and developed in an attempt to clear the screen and gravel packs of accumulated particulate matter.

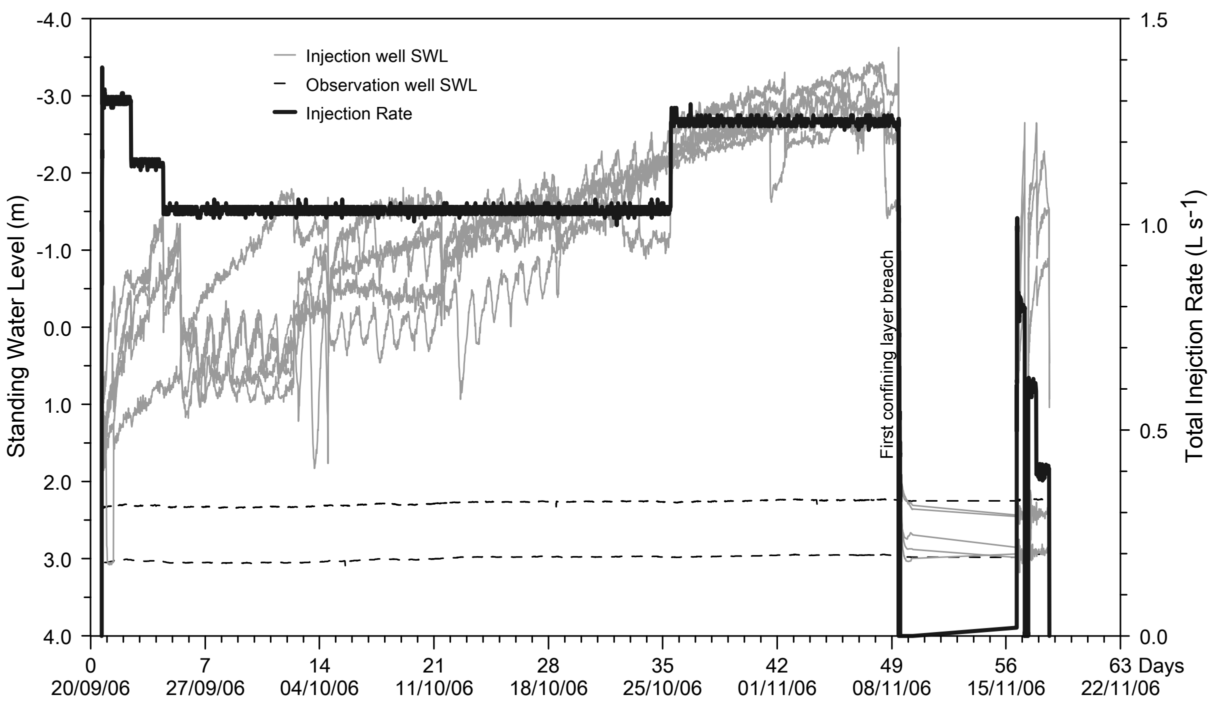

Figure 17. Injection and observation well water levels (pressure heads) and total injection rates.

Figure 18. Photos of aquifer breach, seen as pale coloured sand spills (flows) approximately 2 m from the injection wells

4.1.1 INJECTION WELL FLUSHING

The redevelopment of injection wells EI1, EI2 and EI5 occurred on the 15th November 2006. EI1 was pumped for 50 minutes, EI2 and EI5 for 30 minutes, until the water quality visually improved (Figure 19). Each well was monitored for EC and total suspended solids (TSS). Pumping rates, visual observations, and measured data are summarised in Table 8.

The pumping rate for EI5 was between 0.4 L/s and 0.6 L/s. The initial slug of back flush water was dark, murky with a strong organic aroma, appearing high in particulate matter (TSS of 255 mg/L). The back flush progressively cleared to a point after 15 minutes where the running water was ‘clean’ in appearance (TSS of 29 mg/L).

The development of EI1 produced an initial slug of water that was remnant in the lines from the EI5 redevelopment. The production yield of 0.3 - 0.4 L/s was considerably lower than the pre-injection yield. The first slug of EI1 water appeared very high in particulate matter and had a strong organic aroma (TSS of 2730 mg/L). After approximately 10 minutes the water began to run clear with a final TSS of 40 mg/L.

EI2 was developed for 30 minutes at a rate of 0.7 L/s. As experienced at EI5 and EI1, a back flush of visibly poor quality water was expected, but was not observed with water running visibly clean for the duration of the development. TSS results however, indicated a noticeable improvement in water quality during development (TSS of 257 mg/L to 28 mg/L). Without a visual cue it was difficult to determine the interface between remnant EI1 water and source EI2 water. The clearing of lines before each development would be recommended in future.

Table 8. Summary of flow rates, production times and total suspended solid content of water collected during injection well flushing.

Well	Total time (min)	Productio n rate (L/s)	Visual water appearance		Total suspended solids (mg/L) & sample time (min)		
			Start	*End*	*Sample01* *mg/L (minutes of pumping)*	*Sample02* *mg/L (minutes of pumping)*	*Sample03* *mg/L (minutes of pumping)*
EI1	50	0.3 – 0.4	Murky	Clear	2730 (0)	354 (10)	40 (50)
EI2	30	0.7	Clear	Clear	257 (0)		28 (30)
EI5	30	0.4 – 0.6	Murky	Clear	225 (0)	178 (5)	29 (30)

Figure 19. Photograph of visual water quality at EI5 before and after well development (right), and EI1 at the start of development (left).

4.2 GROUNDWATER LEVELS

4.2.1 INJECTION WELLS

Figure 17 presented groundwater level at the injection wells on a linear plot of standing water level over time in days. The same data is presented Figure 20, plotting head development over time in minutes. The data indicates a steady rise in water level over the course of the trial. Gradual rises in piezometric head and associated falls in injection rate are suggestive of hydraulic conductivity reductions due to gradual clogging (Pavelic et al., 2006) and represent an increasing inefficiency in recharging the aquifer. Similar effects may also be noticed due to aquifer geometry (boundary effects), however this is not considered to be an influence in this case. On average across the injection wells the groundwater level/head increased at the rate of 0.09 m/day (Figure 20, Table 9).

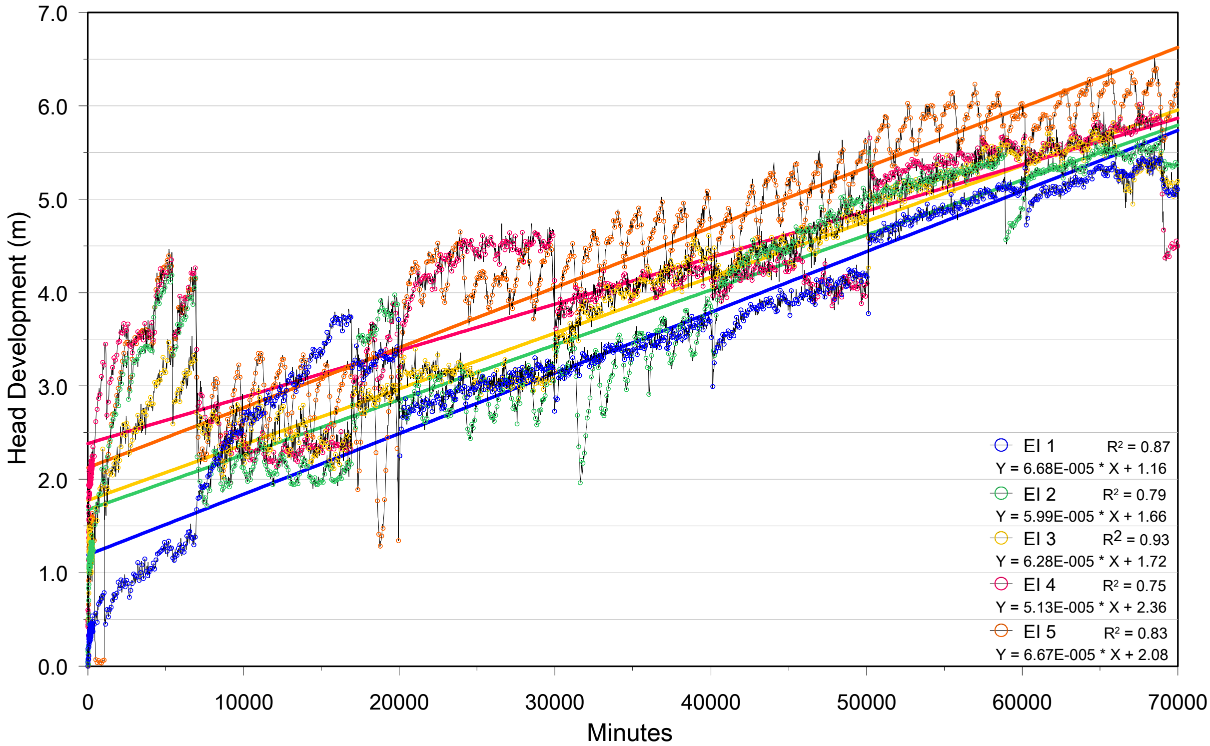

Figure 20. Head development at the injection wells

Table 9. Rate of head development at the injection wells.

Injection Well	Rate of injection well head development and equation of slope best fit		
	m/min	R^2	*m/day*
EI1	6.68E-05	0.87	0.096
EI2	5.99E-05	0.79	0.086
EI3	6.28E-05	0.93	0.090
EI4	5.13E-05	0.75	0.074
EI5	6.67E-05	0.83	0.096
		AVERAGE	0.09 m/day

4.2.2 OBSERVATION WELLS

Groundwater level in the observation wells did not significantly rise in response to the injection of water. During the period of the trial, groundwater level remained between 9.9 mAHD and 10.1 mAHD (Figure 21). The increase that was observed is coincident with a rise in river level. Local changes in river height were monitored at Clark's Floodplain gauging station (A4261083). As a control, the hydrograph of Site B observation well B4, located at the rivers edge is plotted Figure 21, and displays good aquifer and river connectivity.

Although large increases in groundwater level were not evident, a number of injection induced responses were observed. At the initial onset of injection (20 September 2006) there was a slight (0.05 m) yet rapid increase in groundwater level. The magnitude of response decreases with increasing distance from the injection array, with distant observation wells EO4 and EO7 not influenced. The groundwater level soon returned to the initial level due to the reduction in injection rate from 1.25 L/s to 1 L/s. Neither the river nor the B4 hydrographs recorded an increase at this point, thus isolating the groundwater response due to the commencement of injection.

All wells (excluding the distant wells EO4 and EO7) showed subtle decreases in groundwater head as the aquifer depressurised when the trial was shut down on 8 November 2006. The river and B4 hydrograph behaved independently, showing a contrasting increase in level during this period, confirming the groundwater response was due to the variation in injection stress. Following well back flushing and re-development, the resumption of injection observed an increase in groundwater level, similar to that observed at the start of the initial injection.

The effect on groundwater level was minimal with only subtle responses observed. Had greater injection rates been achieved, greater increases in groundwater level would have been observed. It is apparent that groundwater level beyond the direct vicinity of the injection wells were not greatly influenced indicating a number of points:

- The aquifer is sufficiently transmissive to accommodate and disperse the injected water without greatly increasing groundwater levels.
- This is an accompaniment to the low rates of injection, a factor of the poor hydraulic capacity of the injection well.
- Head development is limited to the injection wells, which indicates that the injection wells are hydraulically inefficient.

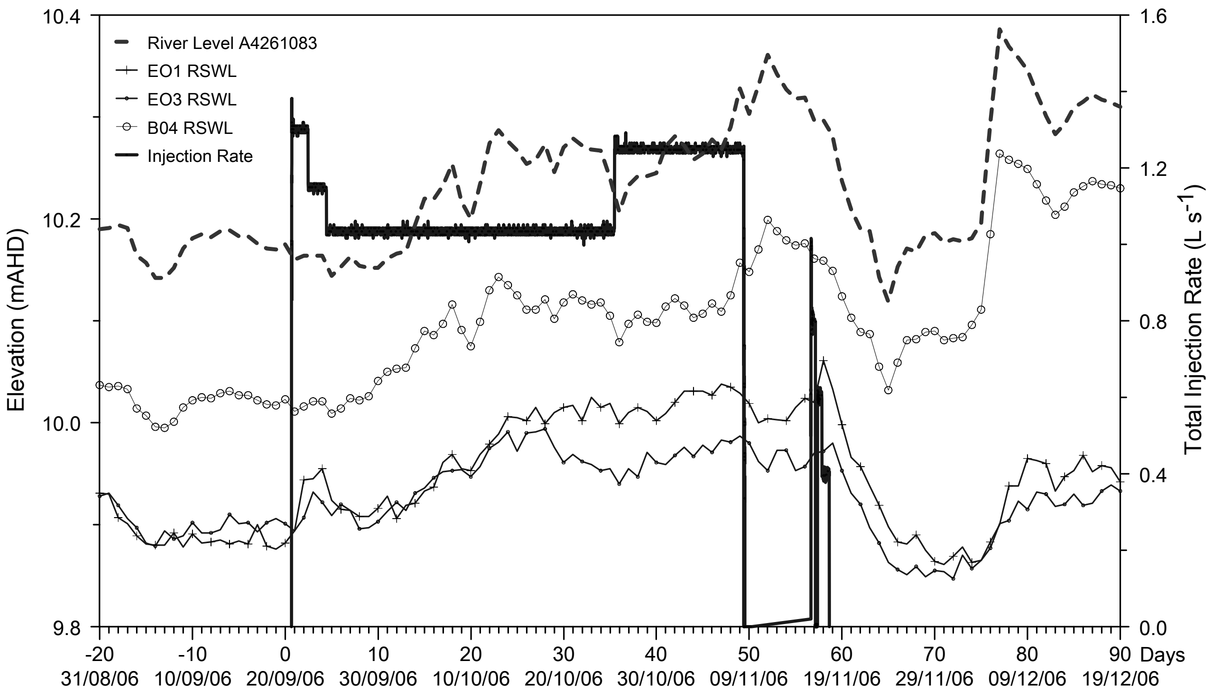

Figure 21. Observation well and river water levels including injection rate time series.

4.3 GROUNDWATER SALINITY

Groundwater salinity was monitored in the observations wells using both continuous data logging and periodic down-hole fluid conductivity profiling. The observation well locations were based on modelled injection rates of 5 L/s, however the low injection rate of 1.25 L/s at the site resulted in limited groundwater salinity change. The only significant manipulated variation in groundwater salinity was observed in the injection wells themselves and in observation well EO1 located less than 5 m from its nearest injection well (EI5) (Figure 22). The salinity in all other observation wells was not altered to any notable degree, remaining at native background salinity levels.

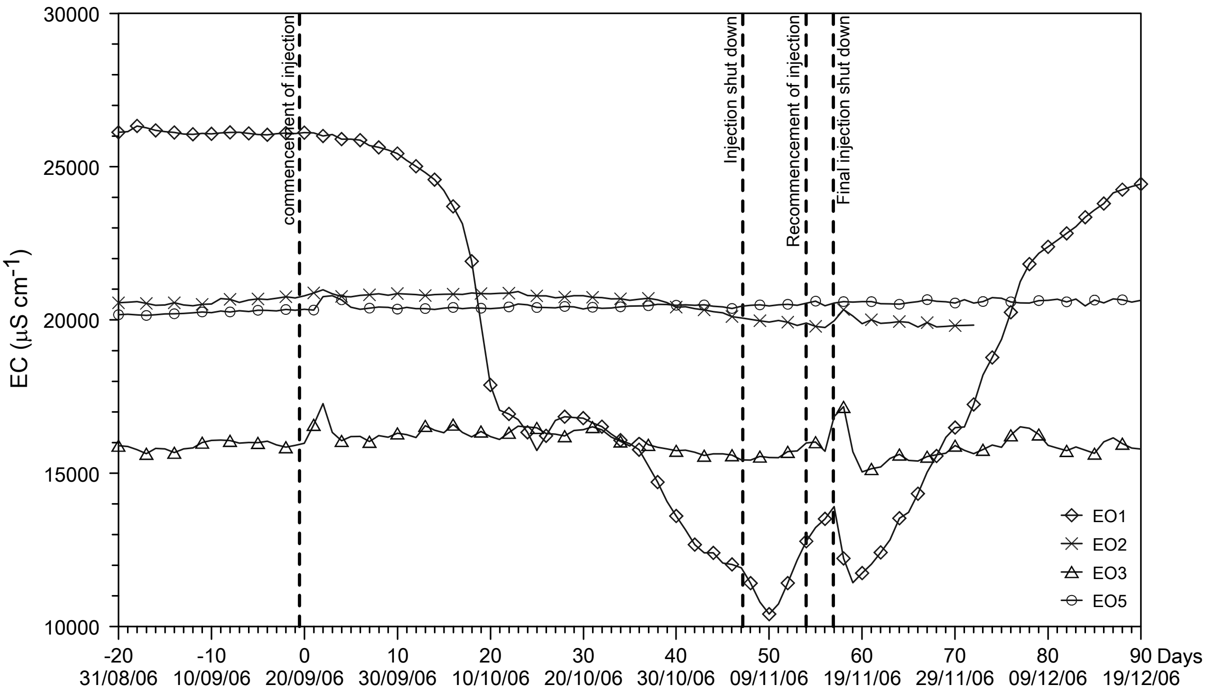

Figure 22. Observation well salinity.

4.4 ELECTROMAGNETIC SURVEY

A Geonics EM31 conductivity meter was used to survey Site E on 2 November 2006. Electromagnetic (EM) surveying operates on the principles of electromagnetic induction, whereby alternating currents in the transmitter coil (with a set frequency) induce time varying magnetics fields, which in turn induce a small electrical current within the earth. These currents generate a secondary magnetic field, which is sensed at the receiver together with the primary field, the ratio of which indicates the grounds conductivity (McNeill, 1980a). Thus the instrumentation is able to remotely sense the subsurface ability to conduct electrical current. The EM31 has an effective penetration depth of around 4 – 6 m dependant on the conductivity of the subsurface and the resultant apparent conductivity output is a bulk representation of this near surface zone. Variables that may typically influence the results of the EM31 surveys in this environment include the groundwater level and salinity, variations in soil moisture, salt content and clay content, which is less significant in soils having highly saline pore waters (McNeill, 1980b).

Figure 8 provides a conductivity image over the central injection area that passes all injection and observation wells and extending to the south-eastern riverbank. The broad patterns in the data can be intuitively interpreted to indicate changes in native groundwater salinity, which was supported by manual observations of the groundwater salinity. Measured conductivities are lowest (blue) nearest the river channel and increase towards the centre of the floodplain peninsula (red). The location with the highest conductivity (~220 mS/cm) was at the northern extent of the survey.

Conductivity typically increases as you move landward from the river channel however, lower conductivity zones (green) are observed around the injection wells post injection (Figure 8). The conductivity survey suggests that the injected fresh river water provides a suitable salinity contrast for mapping using EM31. It is apparent that these zones of lower conductivity do not extend to the location of the adjacent observation wells, excluding EO1, which was the only observation well to observe a reduction in groundwater salinity. Both the geophysical and groundwater data sets show that the injected fresh water did not disperse any great distance beyond the injection points.

4.5 SOIL SALINITY

Soil samples where collected in 0.5 m increments from the unsaturated zone from five wells (EI1, EO1, EO2, EO3 and EO5) during drilling in April 2006. Post injection samples were collected adjacent to the wells on 4 December 2006 and 20 April 2007. Gravimetric water content (gg^{-1}) was measured by oven drying at 105^{o}C for 24 h. Matric potential (Ψ, MPa) was determined using the filter paper technique (Greacen et al., 1989). As described in Mensforth et al., (1994) and Holland et al., (2006), soil samples were analysed for matric potential (soil dryness) and osmotic potential (soil salinity), with the total soil water potential being the sum of these values (Figure 23). Total chloride was measured by ion chromatography, and then converted to the chloride concentration in the soil solution (mg L^{-1}) using the gravimetric water content. Osmotic potential (Ψ_{π}, MPa) was estimated from the chloride concentration of the soil solution calculated using the Van't Hoff equation. This method assumes that all salts in the soil solution are present as sodium chloride and that the concentration used to calculate this relationship is appropriate for the range of soil salinities encountered by floodplain trees. Gravitational water potentials are not included as they are minimal in comparison with to the measured matric and osmotic potentials.

Soil water total potential was used to indicate soil water availability for root uptake; a clear relationship is derived from the knowledge of a tree's predawn water potential, an integrated measure of soil water availability to vegetation (Eamus et al, 2006). Soil regions with a higher soil water potential than the tree water potential are available to the tree for water use. The more negative the value, the harder it is for plants to source water (Figure 23).

Previous studies in similar environments have found river red gum predawn water potentials around –2 MPa (Mensforth et al, 1994, Holland et al, 2006). At the collaborative Site B trial, predawn water potentials measured by CSIRO indicated the upper limit of river red gum water stress at -5.38 MPa (Holland et al, 2009). The river red gum Site B results measured by Holland et al (2009) show a shift in river red gum water-stress threshold during drought periods, indicating that trees subject to continued periods of stress require increasingly better soil water conditions in order to respond positively.

A line representing the -2 MPa threshold for river red gums on Clark's Floodplain over this sampling period is annotated in Figure 23. If the total soil water potential (black triangles) is to the left of this line, then the trees should not be able to access water from that part of the profile. The results indicate total potential to be within the annotated threshold only at the deeper regions of the soil profile (typically > 2 m). This was observed in the April 2006 and April 2007 data excluding EO1 in April 2006. The vertical extent of the December 2006 data sets are truncated in comparison, suspected to be due to a collection inconsistency with respect to the point of saturation, thus making it difficult to analyse results from December 2006.

Of the soil sample sites, observation well EO1 and adjacent injection well EI1 were the only wells to record groundwater freshening during the injection trial (Figure 22). At these two locations there was a noticeable increase in the soils total potential and thus water availability at depths greater than 2 m (April 2006 to April 2007). However, similar observations were not as apparent where groundwater salinity had not been reduced. At all sites, in the upper soil profile, generally an increase in soil chloride (decreased osmotic potential) was measured (Figure 23), likely to be due to evaporative concentration.

Soil condition improvement was observed at the deeper profile interval at locations where the groundwater was freshened by injection. Even though the trees could be up-taking water from this deeper and ‘fresher’ part of the profile, this zone may typically represent the regular zone of saline water table fluctuation due to the hydraulic link with the river, such that roots may not be encouraged to grow or source water. Both field and laboratory studies have found that groundwater salt concentration of 20,000 EC causes river red gum death (Eamus et al, 2006), with the groundwater salinity across the injection zone ranging from 16,000 – 25,000 EC. Roots at these greater depths would be exposed to the high salinity groundwater, limiting water uptake, promoting tree water stress.

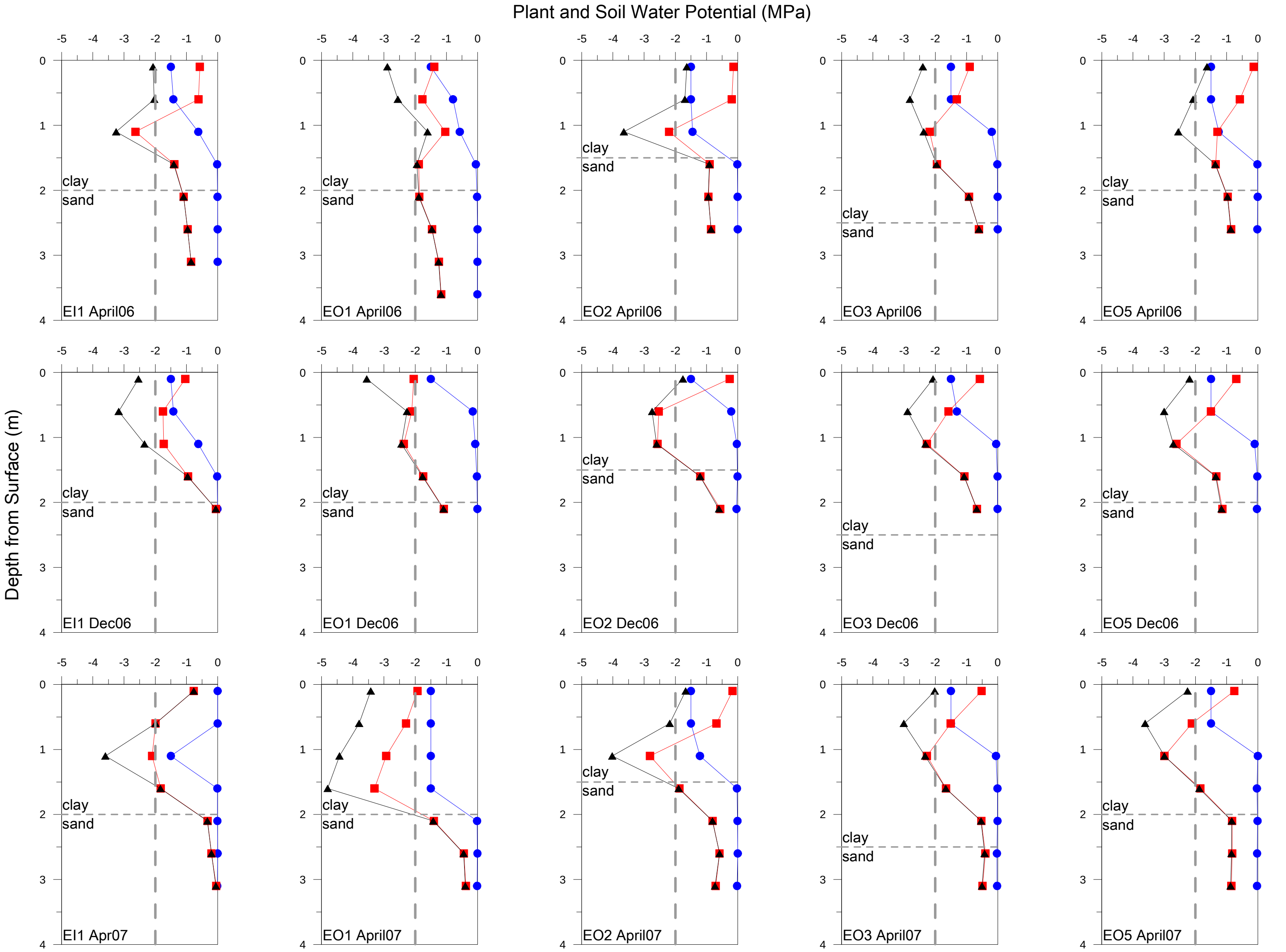

Figure 23. Total soil water potential (▲), matric soil water potential (●), and osmotic soil water potential (■)

4.6 VEGETATION

River red gum condition (crown cover) did not change during the investigation when comparing six control trees (χ^2_3 = 0.818, p = 0.85), which were in the same baseline condition as six trees located within the freshened injection zone (χ^2_3 = 2.0, P = 0.57) (Figure 24). These results concluded that injection did not improve river red gum condition.

Whilst large changes in condition were not observed in the 12 trees, small behavioural changes may be more readily detected in response to environmental changes e.g. Epicormic growth, a behavioural response to improved conditions such as environmental watering and rainfall. For this reason response data was analysed separately. Raw response data was analysed as it upheld the assumption of homogeneity of variance. However, as the assumption of sphericity was violated (W = 0.27; χ^2_5 = 11.404; P = 0.044), the results were adjusted using the Greenhouse Geisser and Huyhn-Feldt ε.

There was no significant difference in response between the six trees within the freshened injection zone compared to the six control trees (Figure 25, Table 10). However the magnitude of response changed over the course of the survey with a significantly higher response on the third survey date compared with either the first or second dates. There was no interaction between treatment (injection) and time.

Due to the increase in response of the 12 injection and control trees on the third assessment date, all 60 river red gums were then assessed against rainfall. Rainfall is an alternative water source utilised by river red gums (Mensforth et al, 1994) and notable above average rainfall was recorded before the third assessment date (Figure 26).

Below average rainfall was recorded during the injection trial and the 3 months prior to injection (Figure 26) allowing for discrimination between injection and rainfall influences. The increase in river red gum response in February 2007 was observed across all 60 trees at Site E (Figure 27). To accurately discriminate the water source that the river red gums were using, isotope analysis is required. Whilst isotope samples are being collected as part of this project in the Site B trial, no data was available for Site E injection trial.

The soil salinity, groundwater EC and tree response results all indicate that changes to the groundwater from the injection did not influence tree health. The river red gums at this site responded to rainfall events, though this would not be enough to sustain them in the long term. Both the poor health class and mortality rate increased by 18% over 16 months, and the combination of ‘no crown’ and ‘crown cover < 25%’ at the site had increased from 69% of trees in April 2006, to 87% in August 2007 (Figure 28).

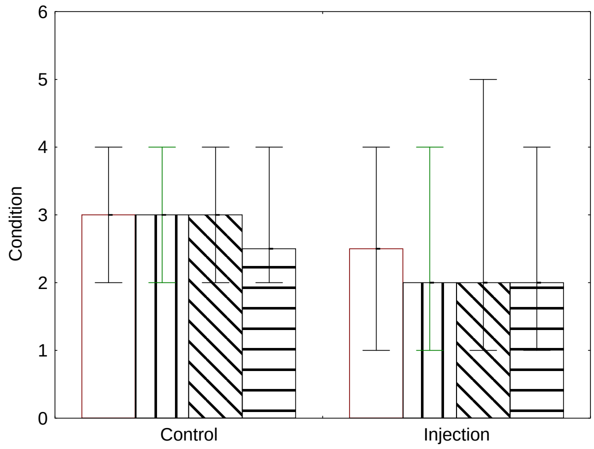

Figure 24. **Median (±5,95% percentiles) *Eucalyptus camaldulensis* condition for control and injection trees at Site E during April 2006, clear bars; November 2006, vertical bars; February 2007, diagonal bars and August 2007, horizontal bars.**

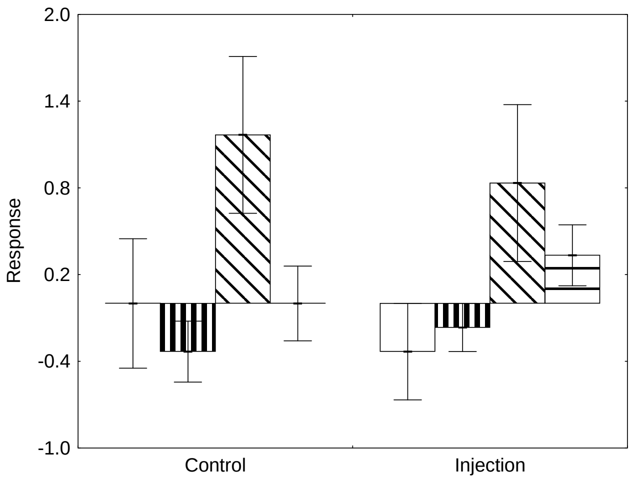

Figure 25. **Mean (±SE) *Eucalyptus camaldulensis* response for control and injection trees at Site E during April 2006, clear bars; November 2006, vertical bars; February 2007, diagonal bars and August 2007, horizontal bars.**

Table 10. **Repeated measures ANOVA results for differences in response between injection and control trees at Site E Bookpurnong(**P<0.01).**

	df	MS	F	P	G-G	H-F
Between subjects						
Injection treatment	1	0.0208	0.0207	0.888		
Error	10	1.0042				
Within subjects						
Time	3	3.9097	5.223	0.005**	0.018**	0.009**
Treatment x time	3	0.3542	0.473	0.703	0.613	0.665
Error	30	0.7486				

Adjusted P: G-G (Greenhouse-Geisser ε = 0.60838); H-F (Huynh-Feldt ε = 0.81150)

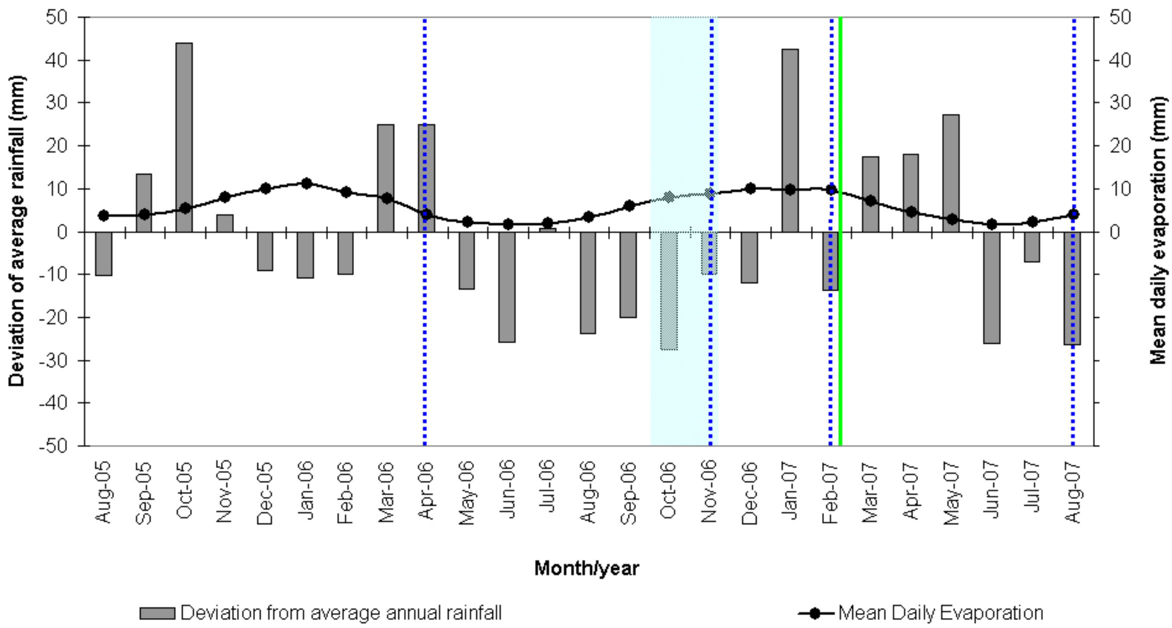

Figure 26. **Deviation of average rainfall at the Loxton Research Centre (024024), Bureau of Meteorology 2008. The shaded blue area represents the injection well operation period, dotted blue lines being the dates when tree assessments were undertaken with the green line representing the assessment when a significant response was recorded.**

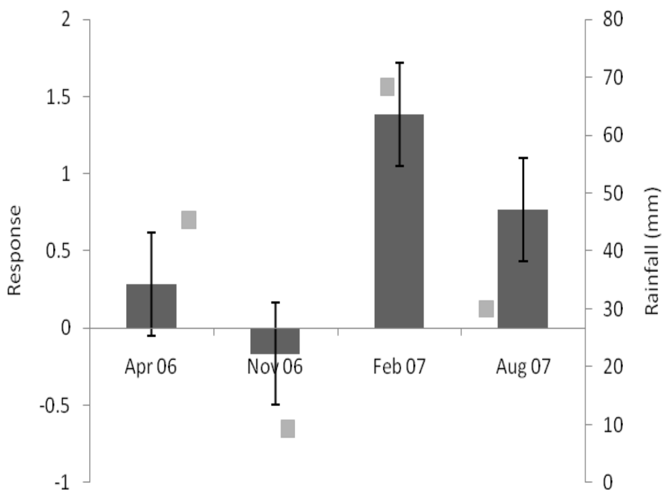

Figure 27. **Mean (±SE) *Eucalyptus camaldulensis* response for all trees at Site E (dark grey bars) and total rainfall for 57 days prior to sampling (light grey squares) in April 2006; November 2006, February 2007 and August 2007. Note: 57 days = injection duration.**

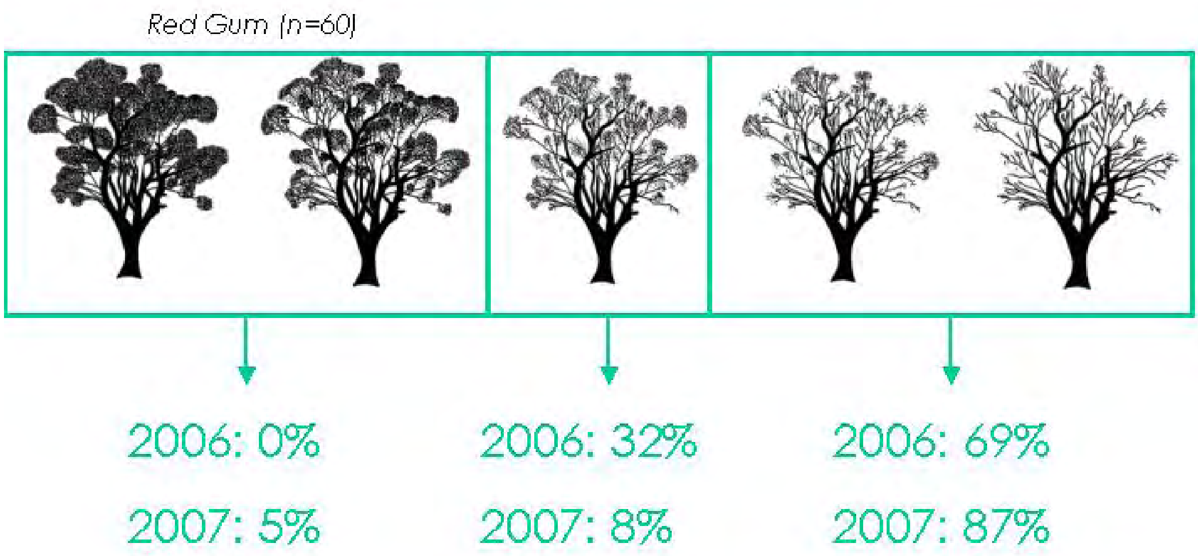

Figure 28. Visual summary of overall tree crown cover decline at Site E over the 16-month assessment period. Crown extent categories in boxes from left to right are 91-100% and 76-90%, 25-75%, 1-25% and 0%.

5. CONCLUSIONS AND RECOMMENDATIONS

The Living Murray trials were developed to monitor the interaction between surface water, groundwater and vegetation condition. The monitoring of groundwater indicated a good connection between the River Murray and the aquifer across this floodplain. The trial of river water injection was not able to alter groundwater conditions to any significant degree and was greatly hampered by poor injection volumes.

This trial has highlighted a suite of problems that needs to be addressed if shallow injection trials are to be undertaken for floodplain benefit. If such a trial were to translate to the Chowilla Floodplain, it would be important to not only consider the technical and physical aspects of injecting river water into the shallow aquifer, but the long term infrastructure requirements also need to be taken in to account. A project of this nature should be split into two components, that of a feasibility study and an operational component. If the feasibility study is unfavourable for a particular site, then the operational component of the study should not go ahead and until such time as a more suitable site has been located.

The outcomes of this trial suggest that locating a stressed tree community that not only requires intervention but also overlies an appropriate aquifer for injection is difficult. Initially, the aim of this project was to find an alternative way to deliver water to stressed black box communities. Within the timeframe of this project we were unable to find a suitable site and hence switched focus to a river red gum community that seemed to have suitable injection potential, with the new focus of this trial testing the methodology of shallow injection.

The river red gums in this trial did not respond to groundwater freshening via the injection method. The most significant increase in tree response occurred three months post-injection and corresponded with the highest rainfall seen over the life of the trial. Mensforth et al. (1994) found that river red gums are opportunistic in sourcing the water they use. Under current drought conditions, it is hypothesised that the river red gums on this floodplain are reserving their energy stores and are surviving on rainfall, though rainfall alone will not keep these extremely stressed populations alive in the long term. An increase in mortality and poor tree condition was recorded at the site.

The Site B trial was successful in rejuvenating tree condition by providing a freshened aquifer water supply in the root zone (Berens et al, 2009). Over a two year period, the results from the Site B trial indicate that injection for rejuvenating floodplain tree species could be an intervention method that may be met with some success in the future. Though, injection as an intervention method to freshen an aquifer is not recommended at this stage unless the ideal site conditions and aquifer requirements can be met, and well clogging issues can be resolved so injection can be maintained over a longer period than what occurred during this trial.

Injection should only be used as one step in the restoration process, as surface water flooding is still needed to keep the landscape functioning. Even if artificial aquifer freshening can be achieved to target the root zone and have a positive effect on tree health, it will not provide the microhabitat needed for germination and hence recruitment in these declining floodplain tree populations on the Lower Murray River floodplains. During periods of drought, aquifer freshening may sustain tree condition in saline areas over the short term until inundation can be provided to replenish the larger aquifer, and initiate understorey response and tree germination.

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APPENDICES

A. PHOTO-POINTS

Photopoint 1

April 2006

April 2007

August 2007

Photopoint 1.2

April 2006

April 2007

August 2007

Photopoint 2

April 2006

April 2007

August 2007

Photopoint 3

April 2006

April 2007

August 2007

Photopoint 4

April 2007

August 2007

April 2006

B. WELL CONSTRUCTION AND GEOLOGICAL LOGS

Government of South Australia
Department of Water, Land and Biodiversity Conservation

IDENTIFICATION DATA

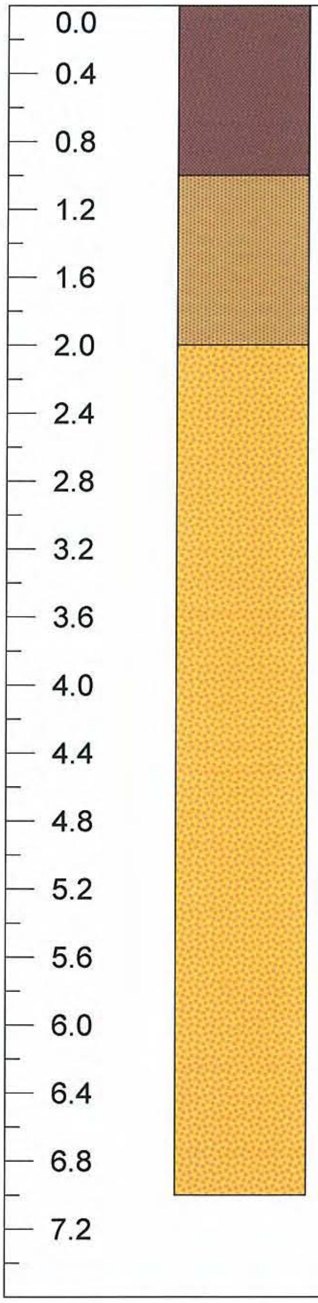
Unit No.	702902233
Permit No.	115756
Drill Hole Name.	EI 1
Drill Hole Purpose.	INJECT

REFERENCE & LOCATION DATA

Reference Elevation.	13.13
Ground Elevation.	12.35
MGA Easting.	461500
MGA Northing.	6196820
MGA Zone.	54
Hundred.	GORDON

LATEST HYDRO INFORMATION

Latest Open Depth.	0	Date.	5/15/08
Latest Status.	BKF	Date.	5/15/08
Latest EC (μS/cm).	-	Date.	-
Latest TDS (mg/L).	-		
Latest SWL (m).	2.48	Date.	8/30/07
Latest RSWL (m).	9.85		



Well sorted clay to silt, dark grey

moderately sorted silt to medium sand with minor clay and minor coarse sand, grey

poorly sorted silt to medium sand with minor coarse sand, pale yellow

poorly sorted fine to coarse sand, light yellowish brown

moderately sorted medium to coarse sand, light yellowish brown

CONSTRUCTION DETAILS

Drilling.

From (m)	To (m)	Diameter (mm)	Method	Completion Date.
0	7	310	RTM	4/12/06

Casing.

From (m)	To (m)	Diameter (mm)	Material
0	7	200	PVC

Production Zone.

From (m)	To (m)	Diameter (mm)	Type	Material	Aquifer
3	7	200	SB+SC	PVC	Qam

cement
screen
slotted casing
casing
open hole completion
packer / swage

Government of South Australia
Department of Water, Land and Biodiversity Conservation

IDENTIFICATION DATA

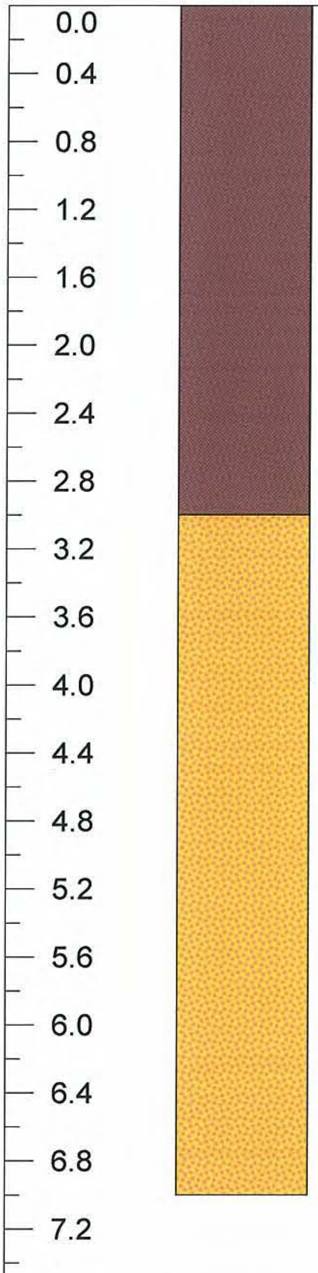
Unit No.	702902234
Permit No.	116502
Drill Hole Name.	EI 2
Drill Hole Purpose.	INJECT

REFERENCE & LOCATION DATA

Reference Elevation.	13.25
Ground Elevation.	12.88
MGA Easting.	461538
MGA Northing.	6196813
MGA Zone.	54
Hundred.	GORDON

LATEST HYDRO INFORMATION

Latest Open Depth.	0	Date.	5/15/08
Latest Status.	BKF	Date.	5/15/08
Latest EC (µS/cm).	-	Date.	-
Latest TDS (mg/L).	-		
Latest SWL (m).	2.98	Date.	8/30/07
Latest RSWL (m).	9.85		



well sorted clay to silt, grey

well sorted clay, silt and fine sand, pale yellow

moderately sorted silt to medium sand, light yellowish brown

poorly sorted fine to coarse sand, light yellowish brown

CONSTRUCTION DETAILS

Drilling.

From (m)	To (m)	Diameter (mm)	Method	Completion Date.
0	7	310	RTM	4/11/06

Casing.

From (m)	To (m)	Diameter (mm)	Material
0	7	200	PVC

Production Zone.

From (m)	To (m)	Diameter (mm)	Type	Material	Aquifer
3	7	200	SB+SC	PVC	Qam

cement
screen
slotted casing
casing
open hole completion
packer / swage

Government of South Australia
Department of Water, Land and Biodiversity Conservation

IDENTIFICATION DATA

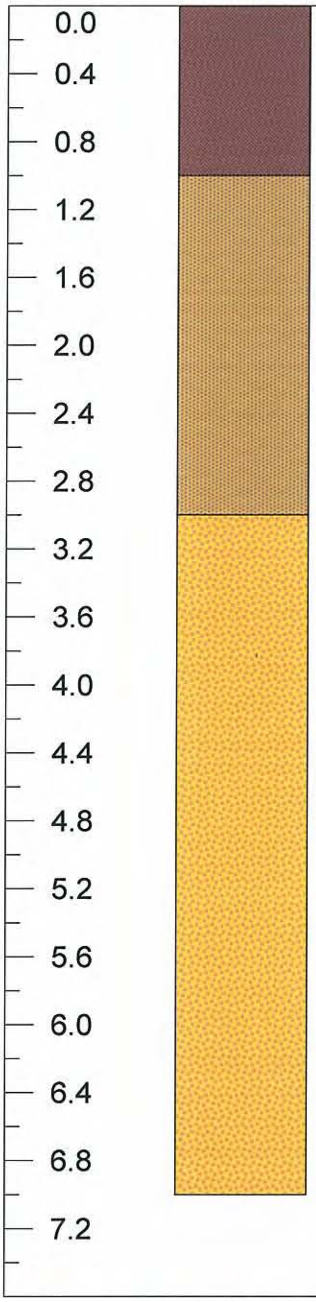
Unit No.	702902235
Permit No.	116501
Drill Hole Name.	EI 3
Drill Hole Purpose.	INJECT

REFERENCE & LOCATION DATA

Reference Elevation.	13.63
Ground Elevation.	13.02
MGA Easting.	461498
MGA Northing.	6196774
MGA Zone.	54
Hundred.	GORDON

LATEST HYDRO INFORMATION

Latest Open Depth.	0	Date.	5/15/08
Latest Status.	BKF	Date.	5/15/08
Latest EC (μS/cm).	-	Date.	-
Latest TDS (mg/L).	-		
Latest SWL (m).	3.1	Date.	8/30/07
Latest RSWL (m).	9.85		



well sorted silt to clay with minor fine sand, grey

well sorted silt to fine sand with minor clay and minor medium sand

moderately sorted silt to medium sand, light yellowish brown

poorly sorted fine to coarse sand, light yellowish brown

CONSTRUCTION DETAILS

Drilling.

From (m)	To (m)	Diameter (mm)	Method	Completion Date.
0	7	310	RTM	4/11/06

Casing.

From (m)	To (m)	Diameter (mm)	Material
0	7	200	PVC

Production Zone.

From (m)	To (m)	Diameter (mm)	Type	Material	Aquifer
3	7	200	SB+SC	PVC	Qam

- cement
- screen
- slotted casing
- casing
- open hole completion
- packer / swage

Government of South Australia
Department of Water, Land and Biodiversity Conservation

IDENTIFICATION DATA

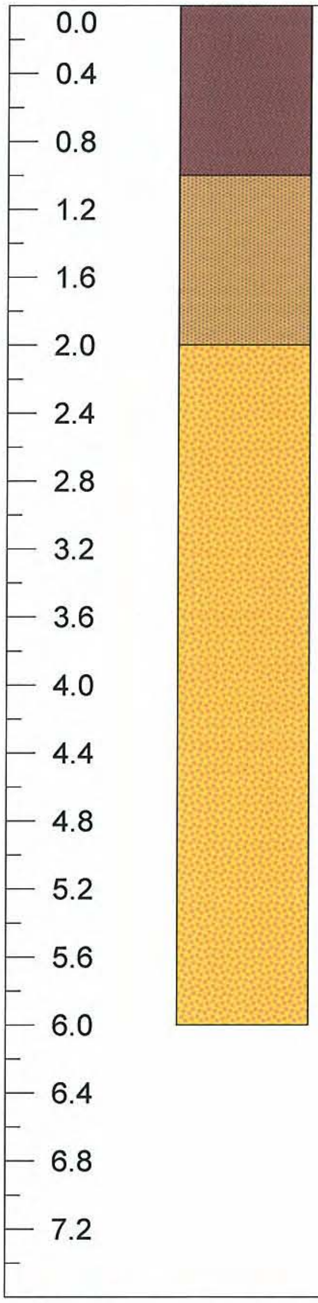
Unit No.	702902236
Permit No.	116500
Drill Hole Name.	EI 4
Drill Hole Purpose.	INJECT

REFERENCE & LOCATION DATA

Reference Elevation.	12.97
Ground Elevation.	12.47
MGA Easting.	461544
MGA Northing.	6196781
MGA Zone.	54
Hundred.	GORDON

LATEST HYDRO INFORMATION

Latest Open Depth.	0	Date.	5/15/08
Latest Status.	BKF	Date.	5/15/08
Latest EC (µS/cm).	-	Date.	-
Latest TDS (mg/L).	-		
Latest SWL (m).	2.41	Date.	8/30/07
Latest RSWL (m).	9.89		



well sorted clay to silt, grey

moderatey sorted silt to medium sand with minor clay, light grey

well sorted fine to medium sand with minor silt, pale yellow

poorly sorted fine to coarse sand, light yellowish brown

moderately sorted medium to coarse sand, light yellowish brown

well sorted fine to medium sand with minor coarse sand, pale yellow

CONSTRUCTION DETAILS

Drilling.

From (m)	To (m)	Diameter (mm)	Method	Completion Date.
0	6	310	RTM	4/12/06

Casing.

From (m)	To (m)	Diameter (mm)	Material
0	6	200	PVC

Production Zone.

From (m)	To (m)	Diameter (mm)	Type	Material	Aquifer
2	6	200	SB+SC	PVC	Qam

cement
screen
slotted casing
casing
open hole completion
packer / swage

Government of South Australia
Department of Water, Land and Biodiversity Conservation

IDENTIFICATION DATA

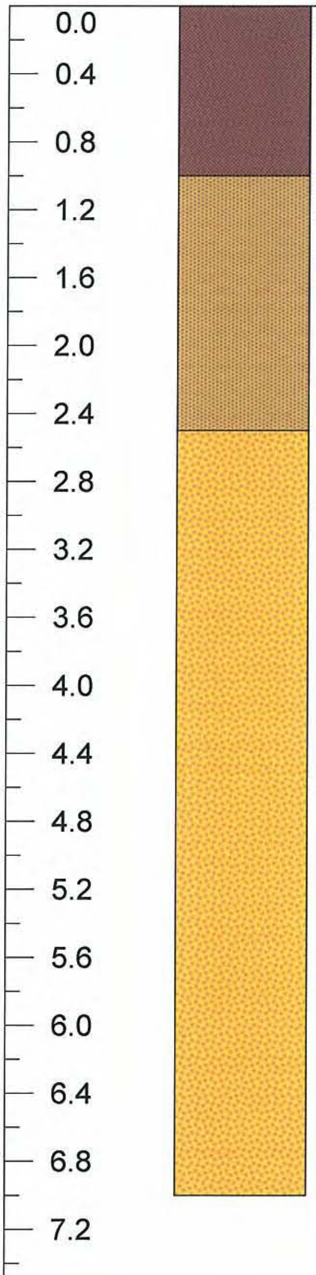
Unit No.	702902237
Permit No.	116499
Drill Hole Name.	EI 5
Drill Hole Purpose.	INJECT

REFERENCE & LOCATION DATA

Reference Elevation.	13.5
Ground Elevation.	13.12
MGA Easting.	461517
MGA Northing.	6196798
MGA Zone.	54
Hundred.	GORDON

LATEST HYDRO INFORMATION

Latest Open Depth.	0	Date.	5/15/08
Latest Status.	BKF	Date.	5/15/08
Latest EC (μS/cm).	-	Date.	-
Latest TDS (mg/L).	-		
Latest SWL (m).	3.04	Date.	8/30/07
Latest RSWL (m).	10.08		



moderateky sorted clay, silt and fine sand, grey

well sorted silt to fine sand with minor clay and minor medium sand, pale yellow

well sorted fine to medium sand, light yellowish brown

poorly sorted fine to medium sand, light yellowish brown

well sorted medium sand, light yellowish brown

CONSTRUCTION DETAILS

Drilling.

From (m)	To (m)	Diameter (mm)	Method	Completion Date.
0	7	310	RTM	4/12/06

Casing.

From (m)	To (m)	Diameter (mm)	Material
0	7	200	PVC

Production Zone.

From (m)	To (m)	Diameter (mm)	Type	Material	Aquifer
3	7	200	SB+SC	PVC	Qam

cement
screen
slotted casing
casing
open hole completion
packer / swage

Government of South Australia
Department of Water, Land and Biodiversity Conservation

IDENTIFICATION DATA

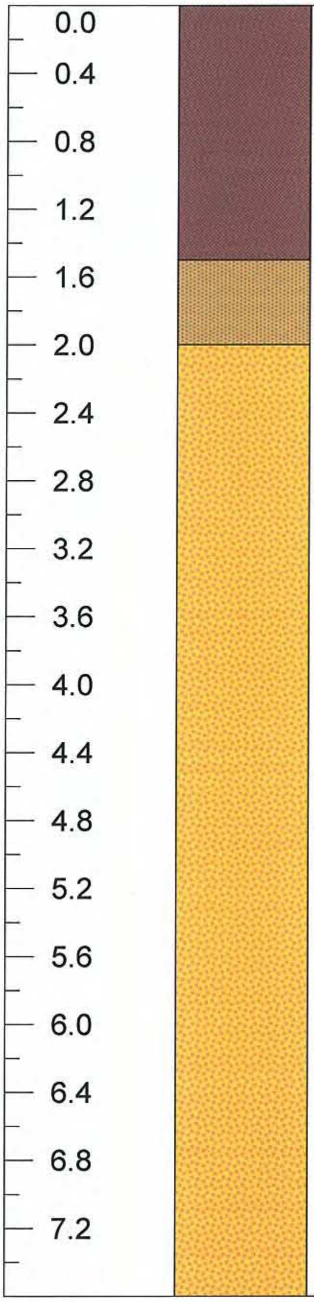
Unit No.	702902238
Permit No.	115757
Drill Hole Name.	EO 1
Drill Hole Purpose.	OBS

REFERENCE & LOCATION DATA

Reference Elevation.	13.82
Ground Elevation.	13.03
MGA Easting.	461522
MGA Northing.	6196796
MGA Zone.	54
Hundred.	GORDON

LATEST HYDRO INFORMATION

Latest Open Depth.	12.5	Date.	4/7/06
Latest Status.	-	Date.	-
Latest EC (µS/cm).	26200	Date.	6/23/06
Latest TDS (mg/L).	15848		
Latest SWL (m).	3.03	Date.	3/1/07
Latest RSWL (m).	10		



well sorted, clay, silt and fine sand, grey

moderately sorted silt to fine sand with minor clay and minor medium sand, pale yellow

well sorted fine sand, light yellowish brown

moderately sorted fine to medium sand with minor coarse sand, yellowish brown

moderately sorted medium to coarse sand with minor fine gravel, grey

moderately sorted medium to coarse sand, pale yellow

CONSTRUCTION DETAILS

Drilling.

From (m)	To (m)	Diameter (mm)	Method	Completion Date.
0	12.5	135	RTM	4/7/06

Casing.

From (m)	To (m)	Diameter (mm)	Material
0	12.5	80	PVC

Production Zone.

From (m)	To (m)	Diameter (mm)	Type	Material	Aquifer
2.5	12.5	80	SB+SC	PVC	Qam

cement
screen
slotted casing
casing
open hole completion
packer / swage

Government of South Australia
Department of Water, Land and Biodiversity Conservation

REFERENCE & LOCATION DATA

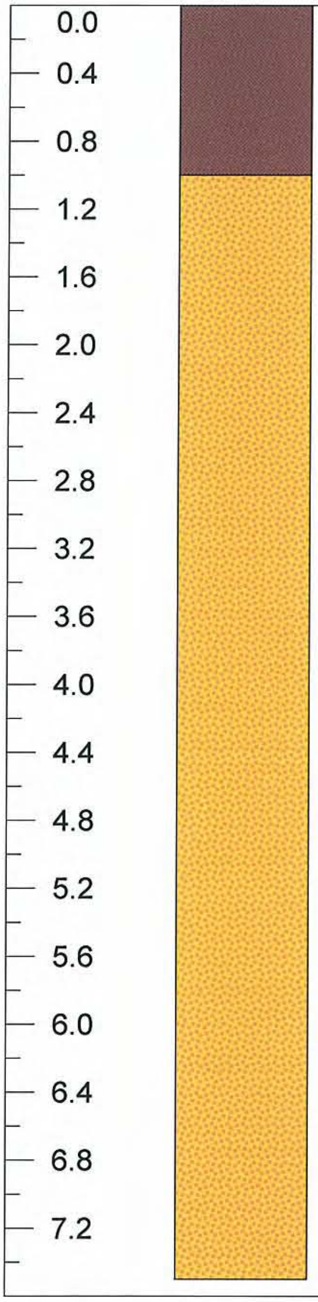
Reference Elevation.	13.37
Ground Elevation.	12.4
MGA Easting.	461541
MGA Northing.	6196797
MGA Zone.	54
Hundred.	GORDON

LATEST HYDRO INFORMATION

Latest Open Depth.	7.5	Date.	4/8/06
Latest Status.	-	Date.	-
Latest EC (μS/cm).	24100	Date.	6/23/06
Latest TDS (mg/L).	14476		
Latest SWL (m).	2.65	Date.	8/30/07
Latest RSWL (m).	9.75		

IDENTIFICATION DATA

Unit No.	702902239
Permit No.	115758
Drill Hole Name.	EO 2
Drill Hole Purpose.	OBS



well sorted clay to silt, grey

well sorted fine to medium sand, pale yellow

moderately sorted fine to medium sand, light yellowish brown

poorly sorted fine to coarse sand, light yellow brown

well sorted medium sand with minor coarse sand, light yellow brown

CONSTRUCTION DETAILS

Drilling.

From (m)	To (m)	Diameter (mm)	Method	Completion Date.
0	7.5	135	RTM	4/8/06

Casing.

From (m)	To (m)	Diameter (mm)	Material
0	7.5	80	PVC

Production Zone.

From (m)	To (m)	Diameter (mm)	Type	Material	Aquifer
2	7.5	80	SB+SC	PVC	Qam

cement
screen
slotted casing
casing
open hole completion
packer / swage

Government of South Australia
Department of Water, Land and Biodiversity Conservation

IDENTIFICATION DATA

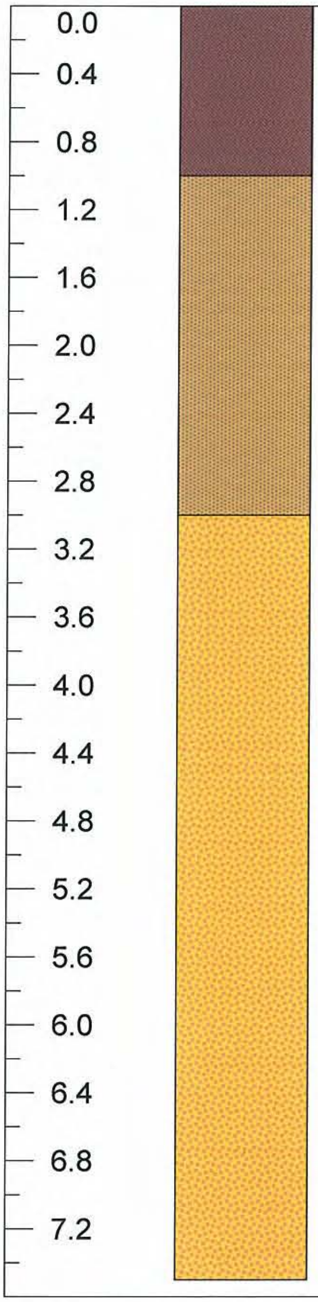
Unit No.	702902240
Permit No.	115759
Drill Hole Name.	EO 3
Drill Hole Purpose.	OBS

REFERENCE & LOCATION DATA

Reference Elevation.	13.35
Ground Elevation.	12.36
MGA Easting.	461571
MGA Northing.	6196798
MGA Zone.	54
Hundred.	GORDON

LATEST HYDRO INFORMATION

Latest Open Depth.	7.5	Date.	4/8/06
Latest Status.	-	Date.	-
Latest EC (µS/cm).	20940	Date.	6/24/06
Latest TDS (mg/L).	12423		
Latest SWL (m).	2.61	Date.	8/30/07
Latest RSWL (m).	9.76		



well sorted clay to silt with minor medium sand, grey

moderately sorted silts to fine sand with minor clay and medium sand, light grey

poorly sorted silts to medium sand with minor clay and coarse sand, light grey

moderately sorted medium to coarse sand, orange brown

well sorted medium sand with minor coarse sand, light yellowish brown

moderately sorted medium sand with minor coarse sand, light yellowish brown

well sorted medium sand, light yellowish brown

CONSTRUCTION DETAILS

Drilling.

From (m)	To (m)	Diameter (mm)	Method	Completion Date.
0	7.5	135	RTM	4/8/06

Casing.

From (m)	To (m)	Diameter (mm)	Material
0	7.5	80	PVC

Production Zone.

From (m)	To (m)	Diameter (mm)	Type	Material	Aquifer
2	7.5	80	SB+SC	PVC	Qam

cement
screen
slotted casing
casing
open hole completion
packer / swage

Government of South Australia
Department of Water, Land and Biodiversity Conservation

IDENTIFICATION DATA

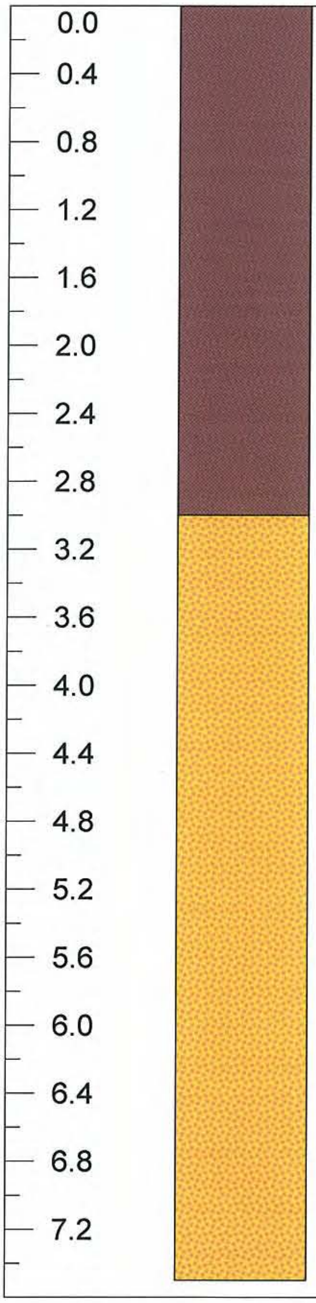
Unit No.	702902241
Permit No.	115760
Drill Hole Name.	EO 4
Drill Hole Purpose.	OBS

REFERENCE & LOCATION DATA

Reference Elevation.	13.45
Ground Elevation.	12.33
MGA Easting.	461621
MGA Northing.	6196801
MGA Zone.	54
Hundred.	GORDON

LATEST HYDRO INFORMATION

Latest Open Depth.	7.5	Date.	4/8/06
Latest Status.	-	Date.	-
Latest EC (μS/cm).	14200	Date.	6/24/06
Latest TDS (mg/L).	8228		
Latest SWL (m).	2.23	Date.	1/29/07
Latest RSWL (m).	10.1		



well sorted clay to silt, grey

moderately sorted clay to fine sand, pale yellow

poorly sorted fine to coarse sand, light yellowish brown

well sorted fine to medium sand, light yellowish brown

well sorted medium sand with minor coarse sand, light yellowish brown

CONSTRUCTION DETAILS

Drilling.

From (m)	To (m)	Diameter (mm)	Method	Completion Date.
0	7.5	135	RTM	4/8/06

Casing.

From (m)	To (m)	Diameter (mm)	Material
0	7.5	80	PVC

Production Zone.

From (m)	To (m)	Diameter (mm)	Type	Material	Aquifer
2	7.5	80	SB+SC	PVC	Qam

cement
screen
slotted casing
casing
open hole completion
packer / swage

Government of South Australia
Department of Water, Land and Biodiversity Conservation

IDENTIFICATION DATA

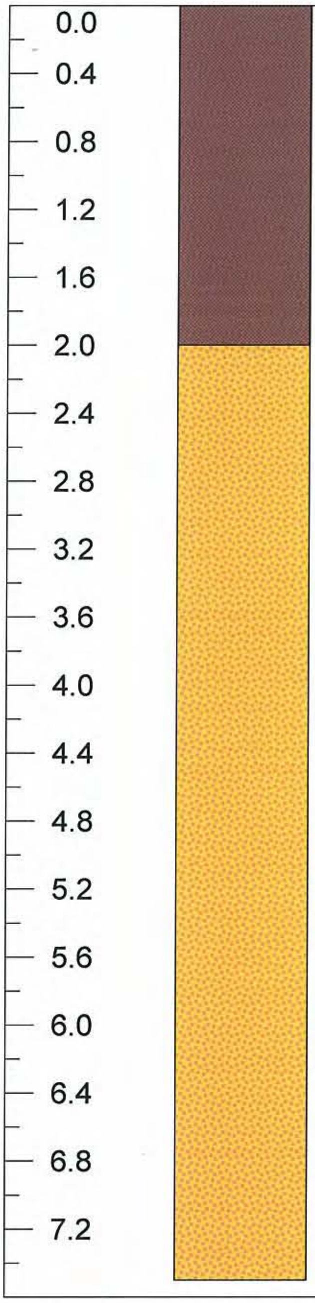
Unit No.	702902242
Permit No.	115761
Drill Hole Name.	EO 5
Drill Hole Purpose.	OBS

REFERENCE & LOCATION DATA

Reference Elevation.	13.18
Ground Elevation.	12.4
MGA Easting.	461519
MGA Northing.	6196777
MGA Zone.	54
Hundred.	GORDON

LATEST HYDRO INFORMATION

Latest Open Depth.	7.5	Date.	4/7/06
Latest Status.	-	Date.	-
Latest EC (µS/cm).	22900	Date.	6/23/06
Latest TDS (mg/L).	13683		
Latest SWL (m).	2.64	Date.	8/30/07
Latest RSWL (m).	9.76		



well sorted clay to silt with minor fine sand, grey

well sorted clay to fine sand, light grey

well sorted silt to fine sand with minor medium sand, pale yellow

poorly sorted fine to coarse sand, light yellowish brown

poorly sorted fine to coarse sand with minor fine gravel, light yellowish brown

CONSTRUCTION DETAILS

Drilling.

From (m)	To (m)	Diameter (mm)	Method	Completion Date.
0	7.5	135	RTM	4/7/06

Casing.

From (m)	To (m)	Diameter (mm)	Material
0	7.5	80	PVC

Production Zone.

From (m)	To (m)	Diameter (mm)	Type	Material	Aquifer
2	7.5	80	SB+SC	PVC	Qam

- cement
- screen
- slotted casing
- casing
- open hole completion
- packer / swage

Government of South Australia
Department of Water, Land and Biodiversity Conservation

IDENTIFICATION DATA

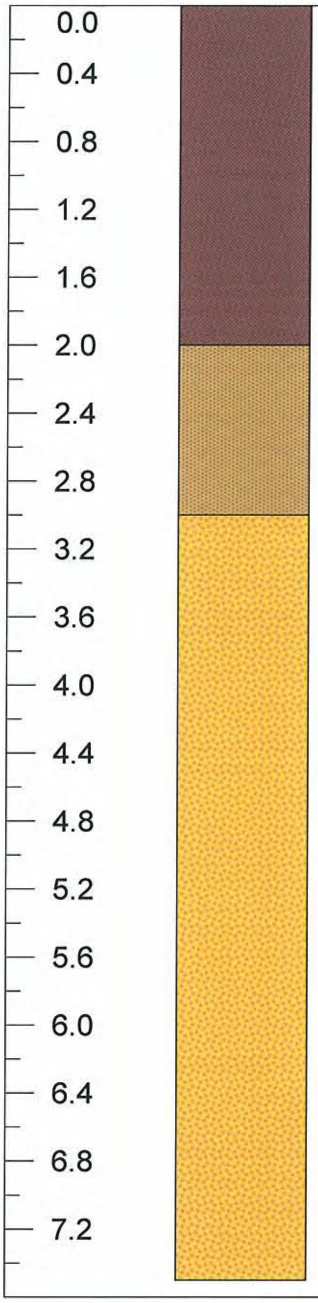
Unit No.	702902243
Permit No.	116687
Drill Hole Name.	EO 6
Drill Hole Purpose.	OBS

REFERENCE & LOCATION DATA

Reference Elevation.	12.88
Ground Elevation.	12.03
MGA Easting.	461519
MGA Northing.	6196732
MGA Zone.	54
Hundred.	GORDON

LATEST HYDRO INFORMATION

Latest Open Depth.	7.5	Date.	4/9/06
Latest Status.	-	Date.	-
Latest EC (µS/cm).	15960	Date.	6/24/06
Latest TDS (mg/L).	9300		
Latest SWL (m).	2.27	Date.	8/30/07
Latest RSWL (m).	9.77		



well sorted clay to silt with minor fine and medium sand, grey

well sorted clay to fine sand, light grey

moderately sorted slit to medium sand with minor clay, light grey

well sorted medium sand, with minor coarse sand, orange brown

moderately sorted fine to medium sand with minor coarse sand, light yellowish brown

moderately sorted medium to coarse sand, light yellowish brown

CONSTRUCTION DETAILS

Drilling.

From (m)	To (m)	Diameter (mm)	Method	Completion Date.
0	7.5	135	RTM	4/9/06

Casing.

From (m)	To (m)	Diameter (mm)	Material
0	7.5	80	PVC

Production Zone.

From (m)	To (m)	Diameter (mm)	Type	Material	Aquifer
2	7.5	80	SB+SC	PVC	Qam

cement
screen
slotted casing
casing
open hole completion
packer / swage

Government of South Australia
Department of Water, Land and Biodiversity Conservation

IDENTIFICATION DATA

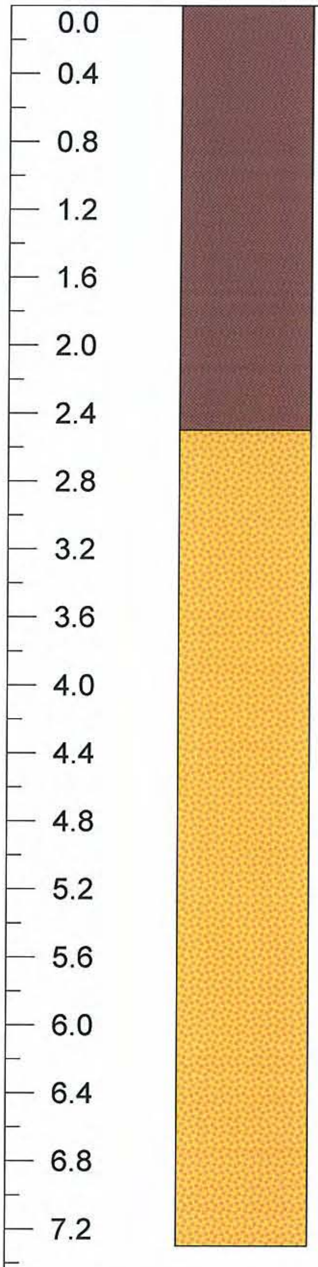
Unit No.	702902244
Permit No.	116686
Drill Hole Name.	EO 7
Drill Hole Purpose.	OBS

REFERENCE & LOCATION DATA

Reference Elevation.	13.64
Ground Elevation.	12.5
MGA Easting.	461526
MGA Northing.	6196644
MGA Zone.	54
Hundred.	GORDON

LATEST HYDRO INFORMATION

Latest Open Depth.	7.3	Date.	4/10/06
Latest Status.	-	Date.	-
Latest EC (μS/cm).	2980	Date.	6/24/06
Latest TDS (mg/L).	1653		
Latest SWL (m).	2.41	Date.	1/29/07
Latest RSWL (m).	10.09		



well sorted clay to silt, grey

moderately sorted clay to fine sand with minor medium sand, light grey

poorly sorted silt to coarse sand with minor clay content, light brownish grey

moderately sorted medium to coarse sand, light yellowish brown

well sorted medium sand with minor coarse sand, light yellowish brown

poorly sorted medium to coarse sand with minor fine gravel, light yellowish brown

moderately sorted medium to coarse sand, light yellowish brown

CONSTRUCTION DETAILS

Drilling.

From (m)	To (m)	Diameter (mm)	Method	Completion Date.
0	7.3	135	RTM	4/10/06

Casing.

From (m)	To (m)	Diameter (mm)	Material
0	7.3	80	PVC

Production Zone.

From (m)	To (m)	Diameter (mm)	Type	Material	Aquifer
1.8	7.3	80	SB+SC	PVC	Qam

cement
screen
slotted casing
casing
open hole completion
packer / swage

C. DETAILED GROUNDWATER SALINITY RESULTS

Pre-injection salinity

Figure A1 displays the sets of downhole salinity profiles for each of the observation wells collected prior to, during and after the injection phase of the trial. The data indicates the background salinity gradients across the site. In both observation Transect 1 (east-west) and Transect 2 (north-south), groundwater salinity increases both laterally and vertically with increasing distance from the river channel. Indicative shallow groundwater salinities are annotated on Figure 8. Both observation transects increase from fresh < 500 EC salinity groundwater to approximately 2,000 EC at E04 and E07, and up to around 25,000 μS/cm at EO1. EO2 and EO5 at the edges of the injection arrays have a similar salinity of around 20,000 EC, and both EO3 and EO6 outside the injection array recorded transitional salinity of 16,000 EC and 12,000 EC respectively. Groundwater salinity at the riverbanks is assumed to be similar to river water salinity, supported by the observations of groundwater salinity at other Bookpurnong investigation sites, as well as the interpretation of ancillary land based, airborne and instream geophysical datasets.

The degree of vertical salinity stratification is more apparent in the observation wells of Transect 1. From this, the salinity gradient is greatest tending east-west away from the centre of the array and toward the flanks of the floodplain peninsula. It is suggested that the hydraulic resistance to surface water loses are less towards the southern end of the peninsula, where the river meanders away from the regional groundwater high.

Post-injection Salinity

Groundwater freshening was not observed to any significant extent with only EO1 displaying a decrease in salinity. EO1 was installed within 5 m of injection well EI5, thus sufficiently close to capture the limited spread of the fresh recharge water. The data from the logger, set 6 m below ground surface indicates salinity reduction from 25,000 EC to 10,000 EC during the period of injection (Figure 22). A brief salinity increase apparent in mid October was coincident with a monitoring event on 11 October when the data logger was temporarily removed from the well. Concurrent increases and decreases in groundwater salinity were observed at the points of injection turn off (08/11/06), reinstatement (15/11/06), and total shut down (17/11/06). Other observation wells installed with salinity loggers did not detect any significant salinity variations.

Downhole fluid profile data was collected using an YSI XL600 multi-parameter sonde, with the results corroborating the fact that salinity reductions were limited to EO1. Each observation well was profiled for salinity shortly after construction in April 06 (grey series). Where the data deviates noticeably from the most of the other later profiles, contamination by the drilling fluid used during construction (which must have not been adequately flushed during well development) is suggested as the likely cause.

For observation well EO1, the April 2006 and June 2006 profiles collected prior to injection show the native groundwater salinity to be around 26,000 EC over the entire profile. The first EO1 profile after the commencement of injection (11/10/06, blue series, 21 days after pumping commenced) recorded a stratified salinity reduction between the water table (~3 m) and 6.5 m below ground level. Freshening was greatest at the water table at approximately 12,000 EC increasing to around 20,000 EC at 6.5 m.

The November profile (02/11/06, green series, after 43 days of injection), just prior to the initial aquifer breeches on November 8th 2006, displayed a greater decrease in salinity. The depth of freshening did not increase greatly but the magnitude with depth was more pronounced with 12,000 EC water present to a depth of 7.0 m below ground surface, sharply increasing to 24,000 EC at 7.5 m. EO1 was profiled during the injection well redevelopment (15/11/06), shortly after injection had ceased, indicating the extent of vertical freshening had begun to diminish. A later profile collected December 7th 2006 (yellow series, 30 days after the first shutdown), showed the depth and thickness of freshening had receded, with the depth of significant freshening approximately 5 m below ground surface. Profiles collected in January (29/01/07, orange series) and March (01/03/07, red series) recorded further decreases in the depth and thickness of freshening.

Encouragingly however, the injected fresher water although decreasing in volume, remained present for a considerable period of time following the end of the injection phase. This is due to the low groundwater gradient across that part of the floodplain. Figure A1 shows injection well profiles for November 2006 and August 2007, and indicates that some fresher water is still present around the injection zones. However, comparison with the earlier observations reveals the temporal dissipation of fresh water at the injection points.

At EO2 in August 2007, there was evidence to suggest fresher groundwater may have migrated over time to form a shallow extended freshwater lens at more distant locations from the injection points. A number of the sonde profiles recorded a small number of fresh data points at the very top (5 – 10 cm) of the water column. These observations are not necessarily a result of the freshwater injection trial as similar observations were made at wells believed to be too distant from the injection zone to be influenced (eg EO6). This phenomenon is believed to be either a localised density stratification effect or a result of partly submerged salinity probe.

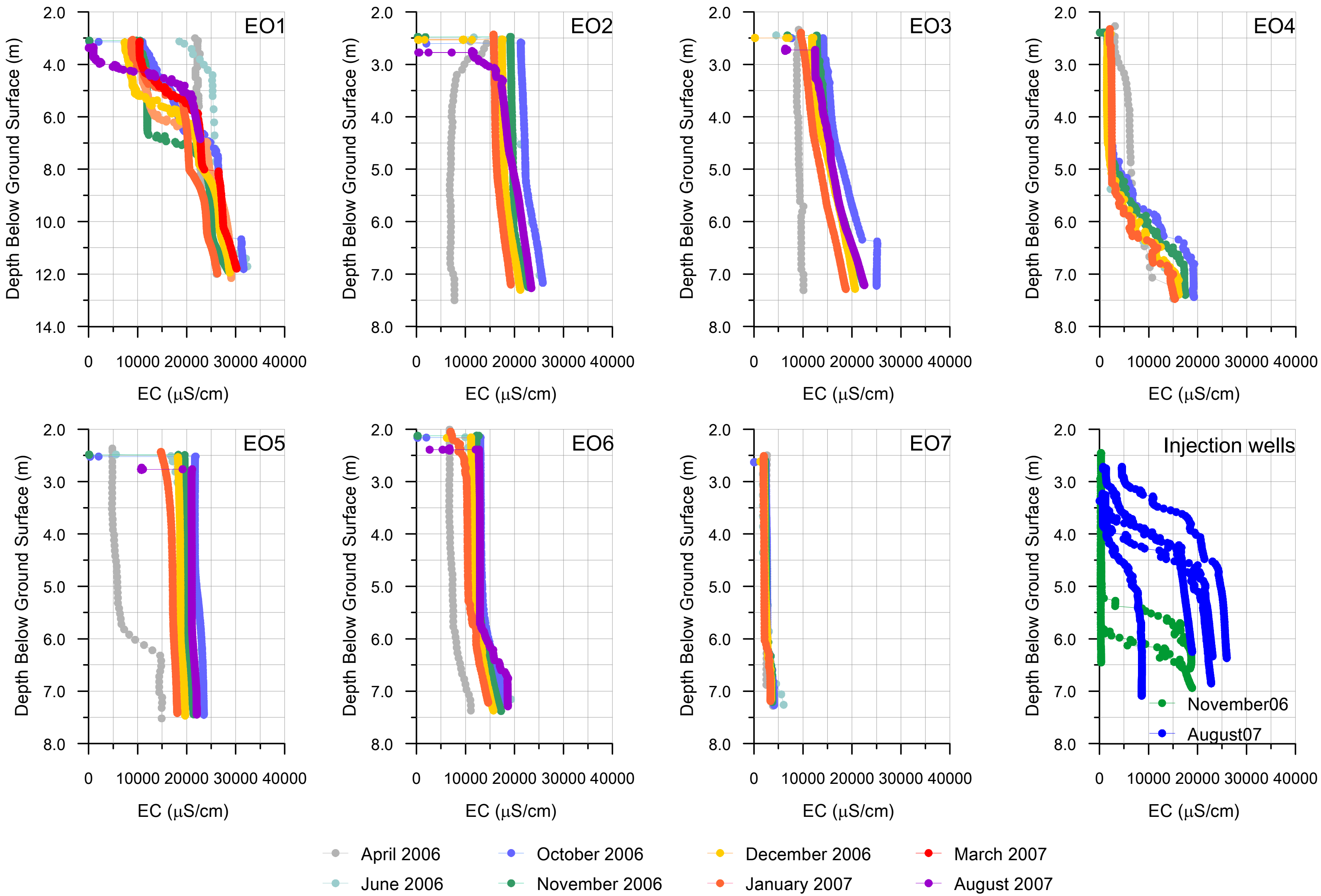


Figure A1 Observation well salinity profiles

D. LITERATURE REVIEW: INJECTION CONSIDERATIONS

Aquifer properties (hydraulic considerations)

Typically sand and gravel aquifers are troublesome for injection with well completions commonly less efficient and more prone to clogging, and clogging more complex to manage requiring a higher quality injectant (ASR, 2007). Aquifer properties such as permeability, transmissivity and storage coefficient will affect the rate at which an aquifer can store and transport water. Low aquifer permeability and transmissivity will contribute to lower rates of recharge (injection) and result in only localised recharged water. Other hydrogeological indicators such as hydraulic conductivity, aquifer consolidation, grain size, piezometric surface, groundwater gradient, aquifer thickness, native groundwater quality and aquifer heterogeneity can also be significant in defining the effectiveness of an injection operation. A greater knowledge of these indicators increases the likelihood of understanding and predicting the behaviour of injectant within the aquifer.

The examination of these variables would require a combination of desktop analysis and site-specific sampling and field examinations including drilling, water and aquifer sampling and aquifer hydraulic testing. Hydraulic testing is critical and should be conducted to determine aquifer properties such as transmissivity, storage coefficient and hydraulic conductivity. It is important also in determining a well equation for the injection well and aquifer hydraulic parameters. Testing should include step injection testing, and constant rate injection to establish long-term behaviour.

The failure to successfully airlift the injection well post drilling was a concerning indication of poor well efficiency. The limited pumping and injection testing assessed only restricted injection capacity, significantly less than had been anticipated. An urgency to complete design and construction of the well field prior to a thorough hydraulic and analytical assessment may have disadvantaged the opportunity to gauge the merit of proceeding with such a trial.

Drilling methods and technical assessment

Unconsolidated aquifers are inherently more difficult to operate within and require particular well constructions and the need for efficient well screens to contact the aquifer. Drilling methods can influence the efficiency of injection wells and in unconsolidated material such as those of the Monoman Sands Formation, rotary mud and reverse circulation are the most likely options. Segalen et al. (2005) presents a literary review of drilling and remediation methods for recharge wells in unconsolidated material, addressing the main issue of well and aquifer clogging and maintenance of well efficiency.

The operational challenge in unconsolidated material is to prevent bore wall collapse requiring the use of drilling fluids (mud). The rotary mud method (as used at Site E) can potentially cause residual mudcake skin effects increasing the likelihood of poor hydraulic conductivity of the near well formation, reduced the specific capacity of the well and a greater susceptibility to clogging. Following mud drilling methods, it is important to pump/airlift develop the well to achieve maximum operating efficiency as residual mud can greatly reduce recharge capacity. The use of biodegradable mud over bentonite based material is believed to cause less clogging (Segalen et al, 2005).

Larger diameter wells (> 200 mm) can help to reduce clogging due to the greater surface area and thus improve well efficiency. Casing material should be non-reactive, such as fibre reinforced plastic (FRP) class 12 PVC or stainless steel, and the annulus should be pressure cemented to surface. The use of wire screens and gravel packs may result in severely decreased well efficiency than that of open hole formations, and the use of slotted casing as used at Site E and emplaced gravel pack will be significantly less efficient than if wire wound screens are used (Segalen et al., 2005). Complete descriptions of well drilling techniques and construction practises are provided by Driscoll (1986).

Partially penetrating wells in comparison to fully penetrating wells may be several times less efficient and result in greater well loses. Partially penetrating wells were specifically selected for this project based on the injection and project requirements, to focus injectant as near to the top of water table as possible. The alternate hypothesis to the one postulated in the project submission (AWE, 2005) could examine injection over the full and deeper aquifer interval, thus targeting the hydraulically superior aquifer material and increasing the injection surface area. In this case allowing density driven saline advection to transport fresher water to the top of the saturated zone.

Injection pressure

Injection pressure must be limited so that rupturing of the confining bed does not occur. Generally the pressure head above the aquifer should be limited to 1.5 times the depth to the aquifer (ASR, 2007). In the case of Site E with an approximate 2 m confining bed, the head should be limited to 3 m above ground. This was the general operating limitation considered at the onset of the Site E trial. An alternate rule of thumb to prevent instability and hydraulic fracturing suggests the injection head should not exceed 0.2 x h, where h is the depth from ground surface to the top of the screen or filter pack (Olsthoorn, 1982). In this case with screens set at 3 m, injection head should be limited to 0.6 m above ground level.

Specifically in order to limit the initiation of fractures in the injection zone, the maximum total pressure gradient (surface injection pressure plus the hydrostatic pressure minus friction losses) should not exceed the overburden pressure gradient of depth from ground surface to the top of the injection zone (ASR, 2007). For a more thorough assessment, the overburden stress could be determined by integration of bulk density logs, and the mean bulk densities of sediments overlying the injection zone may be used to estimate the overburden pressure gradient (ASR, 2007).

Limiting the injection pressure head needs to be incorporated and should be based on some conservative assessment to minimise the risk of a failed project. In dealing with such a restrictive shallow injection interval and thin confining layer as at Site E, the amount of available head to operate within is very limited and the volume of injection is inherently degraded. In the incidence of steadily increasing pressure head, potentially as a result of clogging, the maintenance below a benchmark pressure level would require a continual reduction in injection rate, essentially to the point where the injection rate becomes nil. Temperature variations of the injectant can affect the viscosity of the injectant resulting in potentially damaging increases in pressure head over time.

Well clogging

Well clogging is a recognised hindrance to the efficient operation and lifetime of injection infrastructure with practically all injection operations experiencing some degree of well clogging. Case examples suggest that the potential for clogging is dependent on a great number of variables and includes a high dependence on the hydraulic characteristics of the target aquifer formation. Well clogging has the potential to significantly limit the injection and storage capacity of the aquifer and induce pressure increases that potentially jeopardise formation integrity and project success, often leading to costly pre-treatment and ongoing maintenance (Pavelic et al., 2007). Osei-Bonsu (1996) and a report prepared by CSIRO (Pavelic et al., 2007) for DWLBC's investigation into the Renmark deep injection present concise literature reviews of a range of injection case studies in which clogging has been an impediment. As well, they highlight and discuss the most common mechanisms of clogging including:

1) The potential for clogging of the aquifer pores by suspended particulate matter.
2) The effect of hydrochemical reactions that may occur within the aquifer.
3) The effect of biochemical reactions that may occur within the aquifer.
4) Entrapment of air and dissolution of gases within the aquifer.
5) Rearrangement of particles.
6) Swelling and dispersion of clay materials with the aquifer.
7) The effects of temperature variations between the recharge water and groundwater

Mechanisms of clogging

Biological clogging

Biological clogging arises due to the production of bacterial biomass and polysaccharide slimes. Microbial growth occurs when sufficient organic and inorganic substrates and other key nutrients such as phosperous and nitrogen are present in the source waters. The physical problem is the multiplication and growth, which appears as an accumulation of bacterial cells and extracellular polymeric material (slims) that they secrete (Pavelic et al., 2007). Microbially induced precipitation of hydroxides such as iron or aluminium may also result form the mixing of different water sources under favourable conditions. These biological forms of clogging typically develop over longer time-scales than physical particulate clogging but can cause significant practical problems possibly leading to complete clogging of the well (Vecchioli, 1972). The process of filtration can exacerbate the organic concentration and biological growth at or near the wells screen and gravel pack (Brown and Sniegocki, 1970)

Chemical clogging

Clogging due to chemical reactions can reduce permeability during recharge through mineral precipitation (foremost), dissolution and gas formation and the swelling and dispersion of clay particles. Such reactions can be promoted during the mixing of recharge and groundwater due to changes in water chemistry, redox potential, aquifer mineralogy, pressure and temperature (Hutchinson 1993). The potential for geochemical reactions need to be assessed and can underline the potential for mineral precipitation, gas formation and clay swelling. Sample information on the chemical and mineral composition of the source injectant and ambient groundwater is required to perform adequate analysis.

Mechanical clogging

Mechanical clogging as a result of air entrainment, swelling or dispersion of reactive clays and degassing leading to gas binding can result from a number of influences including biochemical reactions, oxygenation and cavitation of recharge water. Air bubbles can become entrained and transported into the aquifer, which can prevent flow by clogging the pore spaced between the aquifer materials. The construction of the injection wells and supply lines needs to be adequate such that aeration, cavitation and air entrainment is minimised. Gas binding may also be a mechanism of clogging when temperature differences exist between the injectant and groundwater. The mixing of water can cause air and other gases to come out of solution.

Physical clogging

Physical clogging by suspended solids present in the recharge water is the most common form of clogging, a process by which particulate matter physically fills or blocks the pore spaces between aquifer grains, known as filtration or straining. In addition to the presence of suspended silts and clays in the recharge water, the precipitation of minerals and solids due to chemical or bacterial processes can contribute to the particulate loading. Many recharge projects have found suspended solids to be the dominant cause of clogging with the incidence of suspended solids in recharge water and resultant clogging inescapable. There are two generalised types of filtration of suspended solid flowing through a porous media. Deep bed filtration occurs when suspended material migrate into the porous media (aquifer) and are deposited to contribute to the porous media. Cake filtration occurs when the particulate diameter is too large to pass into the aquifer resulting in a cake build up of particles. The thickness of the cake and the amount of cake compression influences the permeability to effectively reduce the well efficiency.

The extent and rate at which physical clogging adversely effects injection is dependant on the concentration, the size and composition of the particulate matter, the size and grain composition of the aquifer material and its permeability, and the rate of injection. The distance from the water-filter media interface at which particle accumulation (filtration) occurs is influenced by the ratio of d_g/d_p, the porous media grain size diameter to the suspended solid diameter (Osei-Bonsu, 1996; Xu, 2006). d_g/d_p is a simple and accepted ratio for discussing the clogging susceptibility of the porous media (aquifer). The larger the ratio d_g/d_p the greater the likelihood that suspended particulate matter will penetrate into the aquifer. After McDowell-Boyer et al. (1986) the ratio d_g/d_p can be used to categorise the type of physical clogging expected; for $d_g/d_p < 10$, cake filtration will occur at the porous media interface. For $10 < d_g/d_p < 20$ physical straining of the suspended solids occurs within the porous media, and for $d_g/d_p > 20$, physical and chemical (physiochemical) interactions between the particulates and the pore media regulate clogging.

Clogging due to suspended solids produces a linear increase in injection head over time. The increase in injection head is dependant upon the permeability of the aquifer and the clogging layer and the concentration of suspended solids in the water. High permeability aquifers will clog at lower rates because suspended solids are less likely to be trapped near the well and high flow rates will cause higher clogging rates due to the increase mass of solids per unit time.

Prevention of Clogging

The prediction of clogging remains complicated to quantify successfully but is valuable towards informing prevention activities. In evaluating the risk (or level) of clogging, a vast number of factors can be examined to determine which of the above mentioned clogging mechanisms are likely to impact the project. Examining source water parameters such as organic carbon, dissolved organic carbon, nitrogen and phosperous can assess the potential for microbial growth and the risk of biological clogging. Determining the mineral phases of the source water and examining the potential for mineral precipitation, gas formation and clay swelling can highlight the geochemical risk of clogging. Knowledge of aquifer hydraulic properties and material characteristic such as grain size distribution, as well, as the particle size distribution of particulate matter in the recharge water is important for estimating the rate of clogging.

There are a number of physical clogging assessments that can be employed in the assessment of source water susceptibility and prediction for clogging such as column studies, batch studies and small scale pilot testing. The likelihood of an injected source water to cause physical clogging can be assessed by examining indicator parameters and physio-chemical measures of water quality such as such Total Suspended Solids (TSS mg/L), Turbidity (NTU), Membrane Filtration Index (MFI), and the levels of organic matter. The MFI is a preferred measure of the potential for a particular water to clog wells by filtration and development of a filter cake and is an assessment of physical clogging that better accounts for the effects of particle size and composition (Dillon et al., 2001).

The clogging potential of any given source water is highly dependent upon the hydraulic characteristics of the target formations, and there is a trade off between the source water quality and the extent of clogging and hence the degree of redevelopment needed to sustain injection rates (Pavelic et al., 2007). Particulate content that is highly unsuitable for injection into one aquifer may present little trouble when injected into another. To help in the prevention of clogging and to ensure operational performance, the quality of the recharge water should to be improved. To avoid blockage around the well, pre-treatment methods are crucial for the removal of suspended material, colloidal and nutrient components. Treatment methods include:

- Primary sedimentation to remove coarser suspended solids
- Filtration to remove smaller particles
- Biological treatment
- Chemical clarification (coagulation, flocculation and sedimentation)

Filtration of suspended solids (such as roughing filter) are used to remove the presence of particulates and algal growth in the source water or from deposits in pipes. Slow sand filters are used for the stabilisation of biological activity via the removal of colloidal and nutrient components, however are limited as the source water needs to be of a high quality to prevent premature filter clogging. Once injection commences close monitoring and early warning may prevent serious clogging, however it is better to reduce clogging agents in the source water than to control clogging (ASR, 2007).

Water quality indicators should be monitored closely during project operation to enable critical judgment on performance and inform future activities. Backwashing (redevelopment) of injection wells is a common practise in managing clogging, and is either employed periodically or when injection yield or pressure head reach specified threshold levels. As a rule of thumb, redevelopment should be initiated once a 10 – 20% reduction is observed (Pavelic et al., 2007). If clogging is allowed to advance then clogging layers can compact potentially reducing the effectiveness of redevelopment.

UNITS OF MEASUREMENT

Units of measurement commonly used (SI and non-SI Australian legal)

Name of unit	Symbol	Definition in terms of other metric units	Quantity
day	d	24 h	time interval
gigalitre	GL	10^6 m^3	volume
gram	g	10^{-3} kg	mass
hectare	ha	10^4 m^2	area
hour	h	60 min	time interval
kilogram	kg	base unit	mass
kilolitre	kL	1 m^3	volume
kilometre	km	10^3 m	length
kilo volt amperes	Kva	0.8 kW	power
litre	L	10^{-3} m^3	volume
megalitre	ML	10^3 m^3	volume
Megapascal	MPa	10.196 kg/cm^2	pressure
metre	m	base unit	length
microgram	µg	10^{-6} g	mass
microlitre	µL	10^{-9} m^3	volume
milligram	mg	10^{-3} g	mass
millilitre	mL	10^{-6} m^3	volume
millimetre	mm	10^{-3} m	length
minute	min	60 s	time interval
second	s	base unit	time interval
tonne	t	1000 kg	mass
year	y	365 or 366 days	time interval

~	approximately equal to
EC	electrical conductivity (µS/cm)
pH	acidity
ppm	parts per million
TDS	total dissolved solids (mg/L)
gg^{-1}	gravimetric water content

GLOSSARY

AEM — Airborne Electromagnetics

ANOVA — Analysis of variance. A collection of statistical models, and their associated procedures, in which the observed variance is partitioned into components due to different explanatory variable.

Aquifer — An underground layer of rock or sediment that holds water and allows water to percolate through.

Aquifer, confined — Aquifer in which the upper surface is impervious and the water is held at greater than atmospheric pressure. Water in a penetrating well will rise above the surface of the aquifer.

ASR — Aquifer, storage and recovery. The process of recharging water into an aquifer for the purpose of storage and subsequent withdrawal.

Aquifer test — A hydrological test performed on a well, aimed to increase the understanding of the aquifer properties, including any interference between wells, and to more accurately estimate the sustainable use of the water resource available for development from the well.

Aquifer, unconfined — Aquifer in which the upper surface has free connection to the ground surface and the water surface is at atmospheric pressure.

Aquitard — A layer in the geological profile that separates two aquifers and restricts the flow between them.

Artificial recharge — The process of artificially diverting water from the surface to an aquifer. Artificial recharge can reduce evaporation losses and increase aquifer yield. *(See natural recharge, aquifer.)*

BSP — British Standard Pipe.

DWLBC — Department of Water, Land and Biodiversity Conservation (Government of South Australia).

EC — Electrical conductivity**.** 1 EC unit = 1 micro-Siemen per centimetre (µS/cm) measured at 25°C. Commonly used to indicate the salinity of water.

Ecology — The study of the relationships between living organisms and their environment.

Ecosystem — Any system in which there is an interdependence upon, and interaction between, living organisms and their immediate physical, chemical and biological environment.

EDMS — Environmental Database Management System (EPA).

Evapotranspiration — The total loss of water as a result of transpiration from plants and evaporation from land, and surface water bodies.

Floodplain — Of a watercourse means: (a) the floodplain (if any) of the watercourse identified in a catchment water management plan or a local water management plan; adopted under Part 7 of the *Water Resources Act 1997*; or (b) where paragraph (a) does not apply — the floodplain (if any) of the watercourse identified in a development plan under the *Development Act 1993*, or (c) where neither paragraph (a) nor paragraph (b) applies — the land adjoining the watercourse that is periodically subject to flooding from the watercourse.

GIS — Geographic information system. Computer software linking geographic data (for example land parcels) to textual data (soil type, land value, ownership). It allows for a range of features, from simple map production to complex data analysis.

Groundwater — *See underground water.*

Habitat — The natural place or type of site in which an animal or plant, or communities of plants and animals, lives.

Hydrogeology — The study of groundwater, which includes its occurrence, recharge and discharge processes, and the properties of aquifers. *(See hydrology.)*

mAHD — meters Australian Height Datum. A geodetic datum for altitude measurement in Australia.

MDBA — Murray-Darling Basin Authority.

MDBC — Murray–Darling Basin Commission.

MFI — Membrane filtration index. A standard test of the rate at which water clogs a membrane filter.

ML — Megalitre**.** One million litres (1 000 000).

Model — A conceptual or mathematical means of understanding elements of the real world which allows for predictions of outcomes given certain conditions. Examples include estimating storm runoff, assessing the impacts of dams or predicting ecological response to environmental change.

MODFLOW — The U.S. Geological Survey modular finite difference flow model, which is a computer code that solves the groundwater flow equation.

Monitoring — (1) The repeated measurement of parameters to assess the current status and changes over time of the parameters measured. (2) Periodic or continuous surveillance or testing to determine the level of compliance with statutory requirements and/or pollutant levels in various media or in humans, animals, and other living things.

Permeability — A measure of the ease with which water flows through an aquifer or aquitard. The unit is m^2/d.

Potentiometric head — The potentiometric head or surface is the level to which water rises in a well due to water pressure in the aquifer; the unit is metres (m).

Riparian — Of, pertaining to, or situated or dwelling on the bank of a river or other water body.

Riparian ecosystems — A transition between the aquatic ecosystem and the adjacent terrestrial ecosystem; these are identified by soil characteristics or distinctive vegetation communities that require free or unbound water.

Riparian habitat — The transition zone between aquatic and upland habitat. These habitats are related to and influenced by surface or subsurface waters, especially the margins of streams, lakes, ponds, wetlands, seeps, and ditches.

Riparian zone — That part of the landscape adjacent to a water body that influences and is influenced by watercourse processes. This can include landform, hydrological or vegetation definitions. It is commonly used to include the in-stream habitats, bed, banks and sometimes floodplains of watercourses.

RTU — Remote Terminal Unit

SA Geodata — A collection of linked databases storing geological and hydrogeological data, which the public can access at the front counters of PIRSA and its regional offices. Custodianship of data related to minerals–petroleum and groundwater is vested in PIRSA and DWLBC, respectively. DWLBC should be contacted for database extracts related to groundwater.

SA Water — South Australian Water Corporation (Government of South Australia).

Specific storage (S_s) — Specific storativity. The amount of stored water realised from a unit volume of aquifer per unit decline in head. It is dimensionless.

Specific yield (S_y) — The volume ratio of water that drains by gravity, to that of total volume of the porous medium. It is dimensionless.

Surface water — (a) water flowing over land (except in a watercourse), (i) after having fallen as rain or hail or having precipitated in any another manner, (ii) or after rising to the surface naturally from underground; (b) water of the kind referred to in paragraph (a) that has been collected in a dam or reservoir.

Surface Water Archive — An internet-based database linked to HYDSTRA operated by DWLBC. It contains rainfall, water level, streamflow and salinity data collected from a network of surface water monitoring sites located throughout South Australia.

TDS —Total Dissolved Solids; the unit is milligrams per litre (mg/L).

TN — Total Nitrogen.

Turbidity — The cloudiness or haziness of water (or other fluid) caused by individual particles that are too small to be seen without magnification, thus being much like smoke in air.

Underground water (groundwater) — Water occurring naturally below ground level or water pumped, diverted or released into a well for storage underground.

Water column — a section of water extending from the surface of a body of water to its bottom. In the sea or ocean, it is referred to as 'pelagic zone'.

Watercourse — A river, creek or other natural watercourse (whether modified or not) and includes: a dam or reservoir that collects water flowing in a watercourse; a lake through which water flows; a channel (but not a channel declared by regulation to be excluded from the this definition) into which the water of a watercourse has been diverted; and part of a watercourse.

Water-dependent ecosystems — Those parts of the environment, the species composition and natural ecological processes, that are determined by the permanent or temporary presence of flowing or standing water, above or below ground. The in-stream areas of rivers, riparian vegetation, springs, wetlands, floodplains, estuaries and lakes are all water-dependent ecosystems.

Well — (a) an opening in the ground excavated for the purpose of obtaining access to underground water; (b) an opening in the ground excavated for some other purpose but that gives access to underground water; (c) a natural opening in the ground that gives access to underground water.

Wetlands — Defined by the Act as a swamp or marsh and includes any land that is seasonally inundated with water. This definition encompasses a number of concepts that are more specifically described in the definition used in the Ramsar Convention on Wetlands of International Importance. This describes wetlands as areas of permanent or periodic to intermittent inundation, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water, the depth of which at low tides does not exceed six metres.

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