The Department of
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Chowilla Floodplain
Numerical Groundwater Model

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FOREWORD

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

Bryan Harris

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ACKNOWLEDGEMENT

During the development of the Chowilla floodplain numerical groundwater model numerous discussions were had regarding model fundamentals, technical issues and progress with Mr Don Armstrong of Lisdon Associates, who also undertook a final review of the model and report.

EXECUTIVE SUMMARY

The Chowilla floodplain is located adjacent to the River Murray primarily in the northwest region of the South Australian part of the Murray Basin. Over the past twenty years, concerns have been raised regarding the hydraulic impacts on the Chowilla floodplain that have occurred in response to the construction of Lock-6 and Lock-7. On average 130 tonnes/day of salt enters the Chowilla floodplain with groundwater inflow. After extended dry periods and low flows in the River Murray, the salt load entering the anabranch creeks from the aquifer system (and thus the river) is 40–60 tonnes/day. The maximum peak of 1,800 tonnes/day followed the 1974 flood.

Numerical groundwater modelling forms a component of the investigation phase of a major program to design and construct a groundwater management scheme that will:

1) Control groundwater levels in targeted areas on the Chowilla floodplain and control the flux of saline groundwater entering the anabranch creeks, i.e. a salt interception scheme (SIS), or:

2) Control groundwater levels below evapotranspiration extinction depth in targeted areas on the Chowilla floodplain, which will:

    a. Allow the regeneration of the natural vegetation across the floodplain.

    b. Control the flux of saline groundwater entering the anabranch creeks.

    i.e. an environmental scheme (ES) plus a SIS, (ES + SIS).

The objectives of the this project were to develop an *impact assessment model of moderate complexity,* capable of simulating the regional aquifer system that could be used to:

1) Estimate the flux of saline groundwater entering the anabranch creeks from the aquifer system, and when combined with groundwater salinities, the salt load.

2) Predict the salt load being delivered to the River Murray under different groundwater management options 100 years into the future.

3) Improve the understanding of the hydrogeology of the regional aquifer system and processes in the Chowilla floodplain.

4) Assist with broad scale planning of conceptual wellfield designs targeting the Monoman Formation, and predict the changes in groundwater levels that would be expected to occur, and the reduction in the salt load being delivered to the River Murray.

5) Provide a sound technical basis for evaluating salt loads being delivered to the River Murray from the Chowilla Floodplain.

This report describes the development, testing and application of the MODFLOW groundwater model that covers the area from Lock-7 to downstream of Lock-6. The model is predominantly associated with the Chowilla floodplains and highlands, but extends across to Lake Victoria. It was calibrated to groundwater measurements (in 2003 and 2004), where available.

The model was designed with features to represent drainage and salt interception in the Chowilla floodplain and highland areas, and used appropriate model features to represent the River Murray. A steady state model was initially used to model pre-locking conditions, after which a transient model was developed and applied to the historic period (1930–2004) to investigate the historic salt load being delivered to the river. The transient model was then applied to the prediction scenarios for a period of 100 years to determine the salt load being delivered to the river, and EC impact at Morgan.

The model can predict the:

1) Flux of saline groundwater (and, given the groundwater salinity, salt load) entering the floodplain (Monoman Formation) from the highland (Pliocene Sands).
2) Flux of saline groundwater (and salt load) entering the anabranch creeks from the floodplain (Monoman Formation), and therefore being delivered to the River Murray.
3) Vertical leakage (and salt load) from the Murray Group Limestone into the overlying Pliocene Sands.
4) Evapotranspiration (note that salt concentrated by evapotranspiration does not figure in these salt load calculations, as this is not additional salt into, or out of, the floodplain).

The model results indicate the following important points regarding the pre-locking hydrogeology and hydrology of the Chowilla floodplain under non-flooding conditions and the salt load being delivered to the River Murray, in comparison with post-locking conditions:

1) No flow occurred from the River Murray into the anabranch creeks. Therefore, a greater hydraulic gradient existed between the groundwater table and the anabranch creeks (in spite of the groundwater table occurring at a greater depth than the post-locking condition) that resulted in a greater flux of saline groundwater, thus flushing salt out of the aquifer system.
2) Evaporation from the anabranch creeks matched the flux of saline groundwater entering the anabranch creeks. This resulted in the temporary storage of 106 tonnes/day of salt that was only flushed to the River Murray (at significantly reduced concentrations) during flood events.
3) Less evapotranspiration occurred from the Chowilla floodplain due to the groundwater table existing at a greater depth (in spite of the recharge resulting from regular flooding) than the evaporation extinction depth over most of the floodplain.
4) The aquifer system in the floodplain was in balance. The total salt that entered into the aquifer system laterally from the highland, and via vertical leakage from Murray Group Limestone, was discharged from the aquifer system via the anabranch creeks.

The anthropogenically modified flow regime of the River Murray resulting from the construction of locks and weirs, storages and diversions for irrigation, industry and town water supply, has resulted in significantly reduced flood magnitude and frequency. As a consequence there is less flushing of the unsaturated zone and aquifer system on the Chowilla floodplain.

The model results indicate the following important points regarding the post-locking hydrogeology and hydrology of the Chowilla floodplain and the salt load being delivered to the River Murray, in comparison to pre-locking conditions:

1) Diversion from the River Murray into the anabranch creeks reduced the hydraulic gradient between the groundwater table and the anabranch creeks (and therefore the flux of saline groundwater entering the anabranch creeks) and resulted in elevation of the groundwater table. The reduced groundwater flux results in an additional ~75 tonnes/day of salt being *stored* in the aquifer system.
2) The elevated groundwater table has resulted in significantly increased evapotranspiration in some parts of the Chowilla floodplain.

3) The constant flow in the anabranch creeks has resulted in a base salt load of 40–60 tonnes/day being delivered to the River Murray (under non-flooding conditions), and this has resulted in an in-river salinity impact of 7.75 EC at Morgan (assuming 3.1 tonnes per EC).

4) The increased storage of salt in the aquifer system has resulted in very large salt loads being delivered to the River Murray during, and after, flood events.

The model results indicate that the anabranch creeks play a vital role in controlling salt on the Chowilla floodplain. The post-locking hydrological modification of the floodplain has resulted in an increase in salt accumulation in the floodplain that is a threat to the salinity of the River Murray and vegetation health. It is evident that the natural hydrologic balance that had been in operation for several thousand years has been significantly disrupted.

The model was used to determine the salt load being delivered to the River Murray under historic and current conditions; and predict the response of the aquifer system 100 years into the future for the following scenarios:

1) S-3 Do nothing.

2) S-4 SIS on floodplain.

3) S-5 ES targeted areas of vegetation significance + SIS on floodplain.

4) S-6 ES entire floodplain (includes SIS).

5) S-7 SIS on highland (and floodplain).

6) S-8 SIS on floodplain + Part-ES targeted areas.

The modelled salt loads (under non-flooding conditions) being delivered to the River Murray are summarised in Table 1 and indicate that:

1) Pre-locking 106 tonnes/day of salt entered the anabranch creeks.

2) Post-locking, (and the current situation), an average of 31 tonnes/day of salt enters the anabranch creeks.

3) The do nothing prediction scenario results in virtually no additional salt entering the anabranch creeks above that already occurring.

4) All of the proposed groundwater management schemes are effective in controlling salt loads entering the anabranch creeks.

5) All of the proposed the groundwater management scheme options result in very similar in-river benefits at Morgan of 7–8 EC, however, the schemes that include environmental protection require considerably more infrastructure with associated greater costs.

Table 1. Summary of modelled salt loads (under non-flooding conditions) being delivered to the River Murray

	Scenarios							
	S-1	**S-2**	**S-3**	**S-4**	**S-5**	**S-6**	**S-7**	**S-8**
	Pre-Locking	**Post-Locking 2003**	**Do Nothing @ 100 yrs**	**SIS flood plain @ 100 yrs**	**ES targeted areas + SIS floodplain @ 100 yrs**	**ES (SIS) entire floodplain @ 100 yrs**	**SIS highland (+ floodplain) @ 100 yrs**	**SIS floodplain + Part-ES targeted areas @ 100 yrs**
Predicted salt load being delivered to the River Murray (tonnes/day)	106	31	32	5	0.3	0.1	5.4	3.8
EC impact at Morgan	-	10.0	10.0	1.6	0.1	0	1.7	1.2
Reduction in salt entering the River Murray compared to S-3 (tonnes/day)	-	-	-	27	32	32	27	28
EC benefit at Morgan	-	-	-	8.4	9.9	10.0	8.3	8.8

*EC at Morgan assumes 3.1 tonnes per EC

INTRODUCTION

BACKGROUND

The Chowilla floodplain is located adjacent to the River Murray in the northwest region of the Murray Basin. The floodplain occurs primarily in South Australia, but extends over the border into New South Wales (Fig. 1). Water bodies and vegetation distribution on the floodplain and surrounding area are clearly distinguishable on satellite imagery (Fig. 2). The floodplain is an important region for native fauna and flora and was listed as a *Riverland Wetland of International Importance* in 1987 under the UNESCO Ramsar Convention.

Numerous hydrological and hydrogeological investigations have been conducted in the region since the commencement of investigations in the 1960s related to the proposed Chowilla Dam. The Department of Water, Land and Biodiversity Conservation (DWLBC) conducted pumping tests on the Chowilla floodplain at Gum Flat and Tareena Bong in 2002–03 (Howles and Marsden, 2003), and at a further two sites in the west of the area in 2004.

Over the past twenty years, concerns have been raised regarding the hydraulic impacts on the Chowilla floodplain that have occurred in response to the construction of Lock-6 and Lock-7. These impacts are discussed in detail in the *Chowilla Resources Management Plan* (Sharley and Goggan, 1995). In summary, controlled pool levels above the locks have resulted in the elevation of the groundwater table across the Chowilla floodplain (Figs 3a, b), and altered flows in the anabranch creek system that occurs on the floodplain. In parts of the floodplain, the elevated groundwater table has resulted in increased salt accumulation and this has resulted in severe consequences for vegetation health. It has generally been accepted that there has been an increase in the flux of saline groundwater entering the anabranch creeks (occurring in response to the elevated groundwater table), and this has resulted in an increased salt load being delivered to the River Murray.

On average 130 tonnes/day of salt enters the Chowilla floodplain with groundwater inflow. After extended dry periods and low flows in the River Murray, the salt load entering the anabranch creeks from the aquifer system (and thus the river) is 40–60 tonnes/day. The maximum peak of 1,800 tonnes/day followed the 1974 flood.

Numerical groundwater modelling forms a component of the investigation phase of a major program to design and construct a groundwater management scheme that will:

1) Control groundwater levels in targeted areas on the Chowilla floodplain and control the flux of saline groundwater entering the anabranch creeks, i.e. a salt interception scheme (SIS), or:

2) Control groundwater levels below evapotranspiration extinction depth in targeted areas on the Chowilla floodplain, which will:

    c. Allow the regeneration of the natural vegetation across the floodplain.

    d. Control the flux of saline groundwater entering the anabranch creeks.

    i.e. an environmental scheme (ES) plus a SIS, (ES + SIS).

OBJECTIVES

Numerical groundwater flow models enable the creation of a computer based mathematical representation of the conceptual understanding of an aquifer system. The model is a powerful tool for confirming the conceptual model of the aquifer system and for predicting the response of the aquifer system to the imposition of existing and potential stresses.

The objective of this project were to develop an *impact assessment model of moderate complexity,* in the terminology of the Murray Darling Basin Commission (2000), capable of simulating the regional aquifer system that could be used to:

1) Estimate the flux of saline groundwater entering the anabranch creeks from the aquifer system, and when combined with groundwater salinities, the salt load.
2) Predict the salt load being delivered to the River Murray under different groundwater management options 100 years into the future.
3) Improve the understanding of the hydrogeology of the regional aquifer system and processes in the Chowilla floodplain, in terms of:
    a) The groundwater flux within and between aquifers.
    b) Recharge to the Monoman Formation.
    c) The behaviour of the aquifer system in floodplain areas.
    d) The hydraulic communication between the aquifer system and the surface water system.
4) Assist with broad scale planning of conceptual wellfield designs targeting the Monoman Formation, and predict the changes in groundwater levels that would be expected to occur under different scenarios, and the reduction in the salt load being delivered to the River Murray. This report does not address the issue of the disposal of pumped saline groundwater that is likely to occur by evaporation from disposal basins at a great distance form the proposed wellfields.
5) Assist with the design and location of investigation wells, production wells, and observation wells for pumping tests on the Chowilla floodplain.

The terms *modelled* and *predicted* are used in this report. The term modelled has been used when output from the model (eg a potentiometric head distribution) can be compared to observed data. The term predicted has been used when the calibrated model has been used to determine the future result of particular scenarios.

HYDROGEOLOGY AND HYDROLOGY OF THE CHOWILLA FLOODPLAIN

REGIONAL HYDROGEOLOGY

The Pliocene (Loxton – Parilla) Sands forms a regionally extensive unconfined – semi-confined aquifer into which the channel of the ancestral River Murray is incised. Within this channel, the Monoman Formation and the overlying Coonambidgal Formation were deposited, and it is within this sequence that the channel of the modern River Murray is incised (Collingham 1990).

The Pliocene Sands and the Lower Monoman Formation are considered to be in direct hydraulic communication. The Monoman Formation and the Pliocene Sands have a total combined thickness of ~50 m. The surficial sediments of the Coonambidgal Formation overlay the Monoman Formation. The groundwater table occurs within the Coonambidgal Formation.

Saline groundwater enters the Chowilla floodplain by lateral flow from the Pliocene Sands, and by slow vertical leakage through the Bookpurnong Formation from the underlying regional confined Murray Group Limestone. Saline groundwater (25,000–50,000 mg/L) enters the River Murray by direct inflow, and via the flux of groundwater entering the anabranch creeks that then deliver the salt load to the river.

The hydraulic communication between Monoman Formation and the anabranch creeks is an important factor controlling salt movement on the Chowilla floodplain. The flux of saline groundwater entering the creeks is determined by the hydraulic conductivity on the sides and bottom of the creeks, and the head difference between groundwater table and the stage of the creeks. Measurements of the groundwater level in the aquifer and the stage of the creeks at a similar time are critical for understanding the conductance between them. This data can then be used to calculate the flux of saline groundwater entering the creeks, and consequently, the total salt load being delivered to the River Murray.

A conceptual hydrogeological model of the 200 square kilometre Chowilla floodplain is given in Figure 4 and indicates the hydrogeological units, surface water features, and the flow directions within the floodplain. The cross-section A-A’ shows a conceptual cross-section upstream of the anabranch creek system on the eastern site of the floodplain. This cross-section indicates groundwater flow in the aquifer system including lateral flow from the highland area, vertical leakage from Murray Group Limestone, discharge to the anabranch creeks, discharge by evapotranspiration from the extensive areas where a shallow groundwater table exists, and lateral flow from the River Murray to the aquifer system. The cross-section B-B’ is located downstream of the anabranch creek system on the western side the floodplain. This cross-section indicates lateral flow from the highland area, vertical leakage from the Murray Group Limestone and direct discharge from the creeks into the river downstream of Lock-6. The creeks can be either losing or gaining.

Sharley and Goggan (1995) and Jolly and Walker (1995) provide the following values for salt entering the Chowilla floodplain and being delivered to the River Murray. On average 130 tonnes/day of salt enters the Chowilla floodplain with groundwater inflow. After extended dry periods and low flows in the River Murray, the salt load entering the anabranch creeks from the aquifer system (and thus the river) is 40–60 tonnes/day. The maximum peak of 1,800 tonnes/day was recorded after the 1974 flood.

HYDROGEOLOGICAL UNITS

The characteristics of each hydrogeological unit (see Fig. 5) are discussed in order of increasing depth below ground surface.

COONAMBIDGAL FORMATION

The Coonambidgal Formation consists of a discontinuous clay layer 0–2 m thick. This formation determines the unconfined - semi-unconfined nature of the Monoman Formation, recharge to the Monoman Formation during and after flooding, and the rate of evapotranspiration.

MONOMAN FORMATION

The Monoman Formation unconfined – semi-unconfined aquifer consists of relatively clean fine to coarse alluvial sands overlain by thin silts and clay (Anon, 1989), but may contain thin clay layers. The groundwater table within the Chowilla floodplain occurs within the Monoman Formation, or within the overlying Coonambidgal Formation. The Monoman Formation is restricted to the River Murray valley and is in direct hydraulic communication with the river, the underlying semi-confined Lower Pliocene Sands, and the laterally adjacent unconfined Upper Pliocene Sands on the highland. The cross-section (Fig. 5) indicates that this aquifer is ~30 m thick and is incised into the underlying Pliocene Sands in the Chowilla region. The Monoman Formation has an hydraulic conductivity of 10–20 m/day.

A potentiometric head contour plan (Fig. 6) has been constructed for the Monoman Formation and the regional Pliocene Sands using monitoring data obtained in May 2003 from selected wells completed at the top and middle of the Monoman Formation. This approach minimises differences in groundwater levels that may result from the use of wells of varying depth when groundwater salinities span a wide range. Outside of the Chowilla floodplain the groundwater table occurs within the Pliocene Sands and data from wells in this area has been used to complete the plan.

This plan indicates a general pattern of groundwater flow towards the River Murray valley. The River Murray pool level above Lock-6 is elevated above the groundwater table of the surrounding Monoman Formation resulting in recharge from the river into the aquifer. A groundwater trough occurs to the north of the river to the west of Lock-6, through which groundwater discharges either from the Monoman Formation to the west of Lock-6 via an evaporative sink, or directly into the Monoman and Chowilla Creeks.

The salinity of groundwater in this aquifer is 5,000–70,000 mg/L. Salinity values and distribution obtained from observation wells is given in Figure 7.

PLIOCENE SANDS

The Pliocene Sands unconfined - semi-confined aquifer consists of fine - medium sand with some clay and silt layers. This aquifer forms the regional unconfined aquifer outside of the Chowilla floodplain but becomes semi-confined below the Monoman Formation within the floodplain (Fig. 5). This aquifer is ~30 m thick.

The salinity of groundwater in this aquifer is 20,000–70,000 mg/L. The Pliocene Sands have an hydraulic conductivity of 2–5 m/day. The regional groundwater flow occurs laterally from the Pliocene Sands into the Monoman Formation and from there into the anabranch creeks. This saline groundwater is then transported to the River Murray.

BOOKPURNONG FORMATION

The Bookpurnong Formation occurs between the Pliocene Sands and the underlying Murray Group Limestone. This aquitard consists of poorly consolidated plastic silts and shelly clays. This aquitard is 20–40 m thick. The Bookpurnong Formation has a vertical hydraulic conductivity estimated at 10^{-7}–10^{-6} m/day.

MURRAY GROUP LIMESTONE

The Murray Group Limestone is a regionally extensive confined aquifer underlying the Bookpurnong Formation. This aquifer consists of a consolidated, highly fossiliferous, yellow-brown to grey, fine to coarse, bioclastic limestone. This aquifer is ~100 m thick and has an hydraulic conductivity of 0.03–2 m/day. A regional potentiometric head contour plan (Fig. 8) has been constructed for the Murray Group Limestone using data obtained in 2003. This plan indicates a general groundwater flow from east to west. The potentiometric head of the Murray Group Limestone is elevated several metres above that of the overlying aquifers. The salinity of groundwater in this aquifer is ~20,000 mg/L (Sharley and Goggan, 1995). This layer was included in the model due to concerns regarding the effects of vertical leakage from the Murray Group Limestone into the overlying sediments.

FLOODPLAIN HYDROLOGY

The discussion in the following two sections is based on the understanding of the hydrology of the Chowilla floodplain developed from previous investigations (Sharley and Goggan, 1995). There are a number of inter-related factors that control groundwater movement into, and out of, the floodplain, including:

1) River regulation by locks and weirs.
2) Depth to groundwater table under the Chowilla floodplain.
3) Regional hydraulic gradients towards the Chowilla floodplain.
4) The presence of anabranch creeks and billabongs.

HYDROLOGY PRIOR TO RIVER REGULATION

Prior to construction of the locks and weirs (locking) on the River Murray in the 1930s (refer Fig. 3a):

1) River pool elevation gradually increased upstream.
2) There was no permanent flow in the anabranch creeks under median and drought conditions (Plate 1).
3) Recharge occurred to the aquifer system during regular flooding in areas where the Coonambidgal Formation is absent.
4) The anabranch creeks were the groundwater sink for the aquifer system underlying the floodplain.

Plate 1. Anabranch creek with no permanent flow, believed to have been common pre-locking

HYDROLOGY POST RIVER REGULATION

Post-locking (refer Fig. 3b):

1) The River Murray was modified into a series of stepped pools.
2) Upstream of Lock-6, elevated river pool levels resulted in elevation of the groundwater table (immediately adjacent to the River Murray) and additional recharge to the aquifer system.
3) Immediately downstream of Lock-7 the average river pool level was not significantly altered, however, further downstream the average river pool level was slightly elevated.
4) Elevated pool levels resulted in constant flow through the anabranch creeks that then delivered a mix of River Murray water and saline groundwater back to the river on a daily basis (Plate 2).
5) Construction of locks, weirs, storages on, and diversions from the River Murray resulted in highly modified reduced flows, and less frequent flood events.
6) Evapotranspiration increased, due to the elevated (1–2 m) groundwater table on the Chowilla floodplain. This resulted in the soil salinisation and thus degradation of the native vegetation (Plate 3).

The modelling undertaken has resulted in an enhanced understanding of the hydrology of the Chowilla floodplain and this is discussed in the conclusion of this report.

Plate 2. Post-locking constant flow in Monoman Creek

Plate 3. Dying trees resulting from rising groundwater table and groundwater salinisation

MODEL CONSTRUCTION

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 3.1.0.86 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, production 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 PCG2 solver was used for all steady state and transient modelling runs.

MODEL CONSTRUCTION

MODEL DOMAIN AND GRID

The model domain simulates an area 55 km (east west) by 45 km (north south) and includes the western part of Lake Victoria and the entire Chowilla floodplain (Fig. 9). The bounding AMG coordinates are (southwest) E470000 N6220000 and (northeast) E525000 N6265000 (GDA 1994).

The selection of a large model domain that incorporates the smaller study area is consistent with good modelling practice. The model domain boundaries are set at a sufficient distance from the study area such that they do not influence the behaviour of the aquifer system in the study area.

The rectangular model grid is divided into 393 rows and 390 columns. The minimum grid size is 76.5 x 62.5 m in the Chowilla floodplain. The maximum grid size is 305 x 250 m in the remaining model area (Fig. 10).

MODEL LAYERS

MODFLOW layer options are given in Table 2.

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.

The regional aquifer system underlying the Chowilla floodplain was conceptualised as five layers, including four aquifer layers and one aquitard layer (Fig. 11, Table 3). The model grid was applied to the five layers resulting in 312,500 finite difference cells.

Table 3. Model layer aquifers and aquitards

Layer No	Hydrogeological unit	Aquifer / aquitard	MODFLOW layer
1	Upper Monoman Formation unconfined – semi-unconfined aquifer and highland Upper Pliocene Sands (Upper Part) unconfined aquifers of variable thickness. Type-3 is used for this layer due to the groundwater table occurring within the Coonambidgal Formation on the floodplain, and the semi-unconfined nature of the aquifer.	Aquifer	Type-3
2	Lower Monoman Formation and highland Upper Pliocene Sands (lower part) – semi-confined aquifers of variable thickness.	Aquifer	Type-3
3	Lower Pliocene Sands, semi-confined low permeability aquifer, thickness ~5 m.	Aquifer	Type-3
4	Bookpurnong Formation - aquitard of variable thickness.	Aquitard	Type-0
5	Murray Group Limestone - confined aquifer of variable thickness.	Aquifer	Type-0

Chowilla floodplain ground surface

The Department of Environment and Heritage (DEH) provided regional elevation data (App. 1). The elevation data on the Chowilla floodplain is at an interval of 5 m with an error less than 0.5 m. The elevation of the floodplain is 16–22 m AHD.

Highland ground surface

Elevation data was collected from New South Wales, Victoria and South Australia (App. 1). The elevation data was less accurate than that on the Chowilla floodplain. The elevation of the highland is 50–60 m AHD.

Layer-1: Upper Monoman Formation, Upper Pliocene Sands (upper part)

Layer-1 simulates the Upper Monoman Formation as an unconfined - semi-unconfined aquifer (on the Chowilla floodplain) and the Upper Pliocene Sands (Upper Part) as an unconfined aquifer (on the highland). Layer-1 is ~10 m thick on the floodplain and 30–60 m thick on the highland. The base elevation of Layer-1 was determined from drillhole logs (where available) and extrapolation of these values (App. 1).

The representation of the Upper Monoman Formation in the model Layer-1 as a Modflow Type-3 layer (confined / unconfined) allows the model to simulate the layer as unconfined when the groundwater table exists below the aquifer top, i.e. is within the aquifer (and confined if the groundwater table exists above the aquifer top).

Layer-2: Lower Monoman Formation, Upper Pliocene Sands (lower part)

Layer-2 simulates the Lower Monoman Formation semi-confined aquifer (on the Chowilla floodplain) and the Upper Pliocene Sands (lower part) semi-confined aquifer (on the highland). Layer-2 is ~10 m thick on the floodplain and 3–10 m thick on the highland. The base elevation of Layer-2 was determined from drillhole logs (where available) and extrapolation of these values (App. 1).

Layer-3: Lower Pliocene Sands

Layer-3 simulates the Lower Pliocene Sands semi-confined aquifer. Layer-3 is ~20 m thick on Chowilla floodplain and 15–30 m thick on the highland. The base elevation of Layer-3 was determined from drillhole logs and cross-sections from previous reports (Anon 1989; Watkins 1992) (App. 1).

Layer-4: Bookpurnong Formation

Layer-4 simulates the Bookpurnong Formation aquitard. Layer-4 is ~20 m thick in the north and 40 m thick in the south of the model domain, and ~25–30 m thick on the Chowilla floodplain. The base elevation of Layer-4 (App. 1) was adopted from previous investigations (Waterhouse 1989).

Layer-5: Murray Group Limestone

Layer-5 simulates the Murray Group Limestone confined aquifer. Layer-5 was assumed to be 100 m thick (Waterhouse 1989). The base was set at ~-180 m AHD (App. 1).

MODEL AQUIFER AND AQUITARD HYDRAULIC PARAMETERS

It is standard practice, when commencing a modelling project, to initially allocate aquifer and aquitard hydraulic properties based on previous reported values.

In order to commence model calibration, regional values of aquifer and aquitard hydraulic parameters were derived from previous reports, and for the Monoman Formation from drilling programs and pumping tests (Anon, 1989; Waterhouse, 1989; Watkins, 1992; Howles and Marsden, 2003).

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. Horizontal hydraulic conductivity values for the Upper Monoman Formation, the aquifer of most interest, remain very close to values determined from the results of pumping tests. Storage coefficient values for the Upper Monoman Formation remain within the same order of magnitude of those determined from pumping tests.

The final aquifer and aquitard hydraulic parameters are given in Table 4, with their distribution within each layer given in Appendix 2.

Table 4. Calibrated model aquifer and aquitard hydraulic parameters

Aquifer / aquitard	Layer	K_h (m/day)	K_V (m/day)	S_Y (-)	S_S(/m)
Upper Monoman Formation	1	0.1*, 10-15	0.1*, 0.15 - 1	0.1	$1x10^{-4}$
Lower Monoman Formation	2	0.1* - 5	0.1*, 0.15 - 1	--	$1x10^{-4}$
Upper Pliocene Sands	1&2	5	0.5	0.1	$1x10^{-4}$
Lower Pliocene Sands	3	3	0.5	--	$1x10^{-5}$
Bookpurnong Formation	4	10^{-7} – $8x10^{-6}$	10^{-7} – $8x10^{-6}$	--	$1x10^{-5}$
Murray Group Limestone	5	0.03 – 0.5	0.03-0.1	--	$1x10^{-5}$

* Lower permeability material under / near the River Murray

Monoman Formation

The Monoman Formation is generally an unconfined – semi-unconfined aquifer, but may be come semi-confined in places due to the existence of the Coonambidgal Formation that varies in thickness, 0–20 m. An hydraulic conductivity of 10–15 m/day, and a specific yield of 0.1 were applied in the model.

Recent drilling and pumping tests on the Chowilla floodplain at Gum Flat and Tareena Bong indicated that the Monoman Formation is separated into an upper and lower aquifer by a thin aquitard (Howles and Marsden, 2003). This situation has been represented in the model by applying differing hydraulic conductivity values to upper and lower aquifers. The transient calibration results in:

1) Upper Monoman Formation hydraulic conductivity of 10–15 m/day, and a specific yield of 0.1.
2) Lower Monoman Formation hydraulic conductivity 5 m/day, and a specific storage of 10^{-4}/m.

These values result in the best fit to the drawdown curves measured at observation wells during the pumping tests conducted at Gum Flat, Tareena Bong, and Lake Littra.

Note:

When the aquifer hydraulic parameters obtained from the analysis of the pumping tests were used, it was not possible to match modelled and observed results. This may be due either to calculations used in the pumping test analysis not correctly accounting for the influence of hydraulic boundaries or the natural variability within the aquifer resulting in local aquifer properties measured in the tests being site specific rather than average regional values.

Pliocene Sands

The Upper Pliocene Sands is unconfined where it occurs in the highland area and is in direct hydraulic communication with the Monoman Formation. An hydraulic conductivity of 5 m/day and a specific yield of 0.1 were applied in the model. These values were adopted from Jolly and Walker (1995).

The Lower Pliocene Sands becomes semi-confined where it occurs beneath the Monoman Formation on the Chowilla floodplain. An hydraulic conductivity of 3 m/day and a specific storage of 10^{-5}/m were applied in the model. These values are those commonly used for representing a confined aquifer.

Bookpurnong Formation

The low vertical hydraulic conductivity of the Bookpurnong Formation controls vertical leakage from Murray Group Limestone into the overlying Pliocene Sands. Vertical hydraulic conductivity values of 10^{-7}–10^{-6} m/day were applied in the model based on previous technical investigations (Barnett, 1990) and from the results of calibration. Sensitivity tests indicate that varying the vertical hydraulic conductivity of the Bookpurnong Formation significantly affects potentiometric head in both the Monoman Formation and the Pliocene Sands.

Murray Group Limestone

An hydraulic conductivity of 0.03–0.5 m/day and a specific storage of 10^{-5}/m were applied to the Murray Group Limestone in the model.

MODEL BOUNDARY CONDITIONS

The five-layer model is complex and differing boundary conditions were applied to simulate the aquifer system and surface water system and their hydraulic interaction.

Layer-1: Upper Monoman Formation & Pliocene Sands (upper part)

The regional groundwater flow is from east to west within the model domain, and laterally from the Pliocene Sands into the Monoman Formation. The following boundary conditions were applied in the model (App. 3):

1) No-flow boundaries where groundwater flow is parallel to the model edge.
2) General head boundaries on the edges where groundwater flows into and out of the model.
3) Constant head boundary cells to simulate Lake Victoria pool level.
    a) In the steady state (pre-locking) model 22 m AHD was applied.
    b) In the transient (post-locking) model 25 m AHD was applied.
4) Constant head boundary cells to simulate the River Murray stage and pool level.
    a) In the steady state (pre-locking) model a value of 19.25 m AHD was applied to the constant head cells upstream of the location of Lock-7 (eastern edge of model) and graded down to 15.3 m AHD downstream of Lock-6 (southern edge of model).
    b) In the transient (post-locking) model the following stepped pool levels were applied:
        i) 22.15 m AHD upstream of Lock-7.
        ii) 19.25 m AHD Lock-6 – Lock-7.
        iii) 16.30 m AHD downstream of Lock-6.
5) River cells were selected to simulate the stage of the anabranch creeks on the Chowilla floodplain, with the conductance varied to simulate the hydraulic communication between the aquifer system and the anabranch creeks. The locations of the creeks, flushing weirs and stage monitoring sites are given in Figures 12 and 13 (Sharley and Goggan, 1995).
    a) In the steady state (pre-locking) model river cells were assigned a stage value the same elevation as the bottom of the anabranch creeks.

b) In the transient (post-locking) model the groundwater level falls around 2–3 m over the weirs and embankments, and the surface water gradient is relatively flat in the anabranch creeks. The stage applied to the river cells gradually declines from upstream to downstream:

    i) 19.25–18.8 along Salt Creek up to inlet on the River Murray.

    ii) 18.8–17.0 along downstream Salt Creek.

    iii) 17.0–16.5 m AHD along Punkah Creek.

    iv) 16.5–16.3 m AHD along Monoman Creek and Chowilla Creek.

6) Drainage cells were applied in the model in areas of reduced elevation to simulate some low land areas where groundwater constantly discharges due to evaporation.

7) Drainage cells (18 m AHD) were applied in the southwest corner to simulate the existing drainage system in the Renmark Irrigation Area.

Layer-2: Lower Monoman Formation & Pliocene Sands (lower part)

The regional groundwater flow is from east to west within the model domain, and laterally from the Pliocene Sands into the Monoman Formation. The following boundary conditions were applied in the model (App. 3):

1) No-flow boundaries where groundwater flow is parallel to the model edge.

2) General head boundaries on the model edges where groundwater flows into and out of the model.

3) Constant head boundaries to simulate hydraulic connectivity between Lake Victoria and aquifers.

Layer-3: Lower Pliocene Sands

The same boundary conditions as Layer-2 (App. 3).

Layer-4: Bookpurnong Formation

Very small volumes of groundwater move laterally into and out of Layer-4 due to its low permeability. No-flow boundaries were used at the model edges (App. 3).

Layer-5: Murray Group Limestone

Regional groundwater flow is from the northeast to southwest within the model domain. General head boundaries were used at the model edges to simulate groundwater flow into and out of the model (App. 3).

MODEL RECHARGE

The Chowilla floodplain has a semi-arid climate with hot dry summers and some rainfall during winter months. The average rainfall in the floodplain is ~300 mm/year with evaporation ~2,000 mm/year (Jolly and Walker, 1995).

Vertical recharge resulting from rainfall is considered to be 0.1 mm/year in highland areas where undisturbed native vegetation exists (Allison et. al., 1990). This value was applied in the steady state model and non-irrigated highland areas in the transient model.

According to research conducted by the CSIRO (Thornburn *et al*. 1993), recharge from rainfall may be as low as 0 mm/year on the floodplain, and this value was used in this non-flooding model.

The recharge that occurs to the aquifer system during flooding is a function of surface elevation (i.e. area that is inundated), soil type (i.e. clay thin or absent) and vegetation vigour following a flood. Locations of potential recharge zones with rates of 1–6 mm/day were provided by CSIRO (Fig. 14). Recharge rates were based on previous investigations (pers. comm. Ian Jolly and Ian Overton CSIRO). The recharge area expands with increasing flood magnitude. This information will be used in further more complex modelling work that will include flooding events over the Chowilla floodplain.

Recharge values of 20–30 mm/year (a reasonable value for drainage from irrigation) were applied in the transient model in the Renmark Irrigation Area to simulate the locally developed groundwater mound.

MODEL EVAPOTRANSPIRATION

Evapotranspiration is an important sink for groundwater, and occurs in areas where shallow groundwater exists (generally less than 3 m below ground surface), and via vegetation. An evapotranspiration rate of 150–200 mm/year, and an extinction depth of 1.5–2 m were applied in the model. These values were adopted from a CSIRO floodplain investigation conducted near Loxton (Holland et al., 2001) and from the results of calibration.

According to Thornburn et al. (1993), ~1 mm/day evapotranspiration could occur from eucalypt forest (Plate 4). This was confirmed during calibration, as modelled potentiometric head could only be matched to observed potentiometric head if a discharge rate of 1 mm/day was applied in forest areas.

MODEL GROUNDWATER ALLOCATION AND USE

There is no groundwater allocation or use in the Chowilla region.

MODEL STRESS PERIOD

The steady state model was used to model the pre-locking equilibrium natural groundwater condition based on the assumption that the long-term pre-locking hydrological regime was approximately in a steady state.

The transient model was used to model the historical period, post-locking of the River Murray, from 1930 to 2004. A one-year stress period was applied during the first five years, as the new river regime became established, and a five-year stress period was applied to the remaining 95 years.

The transient model was applied to predictions over 100-years, with a one-year stress period applied during the first five years, and five-year stress period applied to the remaining 95 years.

A daily stress period was used when the pumping tests were used in the calibration.

Plate 4 High evapotranspiration occurs from areas of dense Eucalypt

MODEL 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 that the model can replicate the behaviour of the aquifer system for at least one set of conditions. A sensitivity analysis must also be undertaken to determine the relative importance of model parameters (i.e. the system drivers) in achieving calibration.

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.

Due to the lack of pre-locking historical correlated groundwater and surface water data, the steady state model was calibrated using an iterative process between the steady state and transient models using the following steps:

1) Run the steady state model.
2) Use the potentiometric heads from the steady state model as initial heads to run the transient model.
3) Compare the modelled groundwater heads (after 75 years of transient calculation) with observed heads from 2003–04.
4) Adjust the model parameters of both models and re-run the steady state model, and then the transient model, until the modelled and observed potentiometric heads adequately match.

In this manner, the steady state model was gradually calibrated such that the modelled potentiometric heads were believed to accurately represent those of the pre-locking aquifer system.

TRANSIENT MODEL CALIBRATION

Transient calibration is undertaken to calibrate aquifer and aquitard hydraulic parameters, and refine boundary conditions. The potentiometric head output from the calibrated steady state model was used as the starting point for transient model runs up to 2004 that include post-locking conditions.

As mentioned in the previous section, the transient and steady state models were calibrated through an iterative process that involved adjusting the boundary conditions and aquifer hydraulic parameters. Each time a change to the boundary conditions and aquifer hydraulic parameters were 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, in accordance with Murray Darling Basin Commission (2000):

1) Qualitative comparison between modelled and observed potentiometric heads.
2) Quantitative comparison between modelled and observed potentiometric heads.
3) Iteration residual error.
4) Using salt load as confirmation (rather than water balance as calibration, as recommended).

MODEL CALIBRATION - QUALITATIVE COMPARISON OF POTENTIOMETRIC HEADS

Initial qualitative calibration of the transient model was undertaken by simulating the regional potentiometric heads that developed post-locking. This transient modelling run commenced in the 1930s, and was run for 75 years to model historical hydrologic conditions. The modelled and observed potentiometric heads from 2003 and 2004 were compared to determine the accuracy of the calibration.

Layer-1: Upper Monoman Formation & Pliocene Sands (upper part)

Qualitative comparison, between the modelled and observed potentiometric heads (Fig. 15) of the Monoman Formation and the Pliocene Sands (Upper Part), indicates the modelled distribution closely represents the shape and form of the observed distribution.

Layer-5: Murray Group Limestone

Qualitative comparison, between the modelled and observed potentiometric heads (Fig. 16) of the Murray Group Limestone, indicates the modelled distribution closely represents the shape and form of the observed distribution.

MODEL CALIBRATION - QUANTITATIVE COMPARISON OF POTENTIOMETRIC HEADS

Quantitative comparison of the modelled potentiometric head response to the pumping tests conducted at Gum Flat, Tareena Bong, and Lake Littra with the observed data. The modelled data indicates, in many cases, a close similarity with the observed data. The location of observation wells and the modelled head response are given in Appendix 4.

The calibration is conservative, in that most of the modelled drawdown is less than that observed. This means that when the model is used for prediction, the resulting drawdown is likely to be less than that which will occur, i.e. conservative in terms of the operation of a SIS.

MODEL CALIBRATION - ITERATION RESIDUAL ERROR

The iteration residual error between modelled and observed potentiometric heads of the Monoman Formation and Pliocene Sands was calculated using data from 2003. The calculation (Fig. 18) indicates a normalised root mean square value of 3.15%. This value is less than the 5% recommended by Murray Darling Basin Commission (2000).

MODEL CONFIRMATION - COMPARISON OF SALT LOAD

Confirmation that the modelled (calculated) 2002 salt load entering the anabranch creeks on the Chowilla floodplain matched the observed 2002 run-of-creek data (where available) was achieved by comparing the modelled and observed values.

The modelled 2002 salt loads entering the anabranch creeks on the Chowilla floodplain was determined by converting the modelled groundwater flux to a salt load by applying relevant values of groundwater salinity for a number of model flow budget zones (Fig. 17).

The modelled salt load values are quite acceptable. Most importantly, the salt load being delivered to the River Murray in Scenario-3 (do nothing) is 32 tonnes/day. This corresponds to the current run-of-river salinity surveys (no flooding for several years) that indicates a salt load increase associated with the Chowilla region of 30 tonnes/day (pers. Comm. Barry Porter DWLBC).

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 fluxes of saline groundwater, and the impacts of specific pumping stresses on groundwater levels, over periods that may range from tens to hundreds of years.

In particular, the model can predict the:

1) Flux of saline groundwater (and the given the groundwater salinity, the salt load) entering the floodplain (Monoman Formation) from the highland (Pliocene Sands).
2) Flux of saline groundwater (and salt load) entering the anabranch creeks from the floodplain (Monoman Formation), and therefore the River Murray.
3) Vertical leakage (and salt load) from the Murray Group Limestone into the overlying Pliocene Sands.
4) Impact of SIS on groundwater levels and salt load being delivered to the River Murray.
5) Evapotranspiration (note that salt concentrated by evapotranspiration does not figure in the salt load calculations, as this is not additional salt into / out of the floodplain).

The salt load moving into and out of the Chowilla floodplain was calculated using the following average groundwater salinities that were assumed to remain constant through time:

1) Highland average groundwater salinity 35,000 mg/L (observed range 34,000–38,000 mg/L).
2) General floodplain average groundwater salinity 25,000 mg/L (observed range 10,000–35,000 mg/L).
3) Floodplain near creeks average groundwater salinity 45,000 mg/L (observed range 10,000–70,000 mg/L).
4) Murray Group Limestone average groundwater salinity 20,000 mg/L (observed range 20,000–25,000 mg/L).

SCENARIOS

The following scenarios (discussed in detail below) were run:

Scenario-1:- The natural aquifer system pre-river regulation.

Scenario-2:- The natural aquifer system post-river regulation to the present (2003).

Scenario-3:- Do nothing management option.

Scenario-4:- SIS on floodplain management option.

Scenario-5:- ES targeted areas + SIS on floodplain management option.

Scenario-6:- ES entire floodplain (includes SIS) management option.

Scenario-7:- SIS on highland (and floodplain) management option.

Scenario-8:- SIS on floodplain + part-ES targeted areas management option.

SCENARIO-1: THE NATURAL AQUIFER SYSTEM PRE-RIVER REGULATION

This steady state scenario simulates the aquifer system in the Chowilla region prior to the anthropogenically modified flow regime of the River Murray resulting from the construction of locks and weirs, storages and diversions for irrigation, industry and town water supply.

Scenario-1: Conditions

The following conditions were applied in the model:

1) River Murray pool level gradually reducing from:
   a) 19.26 m AHD at the location of Lock-7 to 16.3 m AHD at the location of Lock-6.
   b) 16.3 AHD at the location of Lock-6 to 15 m AHD at the southern model boundary.
2) No water in the anabranch creeks.
3) No flooding.

Scenario-1: MODELLING results

The model results are given in Table 5. The results indicate that:

1) The groundwater flux from the highland to the floodplain of 2.55 ML/day was similar to the flux entering the anabranch creeks (2.36 ML/day).
2) The vertical leakage from the Murray Group Limestone to the floodplain was 0.29 ML/day (9% of the total lateral groundwater flux from the highland).
3) Evapotranspiration was 0.17 ML/day, insignificant compared to the groundwater flux into and out of the floodplain.
4) Note that the model indicates a LOSS of salt from the floodplain of 9 tonnes/day (highland to floodplain + vertical leakage – floodplain to anabranch creeks). This loss occurs as the salt entering the anabranch creeks is transported to the River Murray and removed from the floodplain permanently. Allowing for inaccuracies resulting from modeling, it can be accepted that the aquifer system was approximately in balance, in that the salt that entered the system eventually exited the system via the anabranch creeks.

Table 5. Scenario-1: steady state modelling results

	Floodplain to anabranch creeks	**Highland to floodplain**	**Vertical leakage**	**Evapo-transpiration**	**Salt *Lost* from floodplain**
Groundwater Flux (ML/day)	2.36	2.55	0.29	0.17	--
Salt load (Tonnes/day)	106.16	89.32	7.30	--	9

SCENARIO-2: THE NATURAL AQUIFER SYSTEM POST-RIVER REGULATION TO THE PRESENT (2003)

This transient scenario simulates the aquifer system in the Chowilla region post-locking of the River Murray in 1930, to 2003, i.e. the historical on-ground situation.

Scenario-2: Conditions

The following conditions were applied in the model:

1) Locking of the River Murray around 1930.
2) River Murray pool level set at:
   a) 19.26 m AHD between Lock-7 and Lock-6.
   b) 16.3 m AHD from Lock-6 to the southern model boundary.
3) Permanent water in the anabranch creeks.
4) No flooding.

Scenario-2: Modelling results

The model results for 2003 are given in Table 6. The results indicate that, with respect to Scenario-1 (the natural aquifer system pre-river regulation):

1) The total groundwater flux from the highland to the floodplain decreased 0.27 ML/day (11% change which is significant).
2) The vertical leakage from the Murray Group Limestone to the floodplain decreased 0.03 ML/day (10% change which is insignificant).
3) Evapotranspiration increased by 2.86 ML/day (1,700% change which is significant).
4) Groundwater flux entering the anabranch creeks decreased by 1.66 ML/day (70% change which is significant and results in a reduction in the salt being flushed from the floodplain of 75 tonnes/day).
5) In the reach of the River Murray adjacent to the modeled floodplain (above Lock-6), the river is a loosing stream.
6) Total additional salt being STORED in the floodplain amounts to 55 tonnes/day (highland to floodplain + vertical leakage – floodplain to anabranch creeks).

Table 6. Scenario-2: Transient modelling results 2003

	Floodplain to anabranch creeks	**Highland to floodplain**	**Vertical leakage**	**Evapo-transpiration**	**Additional salt *Stored* in floodplain**
Groundwater Flux (ML/day)	0.70	2.28	0.26	3.03	--
Salt load (Tonnes/day)	31.37	79.7	6.58	--	55

SCENARIO-3: DO NOTHING MANAGEMENT OPTION

This transient scenario predicts the response of the aquifer system in the Chowilla region 100 years into the future. The scenario predicts the changes in the aquifer system assuming that there is no additional disturbance.

Scenario-3: Conditions

The following conditions were applied in the model:

1) River Murray pool level set at:
    a) 19.26 m AHD between Lock-7 and Lock-6.
    b) 16.3 m AHD from Lock-6 to the southern model boundary.
2) Permanent water in the anabranch creeks.
3) No flooding.

Scenario-3: Prediction results

The model results 100 years into the future are given in Table 7. The results indicate that, with respect to Scenario-2 (the natural aquifer system post-river regulation to the present (2003)):

1) The total groundwater flux from the highland to the floodplain may increase by 0.17 ML/day (7% change which is insignificant).
2) Vertical leakage from the Murray Group Limestone to the floodplain remains unchanged.
3) Evapotranspiration may increase by 0.14 ML/day (5% change which is insignificant).
4) Groundwater flux entering the anabranch creeks may increase by 0.02 ML/day (3% change which is insignificant).
5) Total additional salt being STORED in the floodplain amounts to 5 tonnes/day (highland to floodplain + vertical leakage – floodplain to anabranch creeks).
6) In the reach of the River Murray adjacent to the modeled floodplain (above Lock-6), the river is a loosing stream.

Scenario-3 predicts continuation of current conditions. The predicted changes in salt load entering the anabranch creek system are small enough to be considered negligible when uncertainties regarding actual salinities are considered.

Table 7. Scenario-3: transient prediction results 100 years into the future

	Floodplain to anabranch creeks	**Highland to floodplain**	**Vertical leakage**	**Evapo-transpiration**	**Additional salt *Stored* in floodplain**
Groundwater Flux (ML/day)	0.72	2.45	0.26	3.17	--
Salt load (Tonnes/day)	32.4	85.6	6.55	--	5

SCENARIO-4: SIS ON FLOODPLAIN MANAGEMENT OPTION

This transient scenario predicts the response of the aquifer system in the Chowilla region 100 years into the future. The scenario models the changes in the aquifer system assuming that a SIS is constructed on the floodplain in 2003.

Previous investigations and modelling indicate that the base salt load occurs mainly on the eastern side of the floodplain. The SIS involves a curtain of continuously pumping production wells (located on the eastern side of the Chowilla floodplain along the eastern edge of Salt Creek and Punkah Creek adjacent to the highland completed in the Monoman Formation) to control the flux of saline groundwater entering the anabranch creeks (Fig. 19). Controlling flood recession will be addressed in a subsequent modelling report.

Scenario-4: Conditions

The following conditions were applied in the model:

1) River Murray pool level set at:
    a) 19.26 m AHD between Lock-7 and Lock-6.
    b) 16.3 m AHD from Lock-6 to the southern model boundary.
2) Permanent water in the anabranch creeks.
3) No flooding.
4) SIS comprising 22 production wells on the floodplain pumping at rates commencing at 5.5 L/s for the initial 5 years and then reducing to 3 L/s.

Scenario-4: Prediction results

The model results 100 years into the future are given in Table 8. The results indicate that, with respect to Scenario-3 (do nothing):

1) The total flux of groundwater from the highland to the floodplain may increase by 0.2 ML/day (8% change which is insignificant).
2) Vertical leakage from the Murray Group Limestone to the floodplain may increase by 0.02 ML/day (8% change which is insignificant).
3) Evapotranspiration may decrease by 2.26 ML/day (71% change which is significant, and will have benefits for the health of floodplain vegetation).
4) Groundwater flux entering the anabranch creeks may decrease by 0.61 ML/day (85% change which is significant).
5) The operation of the SIS will reduce the salt load entering the anabranch creeks (and therefore the River Murray) by 27 tonnes/day. This represents an in-river salinity benefit of 7 EC at Morgan (assuming 3.1 tonnes per EC).
6) Total additional salt being REMOVED from the floodplain amounts to 105 tonnes/day (highland to floodplain + vertical leakage – floodplain to anabranch creeks – pumping).
7) In the reach of the River Murray adjacent to the modeled floodplain (above Lock-6), the river is a loosing stream.

Table 8. Scenario-4: transient prediction results 100 years into the future

	Floodplain to anabranch creeks	Highland to floodplain	Vertical leakage	Pumping	Evapo-transpiration	Additional salt ***Removed*** from floodplain
Groundwater Flux (ML/day)	0.11	2.65	0.28	6.00	0.91	--
Salt load (Tonnes/day)	5.09	92.58	7.05	200	--	105

Scenario-4: Advantages and disadvantages

Advantages of Scenario-4 in comparison to Scenario-7 (SIS on highland (and floodplain)):

1) The production and observation wells will not be as deep or expensive.
2) The construction of the SIS will result in some environmental benefits on the floodplain.
3) More salt will be removed from the floodplain.

Disadvantages of Scenario-4 in comparison to Scenario-7:

1) Greater disturbance of the floodplain resulting from the construction of production and observation wells, construction of pipelines and access roads, and the connection of electricity.
2) May be more difficult to install the pipelines and electricity.
3) Considerable maintenance following flood events.
4) Assuming that production wells are completed in the semi-unconfined Monoman Formation, the control exerted by the SIS will be affected by flooding (this may result in the need for more production wells).
5) Increased flux from the highland into the floodplain.

SCENARIO-5: ES TARGETTED AREAS + SIS ON FLOODPLAIN MANAGEMENT OPTION

This transient scenario predicts the response of the aquifer system in the Chowilla region 100 years into the future. The scenario models the changes in the aquifer system assuming that an ES + SIS is constructed on the floodplain in 2003.

The ES + SIS involves continuously pumping production wells (located across the Chowilla floodplain in targeted areas identified by DEH and CSIRO) to control the flux of saline groundwater entering the anabranch creeks, and to provide benefits for vegetation (Fig. 20). Controlling flood recession will be addressed in a subsequent modelling report.

Scenario-5: Conditions

The following conditions were applied in the model:

1) River Murray pool level set at:
    a) 19.26 m AHD between Lock-7 and Lock-6.

b) 16.3 m AHD from Lock-6 to the southern model boundary.

2) Permanent water in the anabranch creeks.

3) No flooding.

4) ES + SIS comprising 77 production wells on the floodplain pumping at rates commencing at 3–5 L/s for the initial 5 years and then reducing to 1–3 L/s.

Scenario-5: Prediction results

The model results 100 years into the future are given in Table 9. The results indicate that, with respect to Scenario-3 (do nothing):

1) Groundwater levels will be drawn down 2 m below current levels in the targeted areas within five years from the commencement of pumping (Fig. 21).

2) The total flux of groundwater from the highland to the floodplain may increase by 2.47 ML/day (100% change which is significant and which results in an additional 87 tonnes/day of salt entering the floodplain).

3) Vertical leakage from the Murray Group Limestone to the floodplain may increase 0.1 ML/day (38% increase, but this is insignificant due to the relative small value in comparison to other values).

4) Evapotranspiration may decrease by 3.12 ML/day (98% change which is significant, and will have benefits for the health of floodplain vegetation).

5) Groundwater flux entering the anabranch creeks may decrease by 0.71 ML/day (99% change which is significant).

6) The operation of the SIS will reduce the salt load entering the anabranch creeks (and therefore the River Murray) by 32 tonnes/day. This represents an in-river salinity benefit of 8 EC at Morgan (assuming 3.1 tonnes per EC).

7) Total additional salt being REMOVED from the floodplain amounts to 280 tonnes/day (highland to floodplain + vertical leakage – floodplain to anabranch creeks – pumping).

8) In the reach of the River Murray adjacent to the modeled floodplain (above Lock-6), the river is a loosing stream.

Table 9. Scenario-5: transient prediction results 100 years into the future

	Floodplain to anabranch creeks	**Highland to floodplain**	**Vertical leakage**	**Pumping @ 2 L/s @ 35,000 mg/L**	**Evapo-transpiration**	**Additional salt *<u>Removed</u>* from floodplain**
Groundwater Flux (ML/day)	0.01	4.92	0.36	13.00	0.05	--
Salt load (Tonnes/day)	0.27	172.10	8.93	460.00	--	280

Scenario-5: Advantages and disadvantages

Advantages of Scenario-5 in comparison to Scenario-4 (SIS on floodplain):

1.) More environmental benefits.

2.) More salt will be removed from the floodplain.

Disadvantages of Scenario-5 in comparison to Scenario-4:

1.) More disturbance of the floodplain.

2.) Greater costs associated with the additional infrastructure.

3.) More maintenance following flood events.

Increased flux from the highland into the floodplain.

SCENARIO-6: ES ENTIRE FLOODPLAIN (INCLUDES SIS) MANAGEMENT OPTION

This transient scenario predicts the response of the aquifer system in the Chowilla region 100 years into the future. The scenario models the changes in the aquifer system assuming that an ES (includes SIS) is constructed over the entire floodplain in 2003.

The ES (SIS) involves continuously pumping production wells (located across the entire Chowilla floodplain to control the flux of saline groundwater entering the anabranch creeks) and the provide benefits for vegetation (Fig. 22). Controlling flood recession will be addressed in a subsequent modelling report.

Scenario-6: Conditions

The following conditions were applied in the model:

1) River Murray pool level set at:

    a) 19.26 m AHD between Lock-7 and Lock-6.

    b) 16.3 m AHD from Lock-6 to the southern model boundary.

2) Permanent water in the anabranch creeks.

3) No flooding.

4) ES (SIS) comprising 119 production wells pumping at rates commencing at 4 L/s for the initial 5 years and then reducing to 1–2 L/s.

Scenario-6: Prediction results

The model results 100 years into the future are given in Table 10. The results indicate that, with respect to do nothing Scenario-3 (do nothing):

1) Groundwater levels will be drawn down 2 m below current levels over the entire Chowilla floodplain within five years from the commencement of pumping (Fig. 23).

2) The total flux of groundwater from the highland to the floodplain may increase by 3.13 ML/day (128% change which is significant and which results in an additional 110 tonnes/day of salt entering the floodplain).

3) Vertical leakage from the Murray Group Limestone to the floodplain may increase 0.12 ML/day (46% change, but this is insignificant due to the relative small value in comparison to other values).

4) Evapotranspiration may decrease by 3.15 ML/day (99% change which is significant, and will have benefits for the health of floodplain vegetation).
5) Groundwater flux entering the anabranch creeks may decrease by 0.72 ML/day (100% change which is significant).
6) The operation of the SIS will reduce the salt load entering the anabranch creeks (and therefore the River Murray) by 32 tonnes/day. This represents an in-river salinity benefit of 8 EC at Morgan (assuming 3.1 tonnes per EC).
7) Total additional salt being REMOVED from the floodplain amounts to 382 tonnes/day (highland to floodplain + vertical leakage – floodplain to anabranch creeks – pumping).
8) In the reach of the River Murray adjacent to the modeled floodplain (above Lock-6), the river is a loosing stream.

Table 10. Scenario-6: Transient prediction results 100 years into the future

	Floodplain to anabranch creeks	**Highland to floodplain**	**Vertical leakage**	**Pumping @ 1.5 L/s @ 25,000 mg/L**	**Evapo-transpiration**	**Additional salt *Removed* from floodplain**
Groundwater Flux (ML/day)	0.00	5.58	0.38	17.00	0.02	--
Salt load (Tonnes/day)	0.09	195.14	9.48	587	--	382

Scenario-6: Advantages and disadvantages

Advantages of Scenario-6 in comparison to Scenario-5 (ES targeted areas + SIS on floodplain):

1) Considerably more environmental benefits.
2) Considerably more salt removed from the floodplain.

Disadvantages of Scenario-6 in comparison to Scenario-5:

1) Considerably more disturbance of the floodplain.
2) Greater costs associated with the additional infrastructure.
3) Considerably more maintenance following flood events.
4) Considerably increased flux from the highland to the floodplain.

SCENARIO-7: SIS ON HIGHLAND (AND FLOODPLAIN) MANAGEMENT OPTION

This transient scenario predicts the response of the aquifer system in the Chowilla region 100 years into the future. The scenario models the changes in the aquifer system assuming that a SIS is constructed on the highland (and floodplain) in 2003.

Previous investigations and modelling indicate that the base salt load occurs mainly on the eastern side of the floodplain. The SIS involves a curtain of continuously pumping production wells located on the highland adjacent to Salt Creek on the eastern side of the Chowilla floodplain (completed in the Pliocene sands), and floodplain along Punkah Creek (completed in the Monoman Formation), to control the flux of saline groundwater entering the anabranch creeks (Fig. 24). Controlling flood recession will be addressed in a subsequent modelling report.

Scenario-7: Conditions

The following conditions were applied in the model:

1) River Murray pool level set at:
   a) 19.26 m AHD between Lock-7 and Lock-6.
   b) 16.3 m AHD from Lock-6 to the southern model boundary.
2) Permanent water in the anabranch creeks.
3) No flooding.
4) SIS comprising total 24 production wells (18 highland and 6 floodplain) pumping at rates commencing at 5.5 L/s for the initial 5 years and then reducing to 3 L/s.

Scenario-7: Prediction results

The model results 100 years into the future are given in Table 11. The results indicate that, with respect to Scenario-3 (do nothing):

1) The total flux of groundwater from the highland to the floodplain may decrease by 1.09 ML/day (44% change which is significant).
2) Vertical leakage from the Murray Group Limestone to the floodplain may increase by 0.02 ML/day (8% change which is insignificant).
3) Evapotranspiration may decrease by 2.32 ML/day (73% change which is significant, and will have benefits for the health of floodplain vegetation).
4) Groundwater flux entering the anabranch creeks may decrease by 0.6 ML/day (83% change which is significant).
5) The operation of the SIS will reduce the salt load entering the anabranch creeks (and therefore the River Murray) by 27 tonnes/day. This represents an in-river salinity benefit of 7 EC at Morgan (assuming 3.1 tonnes per EC).
6) Total additional salt being REMOVED from the floodplain amounts to 5.2 tonnes/day (highland to floodplain + vertical leakage – floodplain to anabranch creeks – pumping from floodplain).
7) In the reach of the River Murray adjacent to the modeled floodplain (above Lock-6), the river is a loosing stream.

The results indicate that the key differences with respect to Scenario-4 (SIS on floodplain) are:

1) The total flux of groundwater from the highland to the floodplain is 1.36 ML/day compared to 2.65 ML/day in Scenario-4.
2) Total salt being removed from the floodplain is only 5.2 tonnes/day compared to 105 tonnes/day in Scenario-4.

Table 11. Scenario-7: transient prediction results 100 years into the future

	Floodplain to anabranch creeks	Highland to floodplain	Vertical leakage	Pumping From floodplain	Pumping From highland	Evapo-transpiration	Additional salt ***Removed*** from floodplain
Groundwater Flux (ML/day)	0.12	1.36	0.28	1.56	4.67	0.85	--
Salt load (Tonnes/day)	5.43	47.58	7.11	54.43	163.30	--	5.2

Scenario-7: Advantages and disadvantages

Advantages of Scenario-7 in comparison to Scenario-4 (SIS on floodplain):

1) No disturbance of the floodplain resulting from the construction of production and observation wells, construction of pipelines and access roads, and the connection of electricity.
2) May be less difficult to install pipelines and electricity.
3) No maintenance following flood events.
4) Assuming that production wells are completed in unconfined Pliocene Sands, the control exerted by the SIS will not be affected by flooding.
5) Decreased flux from the highland into the floodplain.

Disadvantages of Scenario-7 in comparison to Scenario-4:

1) The production and observation wells will be deeper and more expensive.
2) Considerably less salt will be removed from the floodplain.

SCENARIO-8: SIS ON FLOODPLAIN + PART-ES TARGETED AREAS MANAGEMENT OPTION

This transient scenario predicts the response of the aquifer system in the Chowilla region region 100 years into the future. The scenario models the changes in the aquifer system assuming that a SIS + Part-ES is constructed on the floodplain in 2003.

The SIS involves a curtain of continuously pumping production wells, located on the eastern side of the Chowilla floodplain (along the eastern edge of the Salt Creek and Punkah Creek; and adjacent the highland completed in the Monoman Formation) to control the flux of saline groundwater entering the anabranch creeks (Fig. 25). The Part-ES involves continuously pumping production wells located in targeted areas on the Chowilla floodplain (identified by DEH and CSIRO) to provide benefits for vegetation. Controlling flood recession will be addressed in a subsequent modelling report.

Scenario-8: Conditions

The following conditions were applied in the model:

1) River Murray pool level set at:
    a) 19.26 m AHD between Lock-7 and Lock-6.

b) 16.3 m AHD from Lock-6 to the southern model boundary.

2) Permanent water in the anabranch creeks.

3) No flooding.

4) SIS + Part-ES comprising 38 production wells on the floodplain pumping at rates commencing at 3–5 L/s for the initial 5 years and then reducing to 1–3 L/s.

Scenario-8: Prediction results

The model results 100 years into the future are given in Table 12. The results indicate that, with respect to do nothing Scenario-3 (do nothing):

1) Groundwater levels will be drawn down 2 m below current levels in the targeted areas within three years from the commencement of pumping (Fig. 26).
2) The total flux of groundwater from the highland to the floodplain may increase by 0.66 ML/day (27% change which is significant and which results in an additional 23 tonnes/day of salt entering the floodplain).
3) Vertical leakage from the Murray Group Limestone to the floodplain may increase 0.04 ML/day (15% increase, but this is insignificant due to the relative small value in comparison to other values).
4) Evapotranspiration may decrease by 2.76 ML/day (87% change which is significant, and will have benefits for the health of floodplain vegetation).
5) Groundwater flux entering the anabranch creeks may decrease by 0.63 ML/day (88% change which is significant).
6) The operation of the SIS will reduce the salt load entering the anabranch creeks (and therefore the River Murray) by 29 tonnes/day. This represents an in-river salinity benefit of 7 EC at Morgan (assuming 3.1 tonnes per EC).
7) Total additional salt being REMOVED from the floodplain amounts to 163 tonnes/day (highland to floodplain + vertical leakage – floodplain to anabranch creeks – pumping).
8) In the reach of the River Murray adjacent to the modeled floodplain (above Lock-6), the river is a loosing stream.

Table 12. Scenario-8: transient prediction results 100 years into the future

	Floodplain to anabranch creeks	**Highland to floodplain**	**Vertical leakage**	**Pumping @ 2 L/s @ 35,000 mg/L**	**Evapo-transpiration**	**Additional salt *Removed* from floodplain**
Groundwater Flux (ML/day)	0.09	3.11	0.30	8.87	0.41	--
Salt load (Tonnes/day)	3.83	108.85	7.50	275.56	--	163

Scenario-8: Advantages and disadvantages

Advantages of Scenario-8 in comparison to Scenario-4 (SIS on floodplain) and Scenario-5 (ES targeted areas + SIS on floodplain):

1) More salt will be removed from the floodplain in comparison to Scenario-4.
2) More environmental benefits than Scenario-4.
3) Less cost than Scenario-5.
4) Less disturbance of the floodplain than Scenario-5.
5) Less maintenance following flood events than Scenario-5.
6) Reduced flux of groundwater from the highland to the floodplain in comparison to Scenario-5.

Disadvantages of Scenario-8 in comparison to Scenario-4 and Scenario-5:

1) Less salt will be removed from the floodplain in comparison to Scenario-5.
2) Less environmental benefits than Scenario-5.
3) Greater costs associated with the additional infrastructure than Scenario-4.
4) More disturbance of the floodplain than Scenario-4.
5) More maintenance following flood events than Scenario-4.
6) Increased flux of groundwater from the highland to the floodplain in comparison to Scenario-4.

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 aquifers modelled response. The purpose of sensitivity analysis is to identify the drivers in the system.

STEADY STATE MODEL SENSITIVITY ANALYSIS

During the steady state calibration it became apparent that:

1) The regional potentiometric head is very sensitive to lateral flow into and out of the model domain, which is driven by the potentiometric head and conductance applied to the general head boundary cells (where water flows into, or out of, the model) at the edges of the model. However, as the model boundary is located at considerable distance from the floodplain, any changes to the boundary conditions along the model edge will not cause significant changes to the results in the area of interest in the centre of the model.
2) The potentiometric head in the highland area is dependent on the hydraulic conductivity values used in Layer-1 that represent the Pliocene Sands (Upper Part) in the highland. The larger the hydraulic conductivity value applied in the model, the flatter the hydraulic gradient becomes. The modelled potentiometric head (and therefore, the predicted hydraulic conductivity value) of the Pliocene Sands was based on observed data from nine observation wells located on the highlands. Any changes made to this predicted hydraulic conductivity value will result in changes to the modelled head.
3) The vertical leakage from the Murray Group Limestone through the Bookpurnong Formation is very sensitive to changes in the vertical hydraulic conductivity of Layer-4.
4) Potentiometric heads on the Chowilla floodplain are mainly controlled by the anabranch creek bed levels, the conductance between the anabranch creeks and the aquifers, and the evapotranspiration rates.

TRANSIENT MODEL SENSITIVITY ANALYSIS

SENSITIVITY TEST-1: VARIATION OF UPPER MONOMAN FORMATION HYDRAULIC PARAMETERS BY +/- 15%

This sensitivity test was conducted to test the impact of variations in the aquifer hydraulic parameters of Upper Monoman Formation and increase confidence in the calibrated values. The aquifer hydraulic parameters of the Upper Monoman Formation are critical to the drawdown developed in response to pumping, and therefore wellfield design.

Sensitivity test-1: Conditions

Scenario-6 (ES entire floodplain (includes SIS)) was selected for sensitivity testing. Layer-1 represents the Upper Monoman Formation, Upper Pliocene Sands (Upper Part). Sensitivity tests were conducted by varying the Upper Monoman Formation aquifer hydraulic parameters by +/-15% of the predominant calibrated value (hydraulic conductivity = 15 m/day, specific yield = 0.1) in accordance with Murray Darling Basin Commission (2000), and running the model 100 years into the future.

Sensitivity test-1: Results

The drawdown developed in observation well 7030–85 (located in the centre of the cone of depression resulting from the operation of the wellfield) was used to determine the sensitivity to variations in aquifer hydraulic parameters. The results provide confidence in extrapolating the values calibrated at the sites of the pumping tests to other areas.

Sensitivity test results (Table 13) indicate that:

1) Changes of +/-15% to the calibrated Upper Monoman Formation hydraulic conductivity of 15 m/day (+15% = 17.25 m/day and -15% = 12.75 m/day) result in a maximum of +/-0.2 m change in the drawdown developed in the observation well 100 years into the future, which is insignificant.

2) Changes of +/-15% to the calibrated Upper Monoman Formation specific yield of 0.1 (+15% = 0.115 and -15% = 0.085) result in a maximum of +/-0.2 m change in the drawdown developed in the observation well 100 years into the future, which is insignificant.

This test is based on the worst-case scenario of controlling groundwater levels over the entire floodplain, and 0.2 m difference is considered insignificant.

Table 13. Results of sensitivity testing of variation in Upper Monoman Formation (Layer-1) aquifer hydraulic parameters - predicted drawdown at observation well 100 years into the future

	K_h (m/day)			S_Y		
Layer	**Layer-1 -15%**	**Layer-1**	**Layer-1 +15%**	**Layer-1 -15%**	**Layer-1**	**Layer-1 +15%**
Parameter value	12.75	15	17.25	0.085	0.1	0.115
Modelled drawdown (m)	5.51	5.64	5.67	5.47	5.64	5.84

The results given in Table 13 indicate that potentiometric heads in the Upper Monoman Formation are relatively insensitive to changes in aquifer hydraulic parameters of the order of +/- 15%. However, the accuracy of final calibrated potentiometric heads is highly dependent on the hydraulic parameters of aquifers and aquitards that are in contact with the Upper Monoman Formation. The impact of variation in the Bookpurnong Formation vertical hydraulic conductivity is discussed below. Therefore, the aquifer hydraulic parameter combination that results in calibration must be accepted as a realistic possibility. Any major changes in the aquifer hydraulic parameters will affect the modelled potentiometric heads.

SENSITIVITY TEST-2: VARIATION OF BOOKPURNONG FORMATION VERTICAL HYDRAULIC CONDUCTIVITY BY INCREASING / DECREASING 10 TIMES

This sensitivity test was conducted to test the impact of variations in the vertical hydraulic conductivity of the Bookpurnong Formation and increase confidence in the calibrated value. The vertical hydraulic conductivity of the Bookpurnong Formation is critical to the vertical flux from the Murray Group Limestone into the Chowilla floodplain.

Sensitivity test-2: Conditions

Scenario-3 (do nothing) was selected for sensitivity testing. Layer-4 represents the Bookpurnong Formation. Sensitivity tests were conducted by varying the Bookpurnong Formation vertical hydraulic conductivity by increasing/ decreasing 10 times the calibrated vertical hydraulic conductivity value of 10^{-7}–$8x10^{-6}$ m/d, and running the model until 2003. The magnitude of variation is not in accordance with Murray Darling Basin Commission (2000), however the much more significant variation to the vertical hydraulic conductivity provides greater certainty regarding the effect of this important aquitard in the operation of the groundwater system.

Sensitivity test-2: Results

Sensitivity test results (Table 14) indicate that:

1) The vertical leakage from the Murray Group Limestone represents 10% of the total flux into the floodplain for the calibrated vertical hydraulic conductivity. This value coincides with percentage of vertical leakage to the floodplain estimated in 1997 (pers. comm. Bob Neuman MDBC).
2) An increase of 10 times to the calibrated Bookpurnong Formation vertical hydraulic conductivity of 10^{-7} - $8x10^{-6}$ (ie 10^{-6} - $8x10^{-5}$ m/day) results in an unrealistically large 41% of the total flux to the floodplain originating from the Murray Group Limestone.
3) A decrease of 10 times to the calibrated Bookpurnong Formation vertical hydraulic conductivity of 10^{-7} - $8x10^{-6}$ (ie 10^{-8} - $8x10^{-7}$ m/day) results in an unrealistically small 1% of the total flux to the floodplain originating from the Murray Group Limestone.
4) The calibrated Bookpurnong Formation vertical hydraulic conductivity value results in a normalised RMS value that is lower (and within the desired range as given by MDBC 2000) than the normalised RMS values for both an increased and decreased vertical hydraulic conductivity.

These results indicate that fluxes from the Murray group Limestone to the Chowilla floodplain are very sensitive to vertical hydraulic conductivity of the Bookpurnong Formation. The calibrated Bookpurnong Formation vertical hydraulic conductivity value is reasonable, and any major change will affect the predicted vertical leakage of groundwater from the Murray Group Limestone to the floodplain, and therefore the calibration results for the Monoman Formation.

Table 14. Results of sensitivity testing of variation in Bookpurnong Formation (Layer-4) vertical hydraulic conductivity at 2003

Layer	Layer-4 (decrease 10 times)	Layer-4	Layer-4 (increase 10 times)
K_v (m/d)	10^{-8} - $8x10^{-7}$	10^{-7} - $8x10^{-6}$	$10^{-}6$ - $8x10^{-5}$
Vertical flux from Murray Group Limestone to floodplain (ML/day)	0.03	0.26	2
Flux from highland to floodplain (ML/day)	2.33	2.63	4.87
Vertical flux as % of flux from the highland	1%	10%	41%
Normalised RMS for calibration results	3.19	3.06	4.15

SENSITIVITY TEST-3: INCREASED RECHARGE ACROSS THE CHOWILLA FLOODPLAIN

This sensitivity test was conducted to test the impact of increased recharge on the flux of saline groundwater entering the anabranch creeks and increase confidence in calibrated recharge rates. Recharge rates are critical to the groundwater table elevation that controls the hydraulic gradient towards the creek, and therefore the flux of saline groundwater entering the anabranch creeks.

Sensitivity test-3: Conditions

Scenario-3 (do nothing) was selected for sensitivity testing. Sensitivity tests were conducted by increasing the recharge to the Chowilla floodplain from the conceptual (CSIRO) value of 0 mm/year to 2 mm/year and running the model 100 years into the future.

Sensitivity test-3: Results

This test indicates that increasing the recharge to the Chowilla floodplain may increase the flux of saline groundwater entering the anabranch creeks by 0.17 ML/day (a salt load of 8 tonnes/day) in 100 years time compared to the current situation. This represents a 24% increase, which is significant. It is apparent that an increase in direct recharge to the floodplain area will have a significant impact on the flux of saline groundwater entering the anabranch creeks.

SENSITIVITY TEST-4: ELEVATED POOL LEVEL OF LAKE VICTORIA

This sensitivity test was conducted to test the hypothesis that the flux of saline groundwater entering the anabranch creeks would significantly increase if the pool level of Lake Victoria were elevated. An increased pool level in Lake Victoria may affect the elevation of groundwater table in the highland that controls the hydraulic gradient towards the floodplain, and therefore the flux of saline groundwater entering the anabranch creeks.

Sensitivity test-4: Conditions

Scenario-3 (do nothing) was selected for sensitivity testing. Sensitivity tests were conducted by elevating the pool level of Lake Victoria from the current level of 25 m AHD to 27.5 m AHD, and running the model 100 years into the future.

Sensitivity test-4: Results

This test indicates that a 10% elevated pool level in Lake Victoria may result in an increase in the flux of saline groundwater entering the anabranch creeks by approximately 0.06 ML/day (a salt load of 2.6 tonnes/day) in 100 years time compared to the current situation. This represents an 8% increase, which is considered insignificant.

MODEL LIMITATIONS

Hugh Middlemis (lead author Murray Darling Basin Commission 2000 Groundwater Modelling Guideline) stated in 2004 that:- *It is important to recognise that there is no such thing as a perfect model, and all models should be regarded as works in progress of continuous improvement as hydrogeological understanding and data availability improves. By definition, model limitations comprise relatively negative statements, and they should not necessarily be viewed as serious flaws that affect the fitness for purpose of the model, but rather as a guide to where improvements should be made during work programmes.*

The following limitations of the model may lead to a component of error being associated with the results of the predictive modelling:

1) The model layers are a simplified representation of the natural aquifers and aquitards thickness and hydraulic parameters and may not reflect the natural conditions locally with sufficient accuracy. Therefore, the numbers of production wells involved in any groundwater management scheme, and the final design for each individual production well, needs to be based on detailed site-specific technical investigations.

2) There is uncertainty regarding the anabranch creek bed elevations and stage, aquifer potentiometric heads and groundwater salinity distribution in some areas associated with the inner creeks.

3) The iterative calibration method used to create starting heads for the predictive model runs is believed to be the best available means of overcoming the critical absence of historical groundwater level, surface water stage, and flow volume data. Validation needs to be undertaken if new information becomes available.

4) The estimated historical and predicted salt load entering the anabranch creeks from the aquifer system may be inaccurate due to lack of control on groundwater salinity, and due to a lack of knowledge regarding the true interaction between the creeks and aquifers.

5) The groundwater salinity may change with time. The salt load entering the anabranch creeks under current conditions was based on recent monitoring data. It is unlikely that the current salinity correctly represents groundwater conditions either 75 years ago, or in 100 years time. The MT3D solute transport model will need to be used to estimate historic and future salinity values.

CONCLUSION

GENERAL

DWLBC has developed a numerical groundwater flow model that is capable of simulating the regional aquifer system in the Chowilla region. This model is an impact assessment model in the terminology of Murray Darling Basin Commission (2000) and is of moderate complexity. The model accommodates the Chowilla floodplain within a broad regional context and accounts for the hydraulic interaction of the sediments with the deep confined Murray Group Limestone.

A NEW PERSPECTIVE ON THE HYDROGEOLOGY AND HYDROLOGY OF THE CHOWILLA FLOODPLAIN

The modelling that has been undertaken has resulted in an improved understanding of the hydrogeology, and changes in the hydrogeological regime, of the Chowilla floodplain over time.

HYDROGEOLOGY AND HYDROLOGY PRIOR TO RIVER REGULATION

The model results indicate the following important points regarding the pre-locking hydrogeology and hydrology of the Chowilla floodplain under non-flooding conditions and the salt load being delivered to the River Murray, in comparison with post-locking conditions:

1) No flow occurred from the River Murray into the anabranch creeks. Therefore, a greater hydraulic gradient existed between the groundwater table and the anabranch creeks (in spite of the groundwater table occurring at a greater depth than the post-locking condition) that resulted in a greater flux of saline groundwater, thus flushing salt out of the aquifer system.

2) Evaporation from the anabranch creeks equated to the flux of saline groundwater entering the anabranch creeks. This resulted in the temporary storage of 106 tonnes/day of salt that was only flushed to the River Murray during flood events (at significantly reduced concentrations).

   Aside:- Independent support and Calculation of Evaporation from Anabranch Creeks

   The model results are supported by a previous report (Jolly and Walker, 1995) that notes that there was no permanent flow in the anabranch creeks pre-locking. The model indicates that there was a flux of ~4 ML/day of groundwater entering the anabranch creeks. The anabranch creek system is ~110 km long; and assuming an average evaporative surface width of 5 m, the 4 ML/day of groundwater would result in 7 mm depth of water in the creeks. The evaporation rate from a free water surface in this area is ~2,000 mm/year (5.5 mm/day), sufficient to reduce any flow in the creeks to a minimum.

3) Less evapotranspiration occurred from the Chowilla floodplain due to the groundwater table existing at a greater depth (in spite of the recharge resulting from regular flooding) than the evaporation extinction depth over most of the floodplain.

4) The aquifer system in Chowilla floodplain was in balance. The total salt that entered the aquifer system laterally from the highland, and via vertical leakage from Murray Group Limestone, was discharged from the aquifer system via the anabranch creeks.

HYDROGEOLOGY AND HYDROLOGY POST RIVER REGULATION

The anthropogenically modified flow regime of the River Murray resulting from the construction of locks and weirs, storages and diversions for irrigation, industry and town water supply, has resulted in significantly reduced flood magnitude and frequency. As a consequence there is less flushing of the unsaturated zone and aquifer system on the Chowilla floodplain.

The model results indicate the following important points regarding the post-locking hydrogeology and hydrology of the Chowilla floodplain and the salt load being delivered to the River Murray, in comparison to pre-locking conditions:

1) Diversion from the River Murray into the anabranch creeks reduced the hydraulic gradient (and flux of saline groundwater entering the anabranch creeks) between the groundwater table, and the anabranch creeks, and resulted in elevation of the groundwater table. The reduced groundwater flux results in an additional ~75 tonnes/day of salt being *stored* in the aquifer system.
2) The elevated groundwater table has resulted in significantly increased evapotranspiration in some parts of the Chowilla floodplain.
3) The constant flow in the anabranch creeks has resulted in ~30 tonne/day salt being delivered to the River Murray, and this has resulted in an in-river salinity impact of 7.75 EC at Morgan (assuming 3.1 tonnes per EC).
4) The increased storage of salt in the aquifer system has resulted in very large salt loads being delivered to the River Murray during, and after, flood events.

The model results indicate that the anabranch creeks play a vital role in controlling salt on the Chowilla floodplain. The post-locking hydrological modification of the floodplain has resulted in an increase in salt accumulation in the floodplain that is a threat to the salinity of the River Murray and vegetation health. It is evident that the natural hydrologic balance that had been in operation for several thousand years has been significantly disrupted.

GROUNDWATER MANAGEMENT OPTIONS AND PREDICTED RESPONSE

NO INTERVENTION

Scenario-3: Do nothing management option

The model indicates relatively minor changes 100 years into the future, in comparison to the current situation, with only 5 tonnes/day of additional salt being *stored* in the floodplain.

GROUNDWATER MANAGEMENT SCHEMES

Scenario-4: SIS on floodplain

The model indicates the following significant changes, with respect to Scenario-3 (do nothing) 100 years into the future:

1) 71% decrease in evapotranspiration in the area influenced by the wellfield that will benefit native vegetation.
2) 85% decrease in the flux of saline groundwater entering the anabranch creeks.
3) 27 tonnes/day decrease in the salt load entering the anabranch creeks (and therefore the River Murray) representing an in-river salinity benefit of 7 EC at Morgan (assuming 3.1 tonnes per EC).
4) 105 tonnes/day of salt being removed from the floodplain (it should be noted that this salt being removed from the floodplain is contained in the groundwater pumped from the production wells).

Scenario-5: ES (targeted areas) + SIS on floodplain

The model indicates the following significant changes, with respect to the Scenario-3 (do nothing) 100 years into the future:

1) 100% increase in the flux of groundwater from the highland to the floodplain.
2) 98% decrease in evapotranspiration in the area influenced by the wellfield that will benefit native vegetation.
3) 99% decrease in the flux of saline groundwater entering the anabranch creeks.
4) 32 tonnes/day decrease in the salt load entering the anabranch creeks (and therefore the River Murray) representing an in-river salinity benefit of 8 EC at Morgan (assuming 3.1 tonnes per EC).
5) 280 tonnes/day of salt being removed from the floodplain (it should be noted that this salt being removed from the floodplain is contained in the groundwater pumped from the production wells).

Scenario-6: ES entire floodplain (includes SIS)

The model indicates the following significant changes, with respect to Scenario-3 (do nothing) 100 years into the future:

1) 128% increase in the flux of groundwater from the highland to the floodplain.
2) 99% decrease in evapotranspiration that will benefit native vegetation.
3) 100% decrease in the flux of saline groundwater entering the anabranch creeks.
4) 32 tonnes/day decrease in the salt load entering the anabranch creeks (and therefore the River Murray) representing an in-river salinity benefit of 8 EC at Morgan (assuming 3.1 tonnes per EC).
5) 382 tonnes/day of salt being removed from the floodplain (it should be noted that this salt being removed from the floodplain is contained in the groundwater pumped from the production wells).

Scenario-7: SIS on highland and floodplain

The model indicates the following significant changes, with respect to Scenario-3 (do nothing) 100 years into the future:

1) 44% decrease in the flux of groundwater from the highland to the floodplain.
2) 73% decrease in evapotranspiration in the area influenced by the wellfield that will benefit native vegetation.

3) 83% decrease in the flux of saline groundwater entering the anabranch creeks.

4) 27 tonnes/day decrease in the salt load entering the anabranch creeks (and therefore the River Murray) representing an in-river salinity benefit of 7 EC at Morgan (assuming 3.1 tonnes per EC).

5) 5 tonnes/day of salt being removed from the floodplain (it should be noted that this salt being removed from the floodplain is contained in the groundwater pumped from the production wells).

Scenario-8: SIS on floodplain + part-ES targeted areas management option

The model indicates the following significant changes, with respect to Scenario-3 (do nothing) 100 years into the future:

1) 27% increase in the flux of groundwater from the highland to the floodplain.

2) 87% decrease in evapotranspiration in the area influenced by the wellfield that will benefit native vegetation.

3) 88% decrease in the flux of saline groundwater entering the anabranch creeks.

4) 29 tonnes/day decrease in the salt load entering the anabranch creeks (and therefore the River Murray) representing an in-river salinity benefit of 7 EC at Morgan (assuming 3.1 tonnes per EC).

5) 163 tonnes/day of salt being removed from the floodplain (it should be noted that this salt being removed from the floodplain is contained in the groundwater pumped from the production wells).

MODEL PREDICTIONS OF SALT LOAD BEING DELIVERED TO THE RIVER MURRAY

The modelled salt load (under non-flooding conditions) being delivered to the River Murray are summarised in Table 15 and indicate that:

1) Pre-locking 106 tonnes/day of salt entered the anabranch creeks.

2) Post-locking (and the current situation), an average of 31 tonnes/day of salt enters the anabranch creeks.

3) Scenario-3 (do nothing) results in virtually no additional salt entering the anabranch creeks above that already occurring.

4) All of the proposed groundwater management schemes are effective in controlling salt loads entering the anabranch creeks.

5) All of the proposed groundwater management scheme options result in very similar in-river benefits at Morgan of 7–8 EC, however, the schemes that include environmental protection require considerably more infrastructure with associated greater costs.

Table 15. Summary of modelled salt loads (under non-flooding conditions) being delivered to the River Murray

	Scenarios							
	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8
	Pre-Locking	**Post-Locking 2003**	**Do Nothing @ 100 yrs**	**SIS flood plain @ 100 yrs**	**ES targeted areas + SIS floodplain @ 100 yrs**	**ES (SIS) entire floodplain @ 100 yrs**	**SIS highland (+ floodplain) @ 100 yrs**	**SIS floodplain + Part-ES targeted areas @ 100 yrs**
Predicted salt load being delivered to the River Murray (tonnes/day)	106	31	32	5	0.3	0.1	5.4	3.8
EC impact at Morgan	-	10.0	10.0	1.6	0.1	0	1.7	1.2
Reduction in salt entering the River Murray compared to S-3 (tonnes/day)	-	-	-	27	32	32	27	28
EC benefit at Morgan	-	-	-	8.4	9.9	10.0	8.3	8.8

*EC at Morgan assumes 3.1 tonnes per EC

RECOMMENDATIONS

1) The model should be updated when new groundwater and surface water information becomes available.

   a) Pumping tests (including hydrochemistry sampling) have recently been conducted on the Murray Group Limestone in the Chowilla region. The vertical hydraulic conductivity values used in the model need to be checked against these values to ensure that the order of magnitude is similar.

2) If more accurate answers are required from the model it is recommended that the following investigations be conducted and the model further upgraded with the results:

   a) Extent and thickness of the Coonambidgal Formation (through airborne geophysics and ground-truthing through drilling) to determine areas where recharge occurs following flooding (also determination of recharge rates).

   b) Existence of high permeability channels within the Monoman formation (airborne geophysical methods and ground-truthing through drilling).

   c) Determination of anabranch creek bathymetry and hydrology.

   d) Extent and dynamics of the flushed zone.

3) Additional hydrogeological investigations involving drilling and pumping tests should be conducted in the Pliocene Sands aquifer on the highland to the northeast of Gum Flat and Tareena Bong to confirm the viability of targeting this aquifer for a SIS.

4) Groundwater salinity may change with time. The calculated salt load under current conditions being delivered to the River Murray was based on recent monitoring data. It is unlikely that the current salinity represents the conditions 75 years ago or in 100 years time. The MT3D solute transport model will need to be used to estimate historic and future salinity values.

5) The salt load being delivered to the River Murray from the Chowilla floodplain following flood events under various scenarios has been modelled and will be reported separately.

6) The potential for an enhanced salt load being delivered to the River Murray in the long-term, due to reduced floods and concentration of salt in the Chowilla floodplain, may be investigated via MT3D.

7) The model outputs should be compared to the outcomes predicted by the surface water hydrodynamic model that is in development by DWLBC.

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FIGURES

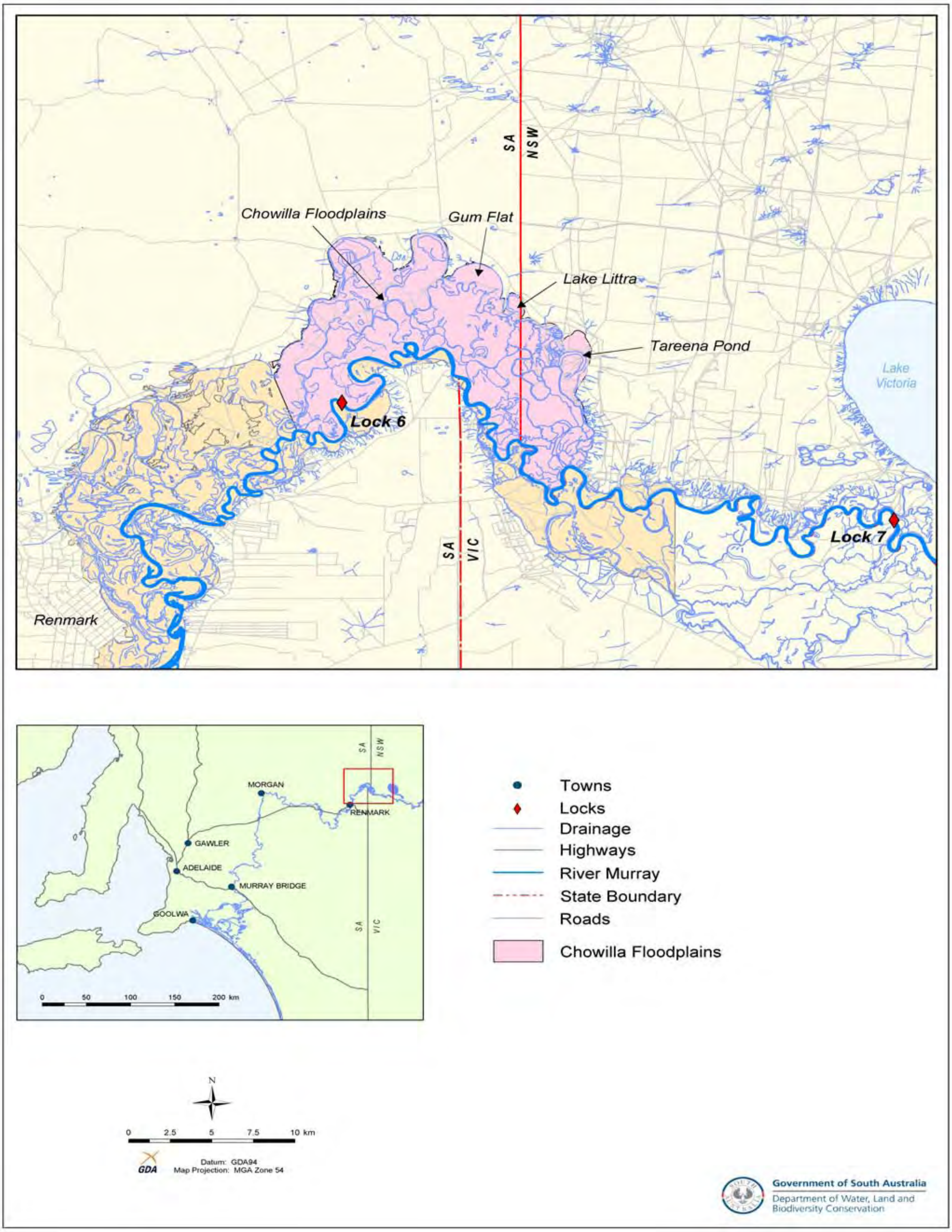

Figure 1 Chowilla floodplain and model area location plan

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Figure 2 Satellite photograph of model domain and Chowilla floodplain

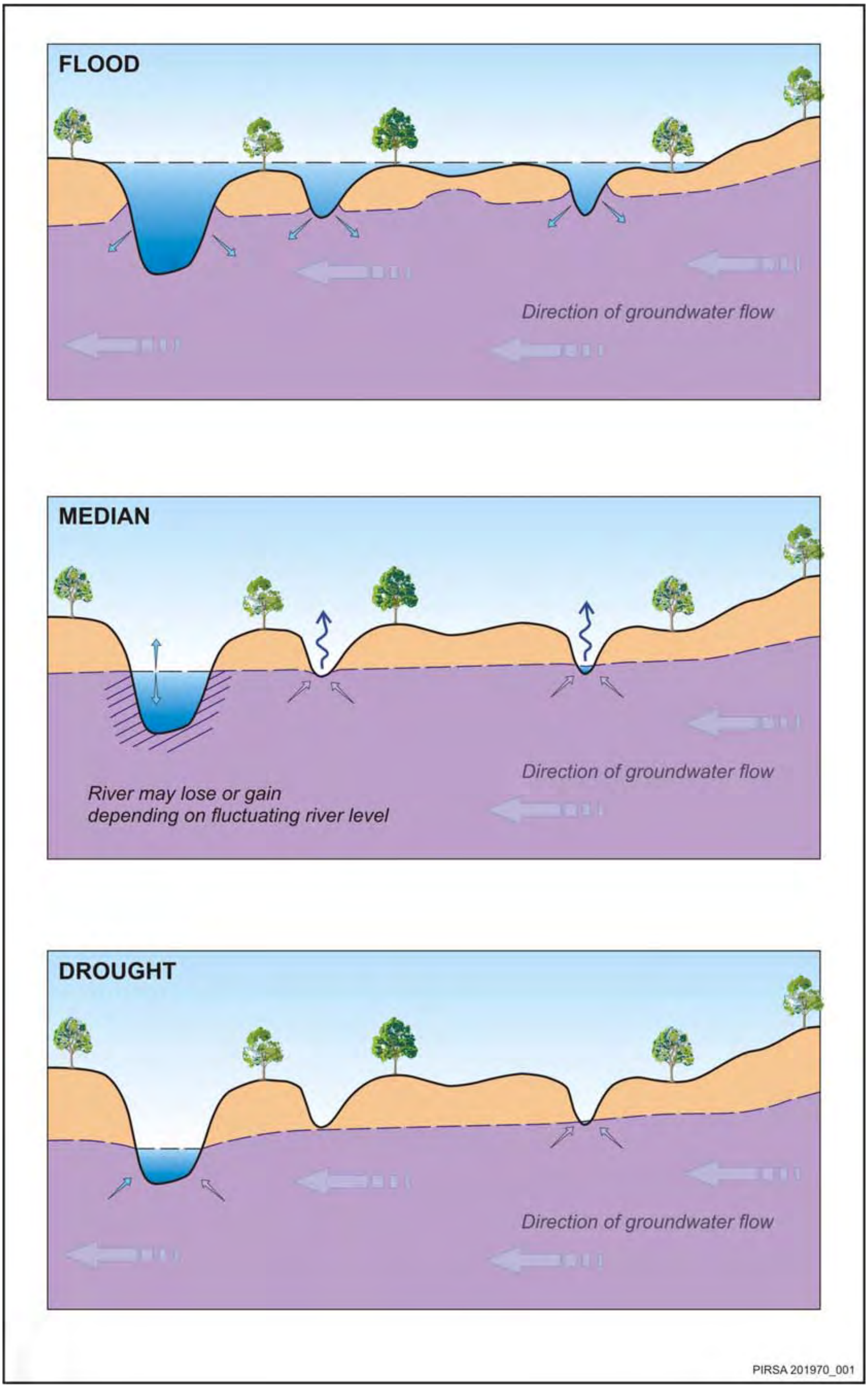

Figure 3a Pre river locking, the river, creek and groundwater interaction

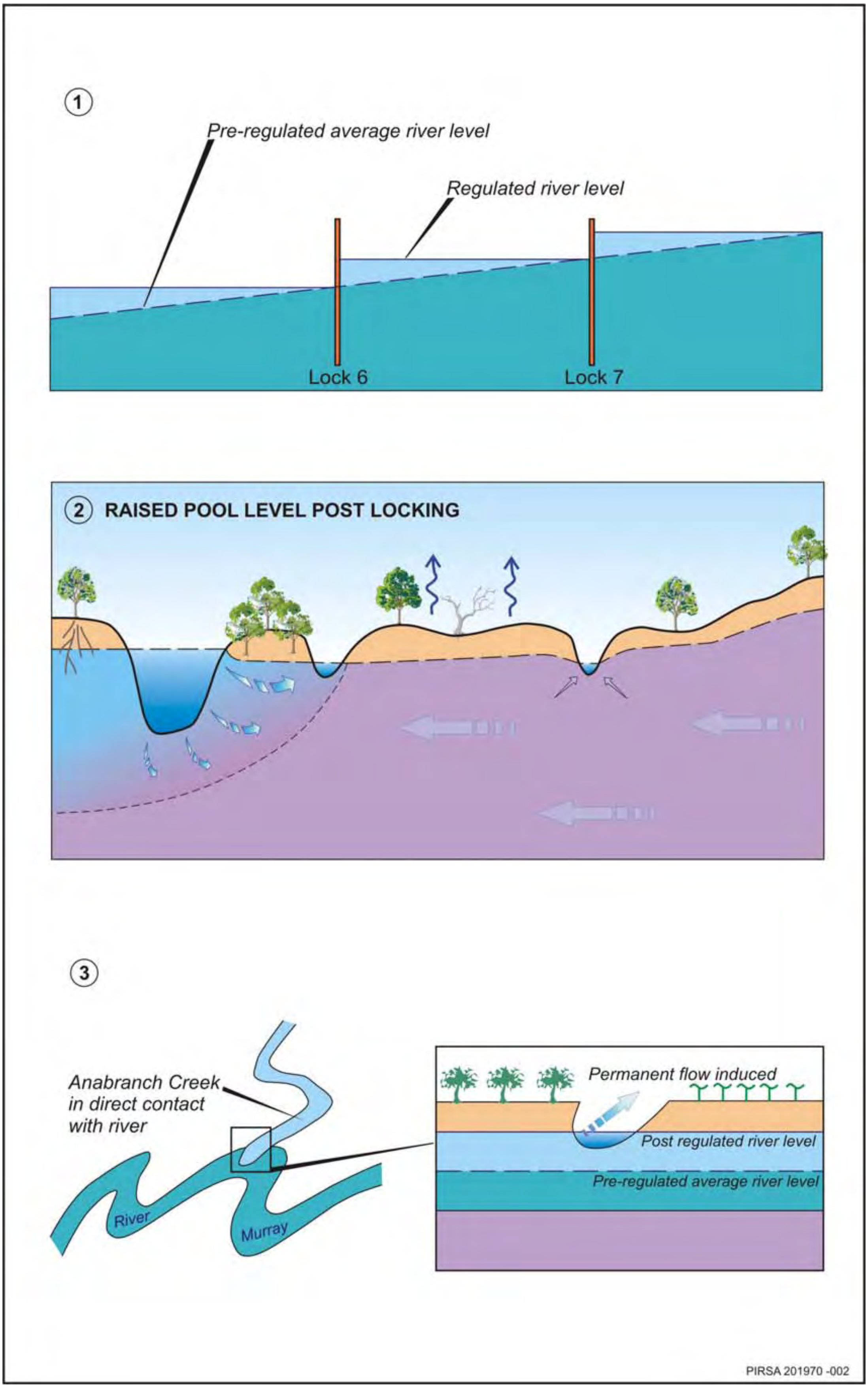

Figure 3b Post river locking, the river, creek and groundwater interaction

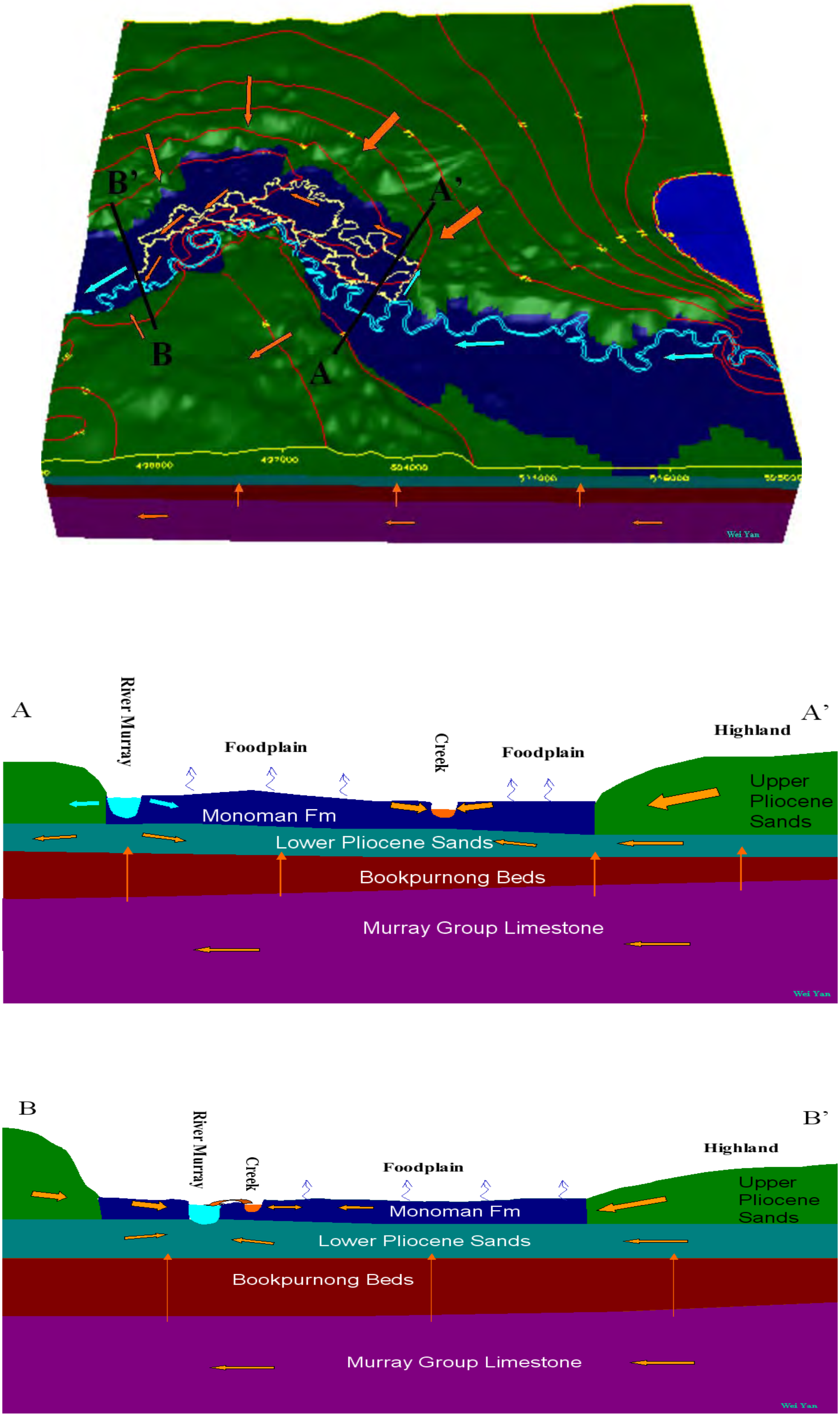

Figure 4: Conceptual hydrogeological cross-section

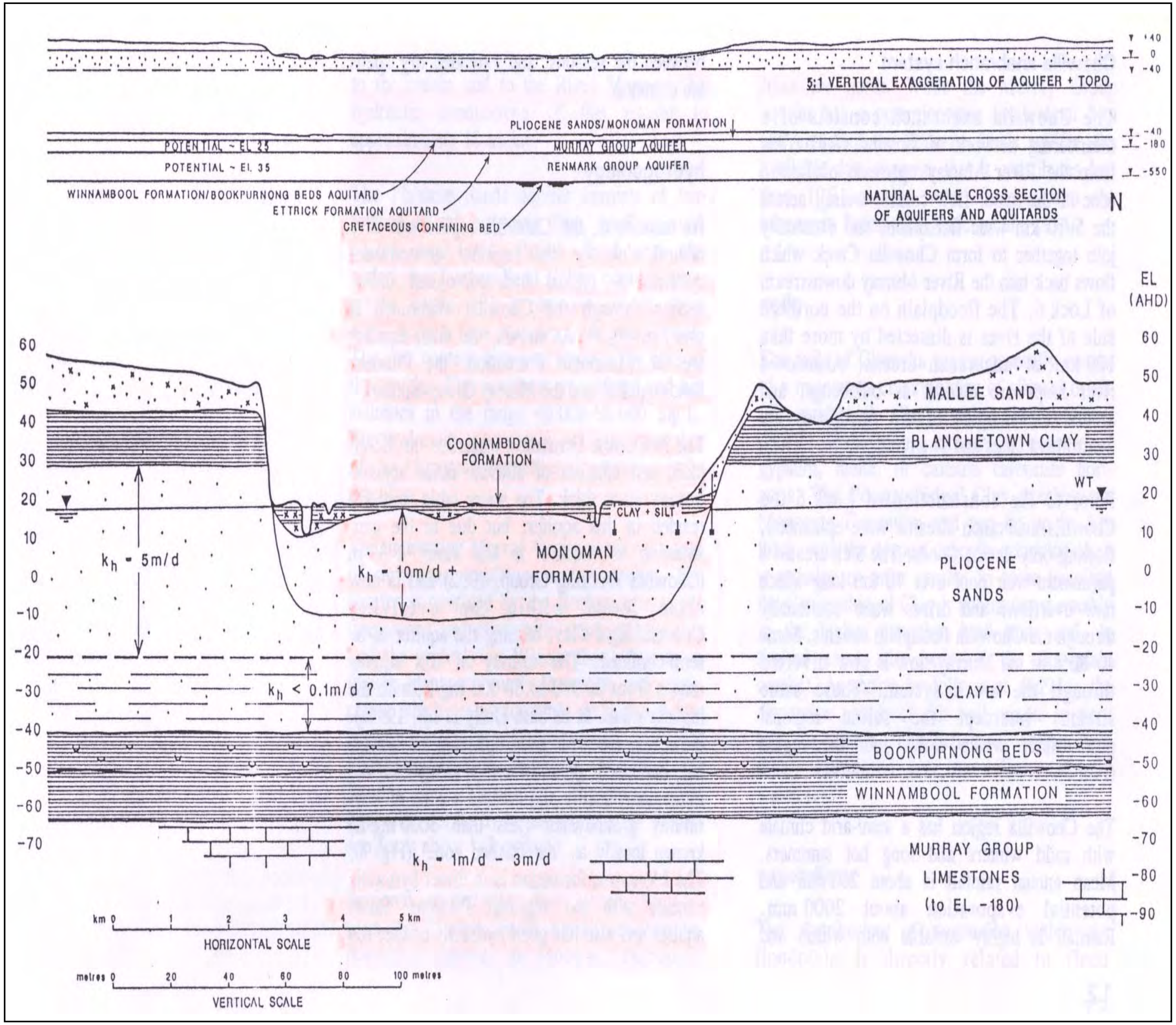

Figure 5 Hydrogeological cross-section (1 July 1995)

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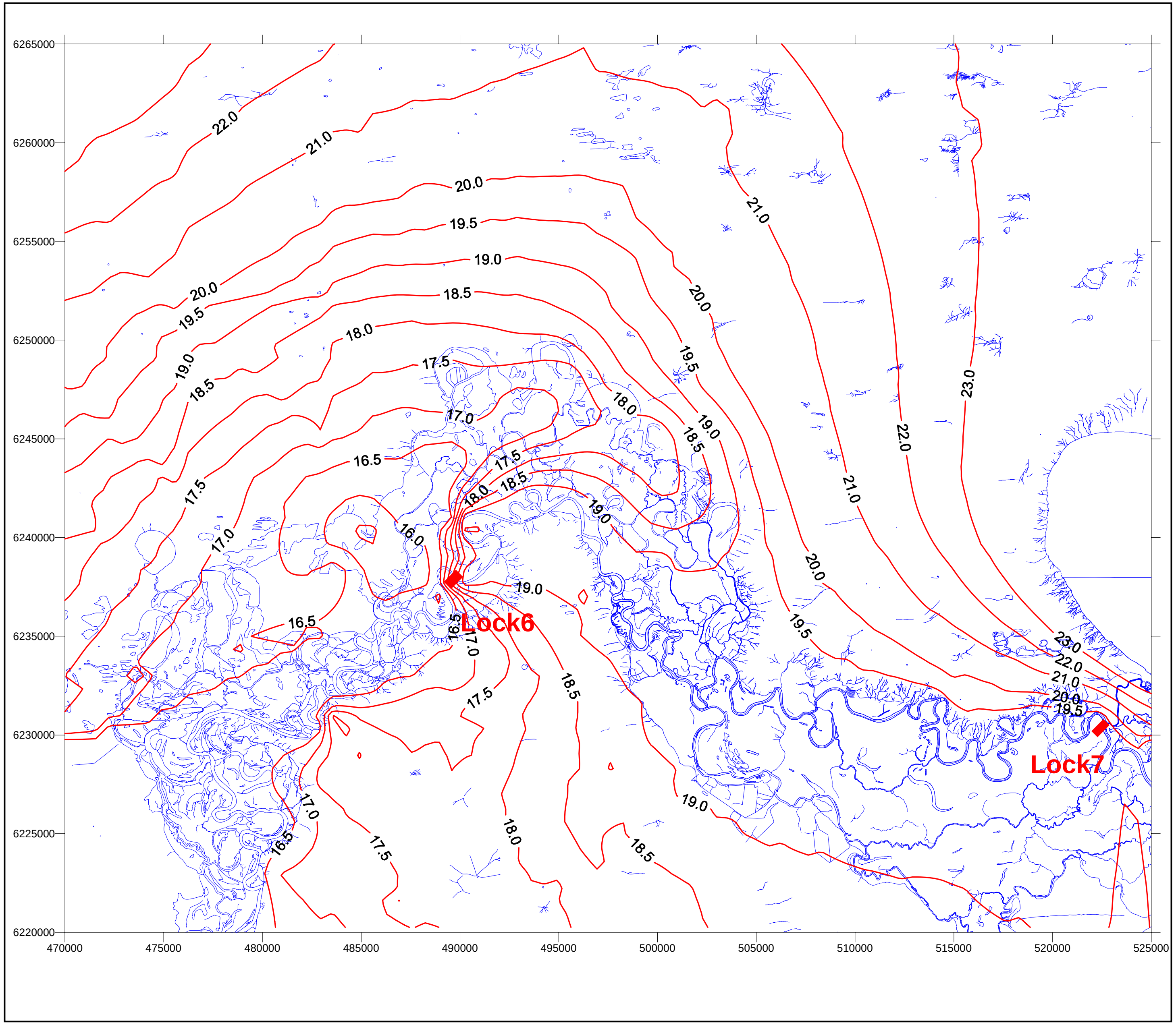

Water table contours (m AHD)

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Figure 6 Elevation of groundwater table, Monoman Sands and Pliocene Sands (m AHD)

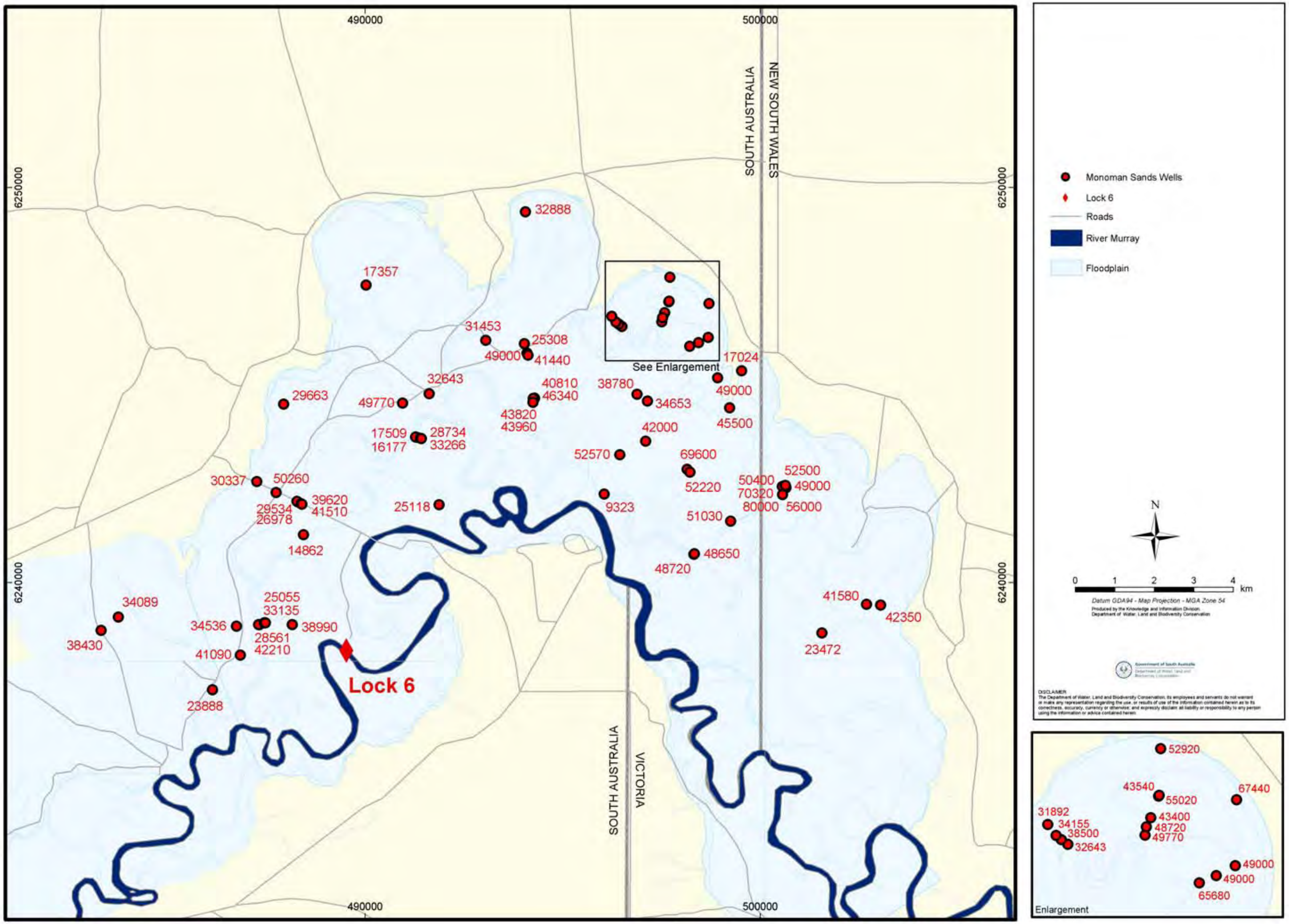
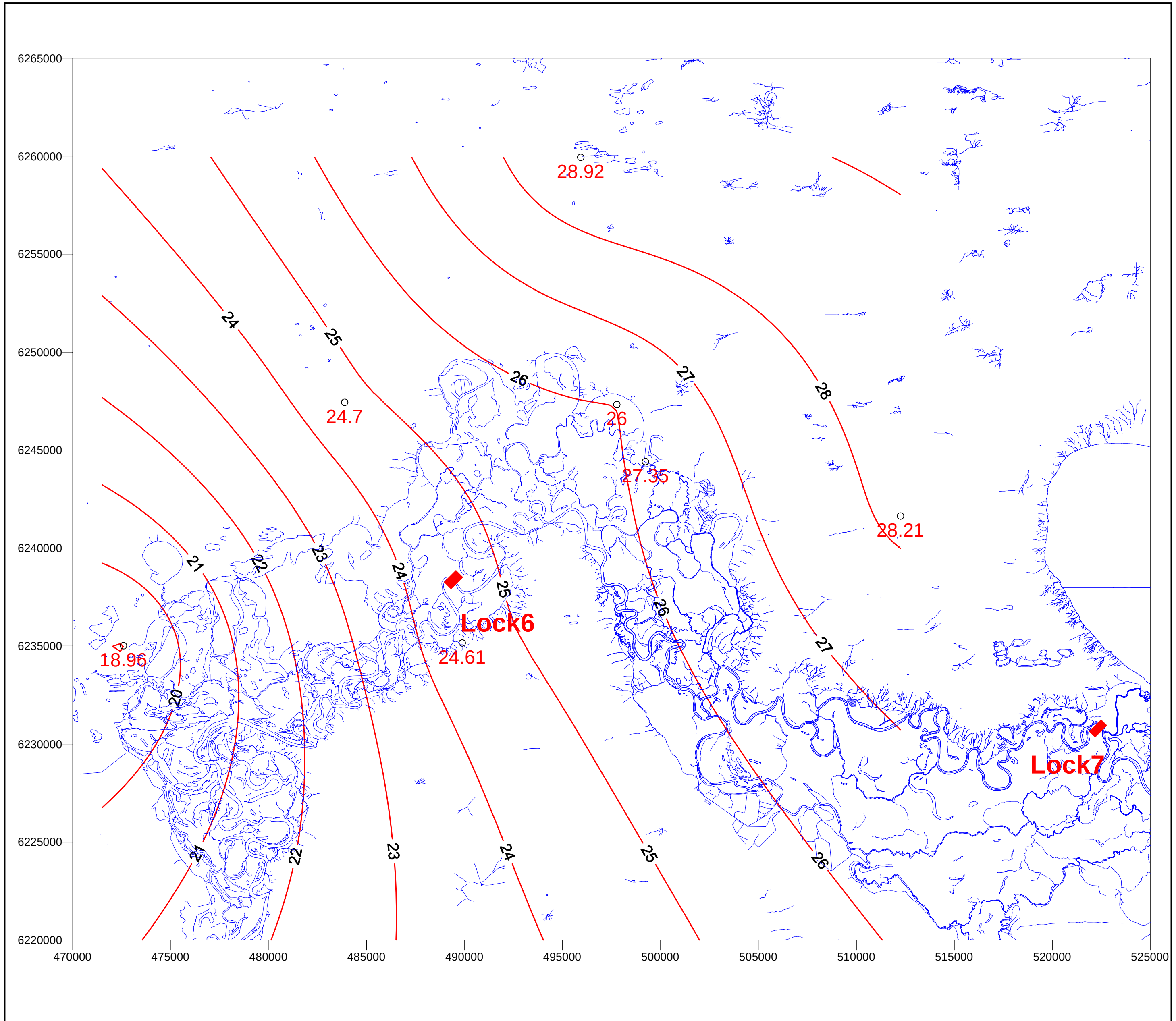


Figure 7. Groundwater salinity (TDS mg/L) in the Monoman Formation across the Chowilla floodplain



Potentiometric head (m AHD)

Anabranches, Backwaters and Water Bodies

Observation bore and Measured Potentiometric head (m AHD)

28.92

N

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Figure 8 Potentiometric head contour plan, Murray Group Limestone (m AHD)

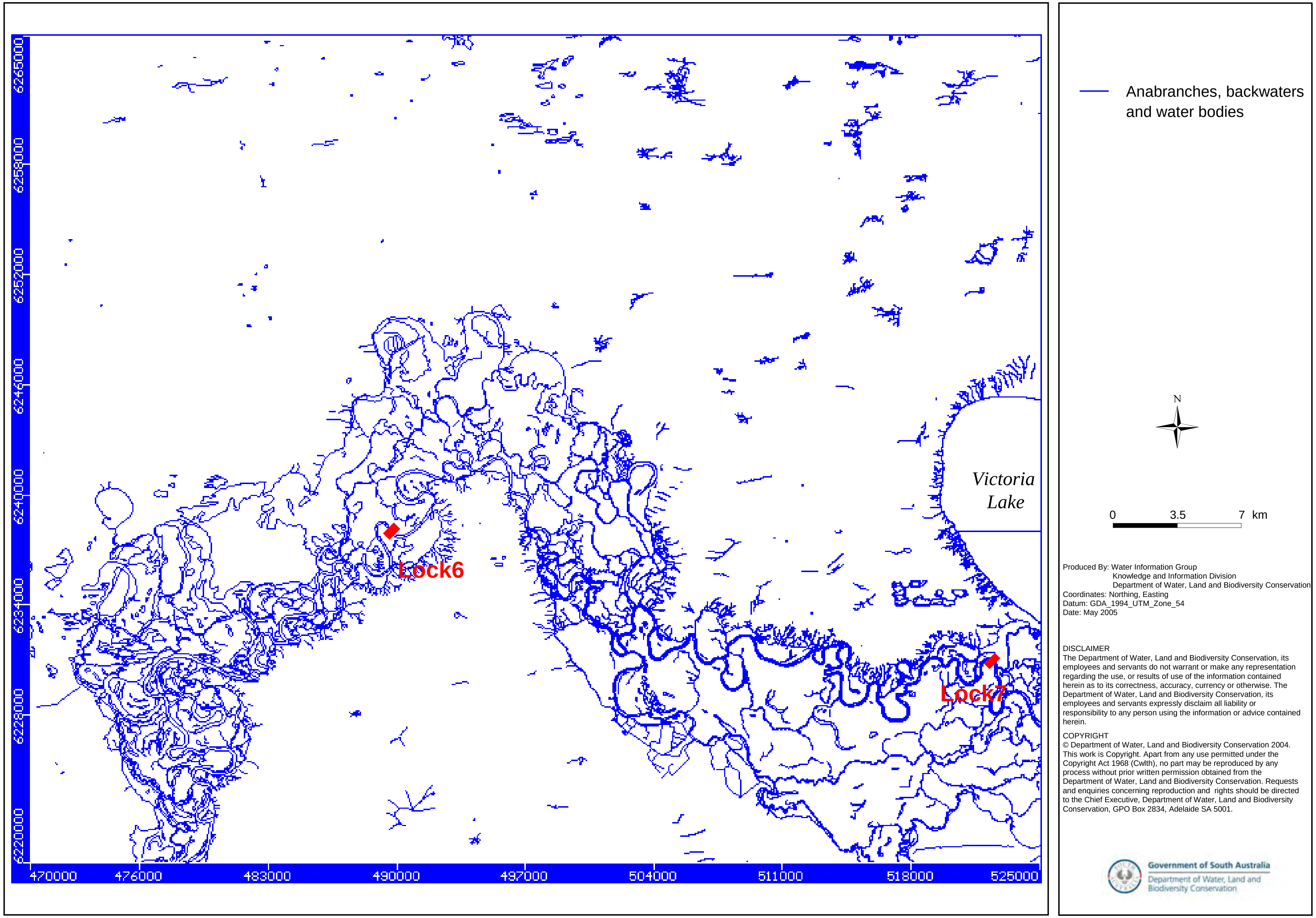
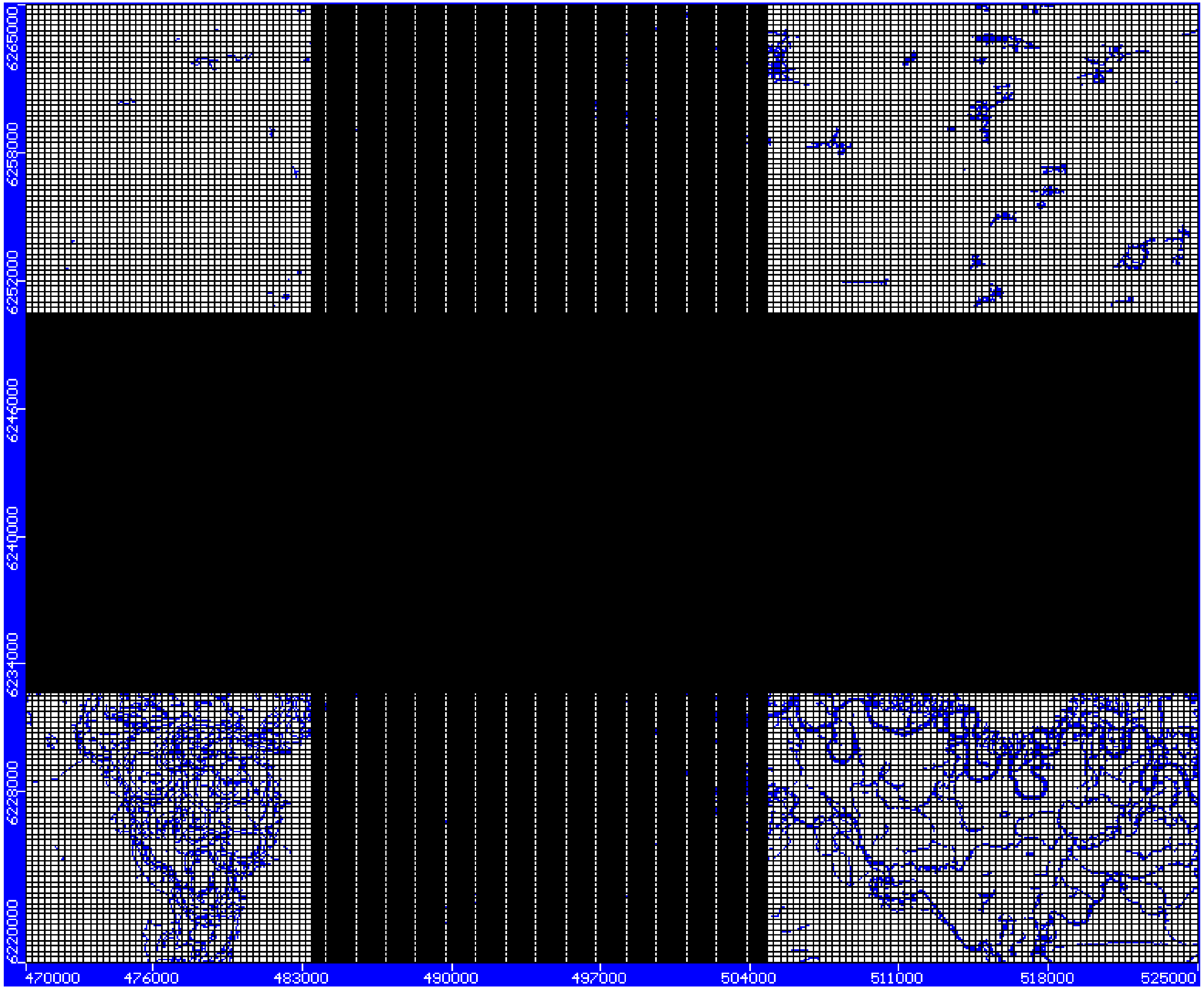


Figure 9 Model domain (55 km east to west by 45km north to south)



N

0 3.5 7 km

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Figure 10 Model grids (76.5 by 62.5 m to 305 by 250 m)

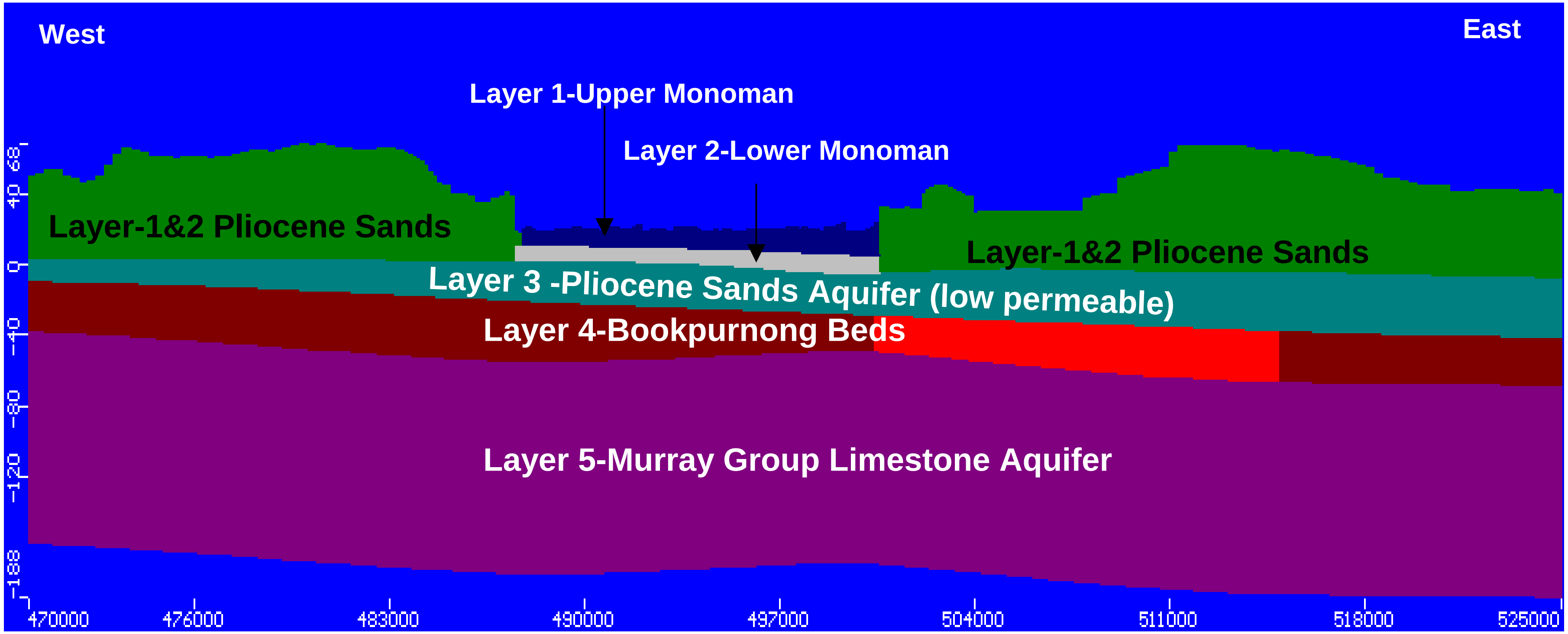


Figure 11 Model layers

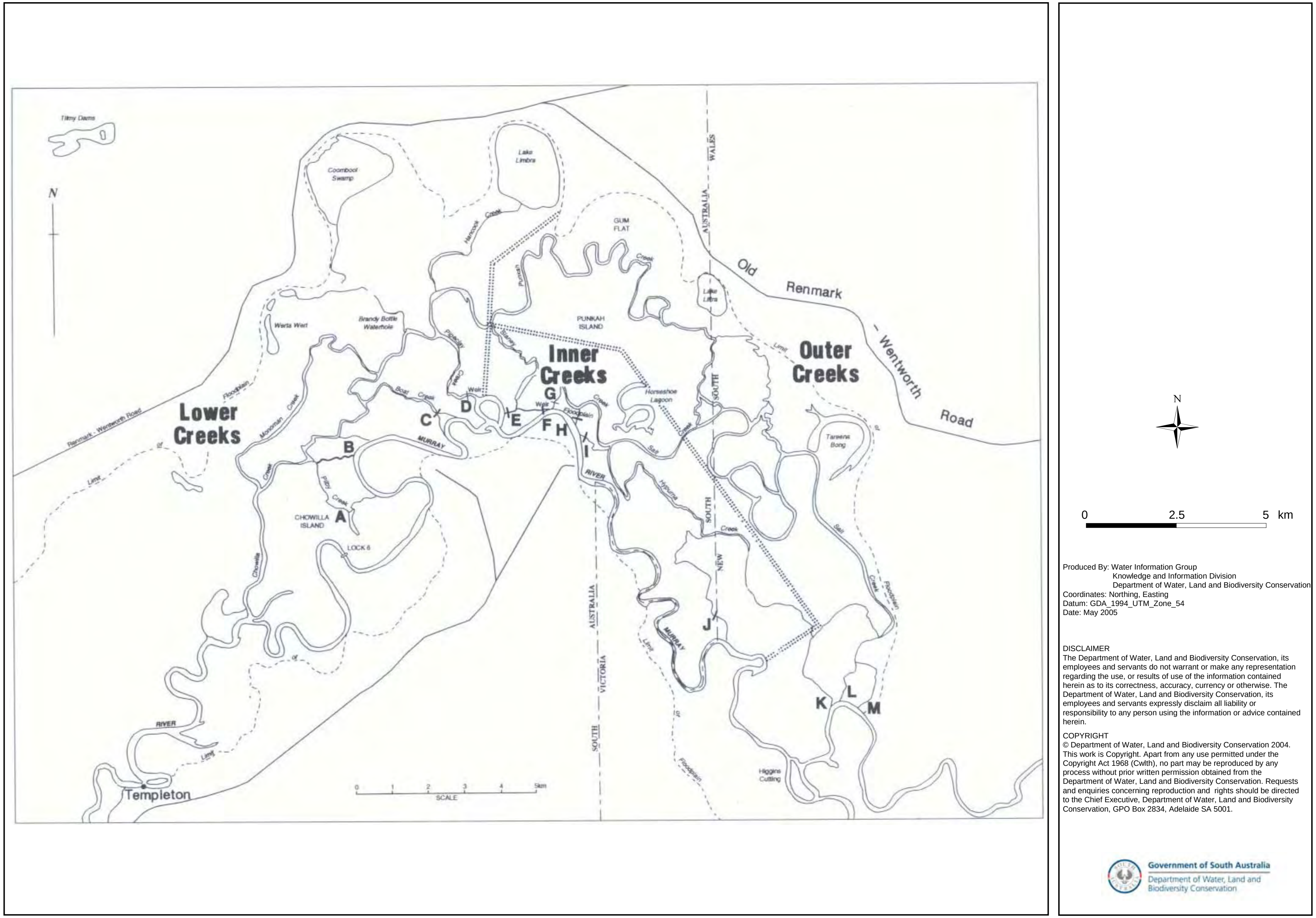


Figure 12 The Chowilla anabranch creeks system components; outer creeks, inner creeks and lower creeks (Letters A to M represent the locations of weirs and embankments)

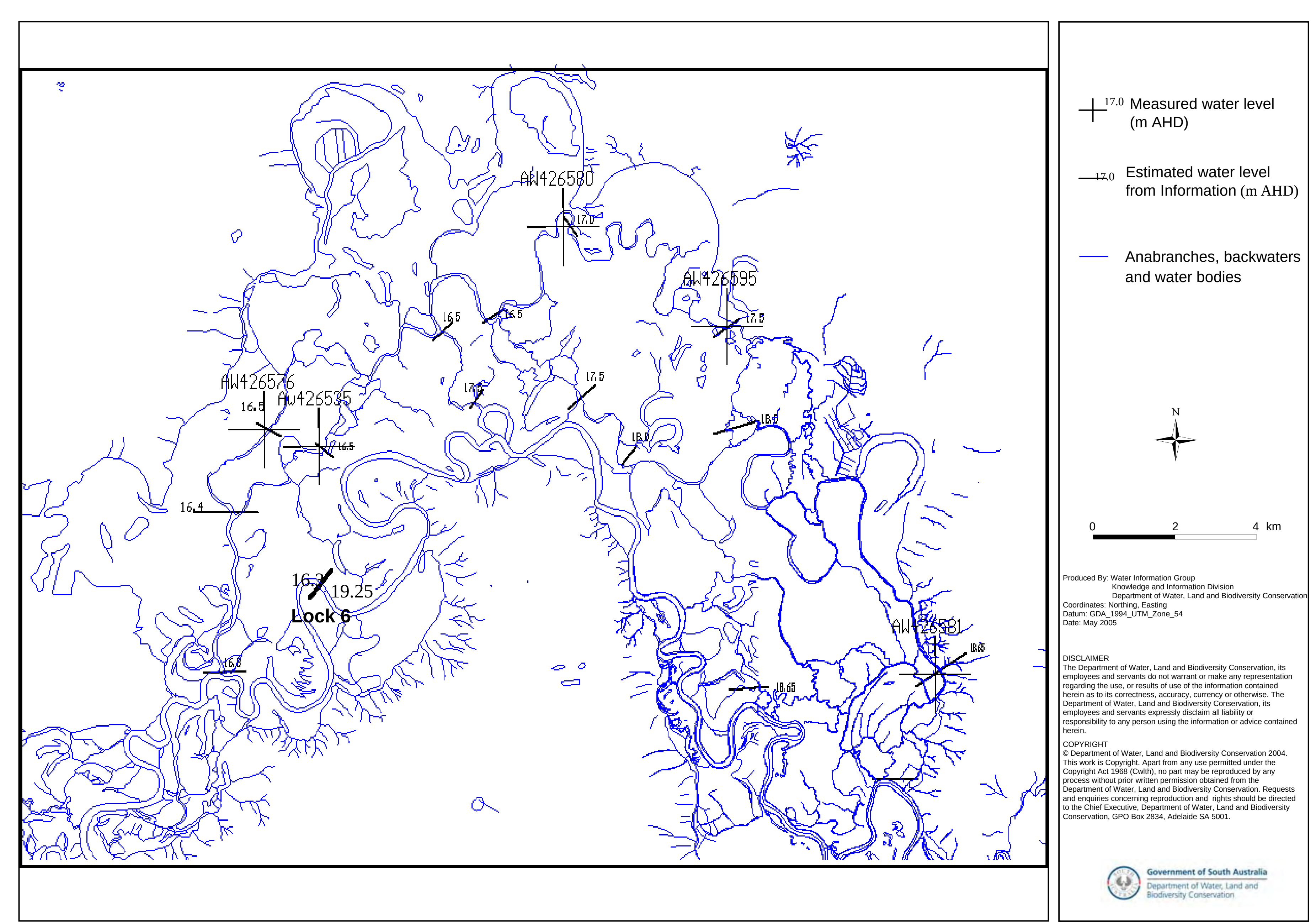


Figure 13 Stage in the River Murray and anabranch creek system

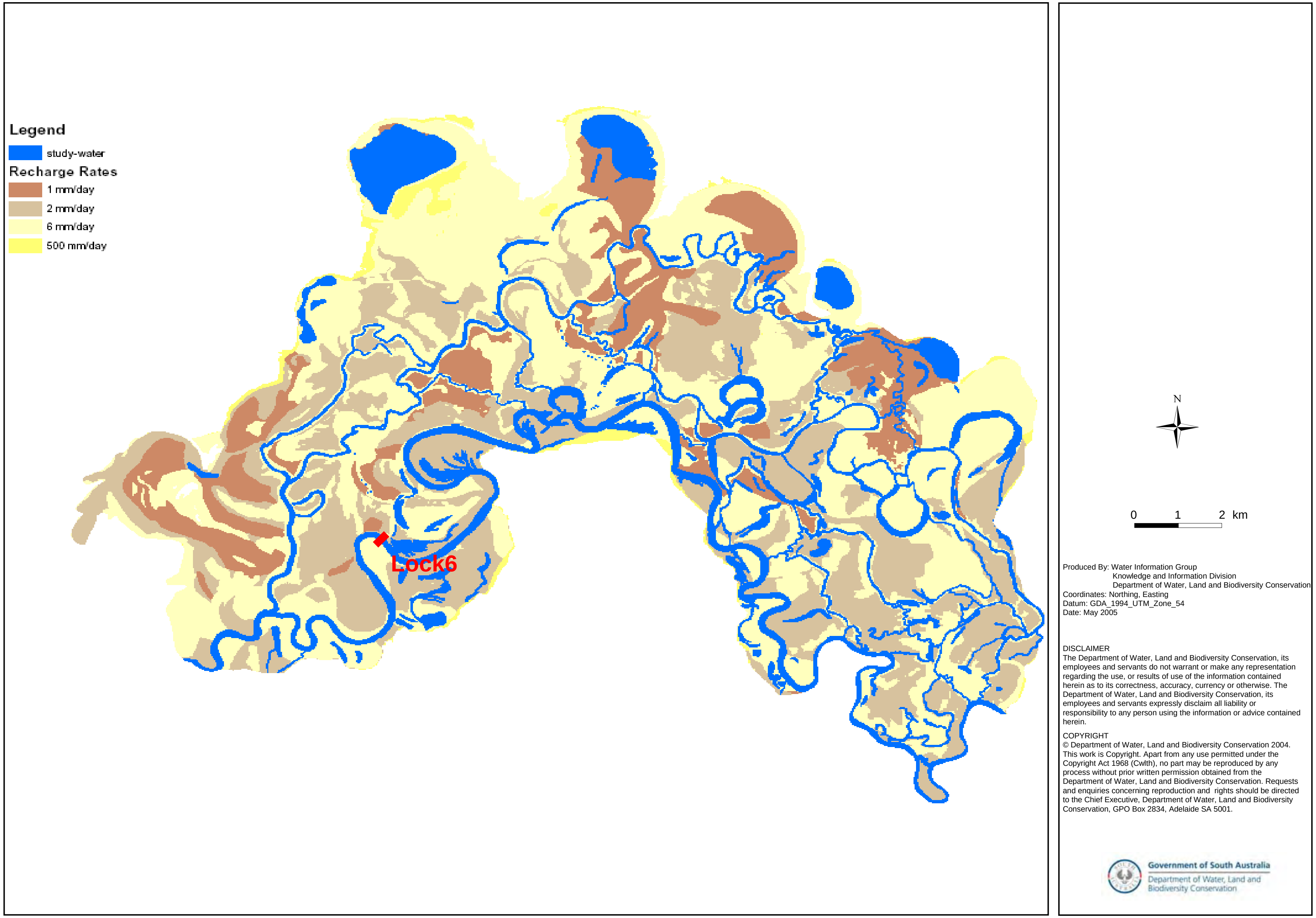
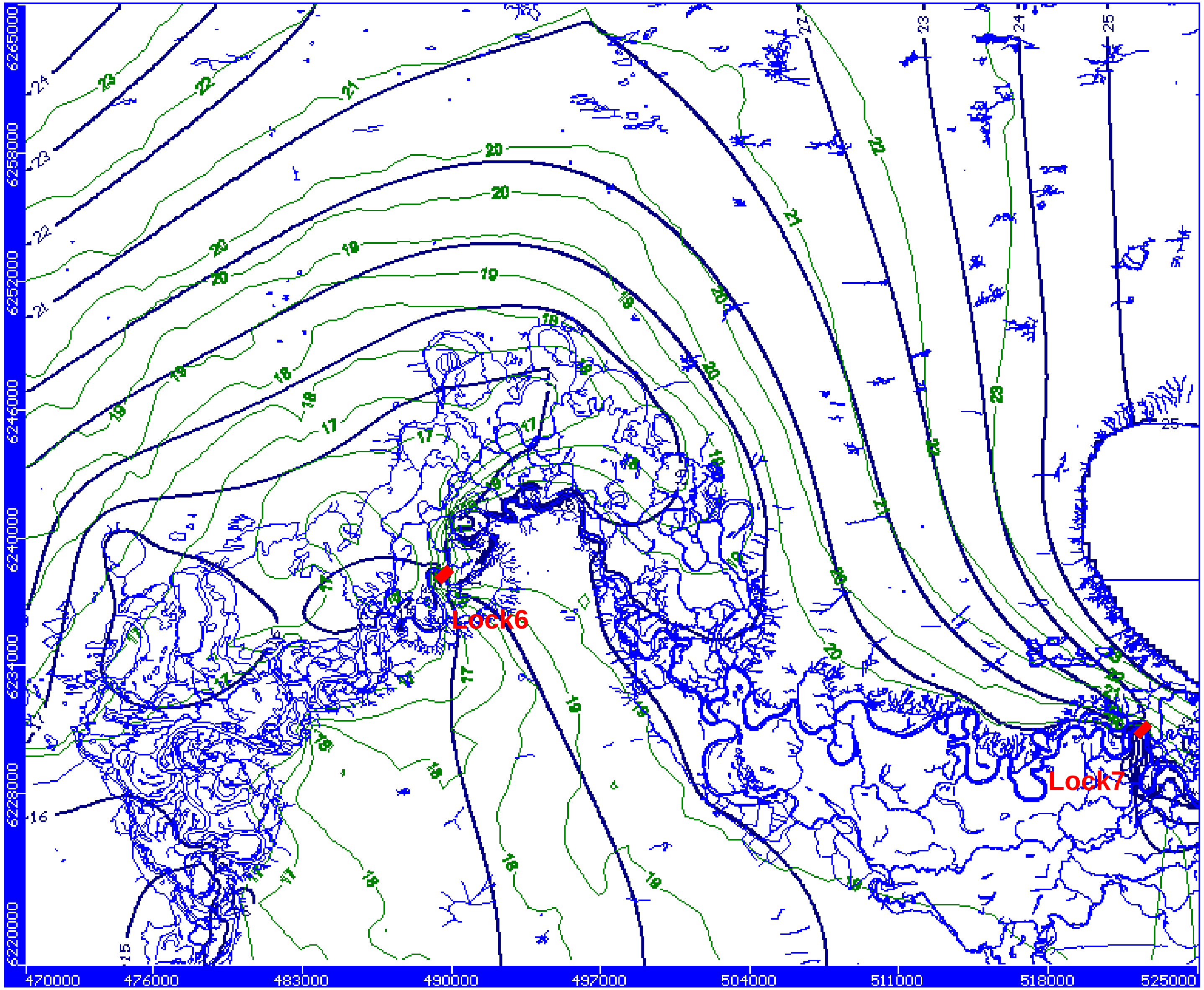


Figure 14 Recharge areas and rates (CSIRO 2004)



Anabranches, backwaters and water bodies

Predicted watertable (m AHD)

Observed watertable (m AHD)

N

0 3.5 7 km

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Figure 15 Calibration results - modelled and observed elevation of groundwater table, Monoman Formation and Pliocene Sands (m AHD)

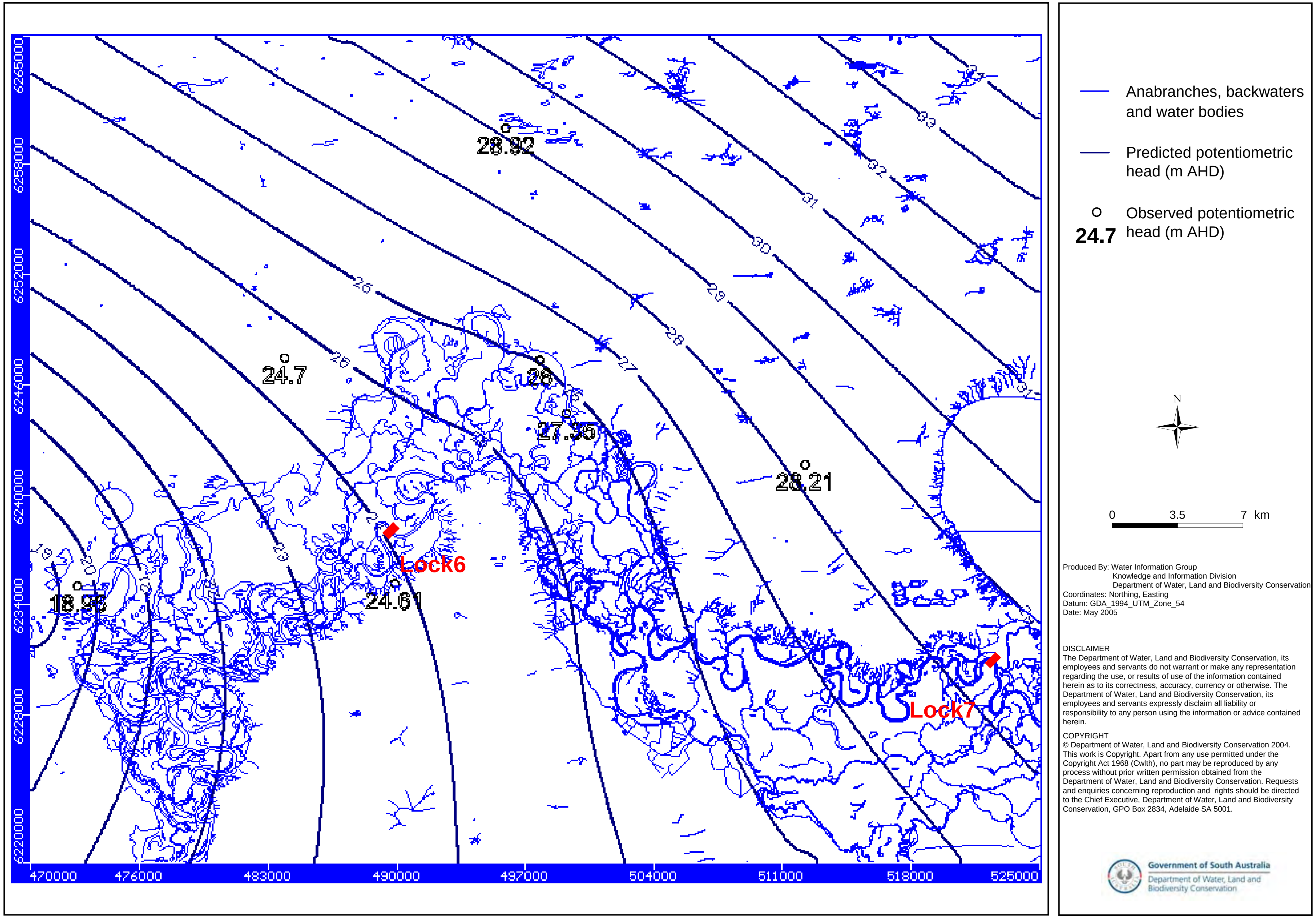

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Figure 16 Calibration results - modelled and observed potentiometric head, Murray Group Limestone (m AHD)

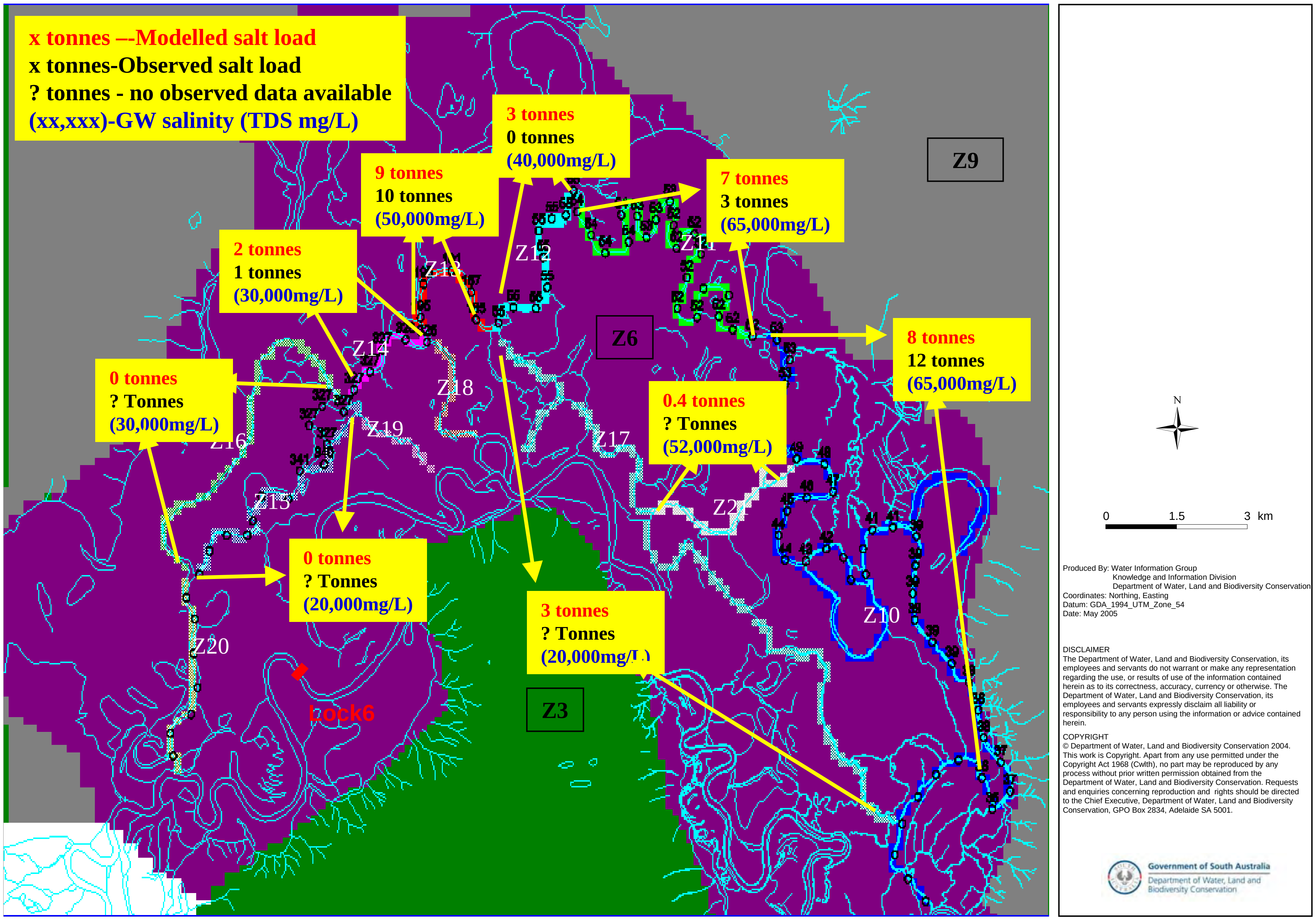


Figure 17 Predicted and observed salt load entering the anabranch creeks 2002 (tonnes/day)

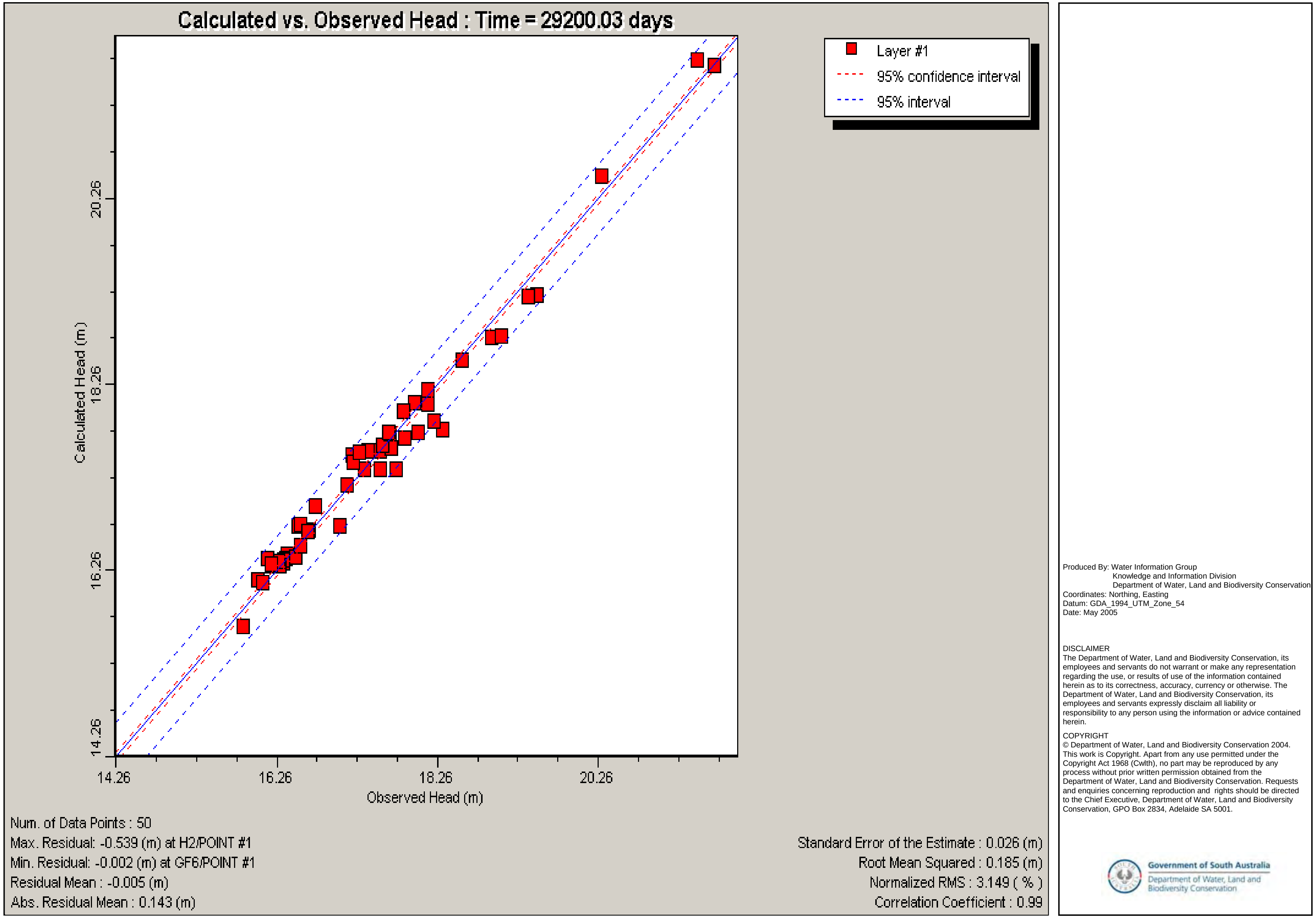
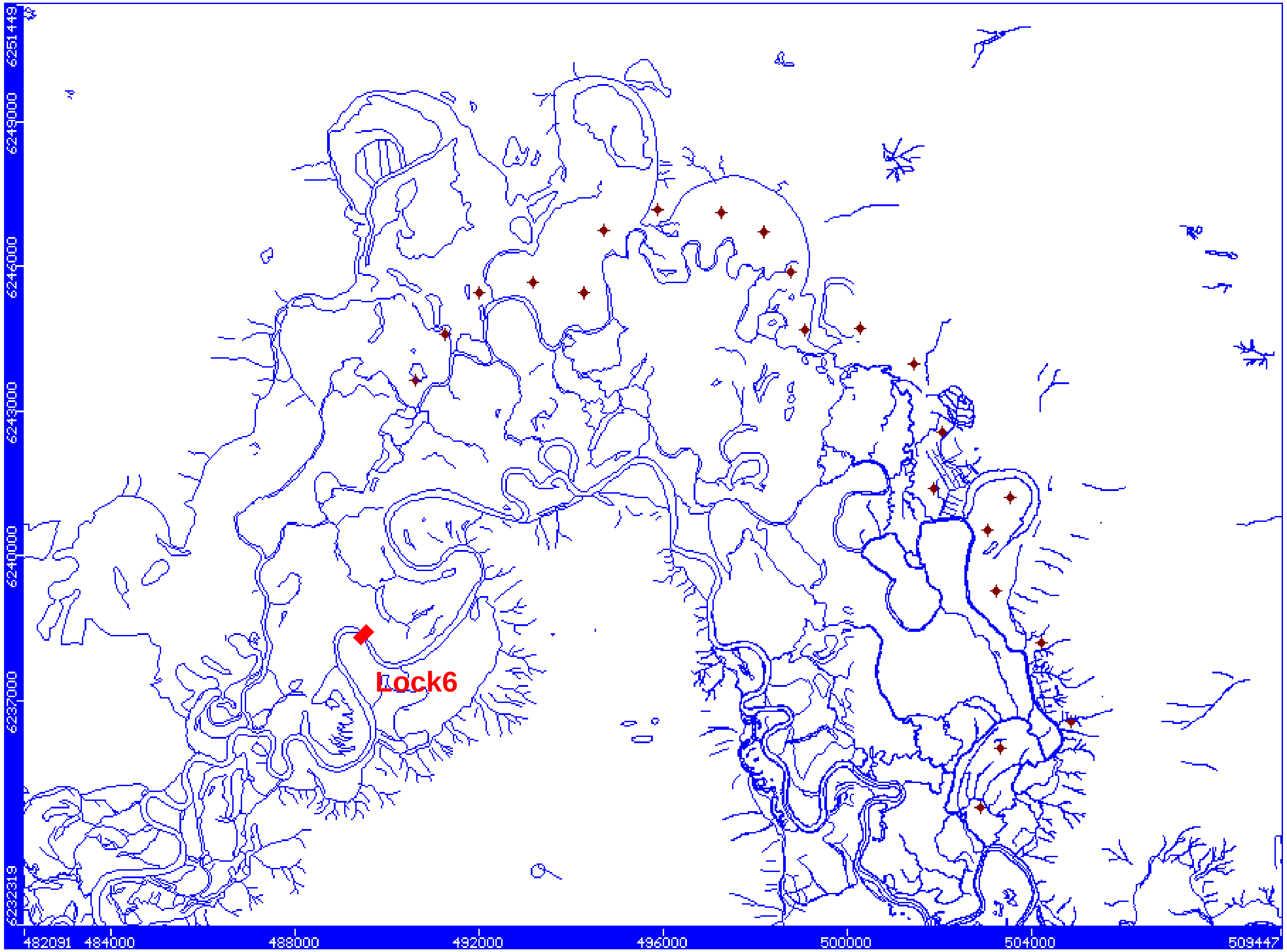


Figure 18 Calibration results – modelled vs observed potentiometric head (2003)

22 wells total flux commencing at 121 L/s, reducing to 66 L/s



Anabranches, backwaters and water bodies

Production bores

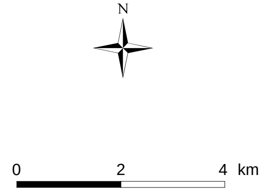


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Figure 19 Scenario-4 Location of production wells

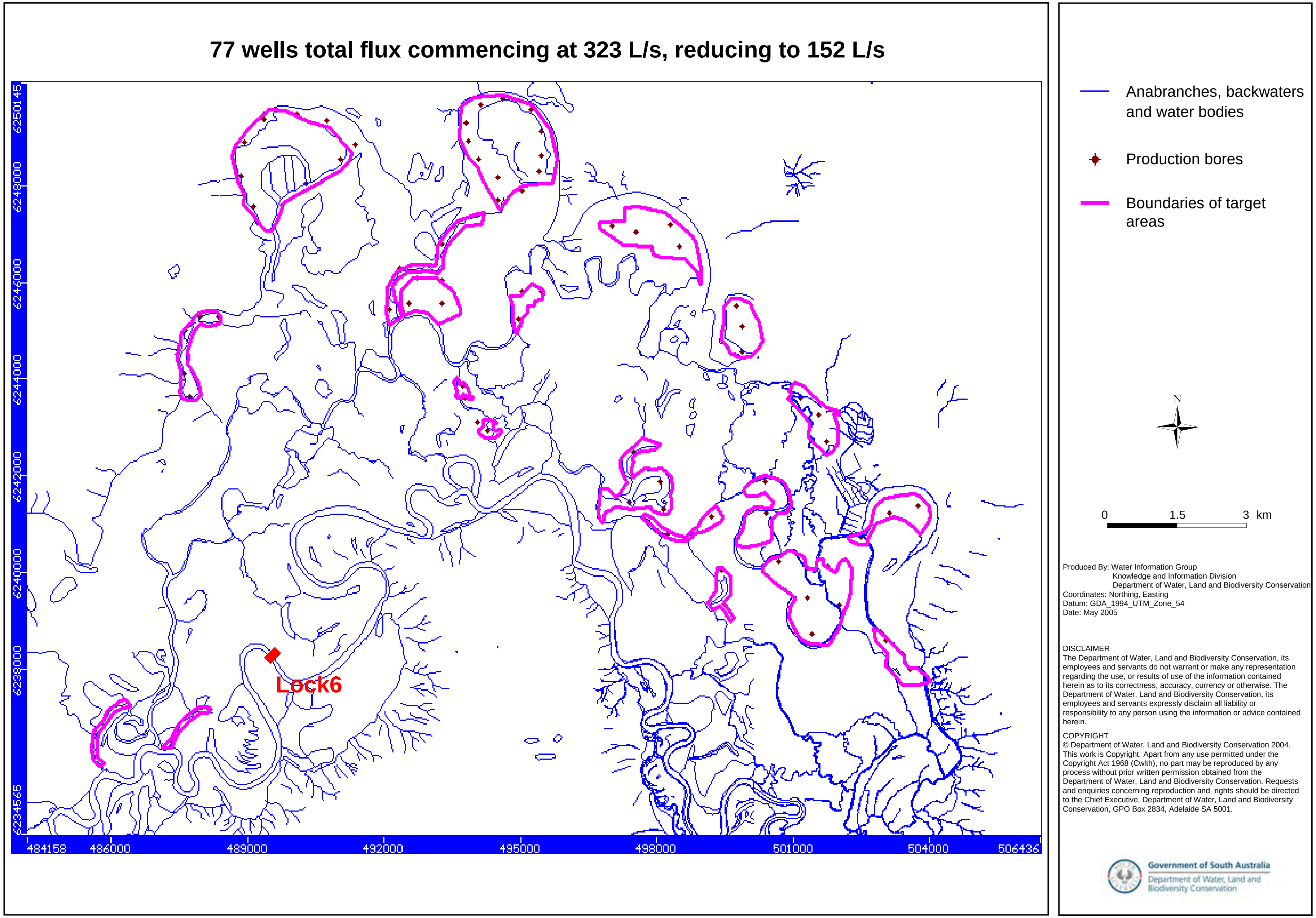
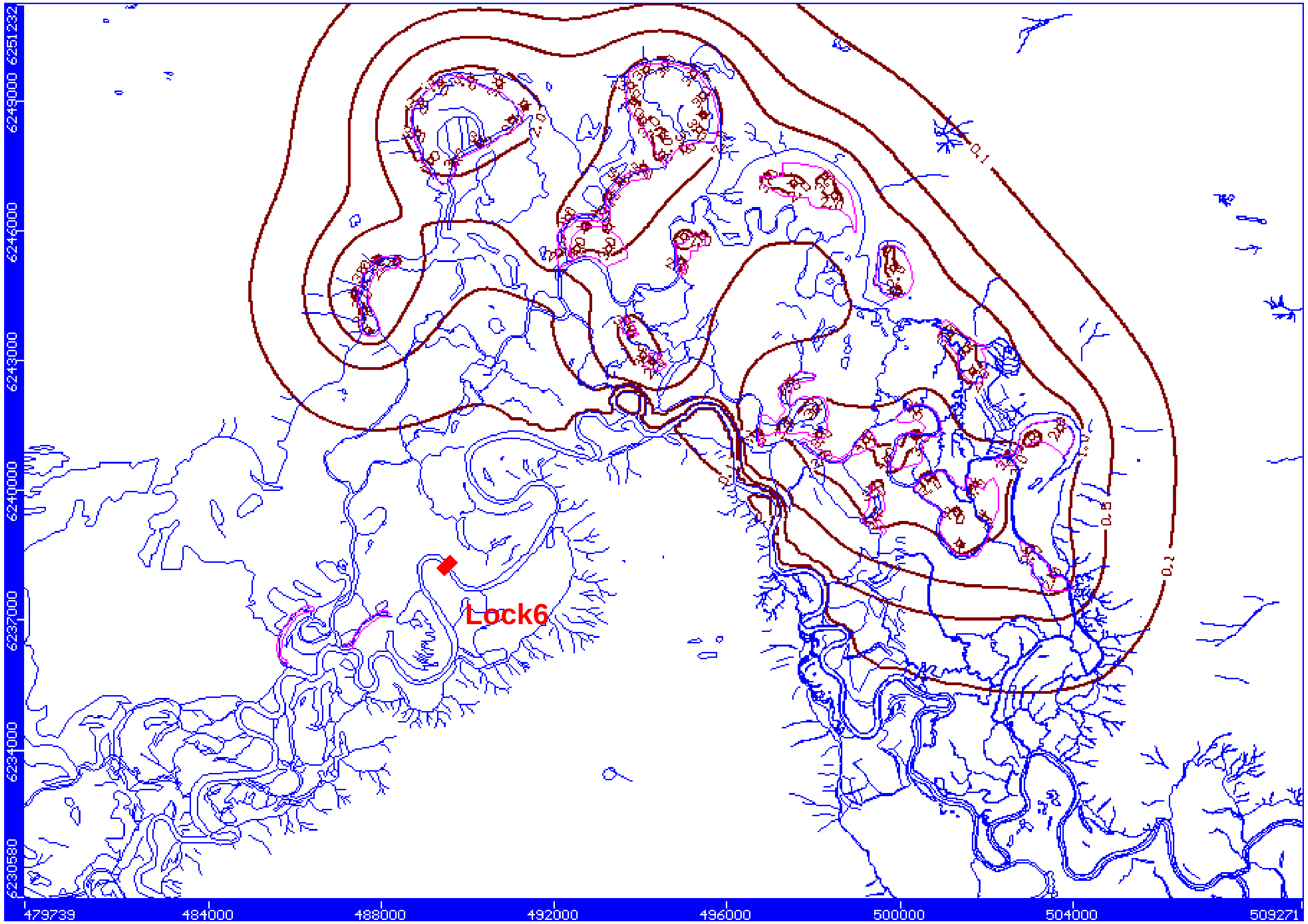


Figure 20 Scenario-5 location of production wells



Anabranches, backwaters and water bodies

Drawdown contours (m)

N

0 2 4 km

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Figure 21 Scenario-5 predicted drawdown contours after 5 years (m)

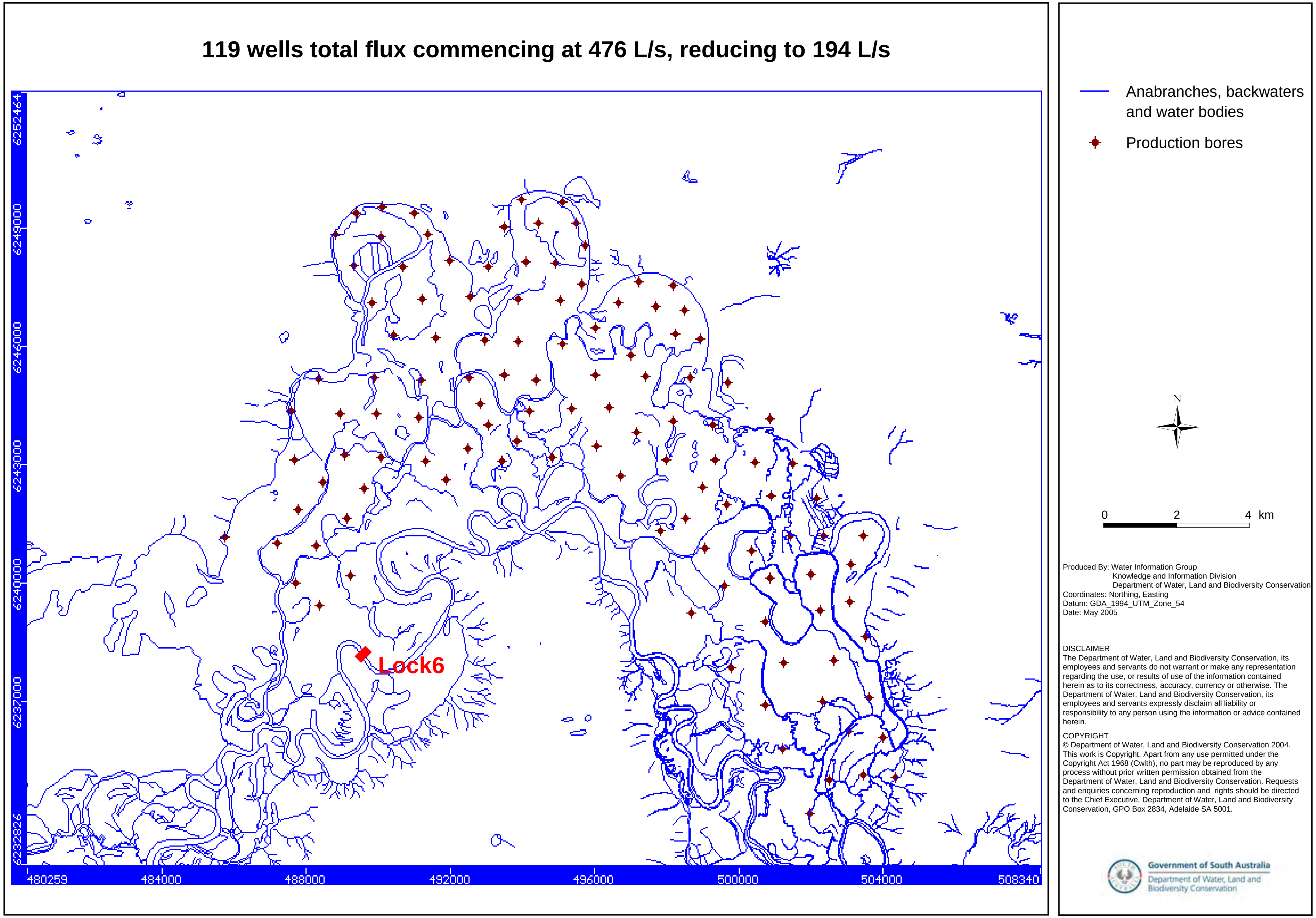
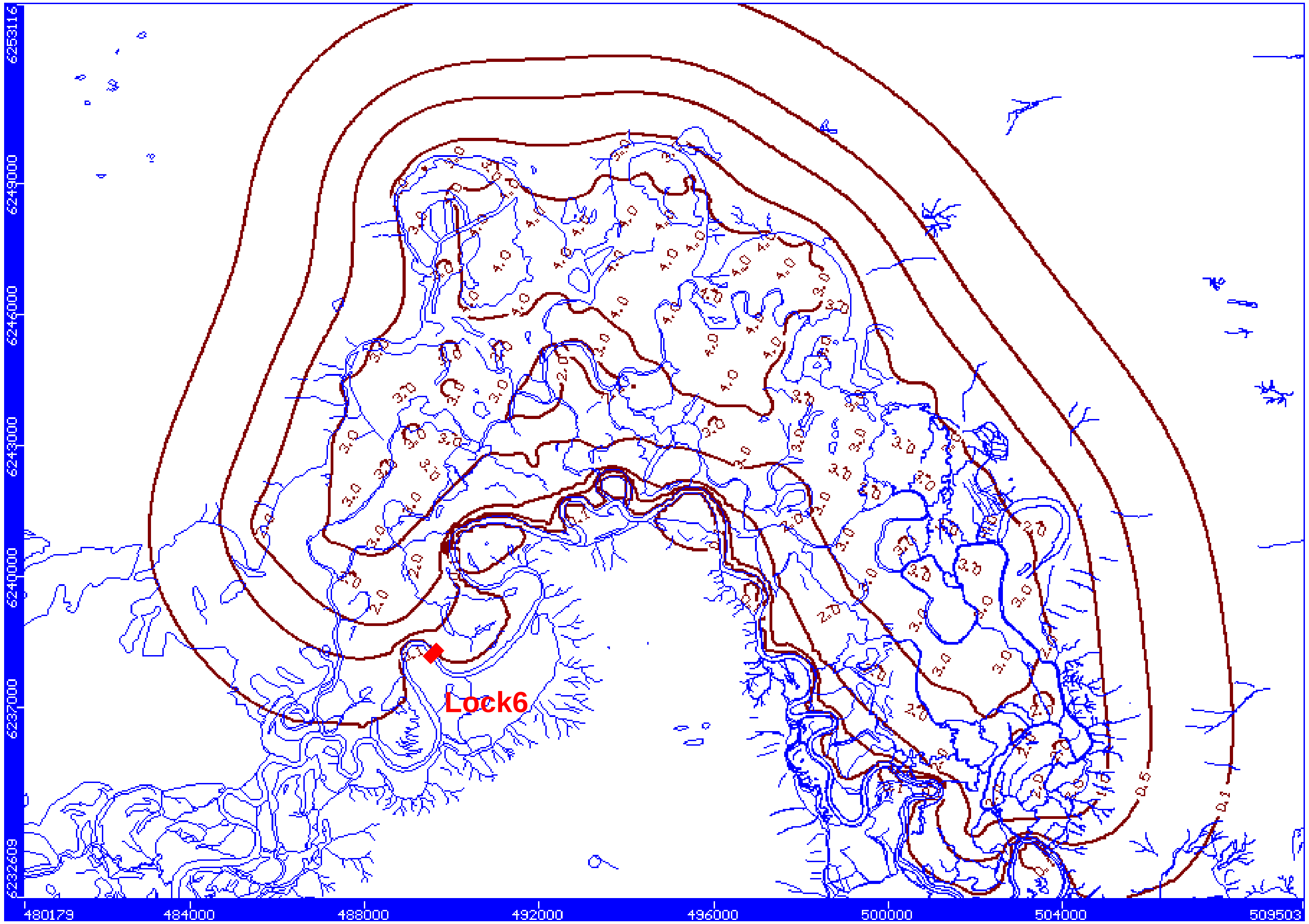


Figure 22 Scenario-6 location of production wells



Anabranches, backwaters and water bodies

Drawdown contours (m)

N

0 2 4 km

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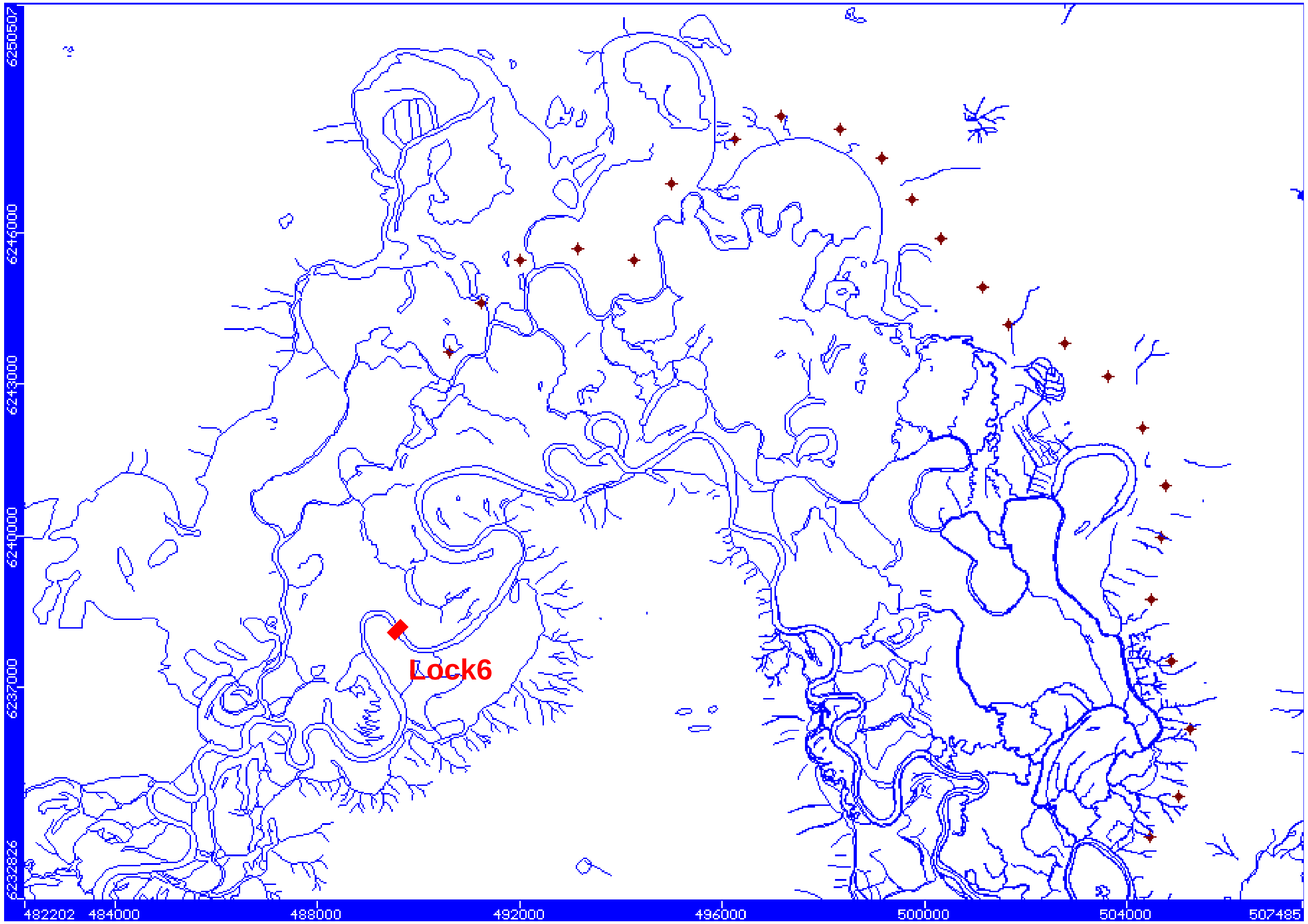
Figure 23 Scenario-6 predicted drawdown contours after 5 years (m)

18 highland wells and 6 floodplain wells
Total flux commencing at 132 L/s reducing to 72 L/s



Anabranches, backwaters and water bodies

Production bores

N

0 2 4 km

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Figure 24 Scenario-7 location of production wells

38 wells with total flux commencing at 190 L/s, reducing to 90 L/s)

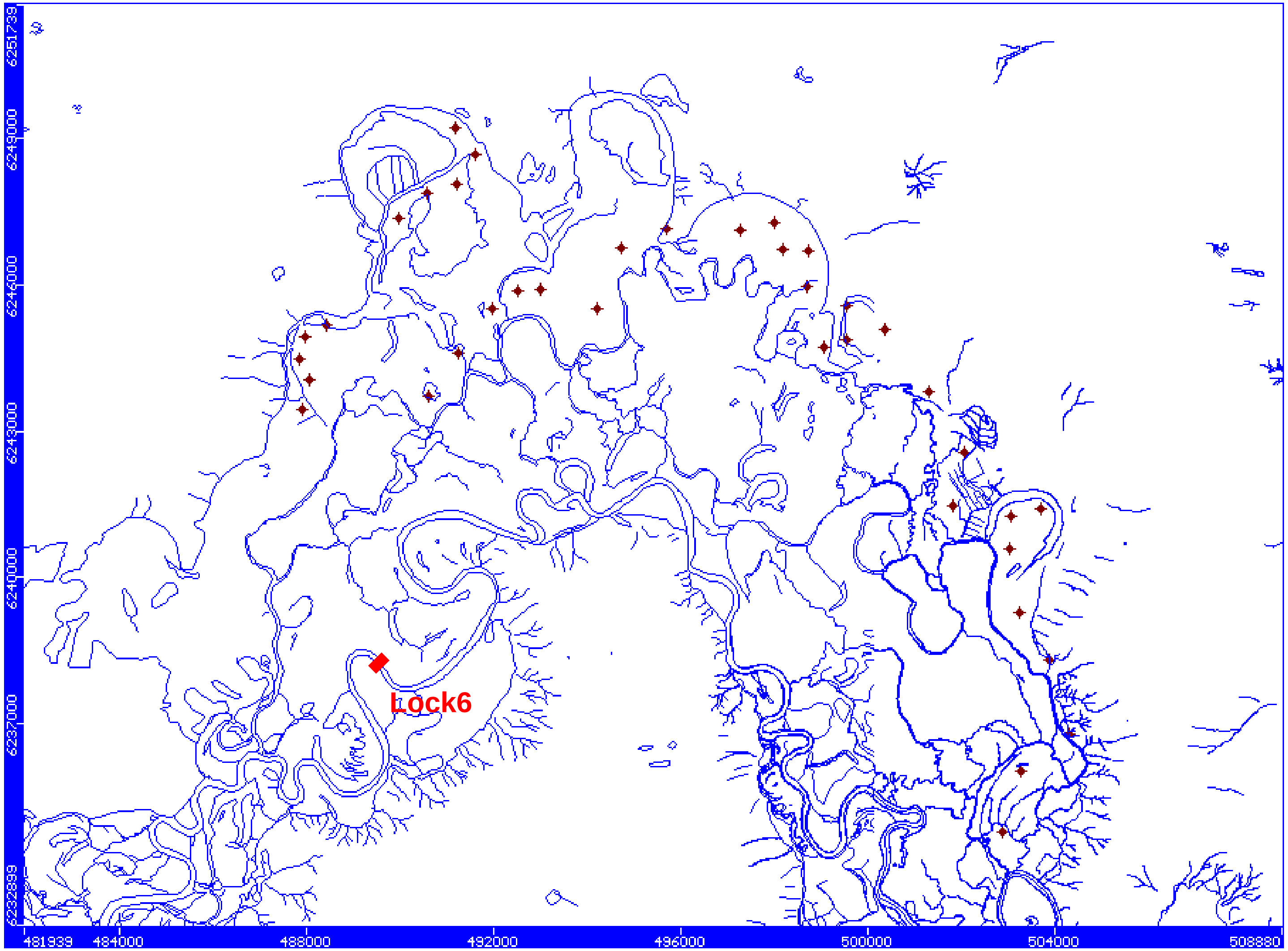

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Figure 25 Scenario-8 location of production wells

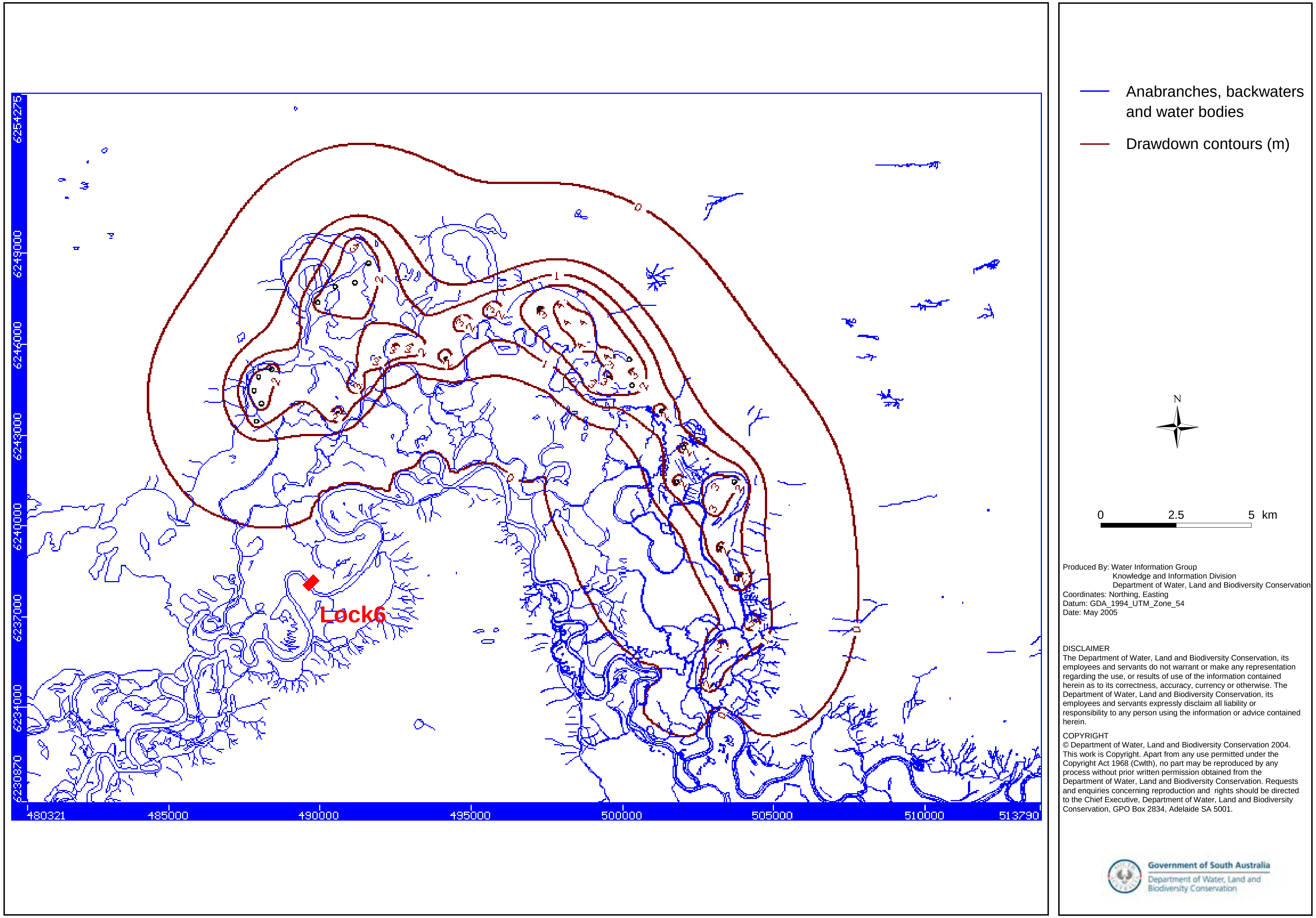
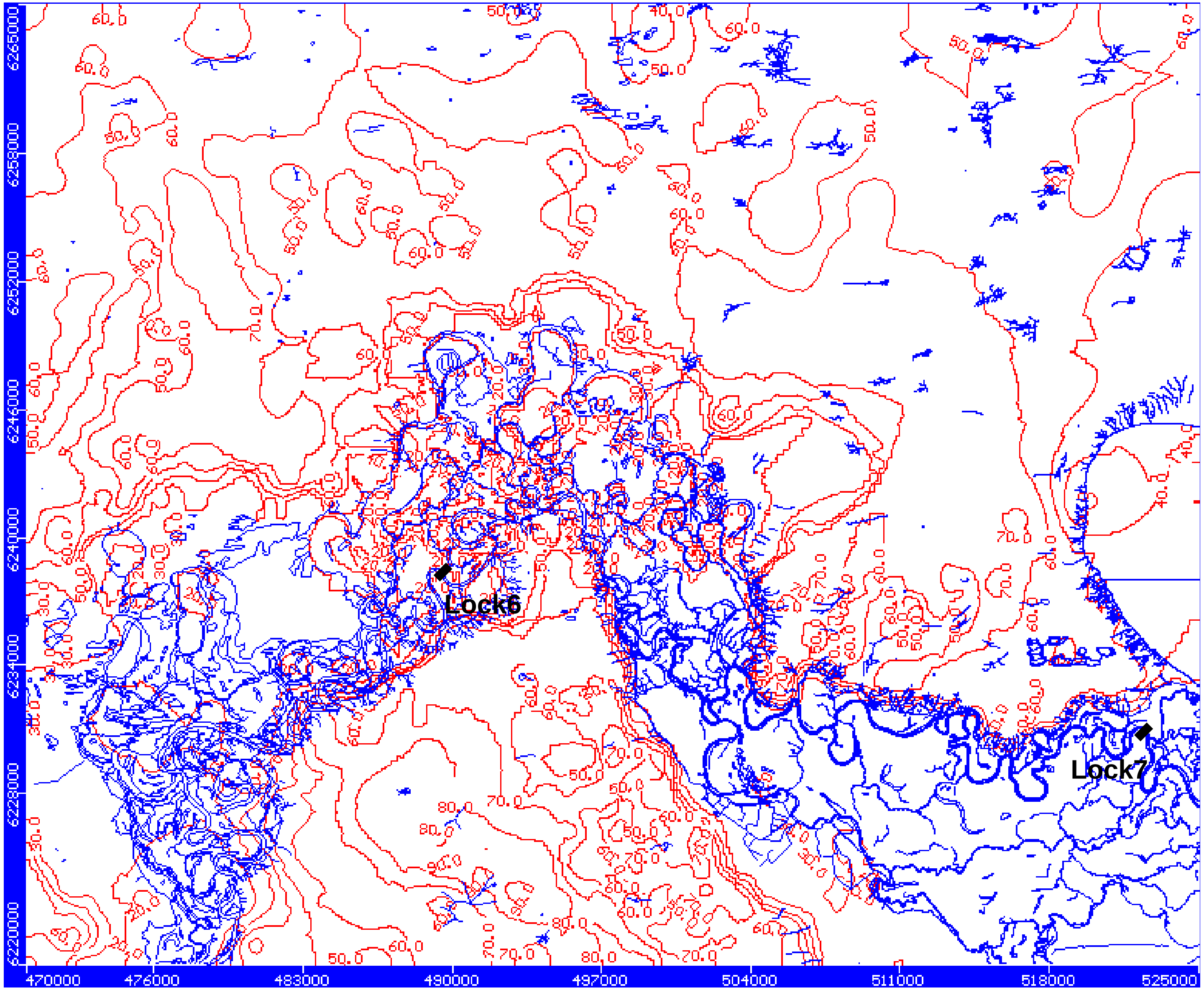


Figure 26 Scenario-8 predicted drawdown contours after 5 years (m)

APPENDIX 1 – SURFACE ELEVATION CONTOURS



Anabranches, backwaters and water bodies

Surface elevation contours (m AHD)

N

0 3.5 7 km

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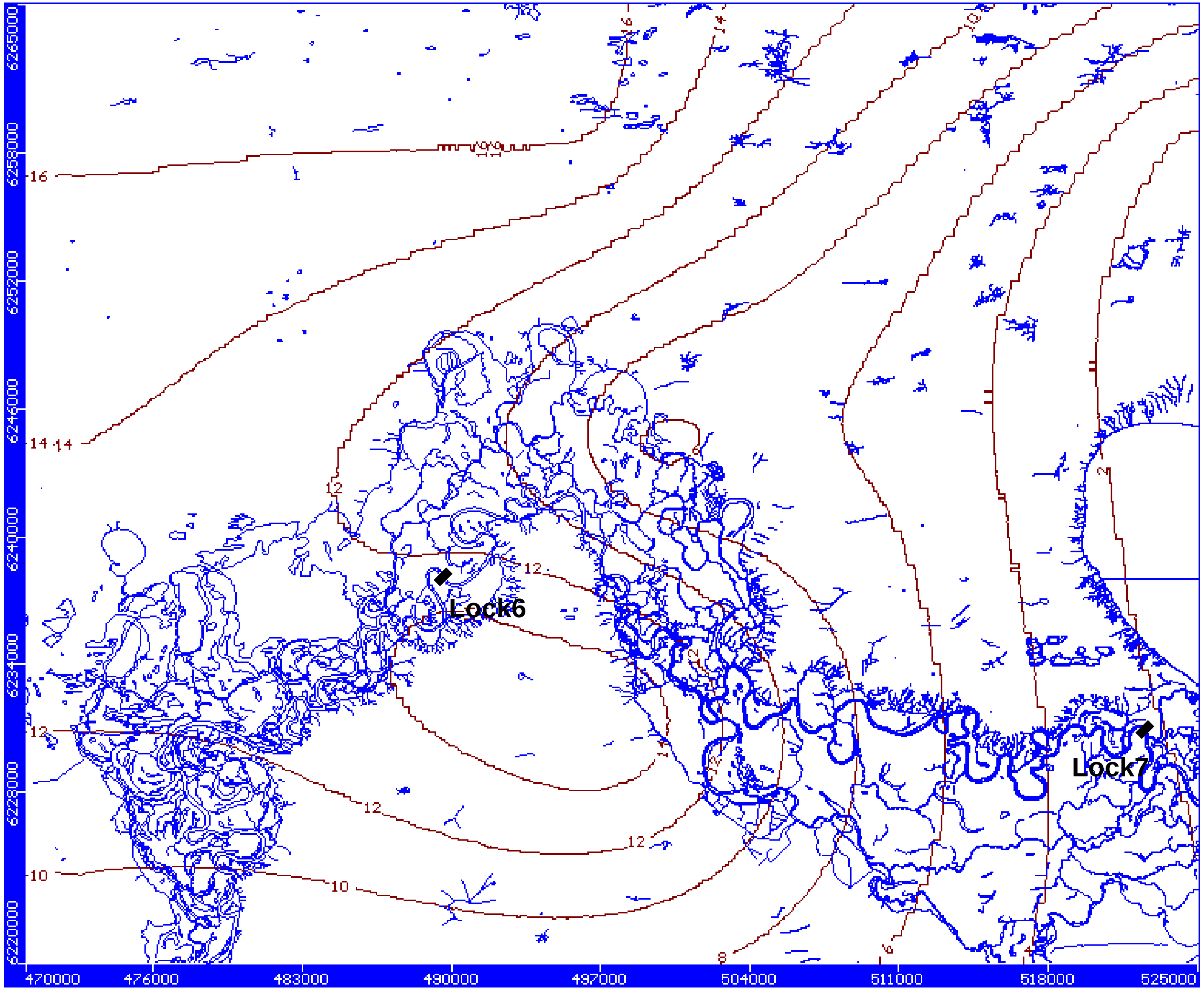
Appendix 1 Figure 1. Ground surface elevation Chowilla floodplain



Anabranches, backwaters and water bodies

Surface elevation contours (m AHD)

N

0 3.5 7 km

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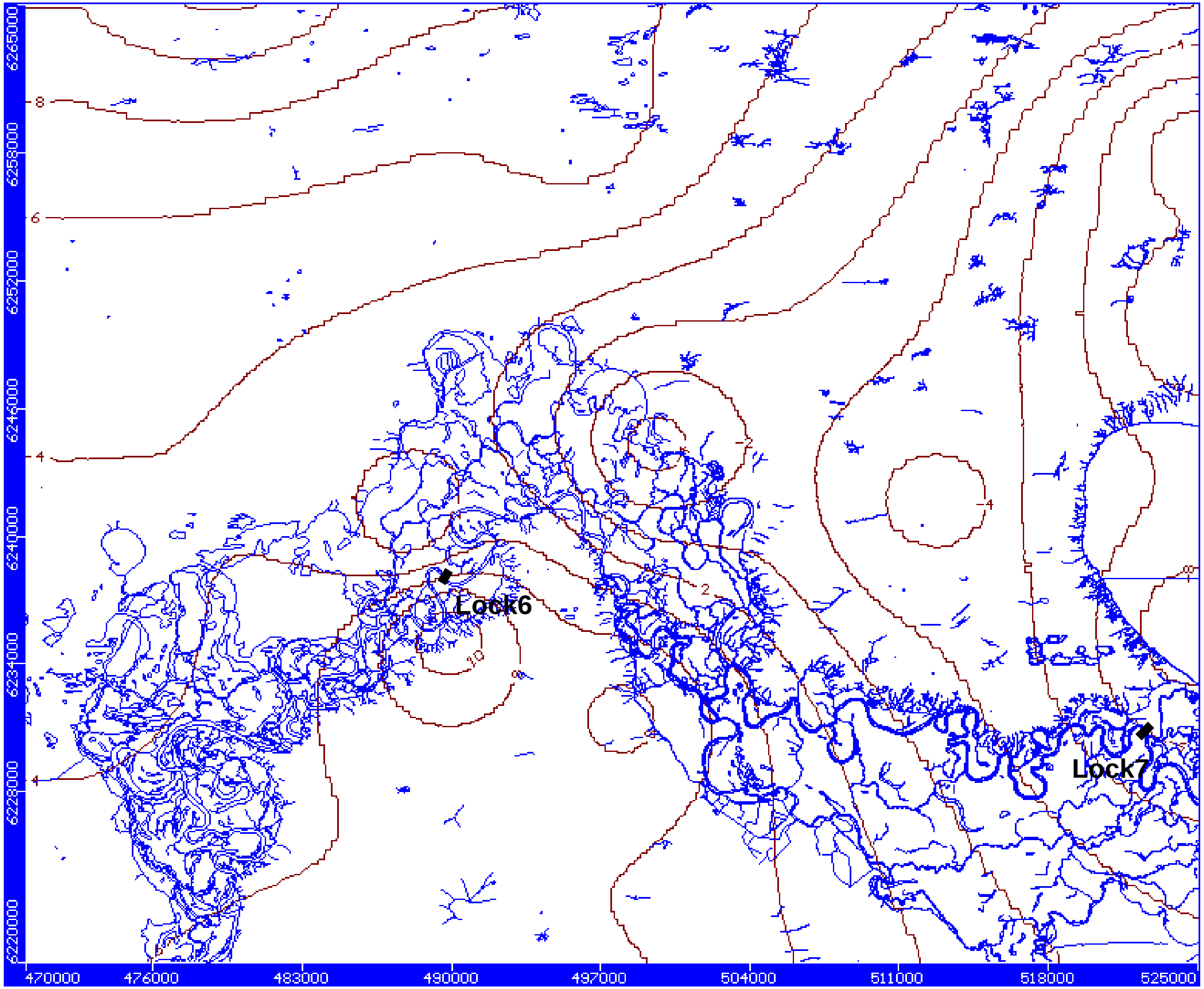
Appendix 1 Figure 2. Base elevation Upper Monoman Formation and Upper Pliocene Sands



Anabranches, backwaters and water bodies

Surface elevation contours (m AHD)

N

0 3.5 7 km

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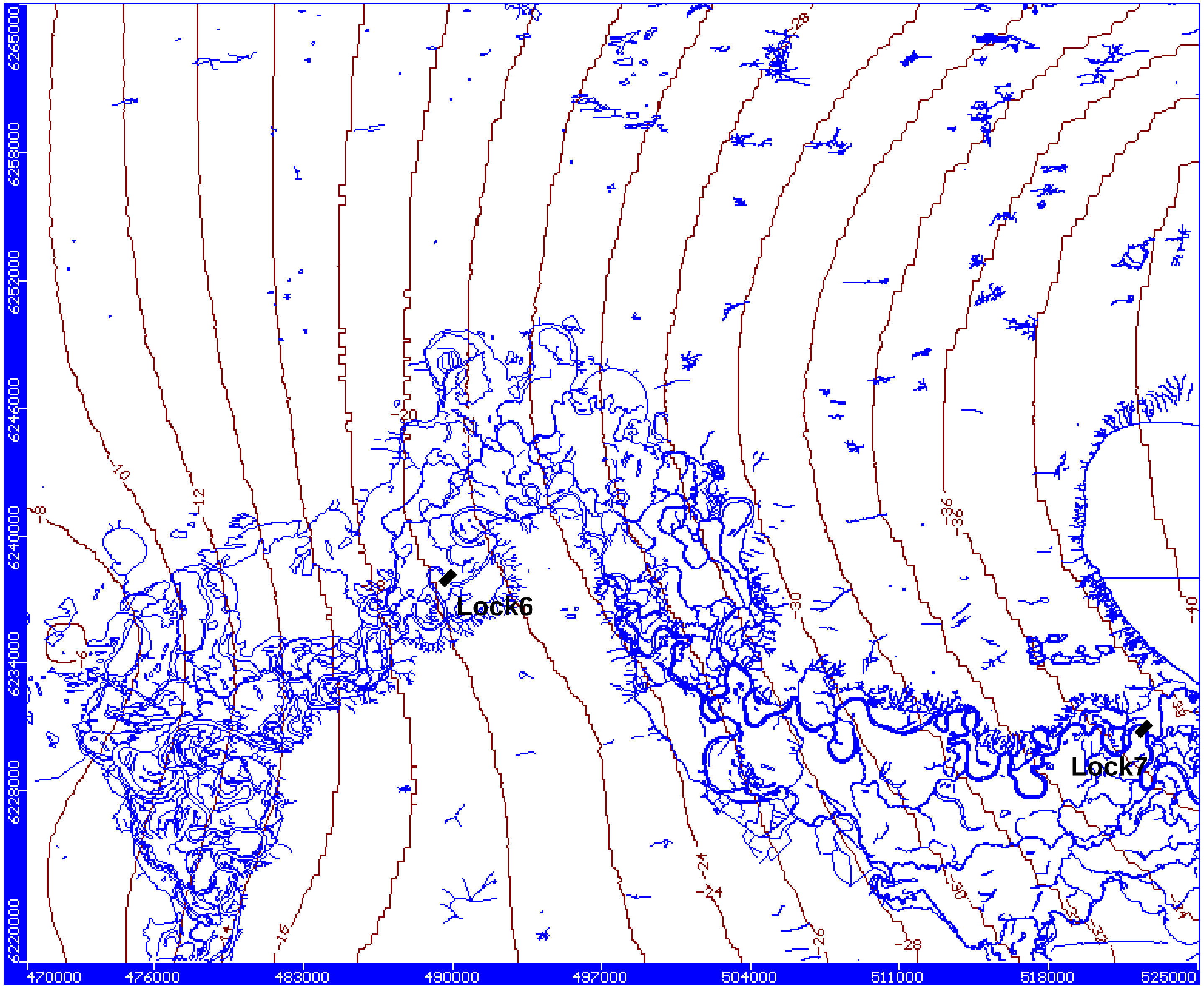
Appendix 1 Figure 3. Base elevation Lower Monoman Formation and Upper Pliocene Sands



Anabranches, backwaters and water bodies

Surface elevation contours (m AHD)

N

0 3.5 7 km

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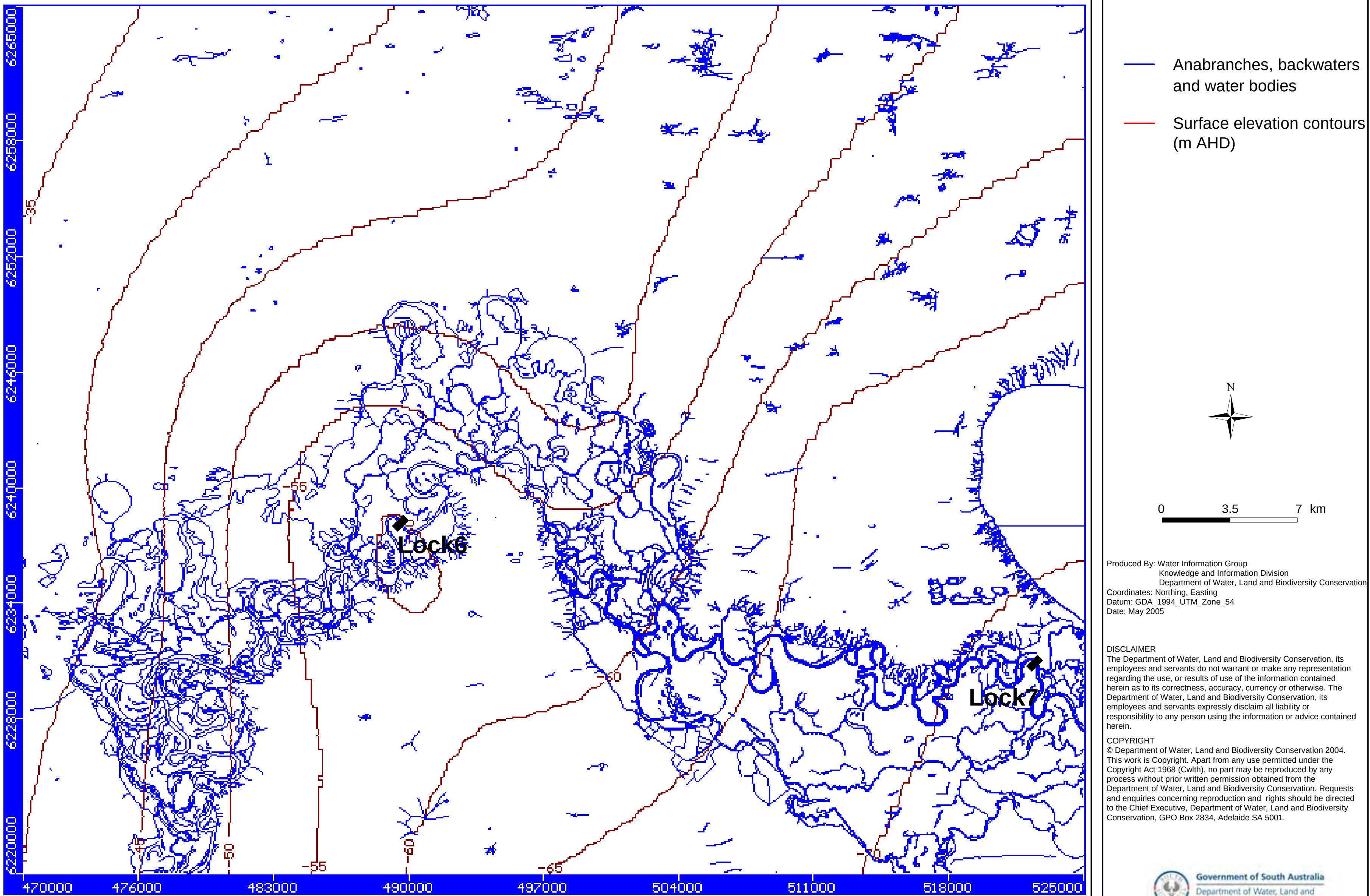
Appendix 1 Figure 4. Base elevation Lower Pliocene Sands



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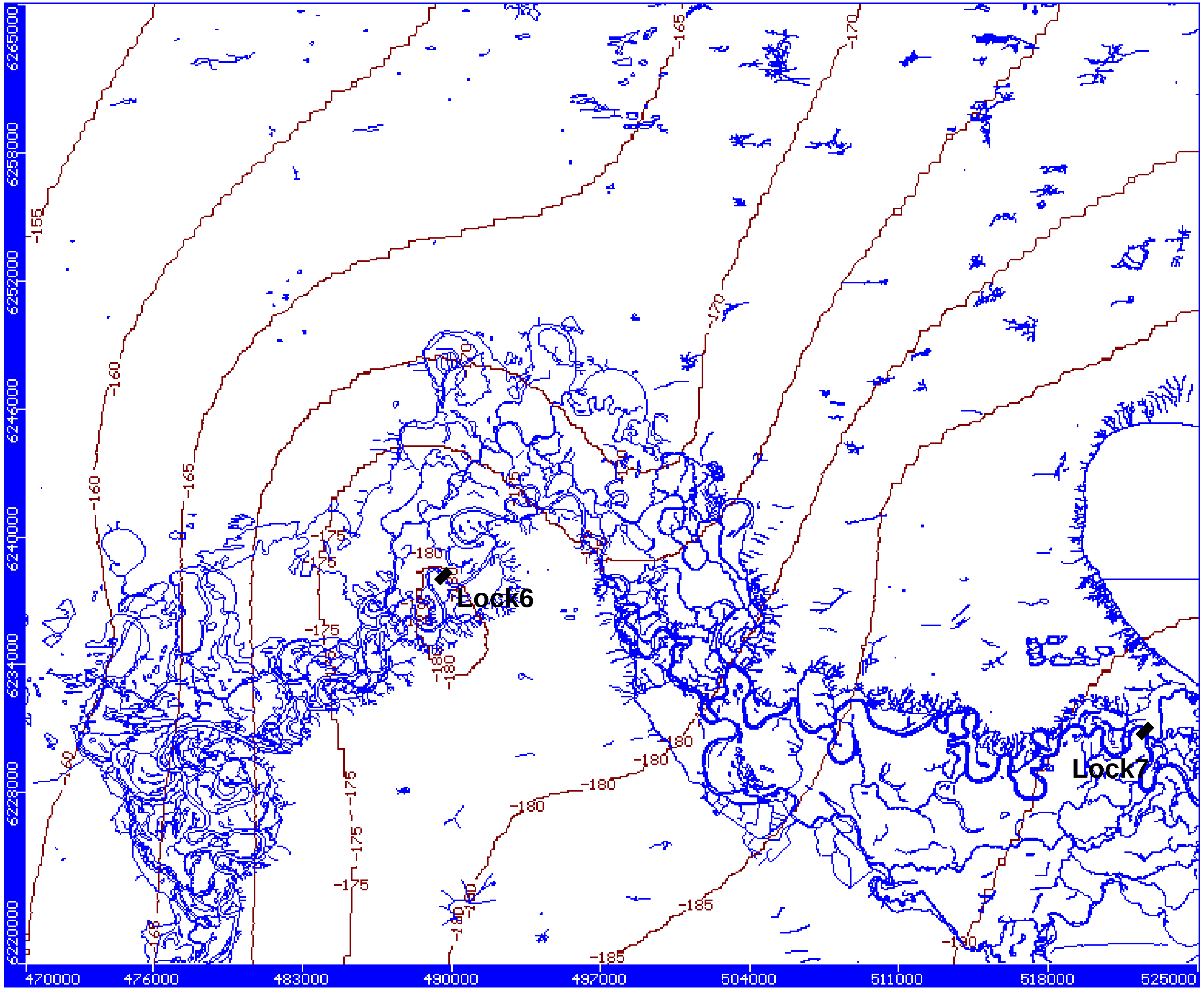
Appendix 1 Figure 5. Base elevation Bookpurnong Formation



Anabranches, backwaters and water bodies

Surface elevation contours (m AHD)

N

0 3.5 7 km

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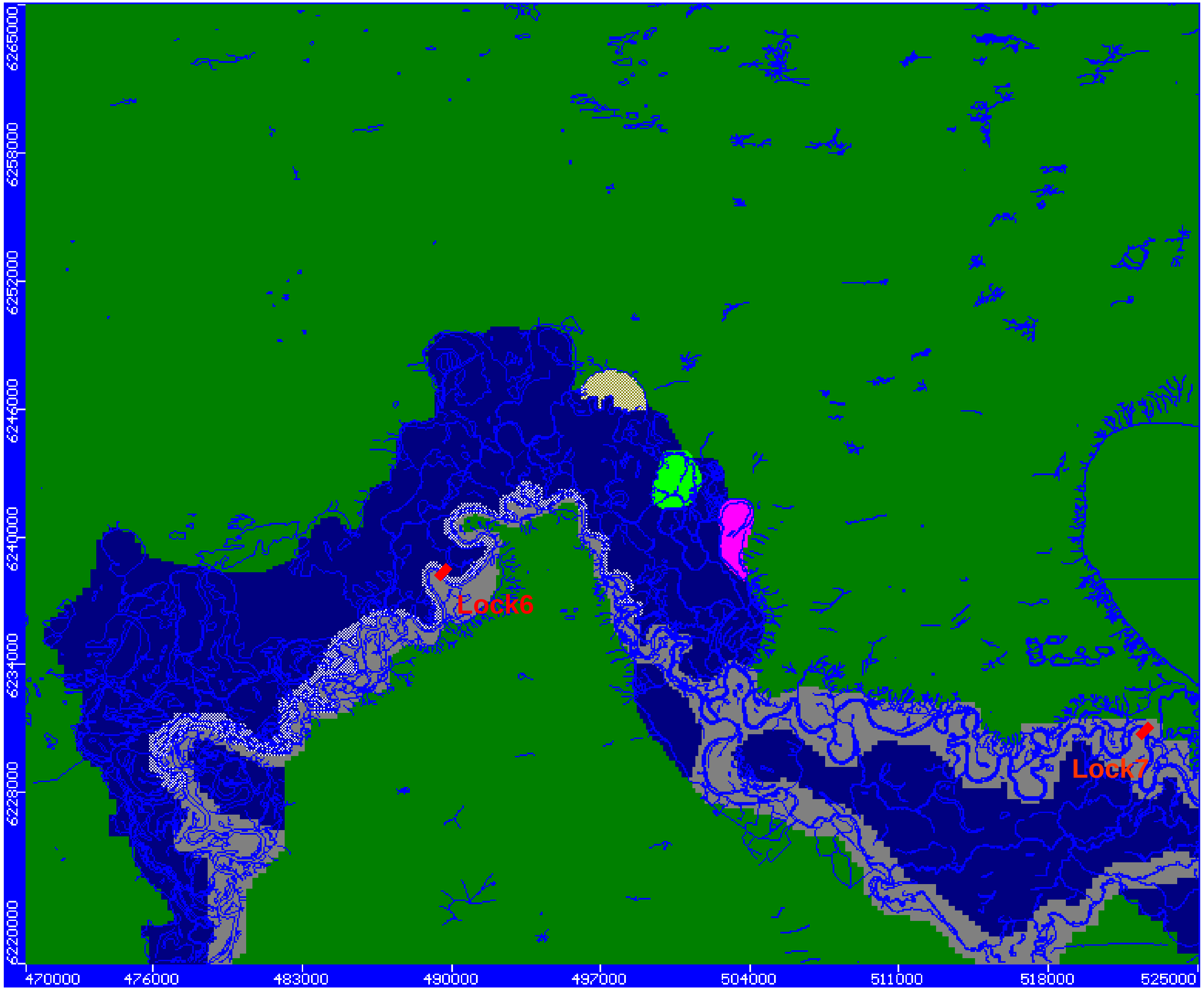
Appendix 1 Figure 6. Base elevation Murray Group Limestone

APPENDIX 2 – HYDRAULIC PARAMETERS



Kh=5 m/day
Kv=5 m/day

Kh=15 m/day
Kv=0.15 m/day

Kh=0.1 m/day
Kv=0.1 m/day

Kh=10 m/day
Kv=0.1 m/day

Kh=15 m/day
Kv=0.1 m/day

Kh=15 m/day
Kv=1 m/day

Anabranches, backwaters and water bodies

N

0 3.5 7 km

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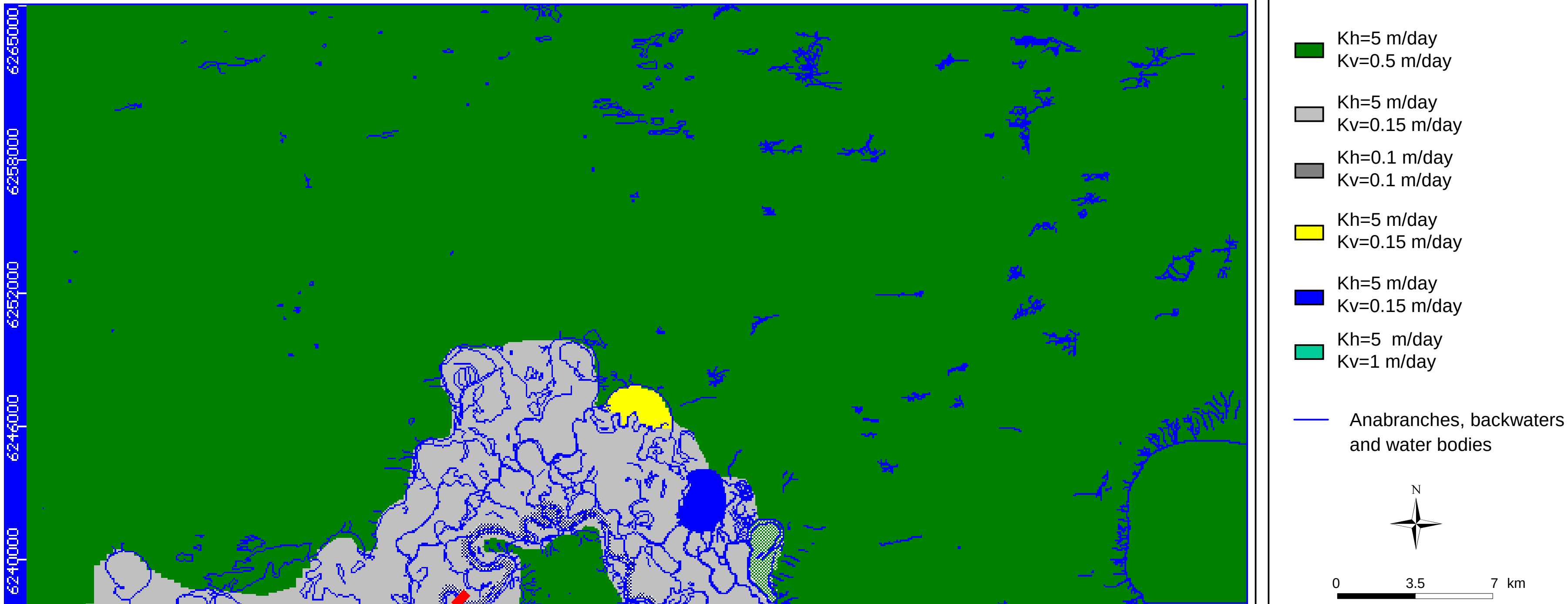
Appendix 2 Figure 1. Layer-1 (Upper Monoman Formation, Upper Pliocene Sands (Upper Part)) hydraulic conductivities



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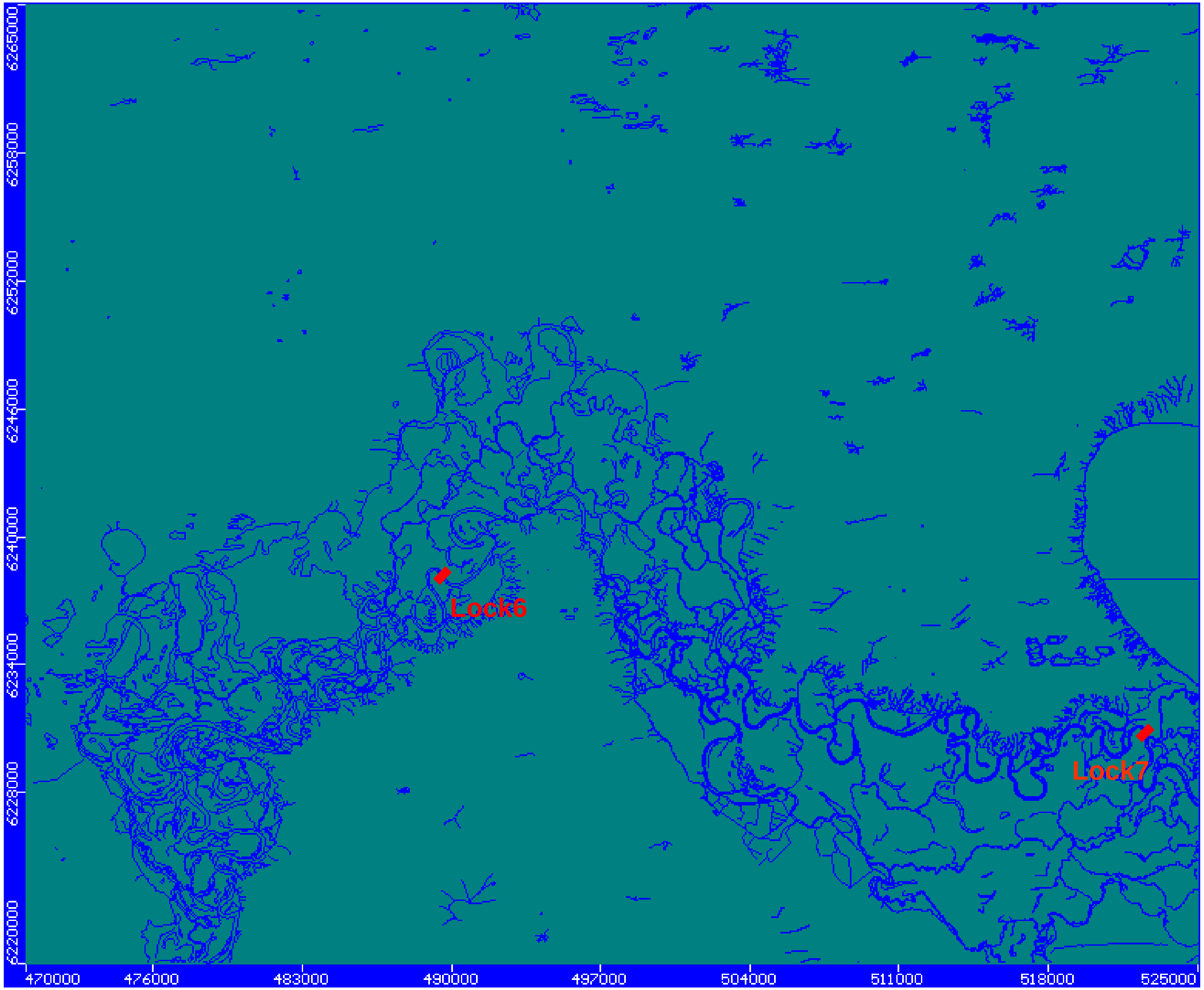
Appendix 2 Figure 2. Layer-2 (Lower Monoman Formation, Upper Pliocene Sands (lower part)) hydraulic conductivities



Kh=3 m/day
Kv=0.5 m/day

Anabranches, backwaters and water bodies

N

0 3.5 7 km

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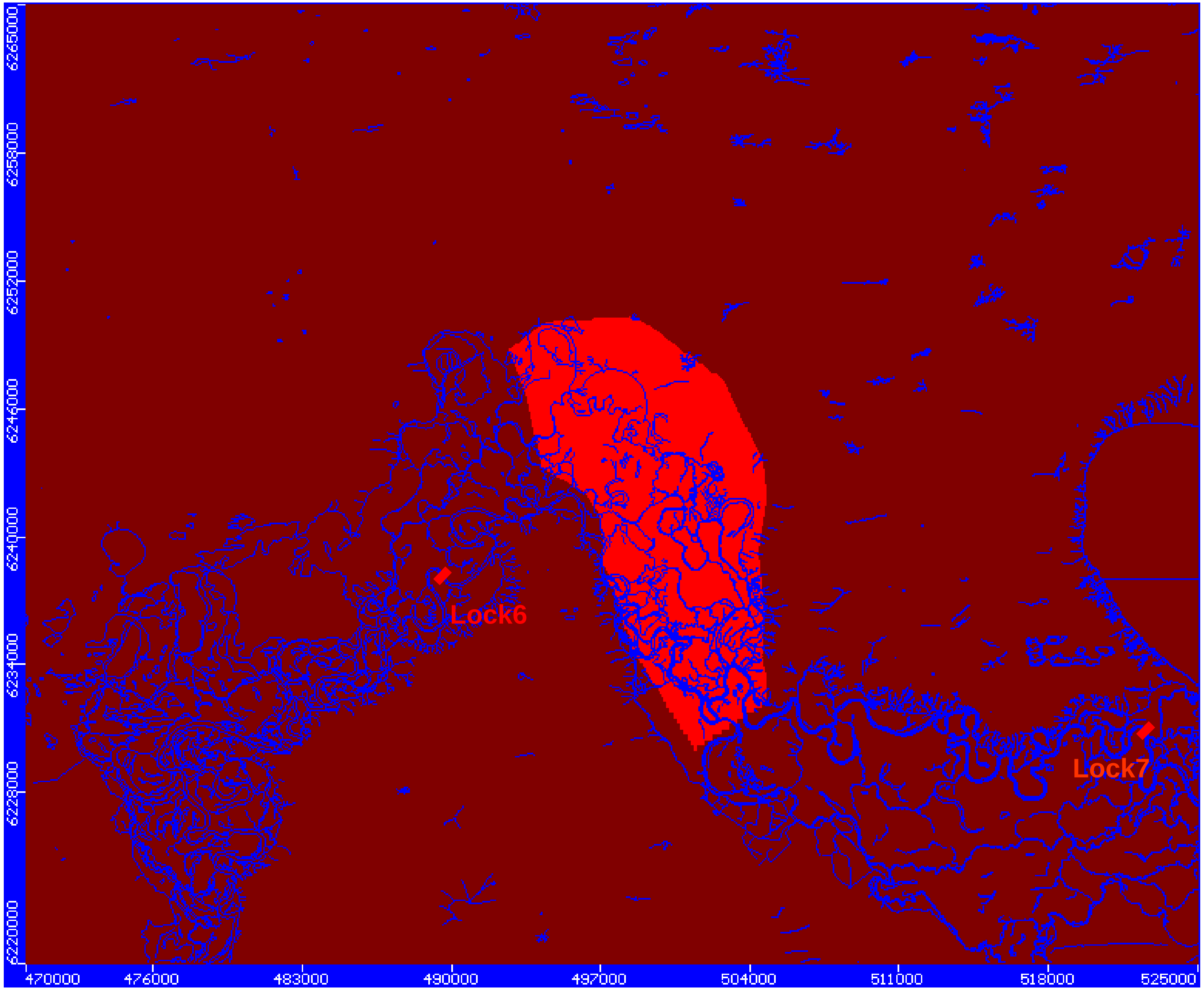
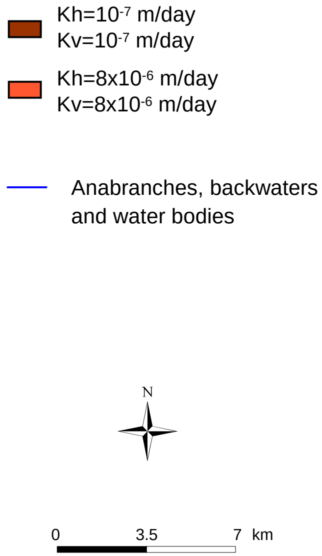
Appendix 2 Figure 3. Layer-3 (Lower Pliocene Sands) hydraulic conductivity





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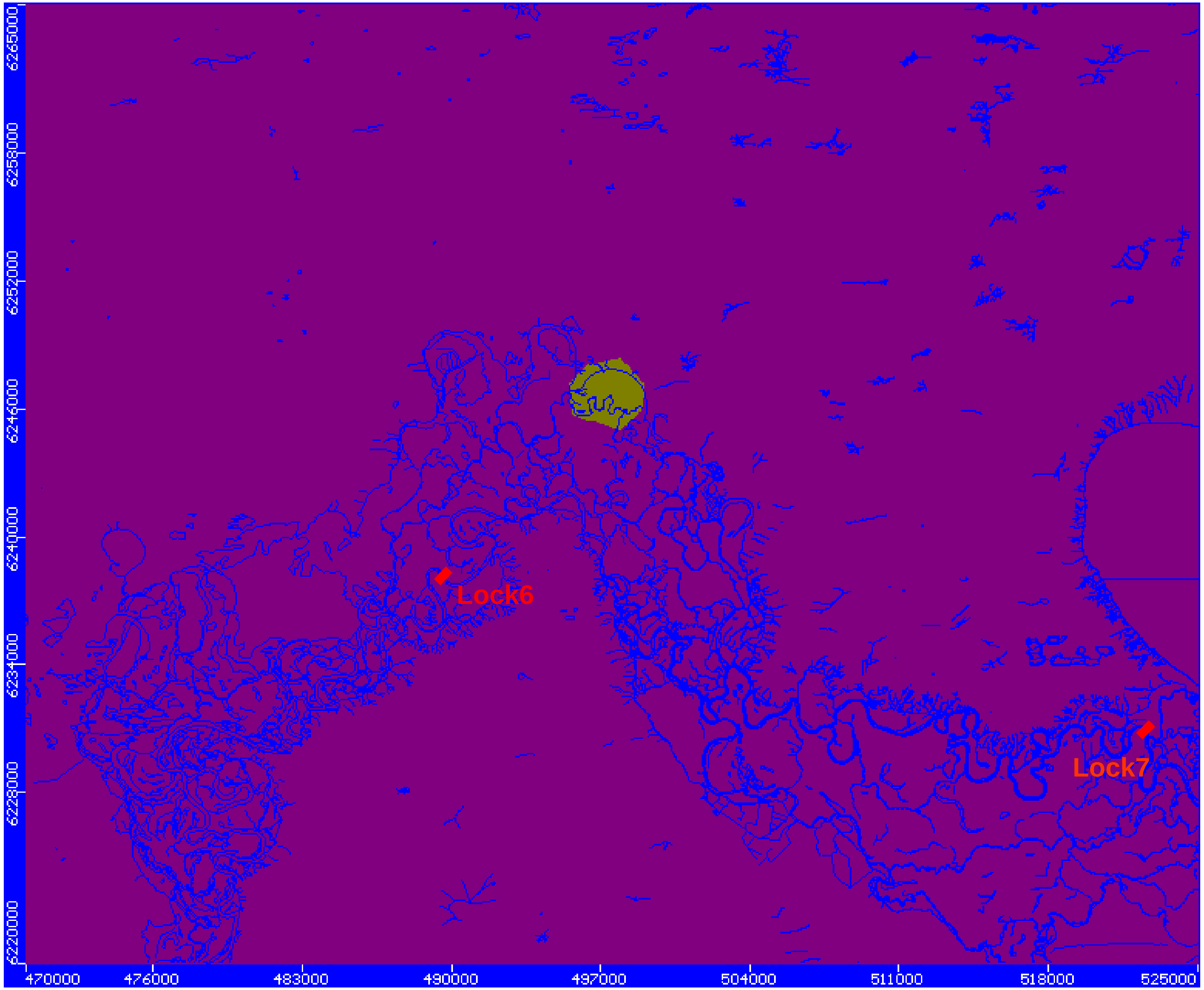
Appendix 2 Figure 4. Layer-4 (Bookpurnong Formation) hydraulic conductivities



Kh=0.5 m/day
Kv=0.1 m/day

Kh=0.1 m/day
Kv=0.1 m/day

Anabranches, backwaters and water bodies

N

0 3.5 7 km

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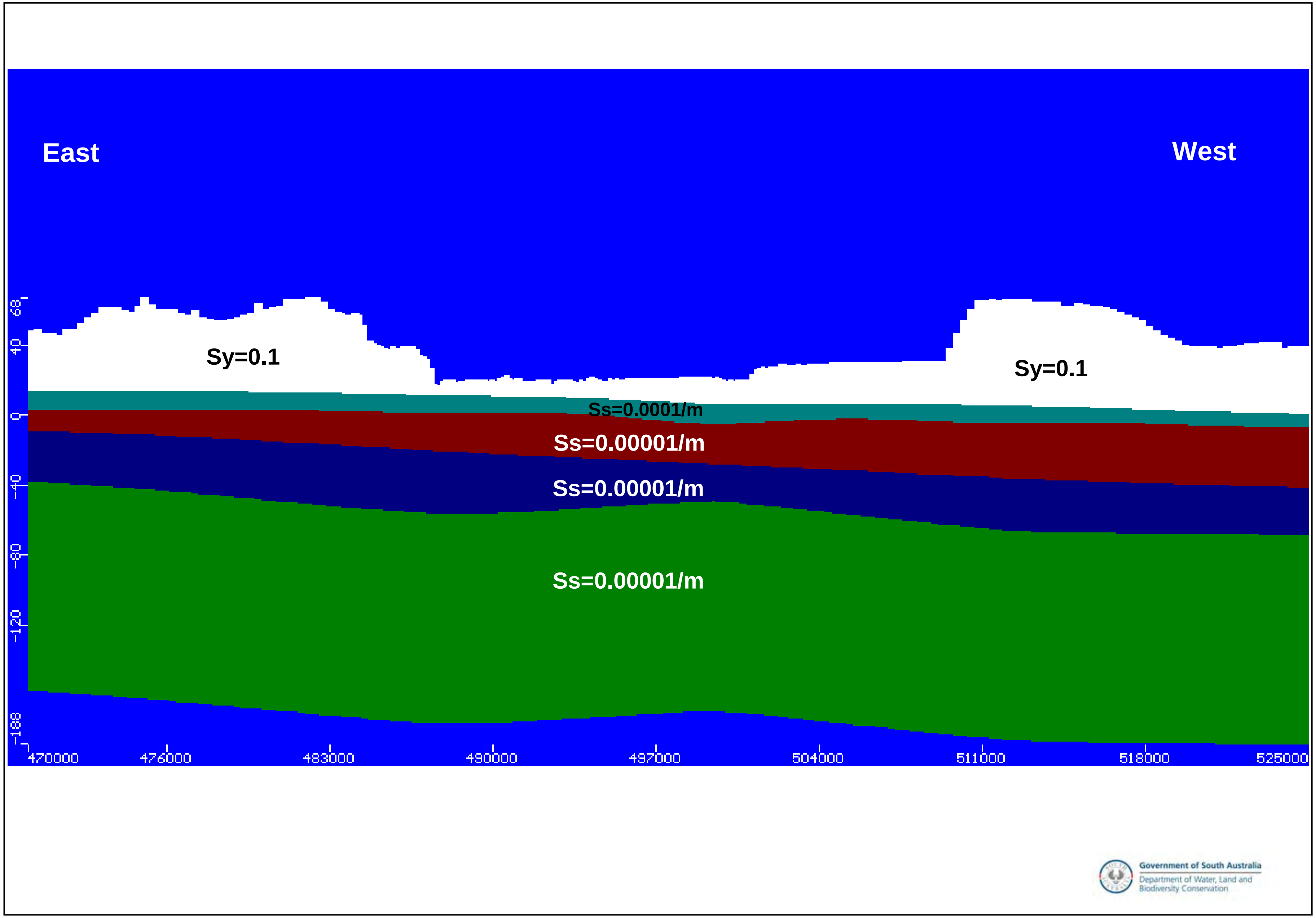
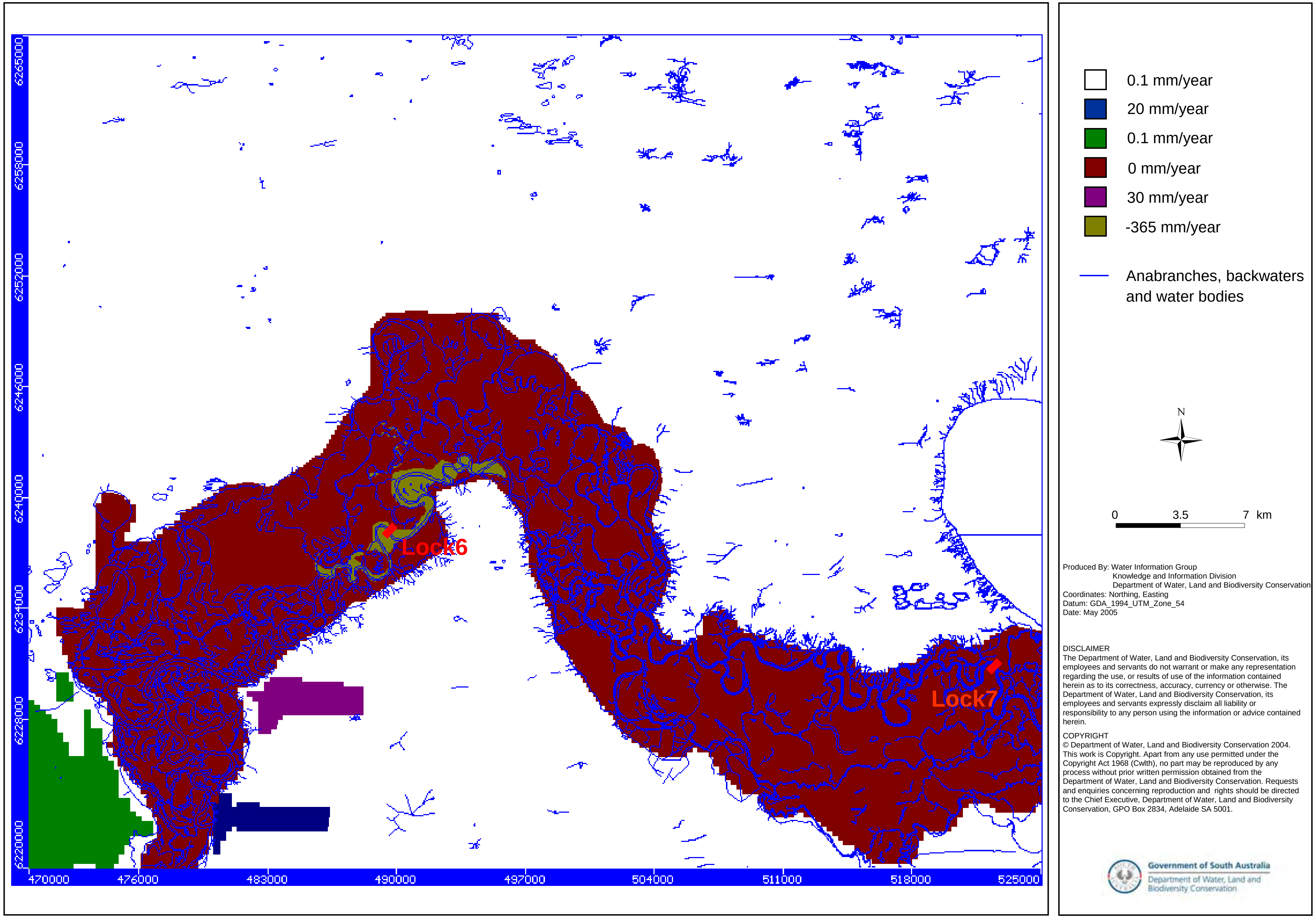
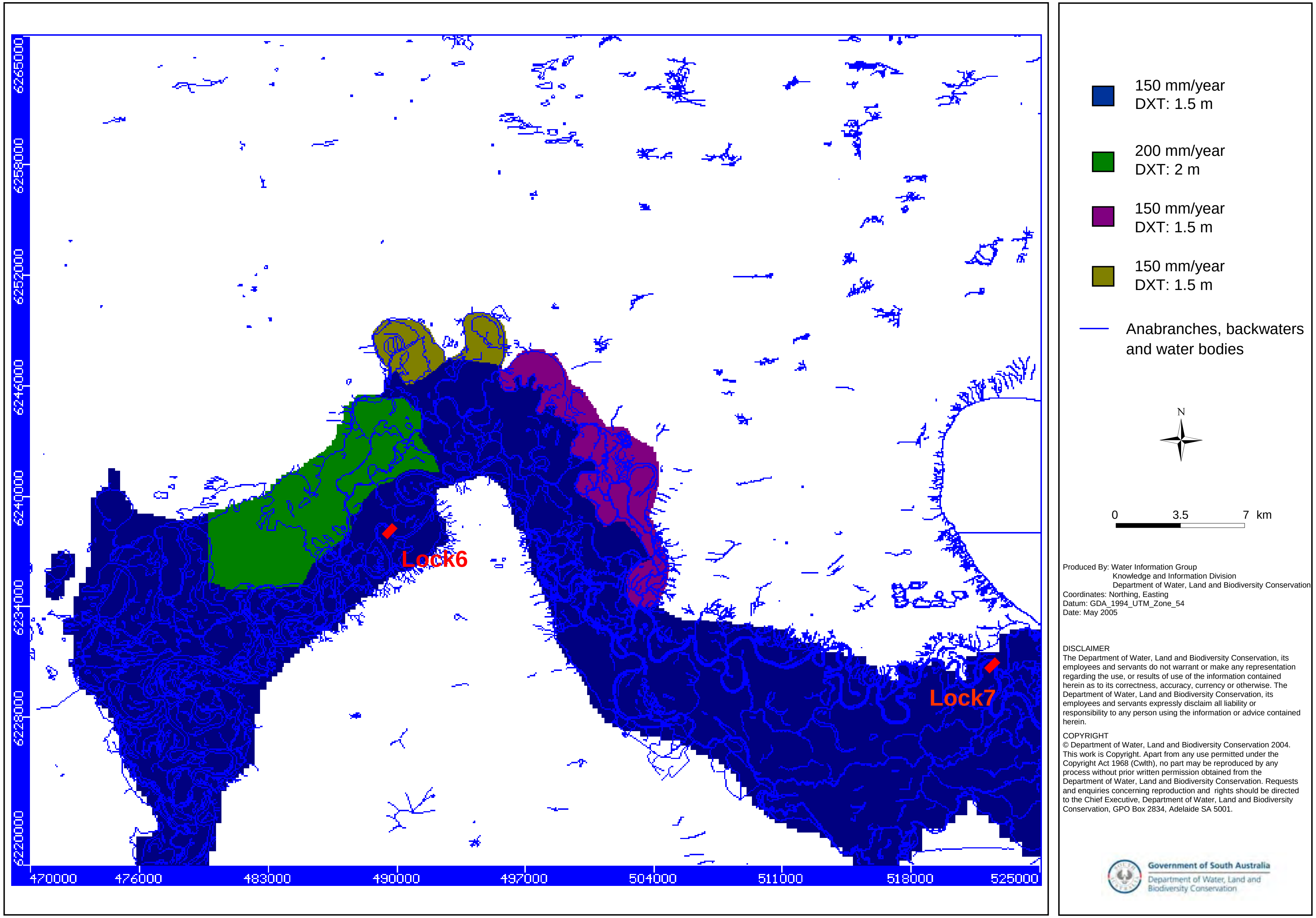
Appendix 2 Figure 5. Layer-5 (Murray Group Limestone) hydraulic conductivity



Appendix 2 Figure 6. Model layers storage parameters

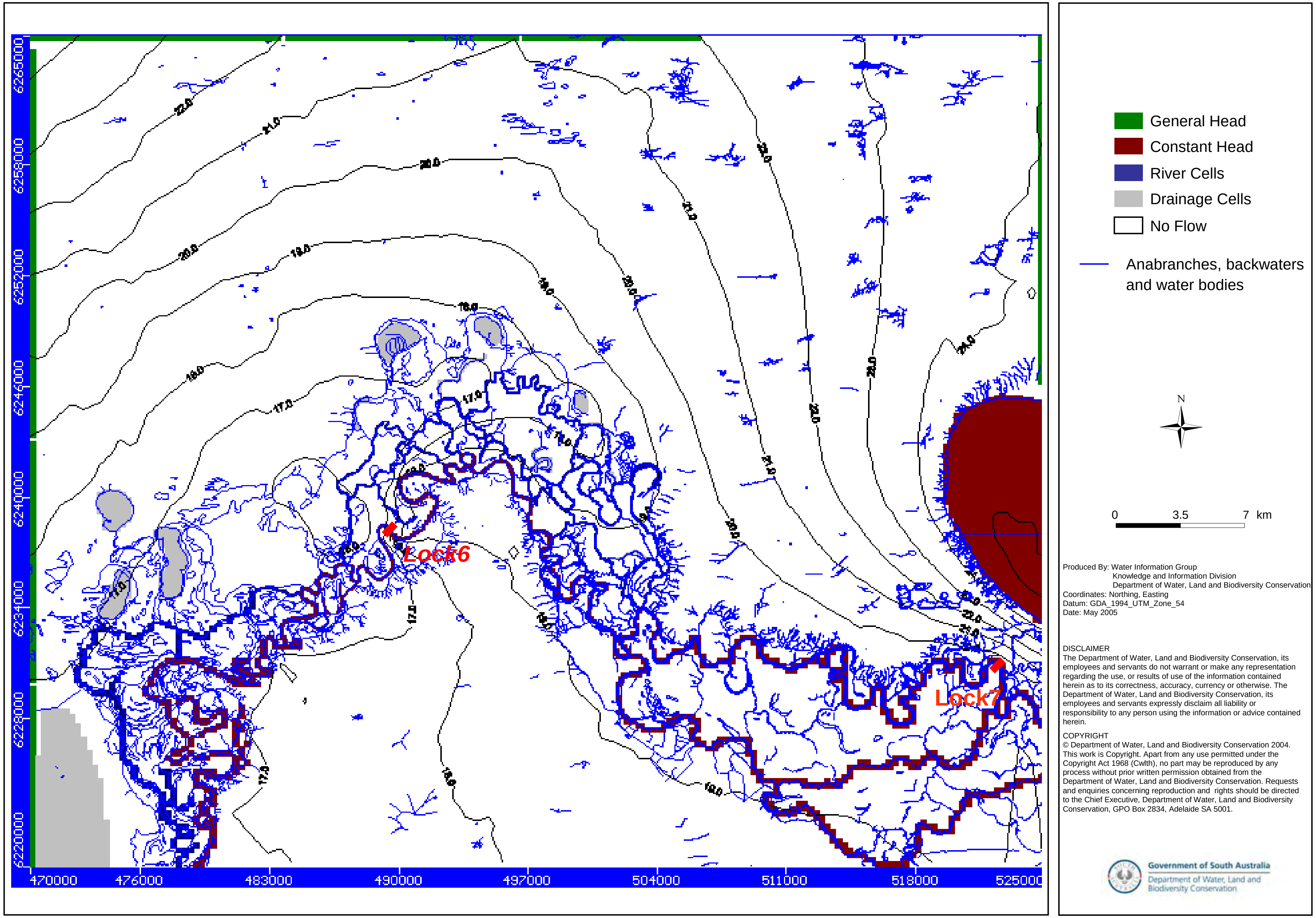


Appendix 2 Figure 7. Model (no flood model) recharge zones and rates

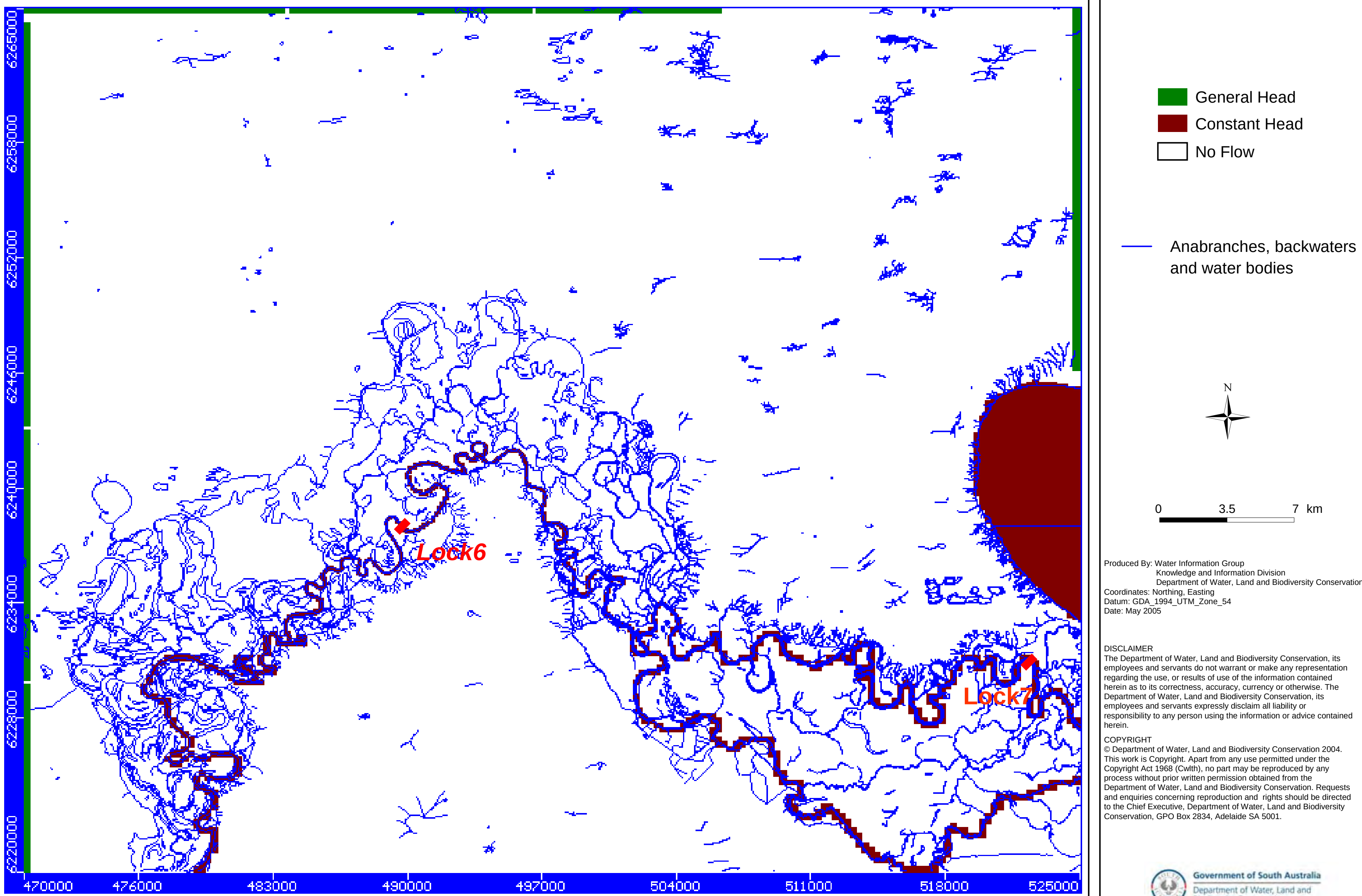


Appendix 2 Figure 8. Model evaporation zones and rates

APPENDIX 3 – BOUNDARY CONDITIONS



Appendix 3 Figure 1. Boundary conditions Layer-1 (Upper Monoman Formation, Upper Pliocene Sands (Upper Part))



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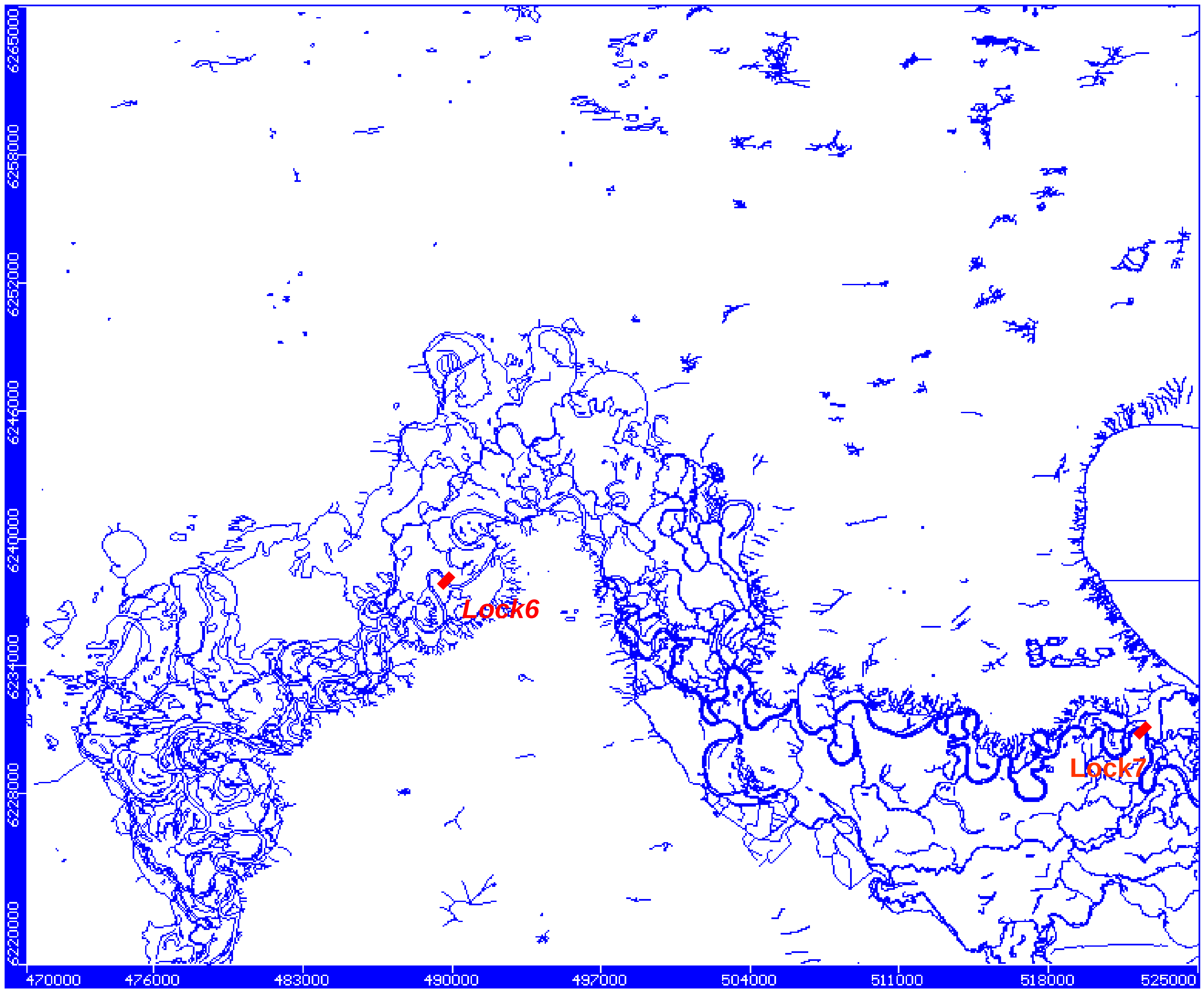
Appendix 3 Figure 2. Boundary conditions Layer-2 (Lower Monoman Formation, Upper Pliocene Sands (lower part)) & Layer-3 Lower Pliocene Sands



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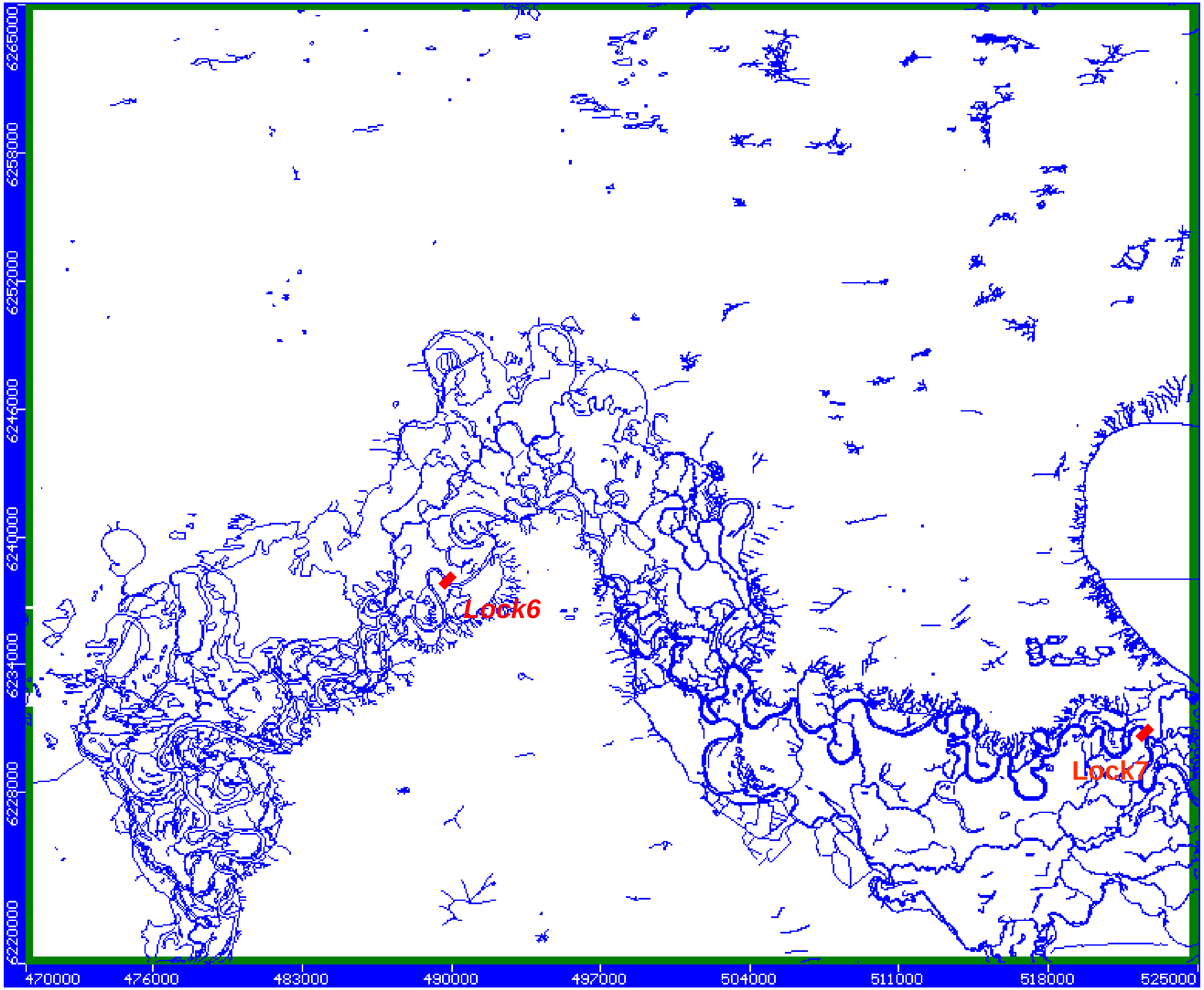
Appendix 3 Figure 3. Boundary conditions Layer-4 (Bookpurnong Formation)



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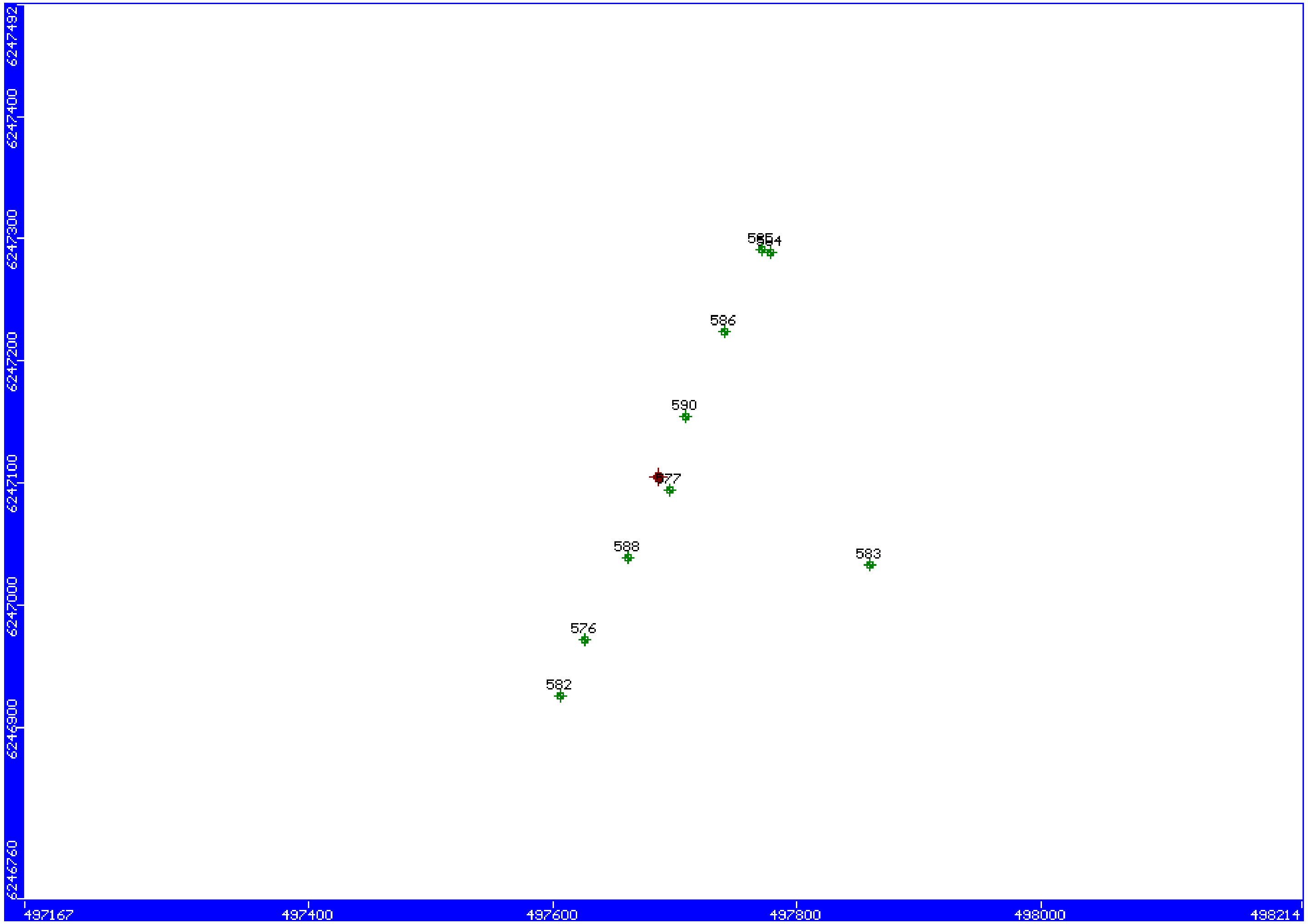
Appendix 3 Figure 4. Boundary conditions Layer-5 (Murray Group Limestone)

APPENDIX 4 – CALIBRATION RESULTS



583 Observation bore and number

Production bore

N

0 0.1 0.2 km

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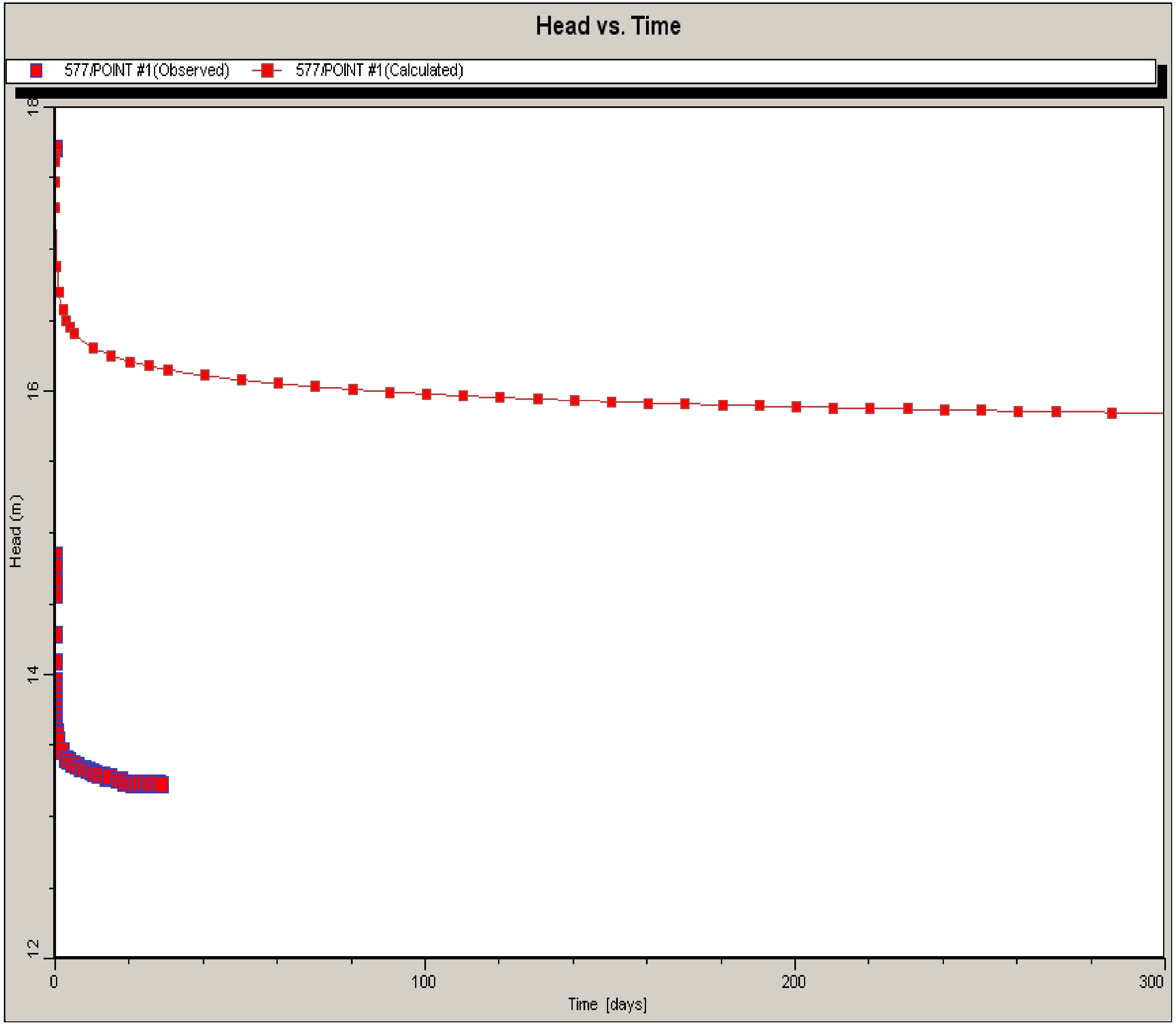
Appendix 4 Figure 1. Location of Observation Wells at Gum Flat



Predicted groundwater Table elevation (m AHD)

Observed groundwater Table elevation (m AHD)

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Datum: GDA_1994_UTM_Zone_54
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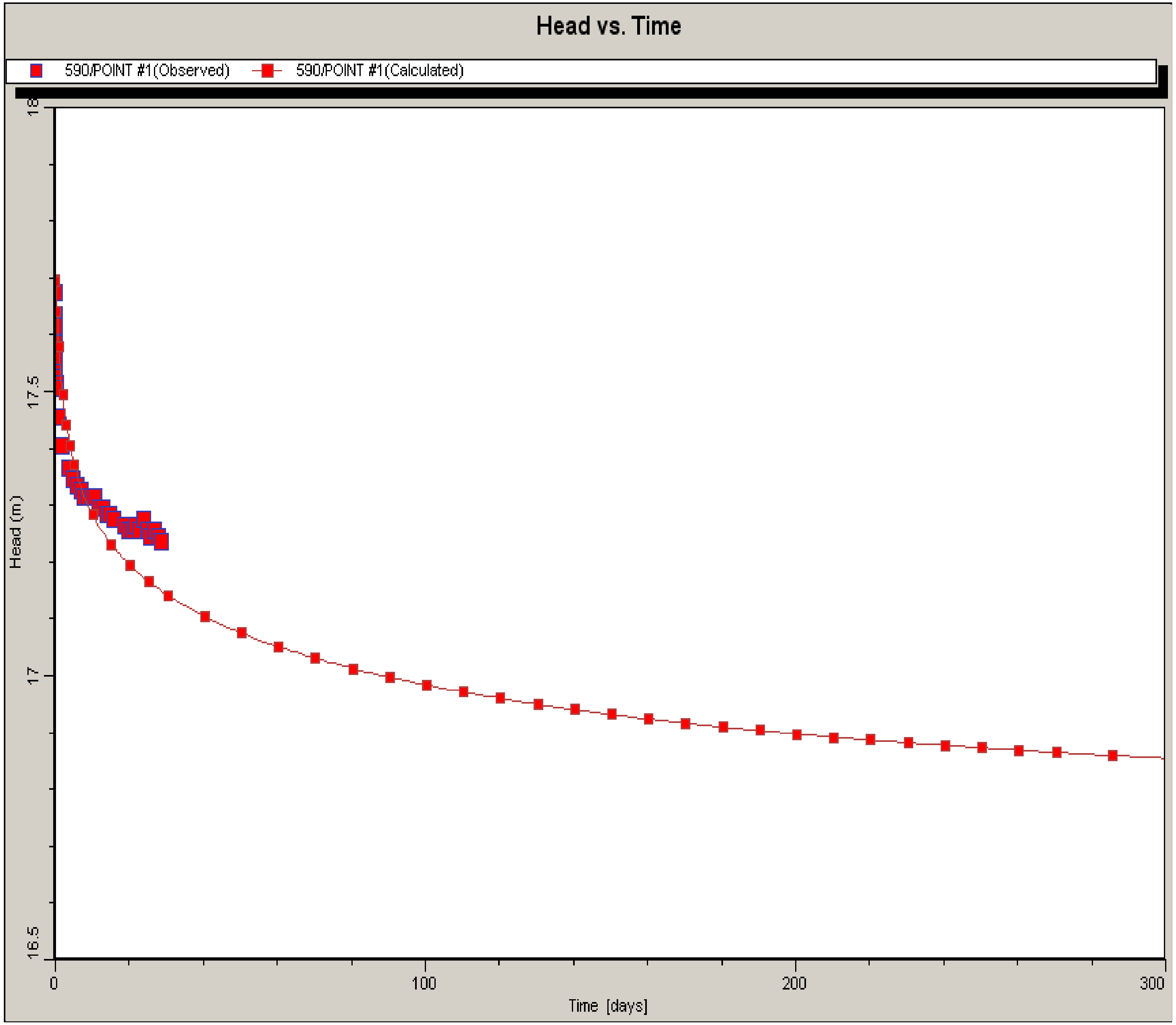
Appendix 4 Figure 2. Calibration graph for Observation Well 7030-577



Predicted groundwater Table elevation (m AHD)

Observed groundwater Table elevation (m AHD)

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Datum: GDA_1994_UTM_Zone_54
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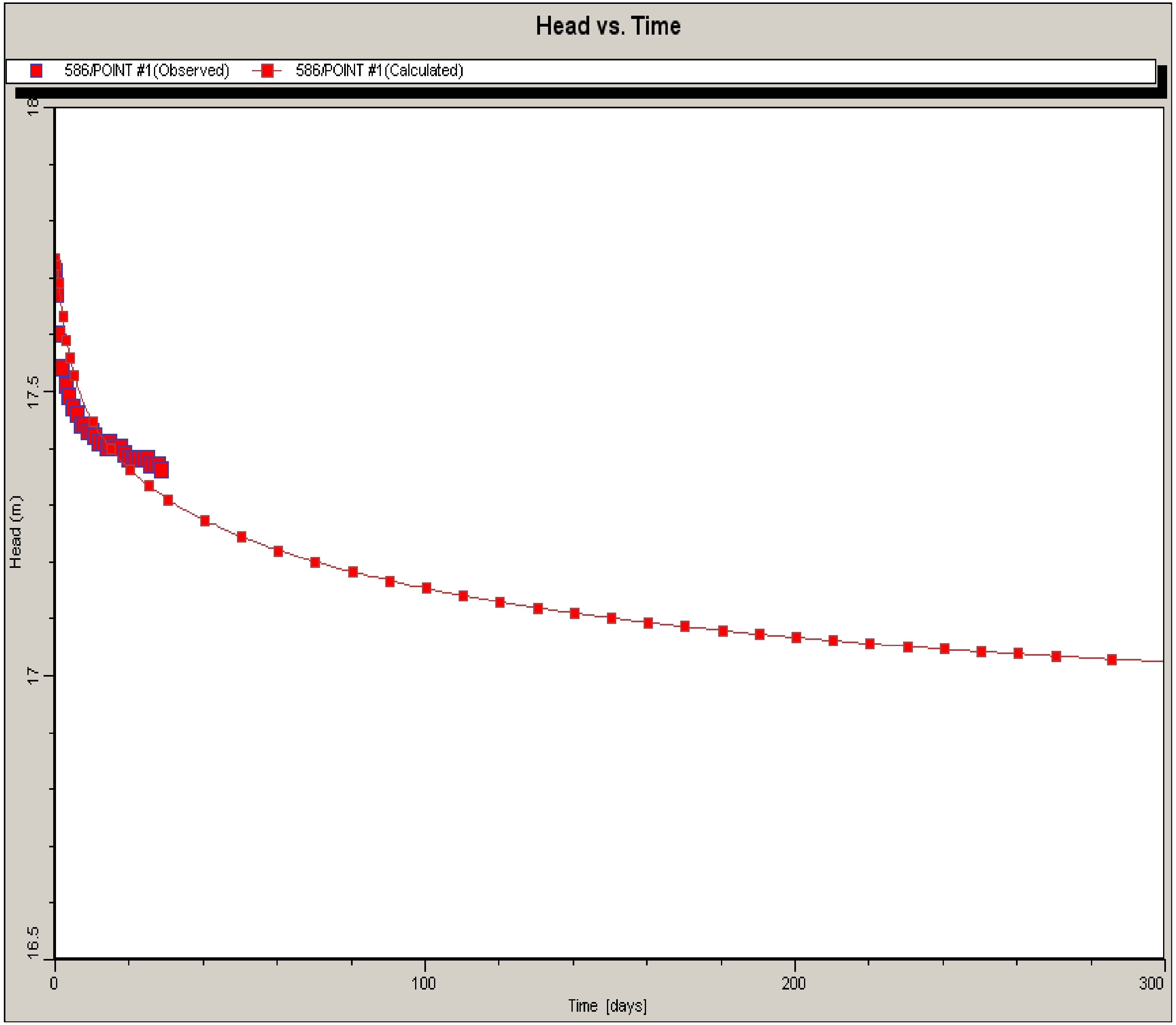
Appendix 4 Figure 3. Calibration graph for Observation Well 7030-590



Predicted groundwater Table elevation (m AHD)

Observed groundwater Table elevation (m AHD)

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Coordinates: Northing, Easting
Datum: GDA_1994_UTM_Zone_54
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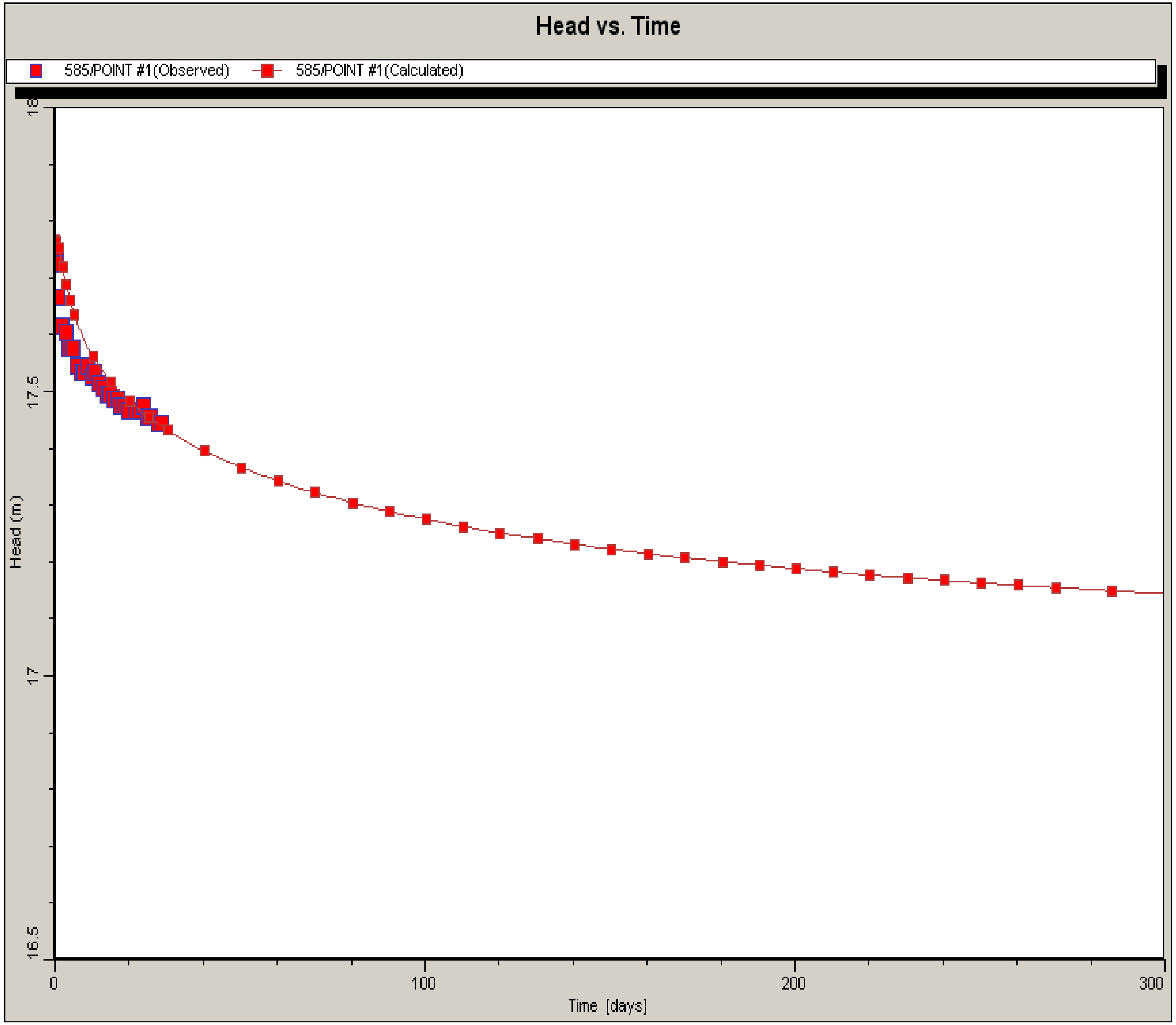
Appendix 4 Figure 4. Calibration graph for Observation Well 7030-586



Predicted groundwater Table elevation (m AHD)

Observed groundwater Table elevation (m AHD)

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Coordinates: Northing, Easting
Datum: GDA_1994_UTM_Zone_54
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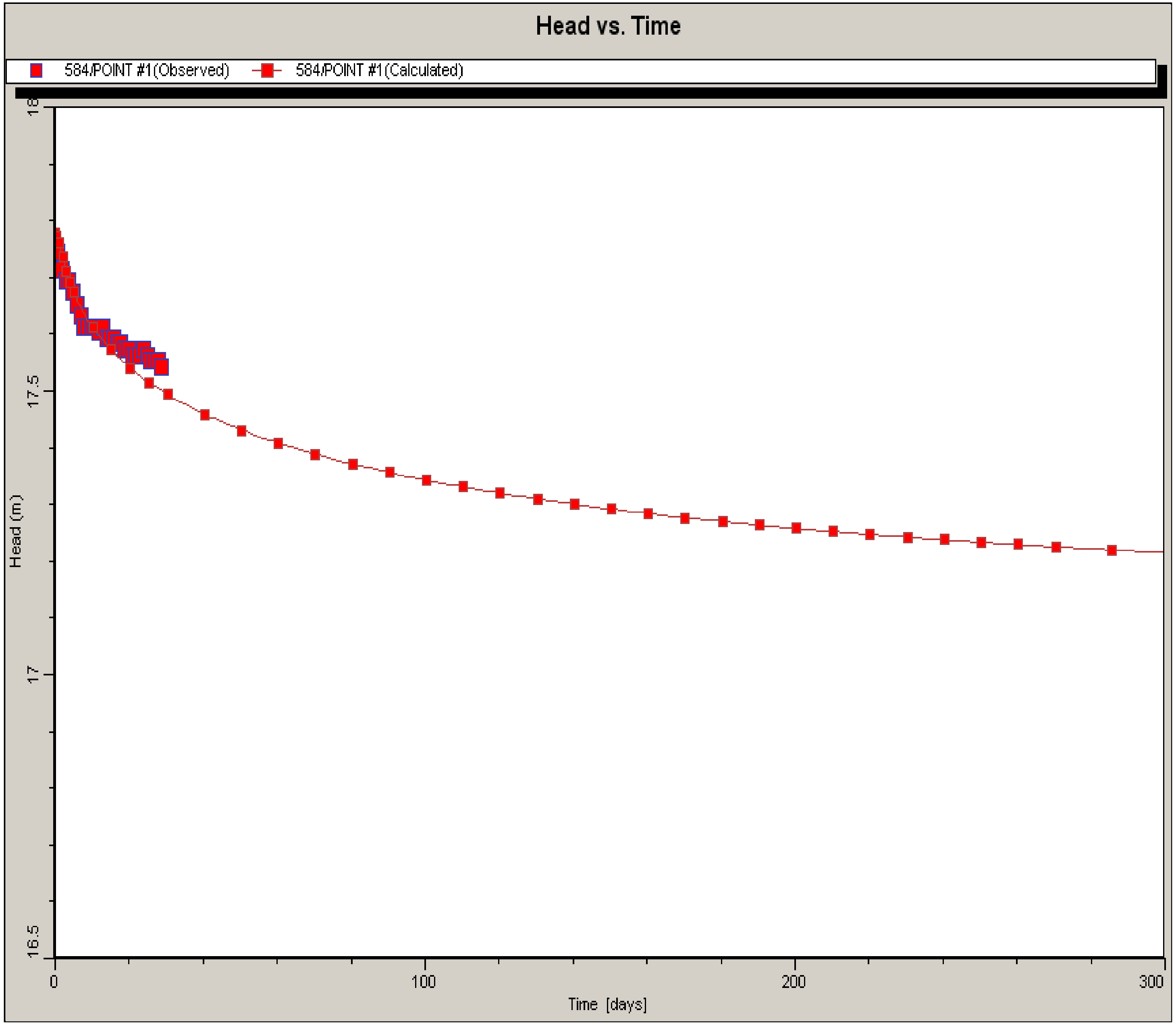
Appendix 4 Figure 5. Calibration graph for Observation Well 7030-586



Predicted groundwater Table elevation (m AHD)

Observed groundwater Table elevation (m AHD)

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Coordinates: Northing, Easting
Datum: GDA_1994_UTM_Zone_54
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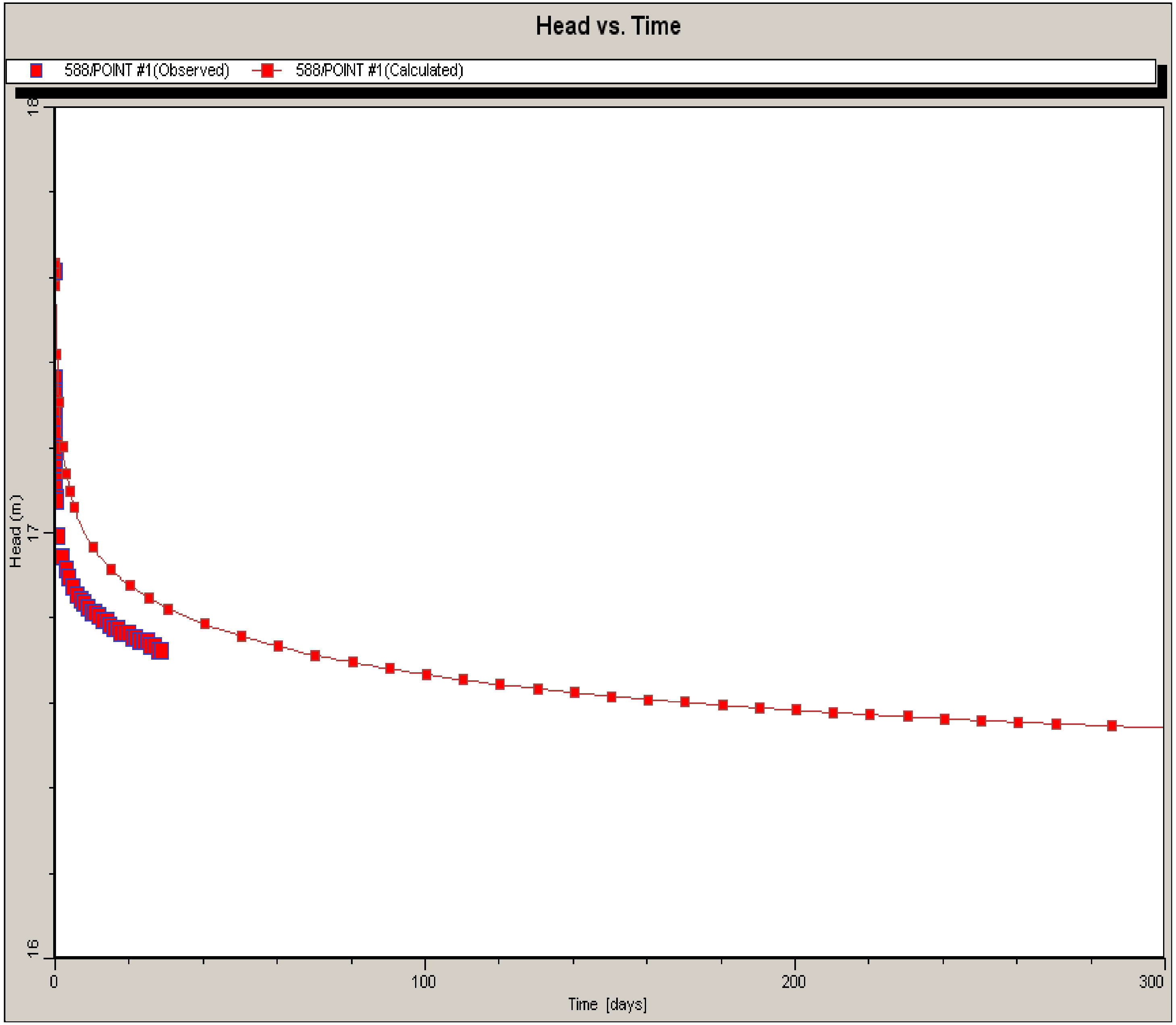
Appendix 4 Figure 6. Calibration graph for Observation Well 7030-584



Predicted groundwater Table elevation (m AHD)

Observed groundwater Table elevation (m AHD)

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Coordinates: Northing, Easting
Datum: GDA_1994_UTM_Zone_54
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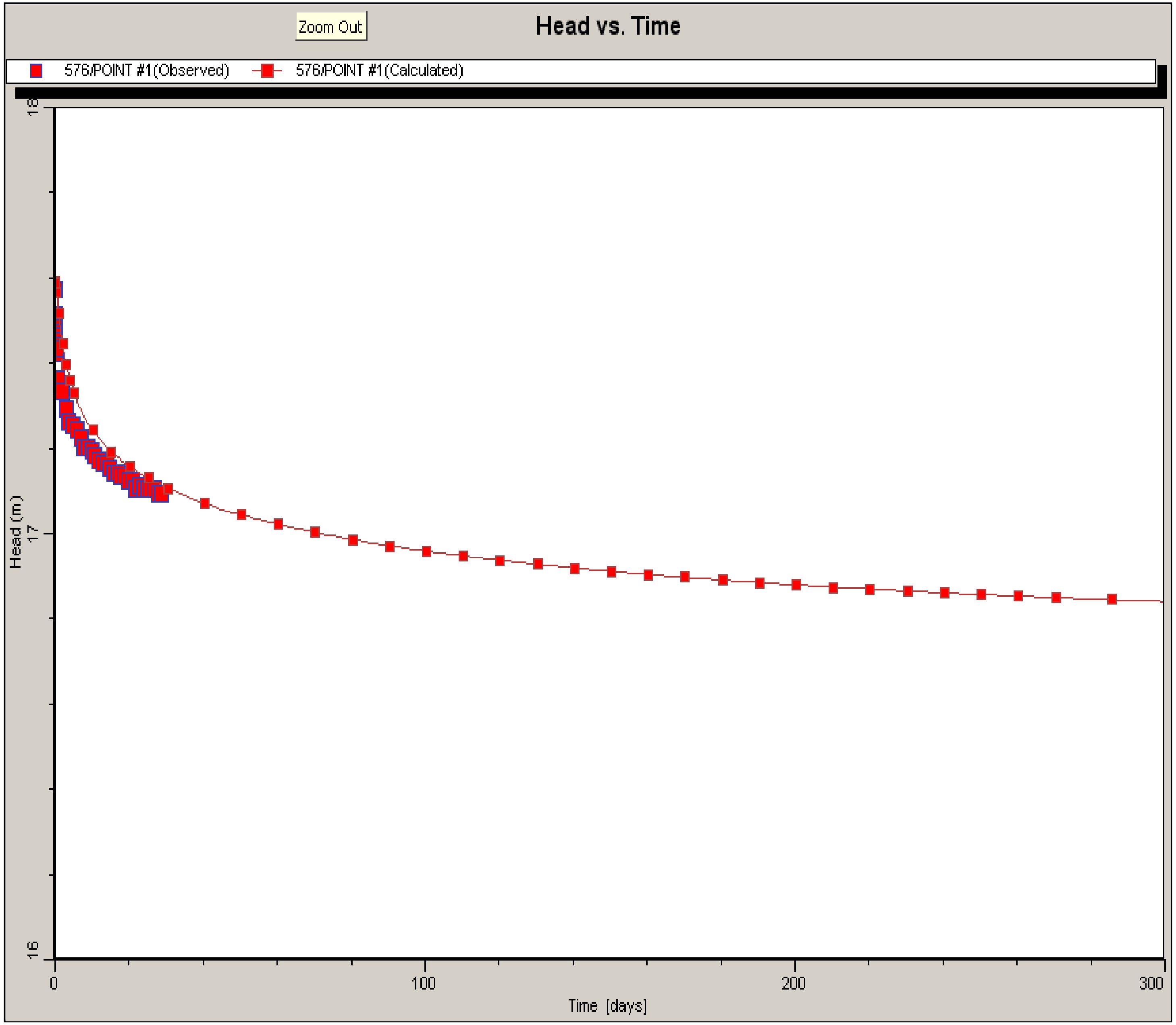
Appendix 4 Figure 7. Calibration graph for Observation Well 7030-588



Predicted groundwater Table elevation (m AHD)

Observed groundwater Table elevation (m AHD)

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Coordinates: Northing, Easting
Datum: GDA_1994_UTM_Zone_54
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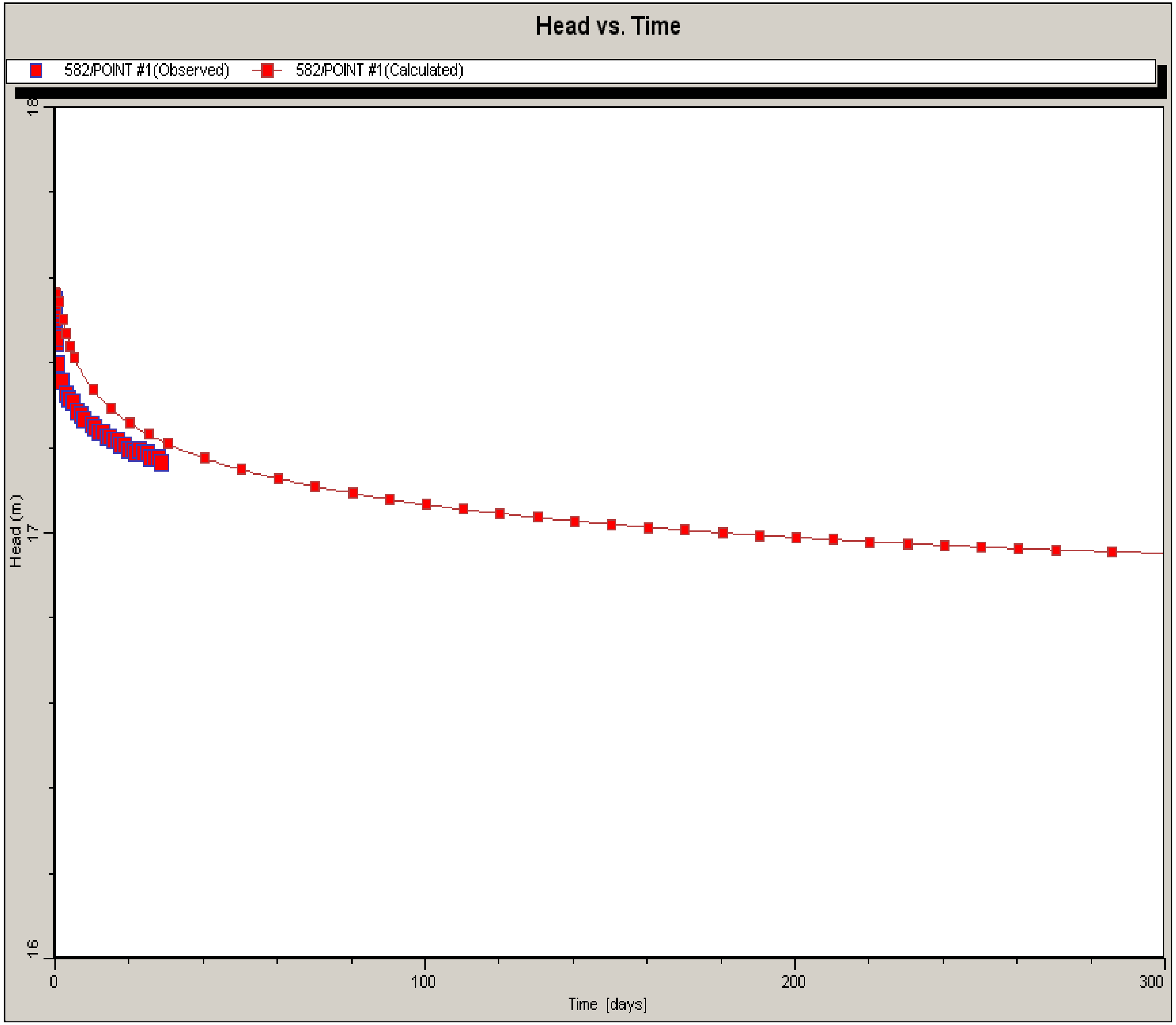
Appendix 4 Figure 8. Calibration graph for Observation Well 7030-576



Predicted groundwater Table elevation (m AHD)

Observed groundwater Table elevation (m AHD)

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Datum: GDA_1994_UTM_Zone_54
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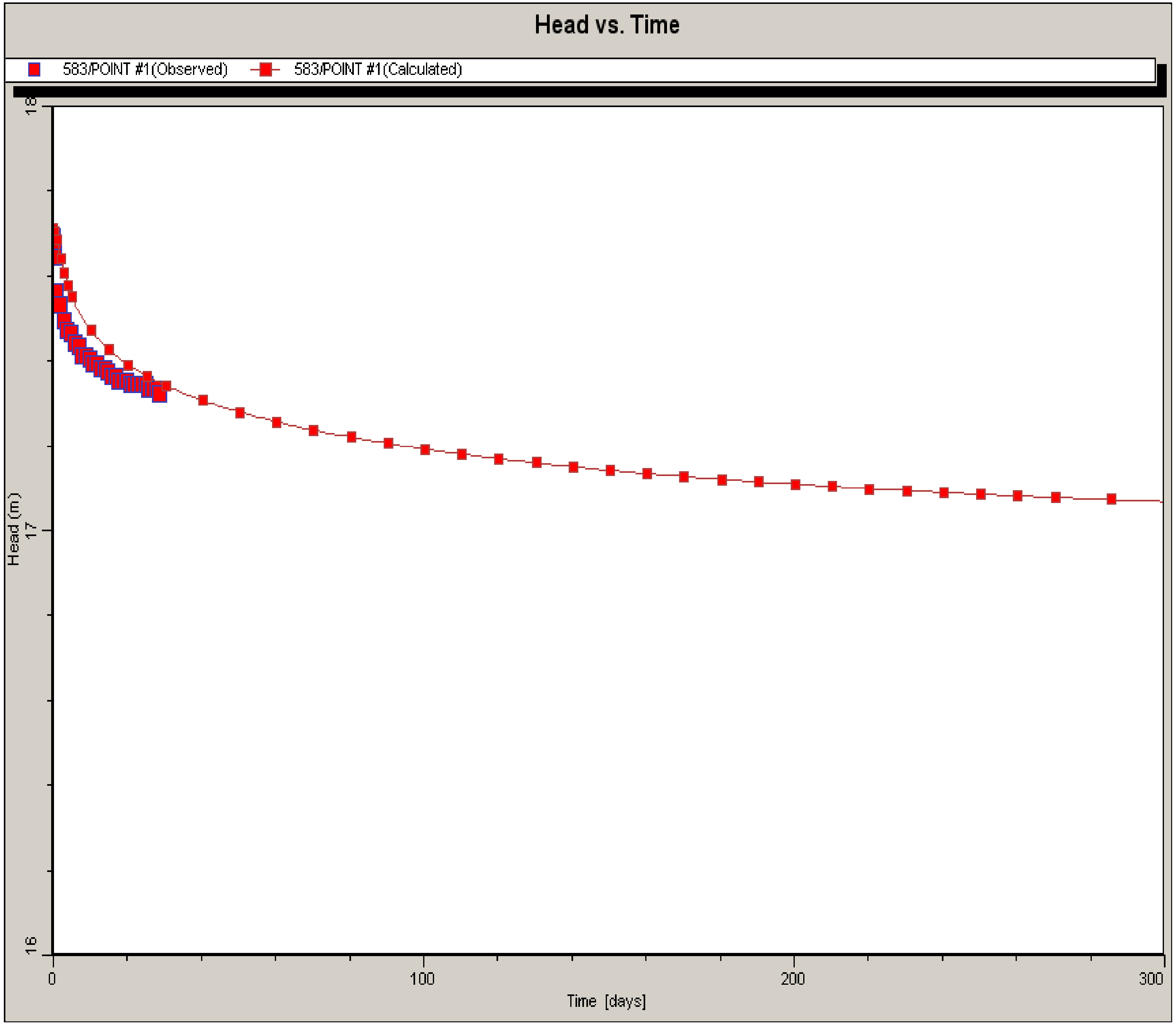
Appendix 4 Figure 9. Calibration graph for Observation Well 7030-582



Predicted groundwater Table elevation (m AHD)

Observed groundwater Table elevation (m AHD)

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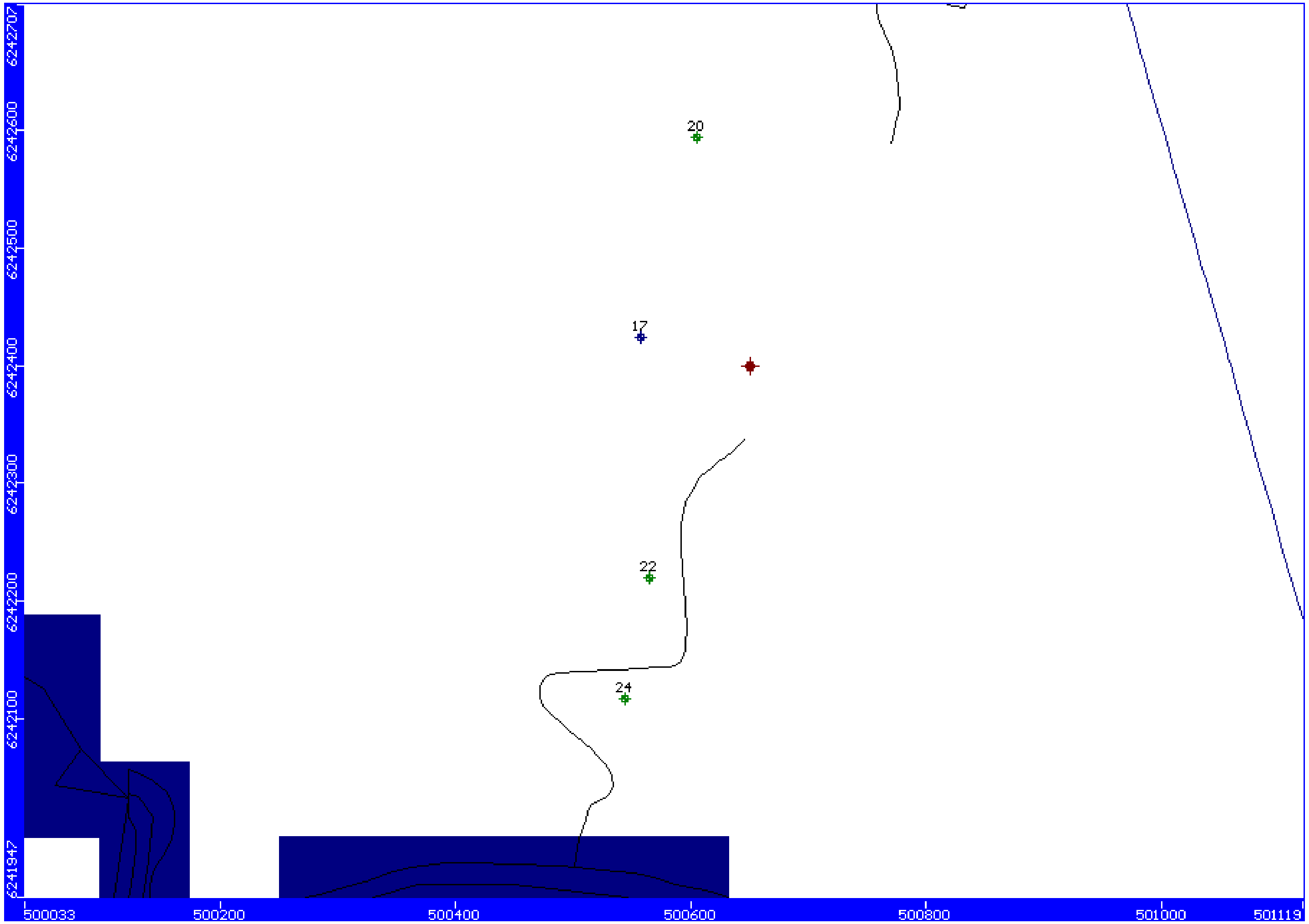
Appendix 4 Figure 10. Calibration graph for Observation Well 7030-583



583 Observation bore and number

Production bore

N

0 0.1 0.2 km

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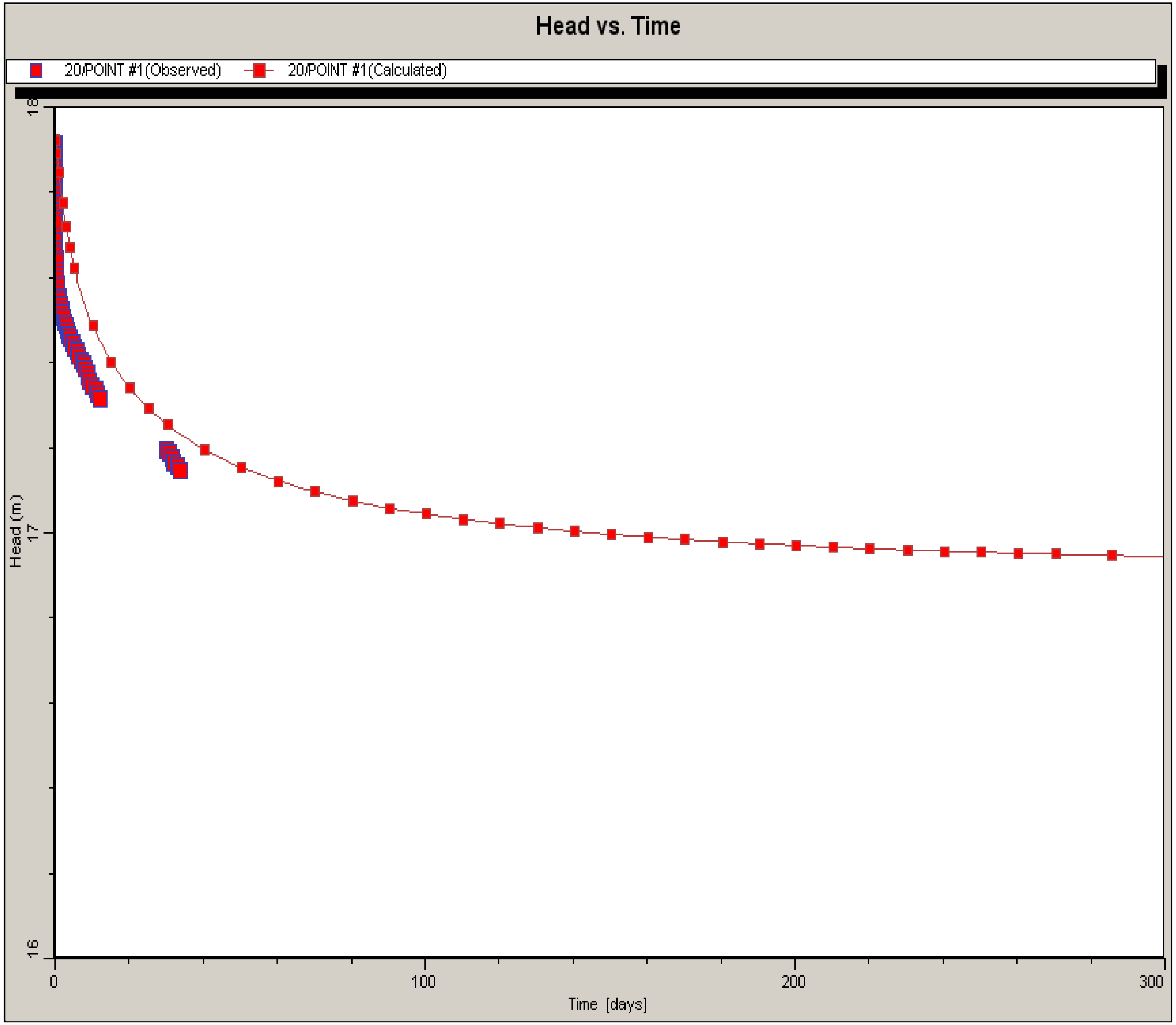
Appendix 4 Figure 11. Location of Observation Wells at Lake Littra



Predicted groundwater Table elevation (m AHD)

Observed groundwater Table elevation (m AHD)

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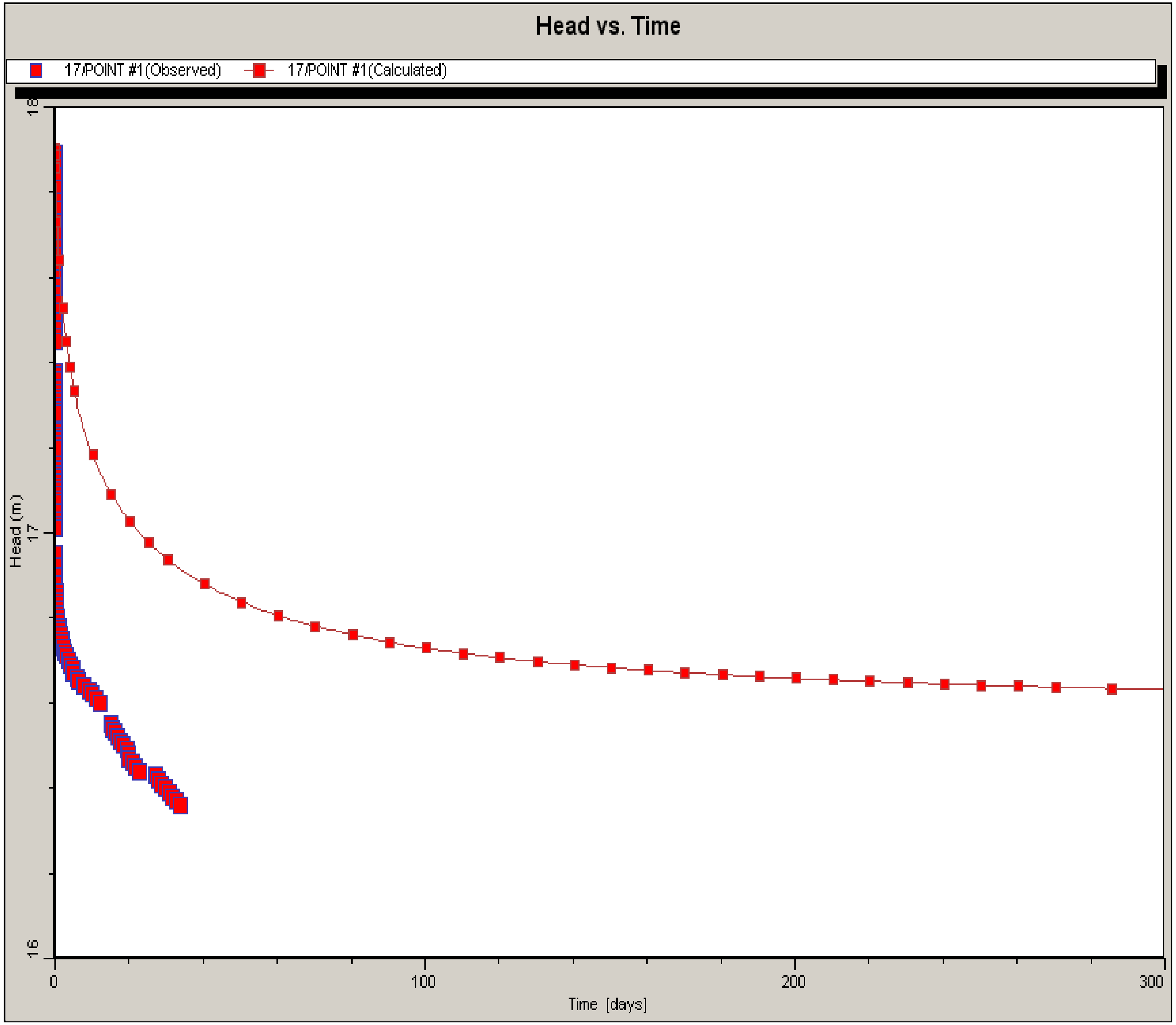
Appendix 4 Figure 12. Calibration graph for Observation Well 7130-20



Predicted groundwater Table elevation (m AHD)

Observed groundwater Table elevation (m AHD)

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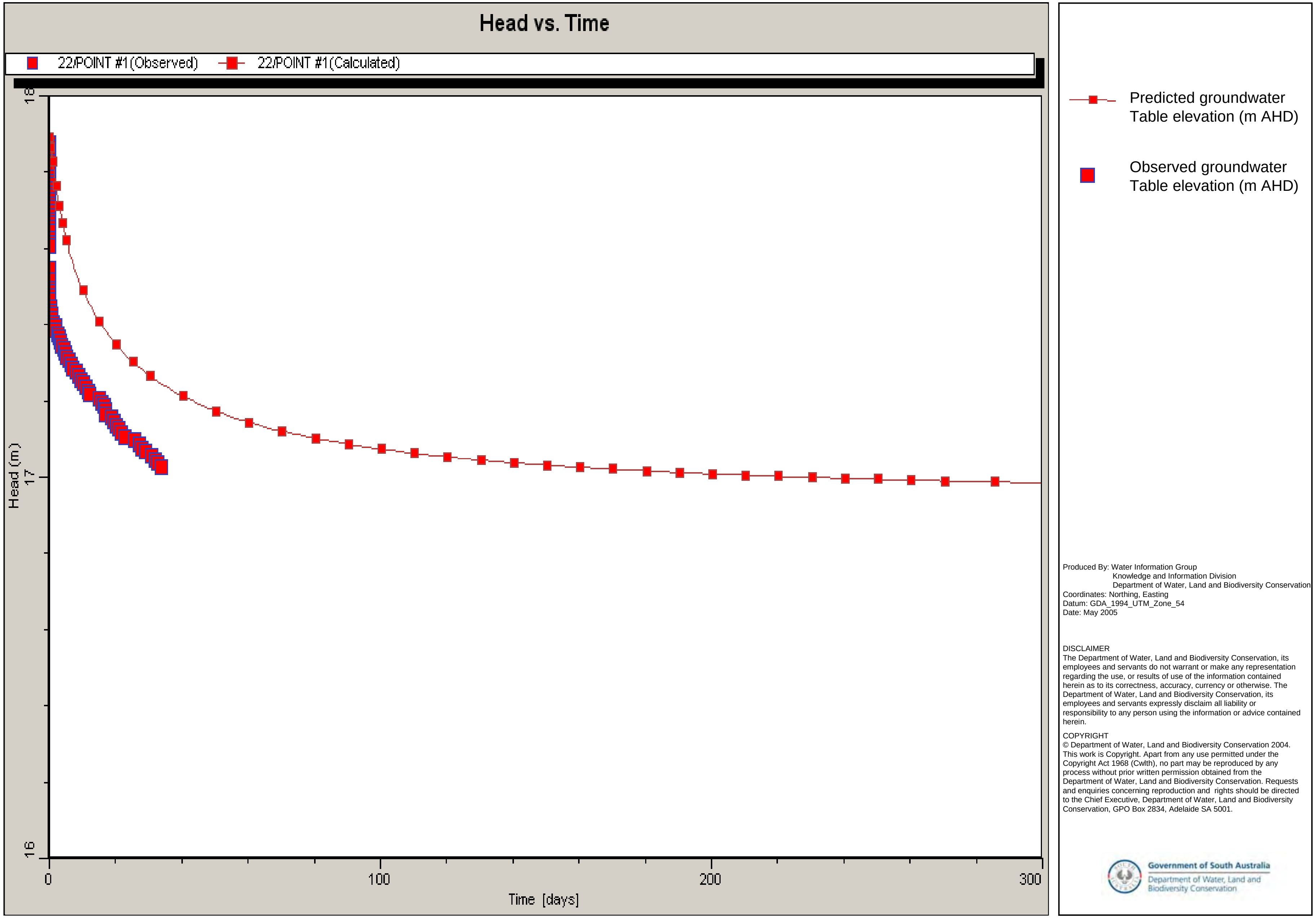
Appendix 4 Figure 13. Calibration graph for Observation Well 7130-17



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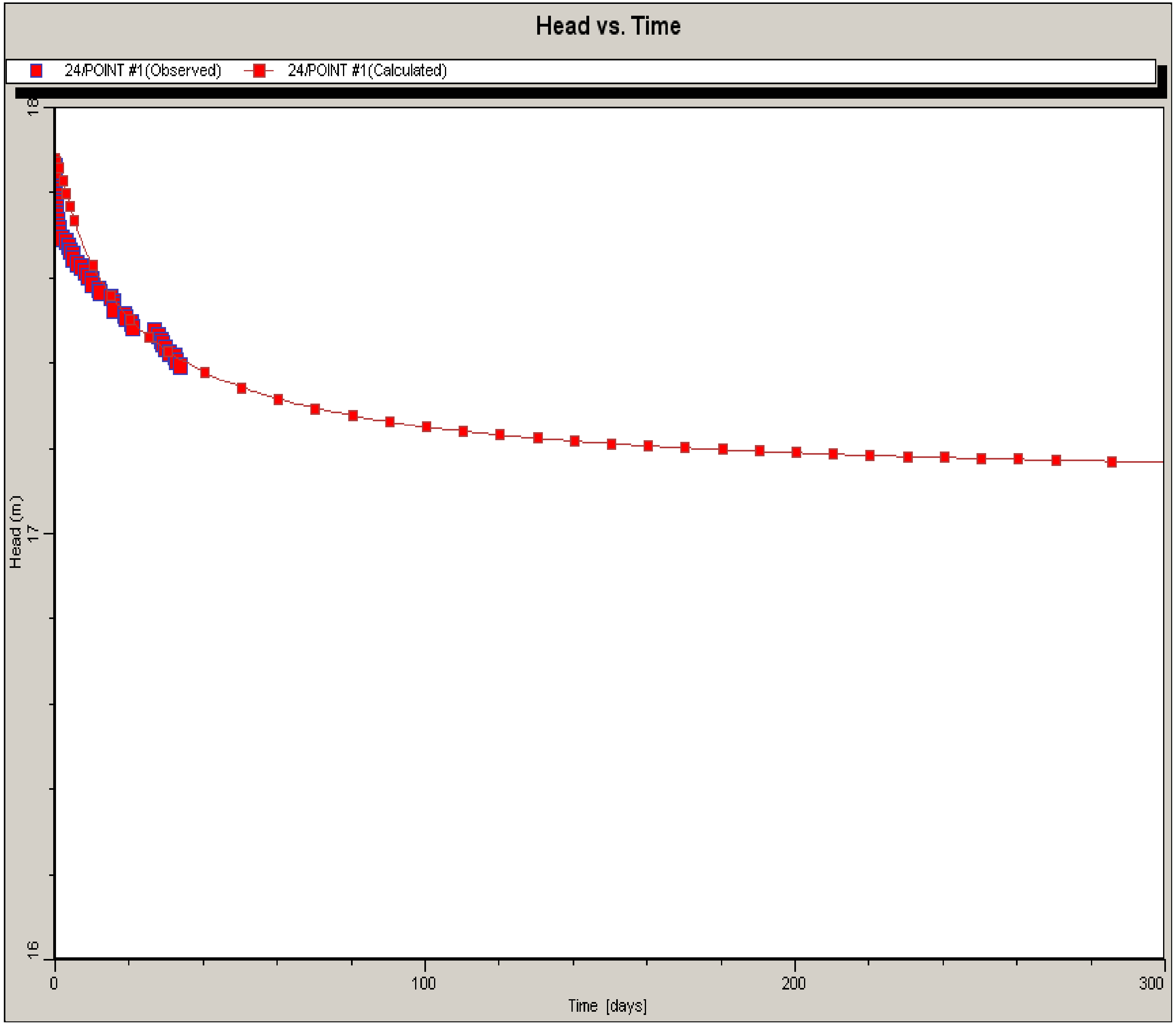
Appendix 4 Figure 14. Calibration graph for Observation Well 7130-22



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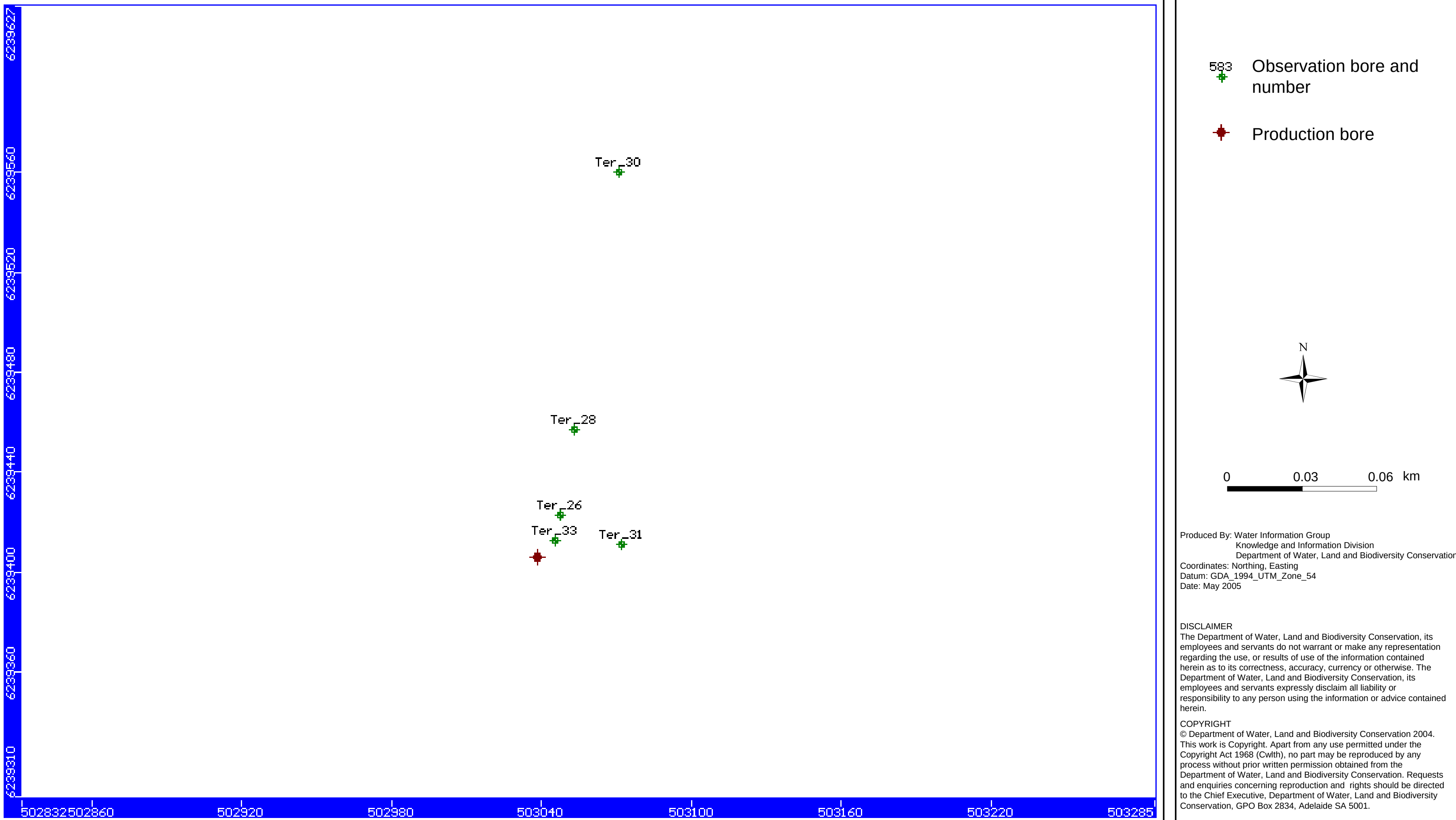
Appendix 4 Figure 15. Calibration graph for Observation Well 7130-24



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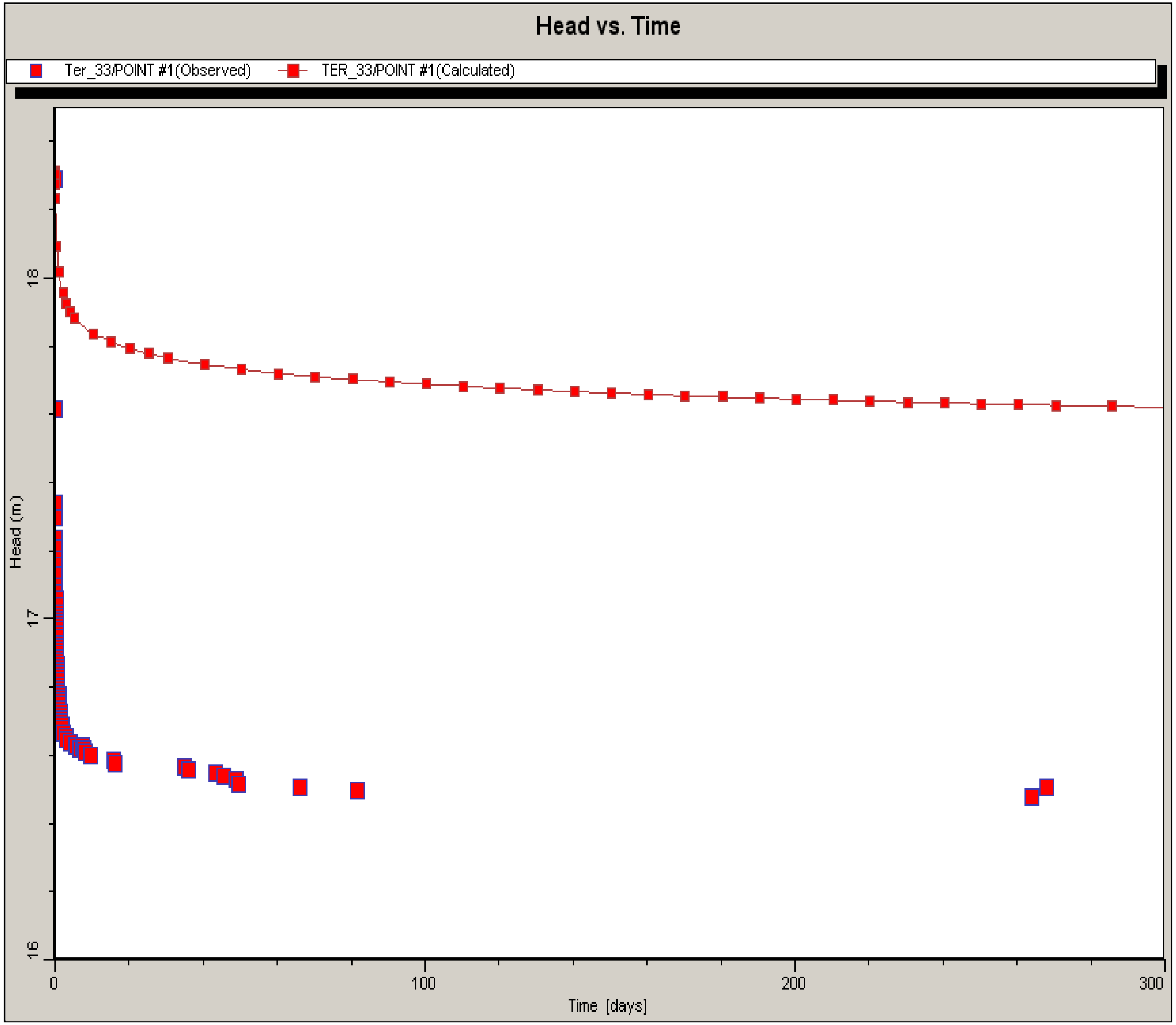
Appendix 4 Figure 16. Location of Observation Wells at Tareena Bong



Predicted groundwater Table elevation (m AHD)

Observed groundwater Table elevation (m AHD)

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Coordinates: Northing, Easting
Datum: GDA_1994_UTM_Zone_54
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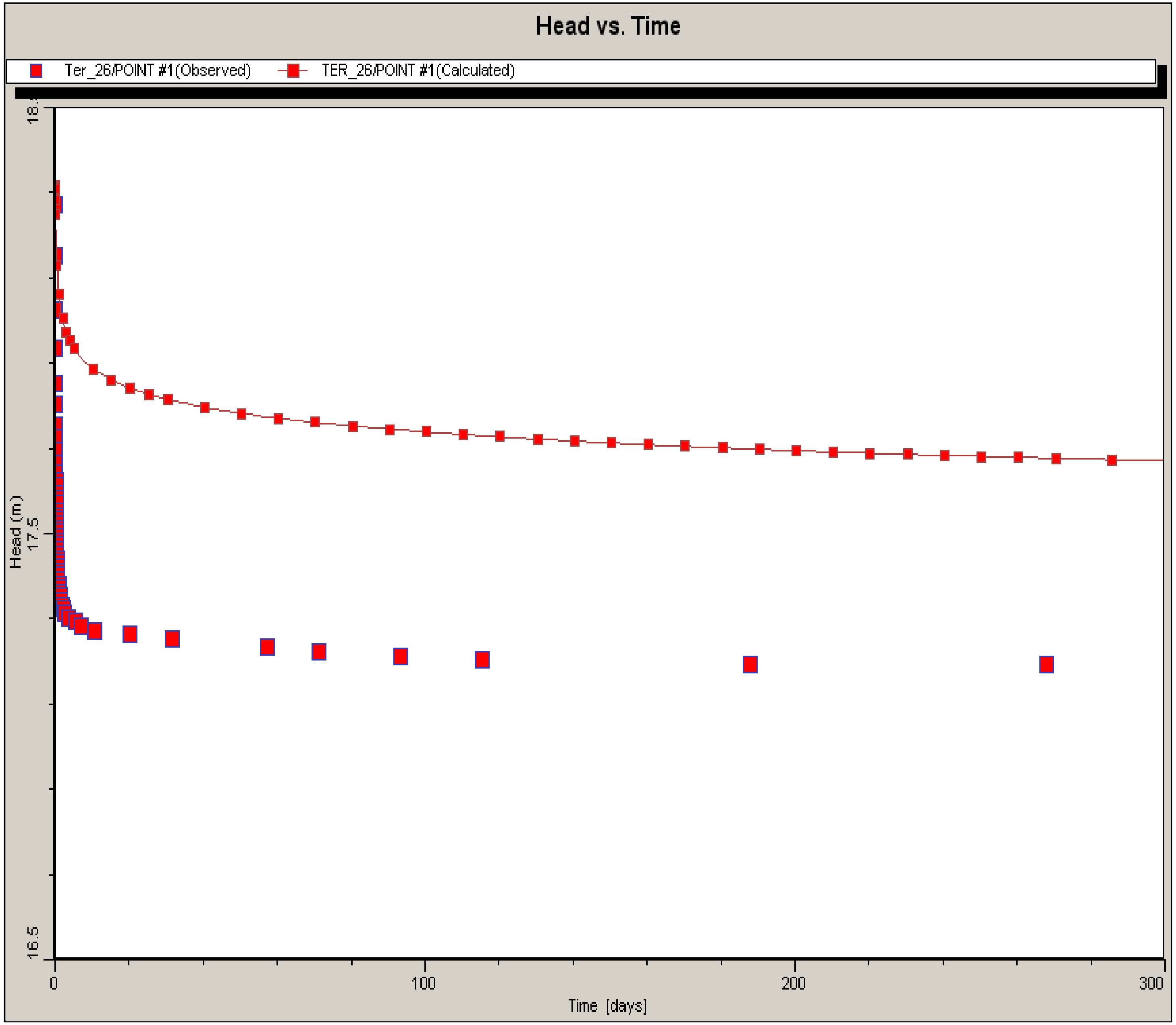
Appendix 4 Figure 17. Calibration graph for Observation Well 7130-33



Predicted groundwater Table elevation (m AHD)

Observed groundwater Table elevation (m AHD)

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Coordinates: Northing, Easting
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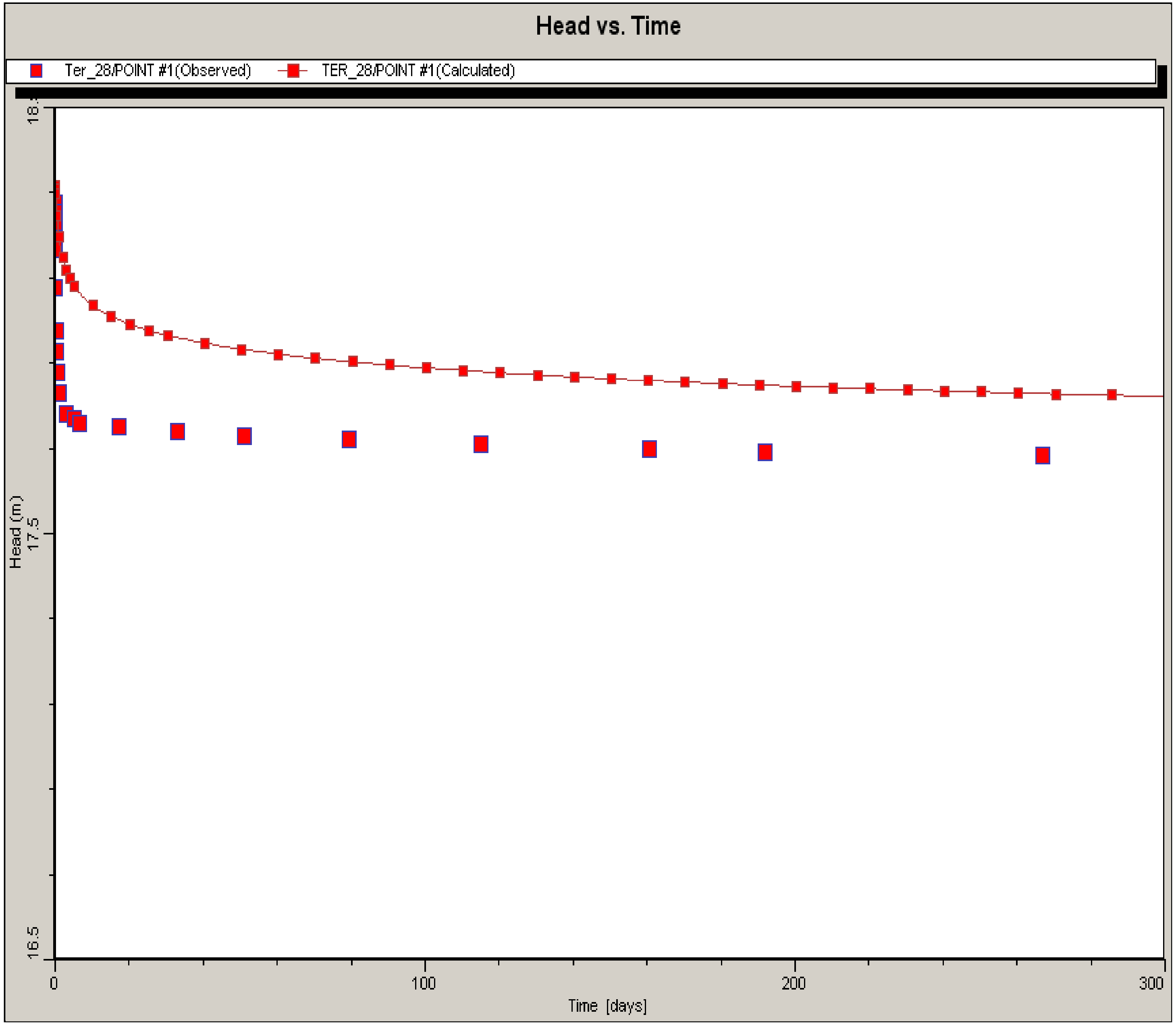
Appendix 4 Figure 18. Calibration graph for Observation Well 7130-26



Predicted groundwater Table elevation (m AHD)

Observed groundwater Table elevation (m AHD)

Produced By: Water Information Group
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Coordinates: Northing, Easting
Datum: GDA_1994_UTM_Zone_54
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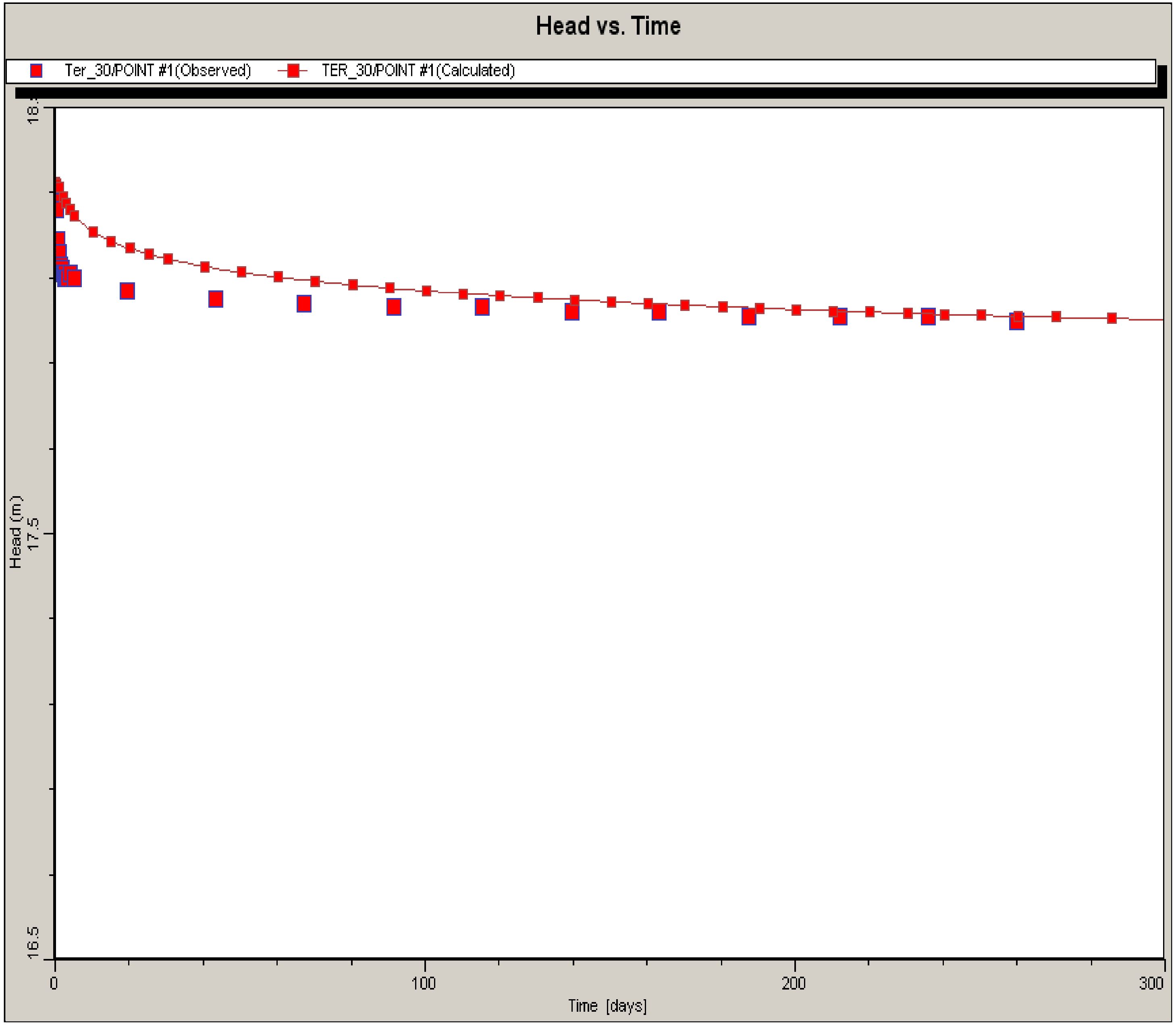
Appendix 4 Figure 19. Calibration graph for Observation Well 7130-28



Predicted groundwater Table elevation (m AHD)

Observed groundwater Table elevation (m AHD)

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Coordinates: Northing, Easting
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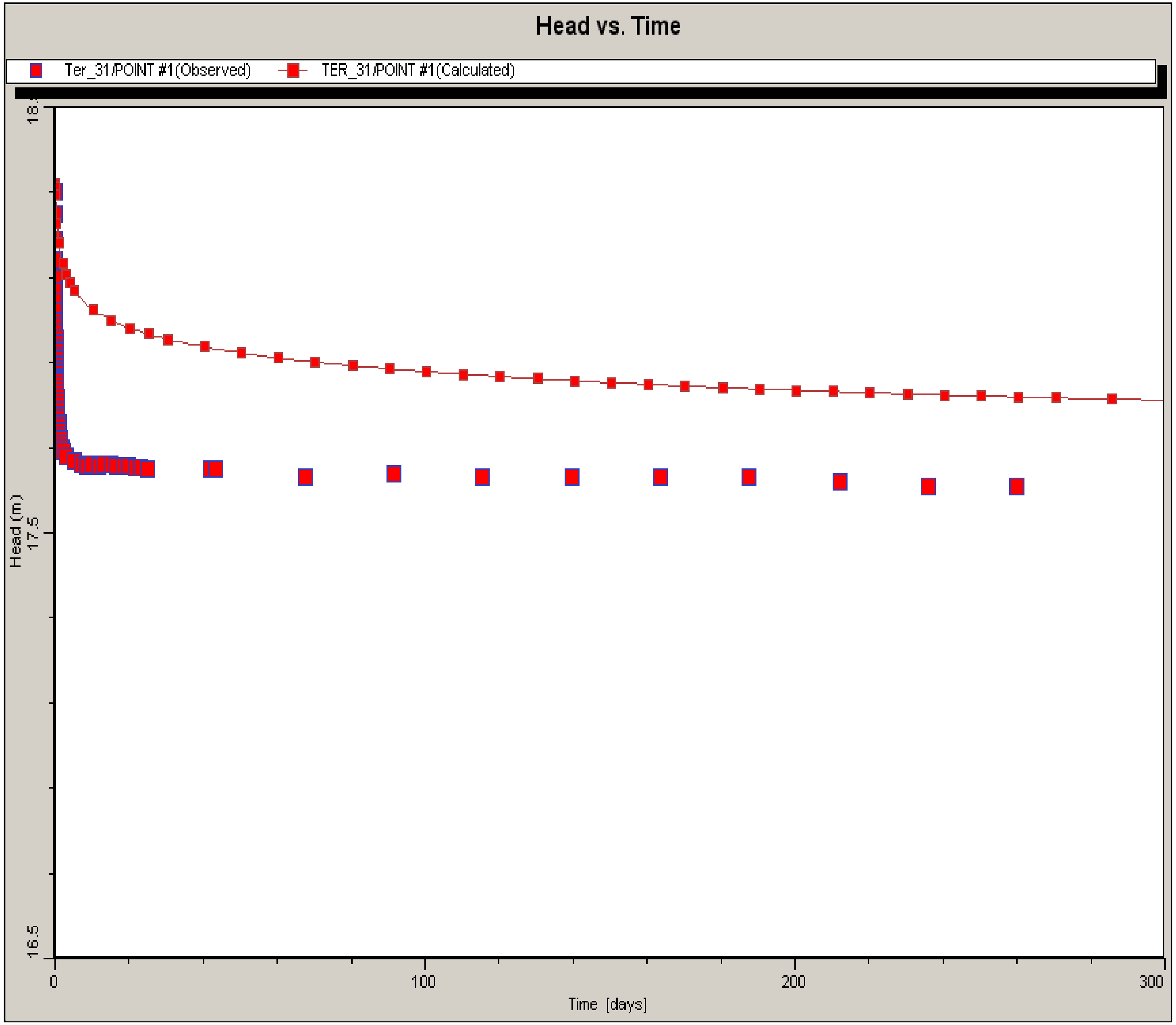
Appendix 4 Figure 20. Calibration graph for Observation Well 7130-30



Predicted groundwater Table elevation (m AHD)

Observed groundwater Table elevation (m AHD)

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Appendix 4 Figure 21. Calibration graph for Observation Well 7130-31