DWLBC REPORT

Loxton Salt Interception Scheme Trial Horizontal Drainage Well: Well and Aquifer Response to Pumping, and Effectiveness in Intercepting Groundwater Flux Discharging to the River Murray

2008/06

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

Loxton Salt Interception Scheme Trial Horizontal Drainage Well: Well and Aquifer Response to Pumping, and Effectiveness in Intercepting Groundwater Flux Discharging to the River Murray

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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.

Rob Freeman
CHIEF EXECUTIVE
DEPARTMENT OF WATER, LAND AND BIODIVERSITY CONSERVATION

ACKNOWLEDGEMENTS

During the course of the work discussed in this report numerous discussions were had regarding technical issues and numerical groundwater modelling with Don Armstrong of Lisdon Associates. The numerical groundwater model was developed by Aaron Smith drawing on the expertise of DWLBC modellers Wei Yan and Kwadwo Osei-Bonsu, and also Don Armstrong of Lisdon Associates. Don Armstrong provided the material in Chapter entitled Independent Assessment of the Effectiveness of Horizontal Drainage Wells and also developed a simplified groundwater model to assist with validating the results of the more complex model developed by Aaron Smith. Don Armstrong also conducted a review of the report and many of his suggestions were incorporated.

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SUMMARY

The Loxton irrigation area is located adjacent the River Murray in the northwest region of the Murray Basin. Run-of-river salinity surveys indicate that a groundwater driven salt load of ~98 t/d enters the river in the Loxton reach at river flows of less than 5000 ML/d. The salt load may double to 188 t/d at flows of 20 000–30 000 ML/d due to the leaching of salt from floodplains and flushing of backwaters

The construction of a salt interception scheme was proposed to intercept the flux of saline groundwater (and therefore the salt load) before it enters the River Murray. The Department of Water, Land and Biodiversity Conservation in partnership with the Murray Darling Basin Commission and SA Water, have designed and constructed the SIS floodplain wellfield component, and have undertaken preliminary investigations in relation to the application of horizontal drainage wells in the highlands.

This report:

1. Provides a general review of the design of the AUS$1.2 m trial horizontal drainage well, which has a total length of 500 m and an operational horizontal production zone ~250 m in length. Recommendations are provided in relation to horizontal drainage well planning, design, construction, and operation; along with a discussion of aspects that require further investigation. Brief comments are provided in relation to the suitability of other sites in the Loxton region for horizontal drainage wells.

2. Details the results and interpretation of a preliminary (3 month) pumping test and a long-term (18 month) pumping test conducted on the Loxton trial horizontal drainage well. Drawdown data is provided from the comprehensive observation well network used to observe the hydraulic behaviour of the well and the aquifer response to pumping. Interpretation of the test results, in terms of the well and aquifer response to pumping is discussed. The pumping test demonstrates the groundwater level can be readily pumped down close to the top of the outer product pipe, and that drawdown develops in the aquifer at great distance from the well.

3. Details the results of transient numerical modelling which predicts the trial horizontal drainage well intercepts 83% of the original groundwater flux passing an imaginary 250 m long plane parallel to the well after one year of pumping. This result is considered to be conservative.

4. Provides an argument for the salt load benefit to the River Murray resulting from the pumping of the trial horizontal drainage well, which is believed to be intercepting ~1.5 t/d, and which will increase to 2–2.5 t/d at five years.

5. Provides the results of an economic analysis comparing the installation and operating cost of potential SIS infrastructure options over a 30 year period, which indicates that horizontal drainage wells are a viable option.

1. INTRODUCTION

1.1 BACKGROUND

The Loxton irrigation area is located adjacent to the River Murray in the northwest region of the Murray Basin in South Australia (Fig. 1). Prior to European settlement, a naturally occurring flux of saline groundwater entered the river in the Loxton area. This groundwater flux was very small in comparison to the current post-irrigation development groundwater flux, which is driven by the existence of a large groundwater mound that has developed in response to irrigation drainage. A small groundwater flux associated with clearing of the Mallee area for dry-land farming will also affect the river in the future. Run-of-river salinity surveys indicate that a salt load of ~98 t/d currently enters the river in the Loxton reach between river-kilometre 482–500 at flows of <5000 ML/d. The salt load may double to 188 t/d at flows of 20 000–30 000 ML/d due to the leaching of salt from floodplains and flushing of backwaters. The Department of Water, Land and Biodiversity Conservation (DWLBC), in partnership with the Murray Darling Basin Commission (MDBC) and SA Water, are constructing a salt interception scheme (SIS) to address the problem. The MDBC and the South Australian Government jointly fund the Loxton SIS through the National Action Plan for Salinity and Water Quality.

Saline groundwater (7000–50 000 mg/L) enters the River Murray predominantly by lateral flow from the Loxton Sand and Monoman Formation (Fig. 2), and by to a small degree by slow upward leakage through the underlying Bookpurnong Formation from the semi-confined Pata Formation (the uppermost aquifer of the regionally confined Murray Group limestone). The Loxton SIS aims to intercept highly saline groundwater where the floodplains areas (Monoman Formation) separate the river channel from the highland area (Loxton Sands) by the construction and operation of a curtain of conventional vertical production wells (pumping the Monoman Formation). Pumping these wells will control the groundwater gradient that exists towards the river by reducing the groundwater table to river pool level. However, potentially half of the salt load being delivered to the river in the Loxton reach may be directly entering from the highland areas (Loxton Sand).

Regional numerical groundwater modelling for the Loxton SIS is documented in Yan et al 2004 and Yan et al 2005. The design and construction of the floodplain component of the SIS is documented in Howles et al 2007.

Investigation drilling on the highland indicated that the Loxton Sand is most permeable above 10 m AHD, and decreases in permeability and porosity with depth. The poorest aquifer sands tend to occur near river pool level (9.8 m AHD). However, a thin unit comprising poorly sorted sands and reworked weakly consolidated shell material (shell hash), up to 2 m in thickness, occurring at depths of 18–24 m below natural surface (close to river pool level), and continuous for 700 m in places, was identified. This unit is overlain by the upward coarsening Loxton Sand, and directly overlies the Lower Loxton Clays and Shells aquitard. The thin (~6 m) unconfined nature of the aquifer (that includes the shell hash unit and the overlying saturated sands) would result in the need for very closely spaced conventional vertical production wells (perhaps 5–10 m) to achieve effective interception, which would be limited by the practical drawdown that could be developed.

When it was recognised that conventional vertical production wells would not provide cost-effective or hydraulically efficient interception, horizontal drainage wells were proposed as a potential solution. This novel approach has not been used in salt interception to date.

Four sites were identified in the Loxton region as being potentially suitable for horizontal drainage wells. In mid 2005 a trial horizontal drainage well was drilled at a site ~10 km north of Loxton with an operational horizontal production zone ~250 m in length. In order to gain complete interception over the entire site, the construction of further (possibly overlapping) horizontal drainage wells would be required. Full details of the trial horizontal drainage well design and construction are given in Costar et al 2006.

The objectives of the project were to:

1. Demonstrate the feasibility of using horizontal drilling to install a trial horizontal drainage well in the Loxton Sand shell hash unit, with an operational horizontal production zone 250 m in length.
2. Demonstrate the trial horizontal drainage well could be successfully developed.
3. Determine the hydraulic performance of the trial horizontal drainage well, in terms of drawing the groundwater table down to the level of the well, and operational issues associated with the well.
4. Determine the effectiveness of the trial horizontal drainage well at intercepting the groundwater flux discharging to the river.
5. Refine contractual issues through the development and administration of a drilling contract for a horizontal drainage well.

The LHZ-2 project site (Fig. 3) is located within a highland area from which numerical groundwater modelling predicts 15.5 t/d of salt is discharged to the River Murray by lateral flow along a river frontage of 1.6 km. A large number of air-core investigation drillholes were drilled to assist in identifying the presence and characteristics of the target Loxton Sand shell hash unit in the area of the trial horizontal drainage well. In addition, two conventional vertical production wells and associated observation wells were drilled. Pumping tests indicated the shell hash had yields of 1–2 L/s, a high hydraulic conductivity (perhaps up to 50 m/d). Although groundwater salinity is low in this area due to irrigation drainage (3000–6000 mg/L), when it is combined with the steep groundwater gradient and high ambient aquifer permeability (50 m/d), this represents a significant salt load entering the river. It should be noted that groundwater salinity tends to increase towards the river.

This report:

1. Provides a general review of the design of the $1.2 m trial horizontal drainage well which has a total length of 500 m and an operational horizontal production zone ~250 m in length.
2. Details the results and interpretation of a preliminary (3 month) pumping test and a long-term (18 month) pumping test that were conducted on the trial horizontal drainage well to determine the hydraulic behaviour of the well, and the aquifer response to pumping.
3. Details the Numerical groundwater modelling that was undertaken to determine the effectiveness of the trial horizontal drainage well at intercepting the groundwater flux (and therefore salt load) entering the river.

4. Provides an argument for the salt load benefit to the River Murray resulting from the pumping of the trial horizontal drainage well, which is believed to be currently intercepting ~1.5 t/d, and which will increase to 2–2.5 t/d at five years.
5. Provides the results of an economic analysis comparing the installation and operating cost of potential SIS infrastructure options over a 30 year period, which indicates that horizontal drainage wells are a viable option.

1.2 HORIZONTAL DRILLING AND HORIZONTAL WELLS

Horizontal directional mud rotary drilling was initially developed to assist the petroleum industry target hydrocarbon deposits that would otherwise be too costly or environmentally disruptive to access. During the 1970s, this technology was adapted to installation of services.

Since 1990 the use of horizontal wells has increased dramatically as the technology has become more widely known and accepted. Today horizontal drilling is more widely used, and the technology makes it possible to install utilities below virtually any obstacle. Increasing environmental and safety concerns make horizontal drilling the best, and often the only, technique for installing utilities. Throughout Europe and the North America the technique is commonly used for contaminated site remediation where the method has significant advantages over conventional vertical production wells when targeting contaminates which are planar in nature. Apart from direct interception of contaminants, the technique has proven extremely effective for air sparging and soil vapour extraction. In these applications, several horizontal wells can effectively replace several hundred conventional vertical production wells.

It is only in recent years that horizontal wells have been considered a viable option as water supply wells with the first dedicated water supply horizontal well being constructed in the Unites States in the early 1990s. Large directional drilling companies such at Longbore Inc. and Directed Technologies Drilling Inc. (DTD) now specialise in horizontal well construction. A key feature of horizontal wells is their ability to increase the use of a thin target aquifer by permitting the placement of a significant amount of screen.

DTD indicate that advantages of horizontal water supply wells include:

1. Increased yield from low production aquifers.
2. Decreased filtration costs.
3. Minimisation of the risk of up-welling and saltwater intrusion when developing aquifers in coastal areas.
4. Replacement of many conventional vertical wells with an equally productive single horizontal well.
5. Decreases in the number of pumps required.
6. Eliminates the need to interconnect conventional vertical production wells.
7. Increases security by decreasing the number of wellheads that need to be protected.
8. Decreases site disruption.

9. Ability to pump from an aquifer located beneath structures or obstacles.
10. Creates a passive water supply when installed on hillsides.

1.3 LOXTON TRIAL HORIZONTAL DRAINAGE WELL DESIGN AND CONSTRUCTION

1.3.1 HORIZONTAL DRAINAGE WELL DESIGN

The Loxton trial horizontal drainage well has a total length of 500 m and an operational horizontal production zone ~250 m in length (Fig. 4). This production zone length was chosen as being a suitable for operational maintenance, although the limit to the length that could be practically drilled is very much greater. Due to the reasonably consolidated nature of the Loxton Sand shell hash unit, it was originally intended that the trial horizontal drainage well be completed with a single product pipe-string (i.e. well casing) of high-density polyethylene (HDPE) pipe. The casing was to be slotted longitudinally (to minimise loss of pipe strength) over 270 m, with ten rows of 200 mm external length (150 mm internal length) x 2 mm wide slots. This configuration results in an open area of ~1%.

At the anticipated maximum pumping rate of 15 L/s, a 1% open area results in an effective entrance velocity of the order of 0.012 m/s, which is considerably less than the nominal maximum value of 0.03 m/s normally recommended for well screens in conventional vertical production wells. At a pumping rate of 7 L/s, the effective entrance velocity reduces to 0.006 m/s, which is an order of magnitude less than the nominal value of 0.03 m/s. These effective entrance velocity calculations assume only 50% of each individual slot is open which brings in an additional level of conservatism in relation to the entrance velocity.

Within days of slotting the first section of product pipe, it was noticed that slots had begun to close and slotting was terminated. It was discovered that all thermoplastic pipes have frozen in stresses, which have their origin in the cooling phase of the manufacturing process. Cutting the pipe can result in movement known as reversion. It was subsequently concluded (following discussions with a materials scientist) that spherical holes would tend to maintain their integrity and remain open. This resulted in a last minute decision to replace the slots with ten rows of 10 mm diameter drillholes spaced at 75 mm centres (Fig. 5) resulting in an open area of ~1%. All slotting and drilling was undertaken by Complete Pipe Systems, Murray Bridge, South Australia.

Concerns regarding the potential infiltration of aquifer material through the drillholes were addressed by coupling the outer product pipe with an inner thin walled HDPE liner slotted radially with one row of 100 mm long x 0.8 mm wide slots cut at 20 mm spacing along each side of the pipe (Fig. 6). The HDPE outer product pipe and inner liner specifications are given in Table 1.

Table 1. HDPE pipe specifications

Specifications	Outer product pipe	Inner liner
Material	SDR9 HDPE PE100	SDR9 HDPE PE100
Pipe joints	Fusion welded, de-beaded inside/outside	Fusion welded, de-beaded inside
Outer diameter	315 mm	220 mm
Inner diameter	245 mm	210 mm
Wall thickness	35 mm	5 mm
Slotting orientation	Longitudinal	Radial
Slot length	Not available	100
Slot width	2 mm, replaced with drillholes	0.8 mm set 20 mm apart
Slotted length	270 m	270 m
Drillhole diameter	10 mm	Not applicable

1.3.2 HORIZONTAL DRAINAGE WELL DEVELOPMENT

Conventional methods of well development such as jetting, surging and airlifting were not expected to be effective for the trial horizontal drainage well due to the very small open area of the outer product pipe. Initial development was conducted over a five day period using a development pig attached to the drill string which swabbed and jetted the outer product pipe using a combination of water and chlorine to accelerate the break down in the drilling fluid. Due to the prohibitively high cost of retaining the rig on site ($30 000/d), it was decided that additional development would have to be undertaken following the installation of the pumps. Further development was subsequently undertaken by pumping, and by pulling a fabricated well development sock through the well. The inner liner was pulled into the outer product pipe on the conclusion of development.

2. TRIAL HORIZONTAL DRAINAGE WELL HYDRAULIC BEHAVIOUR, AND AQUIFER RESPONSE TO PUMPING

2.1 INTRODUCTION

In order to investigate the ability of the trial horizontal drainage well to lower groundwater levels and intercept the groundwater flux discharging to the River Murray, an extensive pumping test program was conducted over a period of two years. Testing was divided into two parts, a preliminary variable rate pumping test (commencing at 18 L/s and reducing to 6 L/s) operating for a duration of 110 700 min (76 days), followed by a long-term pumping test (commencing at 6 L/s and reducing to 4 L/s). Data for the long-term pumping tests until a time 750 000 min (520 days) is provided in this report (Note: This includes the deliberate recovery test conducted between 532 878–542 837 min and extended pump failure between 626 200–638 000 min).

2.2 OBSERVATION WELL CONFIGURATION

Ten observation wells (refer to App. A for well construction data) were drilled and screened within the Loxton Sand shell hash unit to observe the development of drawdown in close proximity to the trial horizontal drainage well during pumping tests. These ten observation wells are positioned in two parallel transects running the length of the production zone. The western transect (comprising LHP44 — an existing production well, and LHO50, LHO55, LHO58, LHO59) is positioned within ~3 m of the horizontal drainage well. The eastern transect (comprising LHO60, LHO61, LHO62, LHO63, LHO64) is positioned ~20 m distant from the horizontal drainage well (Fig. 3). These observation wells were drilled prior to the horizontal drainage well, due to concerns that subsequent installation may interfere with the integrity of the horizontal drainage well. The pilot drillhole for the horizontal drainage well was steered as close to them as was practical without causing blowouts of mud through these wells.

Prior to the commencement of the long-term pumping test, a transect of three additional observation wells (LHO66, LHO67, LHO68), located between the trial horizontal drainage well and River Murray, were drilled and screened within the Loxton Sands to observe the aquifer response to pumping at distance from the horizontal drainage well (Fig. 3). A single observation well (LHO65) was also completed within the semi-confined Pata Formation, thus allowing any leakage from this aquifer (during pumping the overlying Loxton Sands aquifer) to be observed. All observation wells were fitted with pressure transducers. Refer to Appendix A for well construction data.

In order to observe the development of drawdown to the north and south of the trial horizontal drainage well, two existing observation wells screened within the Loxton Sands were monitored manually, commencing at 129 000 min into the long-term pumping test.

These wells were LHO42 (located at a distance of 280 m north of the northern end of the horizontal production zone), and LHO53 (located at a distance of 350 m south of the southern end of the horizontal production zone) (Fig. 3).

Following concerns that observation well LHO68 may be penetrating the Pata Formation; a final observation well (LHO69) was drilled to verify observations at LHO68. Manual observations commenced at 420 000 min, and the observation well was subsequently fitted with a pressure transducer.

Observation well construction generally consists of 80 mm ID PVC with a 3 m slotted section at the base, completed to a nominal depth of between 20–25 m in the Loxton Sands.

2.3 PREPARATION FOR, AND GENERAL CONDUCT OF, PUMPING TESTS

2.3.1 GROUNDWATER LEVEL DATA LOGGING

DWLBC Technical Services installed an automated groundwater level logging system to monitor the ten observation wells forming the two transects parallel to the production zone. These observation wells were fitted with Greenspan PS700, 0–20 m pressure transducers, which in turn were wired to a common data-logging unit programmed to record 1 min readings for the first 24 hours, and 30 min readings thereafter. Security fencing was erected around the trial horizontal drainage well exit points and the data-logging unit installation.

Manual observations of groundwater levels were made to verify logger data accuracy, and to provide backup to the automated system. Selected observation wells were monitored weekly, and other less frequently.

Prior to the commencement of the long-term pumping test a pressure transducer was installed on the pump column, ~1 m from the pump, to provide drawdown data directly above the production zone.

2.3.2 PUMPS, METERS AND INSTALLATION

Project partners SA Water completed site preparation and pump installation at the trial horizontal drainage well which involved the installation of two Grundfos SP45, 6”, 6 stage submersible pumps coupled with 9.2 kW 3-phase motors mounted on 75 mm ID high-pressure polyurethane pipe. The pumps were pushed into the well at the north and south exit points. The northern end pump was set 140 m from the northern exit point, the southern end pump was set 147.5 m from the southern exit point. Groundwater pumped during the tests was directed into the Central Irrigation Trust (CIT) main.

The pump installation included variable speed drives to assist in flow control as well as magnetic Flow (Magflow) meters to measure pumping rates. The pumping rates were monitored and adjusted manually. Sampling taps were installed on the surface pipe-work to allow collection of groundwater samples.

Several pump stoppages occurred during the testing as a result of brief power failures. Due to a lack of a pump failure alarm system, and only weekly site visits, several pump failures went unnoticed for a number of days and are evident as significant recovery in the pumping test data. Upon re-commencing pumping, the pre-exiting drawdown regime was quickly established.

2.3.3 GROUNDWATER SAMPLING

Groundwater samples were collected and analysed for electrical conductivity (EC) every two to three weeks. All EC analysis was conducted at DWLBC water laboratory, Glenside SA. Several analyses were undertaken for common ions, iron aluminium, and iron bacteria. The Australian Water Quality Centre, Bolivar SA, conducted common ion and iron bacteria analyses. All analyses are given in Appendix B.

2.3.4 CAMERA SURVEY

DWLBC Technical Services adapted their down-hole camera for use within the trial horizontal drainage well. The submersible camera is designed with pan, tilt, and focus functions allowing the operator to view in a 90° arc with 360° rotation. A light positioned ahead of the camera provides illumination, with further peripheral lighting being provided by a ring of LED globes. Colour images are relayed to the operator and recorded on DVD.

Several camera surveys were undertaken during the pumping tests in an attempt to gain visual information on the amount of sediment, if any, infiltrating the production zone. A camera run involved the following procedure:

1. Pulling the camera cable through the trial horizontal drainage well on a cable.
2. Allowing 3 hours for sediment stirred-up during cable installation to settle.
3. Attaching the camera to the cable and pulling it back through the horizontal drainage well at a rate of 4–5 m/min.

2.3.5 WELL-SOCK DEVELOPMENT

A suitable method for determining the extent of aquifer material infiltrating the production zone, and a means of extracting this material, was discussed with project partners SA Water. Typically a pipe cleaning pig can be blown or pulled through a fluid filled pipe to force out loose material, however this method was considered inappropriate due to the risk of pushing any aquifer material contained within the trial horizontal drainage well out into the surrounding formation. The possibility of using a submersible pump pulled slowly through the entire length of the production zone was considered the most effective means of removing material, however this has not been attempted to date.

Three prototype well-socks of increasing size were fabricated with the intention that they could be pulled through the production zone to capture loose material. The well-socks consisted of a bag constructed from Geotech fabric with a stiff PVC neck to maintain the bag opening, similar in nature and size to an aerodrome sock (Fig. 7). By pulling the well-sock through the production zone several times during the tests, a comparison and assessment of the infiltration of aquifer material was possible simply by comparing the amount of material removed. The well-socks used during the pumping tests included:

1. 100 mm diameter x 4 m long, designed to be the first to be used to reduce the possibility of the sock becoming stuck (if the production zone contained a significant amount of aquifer material).
2. 175 mm diameter x 4 m long.
3. 190 mm diameter x 12 m long.

2.4 PRELIMINARY PUMPING TEST

2.4.1 OBJECTIVES

The objectives of the preliminary pumping test conducted on the trial horizontal drainage well were:

1. Investigating pump installation and operation.
2. Further development by pumping, in an attempt to clear remanent drilling fluids and aquifer material.
3. Investigate the infiltration of aquifer material.
4. Determine a pumping rate for the long-term pumping test.
5. Determine the hydraulic behaviour of the trial horizontal drainage well.
6. Obtain preliminary data on the hydraulic response of the aquifer to pumping (including extent of pumping influence).

2.4.2 CONDUCT OF TEST

The preliminary pumping test conducted on the trial horizontal drainage well commenced on 7 November 2005 and continued for 110 700 min (76 days), concluding on 23 January 2006. The following points are important:

1. Standard submersible multi-stage pumps were installed without the need for specialised equipment. Placement of the pumps was found to be important and an accurate cross-section of the trial horizontal drainage well was required to determine pump position and maximise the available head.
2. The early time drawdown (210 min) was only recorded manually, due to a technical problem with the data logging equipment
3. The preliminary pumping test was conducted utilising single and dual pump combinations at various pumping rates using a trial and error approach, while monitoring drawdown in the ten observation wells forming the two transects parallel to the production zone.
4. The pumping rate at both the north and south pumps was initially set at 3 L/s giving a combined pumping rate of 6 L/s. Pumping rates were gradually increased over the initial 1200 min of the test to a maximum combined pumping rate of 18 L/s.
5. Deliberate rapid increases and decreases in pumping rates (developmental surging) were applied in an attempt to further develop the trial horizontal drainage well. During

this period the data logging equipment was re-set to 1 min readings to capture groundwater level fluctuations. Surging commenced at 2625 min and continued for a period of 240 min utilising both pumps. During surging groundwater clarity was reduced with slight increase in fine sand content. Following this period an on-site decision was made to cease due to the apparent limited value of this procedure. The groundwater level response is clearly indicated in the western observation well transect with fluctuations of up to 100 mm (Fig. 8).

6. During the period 2895–5820 min, pumping was conducted with only the northern pump set at its maximum capacity of 10.3 L/s. Further surging was conducted at 4045 min for a period of 90 min. Groundwater level fluctuations are indicated in the western observation well transect with some influence extending out to the eastern observation well transect. Drawdown observed during the initial 5000 min of the preliminary pumping test is given in Fig. 8.

7. During the early stages of the test it became evident the southern end pump was cavitating due to insufficient head. An additional 30 m of 75 mm ID high-pressure polyurethane pipe was added to the southern end pump increasing the total distance from southern exit point from 147.5 m to 178 m (Fig. 4). Repositioning the pump reduced its elevation from ~14 m AHD to 13.3 m AHD therefore increasing the available head by 0.7 m. The pump was re-started at 5820 min. Both pumps were then set at a constant pumping rate of 5 L/s.

8. Major rate changes during the preliminary pumping test include:
   a. At 27 400 min the pumping rate of the southern pump was reduced to 2.1 L/s, due to insufficient head, reducing the combined pumping rate from ~9.5 L/s to 6.9 L/s.
   b. At 81 690 min the southern pump was turned off, reducing the pumping rate to ~4.9 L/s.
   c. At 90 660 min the pumping rate of the northern pump was increased to 6 L/s.

9. Pumping ceased at ~110 700 min during which ~48 ML was pumped. Pumps were removed and the trial horizontal drainage well was left to recover for several days prior to a camera survey. Logger data beyond a time of 106 500 min was lost due to an extended power failure.

2.4.2.1 Camera survey

The initial camera survey was conducted on the trial horizontal drainage well on 1 February 2006, nine days after the completion of the preliminary test. Once submerged, camera vision initially indicated a slight film of light brown sediment clearly visible on the bottom of the production zone. Slots in the inner liner could be clearly seen and appeared to be unblocked. Visibility decreased to zero with distance as the disturbed sediment resulted in severe clouding. On removal of the camera it was found to be caked in a green–brown stringy slime. Analysis by Scanning Electron Microscope (SEM) indicated the substance consisted of a high percentage of smectite clay plus organic matter (possibly remnant drilling fluid) with minor mica and quartz sand grains.

The camera survey indicated:

1. The well-rope that had been in place since construction was easily freed suggesting minimal infiltration of aquifer material.
2. Minimal sediment existed in the region of the southern pump.
3. Where sediment existed, the current camera survey method was ineffective due to the disturbed sediment causing clouding.
4. Possible remnant drilling fluid existed in the production zone.

2.4.2.2 Well-sock pull-through

The initial well-sock pull-through was conducted on the trial horizontal drainage well on 1 March 2006 during the recovery period between the preliminary pumping test and the long-term pumping test.

The initial run was conducted using the 100 mm diameter well-sock and retrieved ~10 L of green–grey groundwater with very little sand being captured. The well-sock was easily pulled through the production zone indicating there was no restriction.

The second run was conducted using the 175 mm diameter well-sock. The larger diameter enabled the capture of significantly more material, returning ~3/4 of a 10 L bucket of sand and 60 L of green–grey groundwater. Three subsequent runs were conducted returning reducing amounts of sand.

Four runs were made with a newly fabricated 190 mm diameter 12 m long well-sock capturing over 600 L of groundwater–clay sludge (as above) and 2–3 buckets of sand. Upon drying, the recovered material displayed extensive shrinkage indicating a high percentage of clay.

2.4.3 HORIZONTAL DRAINAGE WELL AND AQUIFER HYDRAULICS

2.4.3.1 Hydraulic behaviour of trial horizontal drainage well

The preliminary constant-rate pumping test conducted on the trial horizontal drainage well indicates the hydraulic behaviour of the well. The drawdown observed during the initial 5000 min of the preliminary pumping test is shown in Fig. 8.

The following general comments can be made:

1. A maximum combined pumping rate of 18 L/s was achieved utilising both pumps, however this was only a short duration during the initial 1200 min of pumping due to cavitation in the southern pump.
2. The initial groundwater level can be rapidly drawn down close to the top of the outer product pipe at pumping rates in excess of 10 L/s. However, pumping at high rates is only possible in the short-term and it is suggested that high rates be applied initially to accelerate the development of drawdown.

3. Very similar drawdown develops along the full length of each of the eastern and western observation well transects indicating a similar consistent drawdown along the length of the trial horizontal drainage well.
4. The long-term sustainable pumping rate appeared to be <6 L/s.
5. The trial horizontal drainage well can be operated with a single pump.

At the maximum combined (both pumps) pumping rate of 18 L/s, the 1% open area results in an effective entrance velocity through the outer product pipe of the order of 0.015 m/s, which is considerably less than the nominal maximum value of 0.03 m/s normally recommended for well screens in conventional vertical production wells. At a combined (both pumps) pumping rate of 6 L/s, this reduces to 0.005 m/s, which is an order of magnitude less than the nominal value of 0.03 m/s. These effective entrance velocity calculations assume only 50% of each individual drillhole is open which brings in an additional level of conservatism in relation to the entrance velocity. It has been previously recommended (Costar et al 2005) that horizontal drainage wells be designed such that the effective entrance velocity is an order of magnitude less than the nominal value of 0.03 m/s used for conventional vertical production wells. This requirement is viewed as essential in minimising the risk of the infiltration of aquifer material.

2.4.3.2 Hydraulic response of aquifer to pumping stress

The preliminary constant-rate pumping test conducted on the trial horizontal drainage well indicates the hydraulic response of the aquifer system to pumping stress. The drawdown observed during the initial 5000 min of the preliminary pumping test is shown in Fig. 8. The following general comments can be made:

1. Drawdown close to the trial horizontal drainage well responds rapidly to changes in pumping rate.
2. Drawdown of ~1 m develops at the western observation well transect.
3. Drawdown of ~0.7 m develops at the eastern observation well transect.

The drawdown observed during the preliminary pumping test to 110 000 min is shown in Fig. 9.

The following general comments can be made:

1. Drawdown of ~2.2 m develops at the western observation well transect.
2. Drawdown of ~1.7m develops at the eastern observation well transect.
3. Drawdown development beyond 30 000 min is very slow.
4. Drawdown of ~1 m develops at observation wells LHO64 and LHO59, which are located out of the field of maximum pumping stress.

2.4.4 GROUNDWATER QUALITY

The initial 10–15 min of the preliminary pumping test resulted in the production of groundwater green–grey in colour with a strong odour. Micaceous fine sand, shell fragments and black poly swarf was present to a reduced extent during significant pumping rate increases and surging.

On repositioning the southern end pump (refer above), the initial 10 min of pumping again produced discoloured water with suspended fine to medium sand (~½ cup/10 L). Groundwater quality, from the visual perspective, improved rapidly following the start of the test with both pumps producing clear water with minimal fines (less than 10 g/10 L).

Groundwater salinity (mg/L and EC) data indicate an increase beyond 250 min, with higher salinity recorded from the southern pump (Fig. 10). The final salinity value for the northern pump was 3407 mg/L (6070 EC) at 94 000 min. The final salinity value for the southern end pump was 3580 mg/L (6370 EC) at 46 000 min (not operated through full length of test). The increase in groundwater salinity may be related to the pumping of groundwater from down gradient where the salinity is likely to be higher, or to the convergence of higher salinity groundwater towards the production zone from beyond the longitudinal limits of the horizontal production zone.

Groundwater samples were collected for common ion analysis at 53 280 min and 110 700 min. The results are given in Appendix B.

2.4.5 OUTCOMES AGAINST OBJECTIVES

Comments regarding the outcomes relative to the objectives of the preliminary pumping test conducted on the trial horizontal drainage well are discussed below:

Objective 1: Investigate pump installation and operation.

Satisfactorily met. Note the trial horizontal drainage well can operate with a single pump.

Objective 2: Further development by pumping, in an attempt to clear remanent drilling fluids aquifer material.

Development by pumping was unsuccessful. Some further development was undertaken using the well-sock.

Objective 3: Investigate the infiltration of aquifer material.

The camera survey was not successful and needs to be repeated. Further well-sock pull-through will provide an indication of the infiltration of aquifer material.

Objective 4: Determine a pumping rate for the long-term pumping test.

Satisfactorily met. The behaviour of the trial horizontal drainage well at different pumping rates is well understood.

Objective 5: Determine the hydraulic behaviour of the trial horizontal drainage well.

Satisfactorily met. The hydraulic behaviour of the trial horizontal drainage well at different pumping rates is well understood.

Objective 6: Obtain preliminary data on the hydraulic response of the aquifer to pumping (including extent of pumping influence).

Satisfactorily met. A good understanding of the hydraulic response of the aquifer to pumping was obtained.

2.5 LONG-TERM PUMPING TEST

2.5.1 OBJECTIVES

The objectives of the long-term pumping test conducted on the trial horizontal drainage well were:

1. Continue investigation into the infiltration of aquifer material by comparing sediment loads recovered using the well-sock.
2. Investigate possible mechanical and/or biogeochemical clogging.
3. Determine the long-term pumping rate.
4. Determine the hydraulic behaviour of the trial horizontal drainage well.
5. Determine the hydraulic response of the aquifer to pumping (including extent of pumping influence).
6. Determine hydraulic response of the semi-confined Pata Formation to pumping.
7. Determine the effectiveness of the trial horizontal drainage well at intercepting the groundwater flux discharging to the river.

2.5.2 DATA ANALYSIS – GENERAL COMMENTS

Manual data and logger data were compared for observation wells LHO65, LHO66, LHO67 and LHO68. Where the pressure transducer deviated (drift) from the manual observations, the logger data was corrected, and has been presented in this report (along with the manual data). The drift was corrected using the following formula:

$$CSt = St \pm (Drift/t) \times Et \qquad \text{Equation-1}$$

Where:

CSt = Corrected logger drawdown (m)

St = Logger drawdown (m)

Drift = Maximum difference between logger and manually observed drawdown (m)

t = Total Time of test (mins)

Et = Elapsed time (mins)

Logged data for observation well LHO65 were corrected using a drift factor of 0.07 m/ 470 000 min, LHO66 and LHO67 were corrected using a drift factor of 0.10 m/470 000 min and logger data for LHO68 was corrected using a drift factor of 0.21 m/470 000 min.

2.5.3 CONDUCT OF TEST

The long-term pumping test conducted on the trial horizontal drainage well commenced on 3 May 2006 and is still in operation at the time of reporting (March 2008). Pumping test results are included in this report to 750 000 min (520 d). The following points are important:

1. Groundwater levels had not fully recovered from the preliminary pumping test prior to commencing the long-term pumping test. The western observation well transect indicated 0.35–0.4 m of residual drawdown.
2. The long-term pumping test was conducted using only the northern end pump commencing at an initial rate of 6 L/s and reducing slowly to 4 L/s.
3. Pump stoppages, mostly due to power failures, are evident in the observed data (Fig. 11, 12). A deliberate pump stoppage of ~10 000 min commenced at 532 878 min. In each case, the time period required to re-establish drawdown following the recommencement of pumping was approximately twice the pump stoppage time.
4. The head above the outer product pipe was not observed due to the failure of the pressure transducer installed on the pump column prior to commencing the long-term pumping test (believed to caused by interference from the pump power cable).
5. The lack of head data directly above the outer product pipe prevented a complete understanding of drawdown development and made adjusting the pumping rate difficult. The pumping rate was adjusted manually when cavitation was believed to be occurring. Cavitation was identified by a fluctuating pumping rate and air escaping from the surface relief valve, at which point it was considered the groundwater level had drawn down to (or close to) the top of the outer product pipe.
6. In an attempt to measure the head above the outer product pipe, both a pressure transducer and air-tube were installed into the southern end of the production zone positioned 174 m (elevation ~13.5 m AHD) from the southern exit point to independently record the head at 525 000 min into the long-term pumping test.

   While the pressure transducer recorded heads above the outer product pipe of 0.05–0.08 m, the air-tube system failed to register, indicating that the reading from the pressure transducer may be due to calibration error, and that both were possibly positioned above the pumping groundwater level.

   This theory was supported when the pump was shut down for ~10 000 min (commencing at 532 878 min). A time lag of ~270 min occurred before the pressure transducer recorded a change in head, compared to the logger at observation well LHO58, which recorded recovery less than 60 min after pump shut down. The results possibly indicate that the groundwater level at the location of the product pipe was initially below the pressure transducer.

   The groundwater level above the product pipe was further analysed using groundwater levels recorded in observation wells LHO60 and LHP44 prior to the long-term test, and at 750 000 min (Fig. 13) into the long-term test. Even without enhanced drawdown occurring above the production zone, the maximum saturated thickness above the product pipe (at the pumping end of the horizontal section) is likely to be ~0.4m.

2.5.3.1 Well-sock pull-through

A second well-sock pull-through was conducted on the trial horizontal drainage well on 1 August 2006 (at 130 000 min when ~42 ML had been pumped).

Three runs were conducted using the 190 mm diameter well-sock producing a total of one full 10 L bucket of sand (the sand content reducing with each run). The groundwater recovered was green–grey in colour and contained a significant suspended clay content.

A third well-sock pull-through was conducted on the trial horizontal drainage well one year after the second, on 19 July 2007 (at 636 400 min when ~160 ML had been pumped). A single successful run was conducted using the 190 mm diameter well-sock capturing approximately one 10 L bucket of sand. Unexpectedly, some tree root material was also recovered (Fig. 14). Subsequent passes could not be conducted due to a possible obstruction at 50 m, and a direct comparison with the second well-sock pull-through is therefore not possible. In contrast to previous well-sock developments, SA Water conducted the development without the supervision of DWLBC.

Representative vegetation samples were collected from tree varieties growing within 100 m of the trial horizontal drainage well. DNA analysis was conducted by the Department for Environment and Heritage (Professor Lowe) to determine the type of tree that had penetrated the well with its roots. Preliminary results indicate the roots are likely to be from a tree of the species Eucalyptus spp, of which there are at least four specimens of significant size at the project site. Further tests may identify the individual tree responsible. It is recommended that a well-sock pull-through be run early in 2008. Routine well-sock pull-through is likely to be sufficient to control any minor invasion of tree roots. In the event of more severe clogging, a drain-cleaning device may be required.

A fourth well-sock pull-through was conducted on the trial horizontal drainage well on 19 February 2008 (at 946 000 min when ~229 ML had been pumped). A single successful run was conducted using the 190 mm diameter well-sock capturing minimal sand, and ~20% the amount of root material recovered in the previous well-sock pull-through. SA Water conducted the development without the supervision of DWLBC.

The well-sock pull-through has proved a simple but effective means of removing sediment from the production zone. Taking into account the limitations of this method, i.e. the well-sock is not a tight fit and therefore cannot recover all material in the production zone, a relatively minor amount of sand must still exist. Between 4–5 10 L buckets of sand were recovered during the first well-sock pull-through, ~one bucket in the second, and ~one bucket in the third, and less in the fourth. This is minimal given the trial horizontal drainage well diameter, length of the production zone, length of pumping, and volume of water pumped.

A comparison of the amount of sediment removed provides a high level of confidence that little sand is infiltrating the production zone at the long-term pumping rate.

The following general comments can be made:

1. Minor amounts of fine clay–silt material and possible remnant drilling fluid exist within the middle reaches of the production zone, however this does not appear to affect the operation of the trial horizontal drainage well.
2. At a pumping rate of 4 L/s, the effective entrance velocity through the outer product pipe is 0.003 m/s, an order of magnitude less that that of a conventional vertical production

well. This very low velocity has little capacity to drive aquifer material into the production zone.

3. The possibility of completing a successful camera survey (which may be able to view the slots on the inner liner and indicate any chemical, biological or mechanical clogging) is highly unlikely while sediment–drilling fluid remains in the production zone. A suitable method for developing the trial horizontal drainage well to a level allowing clear camera footage through the length of the production zone is still considered important and this should be revisited at some time in the future, particularly if a reduction in well performance is observed.

4. It is recommended that a well-sock pull-through be conducted at 12 month intervals to monitor and control minor invasion of tree roots.

2.5.4 HORIZONTAL DRAINAGE WELL AND AQUIFER HYDRAULICS

2.5.4.1 Hydraulic behaviour of trial horizontal drainage well

The long-term constant-rate pumping test conducted on the trial horizontal drainage well confirms the hydraulic behaviour of the well indicated during the preliminary pumping test. The drawdown observed during the long-term pumping test to 750 000 min is shown in Fig. 11 (plotted log-linear) and Fig. 12 (plotted as log-log).

The following general comments can be made:

1. The pumping rate reduces and begins to stabilise after 260 000 min at ~4 L/s.

2. The long-term pumping rate is likely to be 3–3.5 L/s.

3. Pump cavitation indicates the groundwater level can be drawn down to (or close to) the top of the outer product pipe above the pump (13.2 m AHD). This is consistent with the final groundwater level observed in LHP44 (13.73 m AHD), located at a distance of 2.8 m from the production zone and indicating a head 0.53 m above the outer product pipe. It is expected that greater drawdown exists directly above the outer product pipe (Fig. 13). Although the general flow-field towards the trial horizontal drainage well is characterised as parallel (linear) flow (apart from at the ends), as water approaches the well it develops a pattern of convergent radial flow in the vertical section leading to an extremely steep hydraulic gradient close to the entry point.

4. Although drawdown was not observed at the southern end of the production zone, the results from the observation wells imply that drawdown will be similar along its full length. Any concern regarding drawdown development towards the southern end of the trial horizontal drainage well can be overcome by also using the southern pump. If the southern end pump is re-installed it must be positioned ~200 m from the southern exit point due to the slightly elevated product pipe in this location.

5. Submersible pumps generally require a minimum of 1 m head to operate effectively. However Grundfos Pumps Pty Ltd. have indicated that a pump running low on its operating curve can pump at significantly reduced head but with increased cavitation. It was anticipated that this might have implications for pump life and reliability, which was possibly demonstrated by the need to replace the pump at 626 000 min.

2.5.4.2 Hydraulic response of aquifer to pumping stress

The long-term constant-rate pumping test conducted on the trial horizontal drainage well indicates the hydraulic response of the aquifer system to pumping stress. The drawdown observed during the long-term pumping test is shown in Fig. 11 (plotted log-linear) and Fig. 12 (plotted as log-log).

The following general comments can be made:

1. There is rapid development of drawdown until ~70 000 min, followed by very slow but continuous development of additional drawdown.
2. Very similar drawdown, ~1.9 m, develops along the full length of the western observation well transect. Final groundwater levels from the western observation well transect (Fig. 11) indicate that drawdown is greatest at the northern end where the pump is located. Observation well LHP44 develops ~0.23 m more drawdown than observation wells LHO55 and LHO58, which is likely to be due to increased drawdown developing close to the pump.
3. Drawdown of ~1.65–1.75 m develops along the full length of the eastern observation well transect.
4. Drawdown development at the eastern and western observation well transects clearly indicates the effectiveness of the trial horizontal drainage well at intercepting groundwater flux. Any minor perched groundwater will drain with time.
5. Drawdown of ~0.61 m develops at observation well LHO68 located at a distance of 247 m from the production zone towards the River Murray.
6. Drawdown of 0.25 m develops at observation well LHO42 located at a distance of 280 m north of the northern end of the horizontal production zone. Drawdown of 0.29 m develops at observation well LHO53 located at a distance of 350 m south of the southern end of the horizontal production zone.
7. Drawdown of ~0.33 m develops at observation well LHO65, completed in the semi-confined Pata Formation (note this is less than that developed at LHO68), separated from the production aquifer by up to 5 m of low permeability silts and clay and located at a distance of only 3.4 m from the production zone. This clearly indicates that there is minimal leakage through the aquitard. It is anticipated that drawdown developed in the Pata Formation will eventually stabilise at a small percentage of the drawdown developed in the production aquifer (refer below to results of numerical groundwater modelling).
8. A long-term (108 000 min) constant rate pumping test was conducted on conventional vertical production well LHP47 (located adjacent LHP44), during investigations conducted in 2004, indicated a transmissivity value of 100–300 m^2/d. Analytical equations for the analysis of pumping tests are based on conventional vertical wells and cannot be applied to horizontal drainage wells. A number of international papers exist that provide equations for the analysis of pumping test results from horizontal drainage wells, however these methods are typically complex in nature requiring a combination of analytical calculations and numerical modelling. No further attempt has been made to determine transmissivity values for the aquifer system.

9. It is important to note that regional observation wells have indicated a lowering of the potentiometric surface in the range of 0.1–0.4 m between May 2006 and August 2007, believed to be due to the on-going drought and reduced irrigation. Observation wells LHO11 located ~1.2 km north, and LHO13 located ~1.5 km south of the trial site, indicate reductions in groundwater level for the period of 0.15 m and 0.1 m respectively.

   It is possible that over the period of the long-term pumping test, the potentiometric surface at the site of the trial horizontal drainage well may have fallen by 0.1–0.2 m without the influence of pumping. However, the regional lowering of the groundwater table is insignificant in comparison to the very large drawdown observed at the trial horizontal drainage well.

2.5.5 GROUNDWATER QUALITY

Groundwater salinity (mg/L and EC) data indicate an initial reduction from 3661–2892 mg/L (6510–5170 EC), but subsequent increase to a final value of 5044 mg/L (8800 EC) (Fig. 15). Pumped groundwater was clear with minimal fines.

Groundwater samples were collected at times of 130 000 for iron bacteria, and 717 000 min for full analysis, iron, aluminium and iron bacteria. The results are given in Appendix B, and indicate:

1. An aluminium concentration of <0.01 mg/L. The precipitation of aluminium hydroxide was found to be a problem in part of the Bookpurnong region. Harrington (2004) reports that this phenomenon is unlikely to present unless the aluminium concentration exceeds 25 mg/L and the pH is <5.5).
2. An iron concentration of 0.035 mg/L.
3. Growth plate analysis indicated low-level iron bacteria (30 iron associated micro-organisms per millilitre of water) however this could not be verified through microscopical examination. There has been no evidence to-date of iron bacteria on pump or pump column.

2.5.6 OUTCOMES AGAINST OBJECTIVES

Comments regarding the outcomes relative to the objectives of the long-term pumping test conducted on the trial horizontal drainage well are discussed below:

Objective 1: Continue investigation into the infiltration of aquifer material into the production zone by comparing sediment loads recovered using the well-sock.

Satisfactorily met. Aquifer material appears to be stable at the entry velocities encountered during the test with very little accretion of silt, which can be easily managed by regular (recommended annually) maintenance using the well-sock.

Objective 2: Investigate possible mechanical and/or biogeochemical clogging.

Satisfactorily met. Mechanical clogging is not a problem. Biogeochemical clogging has not presented to date. With respect to the potential for iron bacteria clogging, the very low entrance velocities into the well are expected to assist with minimising the potential for this to occur within the production zone. However, there remains the potential for clogging around the pump. An invasion of the production zone by tree roots is a matter for some concern, but as long as regular inspections and maintenance using the well-sock are carried out, the roots should be extracted before complete clogging occurs and/or the roots become sufficiently massive to resist pulling through the well-sock when some form of reaming will be necessary. Identification of a single offending tree has not been possible. The final well-sock pull-through resulted in only a small amount of root material being recovered.

Objective 3: Determine the long-term pumping rate.

Satisfactorily met for the current pumping infrastructure, but the possibility of modification of the pumping set-up to allow extensive drawdown to within the well casing through sustained pumping at the highest possible rate should be considered.

Objective 4: Determine the hydraulic behaviour of the trial horizontal drainage well.

Satisfactorily met. The hydraulic behaviour of the trial horizontal drainage well is well understood apart from accurate recording of the groundwater level above the centre-line of the production interval.

Objective 5: Determine the hydraulic response of the aquifer to pumping (including extent of pumping influence). Satisfactorily met. The hydraulic response of the aquifer to pumping is well understood, but the areal distribution of drawdown would be better understood with more observation wells on the eastern up-gradient side of the trial horizontal drainage well.

Partial deflation of the residual groundwater mound between the trial well and the River Murray commenced but will continue to be compromised due to a groundwater flux passing beneath the well (which will occur while the pumping infrastructure does not allow the groundwater level to be drawn into the outer product pipe - i.e. maximum interception), and due to convergence of groundwater flow, from beyond the longitudinal limits of the well, to between the well and the river.

Even at 100% interception of the groundwater flux approaching the well, there will be some flux bypassing the ends of the well and entering the river along the 270 m long reach of the river covered by the well. This will only cease if further horizontal drainage wells are installed, as would be expected due to the relatively short length of the well in relation to the length of the aquifer strip.

Objective 6: Determine hydraulic response of the semi-confined Pata Formation to pumping.

Satisfactorily met. Minimal drawdown (<0.5 m) has developed in the Pata Formation in response to pumping from the Loxton Sands, despite of the close proximity of the Pata Formation observation well, located only 3.4 m from the trial horizontal drainage well production zone. Pumping from the Pata Formation does not seem to be a very likely option for salt interception at this site.

Objective 7: Determine the effectiveness of the trial horizontal drainage well at intercepting the groundwater flux discharging to the river.

Refer to numerical groundwater modelling section of this report, which discusses this issue in detail.

3. EFFECTIVENESS OF TRIAL HORIZONTAL DRAINAGE WELL AT INTERCEPTING GROUNDATER FLUX DISCHARGING TO THE RIVER MURRAY

3.1 INTRODUCTORY COMMENTS

Regional numerical groundwater modelling of the Loxton-Bookpurnong area was conducted by DWLBC as part of the investigation phase for Loxton and Boookpurnong Salt Interception Schemes (Yan et al 2005). This impact assessment model estimates the current groundwater flux discharging to the River Murray from the aquifer system and predicts the future groundwater flux, under different irrigation and development scenarios until 2104. When the flux is combined with groundwater salinity, the salt load can be calculated. The trial horizontal drainage well spans model Zone-26 and Zone-27 (Fig. 16). The horizontal drainage well is located within a highland area from which modelling predicts 15.5 t/d of salt is discharged to the river by lateral flow along a river frontage of 1.6 km, proportionately representing ~2.4 t/d of salt adjacent to the 250 m horizontal drainage well.

Questions regarding the effectiveness of the trial horizontal drainage well at intercepting the groundwater flux discharging to the River Murray arose following construction due to the final positioning of the top of the outer product pipe at an elevation of ~13.2 m AHD, 0.5–1.0 m above the base of the aquifer (~one-quarter of the aquifer thickness) and ~3 m above river pool level. In addition, the relatively low salinity of the pumped groundwater was regarded as a problem.

The effectiveness of the trial horizontal drainage well has been determined by the use of analytical calculations, and numerical groundwater modelling – which has proved to be the most useful method in this case and has been reported here. Aaron Smith developed the model with the assistance of Wei Yan and Kwadwo Osei-Bonsu (all of DWLBC), and Don Armstrong (Lisdon Associates).

3.2 NUMERICAL GROUNDWATER MODELLING

Numerical groundwater flow models enable complex three-dimensional simulations of an aquifer system and its response to imposed stresses. Numerical modelling is considered a more appropriate method of understanding the aquifer hydraulic response to pumping the trial horizontal drainage well than analytical calculations. The modelling includes a number of assumptions and simplifications, which need to be considered

Numerical modelling was undertaken to determine the effectiveness of the trial horizontal drainage well, and horizontal drainage well construction scenarios, at intercepting the groundwater flux discharging to the River Murray. The MODFLOW numerical model utilises groundwater zone budgets to determine well interception efficiencies (reported as percentage interception), and particle tracking analysis to simulate the groundwater flow capture zone of the well.

It is important to note that numerical modelling of the hydrogeological system at a simplified local scale has limited value in providing accurate steady state or transient estimates of groundwater fluxes discharging to the river. For this reason flux reduction is expressed as a ‘percentage interception’, rather than a volume of groundwater or tonnage of salt.

3.3 OBJECTIVES

The objectives of the numerical modelling were to:

1. Determine the effectiveness of the trial horizontal drainage well at intercepting the groundwater flux:
   a. Passing an imaginary plane parallel to the well.
   b. Discharging to the river.
2. Indicate the groundwater flow capture zone of the trial horizontal drainage well.
3. Determine long-term deflation of the residual groundwater mound between the trial horizontal drainage well and the river.
4. Determine the effect of the well elevation within the Loxton Sands/Loxton Sands Shell Hash on interception efficiency a horizontal drainage well.
5. Indicate the effectiveness of a horizontal drainage well positioned in the semi-confined Pata Formation, at reducing the groundwater flux discharging to the river from the Loxton Sands and Loxton Sand Shell Hash.
6. Determine the long-term pumping rate of the trial horizontal drainage well.

3.4 MODFLOW AND VISUAL MODFLOW

MODFLOW is a three-dimensional finite difference mathematical code that was developed by the US Geological Survey (McDonald and Harbaugh 1988). Visual MODFLOW Version 4.1 was developed by Waterloo Hydrogeologic Inc. in recent years and is a pre-processor for quick generation of data files for MODFLOW.

Visual MODFLOW was used as a tool for generating MODFLOW model grids, boundary conditions, observation well data, drainage wells and zones for aquifer hydraulic parameters. The software was also used for establishing settings to run the model, and to obtain quick and convenient output results. The WHS solver was used for all steady state and transient modelling runs.

3.5 MODEL CONSTRUCTION

3.5.1 CONCEPTUAL MODEL

The conceptual model of the trial horizontal drainage well and the hydrogeological setting is shown in Fig. 17.

3.5.2 MODEL DOMAIN AND GRID

The model domain simulates an area 1500 m (east-west) by 1500 m (north-south). The model represents an area with the approximate AMG coordinates (southwest) E462330 N6190240 and (northeast) E463830 N6191740 (GDA 1994), (Fig. 18).

The square model grid was divided into 282 rows and 170 columns. The minimum grid size is 5 x 5 m in the area of the drainage cells (that are used simulate horizontal drainage wells) and along the river boundary. The maximum grid size is 10 x 10 m (Fig. 19).

3.5.3 MODEL LAYERS

MODFLOW layer options are given in Table 2, and model layer aquifers and aquitards are given in Table 3.

Table 2. MODFLOW layer types

Layer type	Aquifer type	Aquifer hydraulic parameters
Type-0	Confined	Transmissivity and storage coefficient (specific storage, S_S) are constant.
Type-1	Unconfined	Transmissivity varies and is calculated from saturated thickness and hydraulic conductivity. The storage coefficient (specific yield, S_Y) is constant. Type-1 is only valid for the uppermost layer of a model.
Type-2	Confined/ Unconfined	Transmissivity is constant – the storage coefficient may alternate between values applicable to the confined (S_S) or unconfined (S_Y) states.
Type-3	Confined/ unconfined	Transmissivity varies and is calculated from the saturated thickness and hydraulic conductivity. The storage coefficient may alternate between values applicable to the confined (S_S) or unconfined (S_Y) state.

Table 3. Model layer aquifers and aquitards

Layer No	Hydrogeological unit	Aquifer/ aquitard	MODFLOW layer
1	Loxton Sands	Aquifer	Type-1
2	Loxton Sand shell Hash	Aquifer	Type-3
3	Lower Loxton Clay and Shells/Bookpurnong Formation	Aquitard	Type-3
4	Pata Formation	Aquifer	Type-3

The simple four-layer model has been constructed to represent the aquifer system. Layer elevations are based on drillhole data from a single east-west transect of observation wells through the centre of the model domain and this data was extrapolated uniformly to the north and south. Connection between the unconfined and semi-confined aquifers is controlled by simulating the Lower Loxton Clay and Shells/Bookpurnong Formation aquitard as a low conductivity layer.

3.5.3.1 Ground surface

Ground surface was set at an arbitrary 30 m AHD throughout the model.

3.5.3.2 Layer-1: Loxton Sands

Layer-1 simulates the Loxton Sands unconfined - semi-unconfined aquifer.

1. Base elevations of Layer-1 were interpreted from geological logs of drillholes between observation wells LHO68 and LHO63, and extrapolation of these values. The base of Layer-1 is set between 8.9 m and 13.55 m AHD through most of the model domain (Fig. 20). The base of Layer-1 is maintained at 13.55 m AHD between LHO63 and the eastern boundary.

3.5.3.3 Layer-2: Loxton Sand Shell Hash

Layer-2 simulates the unconfined–semi-unconfined Loxton Sand Shell Hash unit.

1. The Loxton Sand Shell Hash is the high conductivity layer within the Loxton Sands in which the trial horizontal drainage well was positioned.
2. For simplicity, and due to a lack of accurate drillhole information, Layer-2 has been assigned a constant thickness of ~1 m, and is continuous throughout the model domain (Fig. 20).

3.5.3.4 Layer-3: Lower Loxton Clay and Shells and Bookpurnong Formation

Layer-3 simulates the Lower Loxton Clay and Shells/Bookpurnong Formation aquitard.

1. Layer-3 is continuous throughout the model domain.
2. The top elevation of Layer-3 was interpreted from geological logs of drillholes between observation wells LHO68 and LHO63, and the extrapolation of these values. The top of Layer–3 is set between 7.85 and 12.6 m AHD (Fig. 20).
3. The top elevation of Layer-3 is 12.35 m at the location of the trial horizontal drainage well.
4. The thickness of Layer-3 was set at ~5 m, consistent with the thickness of the aquifer at observation well LHO65.

3.5.3.5 Layer-4: Pata Formation

Layer-4 simulates the semi-confined Pata Formation low permeability aquifer.

1. Layer-4 is continuous throughout the model domain.
2. The thickness of Layer-4 was set at ~10 m, consistent with the Loxton–Bookpurnong Groundwater Model 2005 (Yan et al 2005).
3. The base of Layer-4 represents the base of the model, and is set between -2.6 and -7.4 m AHD (Fig. 20).

3.5.4 MODEL AQUIFER HYDRAULIC PARAMETERS

In order to commence model calibration, values of aquifer and aquitard hydraulic parameters were derived from the Loxton–Bookpurnong Numerical Groundwater Model 2005, and from data obtained from pumping tests conducted during site investigations prior to the construction of the trial horizontal drainage well.

Some aquifer hydraulic parameters were altered in specific areas during both steady state and transient calibration to achieve the final values required for accurate calibration. The final aquifer and aquitard hydraulic parameters are given in Table 4, with their distribution within each layer shown in Fig. 20.

Table 4. Calibrated aquifer and aquitard hydraulic parameters

Aquifer/aquitard	Layer	Hydraulic conductivity		Storage	
		Kh (m/d)	**Kv** (m/d)	**Sy** (-)	**Ss** (/m)
Loxton Sands	1	14	1.4	0.26	$1x10^{-4}$
Loxton Sand Shell Hash	2	29–31	2.9–3.1	0.35	$1x10^{-4}$
Lower Loxton Clay and Shells/ Bookpurnong Formation	3	$3x10^{-5}$ – $5x10^{-3}$	$3x10^{-5}$ – $2.5x10^{-3}$	0.01	$1x10^{-4}$
Pata Formation	4	0.4	0.04	0.01	$1x10^{-4}$

Model calibration resulted in aquifer and aquitard hydraulic parameters within reasonable ranges, and in most cases within an order of magnitude of those used in the Loxton–Bookpurnong Numerical Groundwater Model 2005:

1. A horizontal conductivity of 14 m/d and specific yield of 0.26 were used for the Loxton Sands (Layer-1). Horizontal hydraulic conductivity values remain within the order of magnitude of those determined from pumping tests.

2. A horizontal hydraulic conductivity of 29–31 m/d, and a specific yield of 0.35 were used for the Loxton Sand Shell Hash (Layer-2), which resulted in the best fit to the observed (historic) observation well data. The horizontal hydraulic conductivity values remain consistent with data from pumping tests conducted during investigations on the site prior to the construction of the trial horizontal drainage well, which indicate a value of 20–50 m/d, which is likely to be related to the Loxton Sand Shell Hash and the existence of coarse sands in some of the wells (Howles and Smith 2005). The lower conductivity zone (29 m/d) located near the river was used to improve calibration and is consistent with drill hole data, which indicates an increase in fines towards the river. A specific yield of 0.35 is within the range for fine sand 0.01–0.46 (Spitz and Moreno 1996).

3. Low (0.5 m/d) hydraulic conductivity zones 100 m in width were included along the southern and northern boundary within Layer-1 and Layer-2 to reduce the effects of the no-flow boundaries (Fig. 21).

4. A horizontal hydraulic conductivity of 0.4 m/d and specific storage $1x10^{-4}$/m were used for the semi-confined Pata Formation (Layer-4) These hydraulic parameters were obtained from reference to existing pumping tests, and remain within an order of magnitude of reported values (Howles and Smith 2005).

5. Appropriate hydraulic parameters were applied to control the upward and downward leakage through the Lower Loxton Clay and Shells/Bookpurnong Formation aquitard

(Layer-3). Bookpurnong Formation vertical hydraulic conductivity was obtained from reference to existing pumping tests (Howles and Smith 2005), which indicate a range $1x10^{-3}$ – $5x10^{-3}$ m/d. Layer-3 includes a zone of higher permeability near the river to simulate the typical thinning of the Bookpurnong layer in the river valley providing a discharge point for the semi-confined Pata Formation.

3.5.5 MODEL BOUNDARIES

The four-layer model utilises different boundary conditions to simulate the aquifer system, River Murray, and their hydraulic communication.

3.5.5.1 Layer-1: Loxton Sands

The regional groundwater flow is from east to west within the model domain with groundwater flux discharging to the River Murray (represented in the model as the western constant head boundary), or taken up as evapotranspiration along the cliff face. Where the aquifers are laterally adjacent, groundwater discharges from the Loxton Sands into the river. The following boundary conditions were applied to Layer-1 (Figs 21, 22):

1. No-flow on the north and south boundaries where groundwater flow is parallel to the model edge.
2. Constant head boundary to simulate the watertable irrigation mound (eastern boundary). The boundary is set at a constant 22.5 m AHD between 0–365 days, after which the boundary reduces at a constant rate to 22.26 m AHD at 11 315 days to simulate the effect of pumping from the trial horizontal drainage well.
3. Constant head boundary to simulate the river set at 9.95 m AHD, the average water level recorded at the Loxton Irrigation Pump Station (river km 494) over the duration of the long-term pumping test conducted on the trial horizontal drainage well.

3.5.5.2 Layer-2: Loxton Sand Shell Hash

The Loxton Sand Shell Hash is a high permeability layer that occurs between the lower permeability Loxton Sands (Layer-1) and the Lower Loxton Clay and Shells/Bookpurnong Formation aquitard (Layer-3). Water moves into this layer laterally in response to the constant head boundary and vertically from Layer-1. Small volumes of water are lost and gained through the underlying aquitard (Layer-3). The Loxton Sand Shell Hash discharges to the river, represented in the model as the western constant head boundary. The following boundary conditions were applied to Layer-2 (Fig. 22).

1. No-flow boundaries where groundwater flow is parallel to the model edge.
2. Constant head boundary to simulate the watertable irrigation mound (eastern boundary). The boundary remains at a constant 22.5 m AHD between 0–365 days after which the boundary reduces at a constant rate with time to 22.26 m AHD at 11 315 days.
3. Constant head boundary to simulate the river set at 9.95 m AHD, the average water level recorded at the Loxton Irrigation Pump Station (river km 494) over the duration of the long-term pumping test conducted on the trial horizontal drainage well.

3.5.5.3 Layer-3: Lower Loxton Clay and Shells and Bookpurnong Formation

Small volumes of water move laterally into and out of this layer due to its low permeability. The following boundary conditions were applied to Layer-3 (Fig. 22).

1. No-flow boundaries were used at all model boundaries.

3.5.5.4 Layer-4: Pata Formation

The regional groundwater flow in the semi-confined Pata Formation is from east to west within the model domain with groundwater flux discharging to the overlying Bookpurnong Formation (Layer-3). The following boundary conditions were applied to Layer-4 (Fig. 22).

1. No-flow boundaries where groundwater flow is parallel to the model edge.
2. Constant head boundary set at 17.1 m AHD used for the eastern boundary to simulate groundwater flow into the model.
3. No-flow boundary on the western model boundary.

3.5.5.5 Simulation of the Groundwater Mound (eastern boundary) within Layer-1 and Layer-2

The regional groundwater irrigation mound, and its response to pumping from horizontal drainage wells, is simulated in Layer-1 and Layer-2 using constant head boundaries which were determined by the following process:

1. The Loxton–Bookpurnong Numerical Groundwater Model 2005, Scenario-6 was used to determine the likely potentiometric head changes resulting from pumping a theoretical horizontal drainage well located at the site of the trial horizontal drainage well Layer-1 with the following alterations to the model:
    a. The highland SIS infrastructure was deactivated.
    b. Recharge in Zone-20 and Zone-21 was increased to 188.1 mm/y and 224 mm/y respectively to more accurately represent the irrigation mound.
2. The trial horizontal drainage well was simulated using two conventional vertical production wells (grid size 125 m x 125 m) positioned ~300 m from the river pumping at a combined pumping rate of 345.6 m^3/d.
3. Pumping rates were based on estimated long-term pumping rates determined from Loxton–Bookpurnong Numerical Groundwater Model 2005, Scenario-8.
4. Modelling was undertaken using steady-state scenarios only to eliminate the impact of varying boundary conditions resulting from changes to recharge.
5. The modelled difference in the non-pumping steady state, and pumping steady state potentiometric surfaces at a point 1500 m east of the river, were used to determine the eastern constant head boundary for Layer-1 and Layer-2 at 365 days and 11 315 days respectively for the current model.

3.5.5.6 Horizontal Flow Barrier

Horizontal Flow Boundaries or Wall Boundaries have been used in the steady state and transient models to enable simulation of the steep watertable slope observed close to the River Murray at the highland–floodplain interface. These wall boundaries are assigned as continuous lines running between the north and south no-flow boundaries within Layer-1 and Layer-2 (Fig. 22). All wall boundaries are assigned a thickness of 1 m, and a horizontal hydraulic conductivity determined through calibration of the steady state model (Table 5).

Table 5. Wall boundary hydraulic conductivity

Wall No.	**Kh** (m/d)
W 1	0.15
W 2	0.15
W 3	0.19
W 4	0.25
W 5	0.33
W 6	0.39
W 7	0.45
W 8	0.48

3.5.6 MODEL RECHARGE

The Loxton area has a semi-arid climate with hot dry summers and some rainfall during winter months. The average rainfall is ~400 mm/y with pan evaporation of ~2000 mm/y.

Prior to clearance of the native vegetation on the highland, vertical recharge to the Loxton Sands resulting from rainfall infiltration is believed to have been as low as 0.1 mm/y (Allison et al 1990). A recharge rate of 0.1 mm/y was applied to the non-irrigated areas in the steady state and transient model.

Approximately 3/4 of the modelled area is subject to irrigation (Fig. 23). A recharge rate of 100 mm/y was applied to the irrigated areas in the steady state and transient model. This rate was obtained from the Loxton–Bookpurnong numerical groundwater model 2005, from the post 1988 recharge of irrigated areas.

3.5.7 MODEL EVAPOTRANSPIRATION

Evapotranspiration was not simulated due to the significant depth of the watertable throughout most of the modelled area. Evapotranspiration is most likely to occur on the floodplain, and while there would be evapotranspiration occurring at the cliff face and riverbank, this has not been included in this simplified model.

3.5.8 MODEL SIMULATION OF HORIZONTAL DRAINAGE WELLS

All model scenarios utilise model drain cells to simulate horizontal drainage wells. The trial horizontal drainage well is simulated through a 250 m line of (5 x 5 m) drain cells set at an elevation of 13.2 m, close to the top of the Loxton Sand Shell Hash (Layer-2). The top elevation of Layer-3 is 12.35 m at the location of the well.

This is consistent with actual completion of the well with the top of the outer product pipe set at 13.2 m AHD (Fig. 24) and the base of the aquifer above river pool level. The drain (horizontal drainage well) is inactive from 0–365 days and active from 365–11 315 days.

A drain conductance of 9 m^2/d is used in the model scenario where drainage cells are located within the Loxton Sands or Loxton Sand Shell Hash (Layer-1 and Layer-2 respectively). Drain conductance was determined through transient model calibration of observed and modelled drawdowns from observation wells, and by matching drain discharge with the pumping rate observed during the long-term pumping test conducted on the trial horizontal drainage well. A drain conductance of 9 m^2/d provided a modelled drain discharge rate that closely matched the observed horizontal drainage well pumping rate (Fig. 25).

The drain conductance can be estimated using a variation on the model river cell conductance formula:

$$C_{River} = \frac{K\,L}{M}\,W \qquad \text{Equation-2}$$

Where:

C_{River} = River conductance (m^2/d)

K = Hydraulic conductivity of the riverbed material (m/d)

L = Length of reach (m)

W = Width of river (m)

M = Thickness of riverbed (m)

The river conductance formula can be adapted to a horizontal drainage well, where:

1. W and M are replaced by the drain circumference.
2. L is disregarded, as it is included in the model with the overall length of drain cells.

The resulting formula for drain conductance is then:

$$C_{Drain} = K\,c \qquad \text{Equation-3}$$

Where:

C_{Drain} = Drain conductance (m^2/d)

K = Hydraulic conductivity of the aquifer (m/d)

c = Circumference of the outer product pipe (m)

Applying Equation-2, the conductance of a horizontal drainage well positioned in the Loxton Sands (Layer-1) can be calculated:

$C_{Drain} = 14 \text{ m/d} \times 0.99 \text{ m}$

$\underline{C_{Drain} = 13.86 \text{ m}^2\text{/d}}$

Applying Equation-2, the conductance of a horizontal drainage well positioned in the Loxton Sand Shell Hash (Layer-2) can be calculated:

$C_{Drain} = 31 \text{ m/d} \times 0.99 \text{ m}$

$\underline{C_{Drain} = 30.69 \text{ m}^2\text{/d}}$

The values obtained from the conductance formula for the Loxton Sand Shell Hash suggest a drain conductance higher than that obtained through model calibration (9 m^2/d).

If a drain conductance of 9 m^2/d is considered correct for a well positioned in the Loxton Sand Shell Hash (Layer-2), with a hydraulic conductivity of 31 m/d, then the calculated drain circumference can be determined by solving Equation-2 for c:

$9 \text{ m}^2\text{/d} = 31 \text{ m/d} \times c \text{ m}$

$c = \dfrac{9 \text{ m}^2\text{/d}}{31 \text{ m/d}}$

$\underline{c = 0.29 \text{ m}}$

Solving for ‘c’ indicates a drain circumference less than that of the actual outer product pipe used in the trial horizontal drainage well (0.99 m). However, this is considered acceptable due to the close match between the transient model potentiometric heads and those observed during the long-term pumping test conducted on the trial horizontal drainage well.

Applying Equation-2, and for consistency, using the drain circumference calculated above (0.29 m) and the hydraulic conductivity of the Pata Formation (Layer-4) a respective drain conductance can be calculated:

$C = 0.4 \text{ m/d} \times 0.29 \text{ m}$

$\underline{C = 0.12 \text{ m}^2\text{/d}}$

Based on the above calculation a drain conductance of 0.1 m^2/d has been used for modelling the drain positioned in the Pata Formation (Layer-4).

3.5.9 MODEL STRESS PERIOD

The transient model includes a historical period between 0–730 days, and prediction period of 730–11 315 days (31 years).

3.6 MODEL CALIBRATION

3.6.1 STEADY STATE MODELS, TRANSIENT MODELS AND CALIBRATION

Steady state models are used to model equilibrium hydrologic conditions and/or conditions when changes in storage are insignificant. Transient models are used to model time dependent stresses and/or where water is released from, or taken into storage.

Calibration of the model with existing data must be conducted in order to have confidence in predictive modelling. Calibration is necessary to demonstrate the model can replicate the behaviour of the aquifer system for at least one set of conditions.

3.6.2 STEADY STATE MODEL CALIBRATION

Steady state calibration is undertaken to develop a broad-scale hydraulic conductivity distribution by matching modelled to observed potentiometric heads. Steady state calibration was performed by adjusting hydraulic conductivities (within reasonable limits) and model boundary conditions. Dynamic stresses and storage effects are excluded from steady state calibration.

The steady state model was calibrated using observation potentiometric head data, obtained prior to pumping the trial horizontal drainage well, from seven observation wells completed in the Loxton Sands–Loxton Sand Shell Hash, and two observation wells completed in the semi-confined Pata Formation. Modelled potentiometric heads closely match the potentiometric head observed on 3 May 2006. A normalised RMS value of 1.651% was achieved (Fig. 26).

3.6.3 TRANSIENT MODEL CALIBRATION

Transient calibration is undertaken to calibrate aquifer and aquitard hydraulic parameters, and refine boundary conditions. The potentiometric surface output from the steady state model was used as the starting point for transient model runs. The transient model was calibrated through an iterative process that involved adjusting the boundary conditions, recharge rates, and aquifer and aquitard hydraulic parameters. Each time a change to the boundary conditions, or aquifer and aquitard hydraulic parameters was made in the transient model, the steady state model was altered and rerun, with the output being used as the starting point for the transient model.

Model calibration was achieved by the following actions:

1. Quantitative comparison between modelled and observed observation potentiometric heads.
2. Iteration residual error.

3.6.4 TRANSIENT MODEL CALIBRATION – QUANTITATIVE COMPARISON OF POTENTIOMETRIC HEADS

Quantitative calibration of the transient model was undertaken by simulating the potentiometric heads observed from seven observation wells completed in the Loxton Sands/Loxton Sand Shell Hash, and three wells completed in the semi-confined Pata Formation from 3 May 2006 to 3 May 2007 (Table 6). This corresponds with the transient model time period of 365–730 days.

Table 6. Observation well completion details

Observation Well Name	Hydrogeological unit	Layer
LHP42P	Pata Formation	Layer 4
LHO58	Loxton Sand Shell Hash	Layer 2
LHO63	Loxton Sand Shell Hash	Layer 2
LHO65	Pata Formation	Layer 4
LHO66	Loxton Sand Shell Hash	Layer 2
LHO67	Loxton Sand Shell Hash	Layer 2
LHO68	Loxton Sand Shell Hash	Layer 2
GDN61	Loxton Sand Shell Hash	Layer 2
GDN62P	Pata Formation	Layer 4
GDN114	Loxton Sand Shell Hash	Layer 2

3.6.4.1 Layer-1 and Layer-2: Loxton Sands–Loxton Sand Shell Hash

Quantitative comparison between the modelled and observed potentiometric heads of observation wells completed in Layer-1 and Layer-2 indicates a satisfactory match of the modelled to the observed data for the period modelled (Figs 27–36). Observation well GDN61, used in steady state calibration, however could not be closely simulated in the transient model due to close proximity to the eastern constant head boundary (Fig. 27).

3.6.4.2 Layer-3: Pata Formation

Quantitative comparison between the modelled and observed potentiometric heads of observation wells completed in Layer-3 indicates the modelled data satisfactorily matches the observed data in LHO65 and LHP42P for the period modelled (Figs 34, 35). Observation well GDN62P could not be closely simulated in the transient model due to the wells proximity to the eastern constant head boundary (Fig. 36).

3.6.5 TRANSIENT MODEL CALIBRATION – ITERATION RESIDUAL ERROR

The iteration residual error, between modelled and observed potentiometric heads of all observation wells, was calculated using data from 3 May 2006–3 May 2007, which corresponds to the modelled period 365–730 days. The calculations (Figs 37–39) indicate a normalised root mean square value of less than 2.9% over the modelled period.

3.7 MODELLING RUNS AND PREDICTIVE MODELLING RUNS

Once satisfactory calibration of the model has been achieved, the transient model provides a useful predictive tool to quantify the impacts of specific pumping stresses on potentiometric heads.

3.8 ZONE BUDGETS

Zone budgets are used to quantify the groundwater flux into and out of sub-regions within a model. Zone budgets were constructed within the steady state and transient models (Fig. 40) to assist in determining the effectiveness of a trial horizontal drainage well at intercepting the groundwater flux:

1. Passing an imaginary plane parallel to the well.
2. Discharging to the River Murray.

The following general comments can be made regarding the use of zone budgets in the model for quantifying groundwater fluxes:

1. The groundwater flux passing the 250 m long trial horizontal drainage well is the flux from Zone-5 to Zone-1.
2. The groundwater flux discharging to the river is the flux from Zone-1 to Zone-2.
3. The groundwater flux passing a simulated horizontal drainage well has been calculated from the difference between the transient and steady state values, and has been expressed as a percentage reduction.

   $$RF_{Well} = 100 \times \frac{Fw\ X}{Fw\ SS} \qquad \text{Equation-4}$$

   Where:

   RF_{Well} = Percentage reduction of flux passing the well in Layer-1 and Layer-2

   Fw X = Flux passing the well in Layer-1 and Layer-2 at year X (m^3/d)

   Fw SS = Flux passing the well in Layer-1 and Layer-2 at steady state (m^3/d)
4. The groundwater flux discharging to the river has been calculated from the difference between the transient and steady state values, and has been expressed as a percentage reduction.

   $$RF_{River} = \frac{100 \times Fr\ X}{Fr\ SS} \qquad \text{Equation-5}$$

   Where:

   RF_{River} = Percentage reduction of flux discharging to river from Layer-1 and Layer-2

   Fr X = Flux discharging to river from Layer-1 and Layer-2 at year X (m^3/d)

   Fr SS = Flux discharging to river from Layer-1 and Layer-2 at steady state (m^3/d)

5. In order to simplify the modelling, the vertical groundwater flux has been assumed to be minimal and has been ignored. Zone budgets only quantify the lateral flux occurring in Layer-1 and Layer-2.

3.9 SCENARIOS

The scenarios are summarised in Table 7 and are designed to determine the effectiveness of the trial well, and a 1300 m long theoretical horizontal drainage well positioned in the Pata Formation, at intercepting groundwater flux:

1. Passing an imaginary plane parallel to the well.
2. Discharging to the River Murray.

Table 7. Summary of modelled scenarios

Scenario	Description	Model Run
S-1	Steady state (pre pumping)	Steady State
S-2A	250 m long trial horizontal drainage well[1], elevation 13.2 m AHD[2]	Transient
S-5	1300 m long theoretical horizontal drainage well positioned in Layer-4, elevation -1 m AHD	Transient

1. Horizontal drainage wells are represented by drainage cells in the model.
2. The top of the trial horizontal drainage well outer product pipe is set at 13.2 m AHD (one-quarter the saturated aquifer thickness above the base of the aquifer).

3.9.1 SCENARIO-1: STEADY STATE (PRE-PUMPING)

Scenario-1 steady state output provides:

1. The starting potentiometric heads for the transient scenarios.
2. The pre-pumping original groundwater flux passing a 250 m long imaginary plane parallel to the inactive 250 m long trial horizontal drainage well (Zone-5 to Zone-1).
3. The pre-pumping original groundwater flux discharging to the river through the 1300 long aquifer strip (Zone-1 to Zone-2).

3.9.1.1 Scenario-1: Conditions

The following conditions were applied in the steady state model:

1. Model layers and parameters based on local hydrogeology determined during investigation program and parameters used in Loxton–Bookpurnong Numerical Groundwater Model 2005.
2. Time period = steady state.

3.9.1.2 Scenario-1: Modelling results

Results from the steady state model are given in Table 8 and indicate a groundwater flux of 182.24 m^3/d passing an imaginary plane parallel to the 250 m long trial horizontal drainage well. A total flux of 955.34 m^3/d discharges to the River Murray through the 1300 m long aquifer strip (Fig. 40).

Table 8. Scenario-1 predicted groundwater flux passing inactive horizontal drainage well and discharging to river

Flux passing 250 m trial horizontal drainage well (Z5 to Z1) (m^3/d)	**Flux discharging to River Murray (Z1 to Z2)** (m^3/d)
182.24	955.34

3.9.2 SCENARIO-2A: 250 M LONG HORIZONTAL DRAINAGE WELL, ELEVATION 13.2 M AHD

Transient Scenario-2A predicts the effectiveness of the trial horizontal drainage well positioned within the Loxton Sand Shell Hash (Layer-2) at an elevation of 13.2 m AHD.

3.9.2.1 Scenario-2A: Conditions

The following conditions were applied in the transient model for Scenario-2A.

1. Model based on local hydrogeology and parameters obtained from the Loxton–Bookpurnong Numerical Groundwater Model 2005.
2. The 250 m long trial horizontal drainage well simulated by drainage cells set within the Loxton Sand Shell Hash (Layer-2) at an elevation of 13.2 m AHD. This positions the well one-quarter the saturated (includes Layer-1 and part Layer-2) aquifer thickness above the base of the aquifer.
3. Drain conductance set such that the modelled drawdown closely matches drawdown observed during the long-term pumping trial conducted on the trial horizontal drainage well, and the drain discharge is consistent with the observed pumping rate during the long-term pumping trial.

3.9.2.2 Scenario-2A: Modelling results

The results for Scenario-2A are given in Table 9 and indicate the percentage reduction in groundwater flux after 1, 5 and 30 years of drain operation (discharge commencing at 7.4 L/s and reducing to 1.4 L/s):

1. Passing an imaginary 250 m long plane parallel to the well (Zone-5 to Zone-1).
2. Discharging to the river through the 1300 m long aquifer strip (Zone-1 to Zone-2).

Table 9. Scenario-2A transient model scenario results

Scenario	**Percentage reduction in flux past well**			**Percentage reduction in flux to River Murray**		
	Year 1	**Year 5**	**Year 30**	**Year 1**	**Year 5**	**Year 30**
S-2A	83.2	83.9	83.6	15.9	22.4	24.7

3.9.3 SCENARIO-5: 1300 M LONG THEORETICAL HORIZONTAL DRAINAGE WELL POSITIONED IN LAYER-4

Transient Scenario-4 predicts the effectiveness of a 1300 m long theoretical horizontal drainage well positioned in the semi-confined Pata Formation (Layer-4) at an elevation of -1 m AHD.

3.9.3.1 Scenario-5: Conditions

The following conditions were applied in the transient model for Scenario-5.

1. Model based on local hydrogeology and parameters obtained from the Loxton–Bookpurnong Numerical Groundwater Model 2005.
2. The 1300 m long horizontal drainage well simulated by drainage cells set within the Pata Formation (Layer-4) at an elevation of -1 m AHD.
3. Drain conductance set using the conductance formula (Equations 1 and 2).

3.9.3.2 Scenario-5: Modelling results

The results for Scenario-5 are given in Table 10 and indicate the percentage reduction in groundwater flux after 1, 5 and 30 years of drain operation (discharge rate commencing at 3 L/s and reducing to 2.3 L/s):

1. Discharging to the river through the 1300 m long aquifer strip (Zone-1 to Zone-2).

Table 10. Scenario-5 transient model scenario results

Scenario	Percentage reduction in flux past well			Percentage reduction in flux to River Murray		
	Year 1	Year 5	Year 30	Year 1	Year 5	Year 30
S-5	N/A	N/A	N/A	9.6	13.5	16.7

3.10 MODEL SENSITIVITY ANALYSIS

Sensitivity analysis is a procedure for quantifying the impact of an incremental variation in aquifer hydraulic parameters, or a stress, on an aquifer modelled response. The purpose of the sensitivity analysis is to identify the drivers in the system.

A sensitivity analysis is a requirement for models used as tools in groundwater assessment/ management where variations of the model parameters impact model outputs.

A sensitivity analysis was not conducted on the horizontal drainage well numerical model for the following reasons:

1. The model is a local scale numerical model, designed to determine the response of a modelled stress on a simplified aquifer system.
2. The model is not designed to determine in river EC benefits.

3.11 MODEL LIMITATIONS AND UNCERTAINTIES

Localised modelling to determine the effectiveness of the trial horizontal drainage well at intercepting groundwater flux discharging to the River Murray is difficult due to the complex nature of the hydrogeology that occurs at the site. Model limitations and uncertainties exist due to:

1. Simplification of hydrogeology.
2. Limited detail of the sloping aquitard between the well and river.
3. Limited detail of hydrogeology (particularly the aquifer thickness) close to river.
4. Anisotropic and heterogeneous nature of the Loxton Sands and Loxton Sand Shell Hash.
5. Limited detail of the thickness and extent of the Loxton Sand Shell Hash.
6. Simplification of the complex boundary conditions.
7. Inability to accurately model the drawdown directly above the trial horizontal drainage well. It is important to note that model Scenario-2A tends to understate the drawdown directly above the well, which reduces well efficiency.
8. Difficulty in replicating the sharply sloping watertable between the trial horizontal drainage well and the river.
9. The use of low permeability walls to assist in replicating the shape of the watertable near the river.
10. Short calibration time. The transient model calibration should be reviewed as further observed data becomes available.

It may be possible to design a model that replicates the observed data using parameters and hydraulic conductivity zones different to those used (model non-uniqueness). However, it should be recognised that such models may differ conceptually and parameters may not be consistent with field observations, which the current model is.

3.12 EFFECTIVENESS OF TRIAL HORIZONTAL DRAINAGE WELL AT INTERCEPTING GROUNDWATER FLUX PASSING AN IMAGINARY PLANE PARALLEL TO THE WELL

Transient numerical groundwater modelling predicts the effectiveness of the trial horizontal drainage well (Scenario-2A) at intercepting the original groundwater flux passing an imaginary 250 m long plane parallel to the well over three decades of pumping. The model positions the 250 m long trial horizontal drainage well at its correct elevation (one-quarter the aquifer thickness above the base of the Loxton Sands/Loxton Sand Shell Hash at 12.35 m AHD at the location of the well – this configuration being consistent with actual completion of the trial well) within a 1300 m long aquifer strip adjacent the river with low permeability boundaries at the north and south. Numerical groundwater modelling predicts the trial well is capable of intercepting 83% of the original groundwater flux passing the well after one year, and the percentage interception remains relatively constant over the modelled period of 30 years. The model drain discharge rate at one year (3.7 L/s), is consistent with the actual trial horizontal drainage well pumping rate of 3.6 L/s.

There remains an element of uncertainty regarding the validity of the model predictions of fluxes passing the MODFLOW drain. The methodology applied was Finite Difference based (MODFLOW) and calculated heads are reported at the centre of each grid element as the average of the heads at the four corners. Unless all corners report a calculated head of zero, there will always be a non-zero head reported. This results in heads in drain cells (used to simulate horizontal drainage wells) being non-zero and therefore the vertical hydraulic gradients towards the drain cells (from all directions) will be conservatively represented, a feature which contributes to a small component of flux bypassing the drain. Vertical gradients around the drain are very strong when the drain is at atmospheric pressure (zero head) and theoretically should divert all flow arriving from the upstream side into the drain in competition with the much weaker, near-horizontal gradient towards the river.

3.13 EFFECTIVENESS OF HORIZONTAL DRAINAGE WELLS AT INTERCEPTING GROUNDWATER FLUX DISCHARGING TO THE RIVER

3.13.1 TRIAL HORIZONTAL DRAINAGE WELL

Transient numerical groundwater modelling predicts (conservatively) the effectiveness of the trial horizontal drainage well (Scenario-2A) at intercepting the original groundwater flux discharging to the River Murray through the 1300 m long aquifer strip over three decades of pumping. Modelling predicts the trial well is capable of intercepting 16% of the original groundwater flux discharging to the river after one year, increasing to 22% and 25% at five and 30 years respectively.

The 250 m long trial well (20% in length of the 1300 m long aquifer strip) intercepts 25% of the original groundwater flux discharging to the river at 30 years due to convergence of groundwater flow towards the well. Simultaneous with the pumping of the trial well, the residual groundwater mound between the well and the river begins to deflate. Complete deflation of the residual groundwater mound is unlikely to occur due to a groundwater flux passing beneath the well, and due to convergence of groundwater flow from beyond the longitudinal limits of the well to between the well and the river (Fig. 41). This would remain a problem regardless of the choice of infrastructure. The flux passing beneath the well may be an artifact of the modelling method used, and can be theoretically eliminated in the real world situation by pumping at a rate sufficient to keep the water level within the horizontal drainage well, allowing the pressure at the top of the pipe to drop to atmospheric.

3.13.2 PATA FORMATION HORIZONTAL DRAINAGE WELL

Transient numerical groundwater modelling predicts the effectiveness of a 1300 m long theoretical horizontal drainage well, positioned in the semi-confined Pata Formation, at intercepting the original groundwater flux discharging to the River Murray through the 1300 m long aquifer strip over three decades of pumping. This interception option was proposed early in the Loxton SIS project. Modelling predicts the well is capable of intercepting only 10% of the original groundwater flux discharging to the river after one year, increasing to 14% and 17% at five and 30 years respectively. The percentage interception at 30 years is less than that achieved by the 250 m long trial well in Scenario-2A (positioned in the Loxton Sands/Loxton Sand Shell Hash).

3.14 PREDICTED PUMPING RATES OF TRIAL HORIZONTAL DRAINAGE WELL

Transient numerical modelling of the trial horizontal drainage well (Scenario-2A) provides an indication of the long-term pumping rates (Fig. 42). Modelling indicates:

1. The modelled drain discharge rate closely matches the observed horizontal drainage well pumping rate over the first 12 months of pumping, with the rate steadily reducing from 637 m^3/d (7.4 L/s) to 321 m^3/d (3.7 L/s).
2. Beyond the first 12 months, the predicted drain discharge rate gradually reduces to 239 m^3/d (2.8 L/s) after 20 years.
3. A predicted drain discharge rate of 125 m^3/d (1.4 L/s) at the end of 30 years of operation.

3.15 OUTCOMES AGAINST OBJECTIVES

Numerical modelling provides a clear indication of the effectiveness of the trial horizontal drainage well, and horizontal drainage well construction scenarios, at intercepting the groundwater flux discharging to the River Murray. Comments regarding the outcomes relative to the objectives of the modelling are discussed below:

Objective 1: Determine the effectiveness of the trial horizontal drainage well at intercepting the groundwater flux:

1. Passing an imaginary plane parallel to the well.
2. Discharging to the River Murray.

Satisfactorily met. Modelling predicts the 250 m long trial horizontal drainage well, positioned one-quarter the aquifer thickness above the base of the Loxton Sands/Loxton Sand Shell Hash, is capable of intercepting:

a. 83% of the original groundwater flux passing an imaginary 250 m long plane parallel to the well after one year. The percentage interception remains relatively constant over the modelled period of 30 years.
b. 22% of the original groundwater flux discharging to the river through the 1300 m long aquifer strip at five years.

Objective 2: Indicate the groundwater flow capture zone of the trial horizontal drainage well.

Satisfactorily met. Modelling predicts the 250 m long trial horizontal drainage well (20% in length of the 1300 m long aquifer strip) intercepts 25% of the original groundwater flux discharging to the river at 30 years due to convergence of groundwater flow towards the well.

Objective 3: Determine the effect of the well elevation within the Loxton Sands–Loxton Sands Shell Hash on interception efficiency a horizontal drainage well.

Satisfactorily met. When the base of the aquifer occurs above river pool level, the effectiveness of a horizontal drainage well is influenced by its positioning in the aquifer. Modelling suggests that total interception of the groundwater flux discharging to the river is not possible in a geological setting where the base of the aquifer occurs at, or above, river pool level. A 100% interception of the groundwater flux passing a horizontal drainage well requires deflation of the residual groundwater mound between the well and the river, and this cannot occur due to some flux passing beneath the well.

Where the outer product pipe is positioned above pool level the greatest possible interception will be achieved if the groundwater level can be drawn into the outer product pipe, thus resulting in atmospheric pressure occurring above the water surface, which theoretically should allow 100% interception.

Objective 4: Determine long-term deflation of the residual groundwater mound between a horizontal drainage well and the river.

Satisfactorily met. Modelling indicates complete deflation of the residual groundwater mound between the trial horizontal drainage well and the river never occurs due to a groundwater flux passing beneath the well and due to convergence of groundwater flow, from beyond the longitudinal limits of the well, to between the well and the river. This would remain a problem regardless of the choice of infrastructure.

Objective 5: Indicate the effectiveness of a horizontal drainage well, positioned in the semi-confined Pata Formation, at reducing the groundwater flux discharging to the river from the Loxton Sands and Loxton Sand Shell Hash.

Satisfactorily met. Modelling predicts a 1300 m long theoretical horizontal drainage well positioned in the semi-confined Pata Formation is capable of intercepting 14% of the original groundwater flux discharging to the river at five years, increasing to 17% at 30 years. The percentage interception is less than that achieved by the 250 m long trial horizontal drainage well (25% at 30 years) positioned in the Loxton Sand Shell Hash.

Objective 6: Determine the long-term pumping rate of the trial horizontal drainage well.

Satisfactorily met. Modelling reflects current pumping rates of the trial horizontal drainage well and predicts the long-term rate is likely to be 1.4 L/s after 30 years.

4. INDEPENDENT ASSESSMENT OF THE EFFECTIVENESS OF HORIZONTAL DRAINGE WELLS

4.1 CONFIRMATION OF EFFECTIVENESS USING A SIMPLIFIED MODEL

A simple Finite Difference, 30-layer conceptual model was constructed by Don Armstrong of Lisdon Associates to illustrate the effect of relative drain (horizontal drainage well) and river levels on percentage interception of groundwater flow towards the river. Importantly, this simple model allows modelling of the drain below river level within an unconfined aquifer. This brief report is included in this section.

4.1.1 CASE-1 DRAIN BASE ABOVE RIVER LEVEL

In this model the base of the drain (horizontal drainage well) was set at EL 9.0 m and the river (right hand model boundary) at EL 7.0 m.

The model was run to steady state and flow lines (Fig. 43) determined by application of MODPATH to the MODFLOW Steady-State flow, clearly do not all terminate in the drain but some pass beneath the drain. The Water Budget describing fluxes in this run is given in Table 11, which indicates:

1. Flux into the left hand side of the model domain is 154.95 m^3/d over the 100 m width.
2. The drain intercepts 136.05 m^3/d or 87.8% of the total influx, which represents 109.7% of the inflow over the 80 m of drain width. Only 18.9 m^3/d reaches the river.
3. There is a small flux passing beneath the drain as can be seen in the plot but the overall capture is greater than 100% over the 80 m length because of end effects capturing a significant part of the flux through the end model cells.

The significant conclusion from this model run is that where a small residual gradient exists direct from drain to river, some flux will pass beneath the drain and combine with fluxes, which have avoided capture at the ends to reach the river.

4.1.2 CASE-2 DRAIN BASE BELOW RIVER LEVEL

This model had the river level set at EL 9.0 m and the base of the drain (horizontal drainage well) at EL 8.16 m.

In this instance all flow lines (Fig. 44) are intercepted by the drain, which is thus 125% efficient over the 100 m width. The Water Budget for this model is given in Table 12, which indicates that all flux is intercepted when even a very small residual gradient remains between the river and the drain.

Theoretically, for a horizontal aquifer base and drain base set below river level the drain will be capable of intercepting 100% of the flux over it's length provided the drainage rate is greater than or equal to the natural flux.

Table 11. Water budget for model with drain base above river pool level

WATER BUDGET OF THE WHOLE MODEL DOMAIN:

FLOW TERM	IN	OUT	IN-OUT
STORAGE	0.0000000E+00	0.0000000E+00	0.0000000E+00
CONSTANT HEAD	1.5495049E+02	1.8896381E+01	1.3605411E+02
WELLS	0.0000000E+00	0.0000000E+00	0.0000000E+00
DRAINS	0.0000000E+00	1.3605412E+02	-1.3605412E+02
RECHARGE	0.0000000E+00	0.0000000E+00	0.0000000E+00
ET	0.0000000E+00	0.0000000E+00	0.0000000E+00
RIVER LEAKAGE	0.0000000E+00	0.0000000E+00	0.0000000E+00
HEAD DEP BOUNDS	0.0000000E+00	0.0000000E+00	0.0000000E+00
STREAM LEAKAGE	0.0000000E+00	0.0000000E+00	0.0000000E+00
INTERBED STORAGE	0.0000000E+00	0.0000000E+00	0.0000000E+00
RESERV. LEAKAGE	0.0000000E+00	0.0000000E+00	0.0000000E+00
SUM	1.5495049E+02	1.5495050E+02	-1.9073486E-05
DISCREPANCY [%]	0.00		

Table 12. Water budget for conceptual model with drain base below river pool level

WATER BUDGET OF THE WHOLE MODEL DOMAIN:

FLOW TERM	IN	OUT	IN-OUT
STORAGE	0.0000000E+00	0.0000000E+00	0.0000000E+00
CONSTANT HEAD	1.6515759E+02	0.0000000E+00	1.6515759E+02
WELLS	0.0000000E+00	0.0000000E+00	0.0000000E+00
DRAINS	0.0000000E+00	1.6515741E+02	-1.6515741E+02
RECHARGE	0.0000000E+00	0.0000000E+00	0.0000000E+00
ET	0.0000000E+00	0.0000000E+00	0.0000000E+00
RIVER LEAKAGE	0.0000000E+00	0.0000000E+00	0.0000000E+00
HEAD DEP BOUNDS	0.0000000E+00	0.0000000E+00	0.0000000E+00
STREAM LEAKAGE	0.0000000E+00	0.0000000E+00	0.0000000E+00
INTERBED STORAGE	0.0000000E+00	0.0000000E+00	0.0000000E+00
RESERV. LEAKAGE	0.0000000E+00	0.0000000E+00	0.0000000E+00
SUM	1.6515759E+02	1.6515741E+02	1.8310547E-04
DISCREPANCY [%]	0.00		

4.1.3 COMMENT IN RELATION TO TRIAL HORIZONTAL DRAINAGE WELL

The sloping aquifer base and relatively high elevation of the trial horizontal drainage well site combine to produce a final water table configuration which, in the MODFLOW modelling described in the preceding section, always appears to retain a small gradient towards the river which may be interpreted to imply that there will always be a small component of the incident flux which escapes capture. In theory 100% interception is possible provided part of the pipe is at atmospheric pressure (i.e. it is running at less than full), as this will result in the drain intercepting all of the up-gradient flow (Fig. 45).

The necessity for the development of a seepage face or the associated convergence of flow lines, allows a drain to be highly effective (85% in the case of the Loxton Horizontal drain) even when the water surface appears, from adjacent observation wells, to be above the top of the pipe.

4.2 CONFIRMATION OF MODELLING USING ANALYTICAL ANALYSIS

The effectiveness of the drains (horizontal drainage wells) may be assessed independent of the numerical model where, in reality, water removed from the drain is water that will not reach the river and may therefore, be considered to have been "intercepted". Dr Hogbin Zhan, Department of Geology and Geophysics, Texas A&M University, 20 March, 2007 (pers. comm.) has provided a simple analysis of interception of flux by a horizontal drainage well. Essentially it says that provided the pumping rate from the well is equal to, or greater than, the natural groundwater flux towards the well, interception will be 100% effective.

4.2.1 ANALYSIS USING HYDRAULIC GRADIENTS

Analytical analysis to determine the effectiveness of the trial horizontal drainage well uses the hydraulic gradient within a few metres of the well on the downstream side to assess the efficiency in comparison with the initial gradient prior to any pumping. Using observation wells LHO58 and LHO66 (3.4 m and 73 m west of the trial well respectively) the gradients and associated efficiencies tabulated in Table 13 and plotted in Fig. 46, were calculated.

Table 13. Gradient analysis between LHO58 and LHO66

LHO66 73 m west of drain			LHO 58 3.35 m west of drain							
Date	Drawdown (m)	Reduced water level (m)	Date	Drawdown (m)	Reduced water level (m)	DELH (m)	Length (m)	Days	Gradient	Interception
03-May-06	0	15.105	03-May-06	0	15.821	0.716	69.6		0.0103	(% of initial flux)
04-May-06	0.03	15.075	04-May-06	0.46	15.361	0.286	69.6	0.8	0.0041	60
15-Jun-06	0.72	14.385	15-Jun-06	1.68	14.141	-0.244	69.6	43.1	-0.0035	134
08-Sep-06	1.01	14.095	08-Sep-06	1.67	14.151	0.056	69.6	128.0	0.0008	92
19-Feb-07	1.22	13.885	19-Feb-07	1.87	13.951	0.066	69.6	292.1	0.0009	91
03-May-07	1.25	13.855	03-May-07	1.86	13.961	0.106	69.6	364.9	0.0015	85
21-Jun-07	1.25	13.855	21-Jun-07	1.87	13.951	0.096	69.6	414.1	0.0014	87

The hydraulic gradient is calculated by dividing the head difference between observation wells LHO66 and LHO59 (DELH) by the distance between the two wells (L). A negative hydraulic gradient value means that there is flow towards the drain from the western (river) side and 100% interception is occurring.

The results indicate the percentage of initial flux intercepted, calculated by comparing the gradient between observation wells LHO58 and LHO66 at a given time, with that of the pre-pumping gradient on 3 May 2006.

Note that on 15/6/2006, 43 days into the long-term pumping test, the gradient was reversed at a discharge rate of 6L/s. The pipe must have been running part full and the interception rate was >100% which means that some water was being "harvested" from the flow by-passing the ends of the trial horizontal drainage well. This situation was not sustainable without a high degree of control over the pumping rate, and the interception rate settled in the 80–90% range for the majority of the trial period.

5. HORIZONTAL DRAINAGE WELL DESIGN, CONSTRUCTION AND OPERATION

5.1 LOXTON TRIAL HORIZONTAL DRAINAGE WELL

5.1.1 LOXTON HIGHLAND SIS CONSTRUCTION CHALLENGES

The initial investigations in the Loxton highland highlighted a number of challenges to the construction of an efficient SIS resulting from:

1. The thin (~4 m) unconfined nature of the aquifer (that includes the Loxton Sand shell hash unit and the overlying saturated sands).
2. The generally reducing aquifer permeability with depth, except for the shell hash unit.
3. The elevation of the base of the aquifer, which in many areas (including the site of the trial horizontal drainage well), occurs above river pool level, which significantly increases the level of complexity in designing an efficient SIS.
4. The (?)sloping nature of the aquitard with distance towards the river.
5. The need to work around a complex network of surface infrastructure and buried utilities.
6. Access for air-core investigation drilling programs.

Once the trial site for a horizontal drainage well had been selected, the final location along the main road to the north of Loxton was dictated by access for the preliminary air-core investigation drilling program and proximity to the disposal pipeline. Although it is correct the groundwater flux discharging to the River Murray would be intercepted more rapidly if the well were located closer to the river, access would have precluded preliminary investigations.

5.1.2 LOXTON HIGHLAND SUITABILITY FOR ADDITIONAL HORIZONTAL DRAINAGE WELLS

Limited existing air-core investigation drillhole data from the original four highland sites proposed to be targeted by the Loxton SIS indicates that horizontal drainage wells are a viable alternative.

At present, the most favourable site is expected to be an interval to the north of the existing trial horizontal drainage well. Due to the apparent dipping of the aquifer below River Murray pool level, it may be possible to position the outer product pipe of any further well(s) below river pool level, resulting in 100% interception of the groundwater flux discharging to the river. It is anticipated that should a continuous interception curtain be required, this will be comprised of 250 m (or perhaps a maximum of 500 m) long horizontal drainage wells, rather than a single long well.

Cost savings may occur with the drilling of further horizontal drainage wells if increased numbers and/or lengths of wells can be drilled at the same time.

5.1.3 HDPE SLOTTING TRIAL

The trial horizontal drainage well highlighted the difficulty in slotting SDR9 HDPE PE100 pipe due to the phenomenon known as reversion, which results from inbuilt stresses created during the manufacturing process. An investigation is currently underway involving the trial slotting and drilling of an annealed section of SDR9 HDPE PE100 pipe. If this proves successful, it may eliminate the need to use an inner liner, thus resulting in a simpler well design. The results of this trial will be reported separately.

5.2 HORIZONTAL DRAINAGE WELLS – POSTIONING OF OUTER PRODUCT PIPE

In the design and construction of a horizontal drainage well, the positioning of the outer product pipe within the aquifer is critical. In order to achieve efficient interception of groundwater flux passing a horizontal drainage well and then discharging to the River Murray, the outer product pipe must be positioned at, or ideally below, river pool level thus enabling drawdown to develop to this level. When the outer product pipe is positioned below river pool level, 100% interception of the groundwater flux discharging to the river can be achieved without the groundwater level being drawn into the outer product pipe.

In situations where the base of the aquifer occurs above River Murray pool level, as is the case at the site of the trial horizontal drainage well, the bottom of the outer product pipe should be positioned at the bottom of the aquifer to maximise drawdown and reduce the possibility of groundwater flux passing beneath the well. In practice this may difficult, unless the level of knowledge acquired during the preliminary air-core investigation drilling is satisfactory, and clearly indicates the surface of the underlying aquitard is not undulating. Depending on the level of knowledge, positioning the outer product pipe 0.5–1 m above the base of the aquifer may be required to reduce the possibility of partially screening the underlying aquitard. Where the outer product pipe is positioned above pool level the greatest possible interception will be achieved if the groundwater level can be drawn into the outer product pipe, thus resulting in atmospheric pressure occurring above the water surface, which theoretically should allow 100% interception.

5.3 HORIZONTAL WELL CONSTRUCTION

Research into international experience in horizontal well construction, operation and maintenance has highlighted similarities in the types of issues that have presented challenges in the Loxton trial horizontal drainage well project. Communication with James Doesburg (DTD), and information from the DTD website (www.horizontaldrill.com) has been of assistance in investigating products and techniques, some of which are listed below, which may benefit the design, drilling and construction of further wells in the Loxton region (or elsewhere).

5.3.1 DRILLING FLUIDS, DEVELOPMENT METHODS AND EQUIPMENT

Xanthan gum (recommended by Kerry Booth, Australian Mud Company Ltd.) was successfully used during the drilling of the trial horizontal drainage well and is an effective biodegradable drilling fluid. This choice is consistent with the type of drilling fluids being used elsewhere. DTD regularly use a mixture of guar, xanthan gum and cornstarch (Pers. Comm. James Doesburg 2007). There are commercially available biodegradable drilling products in the USA such as CleanDrill (CETCO) and Biobore (Baroid). Bentonite is generally avoided due to the difficulty in effectively developing the well. An enzyme breaking solution or sodium hypochlorite is used by DTD to assist in the breakdown of drilling fluid as part of the well development. DTD generally use a three part process to remove drilling fluids and develop a horizontal well which includes:

1. Flushing drilling fluid from the horizontal well with fresh water (two or three flushes with enzyme breaking solution often included as one of the later flushes). The well is then left for 24–48 hours to allow the breakdown of drilling fluids.
2. High volume jetting to clear the slots, generally done using the drilling rig mud pump to supply the volume.
3. Pumping the horizontal well to remove material.

Methods for developing and maintaining horizontal wells remain an area of ongoing investigation with various tools and methods being developed in the USA and Europe. The trial horizontal drainage well has demonstrated that up-hole velocities during pumping are too low to shift aquifer material that has infiltrated into the well, and this settles out. DTD have no one method which can be used in all instances to remove material from a well, however significant success has been achieved using a method of simultaneous jetting and pumping conducted throughout the production zone (Pers. Comm. James Doesburg 2007). Other methods include pumping between a double packer system, swabbing and over-pressuring the well. A method involving pulling a pump through the entire length of the production zone was considered for the trial horizontal drainage well, but has not been attempted to date.

5.3.2 OUTER PRODUCT PIPE OPTIONS

Several screen products are being manufactured in the USA specifically designed to reduce sedimentation within horizontal wells, e.g. Enviroflex well screen (Titan Industries), Fig. 47. However, these screens may not be of sufficient diameter for application at Loxton.

Pre-packed well screens designed with an in-built gravel pack (Fig. 48) are produced by a number of companies including Johnson Screens Pty Ltd and Variperm Canada Ltd. Pre-packed screens have been successfully used within horizontal wells. However, issues regarding the various products robustness, stiffness, weight and cost need to be considered especially in regard to larger diameters.

Stainless steel screens such as the Roscoe Moss Mini-Louver screen have also been successfully been used in horizontal wells (www.roscoemoss.com/horizontal_drill.html). Stainless steel screens are generally recommended in smaller diameter wells due to the increased stiffness of the product in larger diameters.

Fibreglass reinforced epoxy screens have been used with great success (Pers. Comm. James Doesburg 2007). These screens are strong and maintain slot integrity. However, the product tends to be expensive in comparison to similar diameter HDPE pipe.

Consequently, it appears that for horizontal drainage wells at Loxton, fabricated HDPE screen – outer product pipe may remain the best option.

5.3.3 PUMPING SUMP

Submersible pumps require a positive head to operate. Ideally this should be a minimum of at least 1 m, however the trial horizontal drainage well long-term pumping test has demonstrated that pumps can operate with a head significantly less than that at pumping rates low on the pump curve (but generally with some cavitation). The use of a sump would significantly improve the ability to dewater below the top of the outer product pipe. Two options exist:

1. A vertical sump as indicated in Fig. 49, would significantly improve the ability to draw the groundwater table down to the top of the outer product pipe. However, the installation of such a sump would increase installation complexity and cost.
2. An alternative to the vertical sump is to drill a low point at one end (or both ends) of the production zone. At Loxton, this would mean drilling a low point into the underlying aquitard. Similar to the vertical sump option, there are cost implications associated with additional drilling.
3. A further possibility is to use a positive displacement pump, such as a MONO pump, compressed air activated plunger pump or a venturi-type device (jet pump), none of which require continuous total submergence.

Where the horizontal drainage well can be positioned below river pool level, the installation of a sump is not warranted.

5.3.4 SUB-SURFACE WELLHEAD COMPLETION

The DTD website (www.horizontaldrill.com) provides a design for a sub-surface horizontal wellhead completion (Fig. 50). Such a completion reduces the visual impact of the installation and provides greater security. It is essential to design the pit in a manner that provides adequate access for pump installation and well maintenance.

5.4 GENERAL HORIZONTAL DRAINAGE WELL PLANNING, DESIGN, CONSTRUCTION AND OPERATION

The following general issues are critical in relation to the planning, design, construction and operation of horizontal drainage wells:

1. Conducting sufficient preliminary air-core investigation drilling to gain a detailed understanding of the hydrogeology (including the hydraulic continuity of aquifer) to ensure the most effective positioning of the outer product pipe.

2. Ensuring the pilot drillhole is positioned within a 1 m elevation at the base of the target aquifer and does not partially screen the underlying aquitard.
3. Assuming an HDPE casing. Utilising a thick-walled outer product pipe, which will allow a drilling rig to work over the horizontal drainage well (if required) without causing severe damage to the pipe. In an extreme case of sanding of a well a rig can work over the well, and may be able to drill out an inner liner.
4. Installing the outer product pipe such that the slotted (drilled) section is positioned solely within the target aquifer, and does not extend into any unconsolidated and potentially flowing sands which may run into the pipe. Additional blank lengths of pipe should be on hand during construction.
5. Utilising a slotting (drillhole) configuration for the outer product pipe that provides 1–2% open area. Regardless, the effective entrance velocity through the outer product pipe for the long-term pumping rate must be an order of magnitude less than the nominal maximum value of 0.03 m/s applied to conventional vertical production wells. This requirement is viewed as essential in minimising the risk of the infiltration of aquifer material.
6. Positioning the pump(s) to maximise the available head.

The following general issues should also be considered in relation to the planning, design, construction and operation of horizontal drainage wells:

1. The possible use of a horizontal (low point) pumping sump to improve the capacity of pump to draw the groundwater table down to the top of the outer product pipe.
2. If the HDPE reversion issue can be better understood and controlled, a slotting (in preference to drillhole) configuration that provides sufficient open area and pipe pull-back strength may eliminate the need for an inner liner. Ideally the slots should end up 0.5–1.0 mm wide following any reversion. Longitudinal slotting is suggested, however the possibility of radial slotting in the same configuration as was used for the inner liner in this project should be considered if the pipe retains sufficient strength for pull-back.
3. Improved well development equipment and techniques.
4. An improved cleaning method to remove drilling fluids and aquifer material from within the production zone during periodical well maintenance.
5. A sub-surface wellhead completion to reduce visual impact.
6. A more accurate method of determining head above the outer product pipe, e.g. a pressure transducer located close to the pump, or observation wells located very close to the production zone.

5.5 ADVANTAGES AND DISADVANTAGES OF HORIZONTAL DRAINAGE WELLS

Horizontal drainage wells are an effective SIS option where:

1. Conventional vertical production wells need to be very closely spaced to achieve interception and are unlikely to ever achieve an equivalent level of interception.

2. The surface of the underlying aquitard is relatively flat over the length of the production zone, although short intervals set beneath the base of the aquifer may not present a problem.
3. The horizontal drainage well can be positioned close to, or preferably below, river pool level.
4. Surface infrastructure makes access difficult.
5. Minimal disturbance to environment is required.
6. A simple and robust pump installation with minimal ongoing maintenance is required.

The potential advantages of horizontal drainage wells over conventional vertical production wells include:

1. Greater screened area in a thin unconfined aquifer.
2. Negates the need for multiple pumps and connected headworks.
3. Minimal disturbance to the environment.
4. Reduced volumetric flow of water per unit length of screen, which may result in decreased operation and maintenance costs (Louis and Fournier 2005).
5. Possible cost savings associated with the construction and long-term operation of horizontal drainage wells in comparison to other potential alternatives due to the use of single pump for a horizontal drainage well, in comparison to closely spaced conventional production wells and many pumps.

The possible disadvantages of horizontal drainage wells compared to conventional vertical production wells include:

1. Requires a specialised drilling technique, which for the single trial horizontal drainage well was relatively expensive. However economic analysis indicates that for the Loxton highland SIS, the costs of drilling, equipping and maintaining further horizontal wells is cost effective when compared to other options.
2. Requires specialised development.
3. Whilst maintenance is expected to be minimal, horizontal drainage wells do require specialised maintenance techniques.
4. Tree roots may present result in well blockage without regular maintenance.

Theses disadvantages should diminish with time as more horizontal drainage wells are constructed and maintenance experience is gained.

6. LOXTON SIS HIGHLAND OPTIONS – INSTALLATION AND OPERATING COSTS OVER 30 YEAR PERIOD

6.1 LOXTON SIS HIGHLAND INFRASTUCTURE OPTIONS

The benefit/cost of completing the Loxton SIS highland component over the original identified four sites using different infrastructure options were determined by SA Water. This exercise was designed to identify options likely to be cost effective and which should therefore be considered further, or those which stood out as economically unviable.

The following infrastructure options were assessed:

1. Horizontal drainage wells.
2. Conventional vertical production wells at nominal spacings of (say) 150 m, as modelled in the original SIS Concept Design.
3. Closely spaced (10 m) conventional vertical production wells fitted with Airwell Pumps.
4. Cliff toe interception drain (a horizontal drain installed directly adjacent the river below pool level).

These infrastructure options were reviewed in terms of estimated interception efficiency, installation costs, and ongoing costs associated with operating and maintenance. Key results of the analysis are given in Table 14.

Table 14. Highland SIS infrastructure options costs

	Option-1	Option-2	Option-3	Option-4
Total Installation Costs	$9.75m	$10.09m	$18.89m	$15.03m
NPV Costs*	$14.60m	$16.75m	$50.56m	$23.63m
Interception Efficiency	50%	5%	30%	100%
Benefit/Cost Ratio Low	0.59	0.05	0.10	0.73
Benefit/Cost Ratio High	0.80	0.07	0.14	0.99

*Total cost over 30 years calculated in today's dollar value.

It should be noted that:

1. The installation and operating costs are estimates based on past projects and drilling quotations.
2. The net present value (NPV) costs were calculated by estimating the total costs of each alternative calculated over a 30-year period using today's values.
3. Interception efficiency estimation is based on the current level of knowledge of highland hydrogeology and the interception technique. An interception efficiency of 50% for horizontal drainage wells is considered extremely conservative, and takes into account

the placement of wells in less than ideal locations. The results of numerical groundwater modelling presented in this report indicates the interception efficiency is likely to be higher than 50%, thus the benefit/cost ratio will be greater.

4. The benefit/cost ratio (BCR) is calculated by comparing the present value of benefits to the present value of costs with a value of ‘1’ being the break-even point. The range of the BCR values provided above is based on the original benefits analysis undertaken in the original scheme Approval Submission which utilised a number of calculation methods to assess the viability of the project.

6.2 DISCUSSION

The BCR takes into account the estimated cost vs the interception efficiency of the infrastructure option. The BCR for all the infrastructure options is below the break-even value of ‘1’. Option-2 and Option-3 have a very low BCR due to the need for closely spaced (~150 m and 10 m centres respectively) conventional vertical production wells, and the low estimated interception efficiency (5% and 30% respectively). The ongoing operating costs of Option-2 and Option-3 are high, due to the need to equip all wells with pumps and headworks, which adds significantly to the cost of installation, operating and maintenance.

Option-1 and Option-4 have comparable BCRs, which are significantly higher than the methods utilising conventional vertical production wells. Option-1 is identified as having the lowest of all installation and operating costs.

The results of the economic review indicates that even at the conservative interception efficiency of 50%, horizontal drainage wells offer a cost effective solution to salt interception when compared to conventional alternatives. Horizontal drainage wells appear more cost effective than the closely spaced vertical production well options in terms of interception efficiency, installation and operating costs.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSION

7.1.1 HORIZONTAL DRAINAGE WELL PLANNING, DESIGN, CONSTRUCTION AND OPERATION

The successful drilling and construction of the Loxton trial horizontal drainage well demonstrates that horizontal drainage wells can be installed at sites where the application of such wells may present a more practical approach to salt interception than conventional vertical production wells.

In the design and construction of a horizontal drainage well, the positioning of the outer product pipe within the aquifer is critical. In order to achieve efficient interception of groundwater flux passing a horizontal drainage well and then discharging to the River Murray, the outer product pipe must be positioned at, or ideally below, river pool level thus enabling drawdown to develop to this level. When the outer product pipe is positioned below river pool level, 100% interception of the groundwater flux discharging to the river can be achieved.

In situations where the base of the aquifer occurs above River Murray pool level, as is the case at the site of the trial horizontal drainage well, the bottom of the outer product pipe should be positioned at the bottom of the aquifer to maximise drawdown and reduce the possibility of groundwater flux passing beneath the well. In practice this may be difficult, unless the level of knowledge acquired during the preliminary air-core investigation drilling is satisfactory, and clearly indicates the surface of the underlying aquitard is not undulating. Depending on the level of knowledge, positioning the outer product pipe 0.5–1 m above the base of the aquifer may be required to reduce the possibility of partially screening the underlying aquitard. Where the outer product pipe is positioned above pool level the greatest possible interception will be achieved if the groundwater level can be drawn into the outer product pipe, thus resulting in atmospheric pressure occurring above the water surface, which theoretically should allow 100% interception.

The following general issues are important in relation to horizontal drainage well planning, design construction and operation:

1. Conducting sufficient preliminary air-core investigation drilling to gain a detailed understanding of the hydrogeology (including the hydraulic continuity of aquifer) to ensure the most effective positioning of the outer product pipe.

2. Ensuring the pilot drillhole is positioned within a 1 m elevation corridor at the base of the target aquifer and does not partially screen the underlying aquitard (although short intervals of the production zone set beneath the base of the aquifer may not present a problem).

3. Assuming an HDPE casing. Utilising a thick-walled outer product pipe, which will allow a drilling rig to work over the horizontal drainage well (if required) without causing severe

damage to the pipe. In an extreme case of sanding of a well a rig can work over the well, and may be able to drill out an inner liner (although not using an inner liner would be the preferable option).

4. Installing the outer product pipe such that the slotted (drilled) section is positioned solely within the target aquifer, and does not extend into any unconsolidated and potentially flowing sands which may run into the pipe. This will be very difficult to achieve unless a calliper log can be run to detect caving sections before running the outer product pipe. Additional blank lengths of pipe should be on hand during construction.
5. Utilising a slotting (drillhole) configuration for the outer product pipe that provides 1–2% open area. Regardless, the effective entrance velocity through the outer product pipe for the long-term pumping rate must be an order of magnitude less than the nominal maximum value of 0.03 m/s applied to conventional vertical production wells. This requirement is viewed as essential in minimising the risk of the infiltration of aquifer material.
6. Positioning the pump(s) to maximise the available head.

7.1.2 EFFECTIVENESS OF HORIZONTAL DRAINAGE WELLS

The long-term (18-month) pumping test conducted on the trial horizontal drainage well demonstrates the groundwater level can be readily drawn down close to the top of the outer product pipe, and that drawdown develops in the aquifer at great lateral distance from the well.

Numerical groundwater modelling predicts the effectiveness of the trial horizontal drainage well at intercepting the original groundwater flux discharging to the River Murray through the 1300 m long aquifer strip, but is believed to err on the conservative side due to limitations (for horizontal well applications) inherent in the Finite Difference methodology used. The key outcomes of the modelling include:

1. The 250 m long trial horizontal drainage well, positioned one-quarter the aquifer thickness above the base of the aquifer, is capable of intercepting 22% of the original groundwater flux discharging to the river through the 1300 m long aquifer strip at five years. Convergence of groundwater flow occurs towards the trial well. Complete deflation of the residual groundwater mound between the trial well and the river is unlikely to occur due to a flux passing beneath the well (possibly an artifact of the modelling method), and due to convergence of flow from beyond the longitudinal limits of the well to between the well and the river.
2. The results from the trial horizontal drainage well can be extrapolated to a 1300 m long theoretical horizontal drainage well. Modelling predicts interception of 83% of the steady state groundwater flux (182.24 m^3/d) passing an imaginary 250 m long plane parallel to the inactive trial well. This represents 0.61 (m^3/d)/m of well. This result can be extrapolated to a 1300 m long well, indicating 83% interception at a discharge (pumping) rate of 793 m^3/d or 9.2 L/s. As discussed above this is considered to be highly conservative.
3. A 1300 m long theoretical horizontal drainage well, positioned in the semi-confined Pata Formation, is only capable of intercepting 14% of the original groundwater flux discharging to the river through the 1300 m long aquifer strip at five years.

4. Modelling predicts that in geological settings that allow a horizontal drainage well to be positioned below river pool level, 100% interception of the groundwater flux can be achieved.

7.1.3 TRIAL HORIZONTAL DRAINAGE WELL – SALT LOAD BENEFIT

It is considered that the current numerical groundwater modelling is appropriate for determining the percentage interception of groundwater fluxes resulting from pumping horizontal drainage wells with the reservations expressed above regarding inherent difficulties with the Finite Difference methodology. However, it is more appropriate to use the results from the regional model (accredited by the MDBC for calculating salt loads to the River Murray) for the total groundwater flux discharging to the river, as the calculations for the tonnage of salt being intercepted more closely match that being pumped. The percentage interception determined from the current modelling can then be applied to the groundwater fluxes from the regional model to estimate salt load benefits.

The regional numerical groundwater model (Yan et al 2005) predicts the trial horizontal drainage well is located within a highland area from which 15.5 t/d of salt is discharged to the River Murray by lateral groundwater flow along a river frontage of 1.6 km, proportionately representing 2.4 t/d adjacent to the 250 m trial horizontal drainage well, and 12.6 t/d adjacent to the 1300 m long aquifer strip used in the current modelling.

The current numerical modelling predcits that the trial horizontal drainage well is intercepting:

1. 83% of the groundwater flux passing an imaginary 250 m long plane perpendicular to the well after one year. Applying 83% to the regional modelling results indicates 1.99 t/d of salt is intercepted.
2. 16% of the groundwater discharging to the river through the 1300 m long aquifer strip after one year, increasing to 22% at five years. Applying 16% and 22% to the regional modelling results indicates 2.02 t/d of salt is intercepted after one year, increasing to 2.77 t/d at five years. If this is the case, the trial well will be close to 100% effective with regard to the most important objective of reducing salt-load to the river within 1–5 years of operation.

Verification of the tonnage of salt intercepted by the trial horizontal drainage well is derived from the product of the long-tem pumping rate and groundwater salinity (3.5 L/s and 4600 mg/L respectively at the time of reporting), equating to 1.4 t/d. This is very close to the values calculated from the modelling. It should be noted that this calculation may significantly underestimates the benefit to the River Murray, as the groundwater salinity directly adjacent the River Murray is believed to greater that that observed at the well.

It is clear the trial horizontal drainage well is currently intercepting ~1.5 t/d of salt, and this will increase to 2–2.5 t/d at five years.

7.2 RECOMMENDATIONS

The following recommendations are made, based on the results of the investigations that indicate the effectiveness of the trial horizontal drainage well at intercepting groundwater flux discharging to the River Murray:

1. Further horizontal drainage wells are a valid choice as part of the Loxton SIS highland component.
2. Limited existing air-core investigation drillhole data from the original four highland sites to be targeted by the Loxton SIS indicate that horizontal drainage wells are a viable alternative at these sites.
3. The most favourable site for further horizontal drainage wells occurs to the north of the existing trial horizontal drainage well, where it is expected that horizontal drainage well outer product pipe can be positioned below river pool level, and would thus be 100% effective at intercepting the groundwater flux discharging to the river.
4. Prior to the construction of further horizontal drainage wells in the Loxton region, it is recommended that additional modelling be undertaken incorporating further details of site hydrogeology obtained from additional air-core investigation drilling, to determine:
   a. The modelled interception efficiency, particularly taking into account the final elevation of the horizontal drainage well. It is suggested that where the well cannot be set below river pool level it should be positioned as close to the base of the aquifer as practically possible to maximise drawdown and reduce the possibility of groundwater flux passing beneath the well.
   b. The optimal well spacing (if not overlapping wells) to achieve the maximum the benefit/cost.
5. The application of a large diameter vertical pumping sump should be considered.

The following recommendations are made in relation to the operation of the trial horizontal drainage well:

1. A well sock pull-through should be conducted at 12-month intervals to check on, and control, any minor tree root invasion.
2. Monitoring of the observation wells should continue, although a reduction in the number of wells being monitored is warranted.
3. If the southern end pump is re-installed it must be positioned ~200 m from the southern exit point to ensure submergence.
4. A suitable method for developing the trial horizontal drainage well to a level allowing clear camera footage through the length of the well is still considered important, and this should be revisited at some time in the future, particularly if a reduction in well performance is observed.
5. The possibility of using a more appropriate form of pump (less dependant upon submergence) should be investigated.

FIGURES

Figure 1. Location of Loxton trial horizontal drainage well

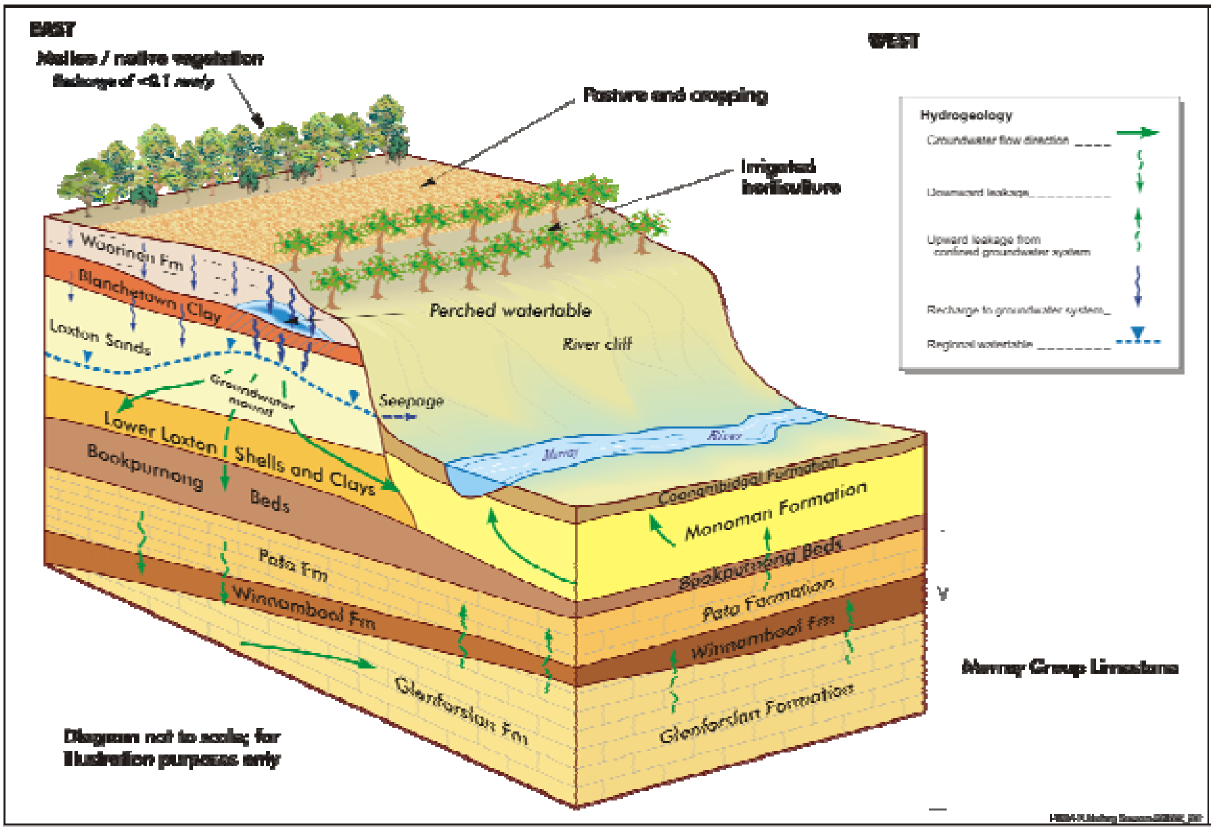


Figure 2. Elementary conceptual hydrogeological model

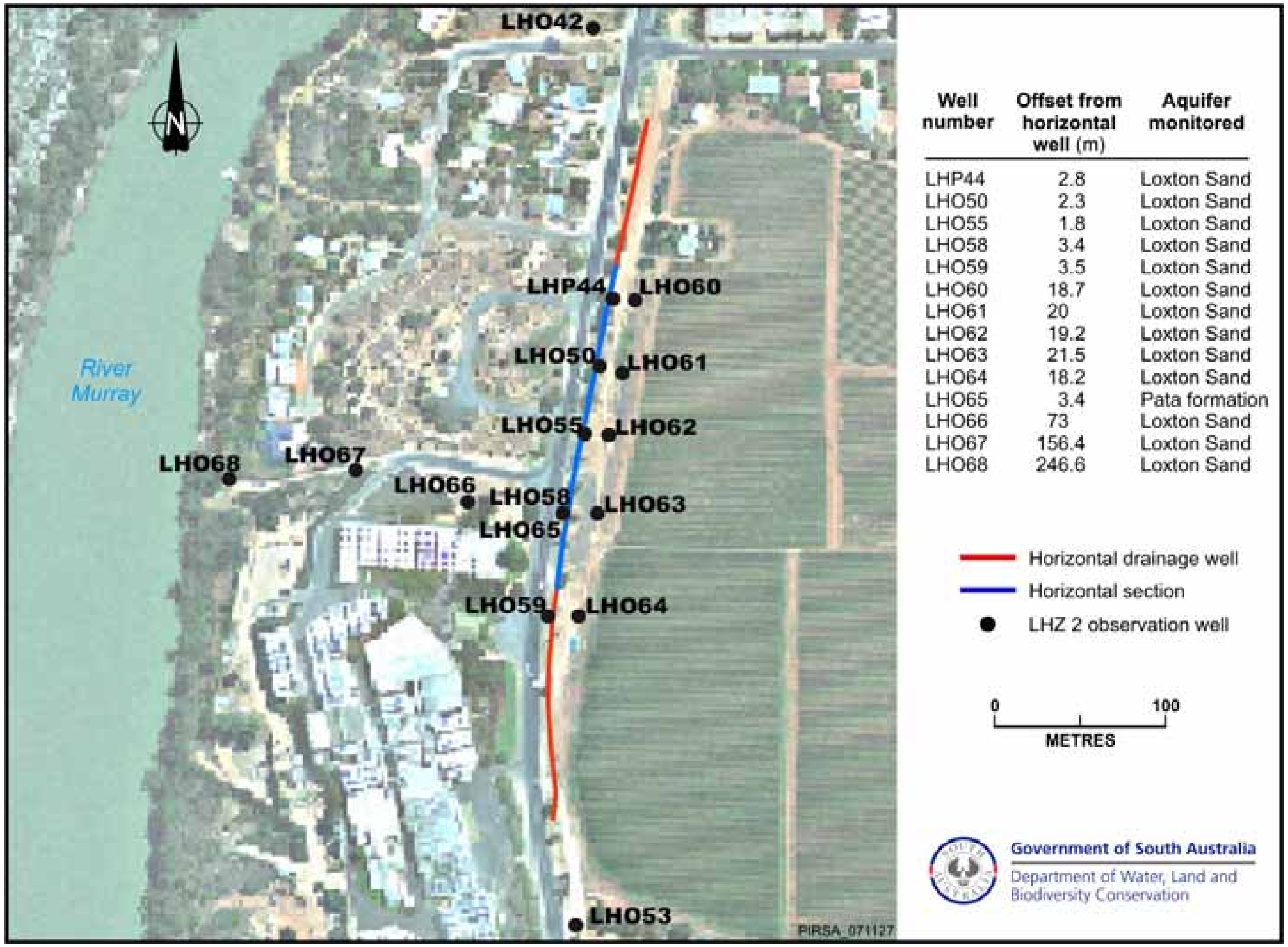


Figure 3. Location of Loxton SIS trial horizontal drainage well and observation wells

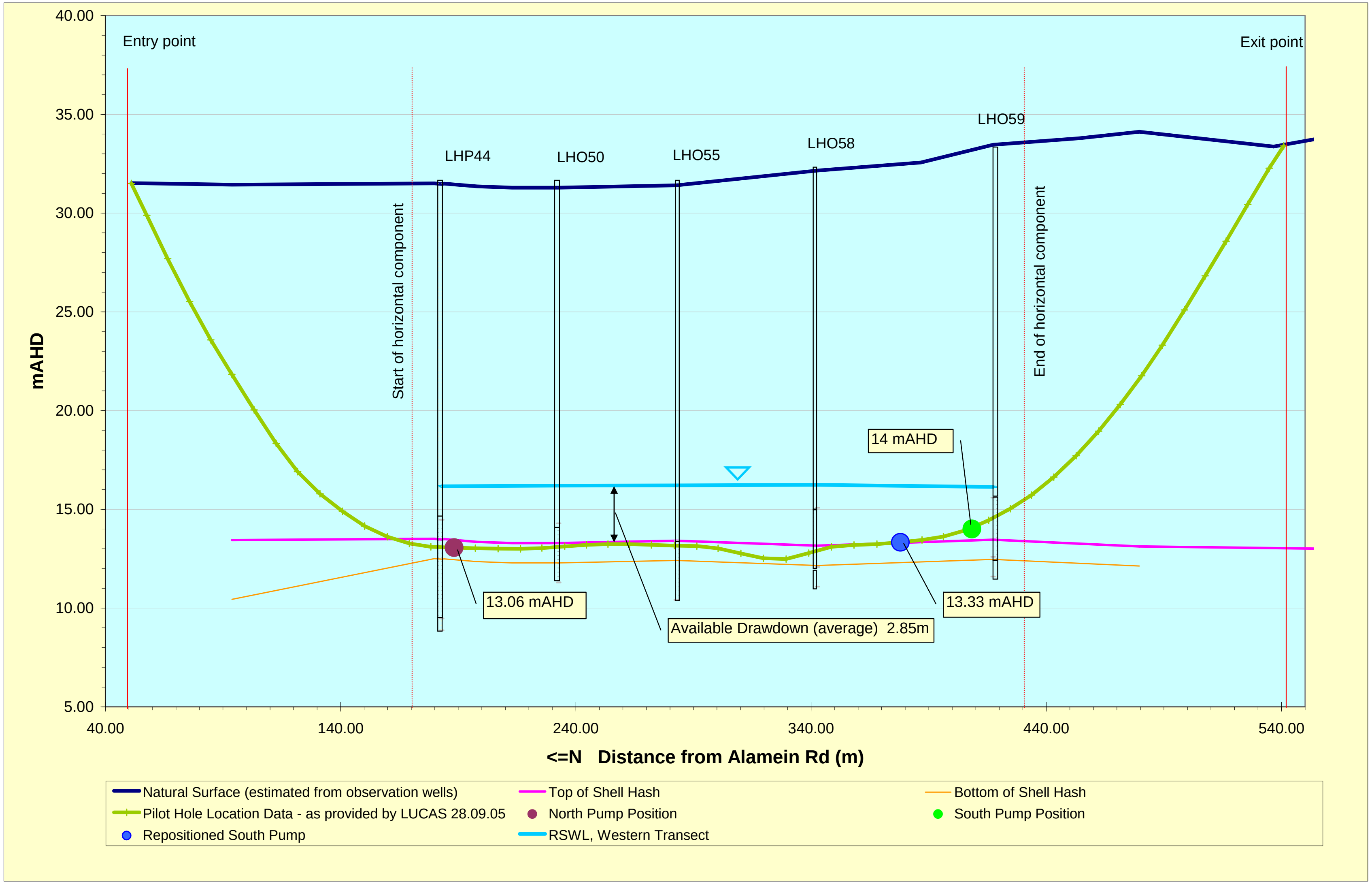


Figure 4. Pilot drill hole profile and pump setting

Figure 5. Outer product pipe drillholes

Figure 6. Inner liner slots

Figure 7. **Well-sock – 190 mm diameter**

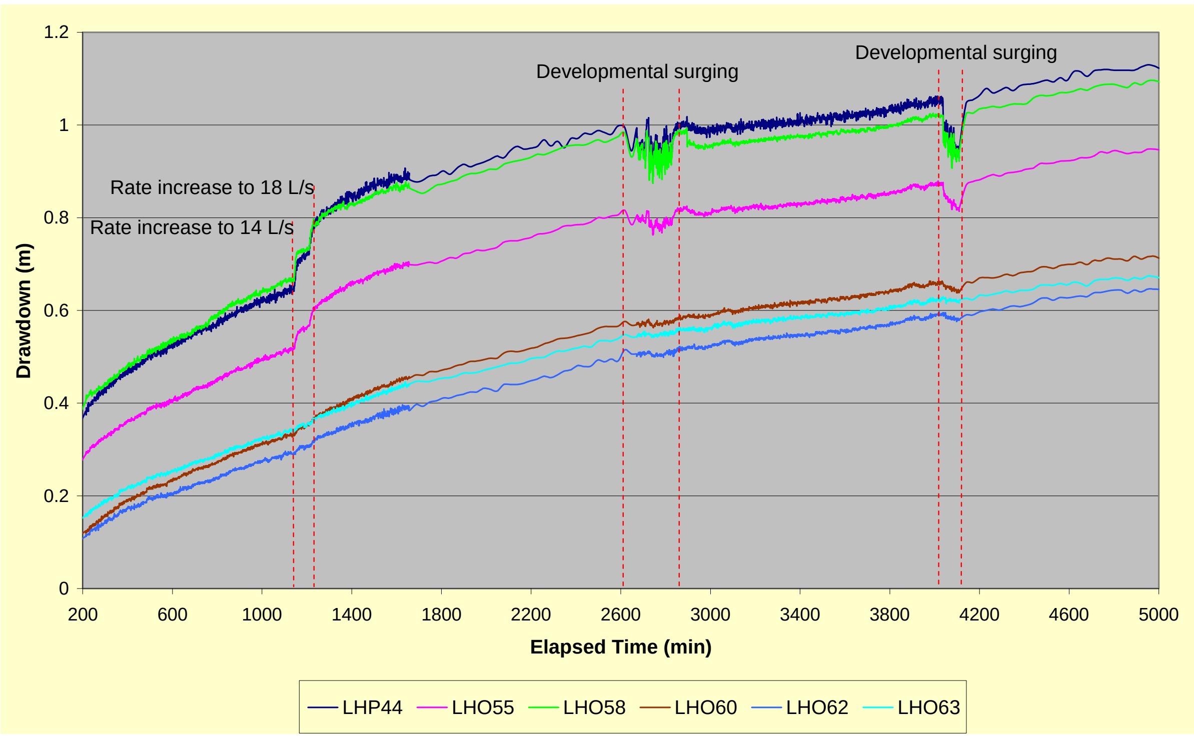


Figure 8. **Drawdown developed during initial 5000 min of the preliminary pumping test (logger data)**

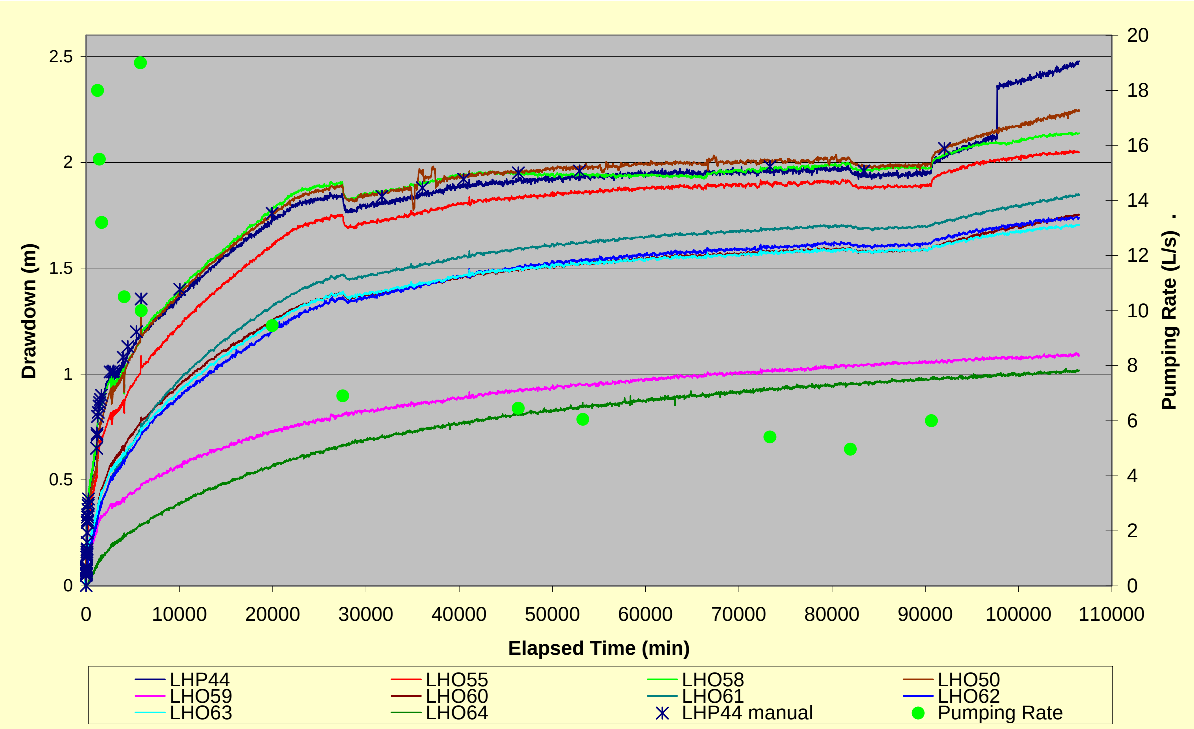


Figure 9. Drawdown developed during preliminary pumping test - full record (logger data)

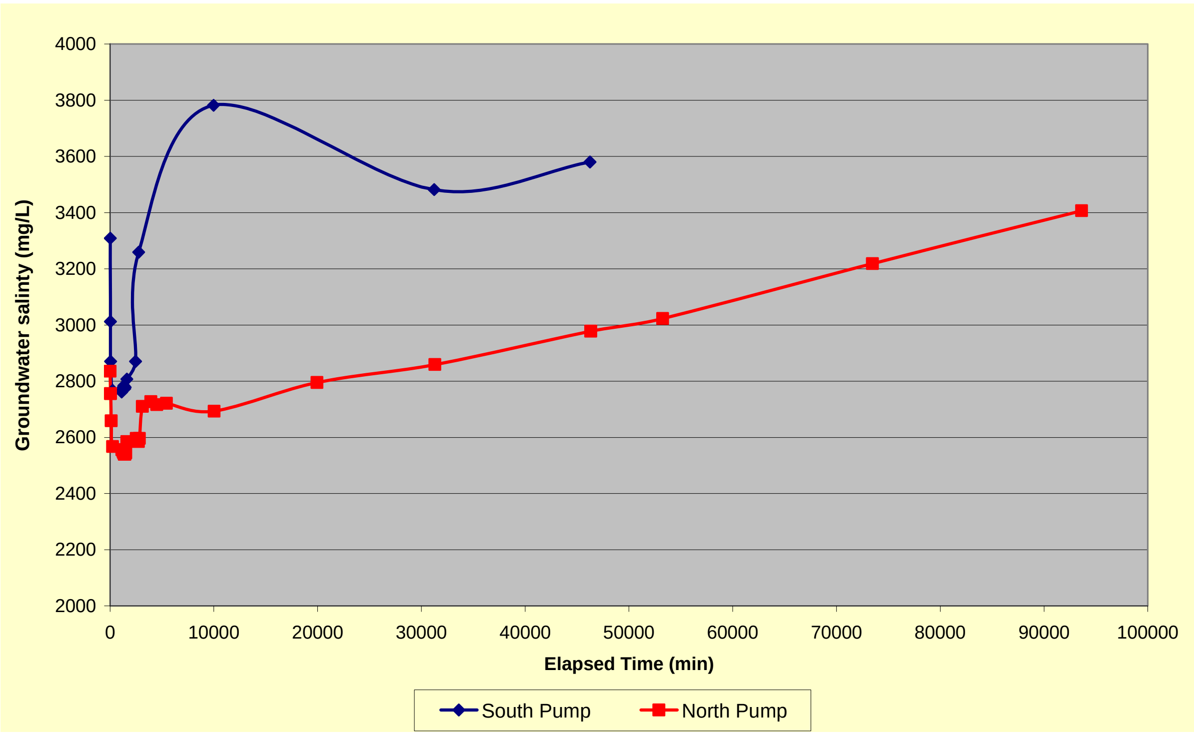


Figure 10. Preliminary pumping test groundwater salinity

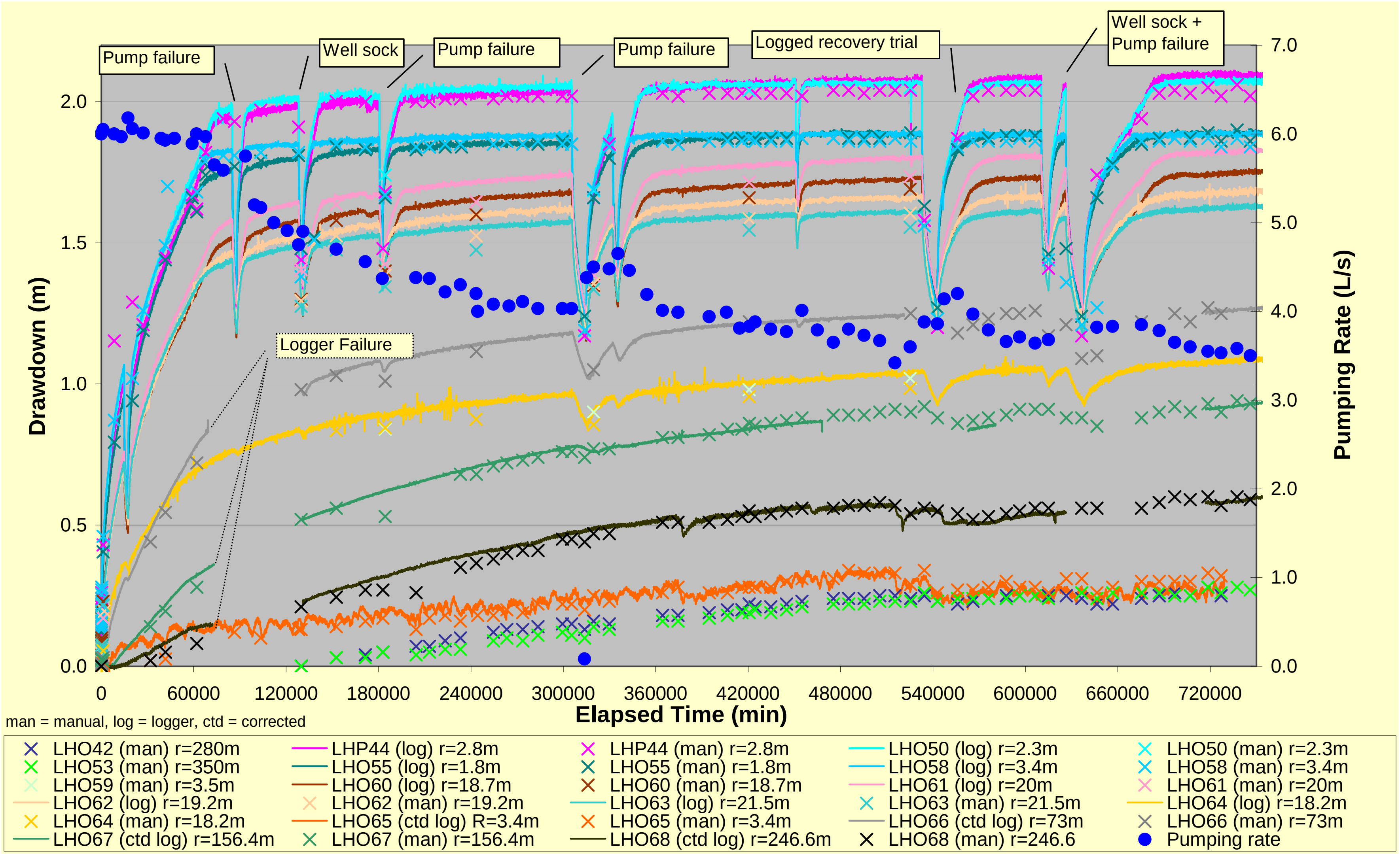


Figure 11. Drawdown developed during long-term pumping test (linear – linear)

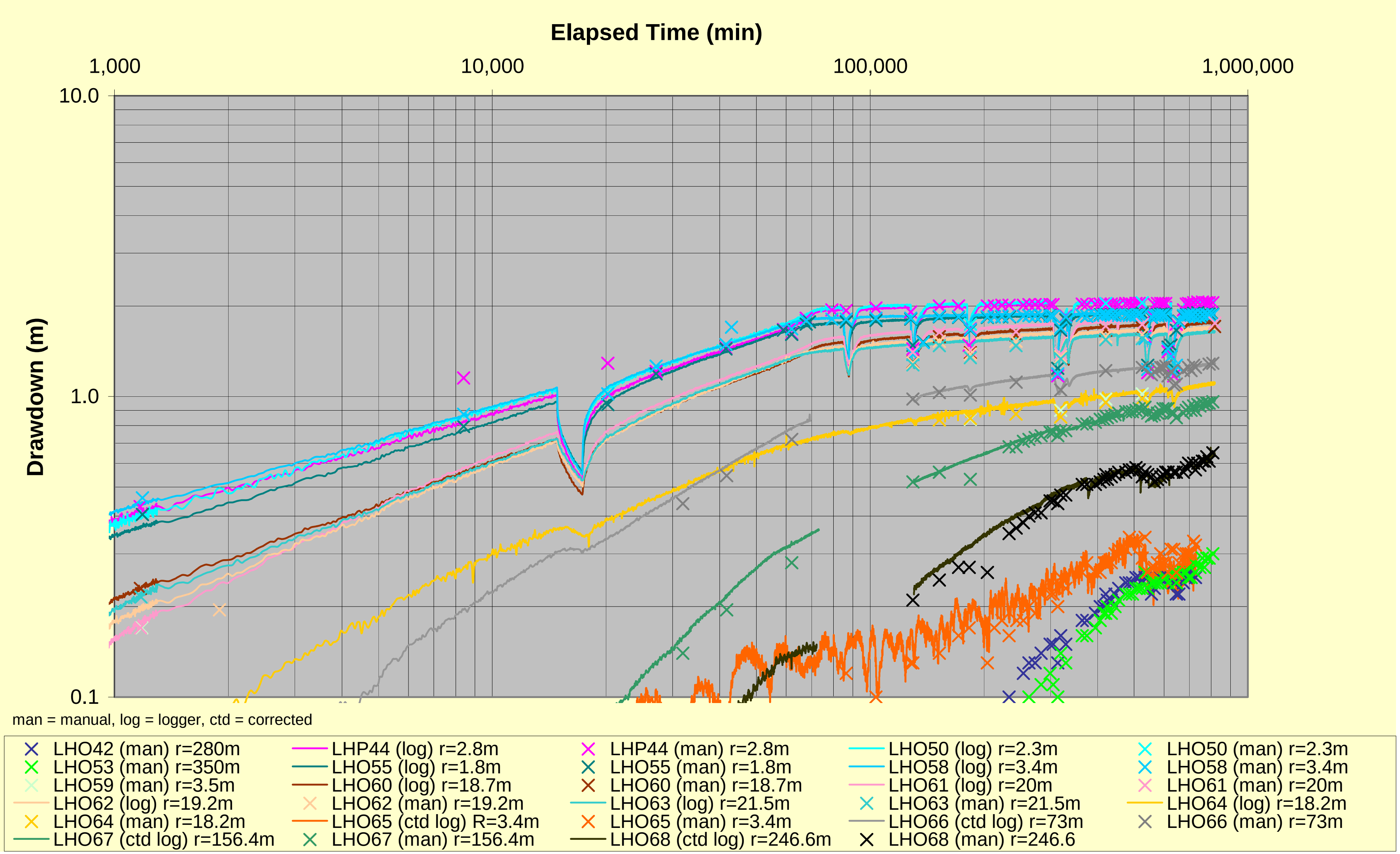


Figure 12. Drawdown developed during long-term pumping test (log – log)

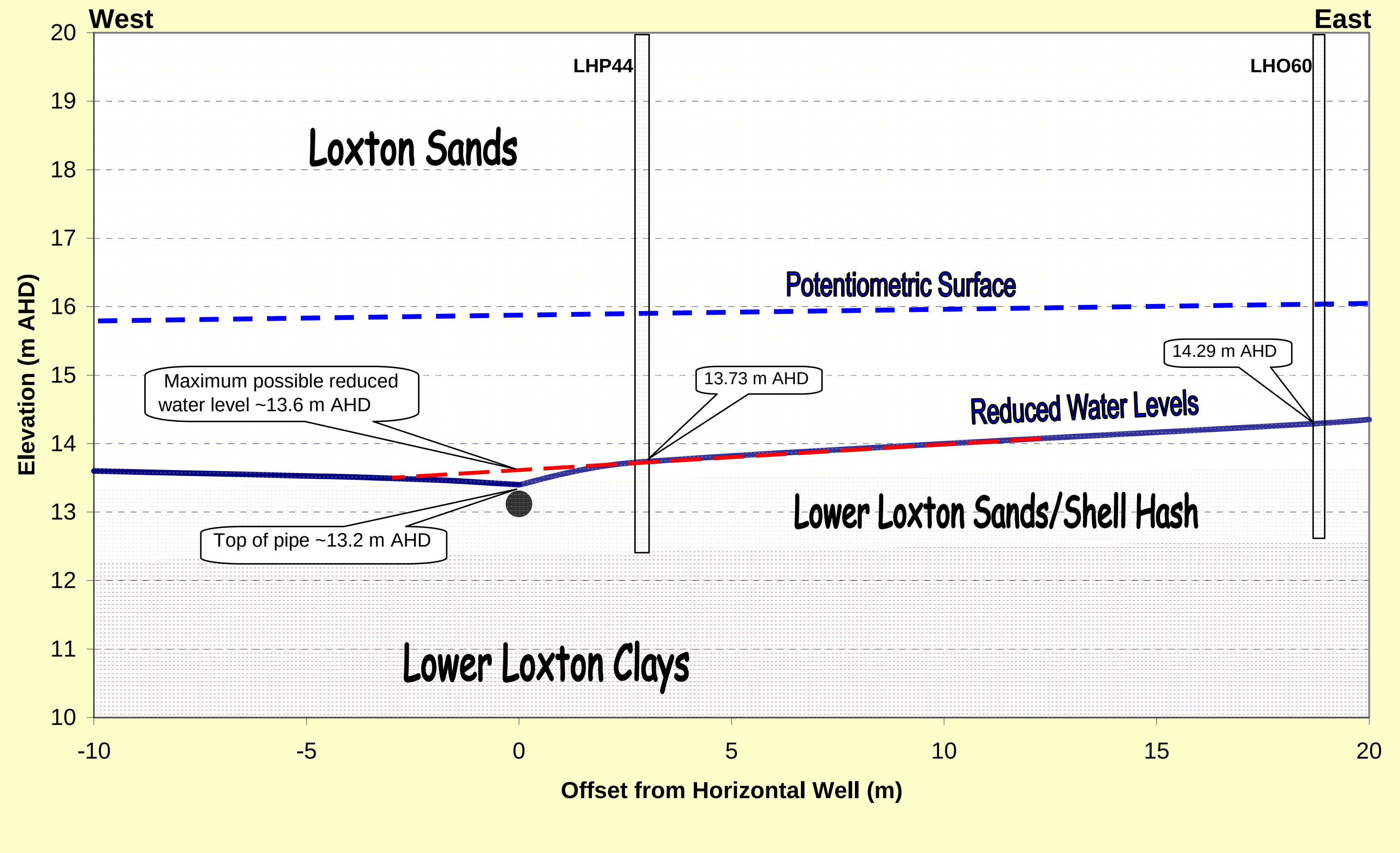


Figure 13. Reduced groundwater level in observation well LHP44 in relation to top of outer product pipe

Figure 14. Tree roots recovered by well-sock on 19 July 2007

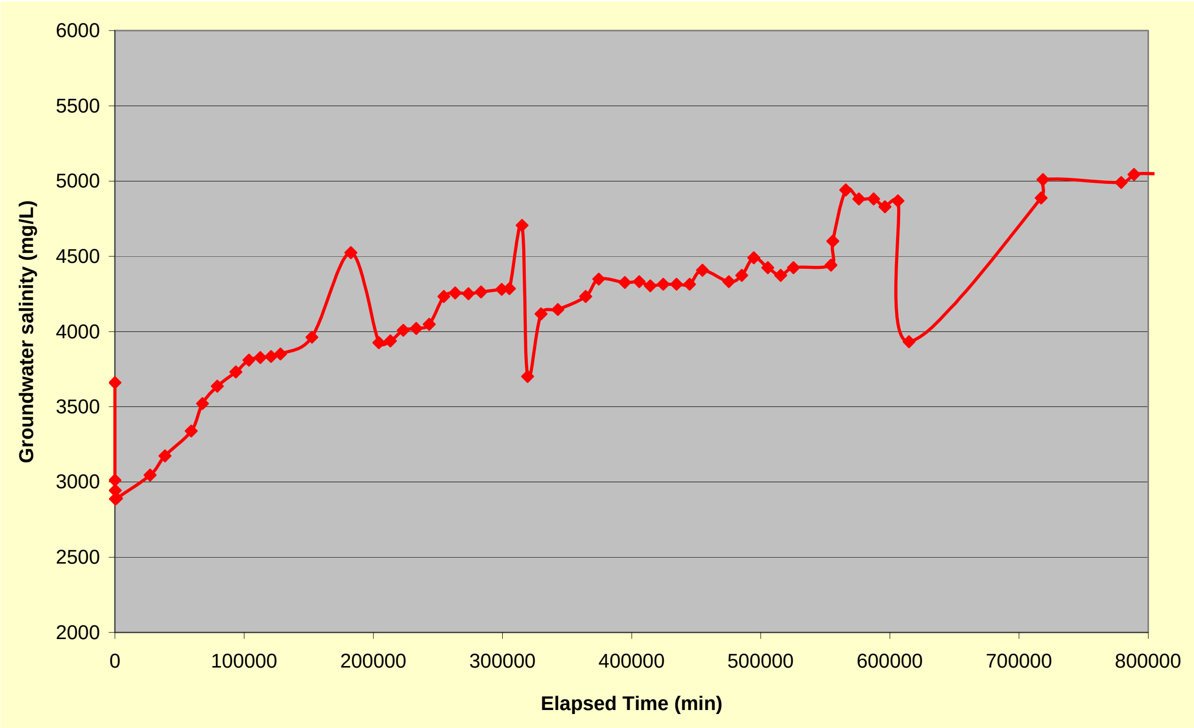
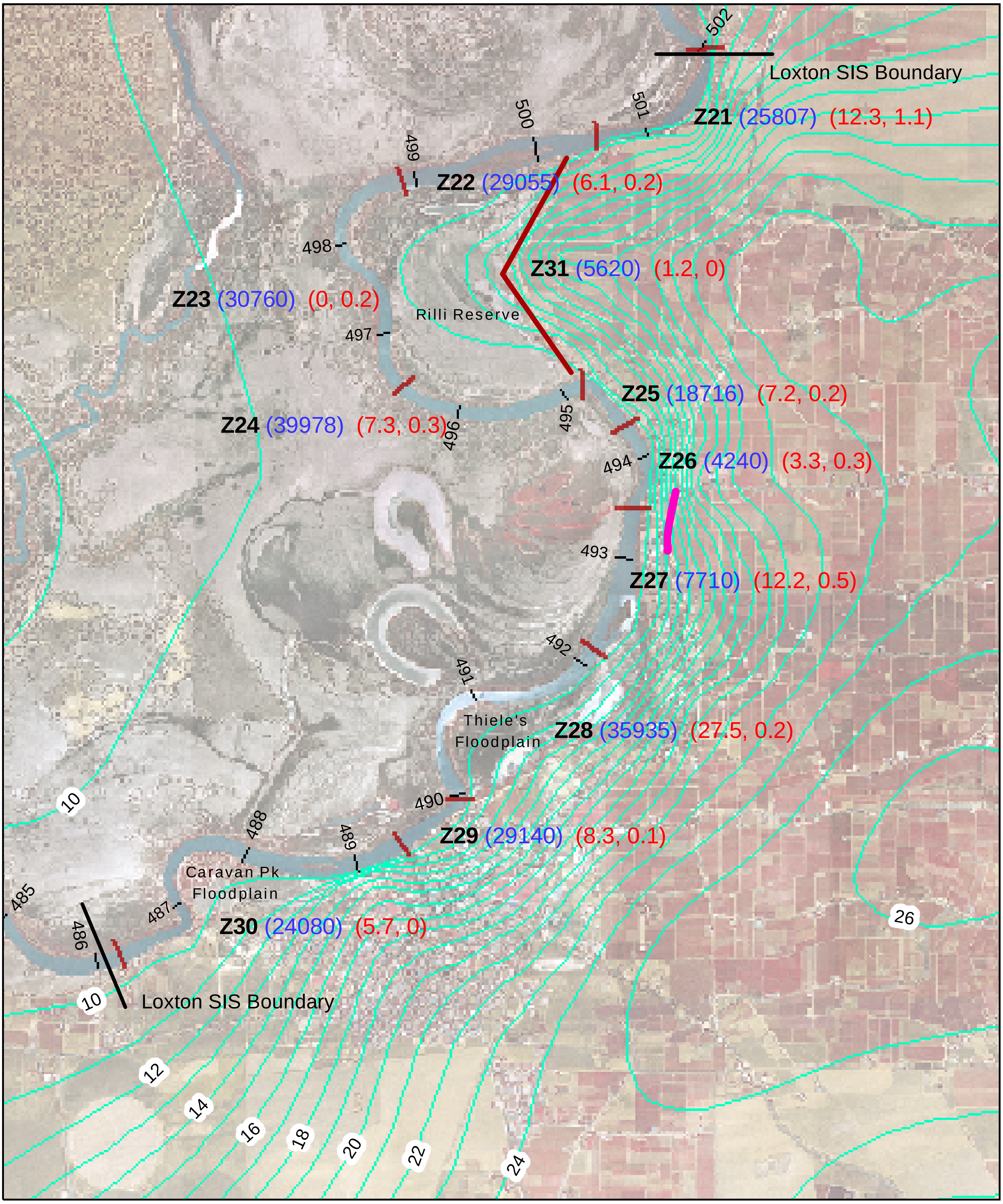


Figure 15. Long-term pumping test groundwater salinity



Trial horizontal drainage well

Potentiometric Surface, May 2004 (mAHD)

Loxton 2004 model budget zone boundary

(25000) Groundwater salinity applied to model zones (mg/L)

(5.0, 1) Modelled salt load (tonnes/day) Lateral, Vertical

Roads

River Kilometre

0 0.5 1 2 km

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Figure 16. Regional groundwater model flow budget zones and salt loads

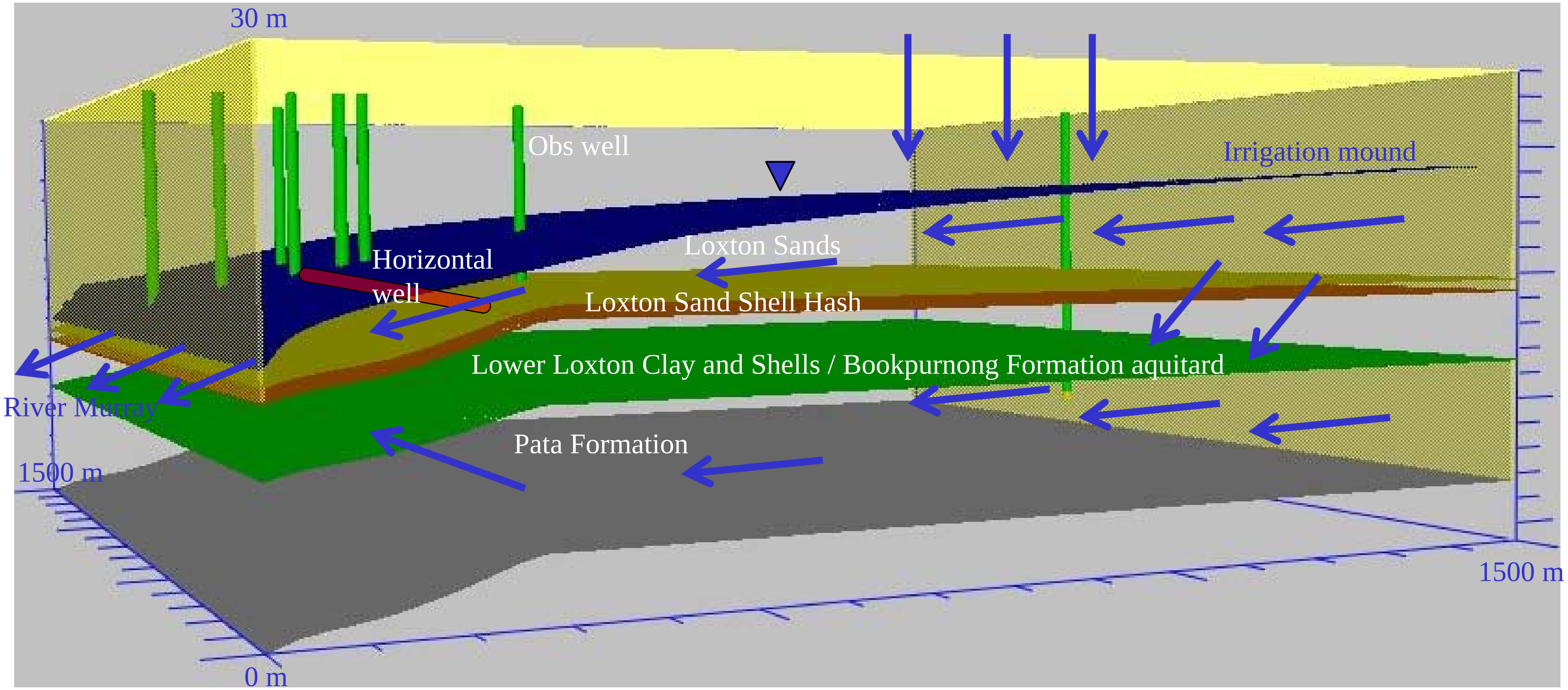

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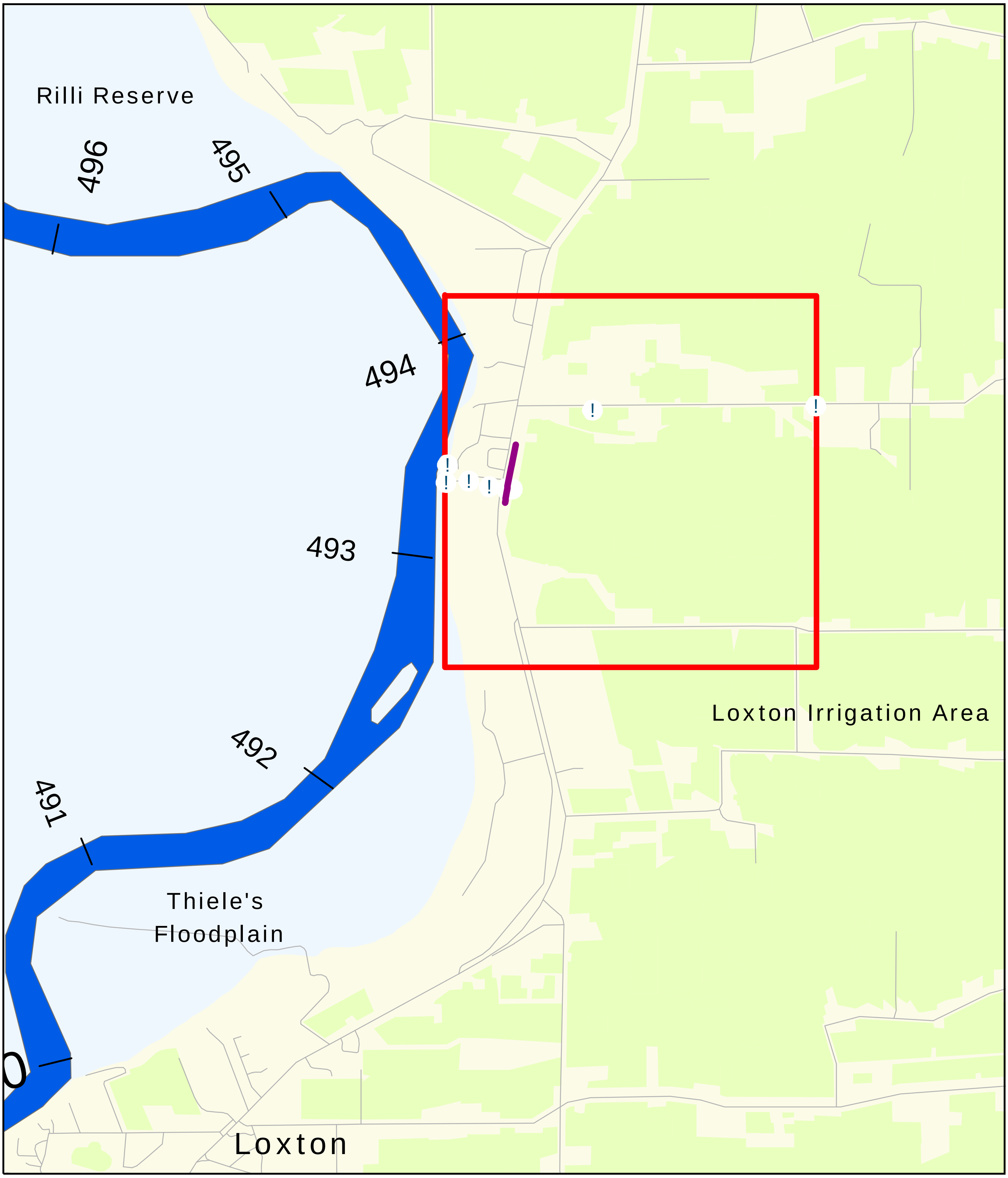
Figure 17. Conceptual hydrogeological model



! Observation well
Loxton trial horizontal well
River Murray
Roads
River Kilometre
Model domain
Floodplain
Irrigated area 2001

0 0.2 0.4 0.8 km

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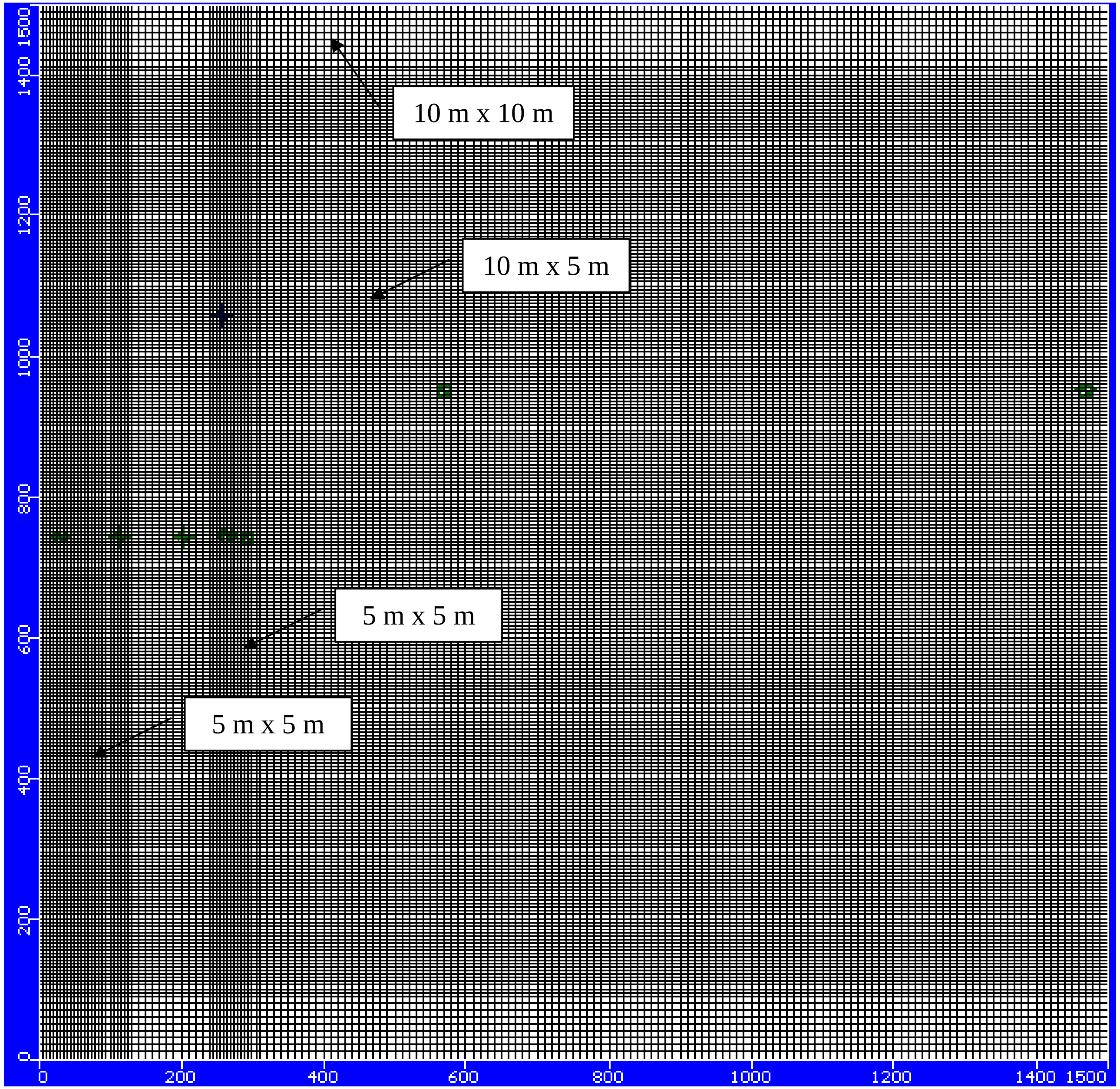
Datum: GDA94
Map Projection: MGA Zone 54

Figure 18. Model domain



Model grids

N

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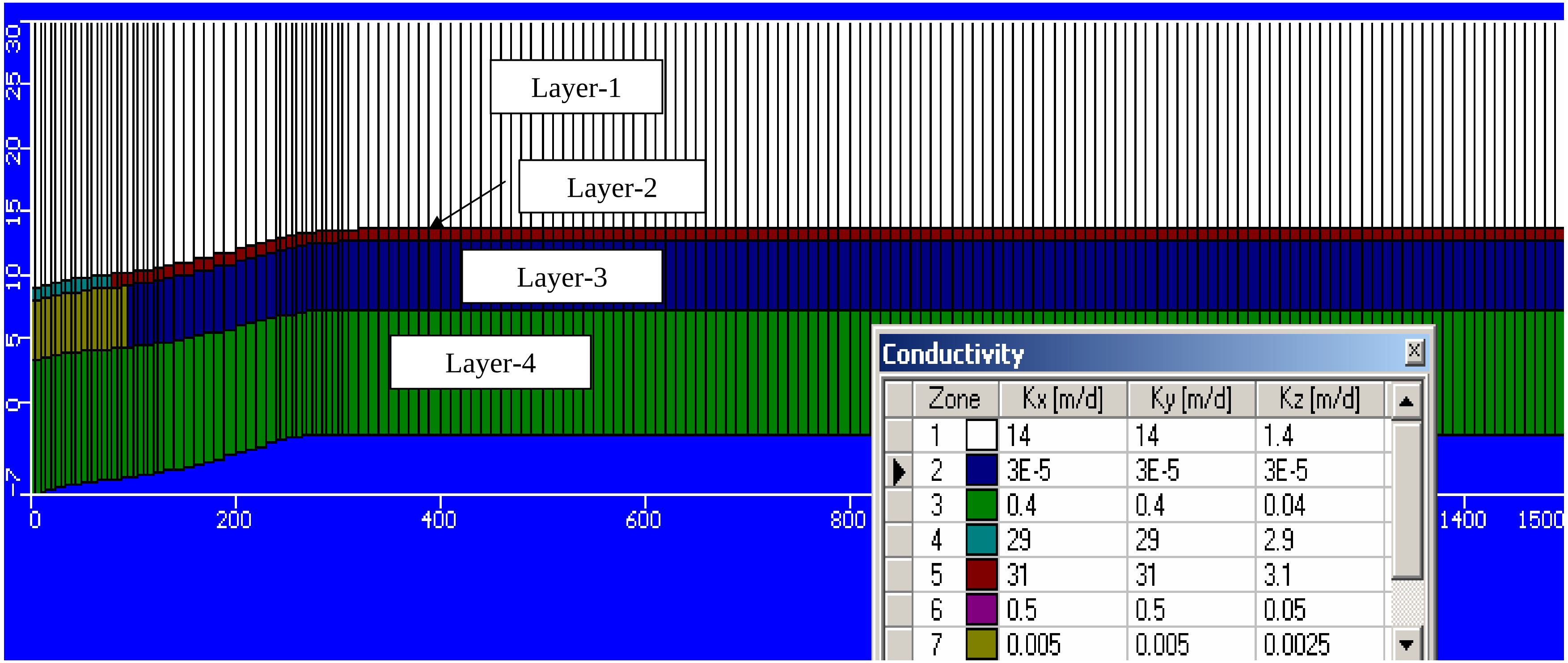
Figure 19. Model grids



Layer-1	-	Loxton Sands and Monoman Formation
Layer-2	-	Loxton Sand Shell Hash
Layer-3	-	Lower Loxton Clay and Shells and Bookpurnong Formation
Layer-4	-	Pata Formation

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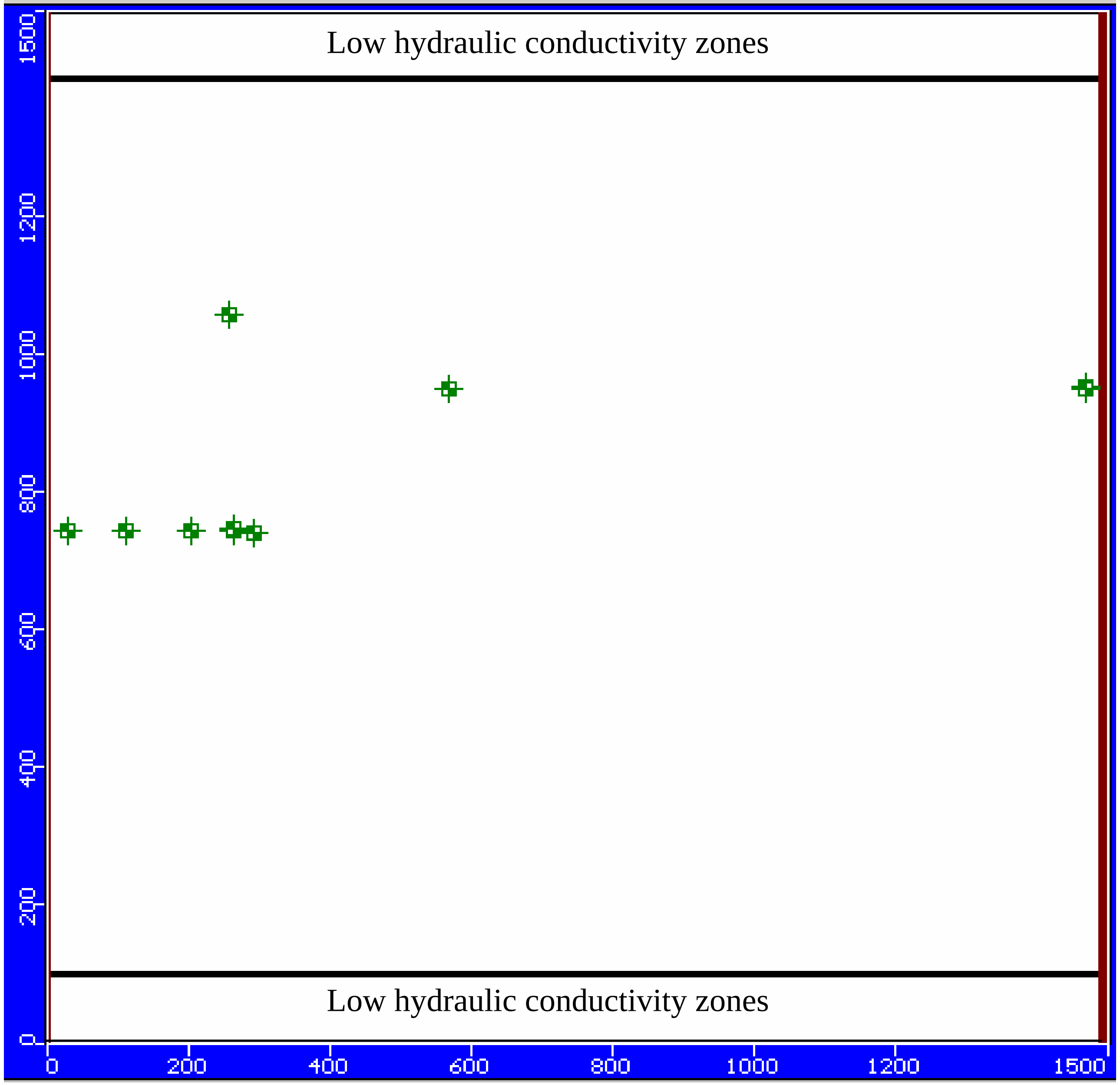
Figure 20. Model cross section showing hydraulic conductivity



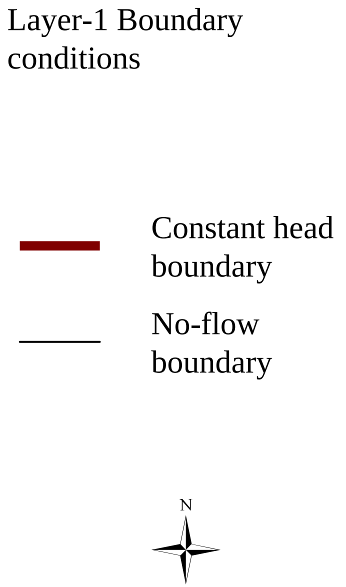


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Figure 21. Layer-1 boundary conditions

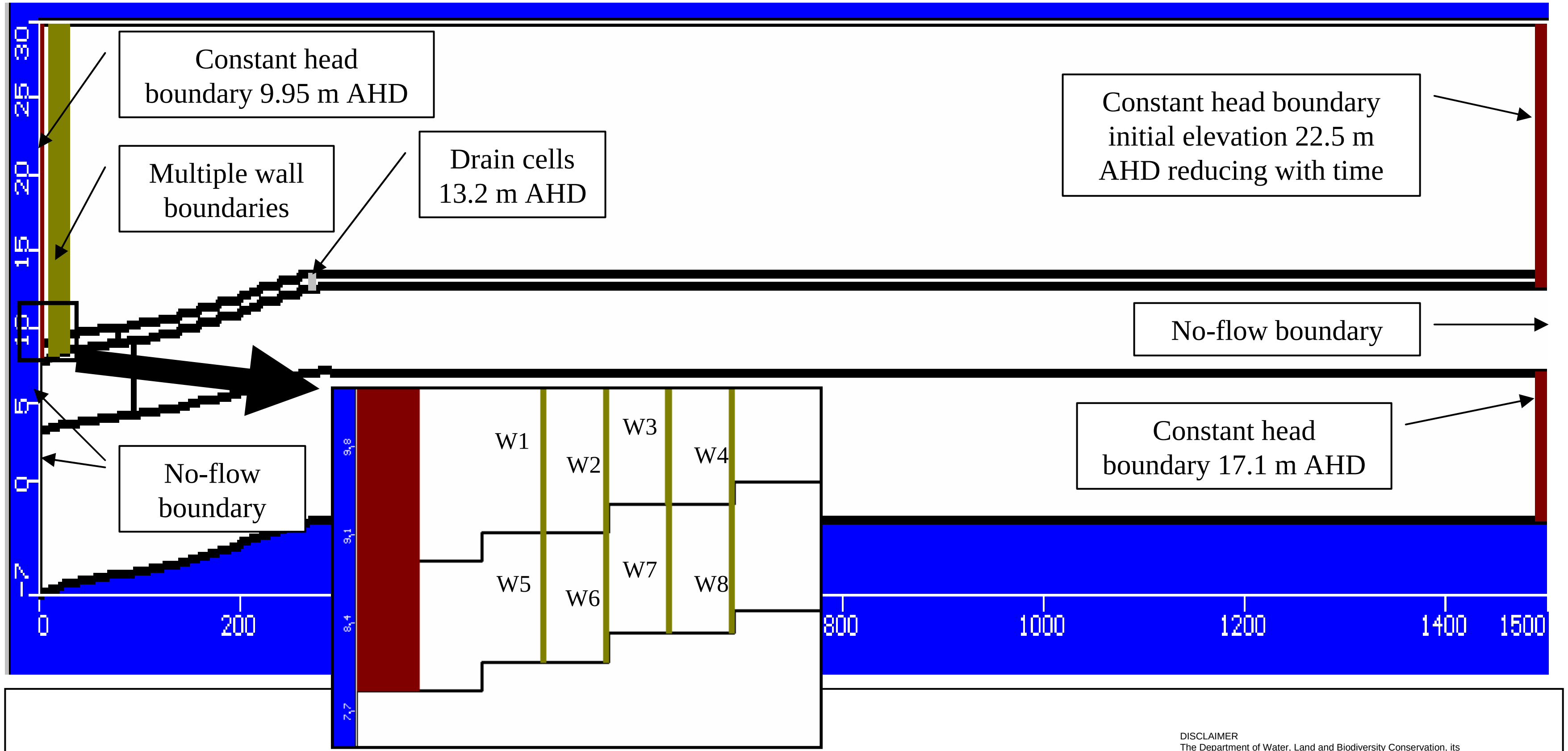

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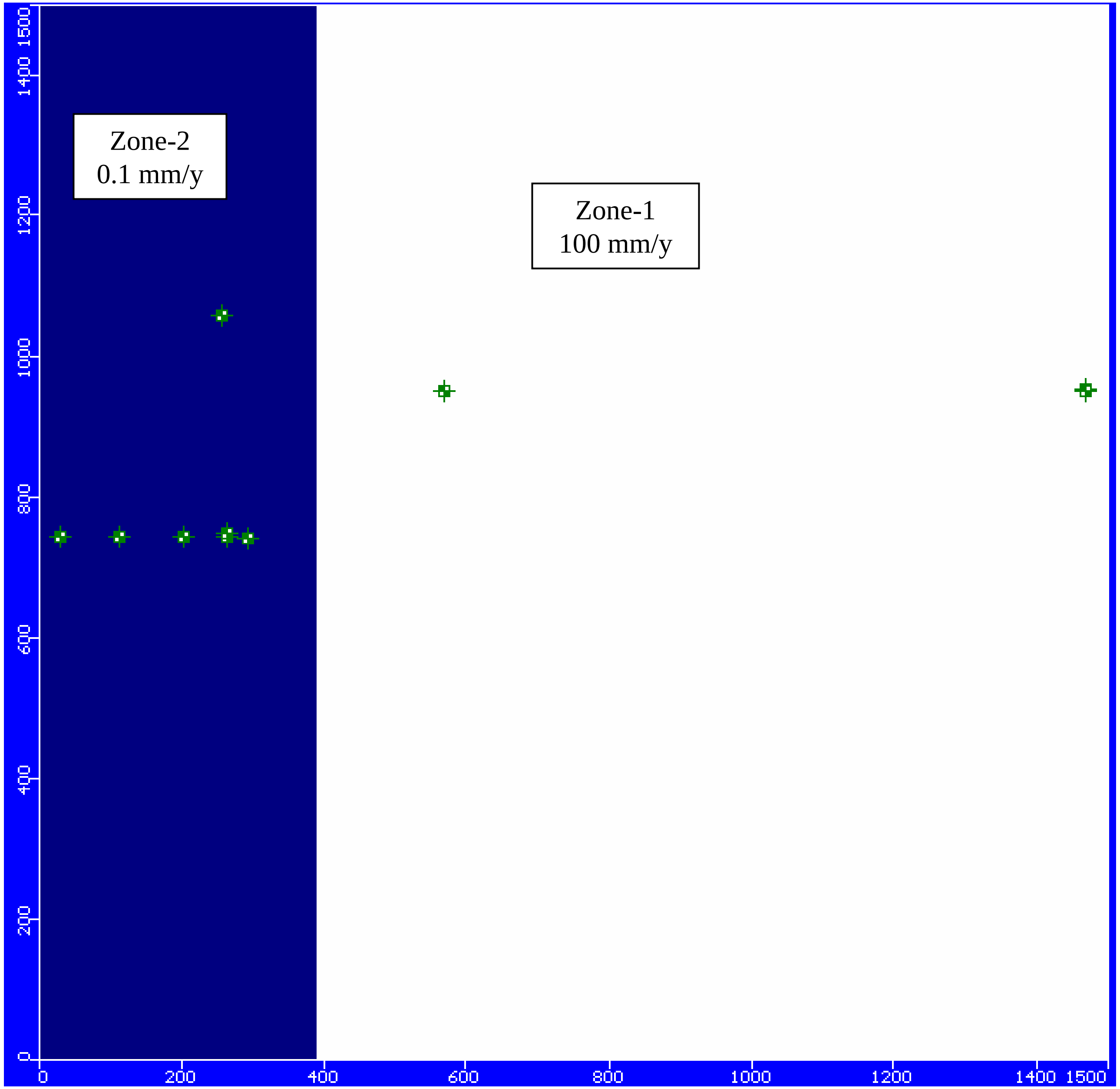
Figure 22. Model boundary conditions



Layer-1 recharge zones

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Figure 23. Layer-1 recharge zones

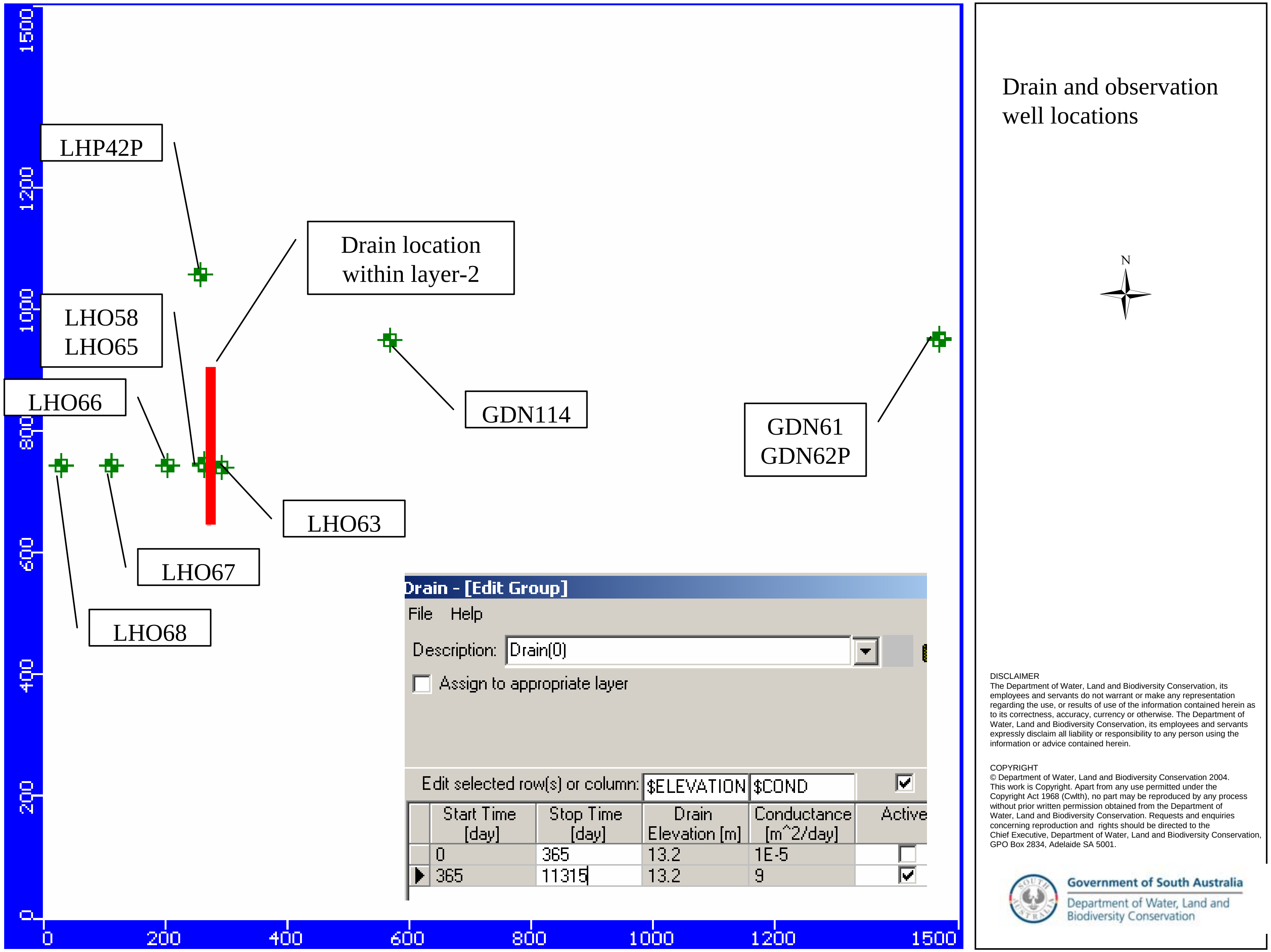


Figure 24. **Location of 250 m horizontal drainage well and observation wells**

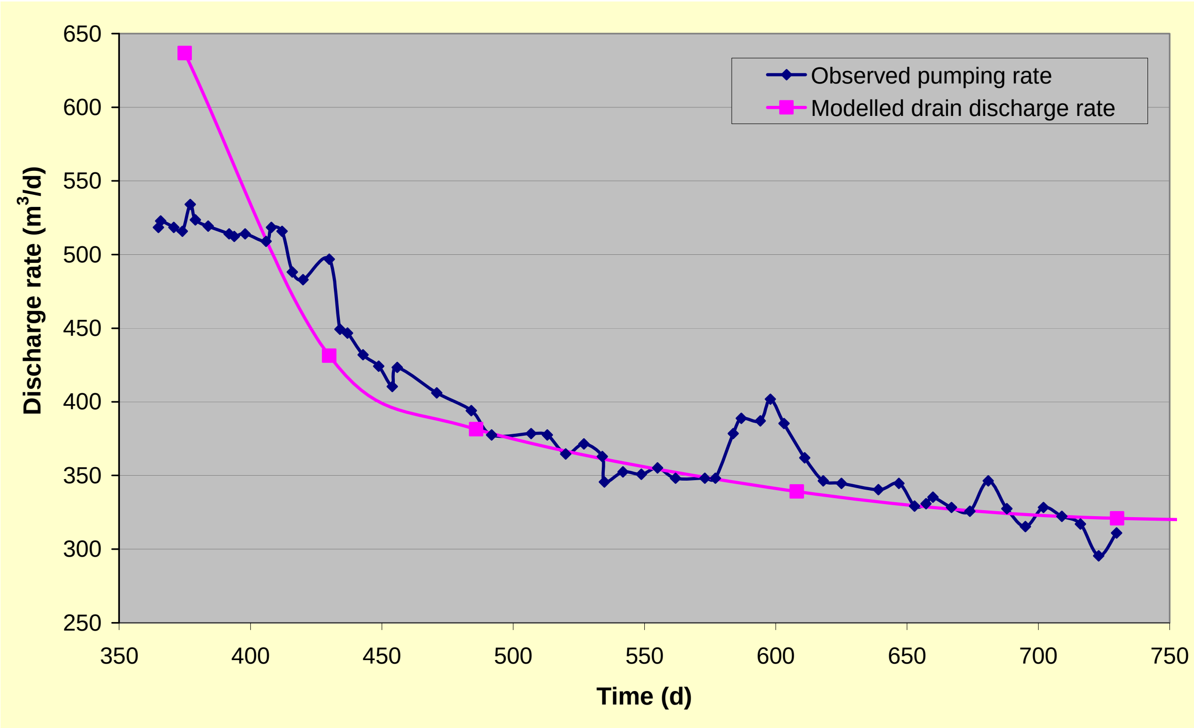
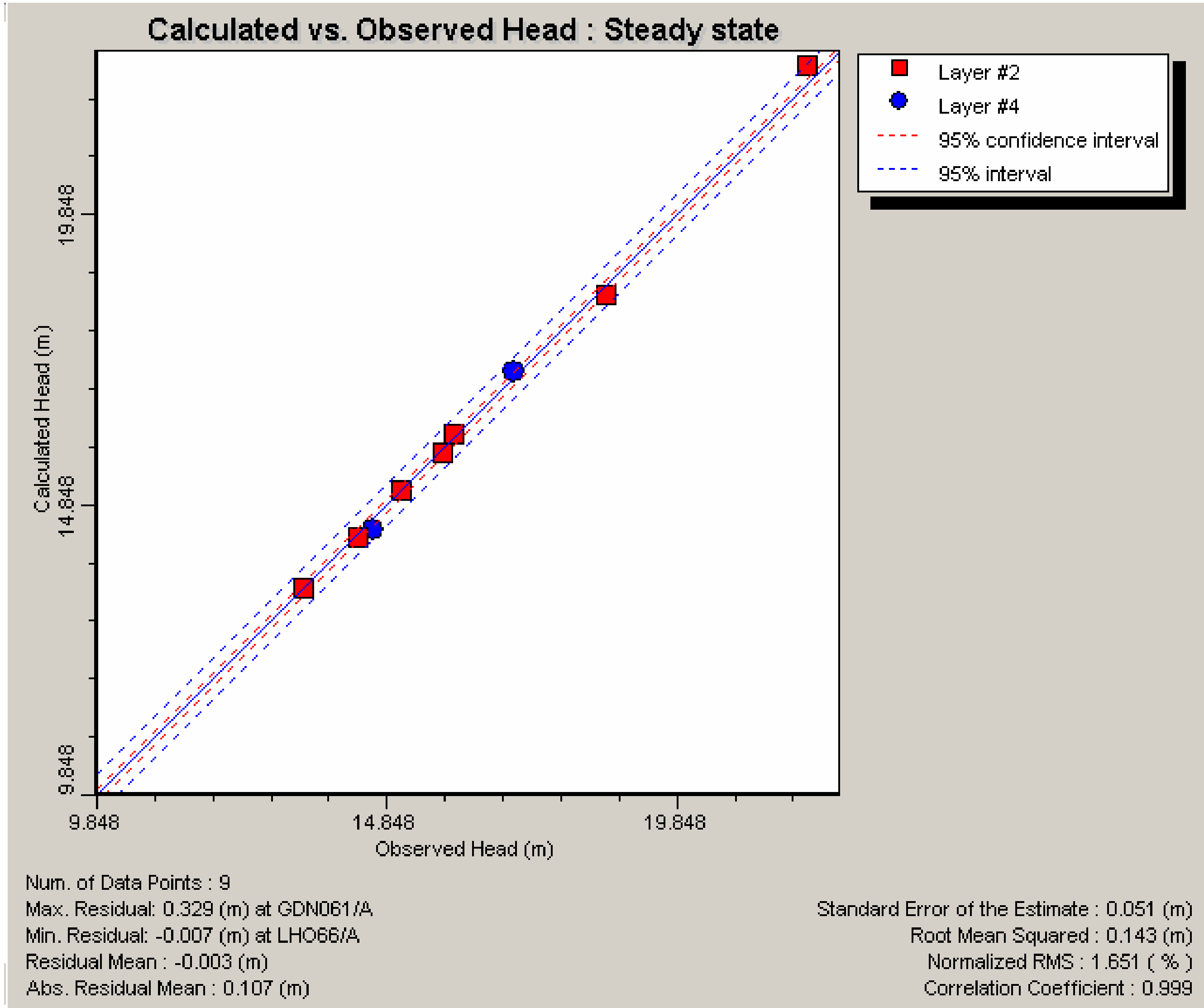


Figure 25. Scenario-2a modelled drain discharge rate vs observed pumping rate



Steady state model root mean square calibration results

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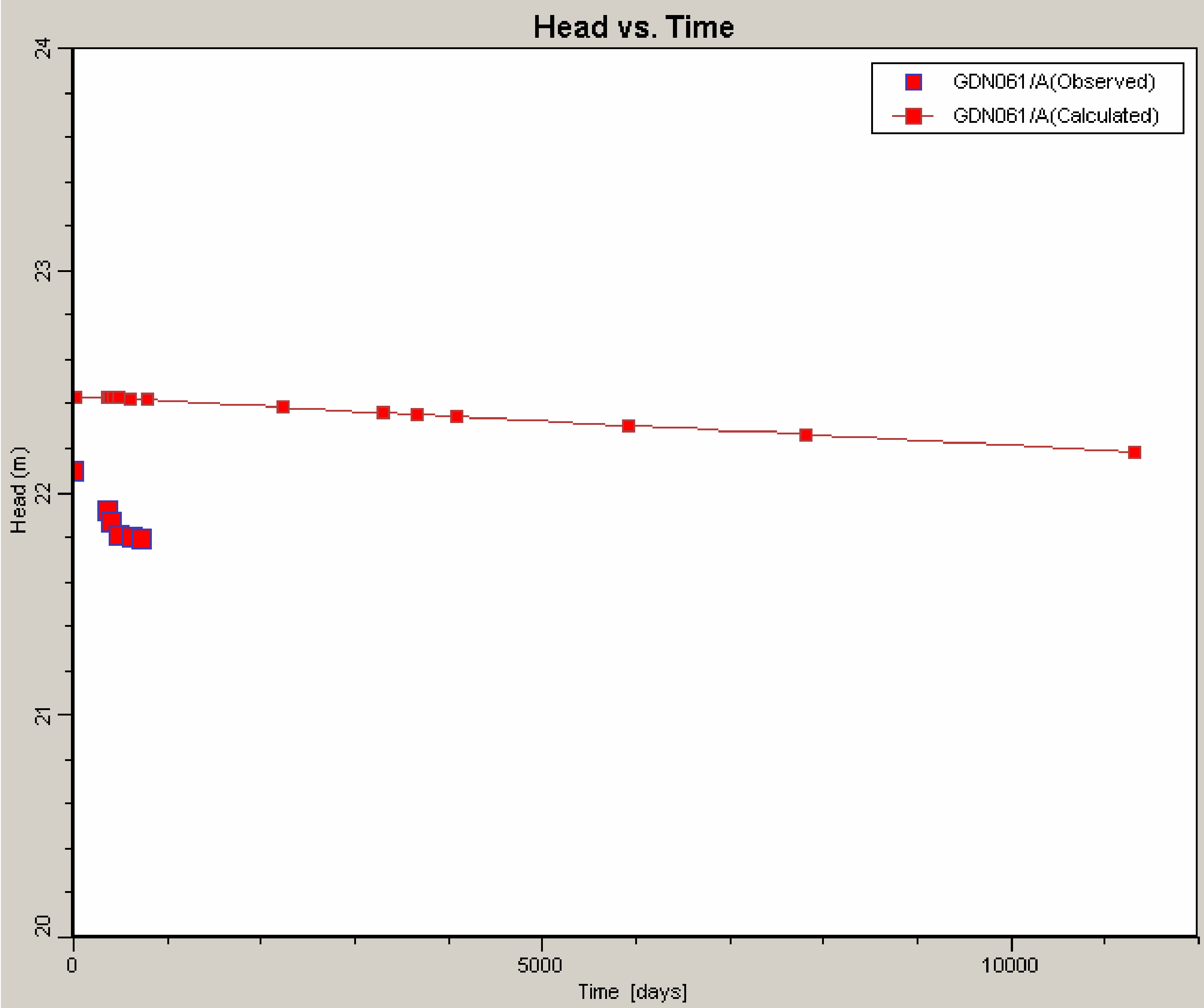
Figure 26. Steady state model root mean square calibration results



Modelled and observed potentiometric heads (m AHD)

-Observation well GDN61

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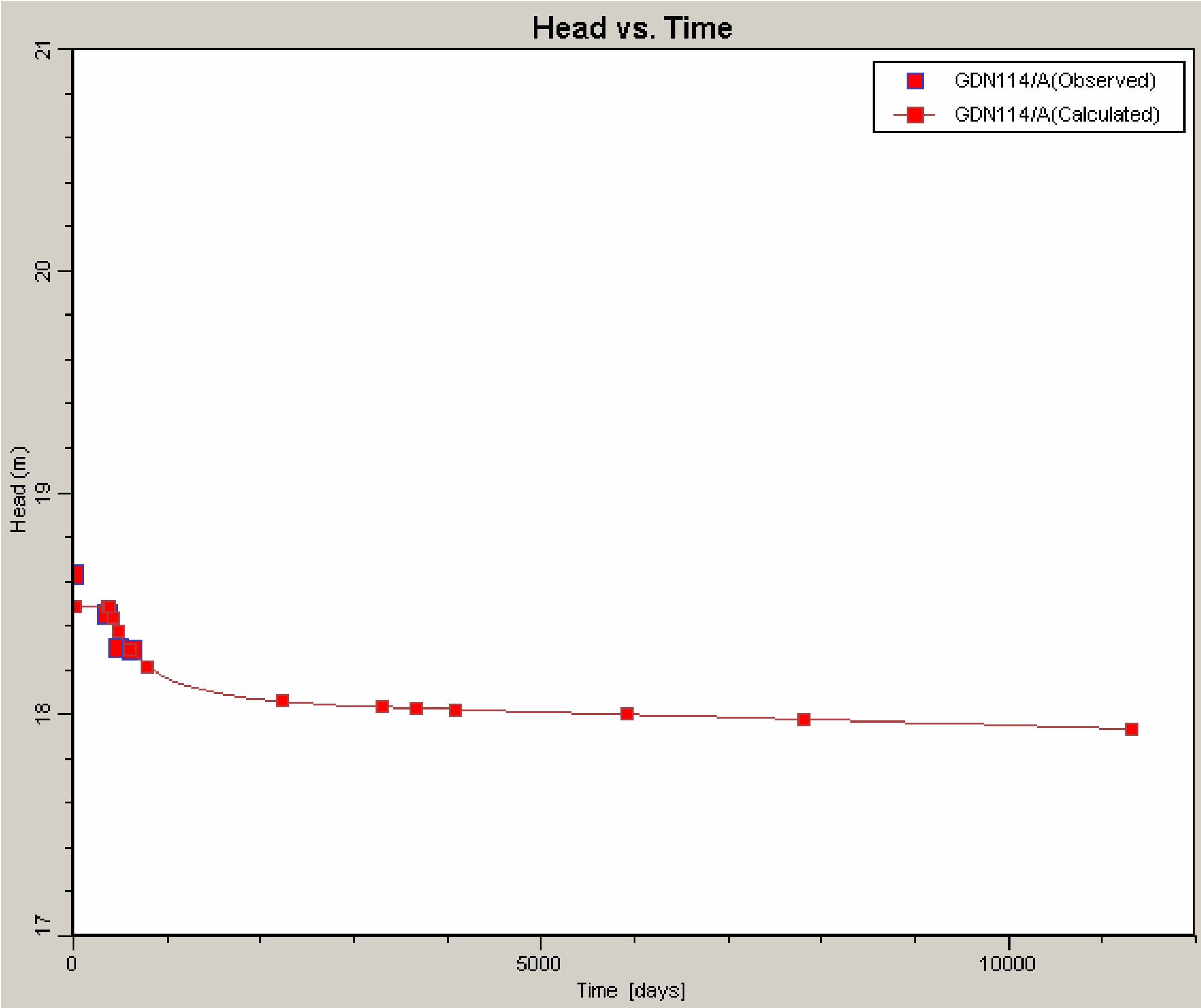
Figure 27. Modelled and observed potentiometric heads (Observation well GDN61)



Modelled and observed potentiometric heads (m AHD)

-Observation well GDN114

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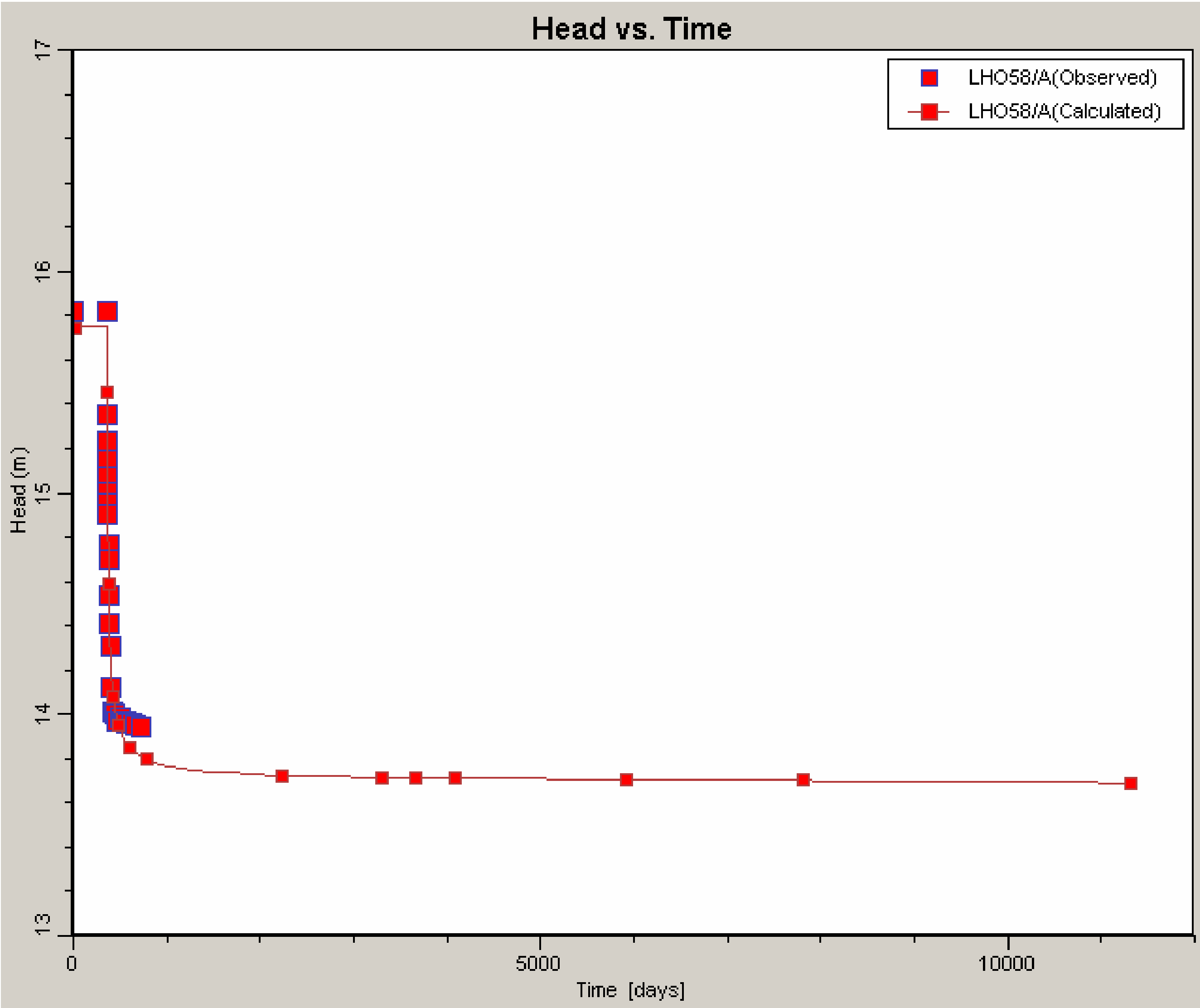
Figure 28. Modelled and observed potentiometric heads (Observation well GDN114)



Modelled and observed potentiometric heads (m AHD)

-Observation well LHO58

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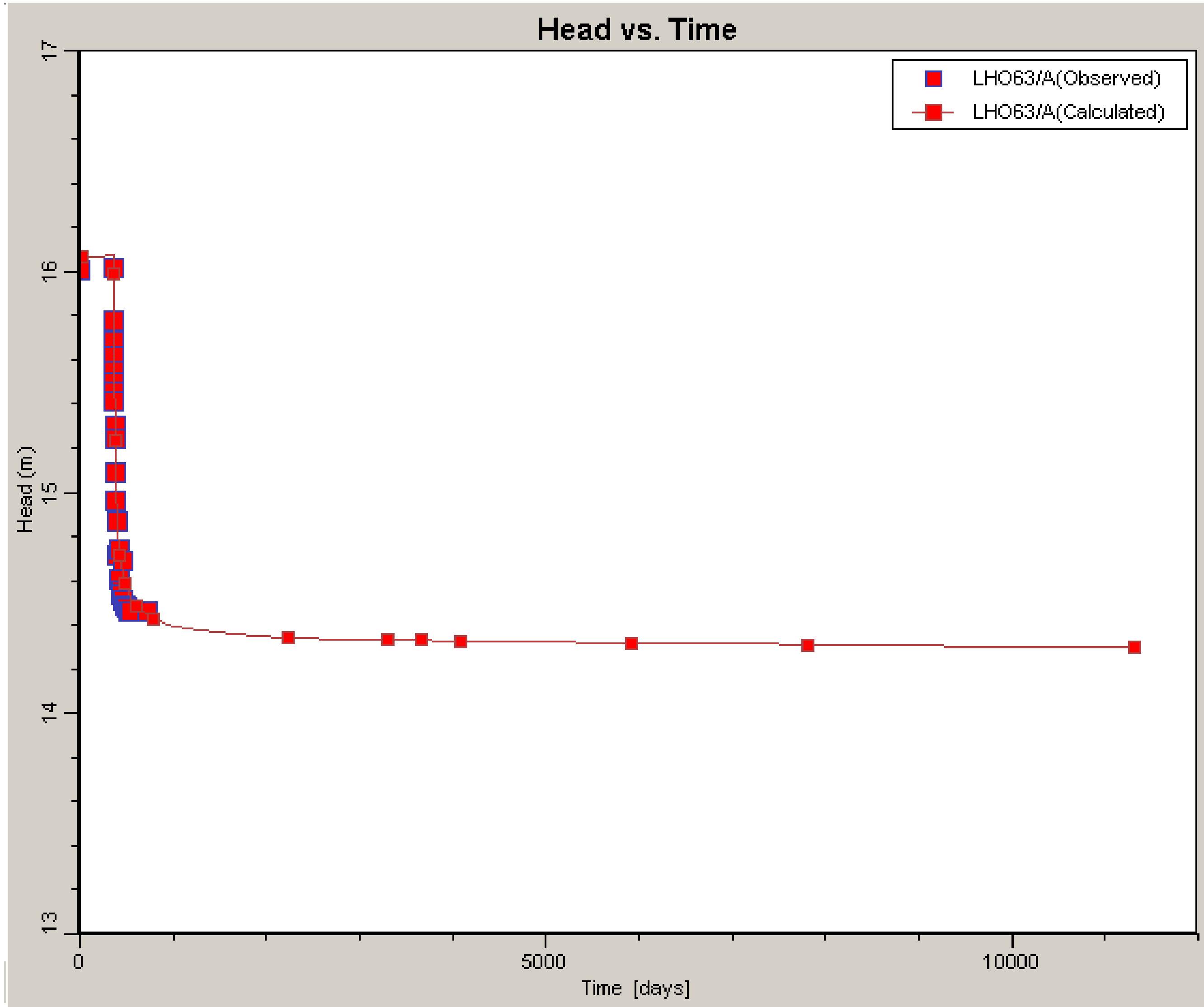
Figure 29. Modelled and observed potentiometric heads (Observation well LHO58)



Modelled and observed potentiometric heads (m AHD)

-Observation well LHO63

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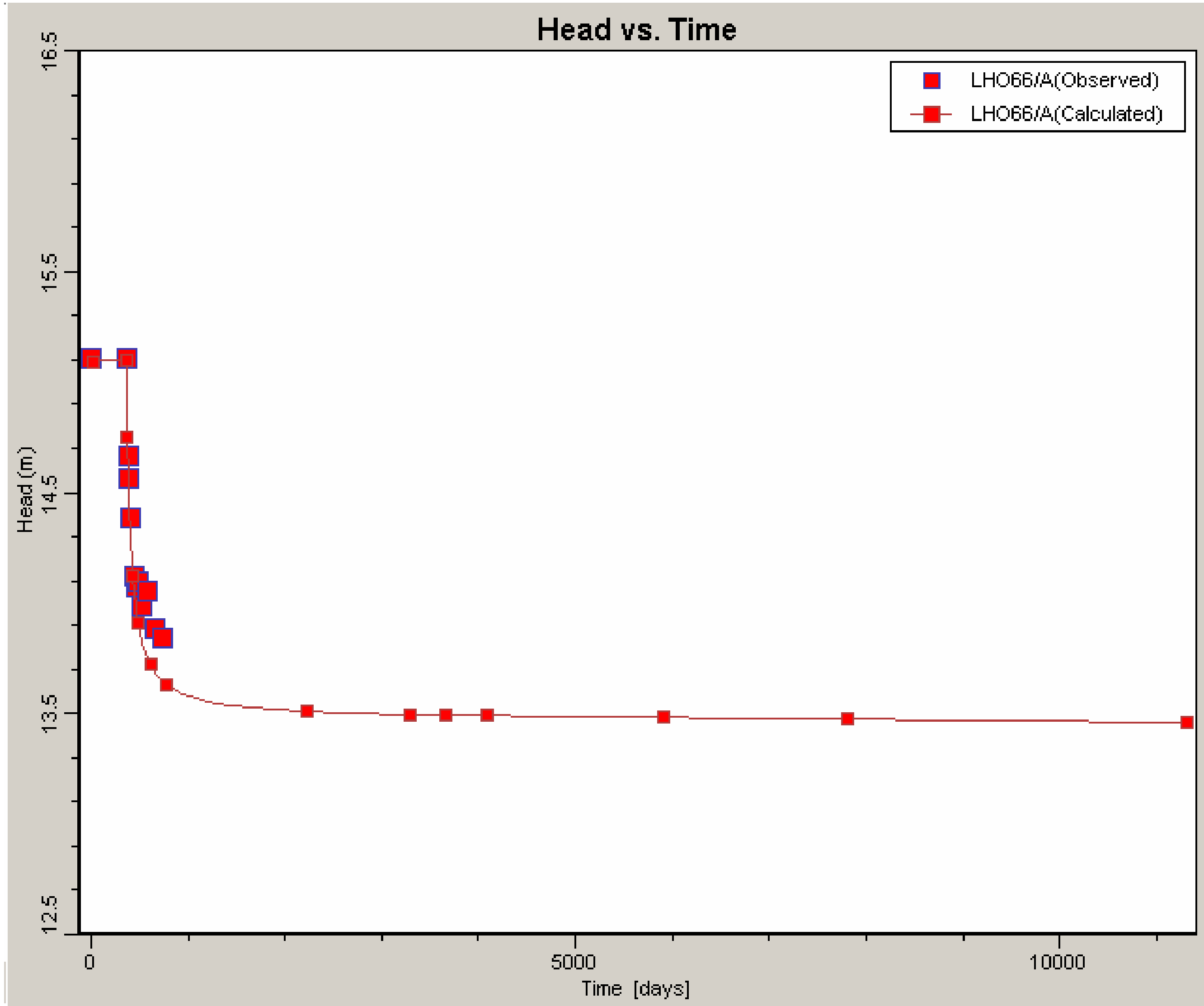
Figure 30. Modelled and observed potentiometric heads (Observation well LHO63)



Modelled and observed potentiometric heads (m AHD)

-Observation well LHO66

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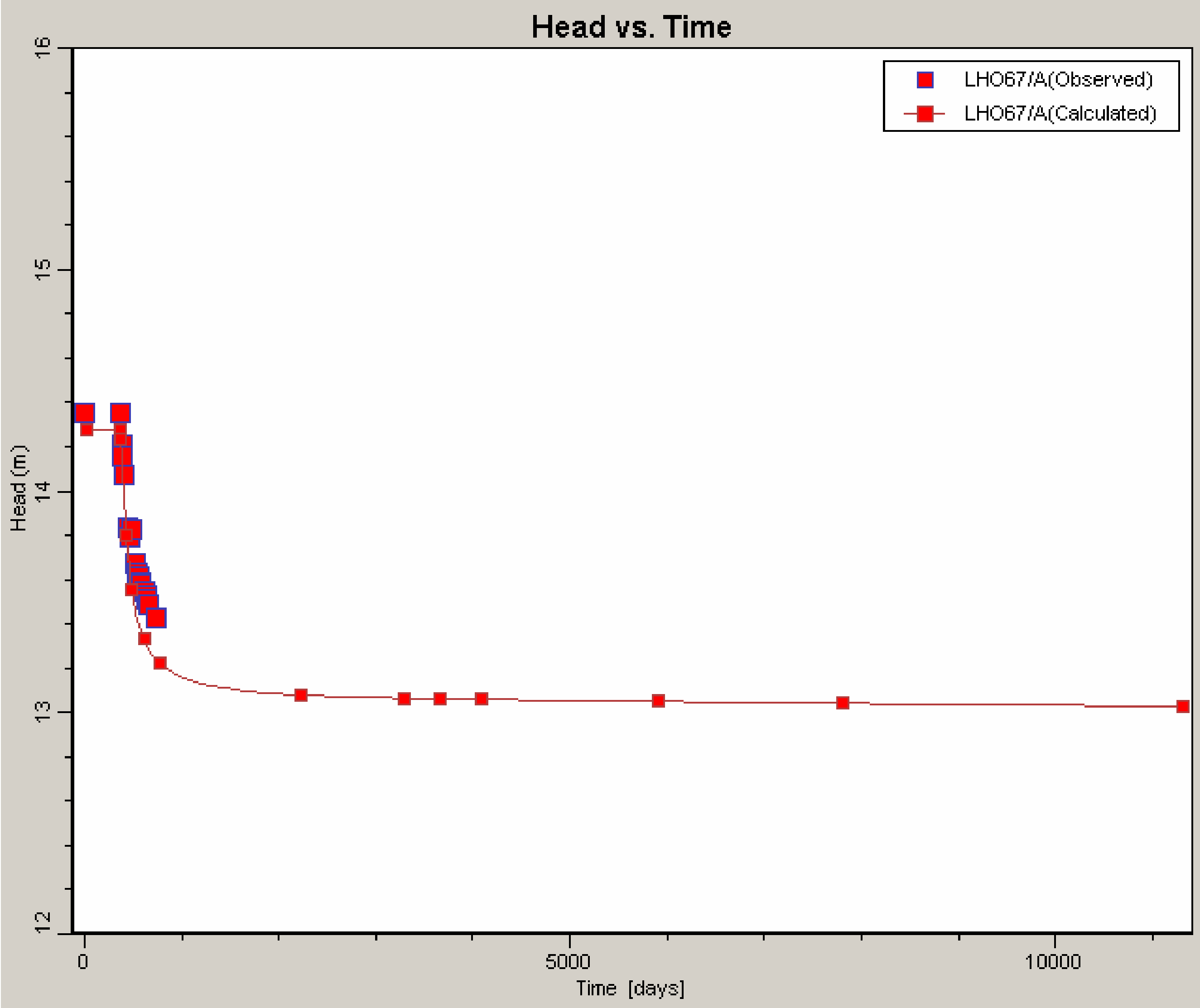
Figure 31. Modelled and observed potentiometric heads (Observation well LHO66)



Modelled and observed potentiometric heads (m AHD)

-Observation well LHO67

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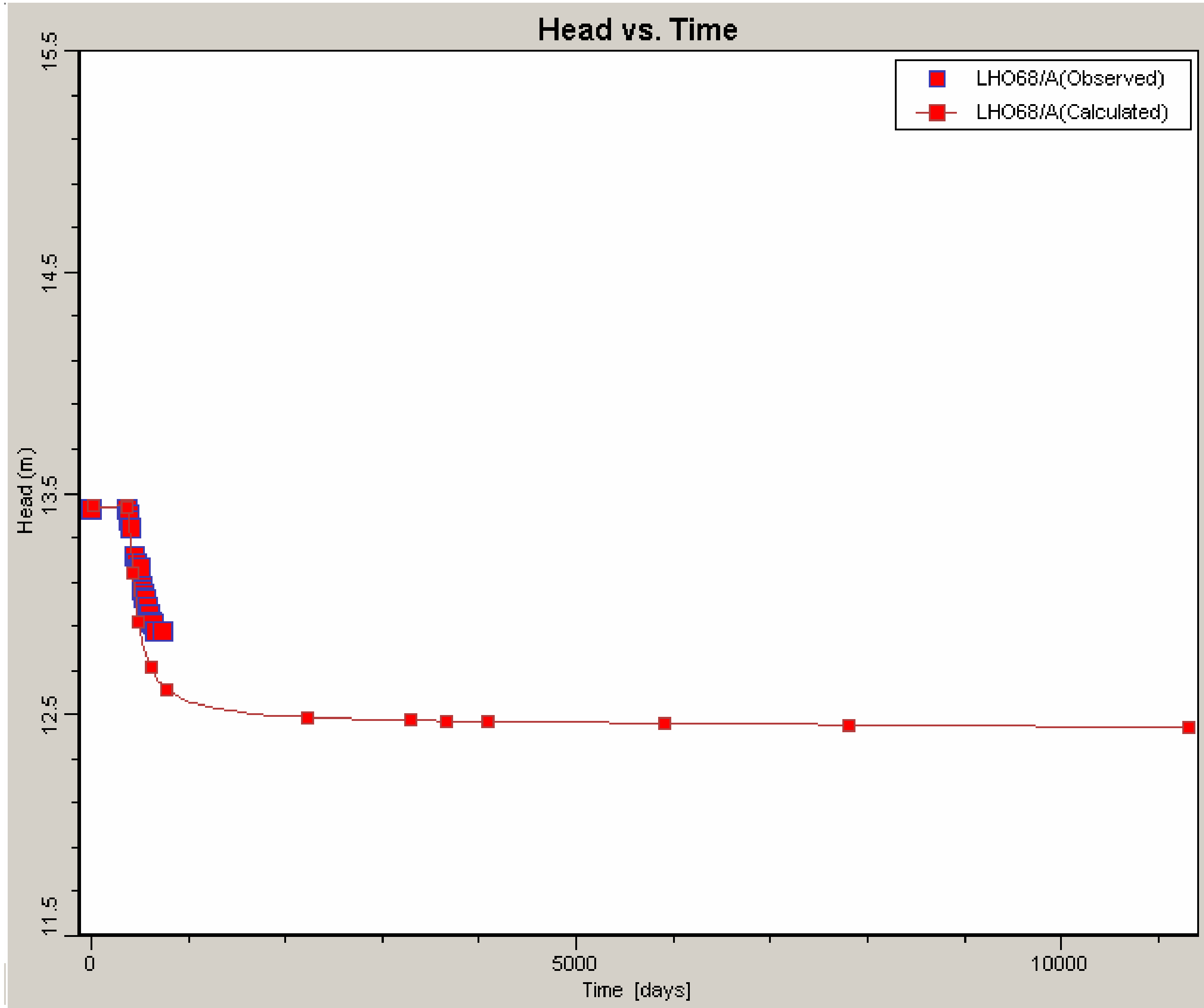
Figure 32. Modelled and observed potentiometric heads (Observation well LHO67)



Modelled and observed potentiometric heads (m AHD)

-Observation well LHO68

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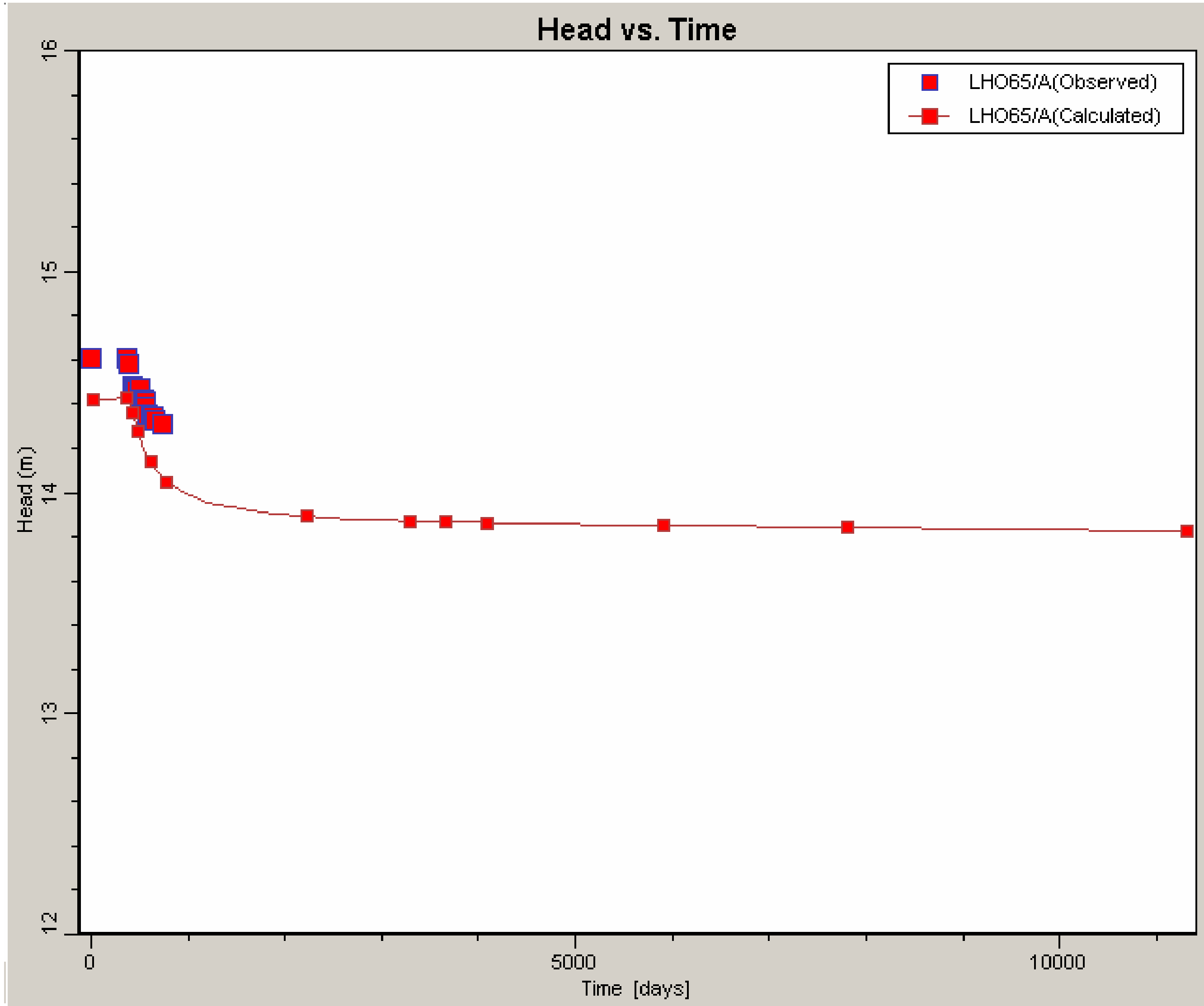
Figure 33. **Modelled and observed potentiometric heads (Observation well LHO68)**



Modelled and observed potentiometric heads (m AHD)

-Observation well LHO65

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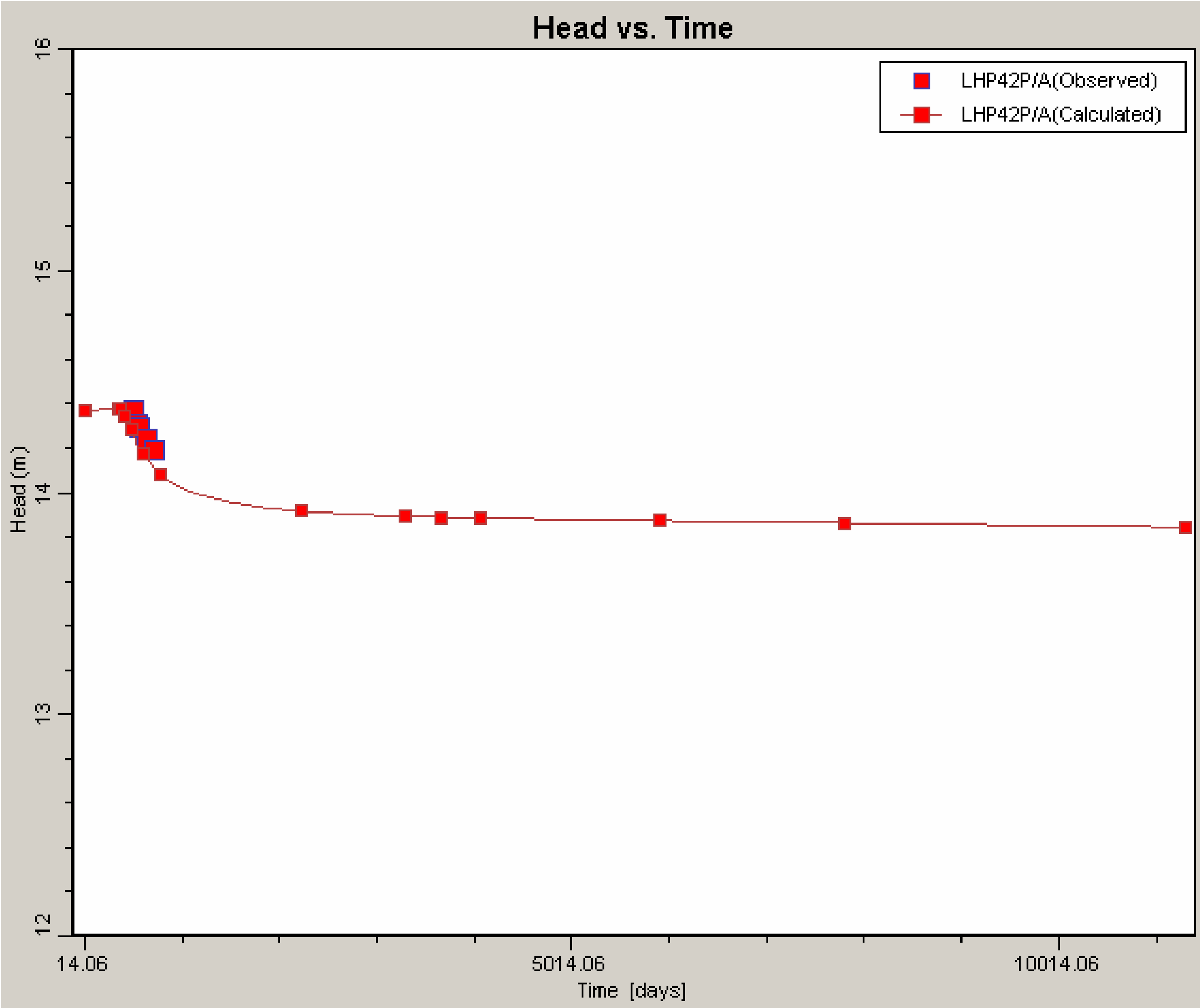
Figure 34. Modelled and observed potentiometric heads (Observation well LHO65)



Modelled and observed potentiometric heads (m AHD)

-Observation well LHP42P

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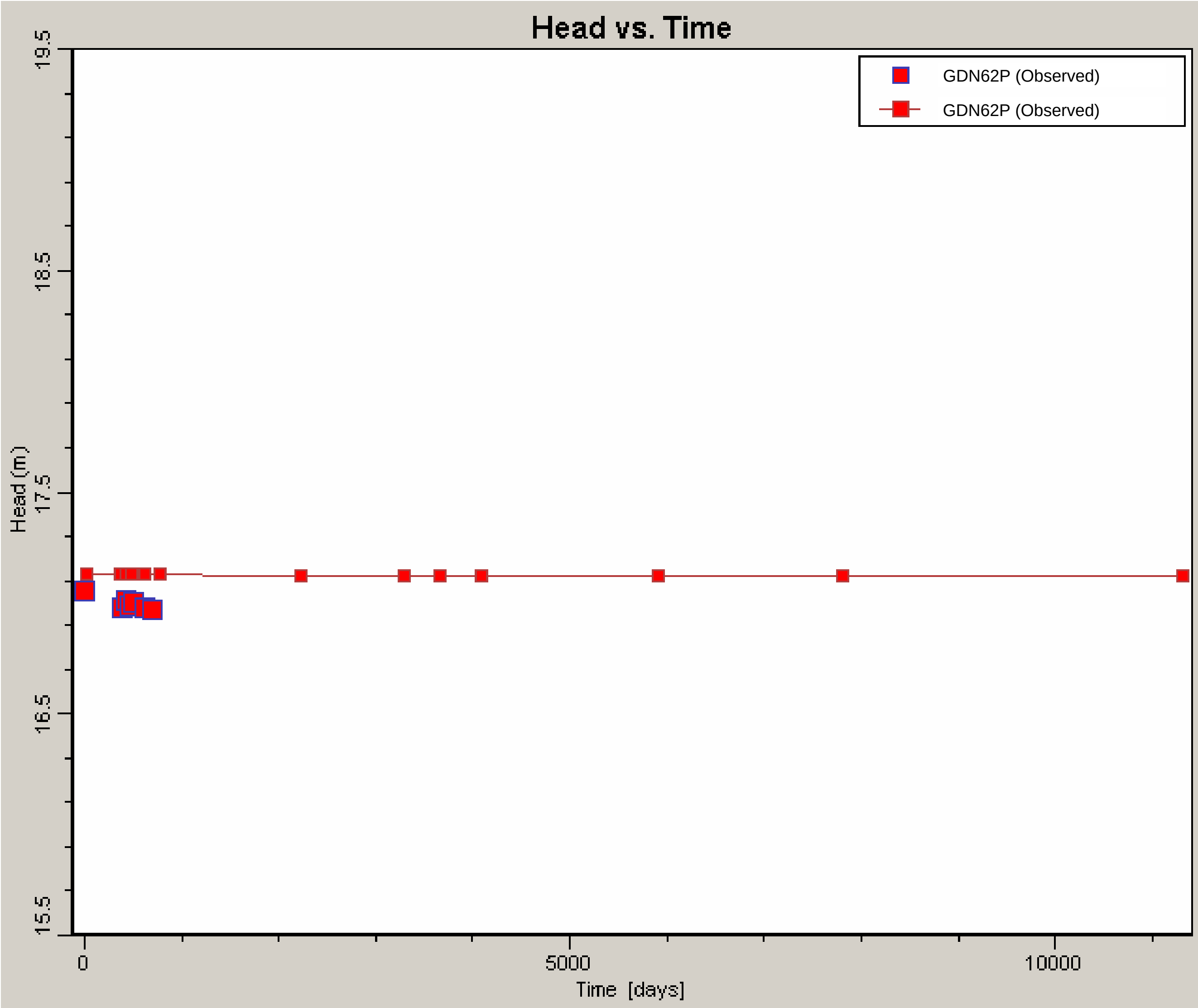
Figure 35. **Modelled and observed potentiometric heads (Observation well LHP42P)**



Modelled and observed potentiometric heads (m AHD)

-Observation well GDN62P

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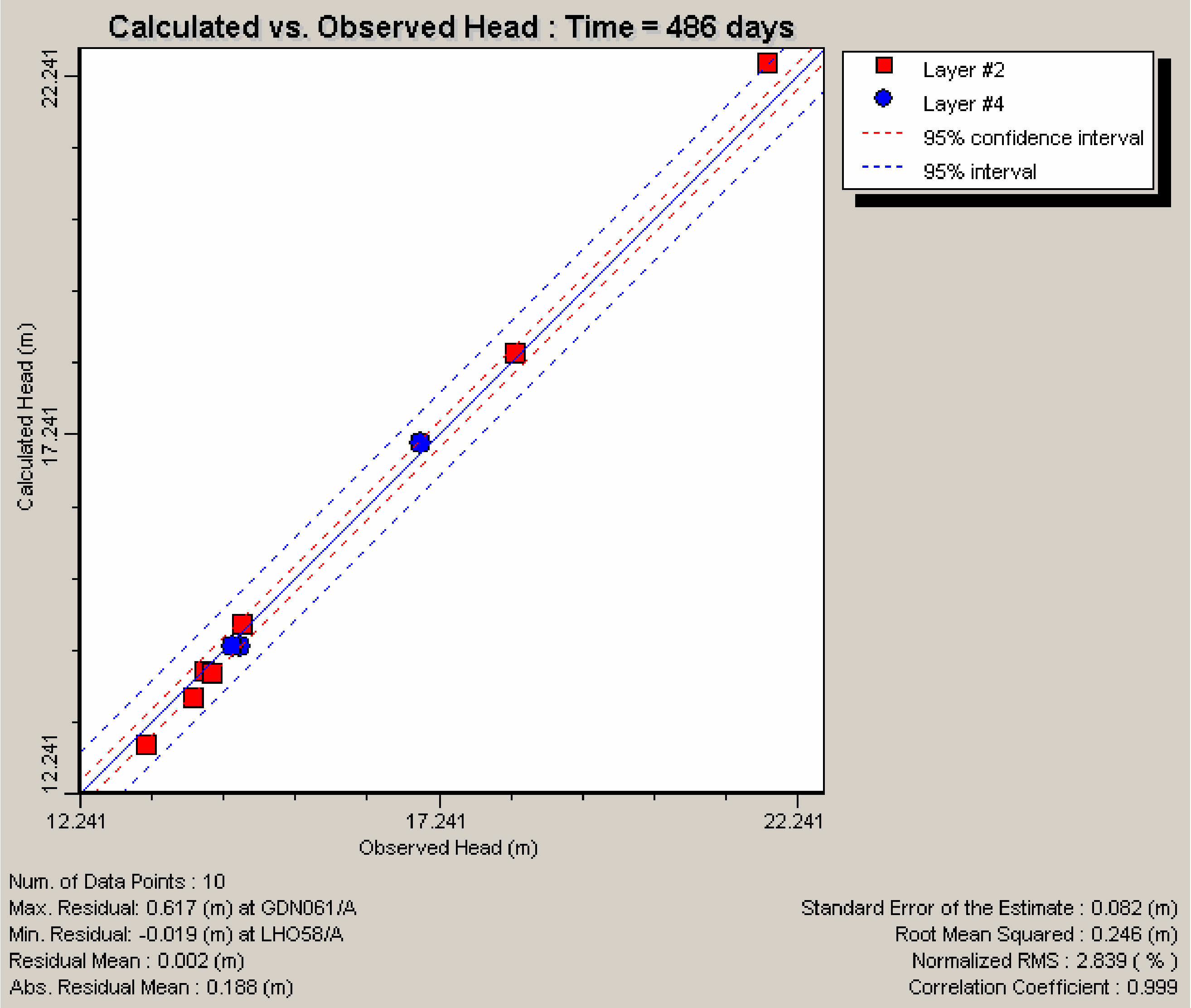
Figure 36. Modelled and observed potentiometric heads (Observation well GDN62P)



Transient model root mean square calibration results

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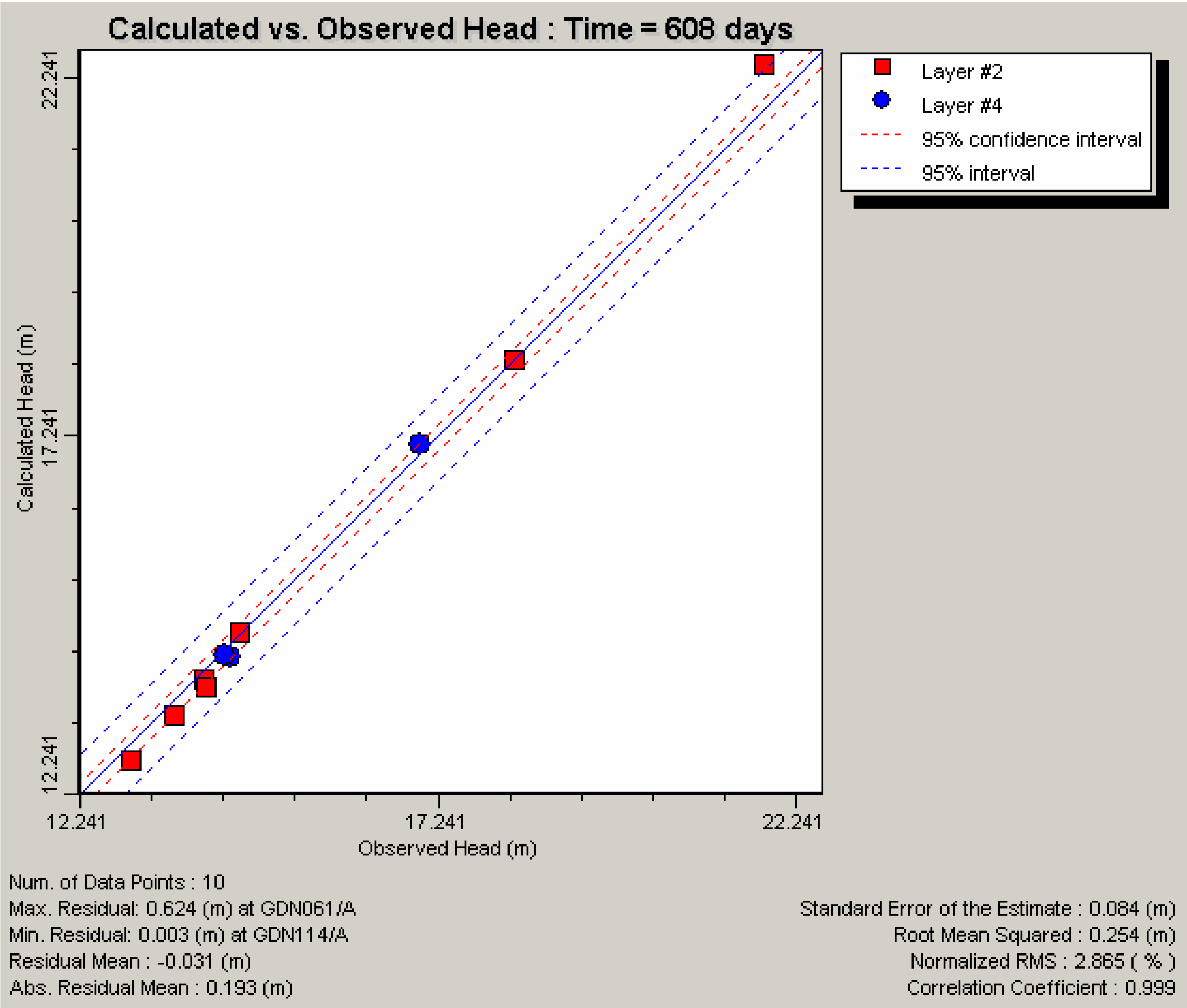
Figure 37. **Transient model root mean square calibration results after 121 days of drain operation**



Transient model root mean square calibration results

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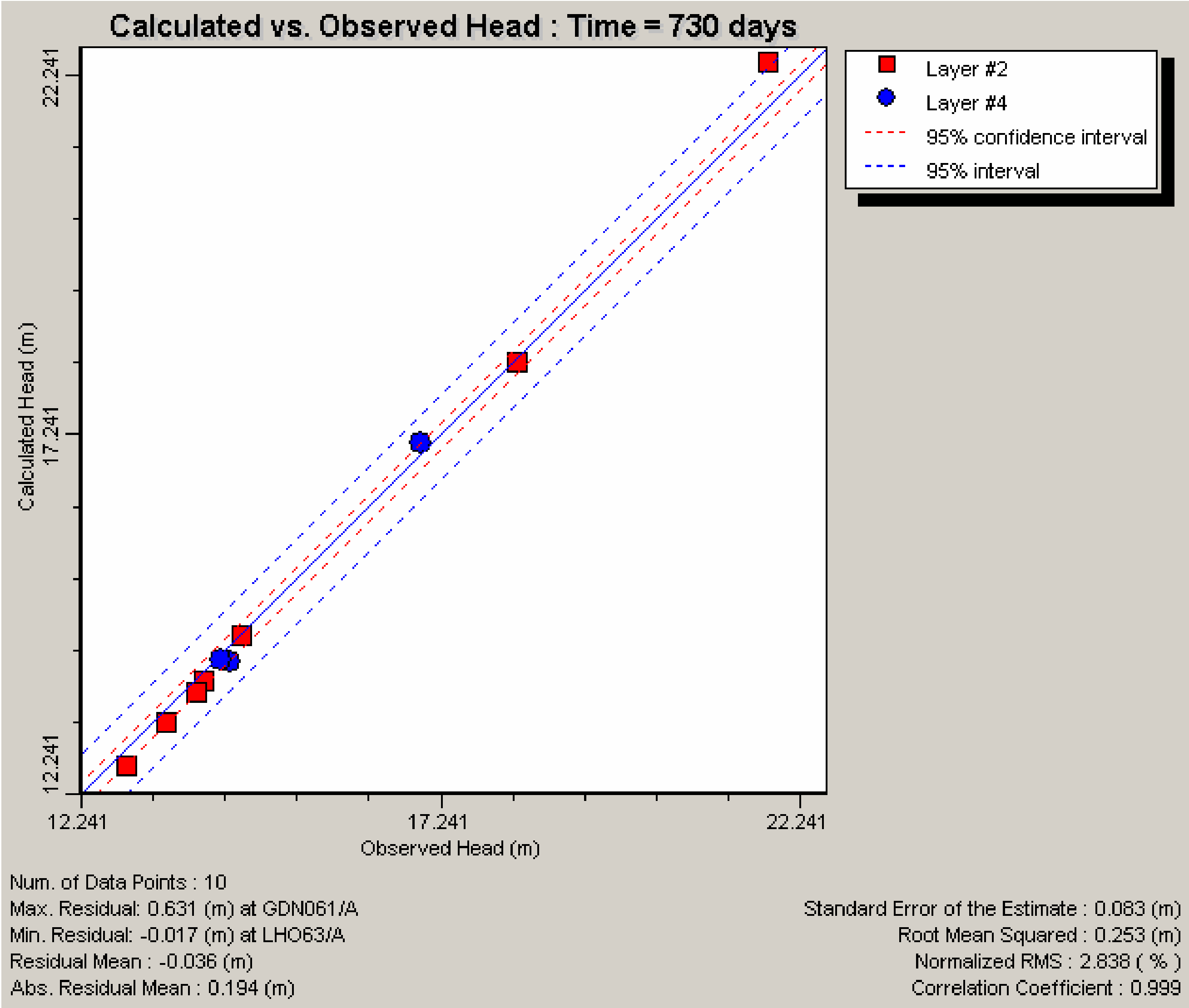
Figure 38. Transient model root mean square calibration results after 243 days of drain operation



Transient model root mean square calibration results

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Figure 39. **Transient model root mean square calibration results after 365 days of drain operation**

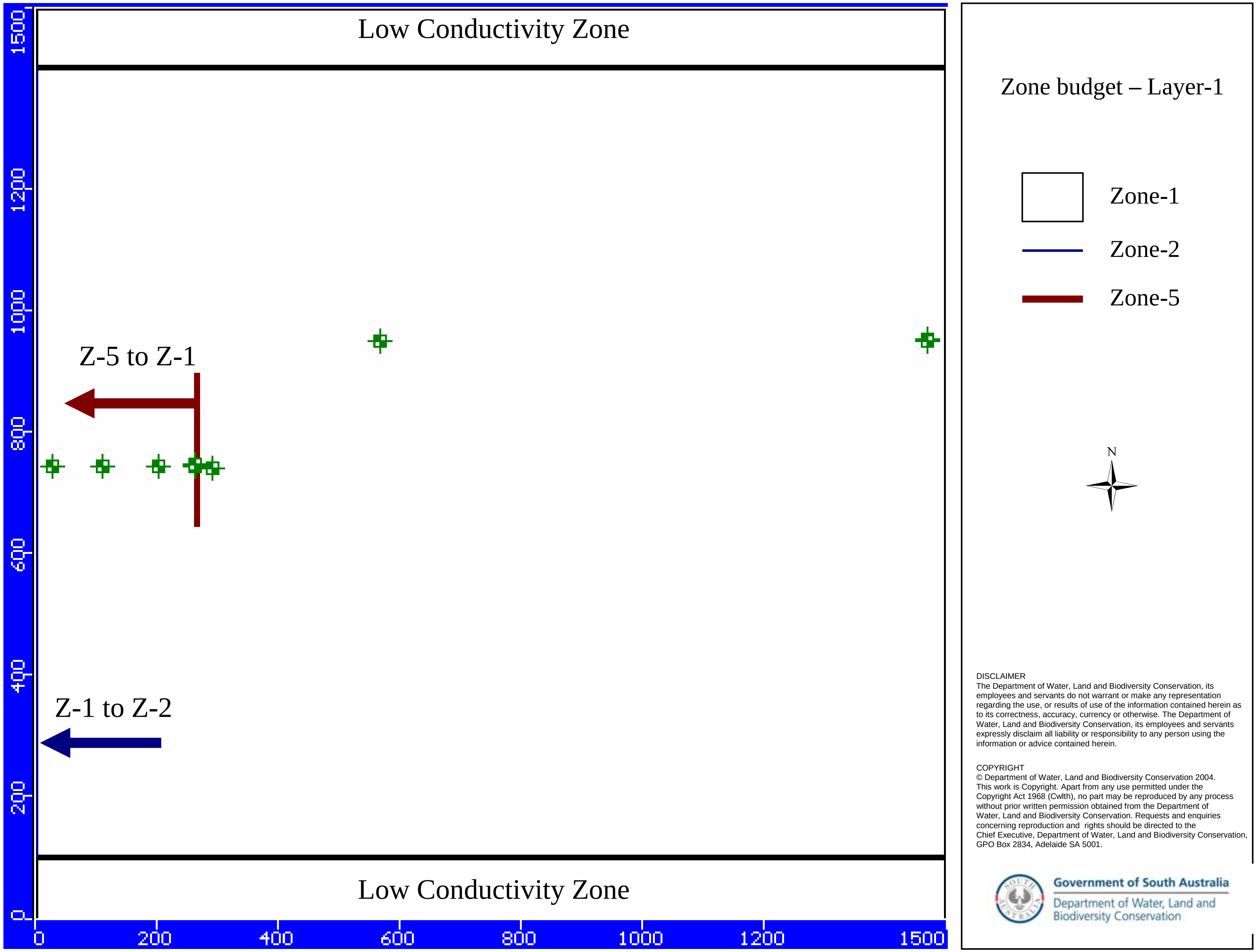

Figure 40. **Zone budget Layer-1**

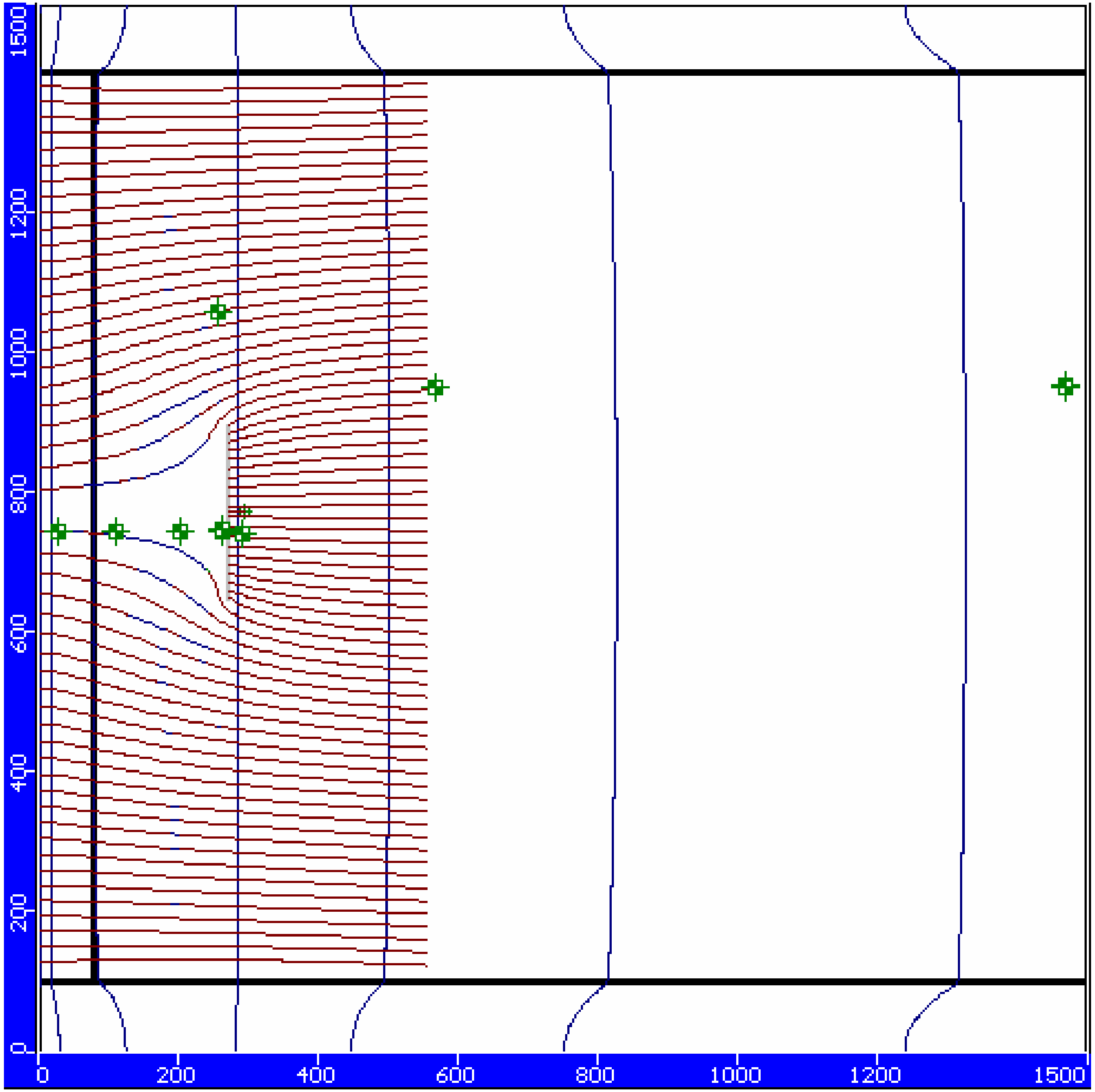

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Figure 41. **Scenario-2a flow capture zone**

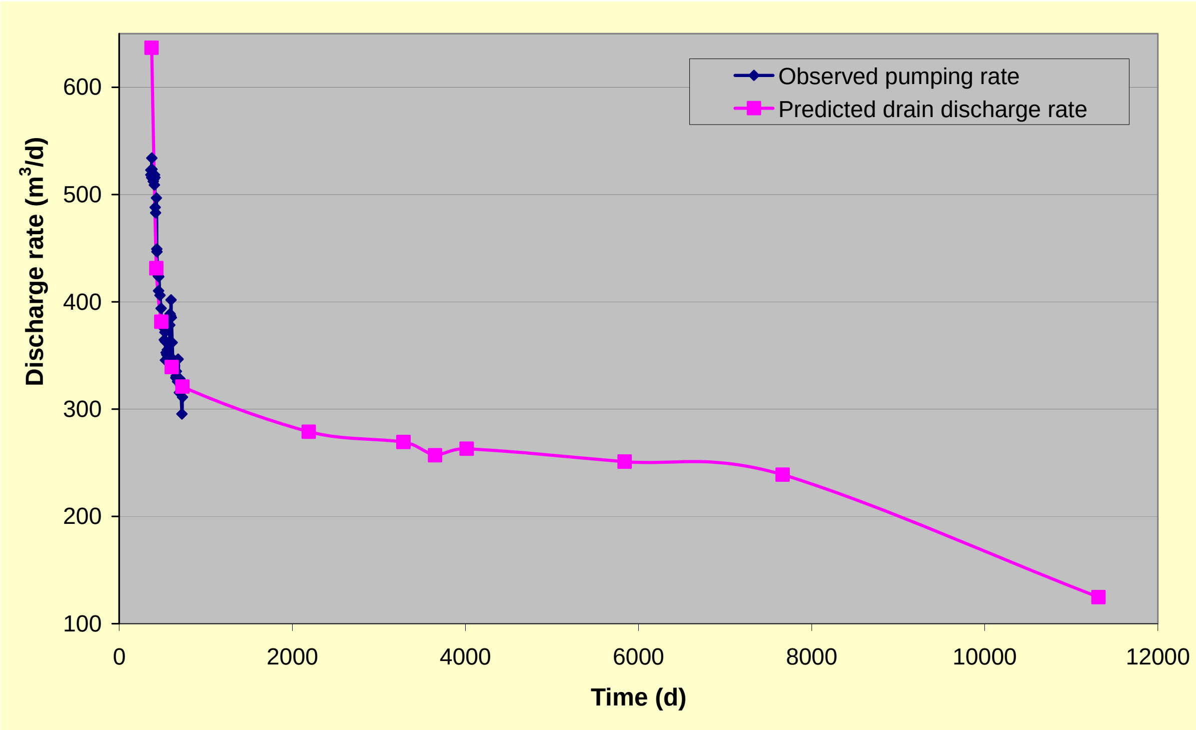


Figure 42. Scenario-2a predicted drain discharge rate

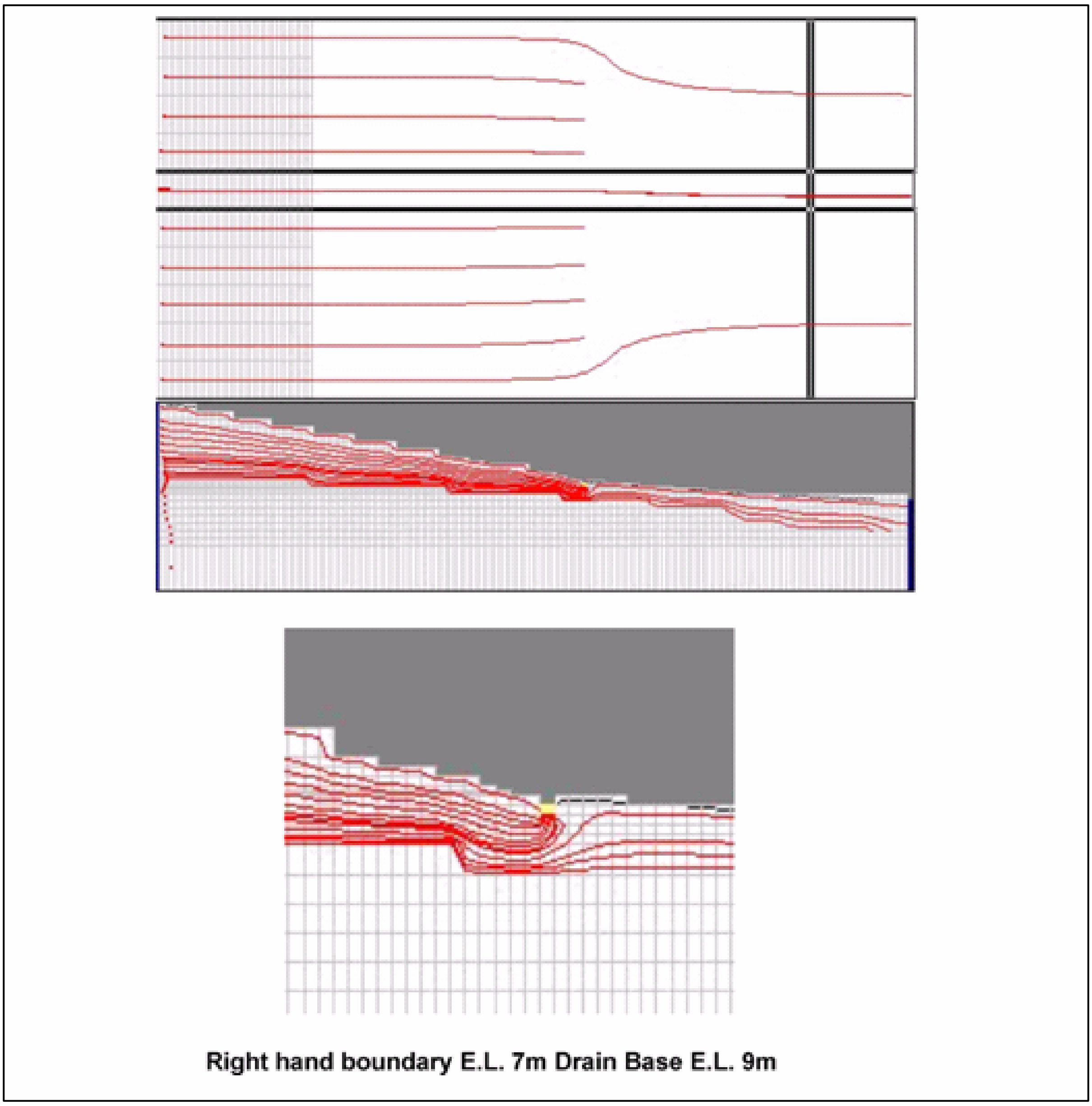


Figure 43. Plan indicating convergent flow and section indicating underflow where drain is positioned higher than river level

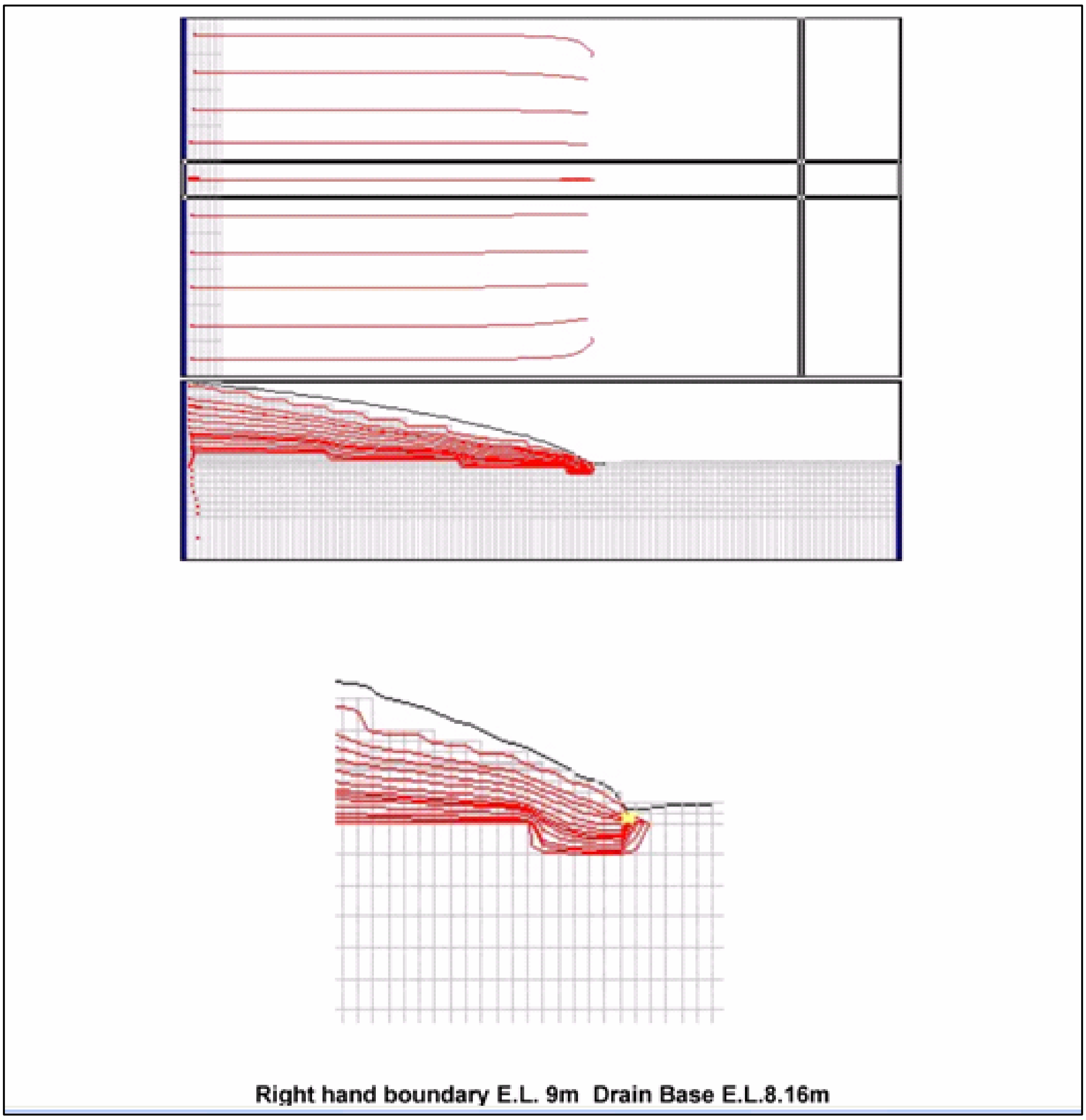


Figure 44. Plan indicating convergent flow and section indicating 100% flux interception where drain is positioned at or below river level

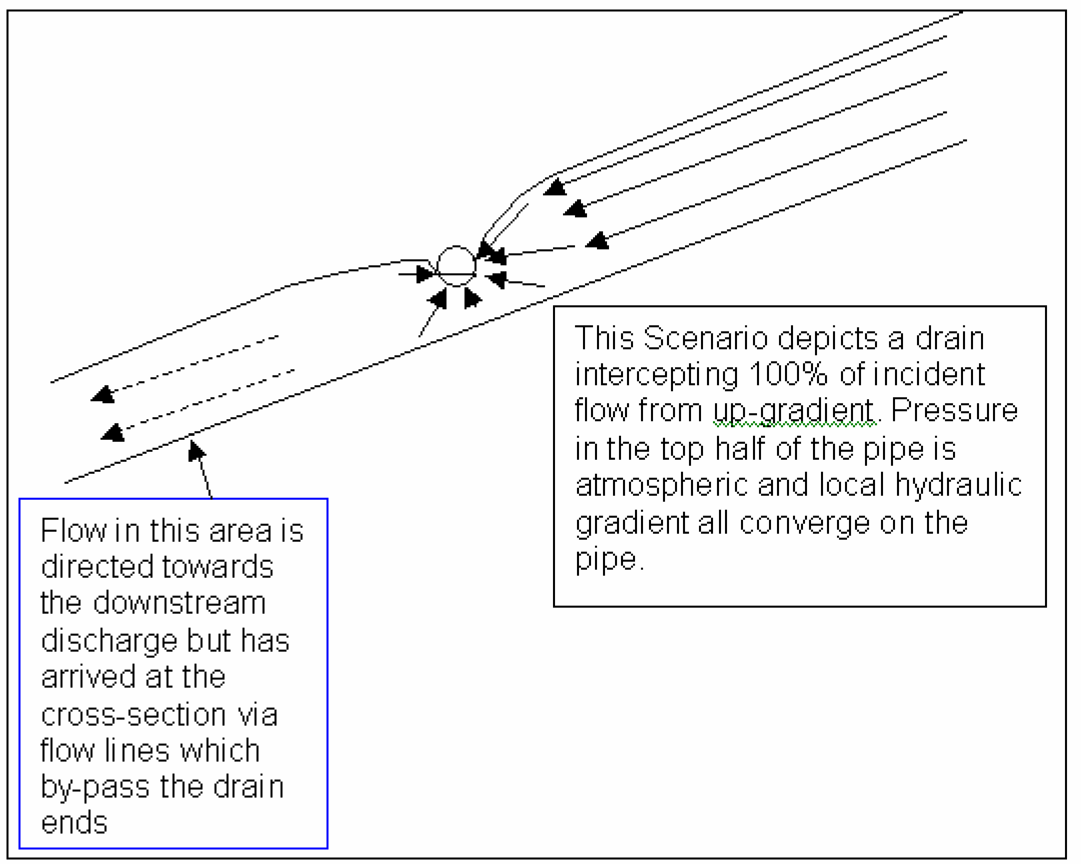


Figure 45. Convergent flow around a horizontal drainage well

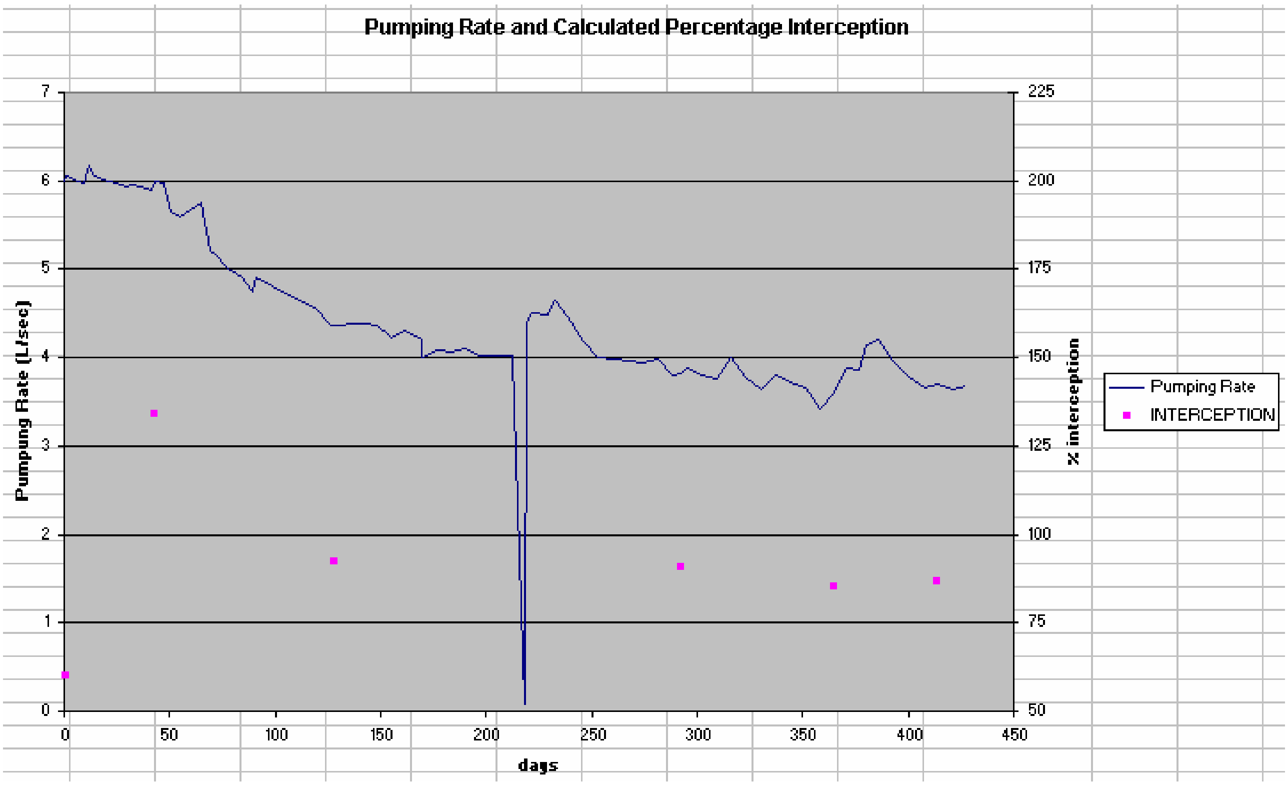
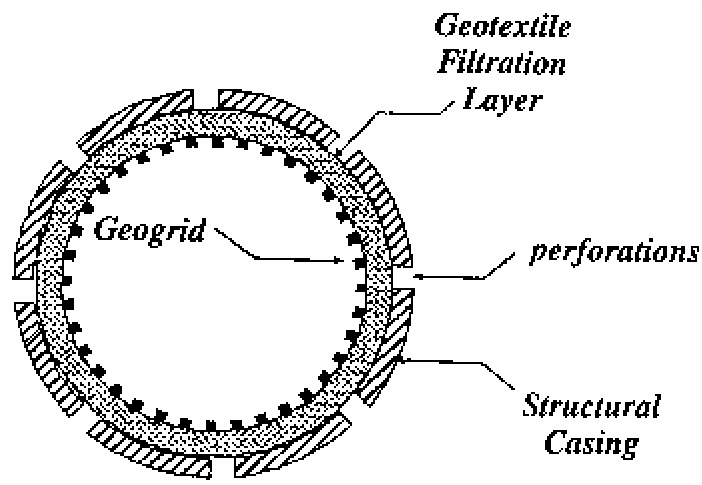


Figure 46. Pumping rate and interception vs time



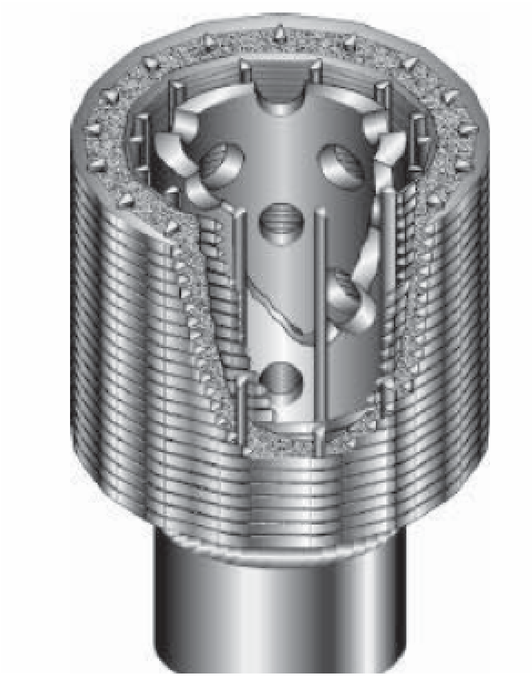
REF www.titanpipe.com/PVC/default.htm

Viewed 27 February 2007

REF www.horizontaldrill.com/assets/pdf/DTD_Horizontal_EnvWell_Handbook.pdf

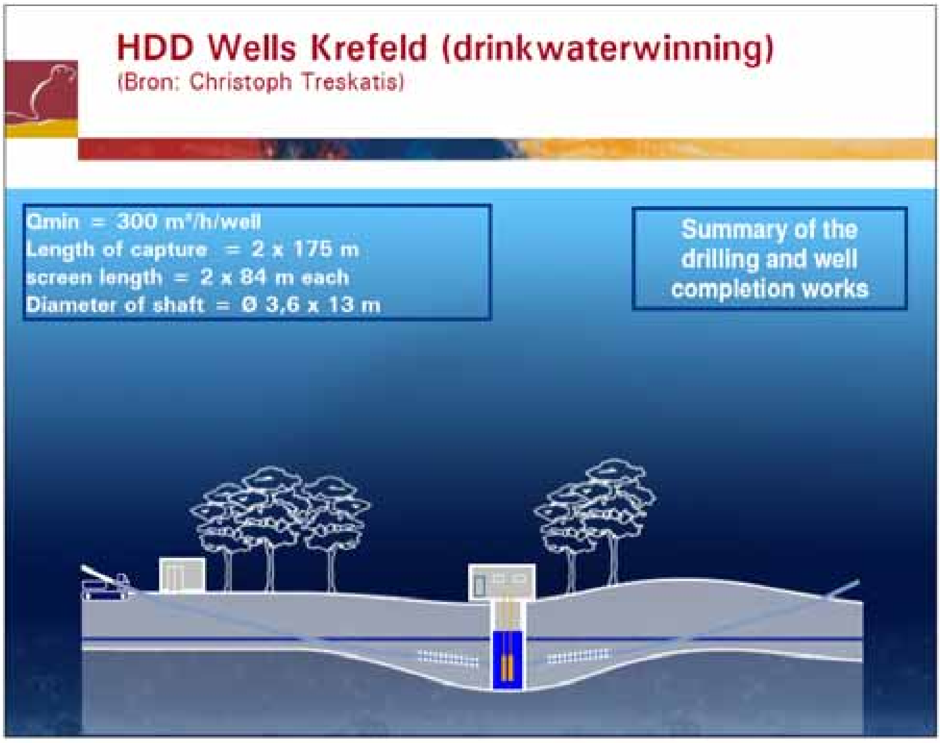
Viewed 27 February 2007

Figure 47. Enviroflex well screen



Viewed 27 February 2007, REF www.variperm.com

Figure 48. Pre-packed well screen



Viewed 30 January 2007, REF www.kiwawaterresearch.eu

Figure 49. Horizontal drainage well completed with vertical sump

Viewed 27 February 2007,

REF www.horizontaldrill.com/assets/pdf/DTD_Horizontal_EnvWell_Handbook.pdf

Figure 50. Sub-surface horizontal well head completion

APPENDICES

A. OBSERVATION WELL CONSTRUCTION DATA

Loxton Trial Horizontal Drainage Well - Observation Well Specifications

where:

SC = Slotted casing
WS = Wirewound screen
OH = Open Hole
NS = Not specified
NR = Not recorded
SWL = Standing water level
LS = Loxton Sands Formation

Note: all depth measurements recorded as below ground surface

											Casing			Production Zone						
Project No.	Unit No.	Permit No.	Easting	Northing	EL natural surface (m AHD)	EL Reference (m AHD)	SWL 7/11/05 (m AHD)[1]	SWL 3/05/06 (m AHD)[2]	Target Aquifer	Total depth (m)	Casing	Casing depth (m)	Casing ID (mm)	Screen	Screen length (m)	Depth screen top (m)	Depth screen bottom (m)	Sump length (m)	Screen ID (mm)	Screen aperture (mm)
LHO-42	7029-1796	64349	462614	6191312	31.45	32.05	NR	(15.27)[3]	LS	22.0	PVC	16.0	80	SC (PVC)	6.0	16.0	22.0	-	80	1.0
LHP-44	7029-1880	65530	462628	6191116	31.47	31.72	16.17	15.78	LS	22.6	PVC	17.0	175	WS (316SS)	5.0	17.0	22.0	0.6	175	0.5
LHO-50	7029-1877	65598	462619	6191067	31.29	32.08	16.20	15.82	LS	20.0	PVC	17.0	80	SC (PVC)	3.0	17.0	20.0	-	80	0.5
LHO-53	7029-1915	65938	462601	6190662	35.79	36.69	NR	(16.31)[4]	LS	24.5	PVC	22.5	80	SC (PVC)	2.0	22.5	24.5	-	80	0.5
LHO-55	7029-1918	69536	462608	6191018	31.41	31.97	16.22	15.85	LS	21.0	PVC	18.0	80	SC (PVC)	3.0	18.0	21.0	-	80	0.5
LHO-58	7029-2260	105444	462595	6190963	32.08	33.05	16.24	15.82	LS	21.0	PVC	17.0	76	SC (PVC)	3.0	17.0	20.0	1.0	76	1.0
LHO-59	7029-2262	105445	462581	6190890	33.59	34.52	16.14	15.79	LS	22.0	PVC	18.0	76	SC (PVC)	3.0	18.0	21.0	1.0	76	1.0
LHO-60	7029-2337	NS	462644	6191117	31.68	32.52	16.35	15.99	LS	20.0	PVC	16.0	76	SC (PVC)	3.0	16.0	19.0	1.0	76	1.0
LHO-61	7029-2335	105447	462634	6191065	31.40	32.37	16.38	16.01	LS	20.0	PVC	16.0	76	SC (PVC)	3.0	16.0	19.0	1.0	76	1.0
LHO-62	7029-2336	105448	462625	6191017	31.58	32.55	16.39	16.02	LS	20.0	PVC	16.0	76	SC (PVC)	3.0	16.0	19.0	1.0	76	1.0
LHO-63	7029-2261	105449	462616	6190961	31.83	32.83	16.38	16.01	LS	20.0	PVC	16.0	76	SC (PVC)	3.0	16.0	19.0	1.0	76	1.0
LHO-64	7029-2263	105446	462601	6190886	33.06	34.07	16.36	16.00	LS	20.3	PVC	16.3	76	SC (PVC)	3.0	16.3	19.3	1.0	76	1.0
LHO-65	7029-2267	115755	462592	6190961	32.25	33.20	NR	14.60	Pata	46.0	PVC	39.5	102	OH	NA	NA	NA	NA	NA	NA
LHO-66	7029-2264	115754	462523	6190969	33.77	34.59	NR	15.11	LS	25.4	PVC	15.4	76	SC (PVC)	9.0	15.4	24.4	1.0	76	1.0
LHO-67	7029-2265	115477	462442	6190992	28.21	29.11	NR	14.35	LS	20.0	PVC	8.0	76	SC (PVC)	11.0	8.0	19.0	1.0	76	1.0
LHO-68	7029-2266	115476	462350	6190985	17.21	18.03	NR	13.43	LS	17.0	PVC	10.0	76	SC (PVC)	1.0	10.0	16.0	1.0	76	1.0

1 Water level recorded 07/11/05, prior to start of Prliminary Test.

2 Water level recorded 03/05/06, prior to start of Long-term Test.

3 Water level recorded 01/08/06, post start of Long-term test.

4 Water level recorded 01/08/06, post start of Long-term test.

B. WATER QUALITY DATA

Preliminary Pumping Test 55 000 minutes

Common Iron analysis, sample taken during Preliminary Pumping Test at 53 000 minutes.

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Australian Water Quality Centre

DWLBC
ATTN: Aaron Smith
GPO Box 2834
ADELAIDE
SA 5001 AUSTRALIA

10/02/2006

Dear Aaron

Please find attached a copy of the Final Analytical Report for

Customer Service Request: 108874-2005-CSR-5.
Account: 108874
Project: AWQC-1381 DWLBC - A Smith - Loxton 14/12/05

Sample Date Range: 14-December-2005 to 30-December-2005

Yours sincerely,

G Radcliffe

Gordon Radcliffe
Client Manager
Gordon.Radcliffe@sawater.com.au
(08) 82590257

NATA
WORLD RECOGNISED ACCREDITATION

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FINAL REPORT: 2812

Report Information

Project Name	AWQC-1381
Customer	DWLBC
CSR_ID	108874-2005-CSR-5

Analytical Results

Customer Sample Description	Well P/N 107837 Loxton
Sampling Point	11438-DWLBC - GENERAL
Sampled Date	14/12/2005 1:30:00PM
Sample Received Date	15/12/2005 1:30:02PM
Sample ID	2005-001-4226
Status	Endorsed
Collection Type	Customer Collected

Inorganic Chemistry - Metals	LOR	Result
Calcium TIC-001 W09-023		
Calcium	0.1	30.1 mg/L
Dissolved Solids by Calculation W09-023		
Dissolved solids by calculation	0	3290 mg/L
Ion Balance W09-023		
Ion balance		2.76 %
Iron - Total TIC-001 W09-023		
Iron - Total	0.030	<0.030 mg/L
Langelier Index W09-023		
Langelier Index		0.57
Magnesium TIC-001 W09-023		
Magnesium	0.3	50.5 mg/L
Potassium TIC-001 W09-023		
Potassium	1.0	32.2 mg/L
Sodium Adsorption Ratio W09-023		
Sodium Adsorption Ratio - Calculation		30.5
Sodium TIC-001 W09-023		
Sodium	0.5	1180 mg/L
Sulphur TIC-001 W09-023		
Sulphate	1.5	396 mg/L
Total Hardness as CaCO3 W09-023		
Total Hardness as CaCO3	2.0	283 mg/L

Inorganic Chemistry - Nutrients	LOR	Result
Chloride T0104-02 W09-023		
Chloride	4.0	1170 mg/L
Fluoride W09-023		
Fluoride	0.1	5.2 mg/L
Nitrate + Nitrite as N T0161-01 W09-023		
Nitrate + Nitrite as N	0.005	4.37 mg/L
Nitrate + Nitrite as NO3 T0161-01 W09-023		

Notes
1. The last figure of the result value is a significant figure.
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6. & Indicates the results have changed since the last issued report.

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Australian Water Quality Centre

FINAL REPORT: 2812

Analytical Results

Customer Sample Description	Well P/N 107837 Loxton
Sampling Point	11438-DWLBC - GENERAL
Sampled Date	14/12/2005 1:30:00PM
Sample Received Date	15/12/2005 1:30:02PM
Sample ID	2005-001-4226
Status	Endorsed
Collection Type	Customer Collected

Nitrate + Nitrite as NO3 T0161-01 W09-023

Nitrate + Nitrite as NO3	0.02	19.4 mg/L

Silica - Reactive T0111-01 W09-023

Silica - Reactive	1	20 mg/L

Inorganic Chemistry - Physical	LOR	Result
Alkalinity, Carbonate, Bicarbonate and Hydroxide T0101-01 W09-023		
Alkalinity as Calcium Carbonate		643 mg/L
Bicarbonate		785 mg/L
Carbonate		0 mg/L
Hydroxide		0 mg/L
Conductivity & Total Dissolved Solids T0016-01 W09-023		
Conductivity	1	5180 µScm
Total Dissolved Solids (by EC)	1.0	2900 mg/L
pH T0010-01 W09-023		
pH		7.9 pH units

Notes
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Australian Water Quality Centre

FINAL REPORT: 2812

Nata Signatories

Roger Kennedy - Inorganic Chemistry Team Leader

G. O'Neil

Greg O'Neil - Inorganic Chemistry Team Leader

Corporate Accreditation No.1115
Chemical and Biological Testing
This document is issued in accordance with NATA's accreditation requirements.

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FINAL REPORT: 2812

Analytical Method

Analytical Method Code	Description
T0010-01	Determination of pH
T0016-01	Determination of Conductivity
T0101-01	Alkalinity - Automated Acidimetric Titration
T0104-02	Chloride - Automated Flow Colorimetry
T0111-01	Reactive Silica - Automated Flow Coloimetry
T0161-01	Nitrate + Nitrate (NOx) - Automated Flow Colorimetry
TIC-001	Determination of Metals-ICP Spectrometry
W-052	Preparation of Samples for Metal Analysis

Sampling Method

Sampling Method Code	Description
W09-023	Sampling Method for Chemical Analyses

Laboratory Information

Laboratory	NATA accreditation ID
Inorganic Chemistry - Metals	1115
Inorganic Chemistry - Nutrients	1115
Inorganic Chemistry - Physical	1115

Notes
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2. Samples are analysed as received.
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Preliminary Pumping Test 110 000 minutes

Common Iron analysis, sample taken during Preliminary Pumping Test at 110 700 minutes.

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Australian Water Quality Centre

DWLBC
ATTN: Aaron Smith
GPO Box 2834
ADELAIDE
SA 5001 AUSTRALIA

20/03/2006

Dear Aaron

Please find attached the Final Analytical Report for

Customer Service Request:	108874-2006-CSR-1.
Account:	108874
Project:	AWQC-2261 DWLBC - Loxton

Sample Date Range: 25-January-2006 to 07-February-2006

Yours sincerely,

Gordon Radcliffe
Client Manager
Gordon.Radcliffe@sawater.com.au
(08) 82590257

WORLD RECOGNISED ACCREDITATION

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Internet: www.awqc.com.au
Email: awqc@sawater.com.au

FINAL REPORT: 4266

Report Information

Project Name	AWQC-2261
Customer	DWLBC
CSR_ID	108874-2006-CSR-1

Analytical Results

Customer Sample Description	Loxton Permit # 107837
Sampling Point	11438-DWLBC - GENERAL
Sampled Date	25/01/2006 12:00:00AM
Sample Received Date	27/01/2006 11:27:29AM
Sample ID	2006-000-5755
Status	Endorsed
Collection Type	Customer Collected

Inorganic Chemistry - Metals	LOR	Result
Calcium TIC-001 W09-023		
Calcium	0.1	32.0 mg/L
Dissolved Solids by Calculation W09-023		
Dissolved solids by calculation	0	3610 mg/L
Ion Balance W09-023		
Ion balance		-0.2 %
Iron - Total TIC-001 W09-023		
Iron - Total	0.030	<0.030 mg/L
Langelier Index W09-023		
Langelier Index		0.49
Magnesium TIC-001 W09-023		
Magnesium	0.3	58.2 mg/L
Potassium TIC-001 W09-023		
Potassium	1.0	35.2 mg/L
Sodium Adsorption Ratio W09-023		
Sodium Adsorption Ratio - Calculation		30.9
Sodium TIC-001 W09-023		
Sodium	0.5	1270 mg/L
Sulphur TIC-001 W09-023		
Sulphate	1.5	474 mg/L
Total Hardness as CaCO3 W09-023		
Total Hardness as CaCO3	2.0	320 mg/L

Inorganic Chemistry - Nutrients	LOR	Result
Chloride T0104-02 W09-023		
Chloride	4.0	1400 mg/L
Fluoride W09-023		
Fluoride	0.1	4.7 mg/L
Nitrate + Nitrite as N T0161-01 W09-023		
Nitrate + Nitrite as N	0.005	4.18 mg/L
Nitrate + Nitrite as NO3 T0161-01 W09-023		

Notes
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FINAL REPORT: 4266

Analytical Results

Customer Sample Description	Loxton Permit # 107837
Sampling Point	11438-DWLBC - GENERAL
Sampled Date	25/01/2006 12:00:00AM
Sample Received Date	27/01/2006 11:27:29AM
Sample ID	2006-000-5755
Status	Endorsed
Collection Type	Customer Collected

Nitrate + Nitrite as NO3 T0161-01 W09-023

Nitrate + Nitrite as NO3	0.02	18.5 mg/L

Silica - Reactive T0111-01 W09-023

Silica - Reactive	1	20 mg/L

Inorganic Chemistry - Physical	LOR	Result
Alkalinity, Carbonate, Bicarbonate and Hydroxide T0101-01 W09-023		
Alkalinity as Calcium Carbonate		641 mg/L
Bicarbonate		782 mg/L
Carbonate		0 mg/L
Hydroxide		0 mg/L
Conductivity & Total Dissolved Solids T0016-01 W09-023		
Conductivity	1	6030 µScm
Total Dissolved Solids (by EC)	1.0	3380 mg/L
pH T0010-01 W09-023		
pH		7.8 pH units

Notes
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FINAL REPORT: 4266

Nata Signatories

Roger Kennedy - Inorganic Chemistry Team Leader

Greg O'Neil - Inorganic Chemistry Team Leader

Corporate Accreditation No.1115
Chemical and Biological Testing
This document is issued in accordance with NATA's accreditation requirements.

Notes
1. The last figure of the result value is a significant figure.
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6. & Indicates the results have changed since the last issued report.

FINAL REPORT: 4266

Analytical Method

Analytical Method Code	Description
T0010-01	Determination of pH
T0016-01	Determination of Conductivity
T0101-01	Alkalinity - Automated Acidimetric Titration
T0104-02	Chloride - Automated Flow Colorimetry
T0111-01	Reactive Silica - Automated Flow Coloimetry
T0161-01	Nitrate + Nitrate (NOx) - Automated Flow Colorimetry
TIC-001	Determination of Metals-ICP Spectrometry
W-052	Preparation of Samples for Metal Analysis

Sampling Method

Sampling Method Code	Description
W09-023	Sampling Method for Chemical Analyses

Laboratory Information

Laboratory	NATA accreditation ID
Inorganic Chemistry - Metals	1115
Inorganic Chemistry - Nutrients	1115
Inorganic Chemistry - Physical	1115

Notes
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Long-term Pumping Test 130 000 minutes

Iron Bacteria analysis, sample taken during Long-term Pumping Test at 130 000 minutes.

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Australian Water Quality Centre

DWLBC
ATTN: Aaron Smith
GPO Box 2834
ADELAIDE
SA 5001 AUSTRALIA

11/08/2006

Dear Aaron

Please find attached the Final Analytical Report for

Customer Service Request: 108874-2006-CSR-16
Account: 108874
Project: AWQC-6311 Depart Water Land & Bio - Aaron Smith - 06/07

Sample Date Range: 01-August-2006 to 14-August-2006

Yours sincerely,

Gordon Radcliffe
Client Manager
Gordon.Radcliffe@sawater.com.au
(08) 8259 0257

NATA
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Australian Water Quality Centre

FINAL REPORT: 9891

Report Information

Project Name	AWQC-6311
Customer	DWLBC
CSR_ID	108874-2006-CSR-16

Analytical Results

Customer Sample Description	Loxton Well Permit # 107837
Sampling Point	11438-DWLBC - GENERAL
Sampled Date	1/08/2006 3:00:00PM
Sample Received Date	3/08/2006 11:03:01AM
Sample ID	2006-004-4580
Status	Endorsed
Collection Type	Customer Collected

Bacteriology	LOR	Result
Iron Bacteria - Heterotrophic T460-01 WMZ-500		
Iron Bacteria - Heterotrophic	10	8500 /mL
Iron Bacteria - Heterotrophic T460-05 WMZ-500		
Iron Bacteria - Microscopic examination		Microscopical examination of the sample did not detect iron associated microorganisms

NATA
WORLD RECOGNISED ACCREDITATION

Corporate Accreditation No.1115
Chemical and Biological Testing
This document is issued in accordance with NATA's accreditation requirements.

Notes
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FINAL REPORT: 9891

NATA Signatories

Vanessa Capurso - Microbiology Technical Officer

Notes

1. **The last figure of the result value is a significant figure.**
2. **Samples are analysed as received.**
3. **# determination of the component is not covered by NATA Accreditation.**
4. **^ indicates result is out of specification according to the reference Guideline. Refer to Report footer.**
5. *** indicates incident have been recorded against the sample. Refer to Report footer.**
6. **& Indicates the results have changed since the last issued report.**

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FINAL REPORT: 9891

Analytical Method

Analytical Method Code	Description
T460-01	Heterotrophic Iron Bacteria - Spread plate
T460-05	Heterotrophic Iron Bacteria - microscopic

Sampling Method

Sampling Method Code	Description
WMZ-500	Sampling Method for Microbiological Analyses

Laboratory Information

Laboratory	NATA accreditation ID
Bacteriology	1115

Notes
1. The last figure of the result value is a significant figure.
2. Samples are analysed as received.
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Long-term Pumping Test 717 000 minutes

Full analysis, sample taken during Long-term Pumping Test at 717 000 minutes.

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Email: awqc@sawater.com.au

Australian Water Quality Centre

DWLBC
ATTN: Aaron Smith
Level 11
25 Grenfell St
Adelaide
SA 5000 AUSTRALIA

10/10/2007

Dear Aaron

Please find attached the Final Analytical Report for

Customer Service Request:	108874-2007-CSR-13
Account:	108874
Project:	AWQC-16254 DWLBC - Loxton Trial Aaron Smith 07/08

Sample Date Range: 01-September-2007 to 30-September-2007

Yours sincerely,

John Winter
Account Manager
John.Winter@sawater.com.au
(08) 8259 0257

NATA
WORLD RECOGNISED ACCREDITATION

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Australian Water Quality Centre

FINAL REPORT: 27574

Report Information

Project Name	AWQC-16254
Customer	DWLBC
CSR_ID	108874-2007-CSR-13

Analytical Results

Sampling Point	11499-DWLBC - Loxton trial horizontal drainage well, permit number 107837
Sampled Date	13/09/2007 1:30:00PM
Sample Received Date	14/09/2007 2:30:32PM
Sample ID	2007-005-7946
Status	Endorsed
Collection Type	Customer Collected

Bacteriology	LOR	Result
Iron Bacteria - Heterotrophic T460-01 WMZ-500		
Iron Bacteria - Heterotrophic	10	30 /mL
Iron Bacteria - Heterotrophic T460-05 WMZ-500		
Iron Bacteria - Microscopic examination		Microscopical examination of the sample did not detect iron associated microorganisms

Inorganic Chemistry - Metals	LOR	Result
Aluminium - Total TIC-004 W09-023		
Aluminium - Total	0.010	<0.01 mg/L
Arsenic - Total TIC-003 W09-023		
Arsenic - Total	0.001	<0.001 mg/L
Boron - Soluble TIC-001 W09-023		
Boron - Soluble	0.040	5.83 mg/L
Cadmium - Total TIC-003 W09-023		
Cadmium - Total	0.0005	<0.0005 mg/L
Calcium TIC-001 W09-023		
Calcium	0.1	45.9 mg/L
Chromium - Total TIC-003 W09-023		
Chromium - Total	0.003	<0.003 mg/L
Copper - Total TIC-003 W09-023		
Copper - Total	0.0010	<0.0010 mg/L
Iron - Total TIC-001 W09-023		
Iron - Total	0.005	0.035 mg/L
Langelier Index W09-023		
Langelier Index		0.43
Lead - Total TIC-003 W09-023		
Lead - Total	0.0005	<0.0005 mg/L
Magnesium TIC-001 W09-023		
Magnesium	0.3	92.9 mg/L
Manganese - Total TIC-003 W09-023		
Manganese - Total	0.0005	0.0098 mg/L
Mercury - Total TIC-003 W09-023		

Notes
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Status	Endorsed
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	LOR	Result
Mercury - Total TIC-003 W09-023		
Mercury - Total	0.0003	<0.0003 mg/L
Nickel - Total TIC-003 W09-023		
Nickel - Total	0.0005	<0.0005 mg/L
Potassium TIC-001 W09-023		
Potassium	1.0	44.8 mg/L
Selenium - Total TIC-003 W09-023		
Selenium - Total	0.003	0.006 mg/L
Sodium Adsorption Ratio W09-023		
Sodium Adsorption Ratio - Calculation		32.2
Sodium TIC-001 W09-023		
Sodium	0.5	1650 mg/L
Sulphur TIC-001 W09-023		
Sulphate	1.5	645 mg/L
Total Hardness as CaCO3 W09-023		
Total Hardness as CaCO3	2.0	497 mg/L
Zinc - Total TIC-003 W09-023		
Zinc - Total	0.003	<0.003 mg/L

Inorganic Chemistry - Nutrients	LOR	Result
Chloride T0104-02 W09-023		
Chloride	4.0	2120 mg/L
Fluoride W09-023		
Fluoride	0.10	4.4 mg/L
Nitrate + Nitrite as N T0161-01 W09-023		
Nitrate + Nitrite as N	0.005	3.84 mg/L
Nitrate as N W09-023		
Nitrate as Nitrogen	0	3.84 mg/L
Nitrite as N T0107-01 W09-023		
Nitrite as Nitrogen	0.005	<0.005 mg/L

Inorganic Chemistry - Physical	LOR	Result
Alkalinity, Carbonate, Bicarbonate and Hydroxide T0101-01 W09-023		
Alkalinity as Calcium Carbonate		619 mg/L
Bicarbonate		755 mg/L
Carbonate		0 mg/L
Hydroxide		0 mg/L
Conductivity & Total Dissolved Solids T0016-01 W09-023		

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Status	Endorsed
Collection Type	Customer Collected

Conductivity & Total Dissolved Solids T0016-01 W09-023

Conductivity	1	7940 µScm
Total Dissolved Solids (by EC)	1.0	4500 mg/L

pH T0010-01 W09-023

pH		7.6 pH units

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NATA Signatories

Vanessa Capurso - Microbiology Technical Officer

Roger Kennedy - Inorganic Chemistry Process Coordinator

David Walker - Inorganic Chemistry Technical Officer

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Analytical Method

Analytical Method Code	Description
T0161-01	Nitrate + Nitrate (NOx) - Automated Flow Colorimetry
TIC-004	Determination of Metals - ICP Spectrometry by ICP2
T460-01	Heterotrophic Iron Bacteria - Spread plate
T460-05	Heterotrophic Iron Bacteria - microscopic
T0107-01	Nitrite - Automated Flow Colorimetry
T0104-02	Chloride - Automated Flow Colorimetry
TIC-001	Determination of Metals-ICP Spectrometry
TIC-003	Elemental Analaysis - ICP Mass Spectrometry
T0101-01	Alkalinity - Automated Acidimetric Titration
T0016-01	Determination of Conductivity
T0010-01	Determination of pH
W-052	Preparation of Samples for Metal Analysis

Sampling Method

Sampling Method Code	Description
W09-023	Sampling Method for Chemical Analyses
WMZ-500	Sampling Method for Microbiological Analyses

Laboratory Information

Laboratory	NATA accreditation ID
Inorganic Chemistry - Metals	1115
Inorganic Chemistry - Physical	1115
Inorganic Chemistry - Nutrients	1115
Bacteriology	1115

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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
litre	L	10^{-3} m^3	volume
megalitre	ML	10^3 m^3	volume
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

Shortened forms

AHD	Australian Height Datum
EC	Electrical Conductivity (µS/cm)
GDA	Geocentric Datum of Australia
pH	acidity
TDS	Total Dissolved Solids (mg/L)
K	hydraulic conductivity (m/d)
~	approximately equal to

GLOSSARY

Act (the) — In this document, refers to the *Natural Resources Management (SA) Act 2004,* which supercedes the *Water Resources (SA) Act 1997*

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 (see 'confining layer') and the water is held at greater than atmospheric pressure; water in a penetrating well will rise above the surface of the aquifer

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 resources 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

Baseflow — The water in a stream that results from groundwater discharge to the stream; often maintains flows during seasonal dry periods and has important ecological functions

Bore — See 'well'

Catchment — That area of land determined by topographic features within which rainfall will contribute to run-off at a particular point

Codes of practice — Standards of management developed by industry and government, promoting techniques or methods of environmental management by which environmental objectives may be achieved

Cone of depression — An inverted cone-shaped space within an aquifer caused by a rate of groundwater extraction that exceeds the rate of recharge; continuing extraction of water can extend the area and may affect the viability of adjacent wells, due to declining water levels or water quality

DSS — Dissolved suspended solids

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 as a measure of water salinity as it is quicker and easier than measurement by TDS

Environmental values — The uses of the environment that are recognised as being of value to the community. This concept is used in setting water quality objectives under the Environment Protection (Water Quality) Policy, which recognises five environmental values — protection of aquatic ecosystems, recreational water use and aesthetics, potable (drinking water) use, agricultural and aquaculture use, and industrial use. It is not the same as ecological values, which are about the elements and functions of ecosystems.

EPA — Environment Protection Authority (Government of South Australia)

Ephemeral streams or wetlands — Those streams or wetlands that usually contain water only on an occasional basis after rainfall events. Many arid zone streams and wetlands are ephemeral.

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

Geological features — Include geological monuments, landscape amenity and the substrate of land systems and ecosystems

Ground surface — Also called the natural surface

Groundwater — Water occurring naturally below ground level or water pumped, diverted and released into a well for storage underground; see also 'underground water'

HDD — Horizontal directional drilling

HDPE — High-density polyethylene

Hydrogeology — The study of groundwater, which includes its occurrence, recharge and discharge processes, and the properties of aquifers; see also 'hydrology'

Hydrology — The study of the characteristics, occurrence, movement and utilisation of water on and below the Earth's surface and within its atmosphere; see also 'hydrogeology'

Infrastructure — Artificial lakes; dams or reservoirs; embankments, walls, channels or other works; buildings or structures; or pipes, machinery or other equipment

Irrigation — Watering land by any means for the purpose of growing plants

Irrigation season — The period in which major irrigation diversions occur, usually starting in August–September and ending in April–May

Lake — A natural lake, pond, lagoon, wetland or spring (whether modified or not) that includes part of a lake and a body of water declared by regulation to be a lake. A reference to a lake is a reference to either the bed, banks and shores of the lake or the water for the time being held by the bed, banks and shores of the lake, or both, depending on the context.

Land — Whether under water or not, and includes an interest in land and any building or structure fixed to the land

Local water management plan — A plan prepared by a council and adopted by the Minister in accordance with the Act

MDBC — Murray–Darling Basin Commission

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

Natural recharge — The infiltration of water into an aquifer from the surface (rainfall, streamflow, irrigation etc). See also recharge area, artificial recharge

Natural resources — Soil, water resources, geological features and landscapes, native vegetation, native animals and other native organisms, ecosystems

NRM — Natural Resources Management; all activities that involve the use or development of natural resources and/or that impact on the state and condition of natural resources, whether positively or negatively

Permeability — A measure of the ease with which water flows through an aquifer or aquitard, measured in m^2/d

PIRSA — Primary Industries and Resources South Australia (Government of South Australia)

Potable water — Water suitable for human consumption such as drinking or cooking water

Potentiometric head — The potentiometric head or surface is the level to which water rises in a well due to water pressure in the aquifer, measured in metres (m); also known as piezometric surface

PWA — Prescribed Wells Area

PWCA — Prescribed Watercourse Area

PWRA — Prescribed Water Resources Area

Recharge area — The area of land from which water from the surface (rainfall, streamflow, irrigation, etc.) infiltrates into an aquifer. See also artificial recharge, natural recharge

Rehabilitation (of water bodies) — Actions that improve the ecological health of a water body by reinstating important elements of the environment that existed prior to European settlement

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

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

Water body — Includes watercourses, riparian zones, floodplains, wetlands, estuaries, lakes and groundwater aquifers

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

Well — (1) An opening in the ground excavated for the purpose of obtaining access to underground water. (2) An opening in the ground excavated for some other purpose but that gives access to underground water. (3) A natural opening in the ground that gives access to underground water.

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