Woolpunda Numerical Groundwater Model 2013

Volume 1: report and figures

Government of South Australia
Department of Environment, Water and Natural Resources

WOOLPUNDA NUMERICAL GROUNDWATER MODEL 2013

VOLUME 1: REPORT AND FIGURES

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FOREWORD

The Department of Environment, Water and Natural Resources (DEWNR) is responsible for the management of the State's natural resources, ranging from policy leadership to on-ground delivery in consultation with government, industry and communities.

High-quality science and effective monitoring provides the foundation for the successful management of our environment and natural resources. This is achieved through undertaking appropriate research, investigations, assessments, monitoring and evaluation.

DEWNR's strong partnerships with educational and research institutions, industries, government agencies, Natural Resources Management Boards and the community ensures that there is continual capacity building across the sector and that the best skills and expertise are used to inform decision making.

Allan Holmes
CHIEF EXECUTIVE
DEPARTMENT OF ENVIRONMENT, WATER AND NATURAL RESOURCES

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Staff from the Department of Environment, Water and Natural Resources (DEWNR) assisted as follows:

- Joel Vandepeer updated the policy discussion of Section 1.
- Linda Vears provided estimates of rainfall and irrigation area and accession over time
- Judith Kirk as the project manager advised on policy and coordinated the Five Year Review Modelling Registers Project Team
- Moji Karbasi assisted with the compilation of the Appendices.

Staff from Australian Water Environments (AWE) assisted as follows:

- Gabor Bekesi provided data and information from the forthcoming *Waikerie and Woolpunda Salt Interception Atlas,* and reviewed Section 2 for its hydrological and hydrogeological accuracy
- Vanessa Peat and Andrew Telfer of AWE provided a preliminary groundwater model for Woolpunda
- Yvonne Weir provided GIS data and produced some figures
- Andrew Telfer and Scott Evans provided additional hydrogeological information and interpretation.

Peter Forward of SA Water provided Salt Interception Scheme data.

The scenarios were refined with input and approval from the Five Year Review Modelling Registers Project Team for Woolpunda:

- Chris Wright, Linda Vears, Judith Kirk, Wei Yan and Juliette Woods of DEWNR
- Phil Pfeiffer and Asitha Katupitiya of the MDBA
- Peter Forward of SA Water.

The report was peer reviewed by Don Armstrong of Lisdon Associates as an expert hydrogeologist, geologist and groundwater modeller and Steve Barnett as Principal Hydrogeologist in DEWNR.

The report was also reviewed on behalf of the MDBA by Ray Evans and Greg Holland of Sinclair Knight Mertz (SKM).

CONTENTS

CONTENTS

CONTENTS

CONTENTS

LIST OF FIGURES

LIST OF TABLES

SUMMARY

Significant volumes of salt from groundwater enter the River Murray within the Woolpunda reach of the river each year. This is driven by a substantial upwelling from the Renmark Group aquifer into the Murray Group Formation which results in a large, naturally-occurring groundwater mound that is drained by the River Murray and its floodplain. As the regional groundwater is highly saline, approximately 200 t/d of salt is added to the Murray along the Woolpunda reach under natural conditions.

To mitigate the salt load impacts of the Woolpunda groundwater mound, a Salt Interception Scheme (SIS) was commissioned in 1990. The SIS pumps groundwater from the Mannum Formation, which has slowly lowered the watertable and reduced the saline groundwater flux to the River Murray.

Unlike adjacent Riverland reaches, recharge from irrigation is not currently a significant driver of groundwater salt to the River Murray. This is because the majority of irrigation at Woolpunda started relatively recently, and there are long lag times between irrigation drainage at the surface and the arrival of the drainage water at the water table to recharge the aquifer. However, while the irrigation areas have minimal recharge to date, substantial impacts are expected in the future.

To meet obligations under the Murray-Darling Basin Authority's (MDBA) Basin Salinity Management Strategy (BSMS), South Australia maintains and updates a suite of accredited MODFLOW groundwater models to bring entries forward to the BSMS Salinity Registers. This work is undertaken by the Science, Monitoring and Knowledge Branch of the Department of Environment, Water and Natural Resources (DEWNR), in liaison with the MDBA. Through the groundwater modelling process, scenarios are established to assist in the determining the origin and volume of salt entering the River Murray from groundwater sources.

DEWNR has developed a MODFLOW numerical groundwater flow model of the Woolpunda reach. It replaces a prior accredited model, the Lock 3 to Morgan model (Rural Solutions 2005) and incorporates the latest hydrogeological information and understanding. The Lock 3 to Morgan model spans two distinct hydrogeological regimes with different key aquifers and salt load mobilisation drivers, so the decision was made to replace it with two separate models, each simulating a different hydrogeological regime: the Waikerie to Morgan model (Yan, Woods and Li 2012) and the Woolpunda model, as described in this report.

The Woolpunda 2013 model is a significant improvement from the Rural Solutions 2005 model as it is based on improvements in hydrogeological understanding and more detailed datasets (particularly irrigation and SIS operation data), and has been calibrated to more observations. The model improvement is demonstrated by a much closer match of modelled salt load to in-stream salt load estimates (i.e. Run-of-River (RoR)) and better calibration performance statistics, compared to the Rural Solutions 2005 model.

The objective of the study is to capture new knowledge within the modelling platform. The updated modelling platform will provide improved estimates of salinity impacts from the Woolpunda reach under the various accountable actions, and hence lead to refinement and improvement in the Salinity Registers.

The aim is to develop a model capable of simulating the regional aquifer system in the Woolpunda study area which:

- Improves the understanding of the hydrogeology of the regional aquifer system and processes

- Provides estimated salt loads entering the River Murray under different accountable development and management actions (100-year predictions from current year) for use as Salinity Register entries, specifically:
    - Mallee clearance
    - Irrigation development
    - Improved irrigation practice
    - Salt Interception Scheme operation
- Assists with the broad-scale planning for groundwater management schemes (e.g. SIS) that help to control the flux of saline groundwater and therefore salt load, entering the River Murray.

Although included in the model domain, the model is currently not designed to evaluate the accountable actions of the river reach above Lock 3. Substantial data reviews have been conducted, such as irrigation data, to inform the model inputs. The model has been updated with the latest data.

The model was successfully recalibrated to head observations and its results confirmed through comparison to RoR salt loads observations and other supporting data. A sensitivity analysis considered how model parameters, when varied within reasonable ranges, impacted the model calibration results, which provides confidence in the model.

After calibration, the transient model was used to run scenarios under the conditions required for the Salinity Register entries. However the simulation of the SIS in some scenarios departs from the calibrated model in that the SIS wells have been replaced by a line of drain cells set to simulate the SIS-controlled water levels at mid-points between SIS wells. This is to ensure that in future scenarios, the SIS controls water levels and fluxes to the river under changing irrigation drainage conditions, an approach agreed on by the Five Year Review Modelling for Salinity Registers Project Team. The scenarios estimate groundwater fluxes and resultant salt load entering the River Murray due to accountable irrigation and management actions in the study area. The results are summarised in Table S-1. An uncertainty analysis evaluated how input parameters which are poorly known and/or highly heterogeneous may impact on key scenario outputs. Recommendations are made for future work to improve data collection and model design.

This report documents the numerical groundwater flow model, including comprehensive information on the model design, model inputs and estimated annual salt loads for different scenarios. It delivers the technical information about the model and model results for the accreditation process.

A further, separate document will be developed on how model results are used to derive Salinity Register entries. The estimated salt loads will be provided to the MDBA for conversion to credits and debits for the BSMS Salinity register following accreditation of the model. The entries will then be submitted through the Basin Salinity Management Advisory Panel for approval prior to being entered onto the Salinity Registers.

Table S-1 Summary of Predicted Salt Load (t/d) entering the River Murray – Woolpunda

Woolpunda					Year/Salt load (t/d)							
Scenario	**Name**	**Irrigation development area**	**IIP[1]**	**SIS[2]**	**1920**	**1988**	**2000**	**2013**	**2015**	**2050**	**2100**	**2113**
Calibrated model	Historical irrigation, IIP & SIS	Irrigation history	Yes	Yes	190.9	191.3	14.5	25.8	25.1	-	-	-
Scenario 1	Natural System (Steady State since 1920)	None	–	–	190.9	190.9	190.9	190.9	190.9	190.9	190.9	190.9
Scenario 2	Mallee Clearance	None	–	–	191.0	191.5	191.6	191.9	191.9	193.1	201.8	202.3
Scenario 3A	Irrigation Pre-1988, no IIP	Pre-1988	No	No	190.9	191.4	194.1	198.2	199.1	201.9	202.2	202.3
Scenario 3C	Irrigation Pre-1988, with IIP	Pre-1988	Yes	No	190.9	191.3	193.5	196.9	197.7	200.0	200.3	200.3
Scenario 4	Current irrigation (business as usual)	Pre-1988 + Post-1988	Yes	No	190.9	191.3	195.4	199.6	201.2	239.3	269.7	272.7
Scenario 5	Current plus future irrigation	Pre-1988 + Post-1988 + Future development	Yes	No	190.9	191.3	195.4	199.6	201.2	240.6	286.6	290.7
Scenario 8A	Current irrigation plus constructed SIS	Pre-1988 + Post-1988	Yes	Yes	191.0	191.3	15.1	15.0	15.1	16.2	16.7	16.8
Scenario 8B	Pre-1988, with IIP plus constructed SIS	Pre-1988	Yes	Yes	190.9	191.3	14.3	14.2	14.2	14.1	14.0	13.9
Scenario 8C	Current plus future irrigation plus constructed SIS	Pre-1988 + Post-1988 + Future development	Yes	Yes	190.9	191.3	15.1	15.0	15.1	16.3	17.1	17.1

[1]IIP: Improved Irrigation Practices *[2]SIS: Salt Interception Scheme*

1 INTRODUCTION

River salinity levels are a significant issue for water supply in South Australia (SA) because of the reliance of SA on the lower reaches of the River Murray. Due to the natural geological structure of the Murray-Darling Basin (MDB), the River Murray in SA acts as a drain for salt out of the landscape. Agricultural practices can mobilise additional salt from groundwater to the river. This affects the water quality of the River Murray for industrial, agricultural and potable use, including the water supply for metropolitan Adelaide. Increases in River Murray salinity can also lead to degradation of aquatic and floodplain ecological health.

Due to its ecological and economic impacts, Federal and State initiatives have been developed to manage River Murray salinity. Many of these rely on numerical groundwater models to estimate the salinity impacts of management strategies on the River Murray. In particular, the Basin Salinity Management Strategy (BSMS) 2001–2015 requires estimates of actions having a significant effect on salinity to be recorded in Salinity Registers A and B (see Section 1.1.1).

The Woolpunda area of the SA Riverland has affected the salinity of the River Murray. The salinity impact has previously been assessed using different groundwater numerical models. Since the models were developed, further hydrogeological investigations and studies have improved the understanding of the Woolpunda region's aquifer systems.

The aim of this project is to redevelop a groundwater flow model of the Woolpunda reach of the River Murray, replacing part of the accredited Lock 3 to Morgan model (Rural Solutions 2005). The model is designed to calculate salt loads as Salinity Register entries for the following accountable actions along the Woolpunda reach:

- Mallee clearance
- Irrigation development
- Improved irrigation practice
- Salt Interception Schemes.

This report extensively documents the groundwater flow model in a format that will assist completion of the Murray-Darling Basin Authority (MDBA) review and accreditation process. It includes comprehensive information on model inputs and details of calculated salt loads for different scenarios. The report has two volumes:

- Volume 1 — Report and Figures, which contains the report and key figures depicting the project area, model structure, parameters and model results
- Volume 2 — Appendices, which contains detailed model inputs (recharge zones and rates), outputs of groundwater flux and salt loads for the various scenarios modelled and data for sensitivity and uncertainty analyses.

A further, separate document will be developed on how model results are used to derive Salinity Register entries. For Salinity Register entry, the estimated salt loads will be provided to the MDBA for conversion to credits and debits for the BSMS Salinity Register following accreditation of the model. The entries will then be submitted through the Basin Salinity Management Advisory Panel for approval prior to being entered onto the Salinity Registers.

1.1 POLICY BACKGROUND

1.1.1 FEDERAL INITIATIVES

Schedule B of the Murray-Darling Basin Agreement (Schedule 1 of the *Water Act 2007* (Commonwealth)) provides the legislative framework to manage and reduce the impacts of salinity in the MDB and the BSMS provides the strategic policy framework. These initiatives followed the adoption of the Ministerial Council's Salinity and Drainage Strategy in 1988 (S&DS).

The BSMS aims to:

- maintain the water quality of the shared water resources of the Murray and Darling Rivers for all beneficial uses — agricultural, environmental, urban, industrial and recreational
- control the rise in salt loads in all tributary rivers of the MDB and, through that control, protect their water resources and aquatic ecosystems at agreed levels
- control land degradation and protect important terrestrial ecosystems, productive farm land, cultural heritage and built infrastructure at agreed levels basin-wide
- maximise net benefits from salinity control across the MDB.

A key feature of the strategy is the adoption of salinity targets for each tributary valley and a basin target at Morgan in South Australia. The Basin Salinity Target is an average daily salinity at Morgan, at a simulated level of less than 800 EC for at least 95% of the time, under the hydrological conditions of the benchmark period. The benchmark period is a climatic/hydrologic sequence (1 May 1975 to 30 April 2000) that provides a means of standardising the assessment of salinity impacts over a variable climate range.

The salinity targets are supported by a system of salinity credits and debits, recorded and reported on the Salinity Registers, where a credit corresponds to an action that decreases salinity and a debit relates to an action that increases salinity. The Salinity Registers track all actions that are assessed to have a significant effect on salinity, defined as a change in average daily salinity at Morgan, which will be at least ±0.1 EC within 100 years. A significant effect can result from a change in the magnitude or timing of salt loads or water flows. Actions that can increase salinity include the clearance of native vegetation and the introduction of irrigation. Actions that can decrease salinity include improved irrigation practice, rehabilitation of water delivery methods and construction of SIS. The BSMS allows for any action resulting in an increase in river salinity to occur, such as new irrigation developments, provided that salinity credits gained by contributing to the funding of SIS or other measures are available to offset any salinity debits arising from these accountable actions.

The S&DS and later salinity agreements adopt a baseline date from which any subsequent actions that affect the River Murray are the responsibility of the State in which the action occurred. The baseline date for New South Wales, South Australia and Victoria is 1 January 1988; the baseline date for Queensland is 1 January 2000. Hence the Registers distinguish between 'legacy of history' and 'future actions' that affect salinity: Register B records the salinity impact of 'legacy of history' actions that occurred prior to the baseline date but which continue to affect river salinity, while Register A records the salinity impact of actions occurring after the baseline date.

In the Mallee region of the MDB, the impact of accountable actions is typically assessed using numerical groundwater flow models. Since the BSMS was agreed, South Australia has developed a series of five numerical groundwater models to estimate salinity debits and credits for the Registers (Figure 1.1). They cover the following reaches of the River Murray:

- Chowilla floodplain, including areas in New South Wales, South Australia and Victoria (Yan, Howles and Marsden 2005)

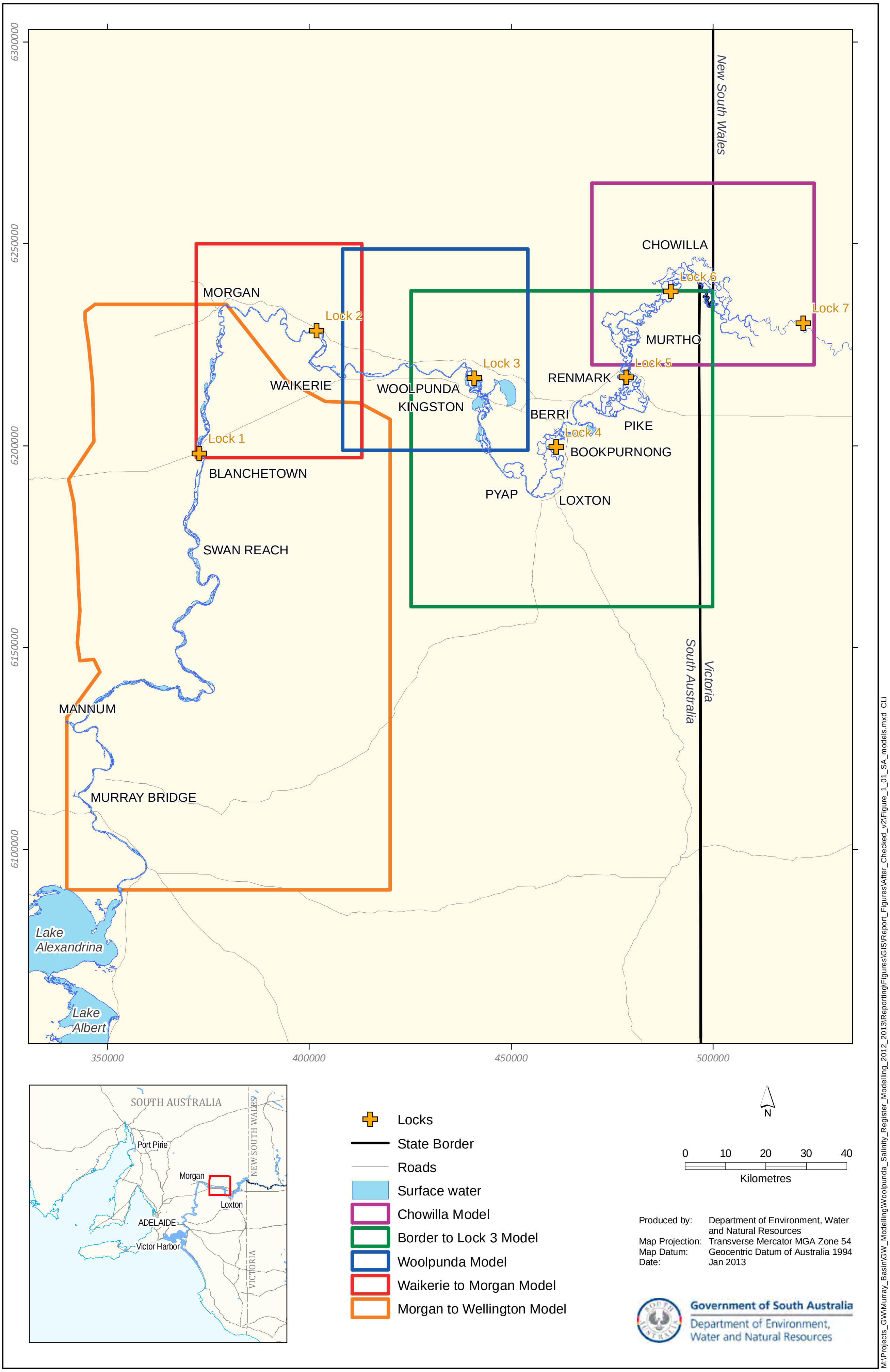

Figure 1.1. Numerical groundwater models developed in South Australia for the Salinity Registers

- SA Border to Lock 3 (Yan, Li and Woods 2011; Yan and Stadter 2008; Yan *et al*. 2007; Yan *et al*. 2006)
- Lock 3 to Morgan (Rural Solutions, 2005)
- Waikerie to Morgan (Yan, Li and Woods, 2012)
- Morgan to Wellington (Yan *et al*. 2010).

These models have been used to assess impacts of native vegetation clearance, irrigation, improvements in irrigation practice and infrastructure and the SIS.

The BSMS commits the partner governments to an investment program of salinity mitigation works and measures implemented across the MDB to deliver 61 EC credits to the river and to offset the States' accountable actions. South Australia proposed a credit allocation and cost-sharing methodology on the basis of the model results of the various accountable actions occurring before and after the baseline date, which in South Australia are typically referred to as 'Pre-1988' and 'Post-1988' actions. The assessment of those impacts must be consistent with the reporting requirements of both Schedule B of the Murray-Darling Basin Agreement and the Basin Salinity Management Strategy Operational Protocols 2005.

One of the main kinds of salinity mitigation works under the BSMS is the construction of SIS, which are built to reduce river salinity. The MDBA currently requires that the salinity impact of each scheme be reviewed and possibly revised for the Registers as part of the periodic Five Year Review of Register entries.

The Basin Plan adopted on 22 November 2012 builds on the successes of the S&DS and BSMS through a Water Quality and Salinity Management Plan that specifies operational salinity targets for event based or "real time" planning to support short term river management. The salinity targets for managing water flows include targets below Morgan at Murray Bridge (830 EC for 95% of the time) and the Lower Lakes at Milang (1000 EC for 95% of the time).

The Basin Plan also sets water quality and salinity targets relating to long-term salinity planning and management, targets to inform development of measures that will be included in Water Resource Plans, and a salt export objective to ensure adequate flushing of salt from the River Murray system into the Southern Ocean.

1.1.2 STATE INITIATIVES

South Australia has a number of State initiatives linked to the BSMS objectives:

- The SA Salinity Zoning Policy specifies that new irrigation developments along the River Murray are limited to areas of low salinity impact, in accordance with the Water Allocation Plan (WAP) for the River Murray Prescribed Water Course.
- Target 77 of South Australia's Strategic Plan is that 'South Australia maintains a positive balance on the Murray-Darling Basin Authority salinity register'.
- South Australia's River Murray Salinity Strategy (SARMSS) also establishes the Basin Salinity Target as a State objective. In addition, under SARMSS, South Australia undertakes monitoring at a number of sites and this may give an ongoing indicator of likely performance against the Basin Salinity Target.

Strategies to achieve these include:

- the construction and maintenance of infrastructure such as SIS to reduce salt loads to the river
- forming partnerships with communities to reduce the salinity impacts of irrigation
- the development and implementation of salinity management policies
- transparent and accurate assessment of South Australia's salinity accountability.

These strategies have proven to be successful with South Australia currently removing more salt than it is putting into the River Murray in terms of accountable actions. As a result, the MDBA's Basin Salinity Management Strategy (BSMS) Salinity Registers currently assess South Australia as having a positive balance. Productive agricultural areas have been able to expand (the recent drought notwithstanding) while significant reductions in river salinity have been achieved, at least above Lock 1.

1.2 THE WOOLPUNDA AREA

Woolpunda is located within the Riverland region of South Australia. In this area, groundwater salt loads to the river are mainly driven by natural upwelling from the Renmark Group. While some water is pumped from the River Murray for irrigation, it is relatively limited compared to other irrigation areas in the Riverland region.

To reduce the natural saline groundwater accessions to the River Murray, improvements have been made to irrigation practices and a SIS has been constructed. The extraction wells lower groundwater gradients toward the river valley and therefore reduce the salt load entering the River Murray.

The Federal and State strategies outlined in Section 1.1 require that future salinity impacts of land clearance, irrigation and SIS be estimated. The numerical groundwater model documented in this report is used to estimate the river salinity impacts for the Woolpunda reach.

1.3 REVIEW OF PREVIOUS MODELS IN THE WOOLPUNDA AREA

The Woolpunda Numerical Groundwater Model 2013 is informed by two prior models of the study area, those of (i) Rural Solutions (2005) and the scenario modelling undertaken by Aquaterra (2007) and (ii) AWE (unpublished).

To meet BSMS requirements, Aquaterra was contracted by Rural Solutions to develop a model from Lock 3 to Morgan (Rural Solutions 2005). The seven-layer model was accredited in 2005 by the MDBA and since the accreditation, it has been used for the assessment of salt load impact and benefit from the Woolpunda SIS. The same model was used by Aquaterra (2007) to improve the scenario modelling.

The Lock 3 to Morgan reach simulated by the accredited Lock 3 to Morgan 2005 model of Rural Solutions (2005) spans two distinct hydrogeological regimes (Figure 1.2). In Woolpunda, the river valley is in contact with the Upper Mannum Formation (AWE 2007a). Irrigation in the area is relatively limited and groundwater salt loads to the river are mainly driven by natural upwelling from the Renmark Group. As documented in Yan, Li and Woods (2012), the river valley in the Waikerie to Morgan reach is mainly in contact with the Glenforslan Formation. There is no evidence of significant upwelling from the Renmark Group at Waikerie and salt loads are driven by irrigation-induced groundwater mounds.

To improve the Lock 3 to Morgan model, the Expert Panel and the 5 Year Review Modelling for Salinity Registers Project Team agreed to replace this model with two models of smaller extents: the Waikerie to Morgan 2012 model (Yan, Li and Woods, 2012) and the Woolpunda 2013 model. Each model represents a different hydrogeological regime.

Splitting the Lock 3 to Morgan model into two models should improve model quality as:

- a closer model grid can be used, due to the smaller model areas
- the reduced number of model layers allows groundwater evapotranspiration (ET) on the floodplain to be simulated using MODFLOW, as some interfaces such as the older version of PMWIN, do not permit groundwater evapotranspiration in layers other than layer 1.

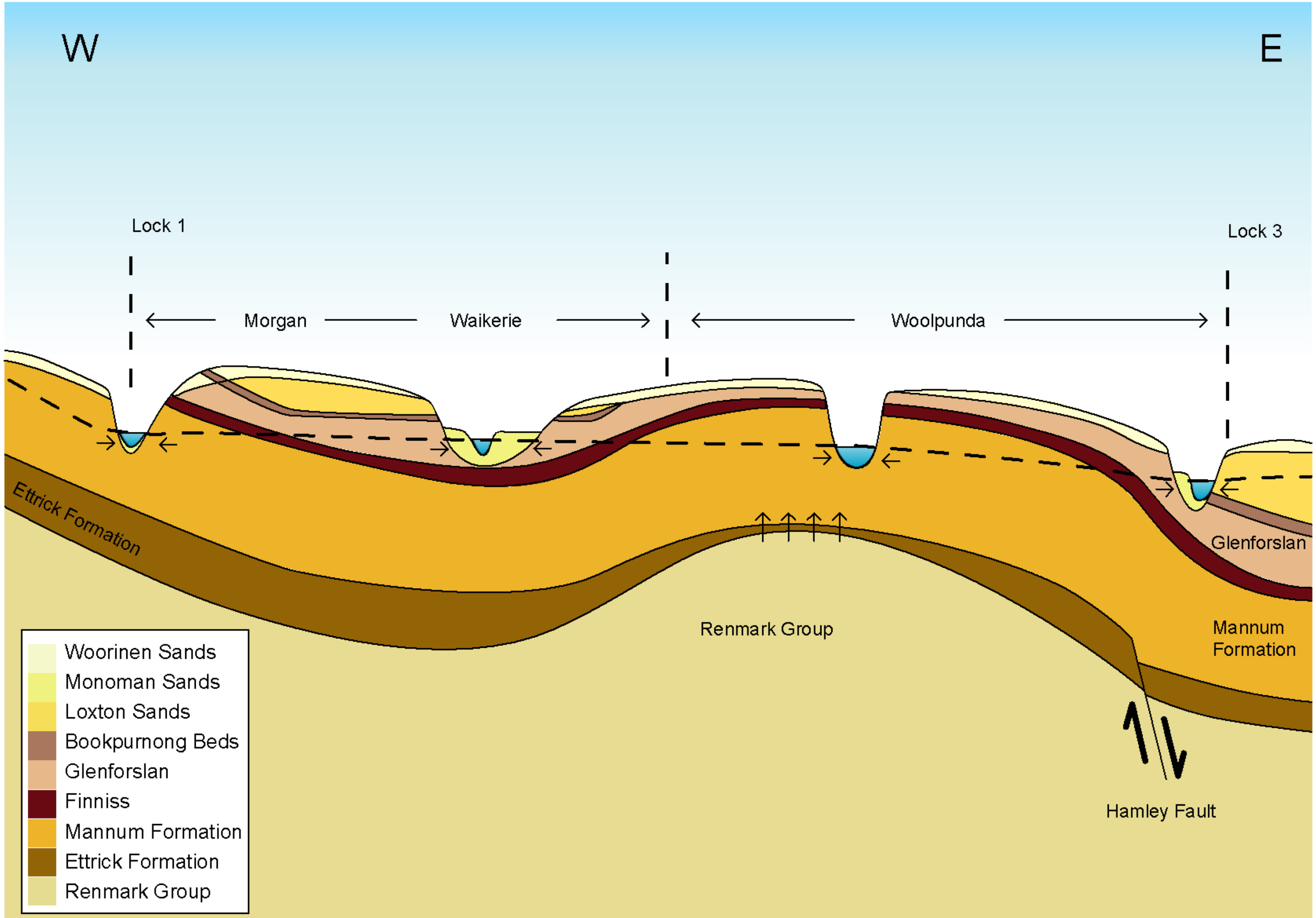

Figure 1.2. Lock 3 to Morgan hydrogeological conceptual model (After Yan, Li and Woods 2012)

- it will be easier computationally to run the models, due to the reduced number of model layers. The Lock 3 to Morgan 2005 model was very computationally unstable, due to the rewetting process involved in simulating the saturation of the Loxton Sands. To ensure solution convergence, the model had to be separated into a sequence of six stepped transient models from historical model to predictions.

In 2012, AWE was engaged by the DEWNR on behalf of the MDBA to design a regional groundwater model that could be used to estimate salt loads to the River Murray in the Woolpunda reach downstream of Lock 3. Occurring concurrently with this study was a detailed review of hydrogeological and scheme operational data as part of the performance assessment for the Woolpunda SIS Five-Year Review. The Five-Year Review of SIS performance was conducted by AWE and outcomes from this analysis have been used to develop the conceptual model for the Woolpunda reach. The updated model encompasses current hydrogeological knowledge gathered during the data compilation phase of the review. The model was calibrated and demonstrated its capability to predict salt load impact from accountable activities but has not been published.

Subsequent stages of the modelling project have been undertaken by DEWNR and have involved refining calibration of the model to a standard required for accreditation, for the purposes of the BSMS Salinity Registers. The Lock 3 to Morgan (Rural Solutions 2005) model and the preliminary AWE model helped to guide the development of the Woolpunda 2013 model. However, all design decisions for the Woolpunda 2013 model are based primarily on the data analysis and conceptual model presented in Section 2.

The current model uses assumptions and methods consistent with other Salinity Register models.

1.4 CURRENT MODELLING EXERCISE

The first Five Year Review of the Woolpunda area for the Salinity Register entries is in progress. As part of the review, this work will refine the unpublished prototype Woolpunda numerical model and the model report to the standard required by the accreditation process for Salinity Register models.

This study will capture new knowledge within the modelling platform. The updated modelling platform will provide improved estimates of salinity impacts from the Woolpunda reach under the various accountable actions, and hence lead to refinement and improvement in the Salinity Registers.

The aim is to develop a model capable of simulating the regional aquifer system in the Woolpunda study area which:

- Improves the understanding of the hydrogeology of the regional aquifer system and processes
- Provides estimated salt loads entering the River Murray under different accountable development and management actions (100-year predictions from current year) for use as Salinity Register entries, specifically:
    - Mallee clearance
    - Irrigation development
    - Improved irrigation practices
    - Salt Interception Scheme operation
- Assists with the broad-scale planning for groundwater management schemes (e.g. SIS) that help to control the flux of saline groundwater and therefore salt load, entering the River Murray.

The upgrade includes the following features:

- Data Review
    - Compilation of detailed irrigation data for areas within the model domain:
        - Irrigation footprints
        - Permanent irrigation is distinguished from temporary pivot irrigation.
        - Recharge estimates based on application volumes and other data (Vears 2013; Laroona Environmetrics 2012; see Appendix C)
    - Review of near-river groundwater salinity
    - Compilation of data for 2007 – 2012 where available, principally:
        - Potentiometric head in observation wells
        - SIS pump rates
        - RoR salt load estimates
- Refinement of Model Design and Construction
    - Replacement of the constant head boundary cells at the model domain boundary with general head boundary cells, which will give a better control of flux into or out of the model through adjusting the conductance term
    - Revised model flow budget zones, which are used for salt load calculation
    - Adjusted recharge rates and areas to reflect the irrigation data review
    - Inclusion of SIS pump rates and head observations for 2007 – 2012
    - Revised groundwater salinities used for salt load calculation
- Model Calibration and Confirmation
    - Increased number of observation wells and hydrographs near Woolpunda SIS used for calibration
    - Improved calibration to potentiometric head, especially in areas adjacent to the River Murray and SIS
    - Confirmation of the model results by comparing to the RoR salt load estimates
- Running scenarios for Salinity Register entry
- Revised representation of SIS pump rates used for the future period (post-2012) to better represent the long-term average conditions
- Additional scenarios, including Scenario 5 (current + future irrigation), Scenario 8b (pre-1988 irrigation + SIS) and Scenario 8C (Scenario 5 + SIS)
- Sensitivity and Uncertainty tests
    - Sensitivity and uncertainty tests to determine the confidence on the model calibration and scenario outputs respectively
- Reporting
    - Full report for the accreditation of Salinity Register model
    - More information and description on irrigation accession and model recharge
    - Documentation of how groundwater salinity values were chosen for each model flow budget zone
    - Scaled Root Mean Square (SRMS) error for selected years
    - Salt load details for each scenario in Appendix B

Revisions have also been made to the conceptualisation of scenarios, as agreed by a committee of MDBA, DEWNR and SA Water representatives. The scenario definitions are included in Appendix A.

2 HYDROGEOLOGY AND HYDROLOGY OF THE WOOLPUNDA AREA

The Woolpunda area lies in the Riverland, within the South Australian portion of the Murray-Darling Basin. Descriptions of the SA Riverland and Murray Basin hydrogeology and stratigraphy include Brown (1989), Evans and Kellett (1989), Barnett (1991), Drexel and Preiss (1995), Lukasik and James (1998), Barnett *et al.* (2002) and McLaren *et al.* (2011).

Reports focussed on Woolpunda include Rural Solutions (2005), which provides a literature review and history of investigations for the years 1984 to 2000. Woolpunda datasets and interpretations have been provided in online databases and numerous reports which are summarised in AWE (2013a). The stratigraphy has been described in Telfer (1987a), DWLBC and SA Water (2003) and AWE (2013a). Groundwater-surface water interaction has been mapped in NanoTEM studies (Telfer *et al.* 2005; AWE 2011d; AWE 2013b). Data reviews and hydrogeological conceptual models form part of numerical model reports of the region. Numerical model reports spanning larger regions including Woolpunda are Miles *et al.* (2001), Barnett *et al.* (2002), Fuller *et al.* (2005), Rural Solutions (2005) and Aquaterra (2007).

A forthcoming hydrogeological atlas of the Waikerie and Woolpunda areas will summarise and evaluate available data (AWE 2013a). Data includes information from DEWNR and PIRSA databases and prior studies. Information from the draft report was provided to DEWNR in advance of publication and these datasets have been used for the development of the Woolpunda model presented in this report. DEWNR has since compiled a further major dataset: historical irrigation data (Appendix C).

This section summarises key aspects of the hydrogeology and hydrology based on these documents. It concentrates on aspects that will be included in the conceptual and numerical model, but also notes hydrogeological features that are omitted from the present model but may be included in later versions.

2.1 LOCATION AND TOPOGRAPHY

The Woolpunda project area is defined to include the River Murray between Lock 3 to Holder, and the surrounding irrigation areas that may impact on the salinity of this reach. It is in the north-western Riverland region of the South Australian part of the Murray Basin, extending from river kilometres 431 to 394 (note: river kilometres give the distance from the river mouth when following the main river channel upstream). Figure 2.1 shows the location and key hydrological features. The Woolpunda project area includes portions of the Land and Water Management Plan areas for Waikerie, Woolpunda, Pyap-Kingston and Taylorville North.

The project area can be divided into highland and floodplain regions. The highland regions are at an elevation of approximately 40 to 80 m AHD, through which the River Murray has carved a floodplain valley with a ground elevation between 5 and 24 m AHD (AWE 2013a). Cliffs are present at the boundary between the floodplain and highland for most of the reach, but cliff seepage is not observed.

2.2 CLIMATE

The climate is characterised by hot dry summers and cool, wetter winters. At Waikerie Eremophila Park Station 024029, which is south of the river and within the project area, the average annual rainfall is 286 mm (Bureau of Meteorology 2013a). The closest location recording evapotranspiration is the Loxton Research Centre Station 024023 with a potential evapotranspiration (ET) of 1904 mm/y (Bureau of

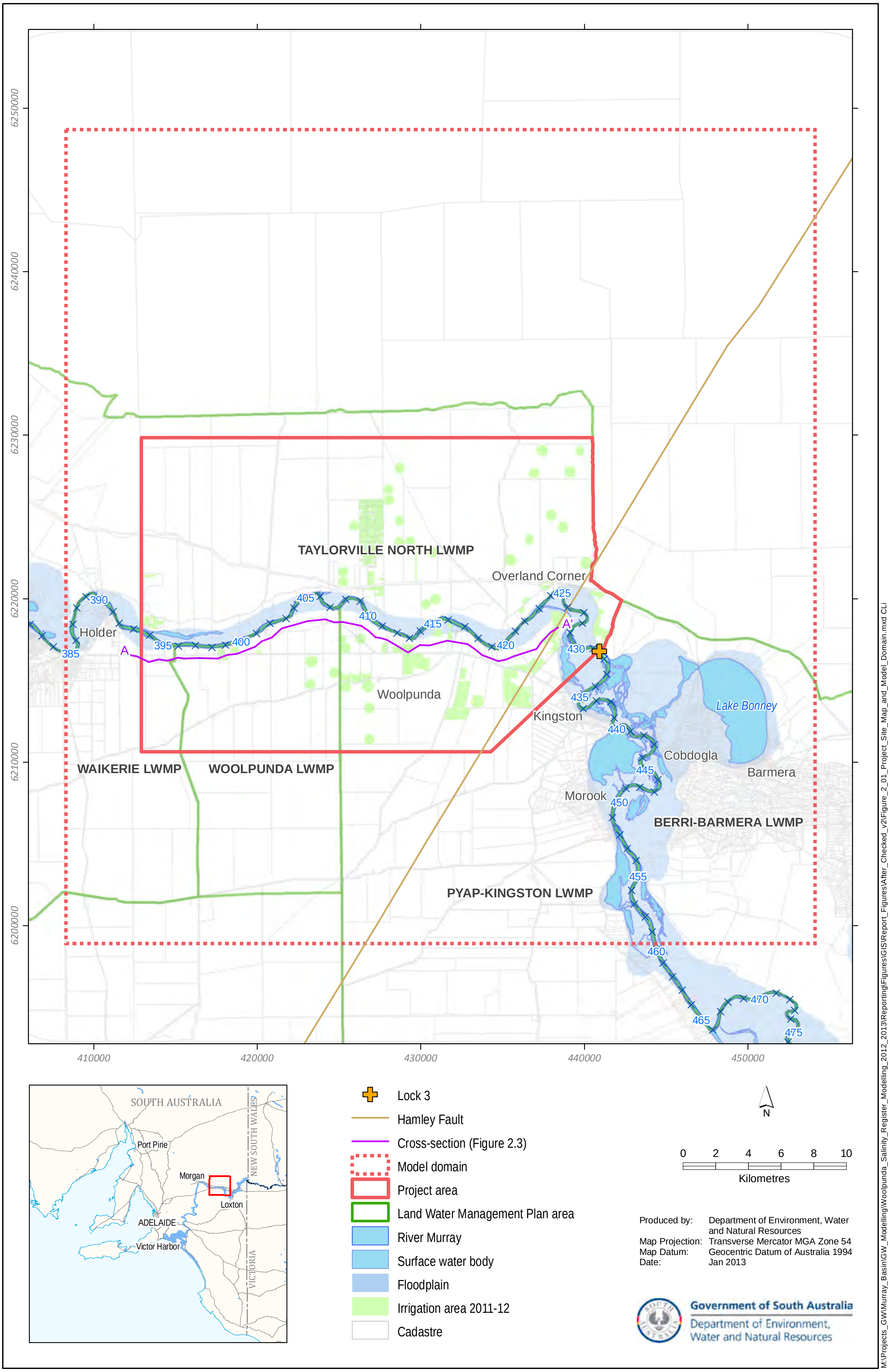

Figure 2.1. Project site map and model domain

Meteorology 2013b). Table 2.1 provides monthly averages for rainfall and evapotranspiration. Rainfall is higher in the winter. The potential ET exceeds rainfall, especially in the summer months where ET exceeds rainfall by an order of magnitude (see also Section 2.4.4).

Table 2.1 Average monthly rainfall at Waikerie Eremophila Park Station and potential groundwater evapotranspiration at the Loxton Research Centre Station

Month	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Rainfall (mm)	18	16	13	20	22	24	29	25	27	31	26	25	286
Potential ET (mm)	291	235	198	120	71	51	53	84	126	183	225	267	1904

2.3 HYDROGEOLOGY

2.3.1 REGIONAL SETTING

The Murray-Darling Basin is a closed groundwater basin consisting of Cainozoic unconsolidated sediments and sedimentary rock (Evans and Kellet 1989). It is wide but shallow, extending up to 900 km east–west and averaging 200 m thick, with a maximum thickness of 600 m (Brown 1989). It includes a number of regional aquifer systems. Its surface waters and groundwater are connected to the sea only at the Murray Mouth (Brown 1989). Salt from rainfall, surface water and groundwater has accumulated within the basin over the past half a million years (Brown 1989).

Drexel and Preiss (1995) provide an overview of the Murray-Darling Basin's geology within South Australia. The basement is overlain by three main sequences of Tertiary sediments, and by Quaternary fluvial sediments. The Tertiary succession is divided into the Late Palaeocene to Early Oligocene sediments (the Renmark Group), the Late Eocene to Middle Miocene transgressive marine sediments (the Murray Group) and the late Miocene to Late Pliocene marine to fluvial sediments which include the Loxton Sands (Drexel and Preiss 1995). The geological sequence is shown in Figure 2.2.

The hydrogeology of the project area is influenced by two faults. The Woolpunda and Waikerie river reaches are situated between the Morgan Fault in the west and the Hamley Fault to the east. The Hamley Fault intersects the Woolpunda project area through Overland Corner; although the Morgan Fault is outside the project area, it is discussed because it exerts significant influence on the hydrogeology. The up-faulted basement along both faults on the western sides has significantly influenced the deposition and thickness, and therefore the groundwater flow patterns in the Tertiary sediments that host groundwater.

The Woolpunda reach has a basement elevation between approximately -150 m and -300 m AHD, dipping towards the north/north-east (Barnett 1991). To the west of the Hamley Fault, the saturated zone is hosted mainly in two aquifer systems: the Murray Group limestone sediments and the Renmark Group sands and gravels. The regional watertable is within the Murray Group. The Murray Group has been subdivided stratigraphically by Lukasik and James (1998) with three sub aquifers recognized (Lower Mannum, Glenforslan and Pata/Bryant Creek). Extensive cross correlation between the stratigraphic divisions and the observed patterns of Murray Group yield in the Waikerie area established that the stratigraphic divisions correlate with aquifer – aquitard units (AWE 2001). Figure 2.3 is a cross-section through the southern production wells of the Woolpunda SIS, illustrating the stratigraphy of the Woolpunda reach.

To the east of the Hamley Fault, between Overland Corner and Lock 3, the elevation of the basement in the Renmark Trough is approximately -400 to -450 m AHD (Barnett 1991).

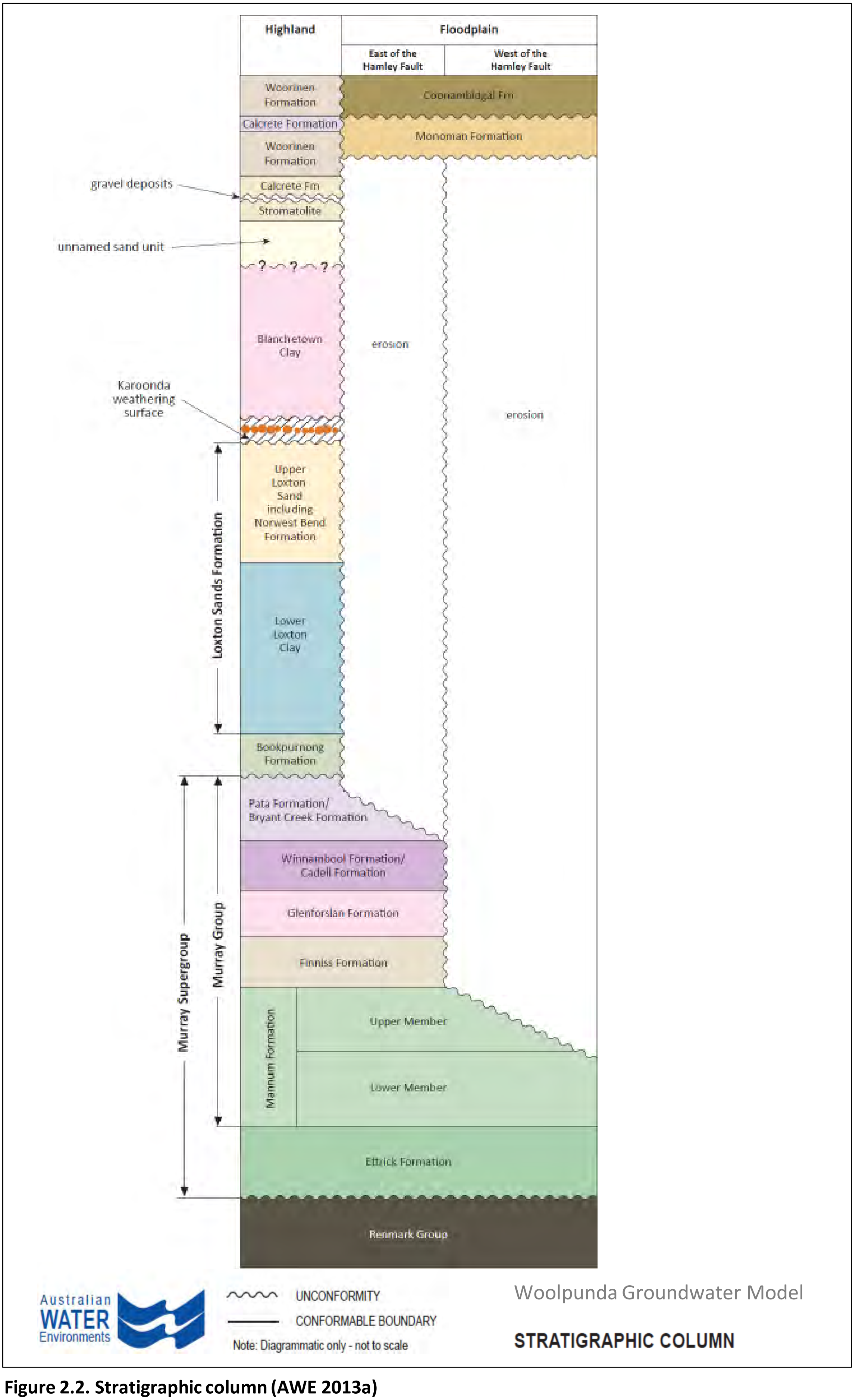

Figure 2.2. Stratigraphic column (AWE 2013a)

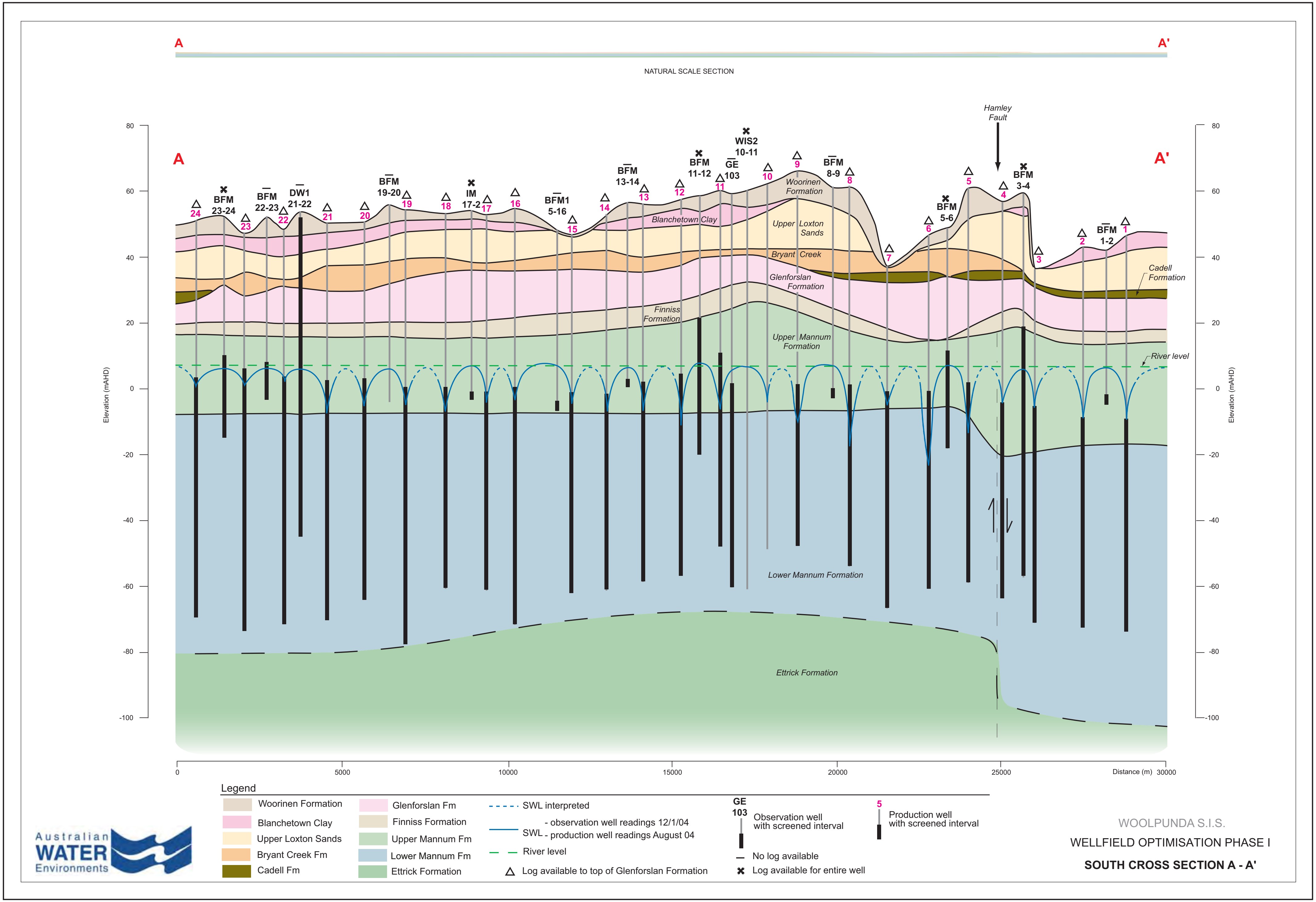

Figure 2.3. Cross-section through the southern wellfield of the Woolpunda SIS (AWE 2007a)

Three significant aquifer systems are developed within the Renmark Group, the Murray Group and in the Loxton Sands (Brown 1989). The regional water table is mainly in the Loxton Sands (Telfer *et al*. 2012).

The channel of the ancestral River Murray is incised into the highland sediments of the regional aquifers. Within this channel, the semi-confined Monoman Formation aquifer has been deposited. The regional watertable aquifers are generally juxtaposed and hence hydraulically connect with the Monoman Formation.

Table 2.2 summarises aquifer and aquitard properties reported in previous studies. Most aquifer tests have been conducted on SIS wells in Woolpunda (e.g. Clarke 1992; Sibenaler 1987, 1988a, 1988b; AWE 2013a), so data are concentrated in the SIS area.

Appendix C includes figures showing the top and bottom surfaces of key hydrogeological units in the project area.

Table 2.2 Summary of hydraulic parameters for Woolpunda area

Hydrogeological Unit	Hydraulic conductivity (m/d)		Transmissivity (m^2/d)	Storage (-)		Source
	K_h	K_v	T	$S^{(1)}$	Sy	
Mannum Formation	0.15 to 2	0.16 to 1.87		3E-4 to 5E-4		Sibenaler (1987)
	0.5 to 2			6.5E-4 to 1.5E-3		Sibenaler (1988a)
	1.2 to 3.2				0.02 to 0.04	Sibenaler (1988b)
			43 to 250			Clarke (1992)
Lower Mannum Formation	1 to 5		10.5 to 98			AWE (2013a)
Ettrick Formation		1E-4 to 1E-5(2)				Watkins (1993)
Renmark Group			70(3)			Magarey and Howles (2009)
	0.25 to 20(2)					Barnett and Osei-bonsu (2006)

(1) S is storage coefficient, which is the product of specific storage (1/m) and layer thickness (m), and is hence dimensionless

(2) These values are not from field measurements but modelling studies

(3) This value was measured in the Chowilla Floodplain, which is outside the model domain. This is the only aquifer test undertaken for the Renmark Group in South Australia.

2.3.2 RENMARK GROUP

The Renmark Group aquifer overlies tectonically stable pre-Cainozoic basement rock (Brown 1989). Its sediments are Tertiary fluvio-lacustrine and are overlain by a Tertiary marine marl, the Ettrick Formation (Barnett 1991).

The sediments consist of fluvial clays, silts, sands and minor gravels with carbonaceous deposits. The Renmark Group aquifer is slightly leaky to confined in Woolpunda, with significant upwards leakage into the overlying Murray Group occurring through a zone of low resistance in the intervening Ettrick Formation aquitard along the Woolpunda reach (Telfer 1987b; Herczeg *et al*. 1989; Rural Solutions 2005).

The base of the Renmark Group is faulted along the north-east trending Hamley Fault that had a strong influence on the pre-Tertiary basement rocks. The base of the Renmark Group is interpreted as steeply dipping towards the north-east between -300 and -500 m AHD east of the fault to the west the base is at -175 to -200 m AHD.

The top of the Renmark Group is approximately 200 m deep (at approximate elevation -150 m AHD) east of the Hamley Fault near Overland Corner with a thickness of 200 - 250 m. To the west of the fault the Renmark Group is approximately 100 m deep (Barnett 1991) with a reduced thickness. The observed gentle east-west arching (Lindsay and Barnett, 1989) is a prominent feature from the Renmark Group up, between Sunlands which is located to the west of Waikerie and Holder (outside the project area) and Overland Corner.

There are only four observation wells monitoring the Renmark Group (Figure 2.4). Hydrographs in the Renmark Group (Figure 4.5) show relatively steady potentiometric head with the exception of an observation well adjacent to the floodplain, MRK18, where levels rose suddenly in the 1990s.

Figure 2.4 shows recent potentiometric head observations for the Renmark Group aquifer. There are a limited number of data points to clearly indicate groundwater flow direction. Over the larger scale of the SA Riverland, the hydraulic gradient is roughly from south and east to west (Barnett 1991). Barnett (1991) provides potentiometric head contours over a wide area that includes Woolpunda, but the choice of plotted contours is such that no contour lines pass through the Woolpunda project area.

In most areas of the Riverland, a head difference greater than 15 m between the Renmark Group aquifer and the aquifers of the Murray Group indicates that the Ettrick Formation acts as an effective confining aquitard (Barnett 1991). However, in the Woolpunda reach upwelling from the Renmark Group causes a natural groundwater mound in the Murray Group (Telfer 1987b). The upwards leakage is discharged into the River Murray in this reach from the Murray Group, and is the reason for the high, naturally induced salt accessions along the Woolpunda reach (Rural Solutions 2005). Another upwelling zone from the Renmark Group occurs within the Renmark Trough south of Loxton (Harrington *et al.* 2005) attracting relatively fresh groundwater from the south and discharging upward into the Murray Group and River Murray.

No aquifer tests are known to have been conducted within the Renmark Group in the project area. Magarey and Howles (2009) report a transmissivity of 70 m^2/d at Chowilla near the basin depocentre. Barnett and Osei-bonsu (2006) give a hydraulic conductivity range of 0.25 to 20 m/d, based on modelling studies but not field data.

Groundwater salinities in the Renmark Group range from 12000 to 27000 mg/L (Herczeg *et al.*, 1989; AWE 2000a; Rural Solutions 2005).

2.3.3 ETTRICK FORMATION

Hydrogeologically, the Ettrick Formation separates the Renmark Group from the aquifers of the Murray Group. The Ettrick Formation consists of grey-green glauconitic and fossiliferous marl. The hydrogeological importance of the Ettrick Formation is that it allows upward flow (leakage) from the Renmark Group to the Murray Group aquifers in the Woolpunda area.

There are few measurements of the thickness of the Ettrick Formation. The available records indicate that the Ettrick Formation is 13 to 22 m thick below the Woolpunda groundwater mound. The Formation is up to 45 m thick in the neighbouring Waikerie region to the west, but is less than 20 m thick between Lock 2 to Morgan (Yan, Li and Woods 2012). Despite the thinner sediments in the Lock 2 to Morgan area, no indications of upward leakage from the Renmark Group have been identified from physical data, and models also do not indicate significant upward leakage (where the Renmark Group

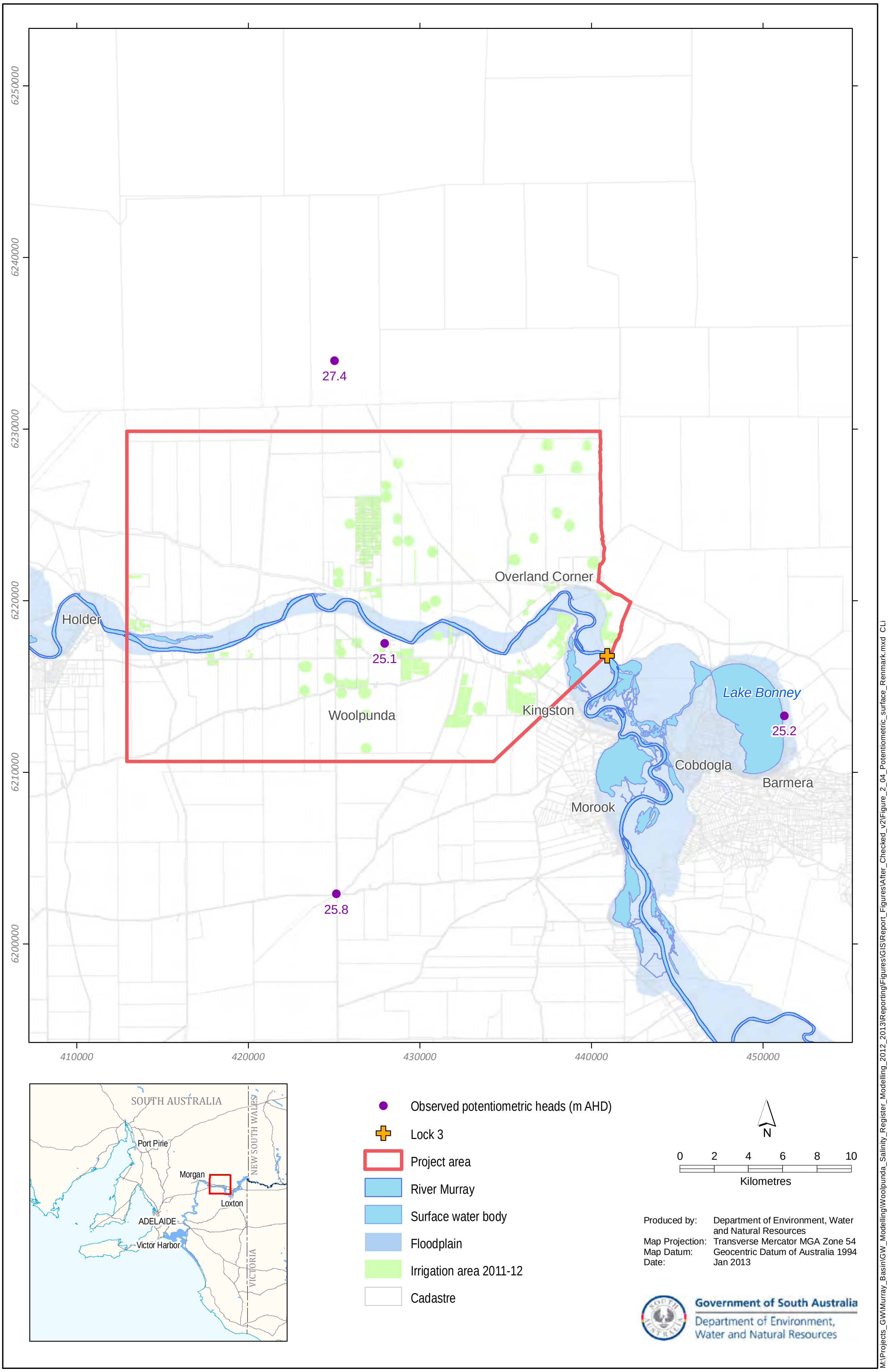

Figure 2.4. Measured potentiometric heads for the Renmark Group 2009 (After AWE 2013a)

has been included in the model domain). This suggests that the upwelling of groundwater from the Renmark Group at Woolpunda is likely to be due to both the thinner sediments and a higher local vertical hydraulic conductivity of the Ettrick Formation (Telfer 1987b).

No aquifer tests have been conducted in the study region to ascertain the vertical hydraulic conductivity of the Ettrick Formation. The Watkins (1993) modelling study estimated the vertical hydraulic conductivity to be 10^{-5} to 10^{-4} m/d. The Rural Solutions (2005) model adopted vertical hydraulic conductivities of 1.4 x 10^{-4} x to 4.5 x 10^{-4} m/d.

2.3.4 MURRAY GROUP FORMATION

The Murray Group Formation is a Tertiary Oligo-Miocene sequence of limestone aquifers and marl aquitards (Brown 1989; Lindsay and Barnett 1989, Lukasik and James 1998). On a regional scale, the Murray Group Limestone may be considered as a single unit but on a local scale three sub aquifers with intervening aquitards are recognised (AWE 2000). The Murray Group exhibits variable thickness due to erosion of its upper surface.

Murray Group subunit stratigraphy in the Riverland is described in Lindsay and Barnett (1989) and Telfer and Watkins (1991) but has since been reinterpreted by Lukasik and James (1998) and refined further by Wall (2001). Reports prior to 2000 typically use the older nomenclature or do not differentiate between the sub-units. The limestones (Pata, Bryant Creek, Glenforslan and Mannum Formations) are separated by marl aquitards (Winnambool, Cadell and Finniss Formations).

Figure 2.5 shows the regional potentiometric head for the Murray Group in 2009 in the Woolpunda area. On the larger scale of the SA Riverland, the predominant lateral flow in the Murray Group is from east to west, ultimately driven by distant recharge sources (Barnett 1991; Yan, Li and Woods 2012) but in the Woolpunda region this trend is modified by a substantial upwelling from the Renmark Group (Telfer 1987b; Herczeg *et al.* 1989). This results in a large, naturally-occurring groundwater mound within the Murray Group which is drained by the River Murray and its floodplain. Along both side of the River, potentiometric head is consistently between 6 to 7 m AHD due to the SIS pumping wells.

2.3.4.1 LOWER MANNUM FORMATION

The Lower Mannum Formation is a highly fossiliferous, sandy and weakly cemented limestone (Lukasik and James 1998) that becomes finer and siltier with depth (Telfer *et al*. 2012).

The Lower and Upper Mannum Formations act as a single unconfined aquifer along the Woolpunda reach.

Figure 2.6 shows transmissivity results from aquifer test estimates for the Mannum Formation aquifer within the project area (AWE 2013a). The transmissivity has declined over time within the SIS wellfield as the watertable has been lowered. Karst conditions occur near the water table at production well 49 of the Woolpunda SIS. At the time of SIS construction, the median transmissivity was 54 m^2/d and 80 percent of transmissivity values were within 17 to 85 m^2/d. The resultant hydraulic conductivity is estimated to be from 0.5 to 5 m/d, assuming a 40 m saturated thickness.

No reliable aquifer test data are available for the specific yield and storativity of the Lower Mannum Formation at Woolpunda. It is not possible to accurately estimate these properties from the start-up period of the SIS production wells, as key data such as the start time of pumping were not recorded; moreover, river level varies significantly during this period and its impact on the potentiometric head is difficult to account for using the standard analytical solutions used for aquifer tests. Specific yield and storativity are difficult to determine at later times because the drawdown curve is comparatively flat.

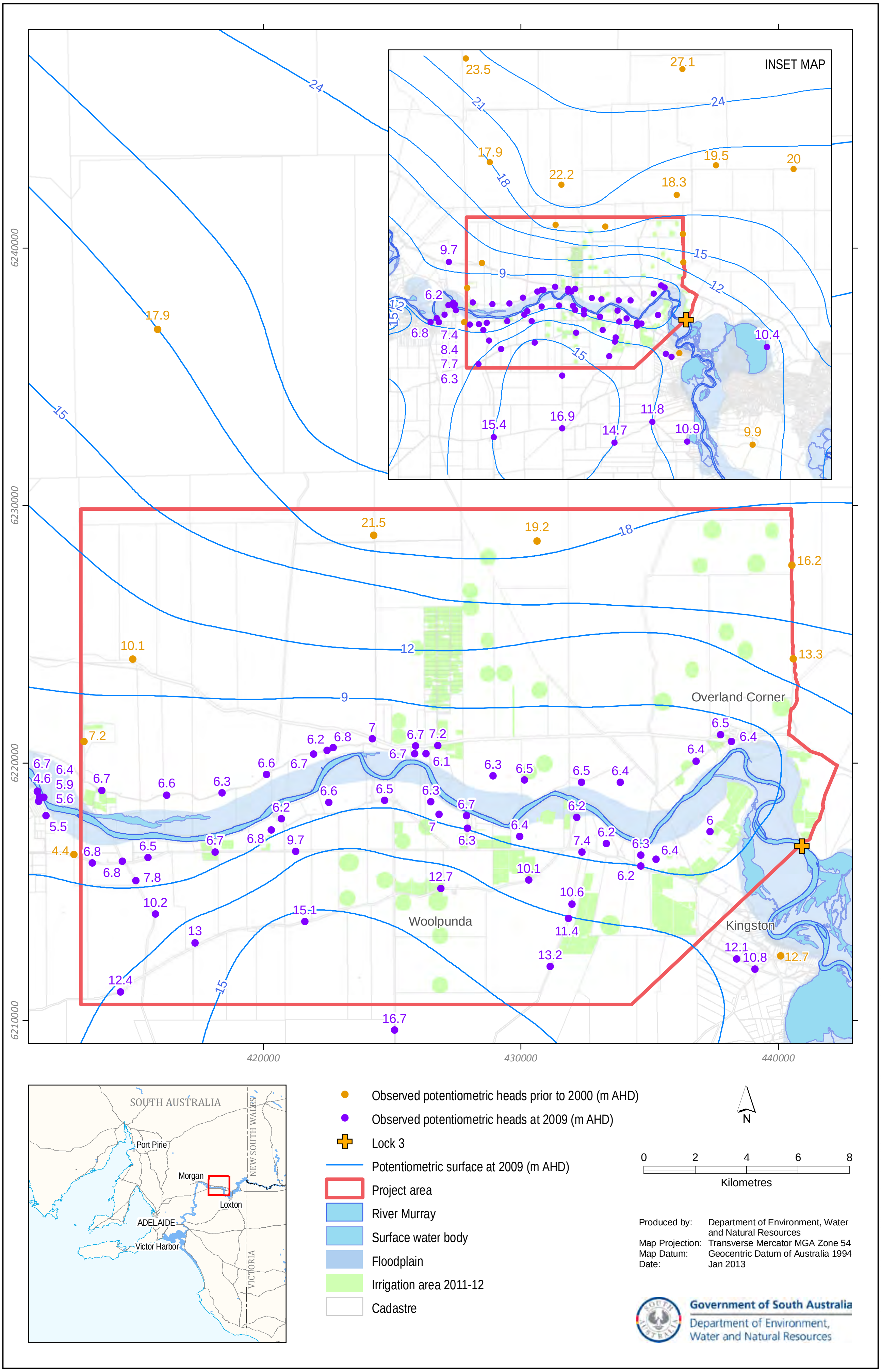

Figure 2.5. Potentiometric surface for the Murray Group 2009 (After AWE 2013a)

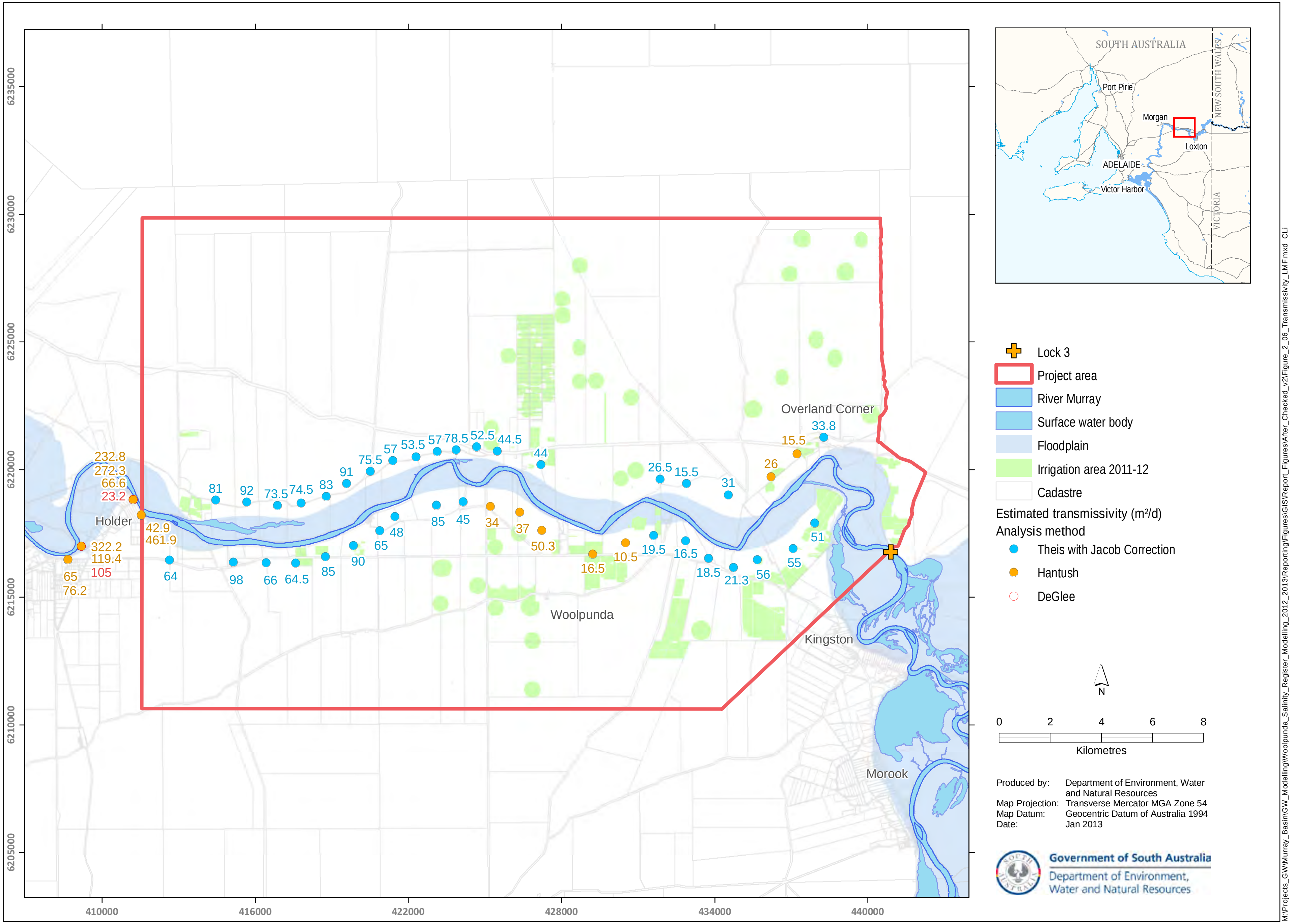

Figure 2.6. Estimated transmissivity for the Lower Mannum Formation (After AWE 2013a)

Despite the lack of appropriate aquifer test data at Woolpunda, there are two sources of information for LMF specific yield and storativity. Firstly, previous groundwater models have estimated a specific yield of 0.06 to 0.12, but the reliability of these estimates is unclear. Secondly, aquifer test data are available for the adjacent Waikerie area (AWE 2011b) and are anticipated to be a reasonable surrogate for the values at Woolpunda. The storativity values for Waikerie, from the Hantush Forward analysis, generally vary between 2.5×10^{-4} (tenth percentile) and 7.5×10^{-4} (ninetieth percentile).

Water level trends depend on the observation well location. Figure 2.10 gives the well locations and hydrographs are given in Figure 4.4. Most Lower Mannum Formation hydrographs in the highland far from the SIS show little or no change in head over time (HLD005 and MAK002). Hydrographs from wells within the Murray Trench or immediately adjacent to it fluctuate significantly with river levels during floods and subsequent recessions (e.g. HLD30, PGK015). Hydrographs along the Woolpunda Reach near the SIS show a sharply declining trend once the SIS commenced e.g. HLD009 and PGK038). No hydrographs show increasing water level trends; neither do they indicate groundwater mounds due to irrigation recharge in the Woolpunda area.

Figure 2.7 displays measured salinity for the Lower Mannum Formation aquifer and includes some salinity values for wells intercepting the Murray Group where the subunit has not been identified. There are 76 observation wells within the project area. The groundwater salinities vary from 1385 mg/L to 27 420 mg/L, with a mean of 19 600 mg/L and a standard deviation of 4084 mg/L. Salinities in the LMF are not expected to have changed significantly over time: little recharge from irrigation has yet reached the watertable (Section 2.6.3.2) and the depth to water is too great for evapotranspiration to occur.

2.3.4.2 UPPER MANNUM FORMATION

The Upper Mannum Formation is a calcarenitic fossiliferous limestone, locally clay-rich to marl (Lukasik and James, 1998). In the Woolpunda reach it is considered to be a weakly-cemented and low yielding aquifer (Telfer *et al*. 2012).

The vertical hydraulic conductivity of the Upper Mannum Formation has been estimated at sites in the adjacent Waikerie region as 10^{-3} to 10^{-2} m/d (Telfer *et al*. 2012).

2.3.4.3 FINNISS FORMATION

The Finniss Formation aquitard is a thin but persistent grey to dark grey clay with thin sand layers and hard bands separating the Glenforslan Formation and Upper Mannum Formation. The Finniss Formation contains sparse aragonitic (white coloured) fossils. The Finniss Formation is interpreted as having been eroded beneath the River trench in the vicinity of Lock 2 and through the Woolpunda SIS. It is not saturated within the Woolpunda reach but may be saturated (where present) east of the Hamley Fault.

2.3.4.4 GLENFORSLAN FORMATION

The Glenforslan Formation was first defined in Lukasik and James (1998). It is a silty and sandy limestone formation with abundant bryozoan and shell fragments (Lukasik and James 1998). In some locations outside the project area the Glenforslan Formation has developed secondary porosity and is karstic (Telfer and Watkins 1991), e.g. the south-west corner of the Qualco-Sunlands irrigated area (AWE 2007b). It is not saturated within the Woolpunda reach but may be saturated (where present) east of the Hamley Fault.

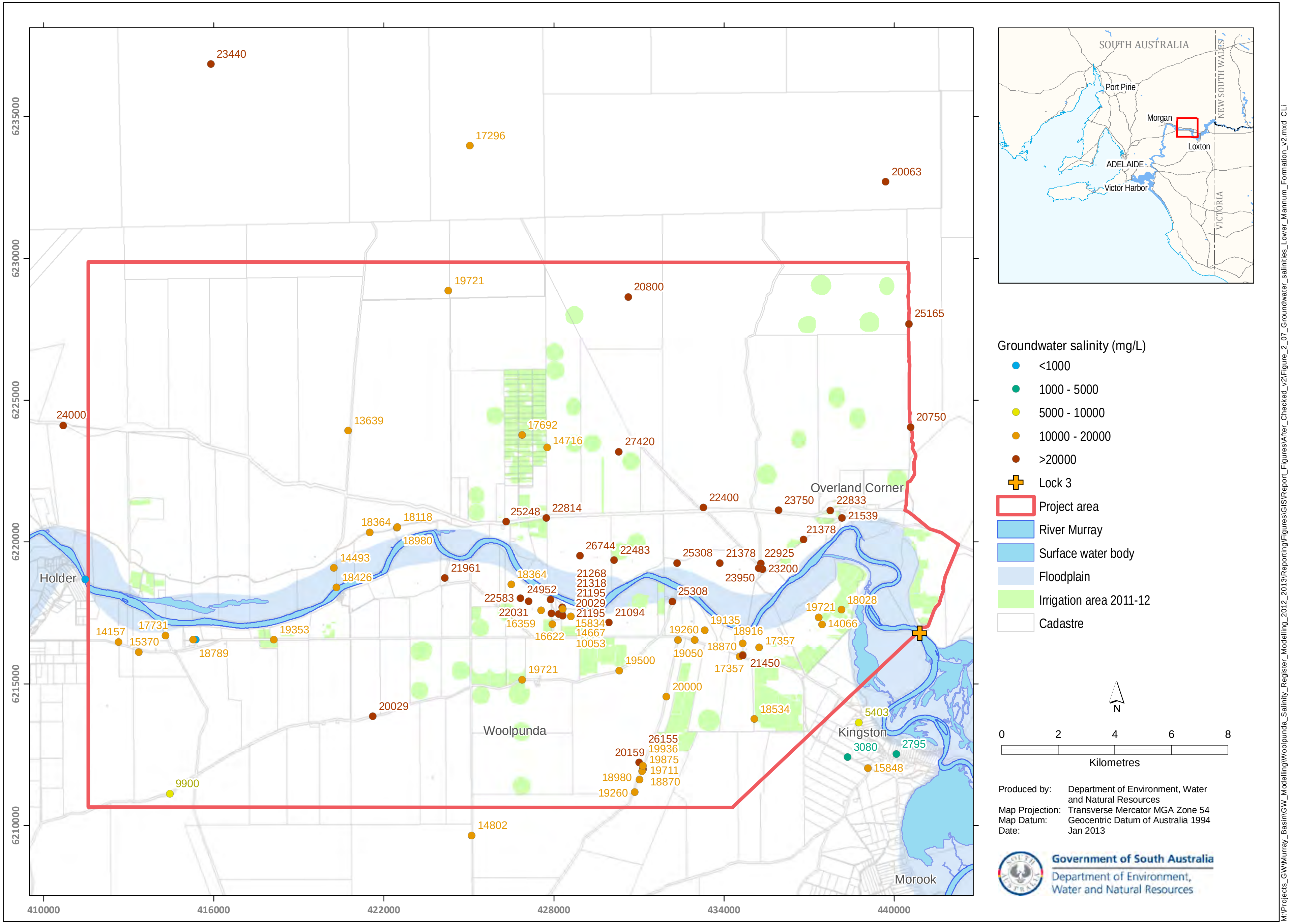

Figure 2.7. Groundwater salinities for the Lower Mannum Formation (After AWE 2013a)

2.3.4.5 WINNAMBOL AND CADELL FORMATIONS

The Winnambool Formation aquitard comprises grey to pale green calcareous clay (marl) and silty clay. The Cadell Formation (marls with green clay, Lukasik and James 1998) is used interchangeably (AWE 2011a). The Cadell Formation is mustard to pale yellow coloured marl. The Formations are not saturated within the Woolpunda reach but may be saturated (where present) east of the Hamley Fault.

2.3.4.6 BRYANT CREEK AND PATA FORMATIONS

The Bryant Creek Formation is a mustard coloured limestone with a lower portion consisting of well - cemented, very fine sands and silts interbedded with clays and a thicker upper portion consisting of calcarenite (Lukasik and James 1998). The Pata Formation consists of a yellow to reddish orange, fine calcarenite with muddy bands. The contact between the Bryant Creek Formation and Pata Formation is not always well defined (Lukasik and James 1998).

The Pata Formation forms generally a poor aquifer due to the presence of marl. In the model domain, it is saturated east of the Hamley Fault.

2.3.5 BOOKPURNONG FORMATION

The Bookpurnong Formation (observed east of the Hamley Fault) forms part of an aquitard that mostly separates the Loxton Sands and the underlying Murray Group. The Bookpurnong Beds are a sequence of poorly consolidated and fossiliferous marls, silts and sands which unconformably to disconformably overlie the Miocene Murray Group. The sediments are locally micaceous, glauconitic and/or carbonaceous and contain abundant molluscs, echinoids, bryozoans and foraminifera (McLaren *et al.* 2011). The Bookpurnong Formation may be differentiated from the Lower Loxton Clays and Shells (grey in colour) on the basis of colour (light to dark khaki), the presence of glauconite, and increased plasticity (AWE 2011a).

The Bookpurnong Formation is often combined conceptually with the overlying Loxton Clay and Loxton Shells members of the geologic Loxton Sands Formation. Together they form a single Loxton-Bookpurnong Aquitard confining the Murray Group aquifer system (AWE 2011a). This unit underlies the majority of the Murray erosion trench east of the fault.

2.3.6 LOXTON SANDS FORMATION

The Loxton Sands were initially defined by Brown and Stephenson (1991) as a single sand sheet, deposited in a complex strandplain environment, including shallow to marginal marine, estuarine and fluvial facies. The composite unit was defined to include the Loxton Sand, Parilla Sand and Diapur Sandstone.

The sediments of the Loxton Sands are generally unfossiliferous and dominantly fine to coarse, well-sorted yellow-brown quartz sand that is generally unconsolidated to weakly-cemented, with minor silt, clay and pebble conglomerates (Brown 1989).

In general, the most permeable coarse grained (and frequently unsaturated sands, Upper Loxton Sand member) occurs at the top of the sequence and the least permeable fine sands (the Lower Loxton Sand member) at the base of the succession (Yan *et. al* 2005). These sands grade to a low permeability silty clay and shell facies towards the base, referred to as the Lower Loxton Clay and Shells member (AWE 2011).

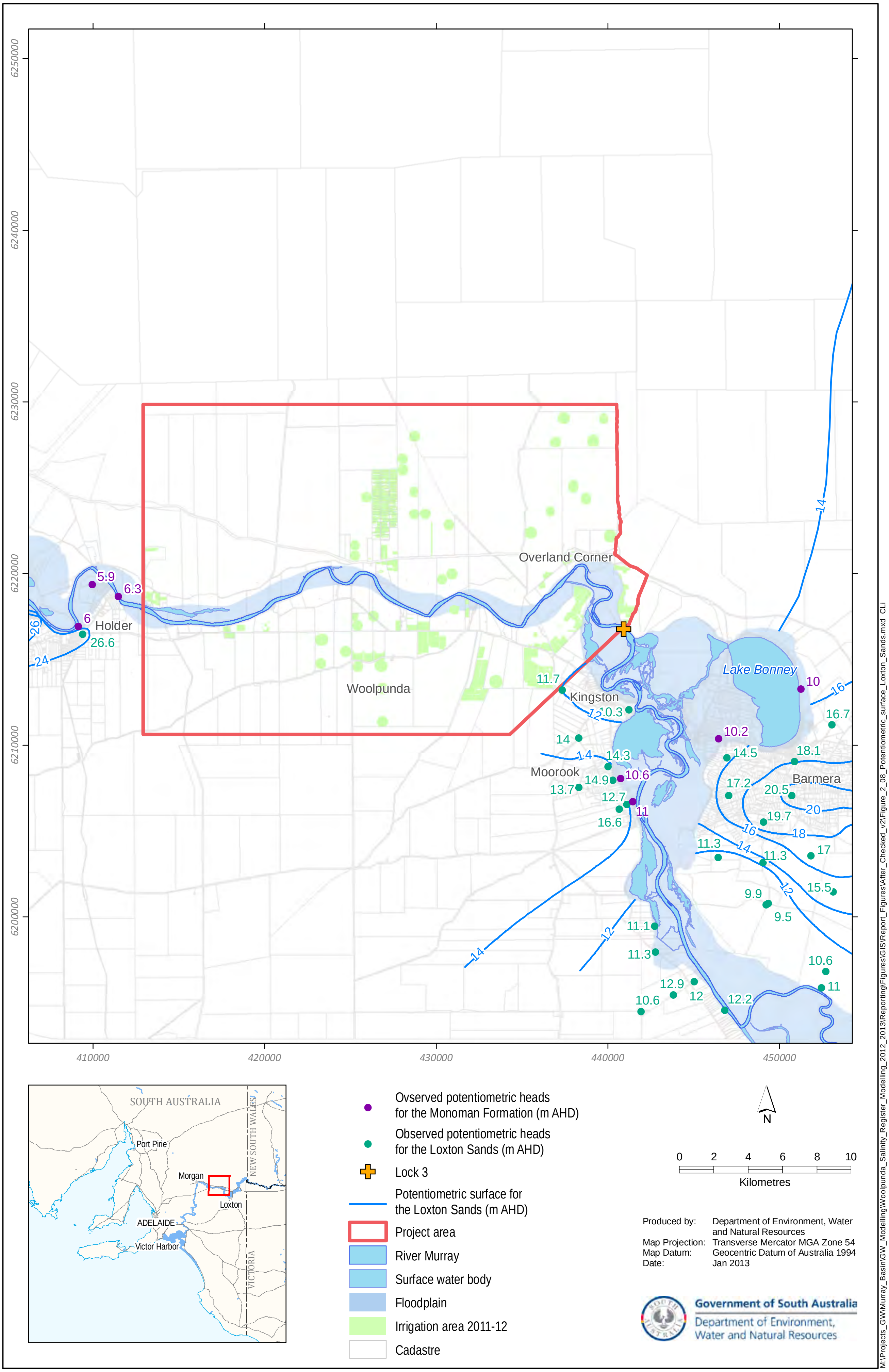

Figure 2.8. Potentiometric surface for the Loxton Sands and observed potentiometric heads for the Monoman Formation 2009 (After AWE 2013a)

The Loxton Sands Formation is unsaturated in the Woolpunda reach but acts as the regional watertable aquifer to the east of the Hamley Fault. The potentiometric surface for the Loxton Sands, in Figure 2.8, shows the influence of the River Murray and high recharge under the Berri-Barmera irrigation areas.

Horizontal hydraulic conductivity values from east of the Hamley Fault, in the Loxton-Bookpurnong area, range between 2 and 80 m/d with a median of 13 m/d (AWE, 2013a). This one and a half orders of magnitude variation of transmissivity and hydraulic conductivity is expected due to the variable nature of sediments that comprise the Loxton Sand Aquifer.

2.3.7 NORWEST BEND FORMATION

The Norwest Bend Formation is a partly cemented grey to yellow limestone and sand unit in the western Murray Basin between Overland Corner and Nildottie, where the Loxton Sands ridges are absent. The stratigraphic position of the Norwest Bend Formation has been the subject of some debate and recently Miranda *et al.* (2008) presented evidence to demonstrate that the unit is a lateral equivalent of the Loxton Sands, restricted to the far west of the Murray Basin in a fault-controlled estuarine system adjacent to the Mount Lofty Ranges. Hence the Formation is treated in this report as part of the Loxton Sands Formation. It is not saturated in the Woolpunda reach.

2.3.8 MONOMAN FORMATION

In the incised River Murray erosive trench, the alluvial infill deposit of the floodplain is the Monoman Sands. It consists of relatively clean, fine to coarse grained, fluvial sands deposited as point bar sands but may occasionally include minor clay and silt layers, and occasional lignite bands towards the base of section (Yan *et al.* 2005). It is commonly 4 to 10 m thick (but can be up to 25 m thick) and may be thin to absent abutting the highlands (AWE 2013a). Generally, the Monoman Formation is underlain by a remaining thickness of Upper Mannum Formation, but it may be in direct contact with the Lower Mannum Formation in an area between river kilometres 412 to 419.

The Monoman Formation forms a mostly confined aquifer. It is juxtaposed with the Loxton Sands Formation to the east of the Hamley Fault and with the Mannum Formation to the west of the fault, and is in hydraulic connection. As groundwater moves laterally towards the River Murray it either transfers to the Monoman Formation (west of the Hamley Fault in the floodplain), or directly discharges to the River at the base of the cliffs, east of the fault. Potentiometric head values observed in the Monoman Formation in 2009 are included in Figure 2.8 but no data are available within the project area.

Transmissivity values for the Monoman Formation in the Loxton-Bookpurnong area are variable and generally high, ranging from 30 to 3750 m^2/d with a median of 237 m^2/d (AWE 2013a). The corresponding median horizontal hydraulic conductivity is 47 m/day (AWE 2011a). Near Qualco, AWE (2011a) estimated hydraulic conductivities for two sites as 6.5 and 11 m/day. These hydraulic conductivities are higher than those for the Loxton Sands, presumably as a result of better sorting of grains during the reworking process (AWE 2013a).

Salinity data are presented in Figure 2.9 sourced from AWE (2013a) and additional data obtained from the Obswell database. Groundwater salinity ranges from 8190 to 28927 mg/L in the project area. The high variability is due to processes such as evapotranspiration and flow between the groundwater and river. Salinographs for the Monoman Formation in the project area are presented in Appendix C-2.

2.3.9 COONAMBIDGAL FORMATION

The Quaternary Coonambidgal Formation forms a local floodplain aquitard and confining bed which in most places overlies the Monoman Formation aquifer. The Coonambidgal Formation comprises clay and silts deposited during periods of episodic flooding (Brown and Stephenson 1991). This unit is commonly

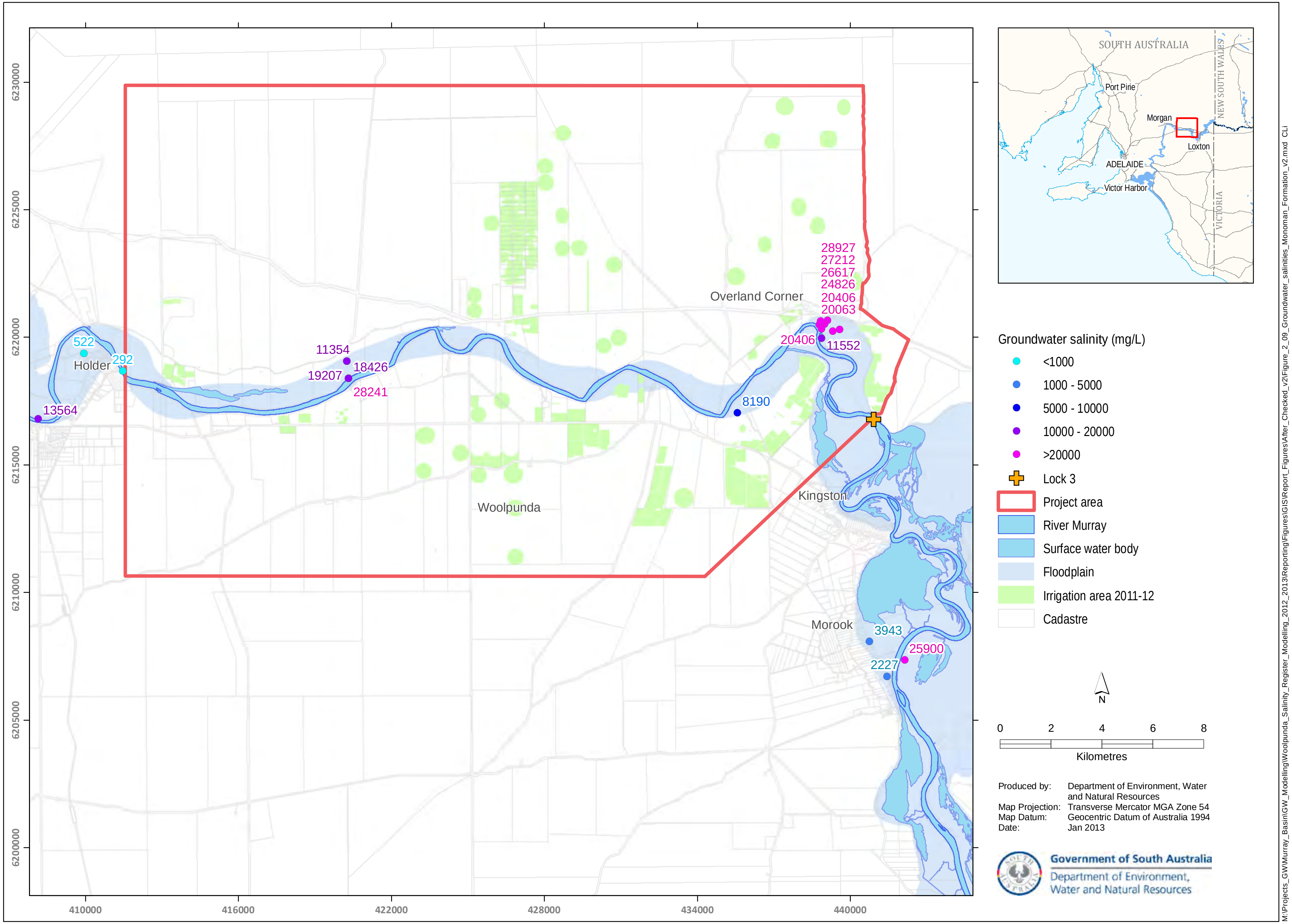

Figure 2.9. Groundwater salinities for the Monoman Formation (AWE 2013a)

4 to 5 m thick but can vary in thickness from 1 to 11 m, with the greater thickness observed adjacent to the highland (AWE 2013a). This unit has been re-worked in part by the meandering River Murray; the re-worked sediments can be more permeable.

2.3.10BLANCHETOWN CLAY FORMATION

The Blanchetown Clay Formation forms a discontinuous regional aquitard on the highland that can cause local perching of shallow groundwater and influence irrigation induced recharge rates. It is a thin lacustrine carbonate interpreted to represent an ephemeral hypersaline lake facies (McLaren et. al 2009). The unit is typically less than a few metres thick and consists of interlaminated and mixed calcite, dolomite, magnesite and clay beds.

2.3.11 WOORINEN FORMATION INCLUDING BAKARA CALCRETE

The Woorinen Formation is an aeolian red-brown fine to medium grained quartz sand with a dune structure (and therefore often variable thickness). The Bakara Calcrete is often described as white to pink, sometimes red calcrete and sand; the variability in colour presumably the result of white calcrete mixing with red-brown Woorinen Sand (AWE, 2013a).

2.4 GROUNDWATER FLOW AND INTERACTION BETWEEN AQUIFERS

Groundwater in the various units may interact both laterally and vertically with each other and with the River Murray. The rate of interaction is influenced by geological, hydrogeological and climate features as well as anthropogenic influences (e.g. irrigation).

The project area is a major discharge zone from the Renmark Group Aquifer, evidenced by groundwater heads, flow directions and chemistry (Telfer 1988). West of the Hamley Fault, the heads in the Renmark Group are 10 to 22 m higher than those in the Murray Group, inducing upward leakage that contributes to the maintenance of a prominent natural mound approximately 15 km south of the Woolpunda river reach, and another, less defined mound, to the north of the river in the Murray Group aquifer (Telfer 1988). At the mound centres, the head difference may be as low at 10 m, while below the floodplain, the head difference is 20 to 22 m. Vertical upward flow will preferentially occur where the intervening aquitards are thin (missing) or of comparatively higher hydraulic conductivity.

Another zone of upward leakage from the Renmark Group to the Murray Group is also present east of the Hamley Fault and south of Loxton (AWE 2011a), as evidenced by potentiometric head observations and salinity patterns in an area west of Loxton. However, the Murray Group accepts downward leakage from the Loxton Sands in some of the irrigation areas due to high heads in the irrigation mounds.

There is the potential for upward leakage into the floodplain throughout the area, both west and east of the Hamley Fault judging by differences in potentiometric heads between the Murray Group and the Monoman Formation. Flux to the floodplain from below is driven by the vertical hydraulic gradient between aquifers, and controlled by the vertical hydraulic conductivity and thickness of the separating aquitard. Lateral flux to the floodplain is dependent on horizontal head gradient, the thickness of the aquifer interface at the highland/floodplain boundary and also the hydraulic conductivity of the Formations.

2.5 GROUNDWATER LEVEL MONITORING

More than 200 observation wells are monitored within the project area, most of which monitor the Murray Group aquifer with a few which monitor the Renmark Group aquifer. A selection of 86 wells is presented in this report for comparison with model results. The wells are well distributed within the

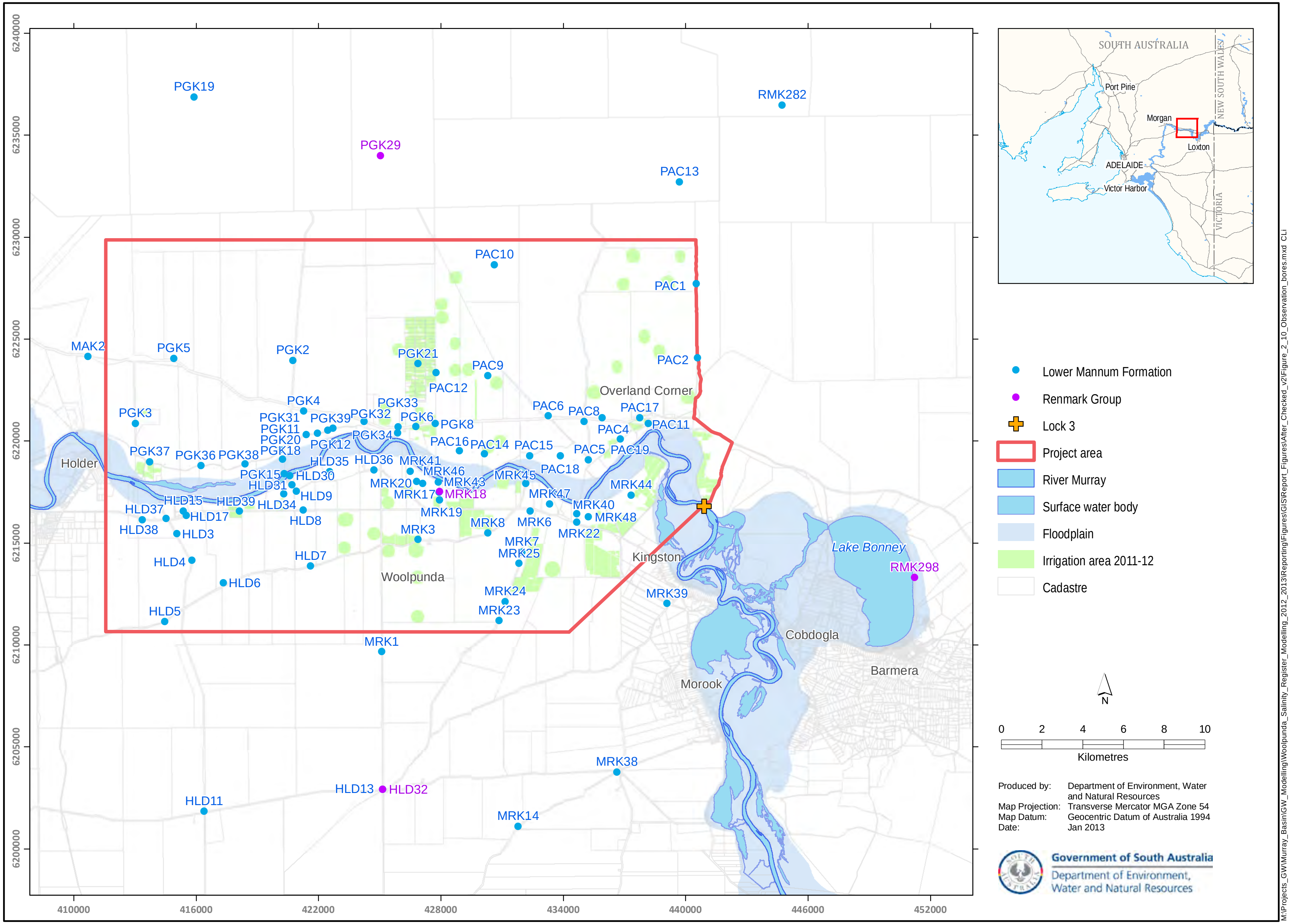

Figure 2.10. Observation well locations

project area and record reliable long-term historical observation data. If there are several nearby wells of similar trends and levels, a single well was chosen to represent them.

Obvious anomalous observations such as physically-impossible head levels are omitted. Water level data are sourced from the Obswell database. Hydrograph data are presented along with calibrated model results in Section 4. Observation well locations in the Woolpunda area are presented in Figure 2.10.

Most of the selected observation wells are in the Lower Mannum Formation and four are in the Renmark Group, as these are the major aquifers that contribute salt load to the River Murray in Woolpunda. No Monoman Formation hydrographs are used during the transient calibration process, as none of them contain reliable long-term historical observation data.

2.6 HYDROLOGY

This section describes data and information available on surface water features within the Woolpunda area which interact with groundwater flow. These include the River Murray, other surface water bodies, areal recharge, groundwater evapotranspiration and SIS pumping.

2.6.1 THE RIVER MURRAY

The River Murray floodplain acts as a groundwater sink in most of the modelled area. The modelled area lies between Lock 4 and Lock 2, where the river pool level is:

- 9.8 m AHD between Lock 4 and 3
- 6.1 m AHD between Lock 3 and 2

The Woolpunda reach is located between Lock 3 and 2, which were constructed in the late 1920s and early 1930s. River levels change over time, which alter the magnitude of the groundwater gradient between the River Murray and the groundwater and hence the flux. However, changes in gradient due to changes in river level are minimal during normal and low flow conditions, when compared to the driving gradients from the Woolpunda groundwater mounds: the average head difference between river level and pool level since 2000 ranges from 0.1 m to 0.5 m at different sites.

Flux to the River Murray from groundwater also depends on the hydraulic resistance between river and aquifer. River bed sediments can provide resistance to flow, as can the hydraulic conductivity of the geological unit that the river is connected to. No field measurements of riverbed conductance have been made in the project area.

Backwaters may also influence river salinity by adding saline surface water during flood recessions.

Additional information on the relationship between the River Murray and groundwater is provided by the NanoTEM geophysical surveys and Run-of-River surveys, as described below.

2.6.1.1 NANOTEM

NanoTEM surveys estimate the electrical resistivity of sediments below the river bed. Low electrical resistivity correlates with potentially high pore water salinities or presence of clay in the subsurface, and suggests a gaining stream reach where high-salinity groundwater flows into the River Murray. High electrical resistivity corresponds to low pore water salinities, suggesting a losing stream reach where low-salinity river water flows into the aquifer. While clays influence the electrical resistivity, NanoTEM surveys have shown a good correlation between riverbed resistivity and salinity for the lower River Murray (Barrett *et al*. 2005; Telfer *et al*. 2005a; Tan *et al*. 2007).

Figure 2.11 shows NanoTEM data collected in 2004 for sediments immediately below the river bed (Telfer *et al.* 2005). By 2004, the SIS had been operational for 14 years and had lowered the watertable.

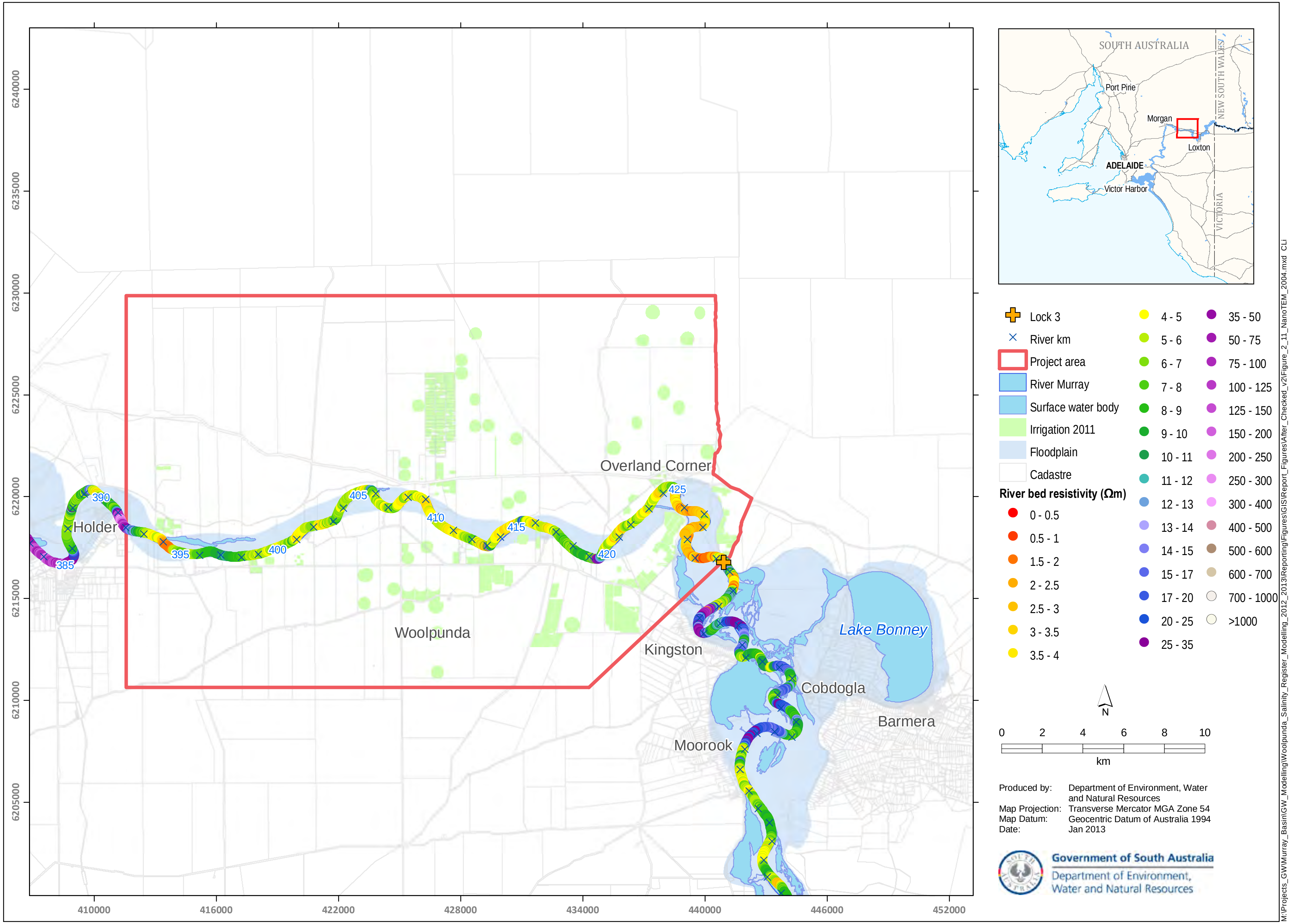

Figure 2.11. In-stream NanoTEM 2004 (Telfer *et al.* 2005)

The SIS is expected to influence the gradients between the River Murray and the Monoman Formation aquifer. Figure 2.11 indicates that most of the reach was still gaining in 2004, though the magnitude is believed to be lower than the pre-SIS period.

The river bed resistivity is noticeably lower (i.e. more saline) east of the SIS at Overland Corner, presumably due to the steep gradients between groundwater and the river below Lock 3 and also the absence of SIS in that area. Some of the reaches appear to have a lower river bed resistivity (i.e. are more saline) but care must be taken in interpretation as this is influenced by river depth. Groundwater normally exhibits decreasing resistivity (i.e. is more saline) with increasing depth beneath the river.

A subsequent 2012 NanoTEM survey shows a significant increase in resistivities (freshening) since 2004, indicating an effective SIS, which may have caused some freshwater lens development (AWE 2013b). The 2012 NanoTEM survey results are not presented here as the 2004 results are viewed as corresponding to more typical conditions; the 2012 results will be influenced by the severe drought years of 2005 – 2010 and the subsequent flood event.

2.6.1.2 RUN OF RIVER

Run-of-River (RoR) analysis results are presented in Figure 2.12. The Woolpunda reach spans river km 393.5 to 431.4 (Holder to Lock 3). There is a great deal of variation in the total salt load from survey to survey, but there is a clear declining trend for the Woolpunda reach.

RoR results can exhibit significant variation due to factors such as river and backwater levels. Consequently, any model that does not simulate changes in river and backwater level will not match all RoR observations.

Figure 2.12 shows a steep decline in salt loads starting in the early 1990s, apart from two high values in the mid-1990s which occurred after a series of floods. As the Woolpunda SIS was commissioned in 1990, this decline is attributed to the SIS.

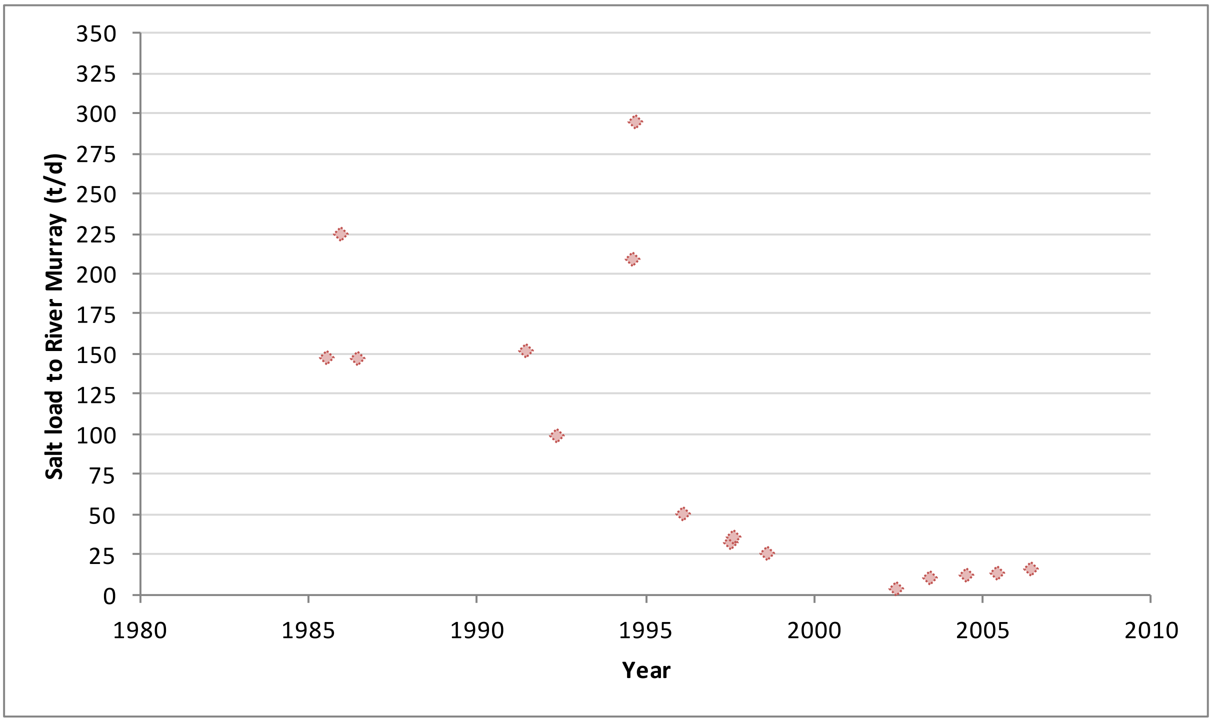

Figure 2.12 Salt load entering the River Murray from RoR Analysis (AWE 2011c)

2.6.1.3 IN-STREAM FIXED (TOROIDAL COIL) SALINITY STATIONS

Along the River Murray, salinity (electrical conductivity, EC of water) is monitored using “Toroidal Coil” stations, which provide continuous salinity data. Temporal EC data for a selected station or a set of stations may be analysed to derive relationships between flow and salinity. EC from selected pairs of stations combined with estimates of flow can also be used to estimate salt inflows, similar to RoR analyses.

Figure 2.13 shows the 95% percentile ECs (95% of in-stream salinities are below those on the vertical axis) for each decade. The impact of SIS is demonstrated by the noticeable decrease in trend since 1990 for the entire reach of Lock 9 to Morgan, with the most significant decreases occurring through the 1990s and 2000s between Lock 3 to Morgan due to the Woolpunda and Waikerie SIS (AWE 2012).

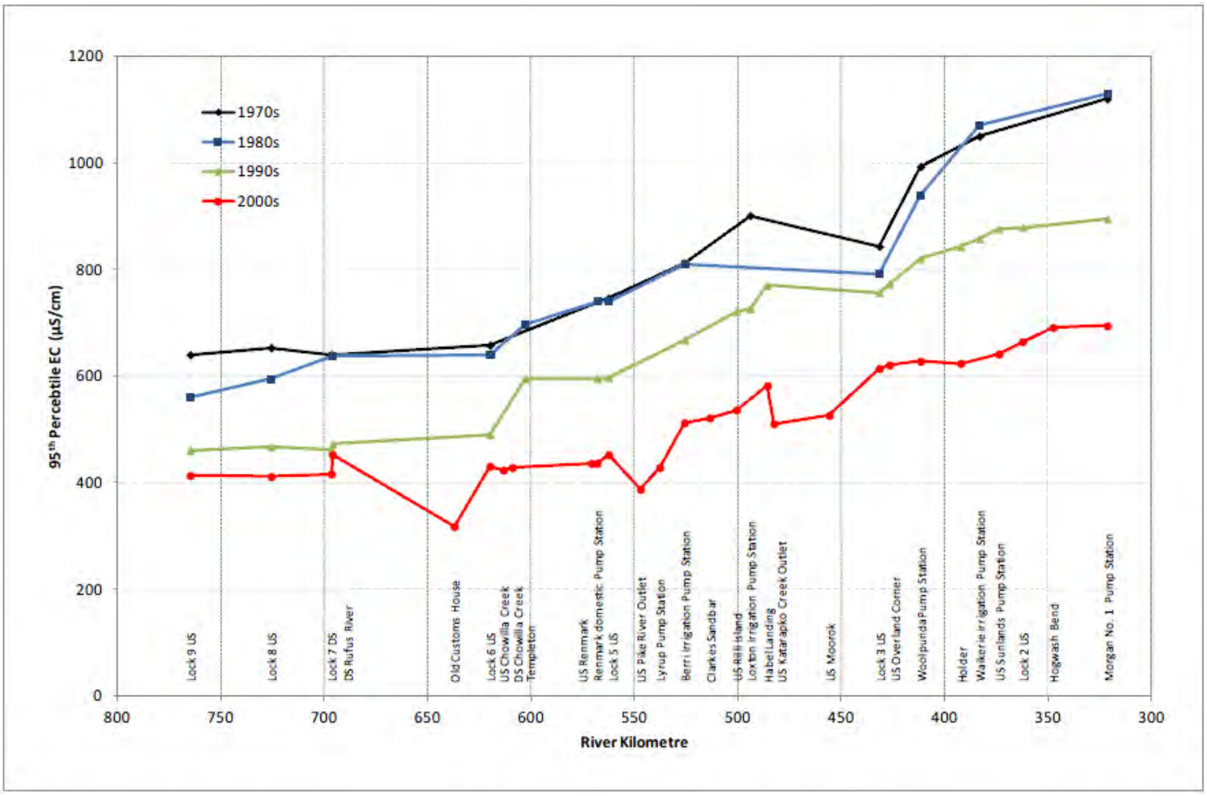

Figure 2.13 In-stream salinity 95 percentile versus river km for selected flows (AWE 2012)

2.6.2 SURFACE WATER BODIES

Surface water bodies may influence groundwater flows and river salinity by adding saline surface water during flood recessions. There are a number of wetlands and lagoons within the model domain. Some of these may have a significant but only temporary impact on salt loads to the River Murray. When their water level is high, they add additional salt load to the River Murray for a short period of time (Yan, Li and Woods 2012).

Surface water bodies that may be important for groundwater-surface water interaction and salt loads in the model domain include:

- Banrock Wetland
- Cobdogla Basin
- Lake Bonney
- Loveday Swamp
- Wachtels Lagoon
- Yarra River
- Yatco Lagoon

Their levels depend on the level of the River Murray, although Banrock Wetland is regulated. Bathymetry data are available for Banrock Wetland, Lake Bonney, Loveday Swamp, and Yatco Lagoon. Depth information is reported as part of the Wetlands Baseline Survey (SAMDBNRMB 2012).

2.6.3 RECHARGE

Areal recharge to groundwater in this region is derived from rainfall and irrigation root zone drainage.

2.6.3.1 DRYLAND RECHARGE

Prior to the clearance of native mallee vegetation on the highland, vertical recharge to the watertable aquifer resulting from rainfall infiltration is believed to have been as low as 0.07 to 0.1 mm/y (Allison *et al.* 1990). This is due to the dry climate and deep-rooted native vegetation.

Cook, Leaney & Miles (2004) estimated recharge at cleared mallee sites in South Australia to be one or two orders of magnitude greater than uncleared sites, up to 11 mm/y after 100 years. The recharge rate depends on soil properties, vegetation and climate. Zones and rates of estimated recharge in dryland areas including Woolpunda are given in Cook, Leaney & Miles (2004).

2.6.3.2 IRRIGATION DEVELOPMENT

Irrigation is mostly confined to highland areas both north and south of the river. DEWNR collated, summarised and verified irrigation data for the Woolpunda area, including changes in irrigation area over time and volume of water applied to crops (Vears 2013). The details are included as Appendix C-1. A brief summary is provided below.

Prior to the installation of electricity to power the Woolpunda SIS in 1988-89, little irrigation existed in the area (less than 500 ha). Once electricity was available, irrigation began to expand steadily from around 500 ha in 1988 to approximately 2000 ha in the late 1990s. This was followed by a significant boom of temporary pivot irrigation (annual plantings) from 2001 to 2006, increasing from 402 ha to 2802 ha (Vears 2013). Figures 2.14 and 2.15 show irrigation areas and their commencement years for permanent and temporary pivot irrigation respectively.

The Millennium Drought and subsequent reductions in water entitlements resulted in a contraction in the area of temporary pivot irrigation and by 2009, only 32 ha of pivot irrigation out of a total irrigated area of 2063 ha remained active. Since 2010, the temporary pivot irrigation areas have increased, to 1000 ha of a total 3036 ha. Whilst temporary pivot irrigation area fluctuated during the Millennium Drought, the area of permanent irrigation, which had increased during the 1990s to around 2000 ha, remained in production albeit with reduced water applied (Vears 2013).

The Woolpunda project area contains private irrigators who draw directly from the River Murray through pipelines. There has been no open channel infrastructure or irrigation trusts within the Woolpunda project area (Vears 2013).

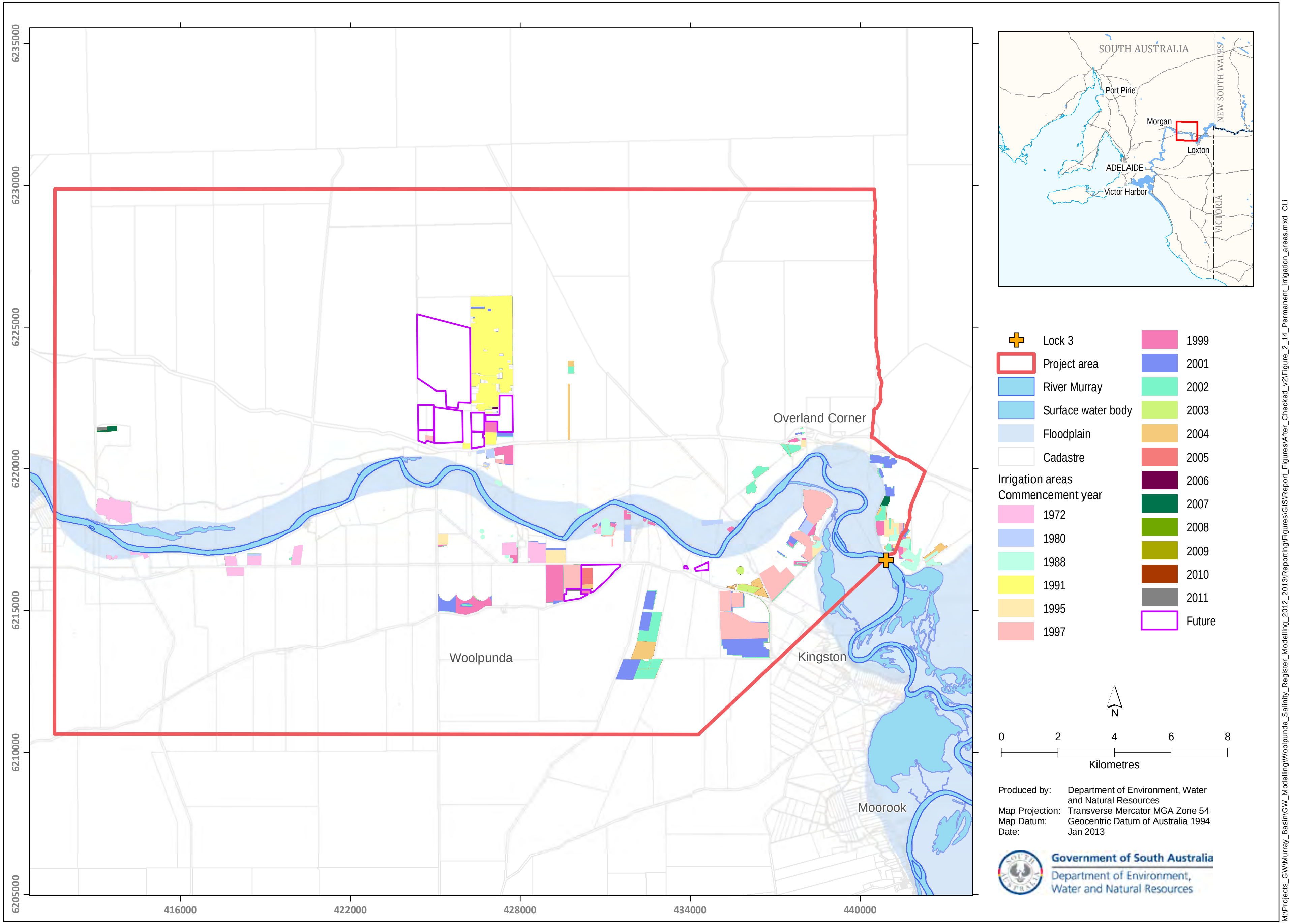

Figure 2.14. Permanent irrigation areas and year of commencement

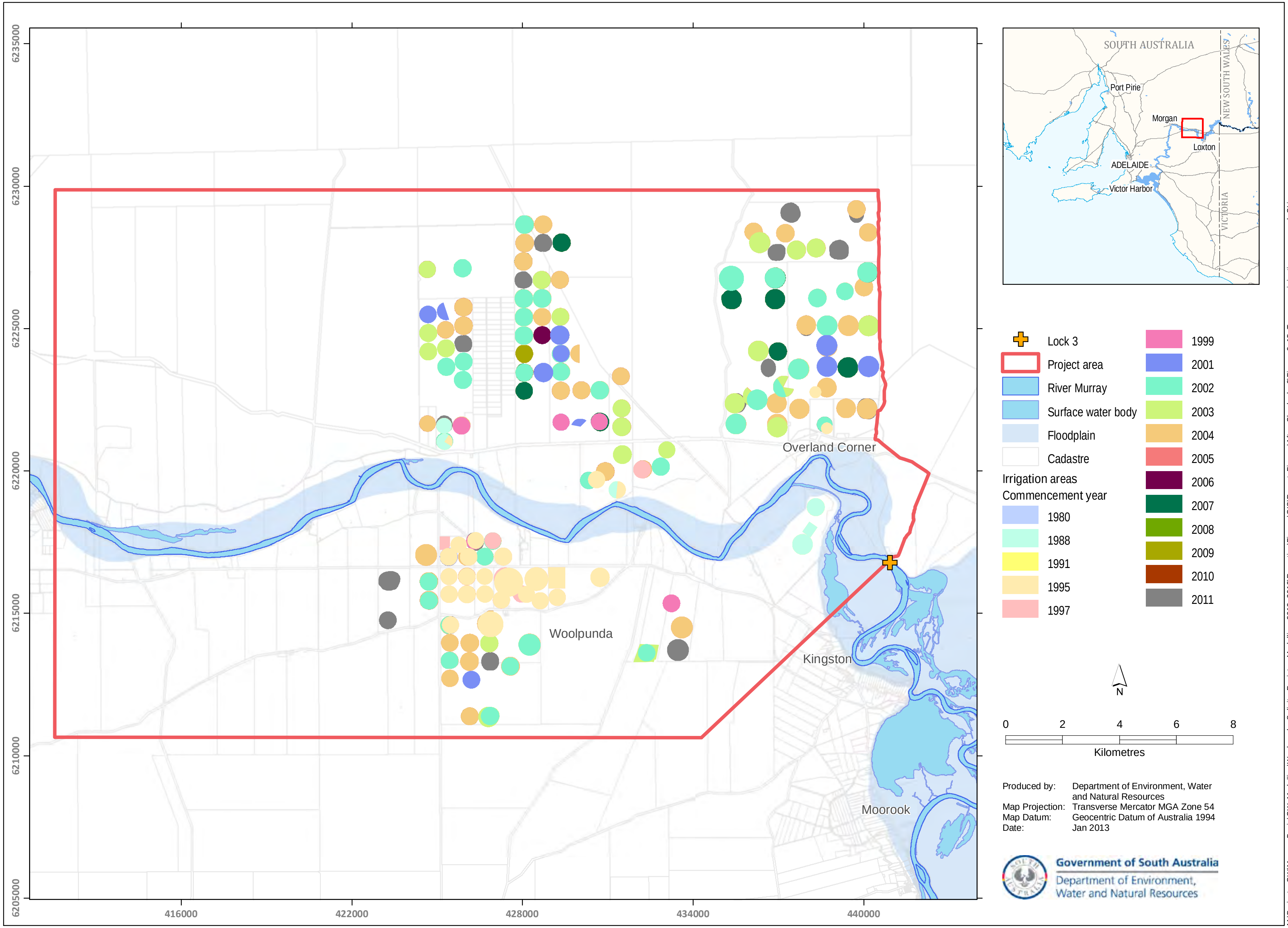

Figure 2.15. Temporary irrigation areas and year of commencement

Root zone drainage volumes can be estimated based on a water balance calculation which includes rainfall and irrigation application volumes, albeit with significant uncertainties. The latest estimates of root zone drainage for the Woolpunda irrigation areas are given in Appendix C-1.

The root zone drainage percolates into the unsaturated sediments and a proportion will remain in the unsaturated zone within the pore spaces. If there is a low hydraulic conductivity layer in the unsaturated zone, such as the Cadell/Bryant Creek Formation aquitard or Blanchetown Clay, a perched aquifer may form. However, no perched aquifers have been recorded in the Woolpunda region.

The root zone drainage takes time to percolate through the unsaturated zone to reach the watertable. Initially, the lag time under a new irrigation area is several years or decades, as the unsaturated sediments become wetter (Fuller *et al.* 2005; Telfer *et al*. 2012). Estimates of lag time under irrigation areas in the Woolpunda region are of the order of twenty to forty years, depending on location (Section 3.7.4.2).

As irrigation has only been recently introduced to Woolpunda, and lag times are thought to be large, only a small proportion of irrigation drainage may have reached the watertable so far. Unfortunately, there are few observation wells located within irrigation areas, and the available hydrographs are yet to show an increase over time. Hydrographs for groundwater monitoring sites PGK021 and PAC012 (see Section 4 for hydrographs) for Jubilee Almonds, one of the earliest irrigated areas (circa 1990), show no indication of groundwater recharge to 1999. In fact the hydrograph for PAC012 indicate a small decline in ground water levels to 2000 when monitoring ceased (AWE, 2013a). An additional monitoring point was obtained for PAC012 (SA Water) in February 2013 and suggests that this decline in groundwater levels has continued since regular monitoring ceased in 2000.

As the root zone drainage starts to reach the watertable, potentiometric heads in the Murray Group will increase.

Irrigation within the model domain but outside the project area has not been included. This is primarily the Berri-Barmera and the Pyap to Kingston regions. As the watertable lies within the Loxton Sands in these regions, it is presumed that the additional recharge due to irrigation there will have minimal impact on the Murray Group aquifer on the other side of the Hamley Fault at Woolpunda. Figure 2.5 shows the potentiometric head for the Murray Group in 2009: there is no sign of irrigation-induced groundwater mounds outside the project area that are likely to significantly influence potentiometric heads within the project area.

2.6.3.3 DRAINS AND DRAINAGE WELLS

No drains or drainage wells are known in the project area.

2.6.4 GROUNDWATER EVAPOTRANSPIRATION

Groundwater evapotranspiration (ET) combines two processes: evaporation of water from groundwater close to the ground surface and transpiration from plants that use groundwater. Groundwater ET varies with depth to groundwater, climate, soil type, vegetation type and groundwater salinity (as plants preferentially use low-salinity sources of water). In the project area, groundwater ET occurs mainly on the floodplain, as elsewhere the groundwater is too far below the ground surface.

The Climatic Atlas of Australia (Bureau of Meteorology 2001) distinguishes between areal actual ET, and areal potential ET: “Areal actual ET is the ET that actually takes place, under the condition of existing water supply, from an area so large that the effects of any upwind boundary transitions are negligible and local variations are integrated to an areal average. For example, this represents the evapotranspiration which would occur over a large area of land under existing (mean) rainfall conditions. Areal potential ET is the ET that would take place, under the condition of unlimited water supply, from an area so large that the effects of any upwind boundary transitions are negligible and local variations are integrated to an areal average. For example, this represents the evapotranspiration which would occur over a very large wetland or large irrigated area, with a never-ending water inflow. A 'large' area is defined as an area greater than one square kilometre." For the Woolpunda region, the annual average areal actual ET rate is between 200 and 300 mm/y while annual average areal potential ET is between 1000 and 1100 mm/y (Bureau of Meteorology 2013b).

There are no known field estimates of actual groundwater ET within the project area. Doody *et al.* (2009) conducted a study at a Bookpurnong floodplain where groundwater ET was estimated from 208 ± 135 mm near the river, to 32 ± 30 mm further from the river over 241 days, giving an actual groundwater ET range of 48 to 315 mm/y, although the uncertainty is large compared to these values.

An unpublished study (K Holland, CSIRO, 2013, pers. comm.) measured an actual groundwater ET of 196 mm/y for the fringing river woodland of River Red Gum, Black Box and River Cooba. In the Loxton–Bookpurnong floodplain areas, the woodland generally covers 30–40% of the total floodplain, suggesting an overall floodplain average groundwater ET of ~60 to 80 mm/y.

2.6.5 CLIFF SEEPAGE

Cliff seepage has not been observed in the Woolpunda area.

2.7 GROUNDWATER PUMPING

2.7.1 GROUNDWATER ALLOCATION AND USE

Apart from the SIS, no groundwater is pumped in the modelled area as the groundwater is too saline for irrigation, stock, or potable use.

2.7.2 SALT INTERCEPTION SCHEMES

The purpose of the Woolpunda SIS (Figure 2.16) is to reduce in-stream salt loads along a 33 km kilometre reach between Holder and Overland Corner (river kilometres 393 and 426 respectively) by reducing midpoint groundwater heads to pool level, thereby flattening or slightly reversing the horizontal groundwater gradients. This is achieved by pumping groundwater to maintain a potentiometric head of approximately river pool level at the midpoint observation wells. The original quantitative aim of the scheme was to provide a mean improvement (decrease in salinity) at Morgan of 47 EC units (an EC unit is equivalent to 1 µS/cm electrical conductivity). The scheme was designed to intercept 95% of the groundwater salt inflow to river, estimated to be 180t/d (AWE 2007).

The initial Woolpunda wellfield design consisted of 47 production wells spaced approximately 1200 m apart and located 600 m inland from the edge of the river valley along both banks of the River Murray (AWE 2007a). Detailed design and the Approval Submission were completed in 1987. Eventually 49 wells were constructed between 1989 and 1990.

The Woolpunda scheme commenced operation in July 1990 and was commissioned in four stages as additional wells were brought into production over the three years. During the commissioning phase, individual wells were operated at rates in excess of their long-term design rates for six to twelve months, but without exceeding the total pipeline and pumping station design capacities (AWE 2007a).

The scheme was considered to be fully operational at the start of 1994 and was operated at a rate of 190 L/s. In 1995, the total scheme flow was increased to 210 L/s (i.e. 1.4 times the long-term pumping rate) to accelerate the salt interception.

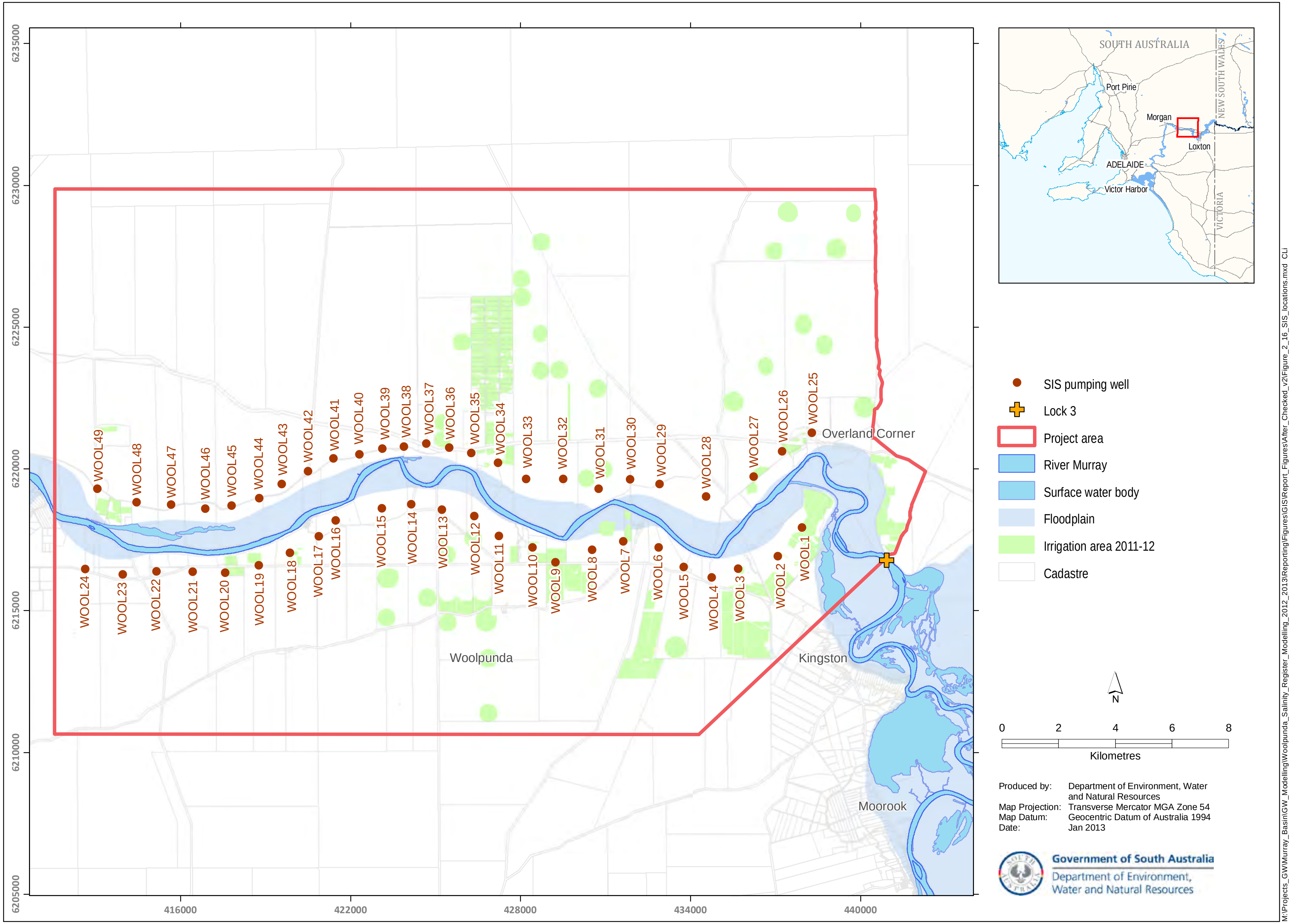

Figure 2.16. SIS pumping well locations

A performance review based on in-stream salinity measurements, was undertaken in 2000 (AWE 2000). Subsequently individual well flows were progressively decreased as target water levels were met in most areas.

Since 2004, almost half of the scheme production wells have operated on night-tariff power, while the remainder are operated 24 hours per day. Scheme flow during this period has averaged around 160 L/s, which compares well to the design long-term pumping rate of 150 L/s.

The saline groundwater is pumped from the unconfined Mannum Formation aquifer (including both the Upper and Lower Mannum Formations) via a collector pipeline to the Stockyard Plain Disposal Basin.

2.8 CONCEPTUAL MODEL

2.8.1 OVERVIEW

The Woolpunda hydrogeological conceptual model is presented in Figure 2.17. It illustrates the major aquifers and confining layers, recharge and discharge process and the interactions between these units and with surface water features. The conceptual model is based on outcomes from the analysis of hydrogeological data from the Five-Year Review process that is detailed in the previous sections.

The stratigraphy of the Woolpunda model area consists of a series of Quaternary and Tertiary sediments underlain by basement. The Hamley Fault passes through the model domain, dividing it into two hydrogeological regions. The River Murray channel is incised into the upper sediments.

The principal hydrostratigraphic sequence in the Woolpunda region consists of the following formations, in order of increasing depth.

The Woorinen Formation and Blanchetown Clay are unsaturated throughout the model domain and although perched water tables may occur locally beneath irrigation districts this is not documented and has not been incorporated into the model.

The Hamley Fault is a major regional feature that extends north-east to south-west at Overland Corner and influences both the geology and groundwater flow paths within the study area. The majority of the Woolpunda study area is located on the up-lifted western side of the fault so that on the highland, the water table resides within the Mannum Formation Aquifer however; to the east, it resides within the Loxton Sands Aquifer. At Overland Corner the ‘draping’ of sediments over the fault and the position of the Loxton Clay to the east, may limit the lateral connection between aquifers at this location. As a result, the following Formations, in order of increasing depth, are modelled as unsaturated units west of the Hamley Fault and as saturated units to the east:

- Upper Loxton Sand including the Northwest Bend Formation (aquifer)
- Loxton Clay and Bookpurnong Formation (aquitard)
- Upper Formations of the Murray Group, i.e. the Pata, Bryant Creek, Glenforslan and Finniss Formations (aquitards and lower-yielding aquifers).

Formations which are saturated throughout the model domain:

- Upper Mannum Formation (low-yielding aquifer)
- Lower Mannum Formation (aquifer)
- Ettrick Formation (aquitard)
- Renmark Group (aquifer)
- Basement Rock.

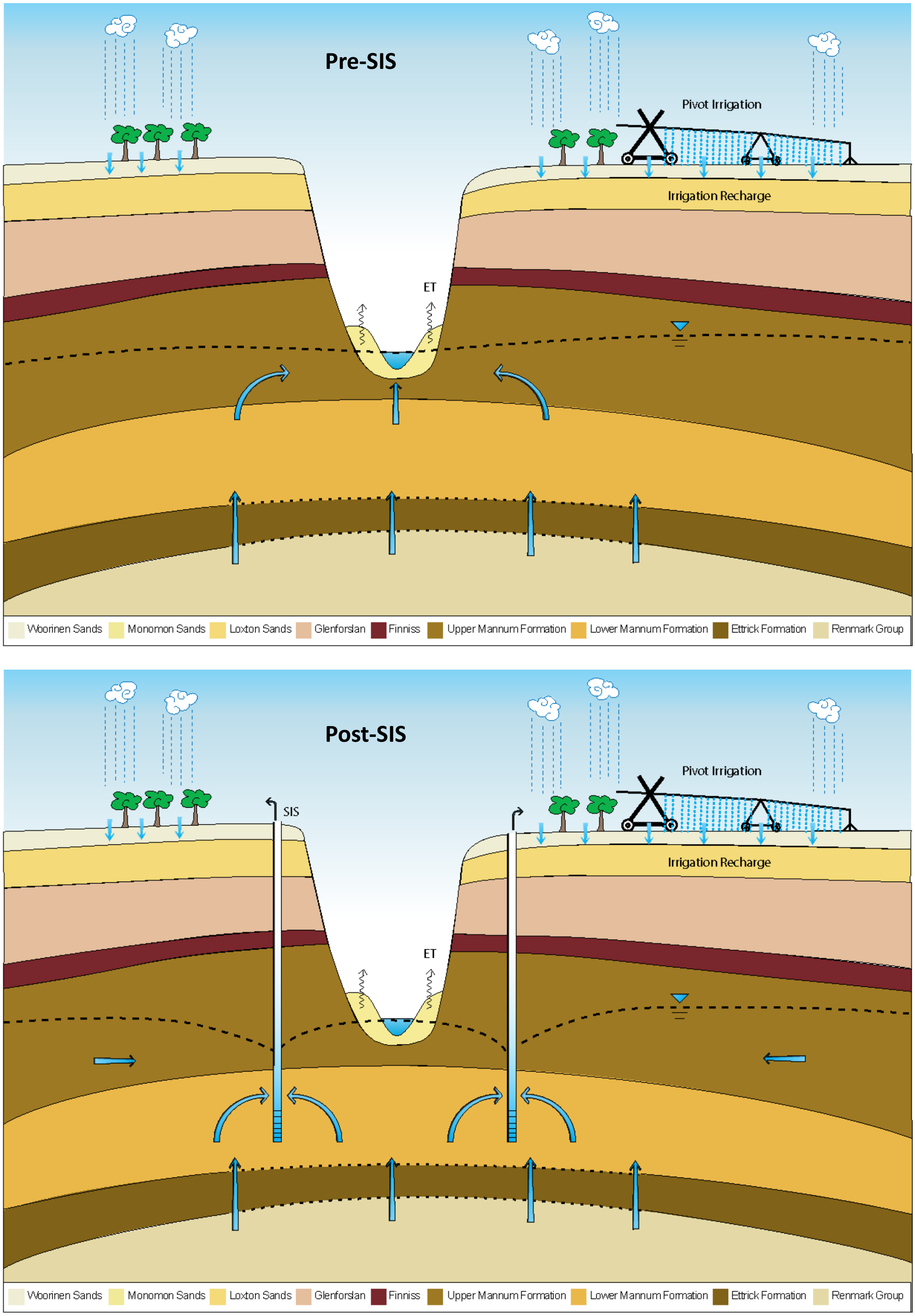

Figure 2.17. Woolpunda hydrogeological conceptual model

The River Murray has carved a valley ('eroded river trench') through the landscape. On the floodplain the Coonambidgal Formation (aquitard) overlies the Monoman Formation (aquifer). To the west of the Hamley Fault the Monoman Formation is hydraulically connected to the Mannum Formation Aquifer however, to the east it is connected to the Loxton Sands aquifer.

The potentiometric head in the Monoman Formation aquifer responds to short-term fluctuations in river level and its backwaters. Due to the shallow watertable in the floodplain, the Monoman Formation aquifer is also influenced by ET from groundwater. The river and other surface water bodies (such as Yarra Creek and Banrock Lagoon) interact with the groundwater system.

Regionally, the dominant direction of lateral groundwater flow is from east to west, as driven by distant recharge sources (Barnett 1991; Yan *et al.* 2001). However, regional groundwater flow paths are modified and controlled by structural features within the Woolpunda reach. To the west of the Hamley Fault, a major feature of potentiometric data from the Mannum Formation is the occurrence of two groundwater mounds to the north and south of the River Murray. These mounds are naturally occurring as the result of upward leakage from the Renmark Group and are driven by head differences between the aquifers. Both the Renmark Group and the Ettrick Formation (which forms the aquitard between the Renmark and Murray Groups) thin to the west of the Hamley Fault. It is suggested that the thinning of these units and a localised zone of high vertical hydraulic conductivity within the Ettrick Formation facilitate the upwelling of groundwater from the Renmark Group to the Murray Group. Groundwater mounds in the Murray Group aquifer also influence lateral flow paths within the Woolpunda reach. Groundwater heads at the centre of the mounds are at an elevation of approximately 22 m AHD to the north and 17 m AHD to the south, well above the 6.1 m AHD pool level of the River Murray. This gradient drives groundwater flow towards the floodplain so that groundwater discharges to the Monoman Formation and then to the River Murray. As the regional groundwater is highly saline, approximately 200 t/d of salt is added to the Murray along the Woolpunda reach under natural conditions.

To mitigate the salt load impacts of the Woolpunda groundwater mound, a Salt Interception Scheme was commissioned in 1990. Production wells within the Woolpunda SIS target the Mannum Formation and intercept discharge flux from this aquifer before it enters the floodplain aquifer (Monoman Formation) and/or the River Murray. The aim of pumping from this aquifer is to reduce midpoint groundwater heads to pool level, thereby flattening or reversing (slightly) horizontal groundwater gradients and the pattern of discharge towards the floodplain. The diverted saline groundwater from Woolpunda is discharged to the Stockyard Plain Disposal Basin, west of the model domain. There are no other groundwater extractions in the area as the groundwater is too saline for crop irrigation, stock or potable use.

Within the study area recharge of the groundwater system occurs via rainfall and irrigation. Rainfall recharge is low due to the dry climate and the presence of water-efficient mallee vegetation, with an estimated recharge rate of 0.1 mm/y (Cook, Leaney and Miles 2004). Land clearance increases root zone drainage by roughly two orders of magnitude, but the time lag between clearance and recharge to the watertable is of the order of decades in the Woolpunda area (Cook, Leaney and Miles 2004) so the additional water is yet to fully impact the hydrogeology.

Little irrigation occurred at Woolpunda prior to the construction of the SIS (Vears 2013). Since then, irrigation has expanded with some permanent irrigation and some temporary pivot irrigation. Irrigation will significantly increase root zone drainage and hence aquifer recharge. Calculation of lag times between the start of irrigation and aquifer recharge suggests that little of the additional drainage has yet reached the watertable. This is supported by the hydrographs available in or near the irrigated areas which show no increase over time. This means that while the irrigation areas have little altered recharge to date, there may be substantial impacts in the future.

There is no irrigation drainage infrastructure in the project area, unlike adjacent irrigation areas. Substantial irrigation has occurred outside the project area but within the model domain to the east: this is neglected as it is not anticipated to substantially affect the potentiometric head in the Mannum Formation at Woolpunda.

Groundwater salinity may change over time due to a number of processes. Near the River Murray, it may decrease due to mixing with river floodwaters from losing reaches and overbank flow. SIS pumping may also change gaining reaches of the river to losing reaches, inducing freshwater flow into floodplain aquifer and decreasing the salinity of groundwater. Groundwater salinity may also decrease in aquifers where significant volumes of low salinity irrigation return water mix with the native saline groundwater. Finally, where the watertable lies close to the ground surface, groundwater salinity may increase due to groundwater evapoconcentration.

2.8.2 PATHWAYS FOR SALT TO THE RIVER MURRAY

Under natural conditions before river regulation and irrigation, there would have been significant flux from the Monoman Formation to the River Murray driven by lateral and vertical head gradients. In any areas where the head in the floodplain was below river level due to ET, there would have been a small flux from the River Murray into the Monoman Formation.

Locks and weirs were constructed on the River Murray in the 1920s and 1930s to regulate the flow. These changed the river level and hence local groundwater gradients and fluxes to and from the river. Fluxes to and from the river were changed further by the commissioning of the Woolpunda SIS in 1990. This pumping may change gaining reaches of river to losing reaches, inducing freshwater flow into floodplain groundwater. Saline groundwater now enters the River Murray by the following mechanisms in the Woolpunda area:

West of the Hamley Fault:

- Direct inflow from the Monoman Formation that acts as a conduit for lateral flow from the Murray Group
- Upward leakage from the underlying Renmark Group via the Murray Group/Monoman Formation
- Discharge during and after periods of flooding from the Monoman Formation, localised hypersaline lakes (salinas) and minimal mobilised salt from the unsaturated zone.

East of the Hamley Fault (after AWE 2011a):

- Direct inflow from just below the watertable in the Loxton Sand aquifer via the Monoman Formation or a seepage face
- Via the Murray Group, from the Loxton Sands Formation down to the Pata/Glenforslan (and in places, potentially the Upper Mannum Formation) and up beneath the floodplain.
- Regional upward flow from the Renmark Group via the Murray Group and Monoman/Loxton Sands Formation
- Discharge during and after periods of flooding from the Monoman Formation, localised hypersaline lakes (salinas) and minimal mobilised salt from the unsaturated zone (Telfer *et al*. 2012).

3 MODEL CONSTRUCTION

The purpose of this model is to estimate groundwater salt loads entering the River Murray from the Woolpunda area for the Salinity Registers for different accountable actions (see Section 1.1 for the policy background). The model provides salt load estimates under a range of past and future land and water use conditions.

The estimation of future impacts due to climate sequences, such as changes in river level due to flood events, are not required for the Salinity Register.

3.1 MODFLOW AND VISUAL MODFLOW

MODFLOW-2000 was selected as the numerical code for the Woolpunda model. It was chosen for reasons of reliability and consistency, as it is the industry standard groundwater flow code and the other South Australian models for the Salinity Register are also MODFLOW-2000 models. It is a three-dimensional finite difference code developed by the US Geological Survey (McDonald and Harbaugh 1988). The choice of code constrains the types of flow processes that can be simulated. For example, the standard version of MODFLOW-2000 simulates flow exclusively within the saturated zone.

Groundwater flow is simulated but solute transport is not included in this project. Salt load is calculated from modelled groundwater fluxes, multiplied by groundwater salinity values specified along river reaches (Section 3.8). This is a simplification of the hydrogeological conceptual model, as it omits groundwater salinity changes due to mixing of irrigation and surface waters with groundwater.

It is currently judged that the substantial additional effort required to simulate the omitted processes of unsaturated zone flow and solute transport would result in only a minor improvement in model accuracy. This is consistent with the other numerical models used for Salinity Register entries.

MODFLOW's PCG2 solver is used for all steady-state and transient modelling runs. The convergence criteria are set to 0.001 m for the maximum absolute change in head (HCLOSE) and 0.01 m^3/d for the maximum absolute change in residual (RCLOSE). This proved to be computationally efficient whilst retaining sufficient accuracy (i.e. percentage discrepancy in the water balance was much less than 1% for all simulation periods).

Visual MODFLOW version 2011 was selected as a pre- and post-processor platform for quick generation of data files for MODFLOW. It is distributed by Schlumberger Water Services. It was used to generate MODFLOW model grids, boundary conditions, and zones for aquifer hydraulic parameters. The software was also used to set model options, to run the model and to obtain output results.

3.2 MODEL DOMAIN AND GRID

The model domain simulates an area 45.8 km east–west by 49.8 km north–south. The domain spans the River Murray from downstream of river kilometre 460 south of Berri, to river kilometre 386 near Holder. This region includes the Woolpunda SIS and also the reach of the proposed Overland Corner SIS (the latter is not simulated). Lake Bonney lies within the eastern part of the model. The bounding GDA 1994 coordinates of the model domain are E408300 N6198900 in the south-west and E454100 N6248700 in the north-east. The entire model domain is shown in Figure 3.1.

The domain is larger than the study area, which is consistent with good modelling practice, as the model domain boundaries should be set at a sufficient distance that they should not be influenced by changes in the behaviour of the aquifer system in the study area over the modelled time period.

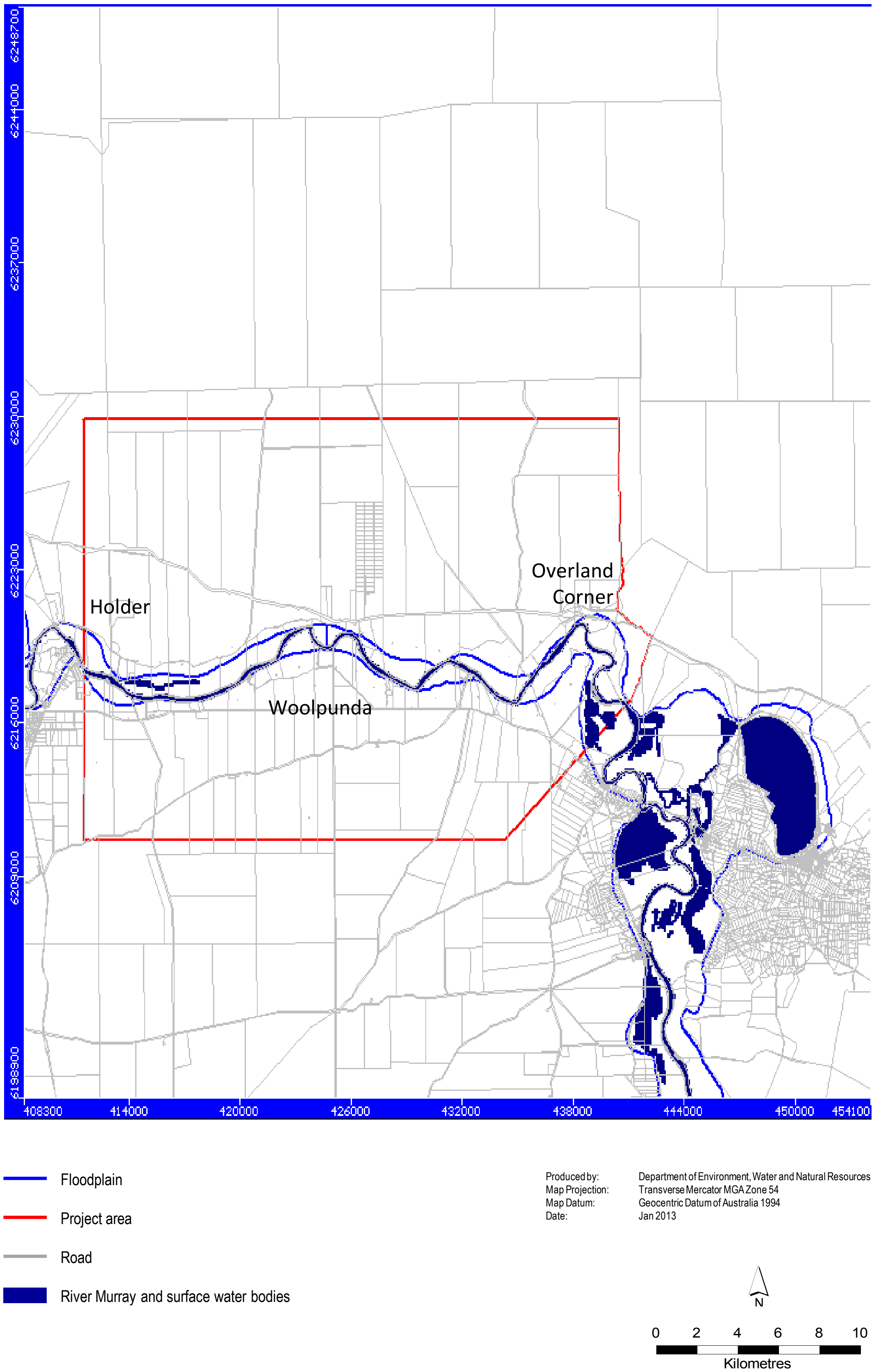

Figure 3.1. Regional model domain

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The northern, southern and eastern model domain boundaries fulfil this criterion, but the western boundary lies close to the study area. The western boundary is set at a location between Woolpunda and Waikerie where the dominating hydrogeological conditions and drivers change.

At Woolpunda, the watertable lies within the Upper Mannum Formation (AWE 2007a) and head gradients are driven by a groundwater mound caused by upward leakage from the Renmark Group while to the west at Waikerie, the watertable lies within or above the Glenforslan aquifer and head gradients are dominated by groundwater mounds induced by downwards drainage from irrigation (Yan, Li and Woods 2012).

It is reasonable to adopt a model boundary close to the area of interest only if:

(i) stresses from outside the domain are unlikely to affect potentiometric head within the model domain
(ii) impacts of stresses within the model domain are not compromised by the boundary conditions.

To determine this, hydrographs were examined of wells lying within the study area close to the model's western boundary. PGK037, an SIS midpoint well to the north of the river, shows a steady decline since the Woolpunda SIS was commissioned in 1990 but there is no clear additional response to the commencement of the Waikerie SIS to the west in 1992. Regional well PGK003 is also to the north of the river but is further away from the SIS wells: its hydrograph shows little change over the monitored period 1982 to 1996. South of the river, HLD037 has declined steadily since 1990, with no steeper decline after 1992. A simulation conducted with the 2005 accredited model (Rural Solutions 2005; Aquaterra 2007) showed that the Woolpunda SIS had negligible impact on salt loads at Waikerie. Based on this evidence, the position of the western boundary is considered reasonable.

The grid is orientated north–south. The rectangular model grid (Figure 3.2) is divided into 458 columns, 498 rows and four layers, resulting in 912 336 finite difference cells. All of the cells have a uniform extent of 100 × 100 m. The objective of using a 100 x 100 m grid is to provide a sufficient resolution for evaluating fluxes to the River Murray while minimising computational times. Cross-sections of the model grid are shown in Figures 3.3 and 3.4.

3.3 MODEL INITIAL CONDITIONS AND STRESS PERIODS

A steady-state model represents the region after the construction of the river locks (i.e. post-regulation) but before the start of the SIS or irrigation. It is simulated as the first stress period of the transient models and provides the initial conditions for the transient simulation. As a steady-state model, it assumes that the potentiometric head is in equilibrium with the boundary conditions. This is a reasonable assumption for the regional flow boundary conditions, but is more approximate for the regulated river levels. In practice, it would take some time after the installation of the locks for the head to equilibrate, but it is presumed that the impact of this on salt loads to the river has been negligible in recent decades.

Transient calibrated models are used to simulate the period from 1920 to 2113, covering both the historical calibration period (1920 to 2012) and future prediction period (2013 to 2113). A total of 101 stress periods are included in these models (Appendix B).

To reduce computational effort, the stress periods of the transient models are up to 20 years in length at the beginning of the simulation, based on the frequency of available irrigation information. Between 1991 and 2012, the models have shorter half-year stress periods to simulate SIS pumping more accurately. Each stress period of the transient models has a time step multiplier of 1.2 and 10 time steps per stress period.

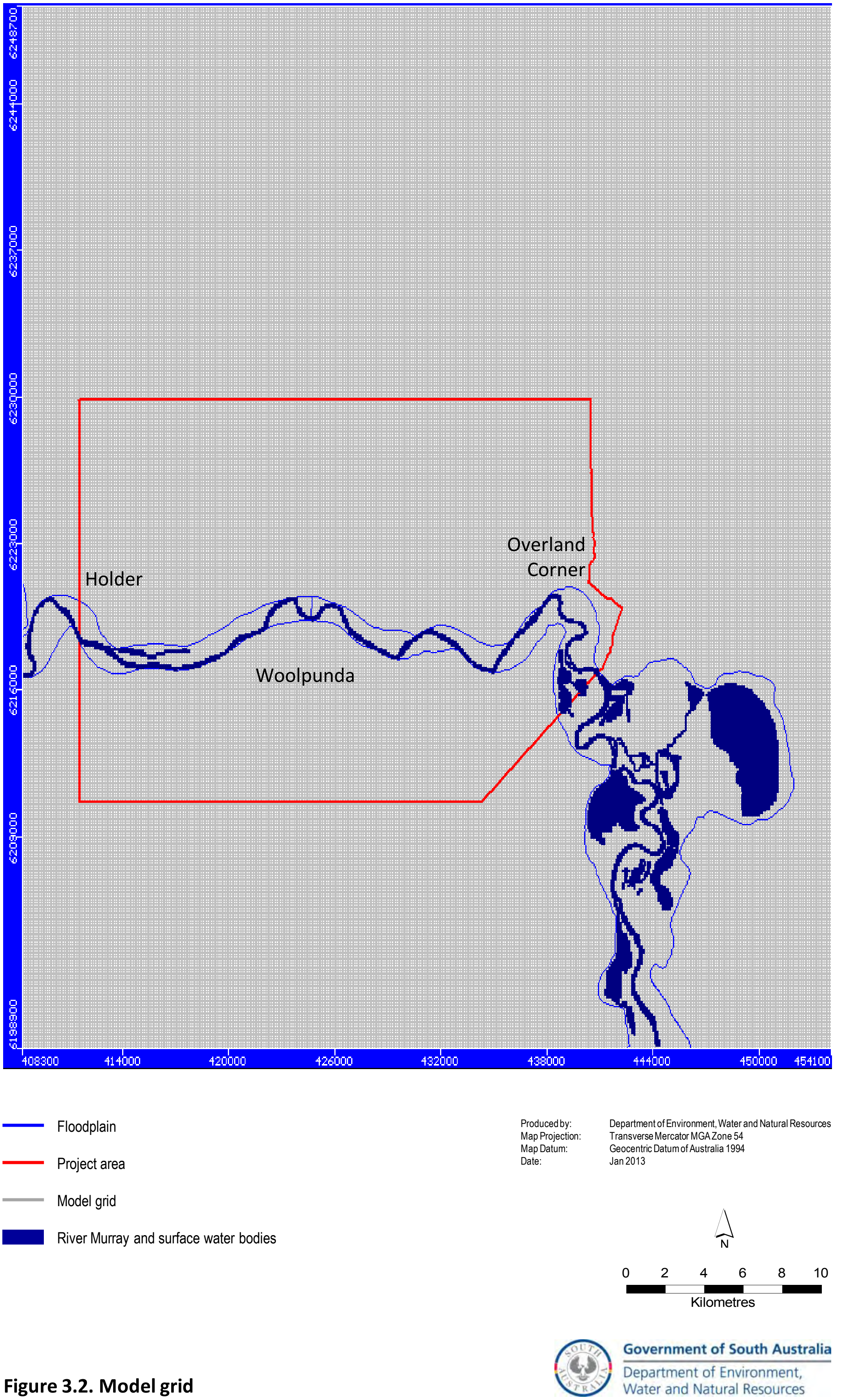


Figure 3.2. Model grid

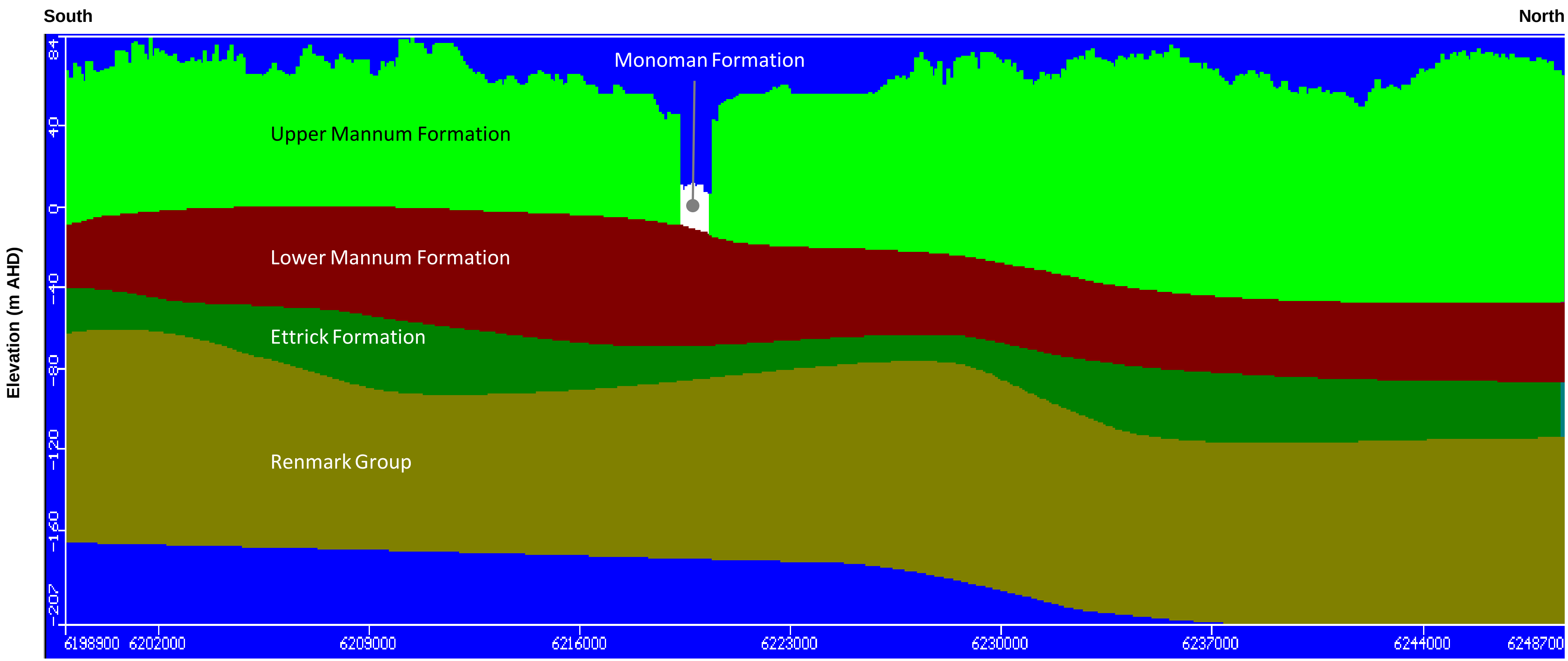


Figure 3.3. Model layers (north-south cross-section through model column 155, E423750)

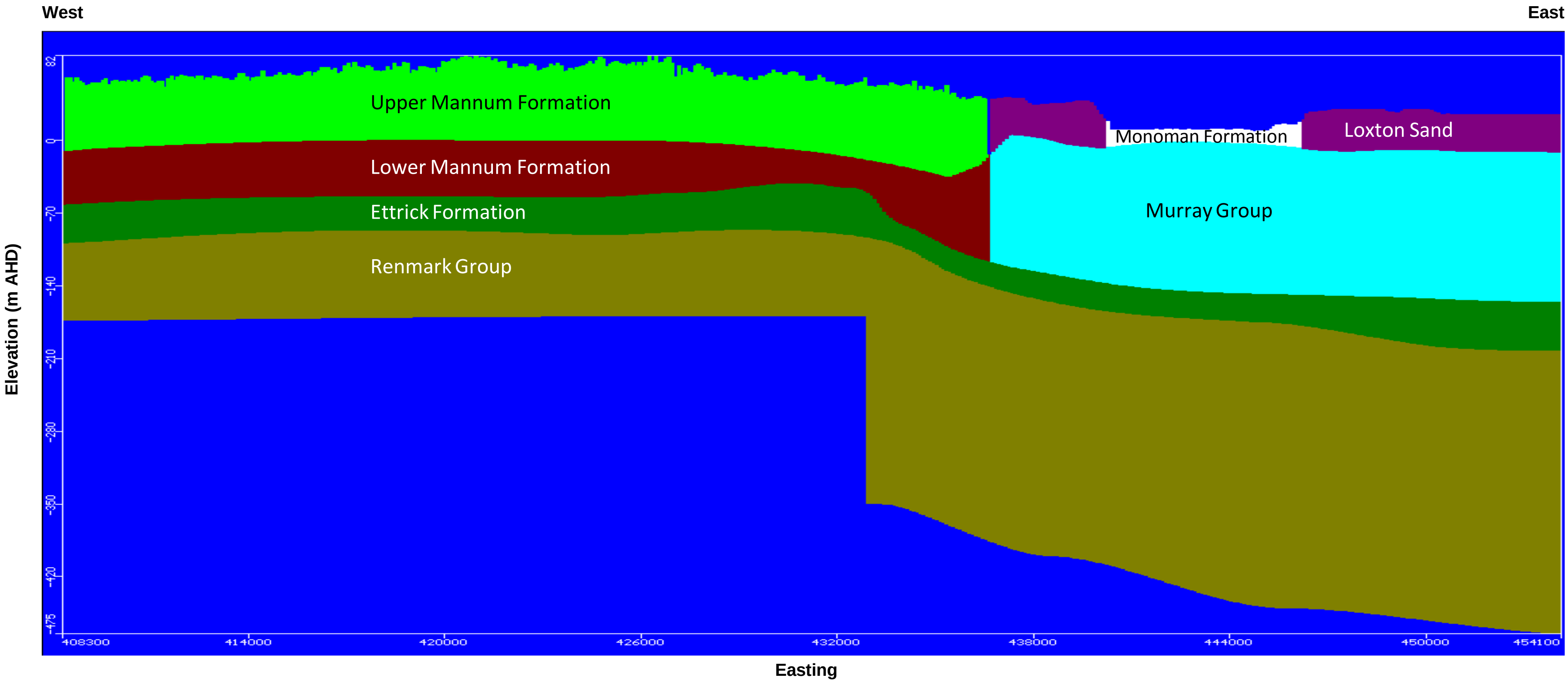


Figure 3.4. Model layers (east-west cross-section through model row 366, N6212150)

For scenario models simulations from 1988 onwards, the stress periods are one year or less in length, as annual salt loads from 1988 to 2113 are required by the MDBA for the Salinity Register but simulation of seasonal changes is not desired.

3.4 MODEL LAYERS IN THE WOOLPUNDA AREA

The Woolpunda numerical model simulates groundwater flow within:

- aquifers which interact directly with the river and floodplain
- aquifers which drive vertical flux into units connected with the floodplain, and
- intervening aquitards. In the study area, these are the Monoman Formation aquifer, the Upper Mannum Formation aquifer, the Lower Mannum Formation aquifer, the Ettrick Formation aquitard and the Renmark Group aquifer. To the east of the Hamley Fault, this also includes the Loxton Sands aquifer and the Lower Loxton Clay/Bookpurnong Formation aquitard.

The Woolpunda model represents the key hydrogeological units within four layers (Figures 3.3 to 3.4 and Table 3.1). The layering chosen reflects the regional hydrogeology to the best of current knowledge based on interpreted data.

The top and bottom of each model layer are based on ground elevation data, wellhole data, the location of faults and estimated structural contours. The accuracy of the structural contours at a location will depend strongly on the proximity of interpreted wellhole data (Appendix C provides figures showing the location of the available wellhole data). The north and south portions of the model domain outside the project area are based on very limited data. A few locations with wellhole data outside the model domain were used to constrain the structural contour interpolations.

Table 3.1 Model layer aquifers and aquitard

Layer	Hydrogeological unit		Aquifer/Aquitard	MODFLOW layer type
	Project area	East of Hamley Fault		
1	Monoman Formation (Floodplain only)		Aquifer	Convertible
	Upper Mannum Formation (Highland)	Loxton Sands (Highland) & Lower Loxton Clay/Bookpurnong Formation		
2	Lower Mannum Formation	Murray Group Limestone	Aquifer	Convertible
3	Ettrick Formation		Aquitard	Confined
4	Renmark Group		Aquifer	Confined

3.4.1 LAYER 1: MONOMAN FORMATION, UPPER MANNUM FORMATION, LOXTON SANDS AND BOOKPURNONG FORMATION

Layer 1 represents the unconfined and semi-confined aquifers within the model domain. To the west of the Hamley Fault, this includes the Upper Mannum Formation and the Monoman Formation. Generally, the Monoman Formation is underlain by a remaining thickness of Upper Mannum Formation, so Layer 1 cells within the floodplain are assumed to include both Monoman Sands sediments and also underlying Upper Mannum Formation sediments. The exception is an area between river kilometres 412 to 419, where the Monoman Formation may be in direct contact with the Lower Mannum Formation. In this area, Layer 1 cells represent the Monoman Formation alone.

To the east of the fault, the unconfined/semi-confined aquifers are the Loxton Sands and the Monoman Formation, which are also included in Layer 1. Layer 1 incorporates the underlying Loxton Clay/Bookpurnong Beds aquitard as zones of low vertical conductivity.

The Coonambidgal Formation occurs ubiquitously across the floodplain, but its impact on model results is expected to be small and hence is not simulated in the model. This means that the Monoman aquifer is modelled as unconfined, whereas it is actually semi-confined. This approach will result in the maximum flux of saline groundwater, and hence salt load, entering the river (Yan *et al.* 2005). This approach ensures that the salinity impact is not underestimated and is also consistent with other Salinity Register models.

The top of model Layer 1 in the highland is the ground surface, generated from re-sampling of a Digital Elevation Model (DEM) to a 100 x 100 m cell size. The DEM is based on STRM data of 77 m resolution, except in the floodplain where it is based on LIDAR data (without bathymetry) of 2 m resolution. The top of Layer 1 elevation contours are shown in Figure 3.5. The elevation ranges from 5 to 93 m AHD in the project area.

Layer 1 is modelled as a "convertible" MODFLOW layer type, which means that it can switch between confined and unconfined depending on the height of the watertable in relation to the top of the aquifer. The Upper Mannum and Loxton Sands aquifers represented within Layer 1 are expected to be unconfined for all modelled cases, but there may be locations where the Monoman Sands aquifer is locally confined by the Coonambidgal Clay which is not included in the model. A consequence of using surface elevation data to represent the top of the Monoman Formation is that the transmissivity of this unit may be overestimated in areas where Coonambidgal Clay overlies and confines the Monoman.

3.4.2 LAYER 2: LOWER MANNUM FORMATION AND MURRAY GROUP LIMESTONE AQUIFERS

Layer 2 represents the Lower Mannum Formation aquifer over the majority of the model domain and the undifferentiated Murray Group to the east of Hamley Fault. The simplified stratigraphy east of the Hamley Fault is suitable for the purpose of this modelling exercise, which focuses on the Woolpunda SIS reach. However, it may require review should the model be repurposed for the simulation of the proposed SIS at Overland Corner. Layer 2 is modelled as MODFLOW layer type "convertible", which means that it can switch between confined and unconfined depending on the height of the water table in relation to the top of the aquifer.

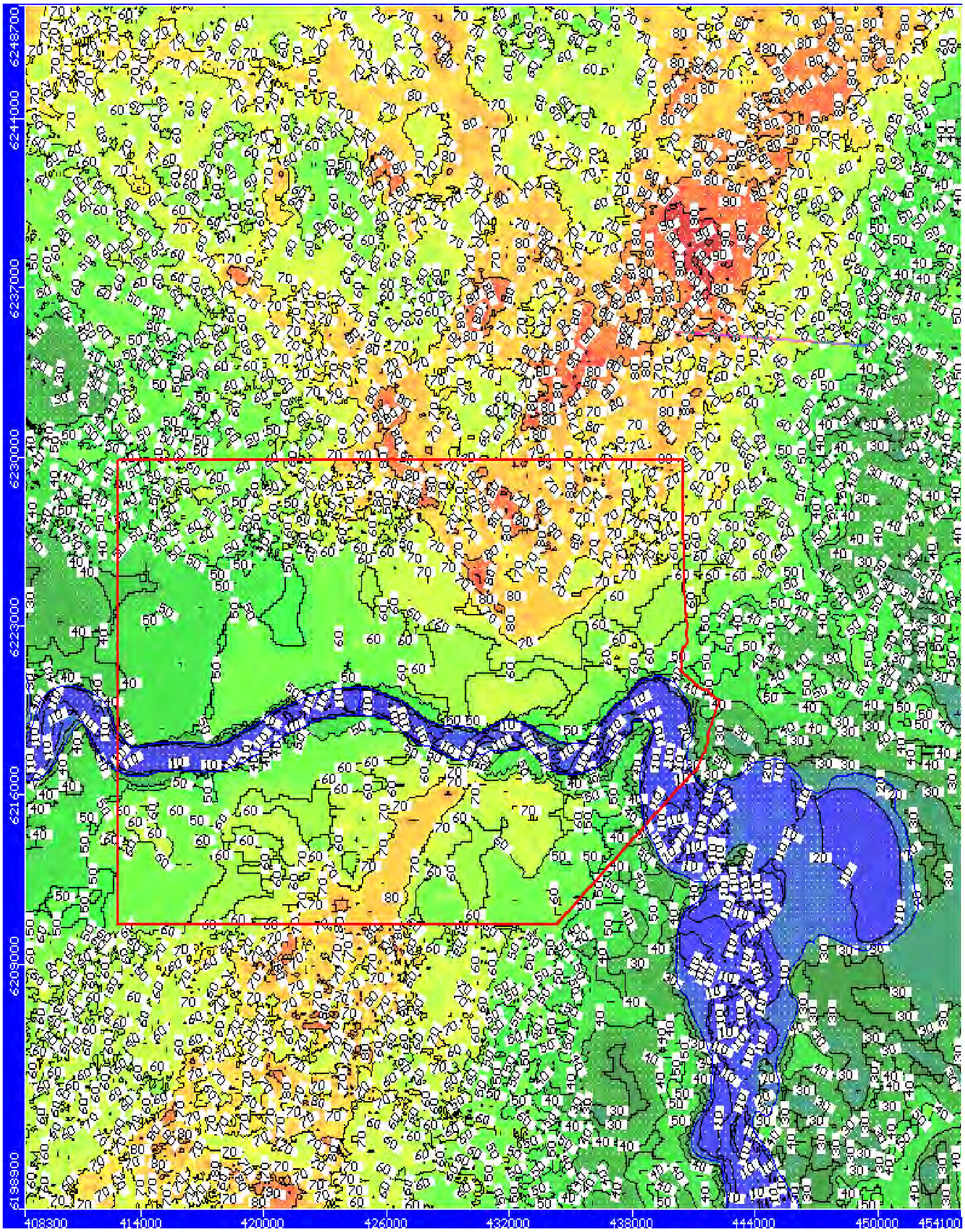
The top of Layer 2 occurs between -41 and 0 m AHD in the project area (Figure 3.6) and is interpolated from spot height data and estimated contours (taking the fault into account) which was then processed into a raster dataset of 100 m cell size and imported into Visual MODFLOW.

3.4.3 LAYER 3: ETTRICK FORMATION

Layer 3 represents the Ettrick Formation aquitard and is modelled as a "confined" MODFLOW layer type. The top of model Layer 3 represents the top of the Ettrick Formation aquitard everywhere in the model domain. The top of the Ettrick Formation is interpolated from spot height data and estimated contours (taking the fault into account), which were then processed into a raster dataset of 100 m cell size and imported into Visual MODFLOW. The top elevation occurs between -41 and 125 m AHD in the project area. The top of layer 3 elevation contours are shown in Figure 3.7.

3.4.4 LAYER 4: RENMARK GROUP

Layer 4 represents the Renmark Group aquifer and is also modelled as a "confined" MODFLOW layer type. Both the top and the base of the Renmark Group are interpolated from spot height data and estimated contours (taking the fault into account), which was then processed into a raster dataset of 100 m cell size and imported into Visual MODFLOW. Figures 3.8 and 3.9 show the top and base of Layer



Elevation contours (m AHD)

Project Area

Floodplain

Elevation (m AHD)

0
10
20
30
50
70
90
110

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Map Projection:	Transverse Mercator MGA Zone 54
Map Datum:	Geocentric Datum of Australia 1994
Date:	Jan 2013

N

0 2 4 6 8 10

Kilometres

Figure 3.5. Elevation contours for top of model layer 1 (ground surface)

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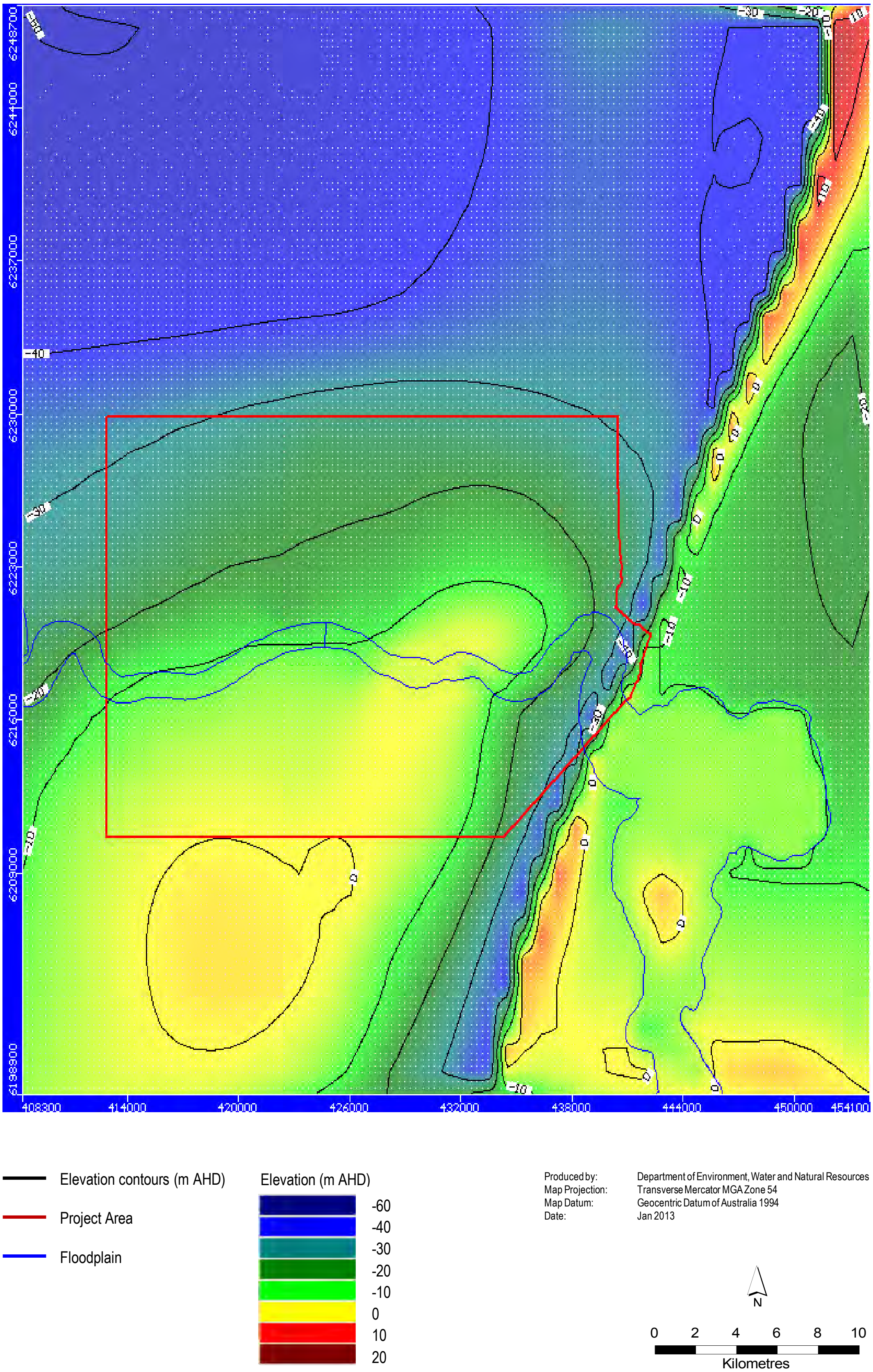

Figure 3.6. Elevation contours for top of model layer 2 (Lower Mannum Formation and Murray Group)

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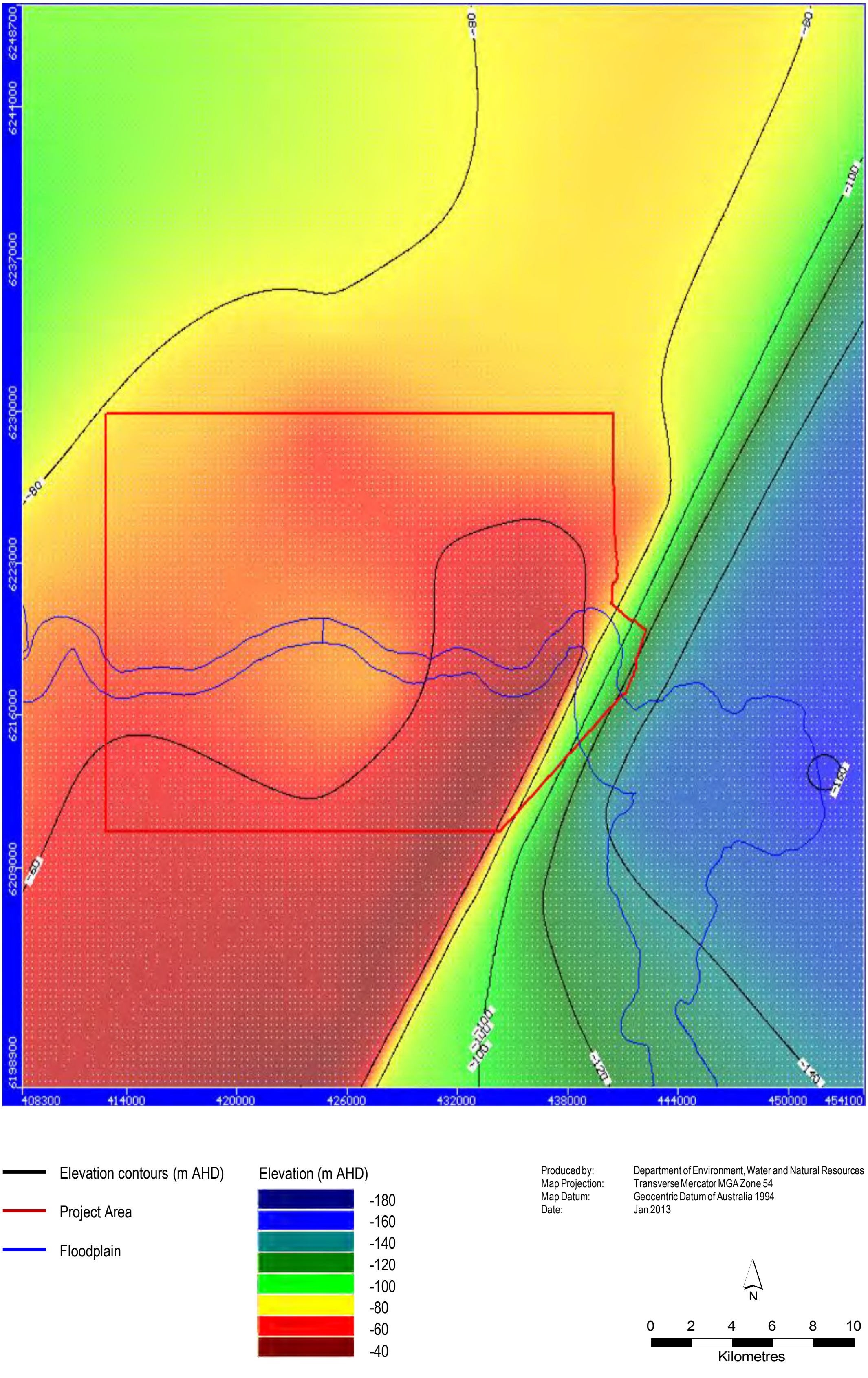

Figure 3.7. Elevation contours for top of model layer 3 (Ettrick Formation)

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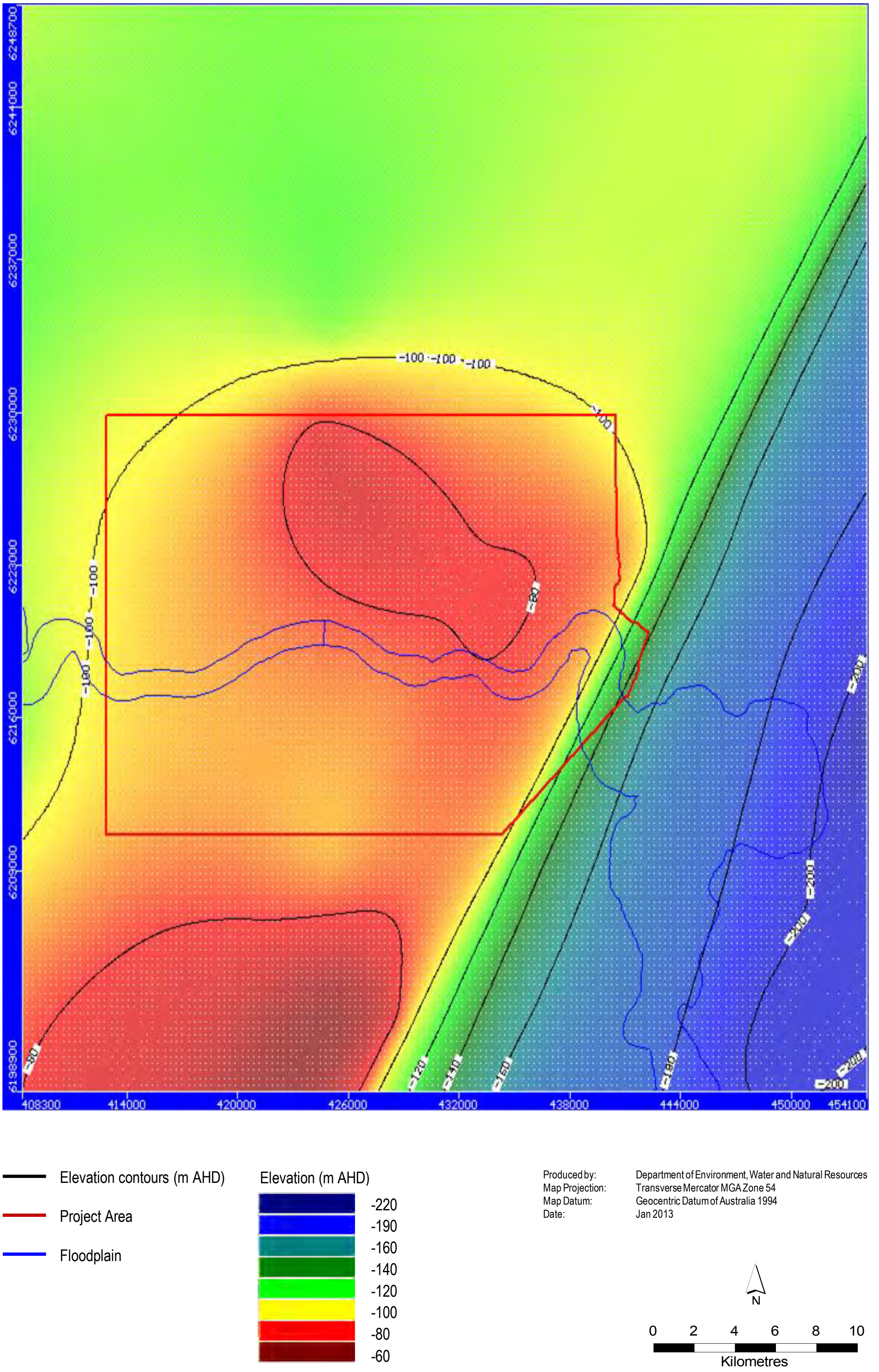

Figure 3.8. Elevation contours for top of model layer 4 (Renmark Group)

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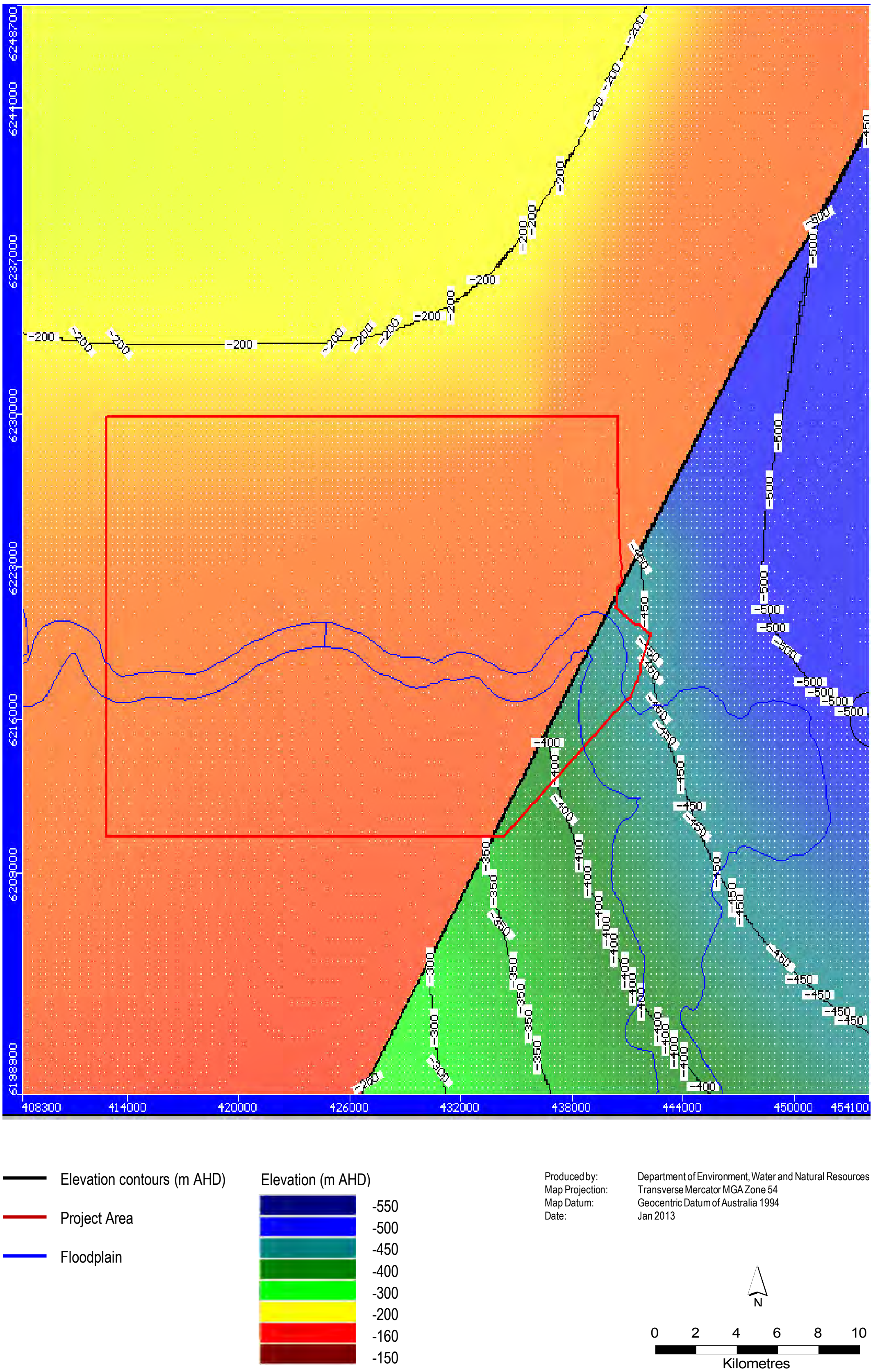

Produced by: Department of Environment, Water and Natural Resources
Map Projection: Transverse Mercator MGA Zone 54
Map Datum: Geocentric Datum of Australia 1994
Date: Jan 2013

Figure 3.9. Elevation contours for bottom of model layer 4 (Renmark Group)

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4 elevation contours, respectively. The top elevation occurs between -145 and 74 m AHD in the project area. The bottom elevation occurs between -450 and -169 m AHD.

3.5 MODEL HYDRAULIC PARAMETERS

The model's hydraulic parameters are based on a physically realistic range of aquifer and aquitard hydraulic parameters derived from previous reports and new data (Section 2.3; Table 3.2). Hydraulic conductivity zones and values are based on available geological information. The initial parameters were varied during calibration (see Section 4 for further details). The adopted aquifer and aquitard hydraulic parameters are given in Table 3.2, with their spatial distribution within each layer shown in Figures 3.10 to 3.13. Figures are not provided for specific yield and specific storage as constant values are adopted for each layer.

There are no aquifer test data available to estimate the Monoman Formation aquifer hydraulic conductivity within the floodplain in Woolpunda; however the hydraulic conductivity chosen is supported by data to the west in the Qualco area (Section 2.3.8; AWE 2011b) and is unchanged from the Lock 3 to Morgan model (Rural Solutions 2005). The Monoman Formation is mainly underlain by the Upper Mannum Formation to the west of Hamley Fault and by the Loxton Clay/Bookpurnong Formation to the east of Hamley Fault. There is an area of Monoman Formation near Woolpunda which is in direct contact with the Lower Mannum Formation. The vertical hydraulic conductivity of the Monoman Formation is zoned according to which unit underlies it within Layer 1: Upper Mannum Formation, Loxton Clay/Bookpurnong Formation or the Lower Mannum Formation.

The vertical hydraulic conductivity of the Upper Mannum Formation is based on aquifer tests in the adjacent Waikerie region (Telfer *et al*. 2012; Yan *et al*. 2012).

Step test data (Figure 2.6) were re-analysed by AWE (2013a) to provide estimates of Lower Mannum Formation aquifer transmissivity. AWE (2013a) estimates the resultant hydraulic conductivity is from 0.5 to 5 m/d, assuming a 40 m saturated thickness (Section 2.3.4.1). A value of 2 m/d is adopted for the model. The Lock 3 to Morgan model used 1 to 1.5 m/d (Rural Solutions 2005).

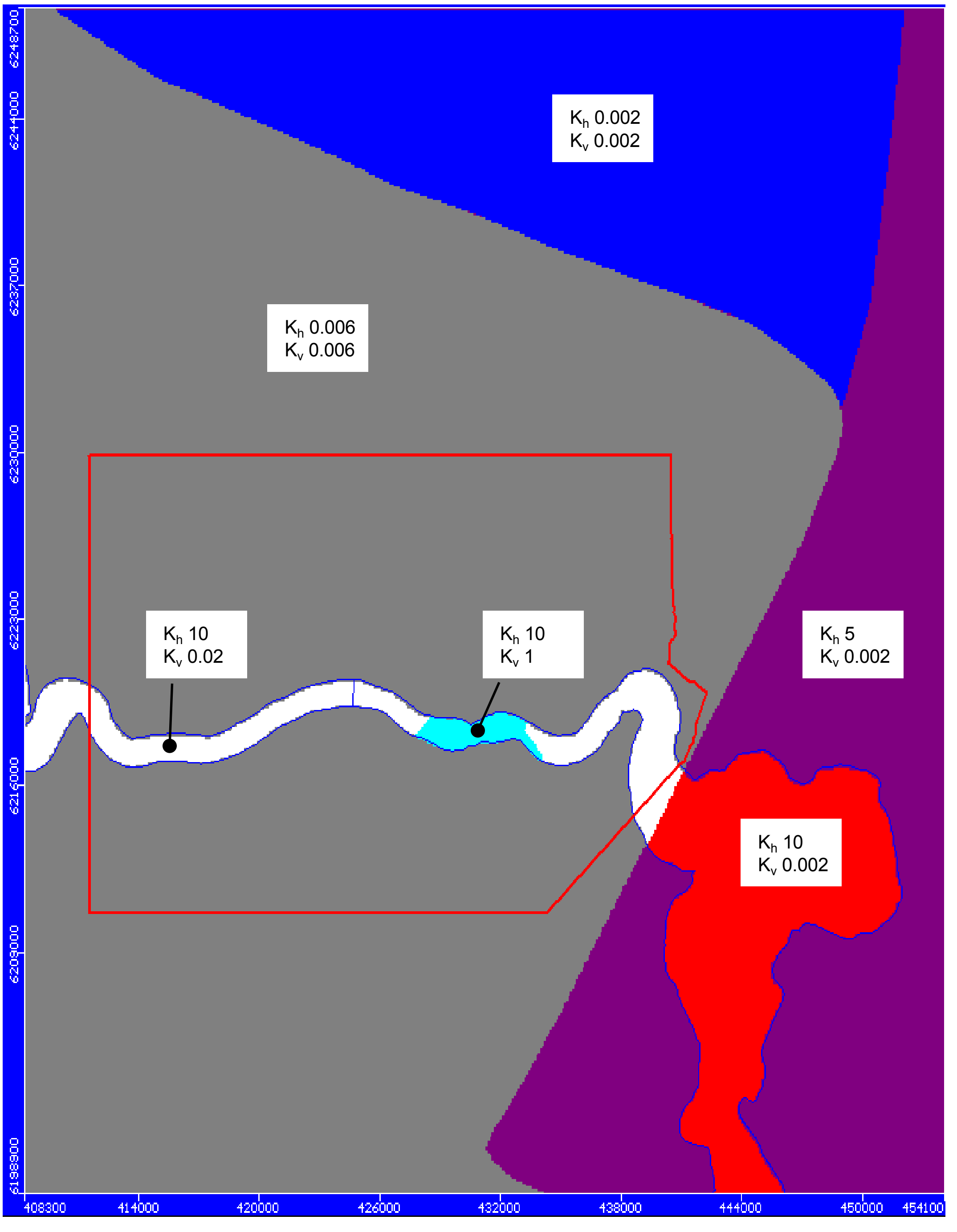
The adopted horizontal hydraulic conductivity of the Loxton Sands of 5 m/d is within the range estimated from aquifer tests in the Loxton-Bookpurnong area (between 2 and 80 m/day with a median of 13 m^2/d; AWE 2013a).

There is no aquifer test data available to estimate the vertical hydraulic conductivity of the Ettrick Formation in Woolpunda. The values used in the Woolpunda 2013 model are in the same range as previous modelling studies (Section 2.3.3): Watkins (1993) calibrated the vertical hydraulic conductivity of the Ettrick Formation within the Woolpunda reach to 1 x 10^{-4} to 1 x 10^{-5} m/d and the Rural Solutions (2005) model adopted vertical hydraulic conductivities of 1.4 10^{-4} x to 4.5 x 10^{-4} m/d. Zones and values were assigned during calibration to match the extent and height of the Woolpunda groundwater mound.

The Renmark Group horizontal hydraulic conductivity of 10 m/d is based on calibration results, prior estimates from Barnett and Osei-Bonsu (2006) and sediment texture. This is considerably less than the 100 to 300 m/d effectively applied in the Lock 3 to Morgan model (Rural Solutions 2005), which is judged to be too high for a unit which is not karstic. This is the only parameter in the Woolpunda 2013 model that is significantly different from the one used in the Lock 3 to Morgan model.

No storativity data are available for the Woolpunda area and hence the values were initially assigned based on values from Waikerie and refined during model calibration.

All the calibrated parameter values agree with the realistic ranges provided in Table 2.2.



K_h Horizontal hydraulic conductivity (m/d)

K_h Vertical hydraulic conductivity (m/d)

Floodplain

Project area

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Map Projection: Transverse Mercator MGA Zone 54
Map Datum: Geocentric Datum of Australia 1994
Date: Jan 2013

N

0 2 4 6 8 10
Kilometres

Figure 3.10. Model hydraulic conductivity for model layer 1 (Monoman Formation, Upper Mannum Formation and Loxton Sands)

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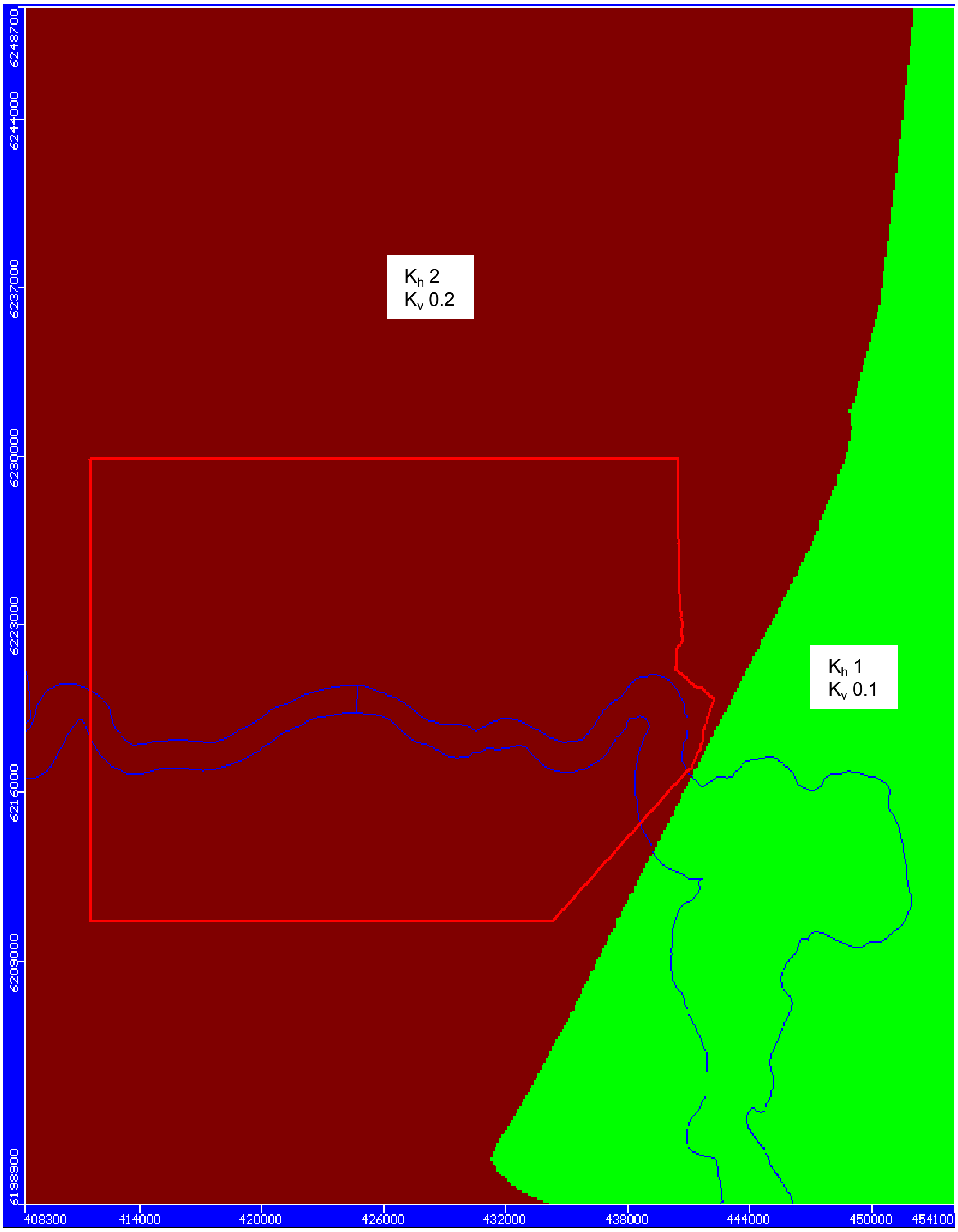

K_h Horizontal hydraulic conductivity (m/d)

K_h Vertical hydraulic conductivity (m/d)

Floodplain

Project area

Produced by:	Department of Environment, Water and Natural Resources
Map Projection:	Transverse Mercator MGA Zone 54
Map Datum:	Geocentric Datum of Australia 1994
Date:	Jan 2013

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0 2 4 6 8 10

Kilometres

Figure 3.11. Model hydraulic conductivity for model layer 2 (Lower Mannum Formation And Murray Group)

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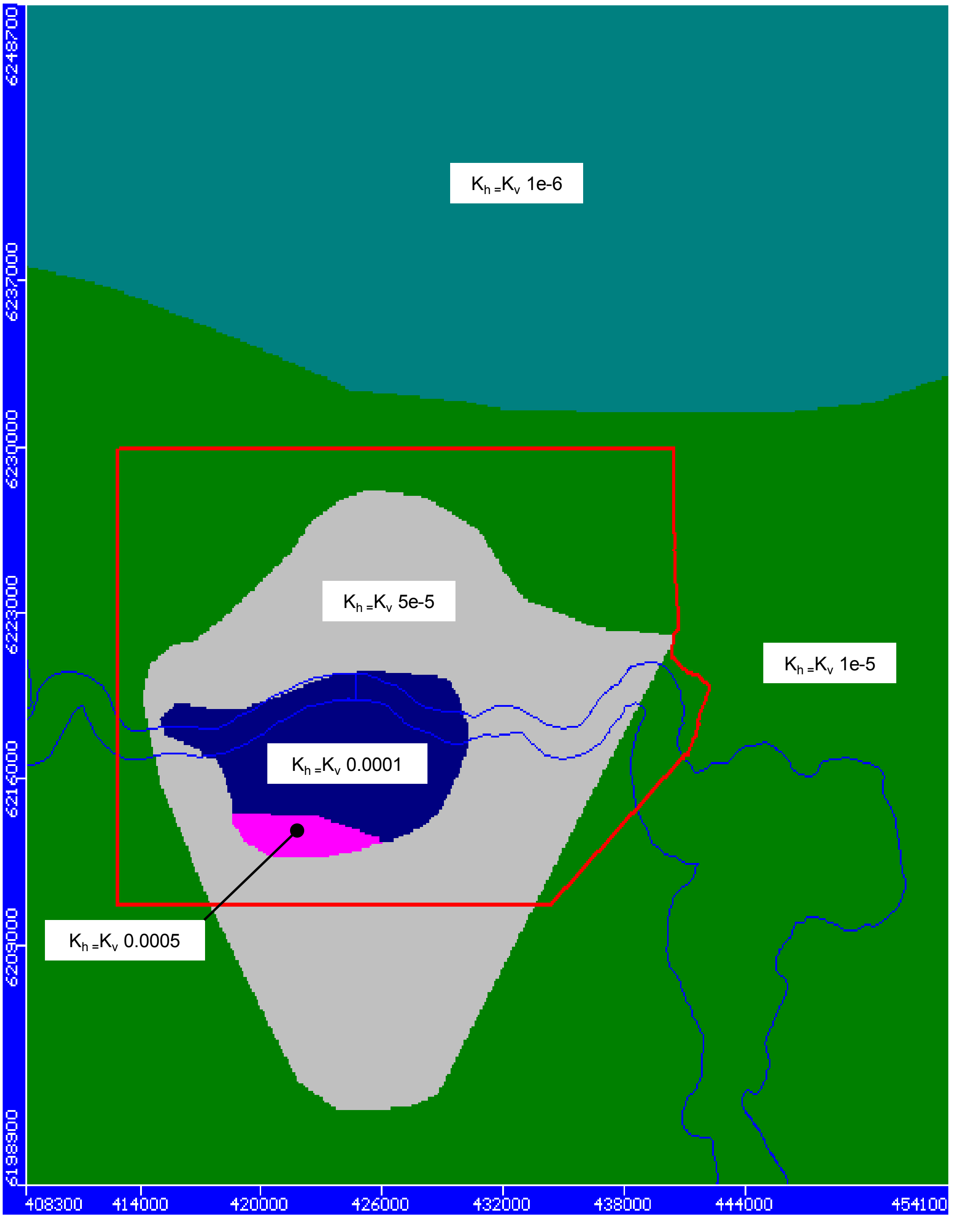

K_h Horizontal hydraulic conductivity (m/d)

K_h Vertical hydraulic conductivity (m/d)

Floodplain

Project area

Produced by: Department of Environment, Water and Natural Resources
Map Projection: Transverse Mercator MGA Zone 54
Map Datum: Geocentric Datum of Australia 1994
Date: Jan 2013

N

0 2 4 6 8 10
Kilometres

Figure 3.12. Model hydraulic conductivity for model layer 3 (Ettrick Formation)

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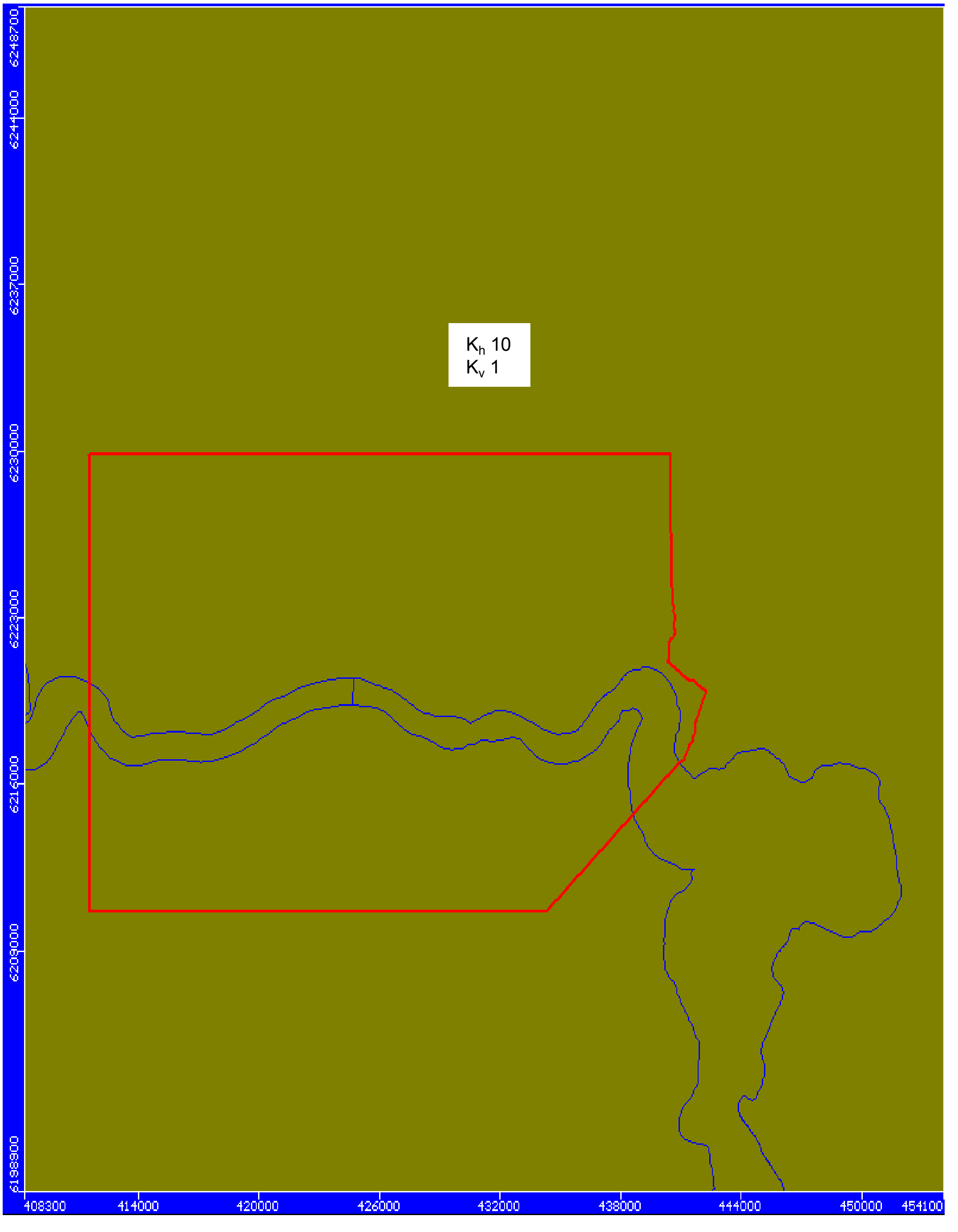

K_h Horizontal hydraulic conductivity (m/d)

K_h Vertical hydraulic conductivity (m/d)

Floodplain

Project area

Produced by: Department of Environment, Water and Natural Resources
Map Projection: Transverse Mercator MGA Zone 54
Map Datum: Geocentric Datum of Australia 1994
Date: Jan 2013

N

0 2 4 6 8 10

Kilometres

Figure 3.13. Model hydraulic conductivity for model layer 4 (Renmark Group)

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Table 3.2 Adopted aquifer and aquitard hydraulic parameters in the Woolpunda model

Hydrogeological unit	Model layer	Hydraulic conductivity		Storage	
		K_h (m/d)	K_v (m/d)	S_s (-/m)	S_y (-)
Monoman Formation/ Upper Mannum Formation	1	10	0.02	0.001	0.1
Monoman Formation	1	10	1	0.001	0.1
Monoman Formation/ Loxton Clay and Bookpurnong Formation	1	10	0.002	0.001	0.1
Upper Mannum Formation	1	0.002 – 0.006	0.002 – 0.006	0.001	0.1
Loxton Sands/Loxton Clay and Bookpurnong Formation	1	5	0.002	0.001	0.1
Lower Mannum Formation	2	2	0.2	5×10^{-4}	0.1
Murray Group Limestone	2	1	0.1	5×10^{-4}	0.1
Ettrick Formation	3	$5 \times 10^{-4} – 1 \times 10^{-6}$	$5 \times 10^{-4} – 1 \times 10^{-6}$	5×10^{-4}	0.2
Renmark Group	4	10	1	5×10^{-4}	0.2

A comprehensive comparison of model hydraulic parameters between the Woolpunda 2013 model and the Rural Solutions 2005 model is provided in Table 3.3.

3.6 MODEL BOUNDARIES

This section describes the numerical model's representation of all boundary conditions except aquifer recharge, which is described separately in Section 3.7. This section includes:

- regional flow in and out of the model domain
- surface water features including the River Murray
- groundwater evapotranspiration
- the Salt Interception Schemes Operation.

The model boundary conditions are summarised for Layers 1, 2 and 4 in Figures 3.14 to 3.16. Layer 3 which represents the Ettrick Formation aquitard, has no boundary conditions applied to it.

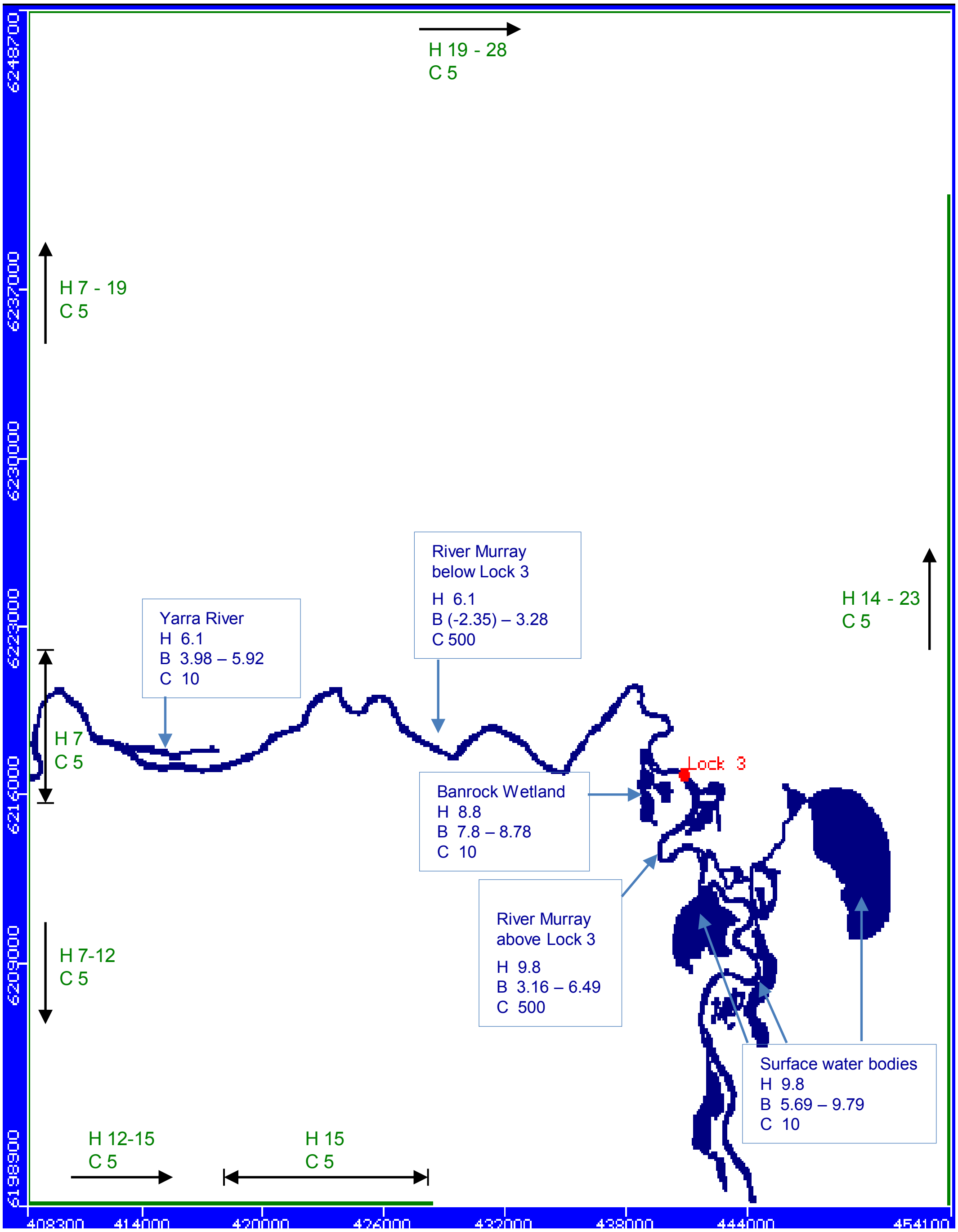
3.6.1 REGIONAL FLOW

Flow in and out of the modelled region is simulated using general head boundary (head-dependent flow) cells along the edges of the model domain where the aquifers are saturated and inflow is expected (i.e. where the estimated potentiometric contours are not at right angles to the domain edge). Areas where potentiometric head contours are approximately perpendicular to the boundary are assigned as

Table 3.3 Model hydraulic parameter comparisons between the Rural Solutions 2005 model and the Woolpunda 2013 model

Geological unit	Hydraulic parameter	Rural Solutions 2005 model		Woolpunda 2013 model	
		Project area	Regional area (if different from project area)	Project area	Regional area (if different from project area)
Monoman Sands	K_h (m/d)	10	-	10	-
	K_v (m/d)	10	-	1	-
	S_y (-)	0.1	-	0.1	-
Mannum Formation	K_h (m/d)	mostly 1, some 1.5	-	2	-
	K_v (m/d)	0.1	0.01	0.2	-
	S_s (m^{-1})	0.0075	-	5.00E-04	-
	S_y (-)	0.1	-	0.1	-
	Bottom elevation (m AHD)	-50 to -75	-	-45 to -70	-
Ettrick Formation	K_h (m/d)	1.4E-4 to 1.4 E-3	1.4E-5 to 1.4E-7	1E-5 to 5E-4	1E-5 to 1E-6
	K_v (m/d)	4.5E-4 to 1.4E-4	1.4E-7	1E-5 to 5E-4	1E-5 to 1E-6
	S_s (m^{-1})	1.5E-5	-	5.0E-4	-
	Thickness (m)	20 to 25	-	15 to 30	-
Renmark Group	T (m^2/d)	20 000 to 30 000, 30 000 to 60 000	-	~1000 (estimated)	~2000 - 3000 (estimated)
	K_v (m/d)	0.01	0.01	1	-
	Ss (-)	1.0E-5	-	5.00E-04	-
	Thickness (m)	200	-	100	300

no-flow boundaries. The assigned head values for the general head boundary (Figures 3.14 to 3.16) are based on observations from Barnett (1991, 1994). The assigned head values do not change with time. There are no hydraulic processes to the north and south which would substantially change the potentiometric head along the boundaries over the period simulated by the model except land clearance, which is considered separately in the uncertainty analysis of Section 6. There are hydraulic processes along the east and west boundaries that will change potentiometric head over time: the Waikerie irrigation area and SIS to the west and the Pyap, Kingston and Berri irrigation areas to the east (Barnett 1991). However, the irrigation impact is primarily on the Loxton Sands Formation which is not saturated within the Woolpunda study area. Downward leakage between the Loxton Sands and the Murray Group has raised the potentiometric head in the Murray Group under these irrigation areas but hydrographs from within the study area closest to these irrigation areas do not show any increase. Hence it is assumed that constant general head boundary conditions are appropriate for the current study.



H	Head level (m AHD)
C	Conductance (m²/d)
B	River bottom elevation (m AHD)
	General head boundary cell
	River cell simulating the River Murray and surface water bodies

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Map Projection: Transverse Mercator MGA Zone 54
Map Datum: Geocentric Datum of Australia 1994
Date: Jan 2013

N

0 2 4 6 8 10
Kilometres

Figure 3.14. Model boundary conditions for layer 1 (Monoman Formation, Loxton Sands and Upper Mannum Formation)

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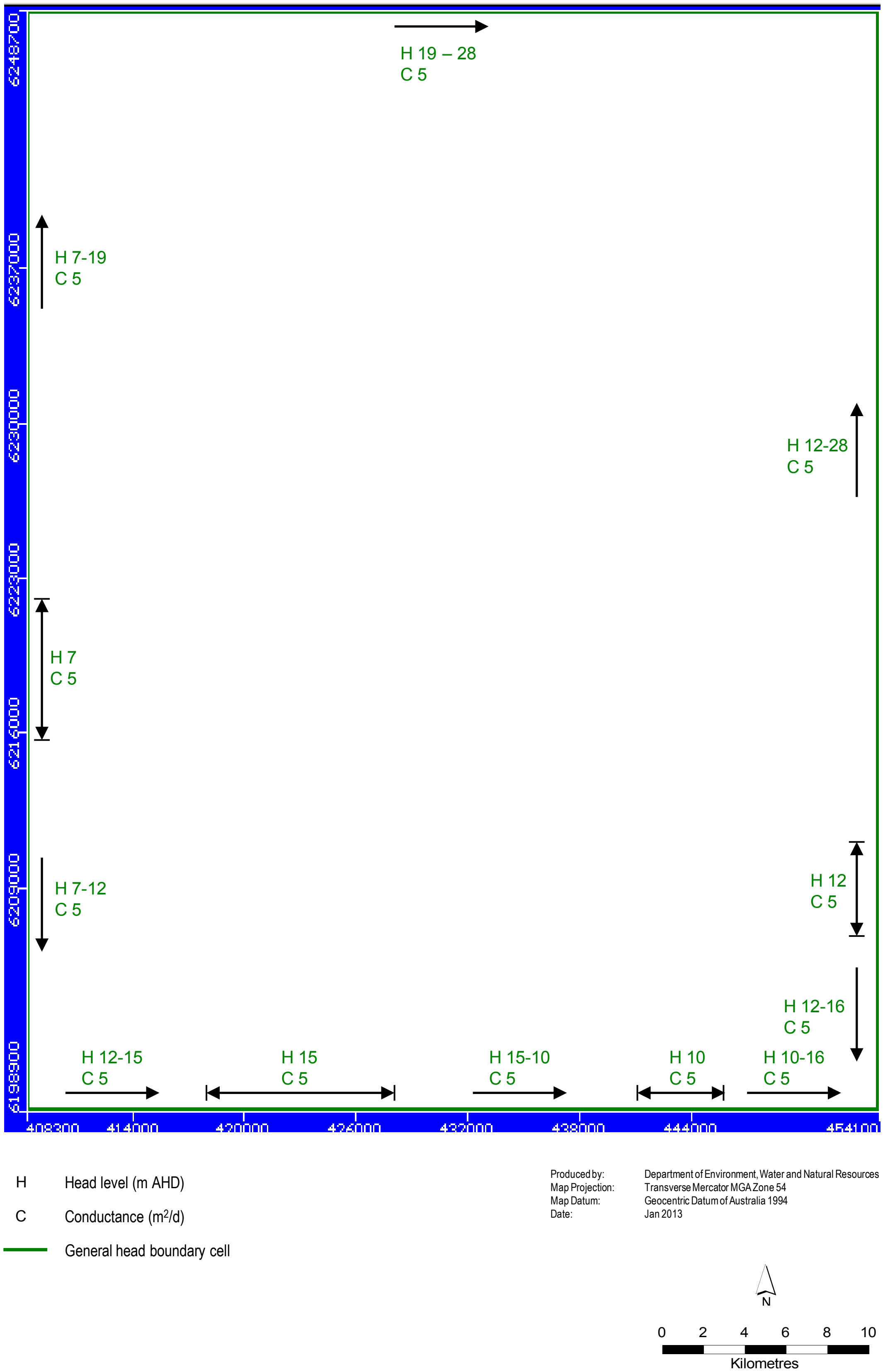

Figure 3.15. Model boundary conditions for layer 2 (Lower Mannum Formation and Murray Group)

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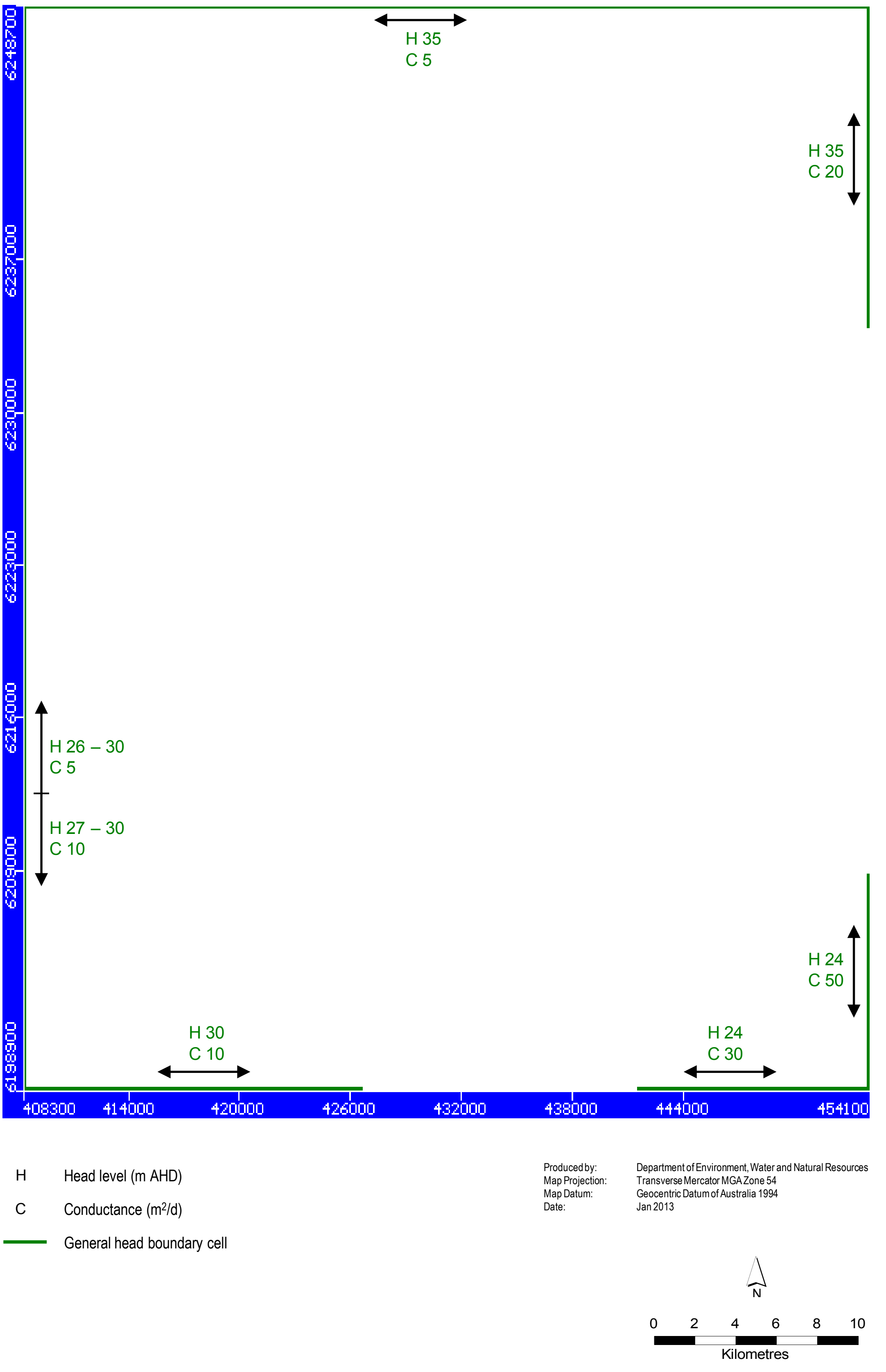

Figure 3.16. Model boundary conditions for layer 4 (Renmark Group)

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Model Layers 1, 2 and 4 have general head cells along the model boundaries. The general head cells are the same for the Upper Mannum Formation in Layer 1 and the Lower Mannum Formation in Layer 2, as there is no confining layer in between and hence their potentiometric heads should be similar in the long term. The conductance was varied during the calibration until a good match to observed heads was achieved regionally.

3.6.2 SURFACE WATER FEATURES

3.6.2.1 RIVER MURRAY

The River Murray, including its anabranches, is simulated using MODFLOW river cells. In terms of the conceptual model, river cells allow for flow in floodplain sediments under the River Murray (throughflow) and the groundwater head in the Monoman Formation may differ from the river stage in the same cell.

Riverbed elevations are sourced from the NanoTEM 2012 survey, smoothed and filtered to 100 m cell size.

The river stages for the River Murray are as follows:

- 9.8 m AHD between Lock 4 and Lock 3
- 6.1 m AHD between Lock 3 and Lock 2.

The river stage is held constant at pool level, which is a simplification that has been made for all other accredited SA Salinity Register models. The Salinity Registers consider the long term salinity impacts of accountable actions which are not believed to be significantly influenced by the impacts of major river fluctuations. This assumption will be investigated in future, but currently the extra work required to simulate changing river dynamics and floods is expected to provide little improvement in accuracy.

The conductance of MODFLOW river cells controls flux to and from the river. Sensitivity tests determined that model results are not sensitive to riverbed conductance (see Section 6), hence a conductance value of 500 m^2/d is used to be consistent with other Salinity Register models.

3.6.2.2 OTHER SURFACE WATER FEATURES

Other surface water features are represented in the model using river cells, specifically: Banrock Wetland, Loveday Swamp, Lake Bonney, Yatco Lagoon, Yarra River, Cobdogla Basin, Lock Luna, Nockbura Creek and Chambers Creek. All features are modelled at river pool level, except Banrock Wetland where the level historically was maintained at approximately 8.8 m AHD (AWE 2010). These features are given a bed conductance of 10 m^2/d (e.g. Kv of 0.001 m/d for 1 m thick river-skin sediments).

Bathymetry data were available for Banrock Wetland, Loveday Swamp, Lake Bonney, and Yatco Lagoon, which was to derive the bed elevation values for these features. Bathymetry data were not available for the other features, which are given bed elevation values based on approximate depths reported as part of the Wetlands Baseline Survey (SAMDBNRMB 2012).

3.6.3 GROUNDWATER EVAPOTRANSPIRATION

Groundwater ET occurs where the watertable is shallow, on the floodplains and in some other lowland areas. Groundwater ET is simulated using the ground surface (top of Layer 1) as the ET surface. The maximum groundwater ET rate is set at 250 mm/y and the extinction depth is set at 1.5 m, which are consistent with previous studies. Calibration results (Section 4) demonstrate that the modelled ET produces a good match between modelled and observed hydrographs in the floodplain and the actual ET from groundwater is within the same order of magnitude as field observations.

3.6.4 SALT INTERCEPTION AND GROUNDWATER CONTROL SCHEMES

The transient calibrated model simulates pumping from 49 wells that comprise the Woolpunda SIS using MODFLOW's Well Package. Figure 2.16 shows the location of these production wells. The wells are screened in the Mannum Formation (both the Upper and Lower Mannum Formations), but modelled extraction is from the Lower Mannum Formation, because it is much more transmissive than the Upper Mannum Formation and hence most of the water being pumped will be sourced from this Formation.

The total metered flow data for the scheme were provided by SA Water and were used to calculate an average flow every six months for each pumping well, assuming that the wells are always operating. These calculated rates were then imported into the model. Note that prior to 2003, the wells did not have flow meters, but spot flow checks were performed by SA Water approximately every six months.

Modelled pump rates for each well and active stress period are provided in Appendix A.

3.7 MODEL RECHARGE

Modelled recharge rates and areas simulate recharge due to rainfall and irrigation.

3.7.1 RECHARGE UNDER NATIVE VEGETATION

Areas covered by native vegetation are given a recharge rate of 0.1 mm/y (Allison *et al.* 1990). This rate is applied across the whole model domain for the steady-state simulation, which simulates the region prior to land clearance and irrigation.

3.7.2 RECHARGE DUE TO MALLEE CLEARANCE

When simulating the impact of mallee clearance on River Murray salt loads, the multiple recharge zones and rates are specified are estimated using SIMRAT and SIMPACT models (Fuller *et. al* 2005). Lag time and recharge rates to the watertable aquifer are estimated using information on soil type, depth to groundwater and thickness of the Blanchetown Clay aquitard. The mallee clearance is assumed to have started in 1920. There are 41 recharge zones and rates vary from 0.1 to 15 mm/y. The details of recharge zones shown in Figure 3.17 and rates are given in Appendix A-1.

3.7.3 RECHARGE DUE TO IRRIGATION

It is not currently possible to accurately measure or calculate recharge over time based on irrigation and hydrogeological information alone. There is a lack of historical irrigation data, some key hydrogeological properties (some of which are not measured at all, while others are not sampled at the scale required to simulate the impact of local heterogeneity) and gaps in the scientific knowledge of unsaturated zone processes. Until these issues are addressed through research, for practical purposes recharge must be estimated by other methods. For the South Australian numerical groundwater models for the Salinity Register, the recharge is normally estimated from measured groundwater levels via inverse groundwater numerical modelling (Yan, Li and Woods 2012). However, this approach cannot be applied in Woolpunda as the hydrographs have not yet shown any responses to irrigation recharge (see Section 4 for hydrographs). This is due to the relatively recent start of irrigation at Woolpunda and also the long lag times. The estimated SIMRAT lag times imply that little of the irrigation drainage water has reached the watertable to recharge the aquifer.

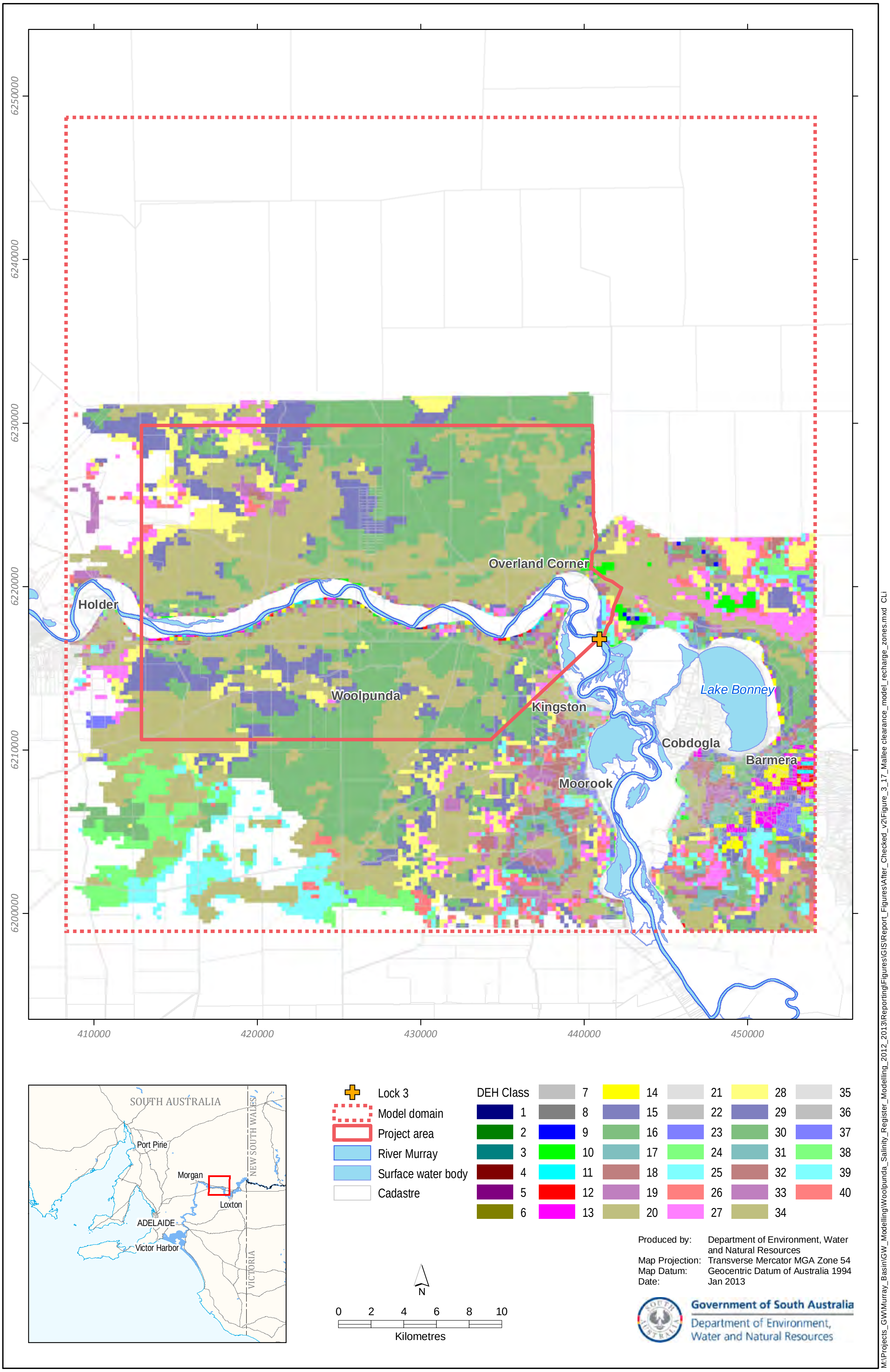


Figure 3.17. Mallee clearance model recharge zones

In some areas where SIMRAT does indicate irrigation accession has reached the watertable, there are unfortunately either no observation wells or the observation wells are no longer monitored to confirm it. Hence the Woolpunda model adopts a different approach for estimating recharge, as described in the sections below.

The irrigated areas are divided into zones based on the year of irrigation commencement, irrigation types (permanent or pivot) and initial lag time.

Irrigation within the model domain, but outside the project area, e.g. the Berri-Barmera and the Pyap to Kingston regions, is not simulated. As the watertable lies within the Loxton Sands at Berri-Barmera and Pyap to Kingston, it is presumed that the additional recharge due to irrigation will have minimal impact on the Murray Group aquifer on the other side of the Hamley Fault at Woolpunda (Section 2.4.3.2).

3.7.3.1 RECHARGE RATES

Modelled recharge rates are based on a review of Woolpunda irrigation data and its estimated water balance (Vears 2013, Appendix C). Recharge rates are assumed to be 100 mm/y for permanent irrigation (irrigation that remains at a fixed location) and 60 mm/y for pivot irrigation (irrigation that is only temporary and does not remain at a fixed location). An exception is made for the small area of irrigation which commenced before 1988, which is assumed to have a recharge rate of 120 mm/y until 1988.

As there is considerable uncertainty about the irrigation recharge rates at Woolpunda, these values are reconsidered as part of the uncertainty analysis of Section 6.

3.7.3.2 RECHARGE AREA

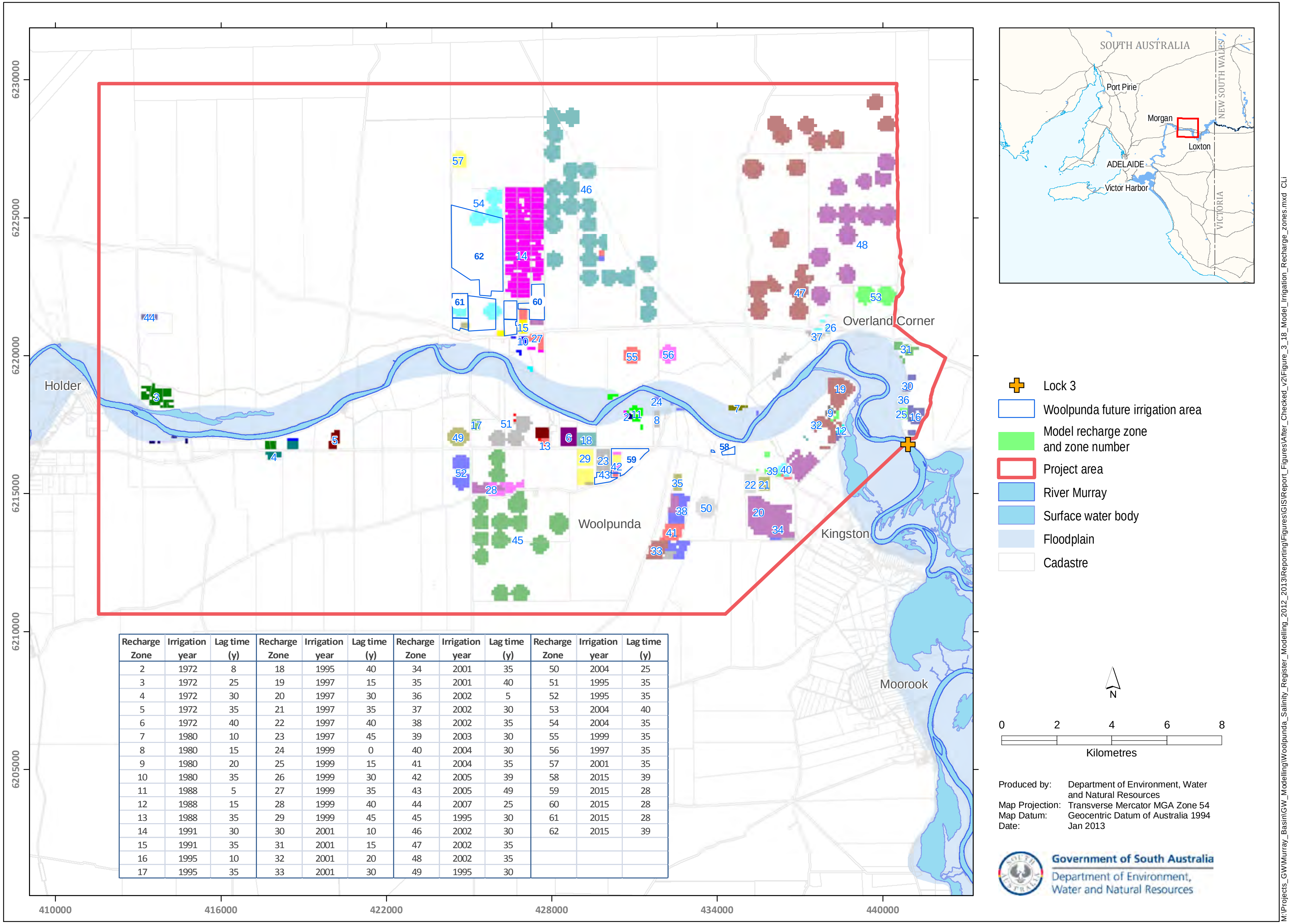
The areas of recharge in the model are assumed to be the same as the irrigation areas. They are based on the GIS irrigation footprint data collected as part of the irrigation data review (Vears 2013) given in Appendix C. The spatial extent of irrigation development at specific milestones (1972, 1980, 1988, 1995, 1997, 1999, and 2001 to 2011 yearly data) was used to generate recharge areas over time. The locations of irrigation areas and starting years are indicated in Figures 2.14 and 2.15.

As the irrigation footprint data indicate that irrigation areas expand with time, the GIS files were used to assign model recharge areas with different starting years. As irrigation continued to develop, more model irrigation recharge areas became active to simulate the irrigation area expanding. The year that an irrigation zone became active depends on the commencement year of irrigation and on the initial lag time. The recharge zones and lag time used in the calibrated model for the Woolpunda area are given in Figure 3.18.

There is a considerable area of pivot irrigation in Woolpunda. Simulating pivot irrigation can be difficult as it is only temporary and can change location with time. To simplify this, 2005 irrigation footprint data are used as they have the largest area of pivot irrigation. The commencement year for each pivot irrigation area in the 2005 dataset was determined based on the historical irrigation footprint data. Within any recharge zone, there may be properties or paddocks that are irrigated in some years but not others, but these small fluctuations in irrigation area are not simulated.

3.7.3.3 INITIAL LAG TIME

Initial lag time is the time taken for the irrigation-water wetting front to pass from the root zone down through the unsaturated zone to reach the watertable — this lag can vary from several years to many decades, depending on key variables, such as local geological conditions in the unsaturated zone, hydrogeological conditions (e.g. depth to watertable), vegetation, soil conditions and irrigation accession rates and history.



Recharge Zone	Irrigation year	Lag time (y)	Recharge Zone	Irrigation year	Lag time (y)	Recharge Zone	Irrigation year	Lag time (y)	Recharge Zone	Irrigation year	Lag time (y)
2	1972	8	18	1995	40	34	2001	35	50	2004	25
3	1972	25	19	1997	15	35	2001	40	51	1995	35
4	1972	30	20	1997	30	36	2002	5	52	1995	35
5	1972	35	21	1997	35	37	2002	30	53	2004	40
6	1972	40	22	1997	40	38	2002	35	54	2004	35
7	1980	10	23	1997	45	39	2003	30	55	1999	35
8	1980	15	24	1999	0	40	2004	30	56	1997	35
9	1980	20	25	1999	15	41	2004	35	57	2001	35
10	1980	35	26	1999	30	42	2005	39	58	2015	39
11	1988	5	27	1999	35	43	2005	49	59	2015	28
12	1988	15	28	1999	40	44	2007	25	60	2015	28
13	1988	35	29	1999	45	45	1995	30	61	2015	28
14	1991	30	30	2001	10	46	2002	30	62	2015	39
15	1991	35	31	2001	15	47	2002	35			
16	1995	10	32	2001	20	48	2002	35			
17	1995	35	33	2001	30	49	1995	30			

Figure 3.18. Model irrigation recharge zones

The SIMRAT model was developed to provide quick impact assessments for future irrigation developments and estimates of the initial lag time (Fuller *et. al* 2005). Although SIMRAT makes a number of simplifying assumptions, such as water moving vertically and not laterally, that may not always apply, this is currently the only available data source for estimating lag time.

SIMRAT is used to develop the lag time for the model recharge areas, assuming a continuous irrigation root zone drainage rate of 100 mm/y. These lag time estimates are shown in Figure 3.19.

The SIMRAT assumptions are consistent with assumptions in the Woolpunda numerical groundwater model for permanent irrigation since 1988 (i.e. 100 mm/y of continuous root zone drainage). The small areas of pre-1988 irrigation are assigned a greater root zone drainage rate (120 mm/y) so the true initial time lag will be shorter than the time lag adopted in the model. The temporary pivot irrigation is not continuous and is estimated to have a root zone drainage rate of 60 mm/y when averaged over a year, so its true initial lag times will be greater than those used in the model.

3.7.3.4 RECHARGE ZONING

The following factors were considered in defining the irrigation recharge zones.

Irrigation commencement year

Model recharge areas were categorised based on the commencement year of the irrigation. For instance, irrigation areas starting in 1972 and 1995 were simulated by two different model recharge zones.

Irrigation type

Model recharge zones were sub-divided based on irrigation type. For example, permanent irrigation for 1995 was simulated by one recharge zone, while the pivot irrigation for the same year was simulated by another recharge zone.

Initial lag time

Model recharge zones that have different lag times were further separated into different zones. For example, if the model recharge zone simulating the irrigation area starting in 1995 consisted of areas with three different lag time values, then that recharge zone was divided into three zones.

3.8 MODEL SALINITY ZONES

Salt loads from groundwater to the River Murray are calculated by multiplying the modelled flux through each river kilometre reach by a salinity value assigned to that river kilometre. This approach was tested and concluded to be valid by Merrick, Middlemis and Williams (2005).

All flow budget zones correspond to a single river kilometre reach except for the first and last zones (i.e. the westernmost and easternmost zones). The extent of the westernmost zone is chosen to be immediately adjacent to the easternmost zone from the Waikerie to Morgan model (Yan, Li and Woods 2012). The easternmost Woolpunda salinity zone ends at Lock 3.

The assigned model salinities do not change with time. Groundwater salinity in the floodplain may in practice change over time due to floods, irrigation-derived recharge, SIS pumping and groundwater ET (Section 2.5), but simulation of these processes is hampered by their complexity and a lack of historical data. In discussion with the MDBA, it was decided to adopt salinity values representative of regional groundwater in most cases. When this assumption is applied to all accountable actions, the salinity debits and credits estimated by the model will be consistent.

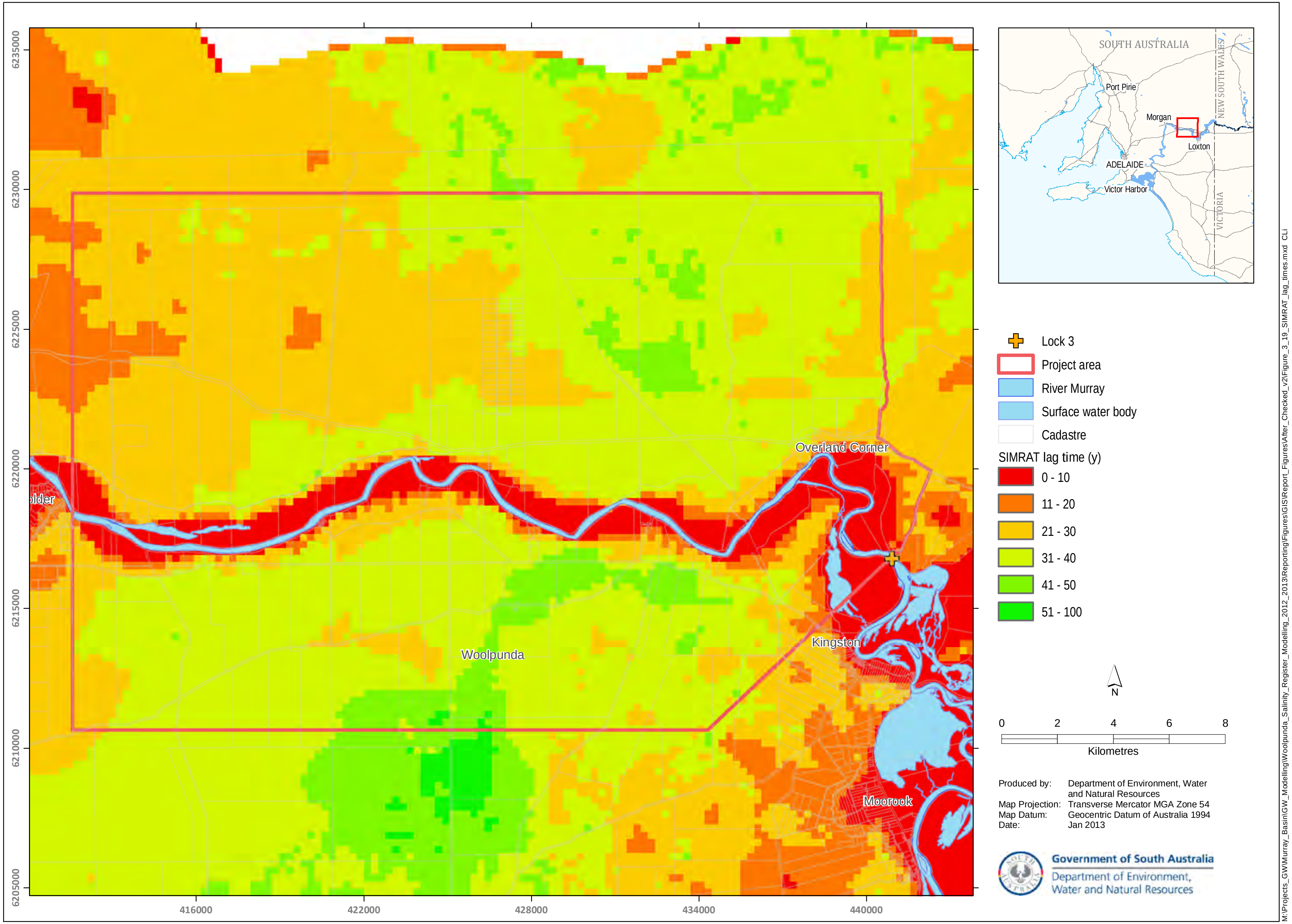


Figure 3.19. Lag time estimates from SIMRAT for Woolpunda (assuming an accession rate of 100 mm/y) (Fuller *et al*. 2005)

The salinity value assigned to a zone is based on the nearest salinity value north and south of the river, choosing the higher value to be conservative. The higher salinities tend to be on the southern side of the river, where there is little floodplain protection.

The location of the model budget zones and the associated groundwater salinity values are shown in Figure 3.2.

3.9 MODEL SIMPLIFICATION

All numerical models are simplified representations of reality. The main simplifications adopted in this model are given below.

3.9.1 SIMULATED PROCESSES

- The model does not estimate future impacts due to climate sequence, such as changes in river level, as these are not required for the Salinity Register. One consequence is that the modelled floodplain heads will not mimic fluctuations in observed head due to changes in river level.
- Flow through the unsaturated zone is not simulated directly; the lag time between irrigation application and recharge to the watertable is instead estimated using SIMRAT.
- The initial lag time applied to all irrigation recharge is based on SIMRAT estimates for a continuous 100 mm/y of root zone drainage. Irrigation areas with discontinuous recharge (i.e. temporary pivot irrigation) or differing recharge rates will have a different initial lag time in practice.
- The salt load is calculated by multiplying the groundwater flux by the appropriate groundwater salinity values for each reach. This neglects groundwater salinity changes over time.

3.9.2 SPATIAL AND TEMPORAL DISCRETISATION

- It is assumed that the Waikerie irrigation and SISs immediately west of the model domain do not significantly impact potentiometric head in the project area.
- Due to the limited data available, the model layer elevations are necessarily approximate and will not reflect the full heterogeneity of the system (this limitation is true of all numerical models).
- The Murray Group to the east of Hamley Fault is simulated as an undifferentiated unit. However, its impact on salt load is considered to be minimal as it is not within the project area.
- The Monoman Sands aquifer is modelled as if it were unconfined rather than semi-confined, as the Coonambidgal Formation is not modelled and the ground surface is used as the top of Layer 1.
- Some aquitards are not simulated as distinct layers but by applying a lower vertical conductivity to an aquifer layer. Layers simulated in this way are:
  - the Upper Mannum Formation underlying the Monoman Formation
  - the Lower Loxton Clay/Bookpurnong Beds Formation below the Loxton Sands and Monoman Formation.

  The saturated thickness of the aquifer is then over-estimated as the base of the aquitard is used as the base of the overlying aquifer.
- Each stress period is six months long from the commencement of SIS in 1991 to the end of the calibration period in 2012, so short-term changes in SIS pump rates are not included.

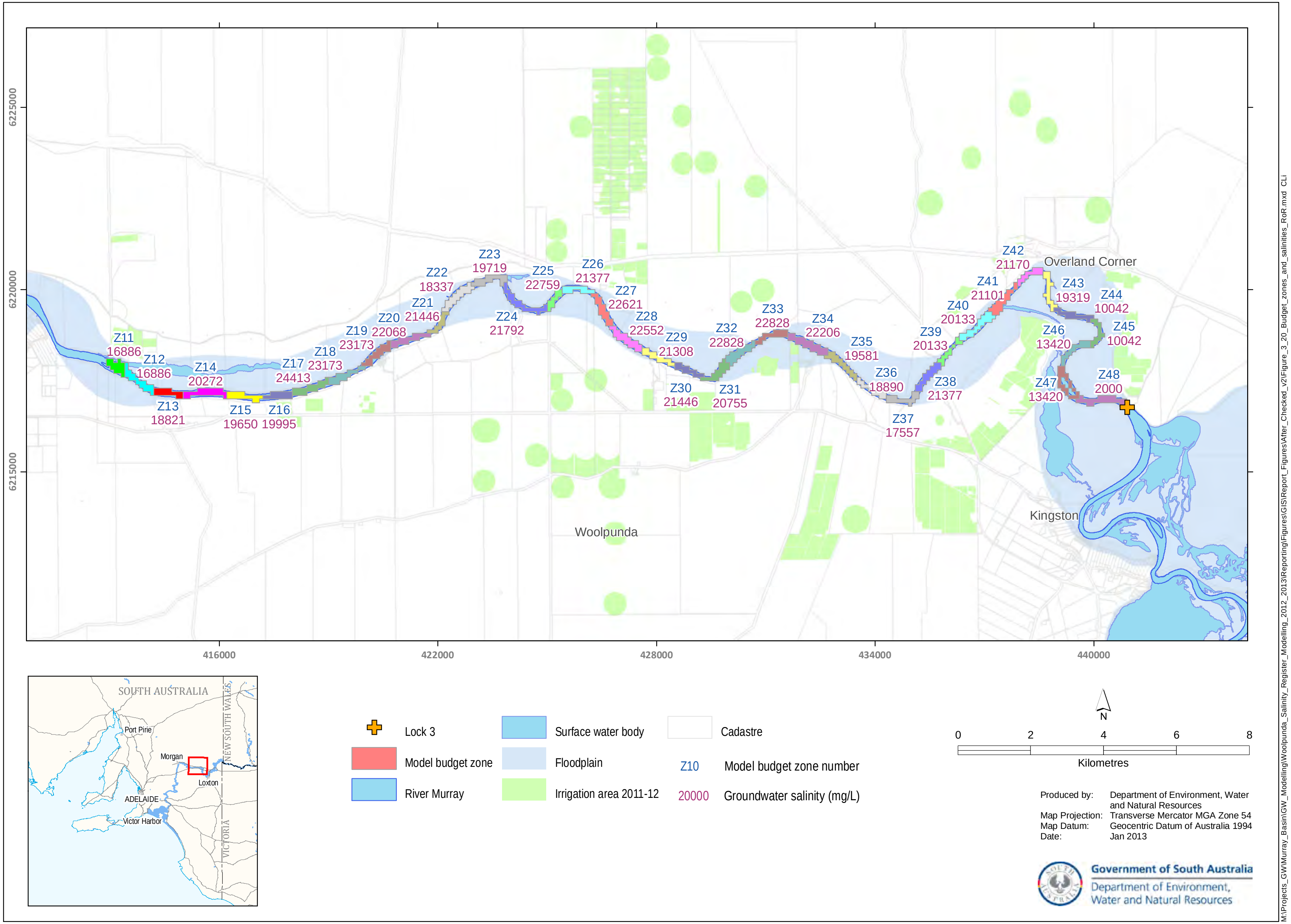


Figure 3.20. Model budget zones and groundwater salinities

3.9.3 MODEL PARAMETERS

- The heterogeneity within each hydrogeological unit is not fully known due to data limitations, but regionally representative aquifer parameters are estimated from available data and are tested during calibration.
- No quantitative data exists to inform the storage of aquifers in the region.
- Few data are available for the majority of the model domain except, near the river, to inform aquifer parameters.
- Groundwater salinities are assumed to remain constant when predicting future salt loads entering the river. However, groundwater salinity will most likely change in the future in response to accessions from brackish irrigation drainage.

3.9.4 MODEL BOUNDARY CONDITIONS

- Model recharge rate is held constant at 120 or 100 mm/y for permanent irrigation and 60 mm/y for pivot irrigation. In reality, the irrigation areas and rates will vary with time and there is considerable uncertainty about the recharge rates.
- Irrigation within the model domain but outside the project area, e.g. the Berri-Barmera and the Pyap to Kingston regions, is not simulated. As the watertable lies within the Loxton Sands in these areas, it is presumed that the additional recharge due to irrigation there will have minimal impact on the Murray Group aquifer on the other side of the Hamley Fault at Woolpunda.
- The model does not simulate seasonal changes such as groundwater ET rates that vary over the year.
- Evapotranspiration is simulated using a linear function with constant extinction depth and ET rate. In actuality, extinction depth and rate will vary based on soil type, vegetation type, vegetation health and groundwater salinity.
- Riverbed hydraulic conductivity has not been estimated in the field, so the conductance of the river boundary was estimated during calibration.
- In all transient simulations except Scenario 2, it is assumed that the recharge rate for non-irrigated areas is 0.1 mm/y. This neglects the impact of land clearance, which is presumed to have a much smaller impact on river salinity than irrigation (Section 6.2.3.4 considers the impact of this assumption).
- The model assumes that the recharge footprint is the same as the irrigation footprint. This is a reasonable assumption unless perched aquifers have formed under irrigation areas.
- Some surface water features are simulated in limited detail owing to a lack of data. They may have significant impact on salt loads over brief periods but are less important for the average conditions required for this model.

4 MODEL CALIBRATION

4.1 CALIBRATION APPROACH

Model calibration to historical data ('history matching') is done to improve confidence in predictive modelling. It demonstrates whether the model can replicate the behaviour of the aquifer system over a set of recorded historical conditions. Sensitivity analyses should also be undertaken to determine the relative importance of model parameters in achieving calibration (Section 6).

The calibration was conducted on a trial-and-error basis rather than using an automated method. Model calibration was guided by the following model outputs and performance measures, as given in the *Australian Groundwater Modelling Guidelines* (2012):

- scattergraph of modelled heads plotted against observed heads
- a simple statistic measuring goodness of fit: the scaled root mean square is chosen
- time series of heads at specific locations
- spatial distribution of heads, comparing contours of modelled heads with observed heads at specific times
- convergence to an iteration convergence criterion that is one or two orders of magnitude smaller than the level of accuracy required in head predictions (1 mm, see Section 3.1)
- a water balance error of less than 1%.

These calibration results are presented in Sections 4.2 and 4.3.

In addition, the possibility of a non-unique solution is reduced by confirmation, by comparing model outcomes with estimates and information on water and solute fluxes (Section 4.4):

- total RoR salt load entering the River Murray
- in-river NanoTEM
- actual groundwater evapotranspiration.

Calibration of the Woolpunda model was conducted in two stages: steady-state and transient. Steady-state models are used to model equilibrium hydrologic conditions, when changes in storage are insignificant. Transient models are used to model time-dependent stresses, when water is released from or taken into storage.

4.2 STEADY-STATE MODEL CALIBRATION

Steady-state calibration was undertaken to develop a broad-scale hydraulic conductivity distribution and regional boundary conditions. Dynamic stresses and storage effects are excluded from steady-state calibration by definition. Here the steady-state model simulates conditions after river regulation (i.e. after the locks were constructed) but before irrigation and the construction of the Woolpunda SIS. This includes the groundwater mound caused by the upwelling from the Renmark Group into the Mannum Formation, which drives most of the present groundwater flux into the River Murray.

Hydraulic conductivities and regional flow boundary conditions were varied within reasonable limits. Modelled heads were compared to head observations in areas where there have been no known major changes to the hydrologic processes since the river locks were built, i.e. areas distant from irrigation areas and pumps. The main aim was to adequately simulate the groundwater mound in the Mannum Formation caused by upwelling of groundwater from the Renmark Group.

The steady-state model is incorporated into the transient model by simulating the first stress period of the transient model as steady state, which is standard practice for MODFLOW-2000. This approach has the advantage that any changes made to the transient model will be automatically applied to the steady-state model.

4.2.1.1 LAYER 1: MONOMAN FORMATION, UPPER MANNUM FORMATION AND LOXTON SANDS

Barnett (1991) provides estimated potentiometric contours for the regional watertable based on limited available data. Figure 4.1 shows these potentiometric contours, providing a provisional description of the pre-SIS heads. Figure 4.1 also presents the modelled steady-state potentiometric head contours of Layer 1 for comparison. Layer 1, representing the Upper Mannum Formation to the west of the Hamley Fault, the Loxton Sands to the east of Hamley Fault and the Monoman Formation in the floodplain, is the appropriate choice for the comparison, as the watertable lies within these Formations.

The estimated (Barnett 1991) and modelled contours match well in both flow direction and level in most areas, especially in the project area. In the centre of the project area, the Barnett (1991) contours imply a groundwater potentiometric head of greater than 10 m AHD in the Mannum Formation close to the river, but hydrographs from observation wells constructed prior to the commencement of the SIS show heads were between 8 and 10 m AHD (Section 4.3.2), so the modelled values are considered to be more accurate. There is also some discrepancy to the east of the model domain, which is likely to be caused by the lack of pre-irrigation data and also the simplified model representation of the hydrogeology in that area. There is further mismatch to the north of the model domain, but as it is far from the project area, its impact on the model results (i.e. salt load) should be minimal.

4.2.1.2 LAYER 4: RENMARK GROUP

There is little information available with which to compare the modelled Renmark Group potentiometric heads. Within the model domain, there are only four observation wells monitoring the Renmark Group and Barnett (1991) does not provide potentiometric head contours which pass through Woolpunda.

Figure 4.2 compares modelled steady-state contours with the latest available observations made at the monitoring wells. The match is very good.

4.3 TRANSIENT MODEL CALIBRATION

The historical period from 1920 to 2012 was simulated, during which time the principle change to the hydrogeological drivers was pumping from the Woolpunda SIS. While irrigation was introduced during this period recharge from irrigation is expected to be minimal. Hence the focus of the transient calibration was to match the response to SIS pumping in the Mannum Formation aquifer. Hydraulic conductivities and boundary conditions were altered within known ranges and reasonable limits, to achieve a good match to observed heads.

Irrigation recharge was not varied during the calibration, as potentiometric heads near irrigation areas show no increase over time and consequently there are no changes which can be used to calibrate recharge. Other SA Salinity Register models simulate regions with well-developed groundwater mounds caused by irrigation recharge, so a different approach is used for those models (e.g. Yan, Li and Woods 2012).

Hydraulic conductivity (especially vertical hydraulic conductivity of the Ettrick Formation) is the major parameter varied during transient calibration, as the aquifer system is driven by the upward flux from the Renmark Group.

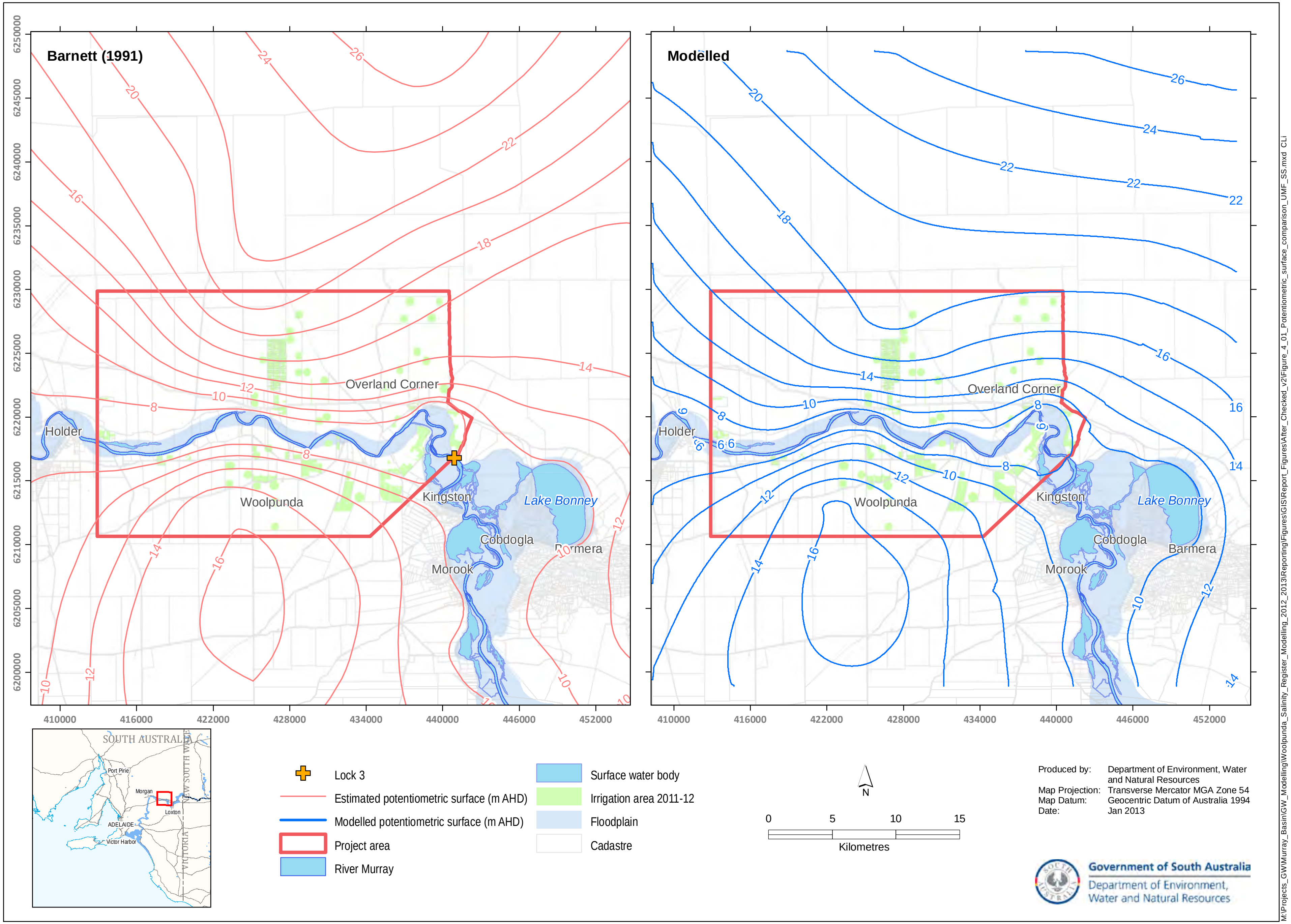


Figure 4.1. Comparison of estimated (Barnett 1991) and modelled potentiometric surface for model layer 1 (Upper Mannum Formation and Loxton Sands in steady-state conditions)

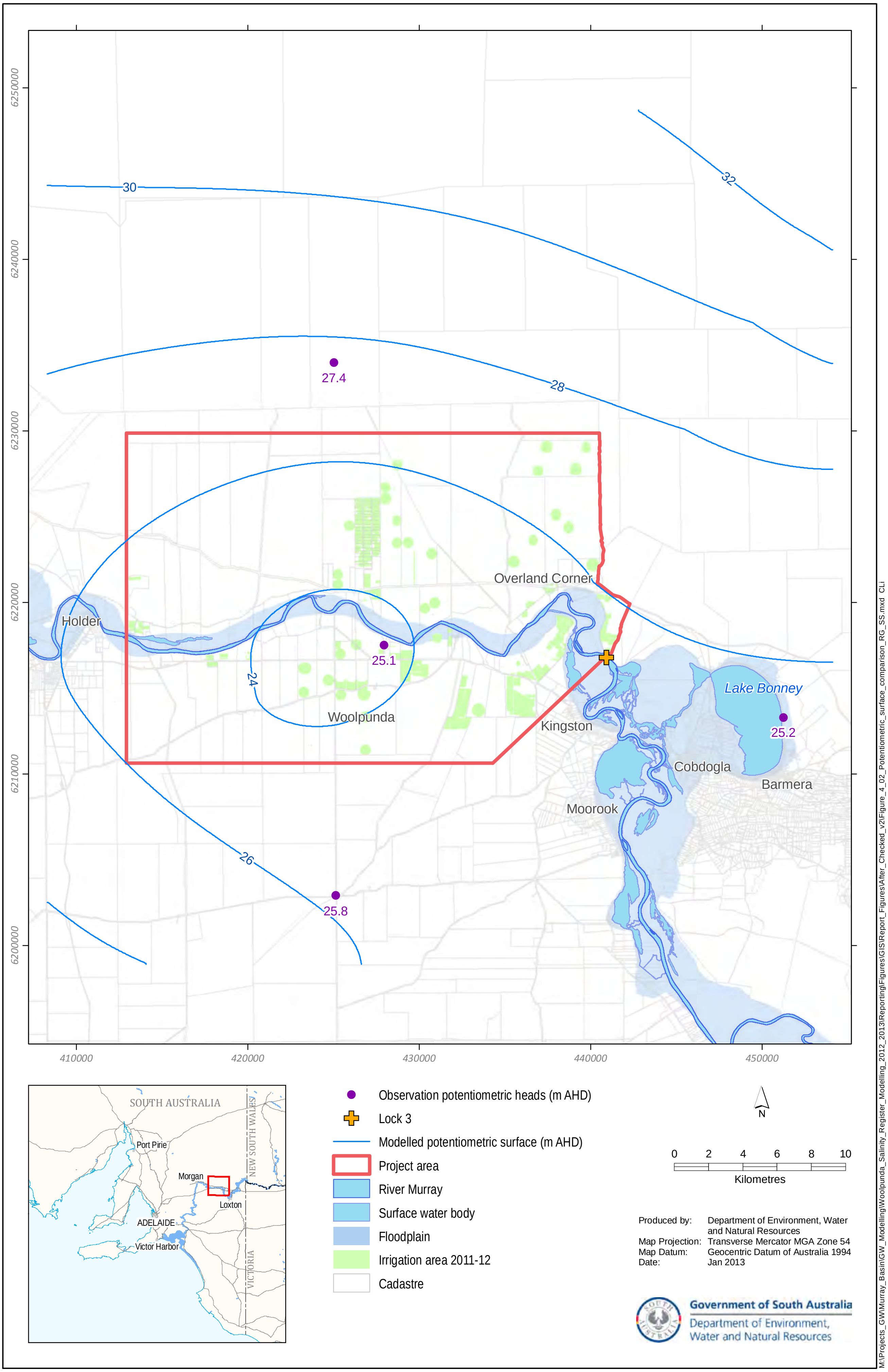


Figure 4.2. Comparison of observed and modelled potentiometric heads for model layer 4 (Renmark Group in steady-state conditions)

4.3.1 CALIBRATION RESULTS – POTENTIOMETRIC HEAD CONTOURS

The major processes that affect the heads in the Lower Mannum Formation include SIS pumping (starting from 1991) and irrigation development. The impact of irrigation recharge is delayed due to a number of reasons, including:

- the relatively late start time of most irrigation areas,
- the relatively deep watertable beneath the highland, and
- the widespread use of temporary pivot irrigation.

Consequently the potentiometric surface for the Lower Mannum Formation in recent years is expected to be similar to the steady-state potentiometric surface, except near the River Murray and SIS pumping wells. Matching observed groundwater levels in the Lower Mannum Formation, especially near the River Murray and SIS pumping wells, was therefore considered imperative during calibration.

Modelled regional potentiometric head contours for the Mannum Formation aquifer were compared with potentiometric head values observed at the end of 2009 (Figure 4.3; AWE 2013a). The model contour shapes were also compared with contours developed from 2009 observations supplemented by older observations in regions with few 2009 data (AWE 2008) (Figure 2.5). Both the head elevations and the flow directions should be evaluated.

The modelled contours match very well with the observations in the centre and south of the model domain, where most of the observation wells are located. The match is less good in the north. SIS pumping wells have caused small, local cones of depression, which show a good match to the mid-point observations. Note that unlike other irrigation districts, there are no irrigation-induced groundwater mounds (at least up to the present day) in Woolpunda.

For the Renmark Group, as no SIS pumping wells target this layer and the impact from recharge is minimal (due to its depth), it is expected that the Renmark Group potentiometric surface does not change significantly with time and is similar to the steady-state potentiometric surface. This is further supported by the observation wells in this layer, which show minor changes in heads.

Figure 4.4 compares modelled 2009 contours with the latest available observations made at the monitoring wells. The match is again very good and very similar to the steady-state results of Figure 4.2.

4.3.2 CALIBRATION RESULTS – HYDROGRAPHS

There are many observation wells in the model area, so a subset of 86 wells was chosen (see Section 2.3.13). The selected wells either contain reliable long-term historical observation data or are SIS observation wells. Most of the observation wells are located close to the river, so a good match to observations would suggest that the model adequately simulates groundwater gradients to the river. The location of the selected observations wells is given in Figure 2.10.

A comparison of modelled and observed (historical) potentiometric heads in the Lower Mannum Formation indicates a close match in most wells (Figure 4.5) in terms of actual levels and trends. The main exception is that model hydrographs do not match observed fluctuations in head which are likely to be due to changes in river level, as the model assumes that the river level is constant over time (e.g. PGK015, PGK018 and HLD015).

Some hydrographs in the regional areas (e.g. RMK282 and MRK014) match the trend but not the level. However, given their distance from the project area, their impact on the model results (i.e. groundwater flux to the river) should be minimal.

Figure 4.6 shows that model hydrographs in the Renmark Group match well with the observed potentiometric heads except MRK018 which records unexplained changes in head.

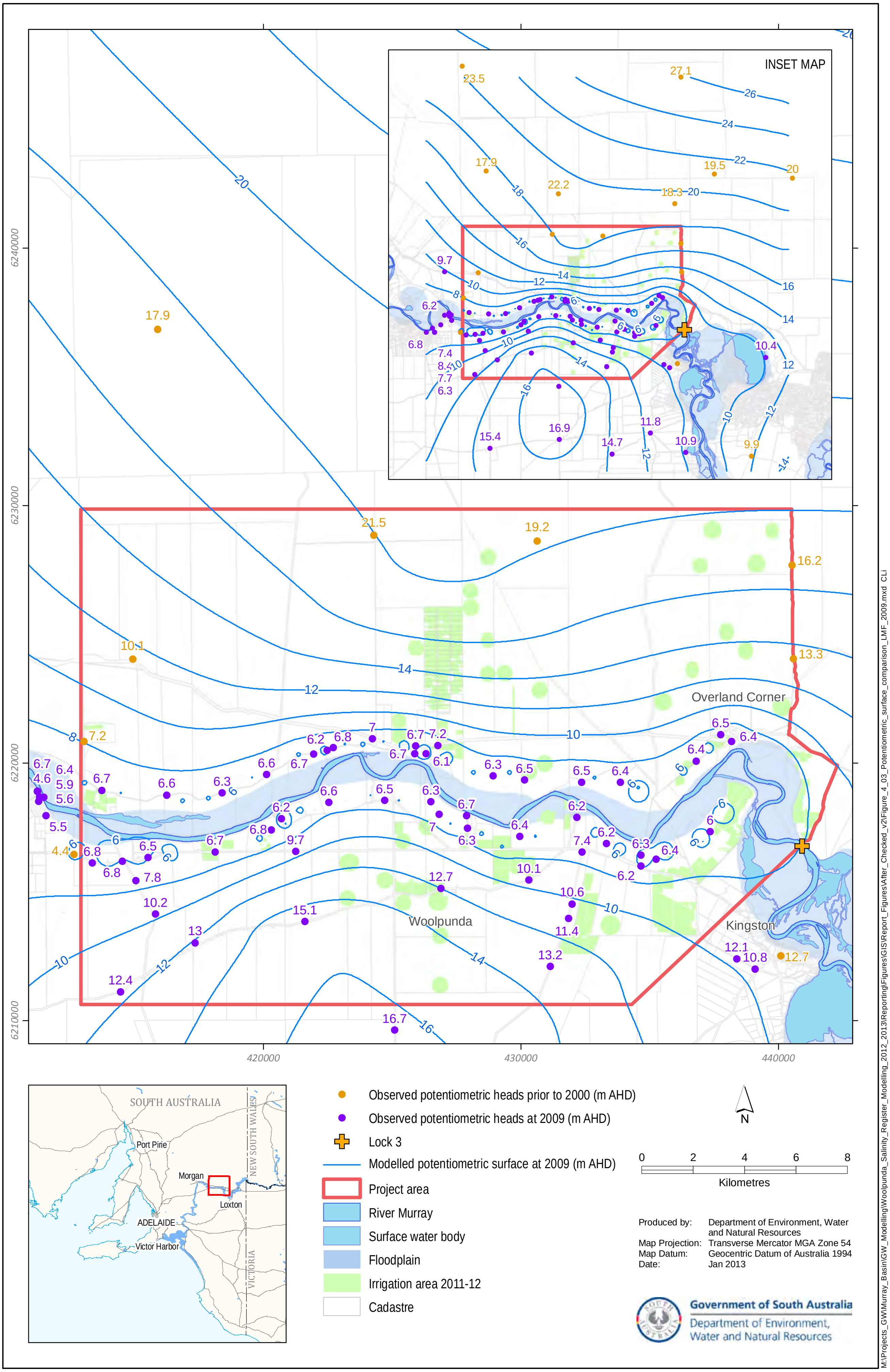


Figure 4.3. Comparison of observed and modelled potentiometric heads for model layer 2 (Lower Mannum Formation 2009)

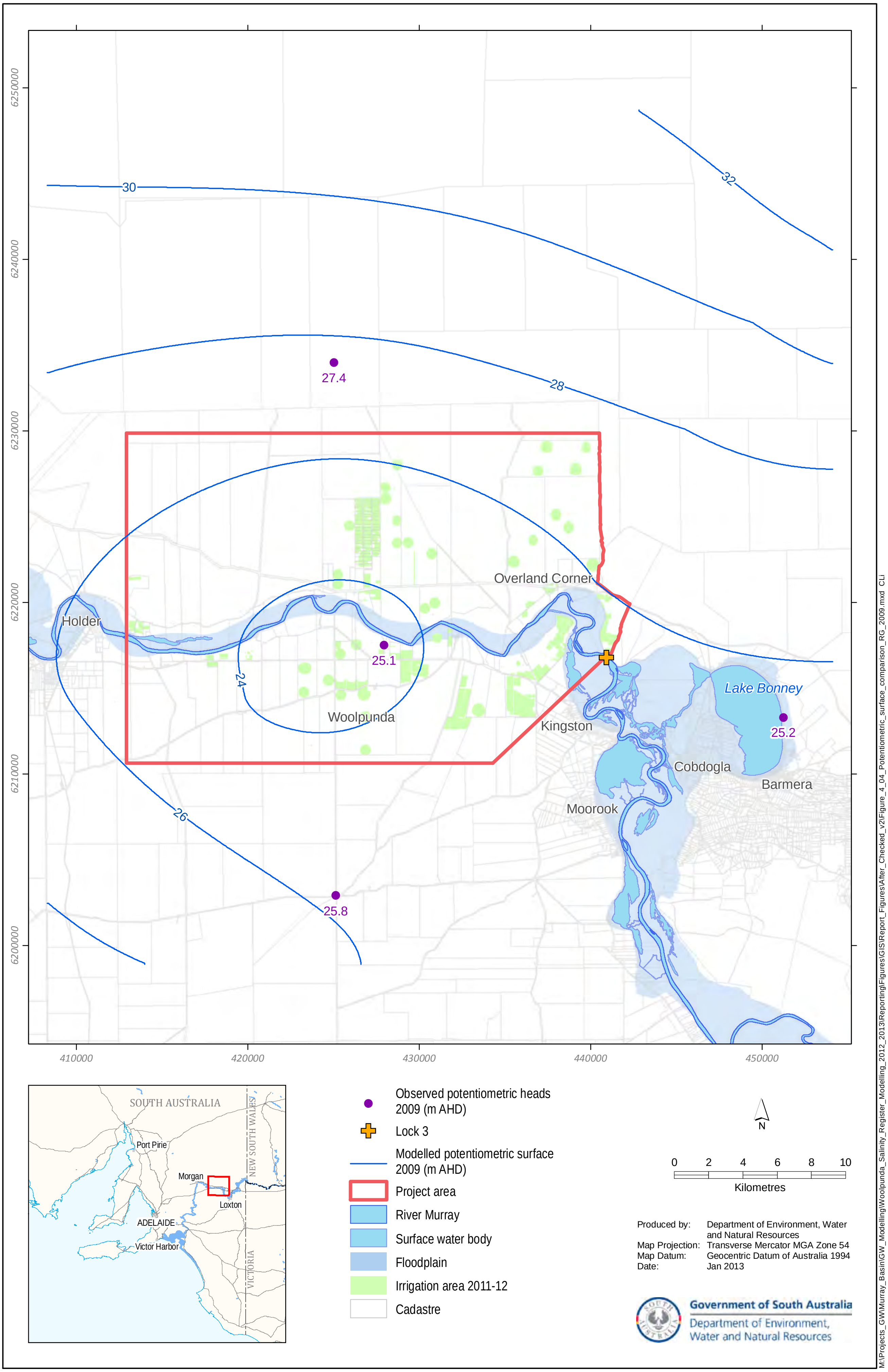


Figure 4.4. Comparison of observed and modelled potentiometric heads for model layer 4 (Renmark Group 2009)

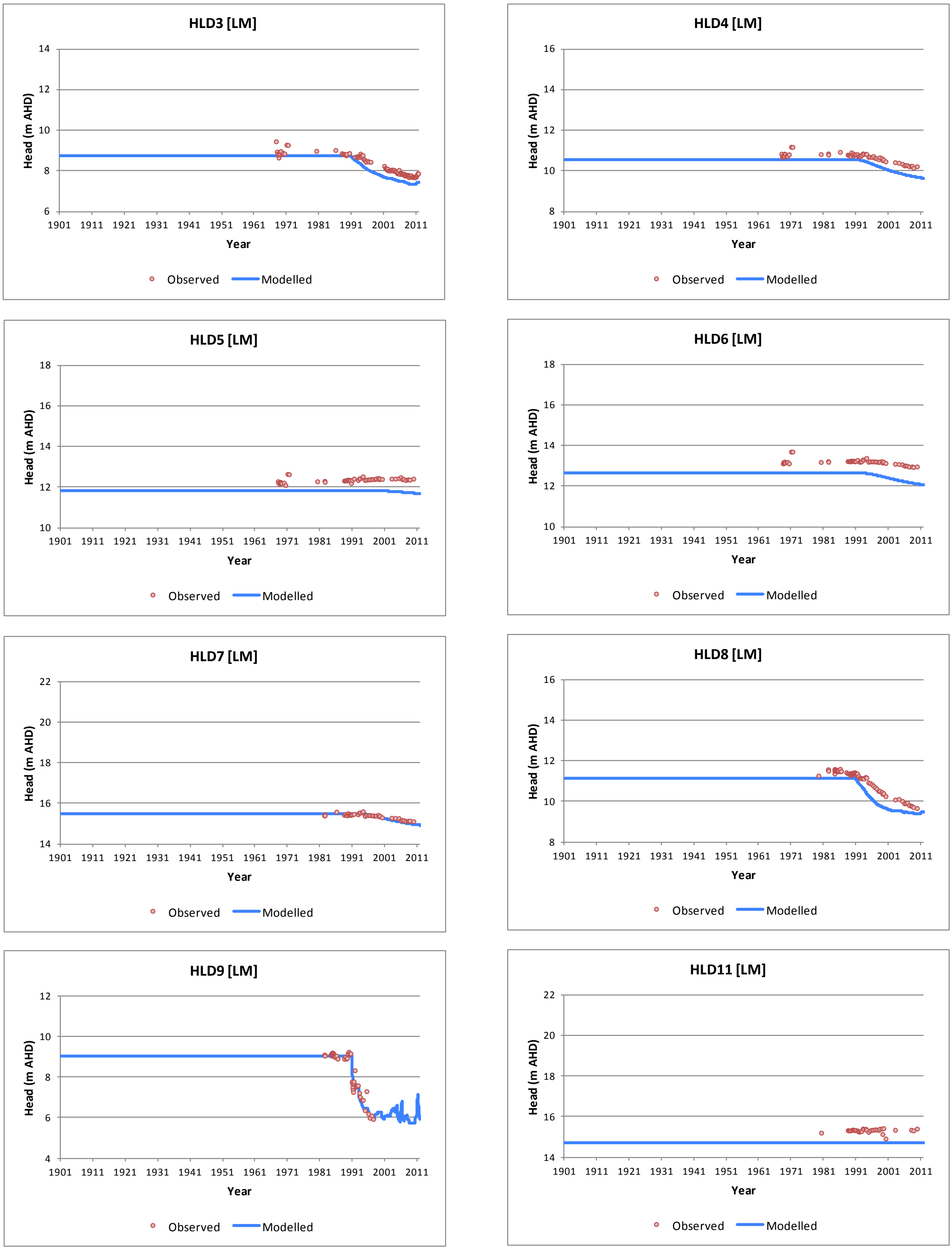


Figure 4.5(a). **Hydrograph comparison between observed and modelled for Woolpunda (Lower Mannum Formation)**

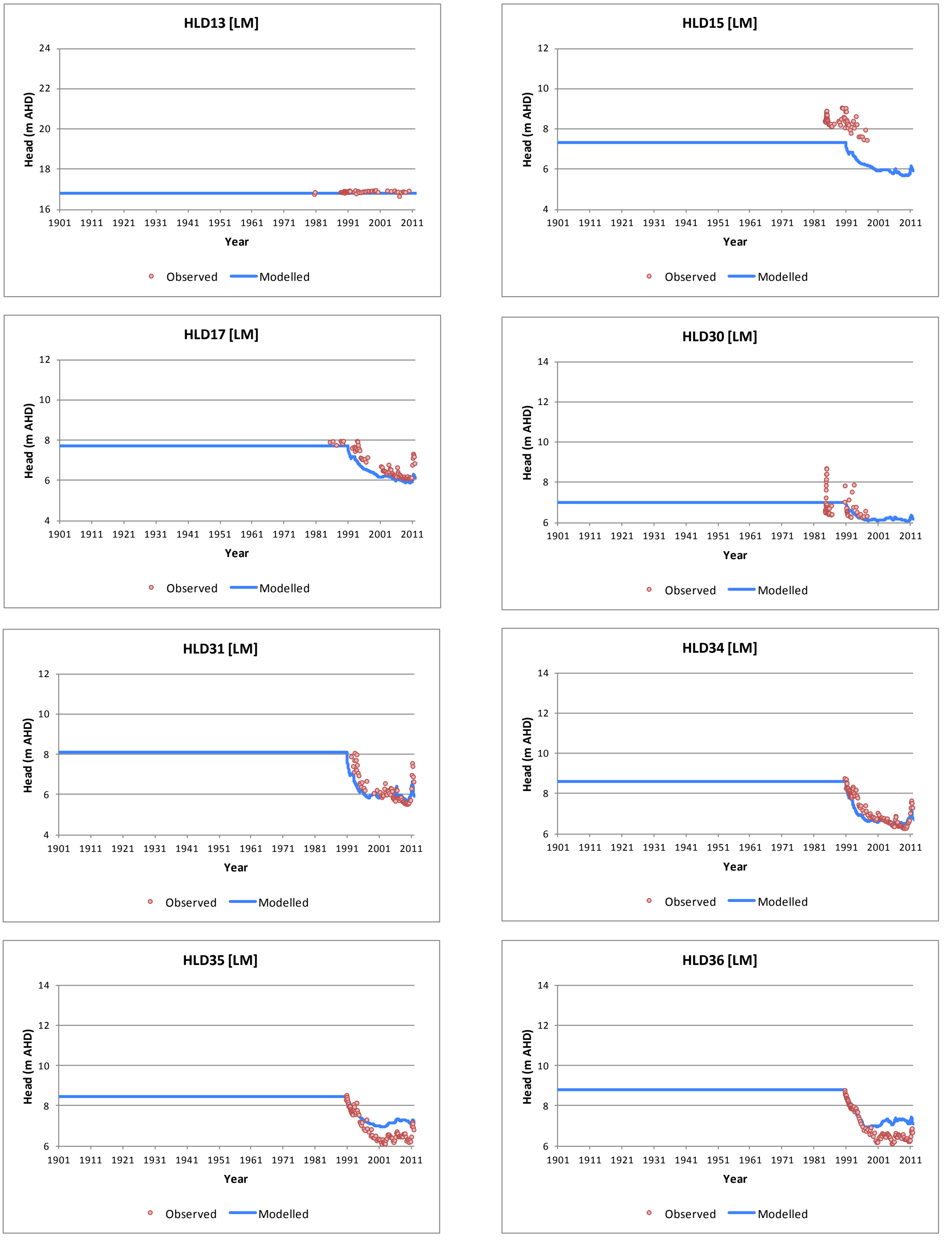


Figure 4.5(b). Hydrograph comparison between observed and modelled for Woolpunda (Lower Mannum Formation)

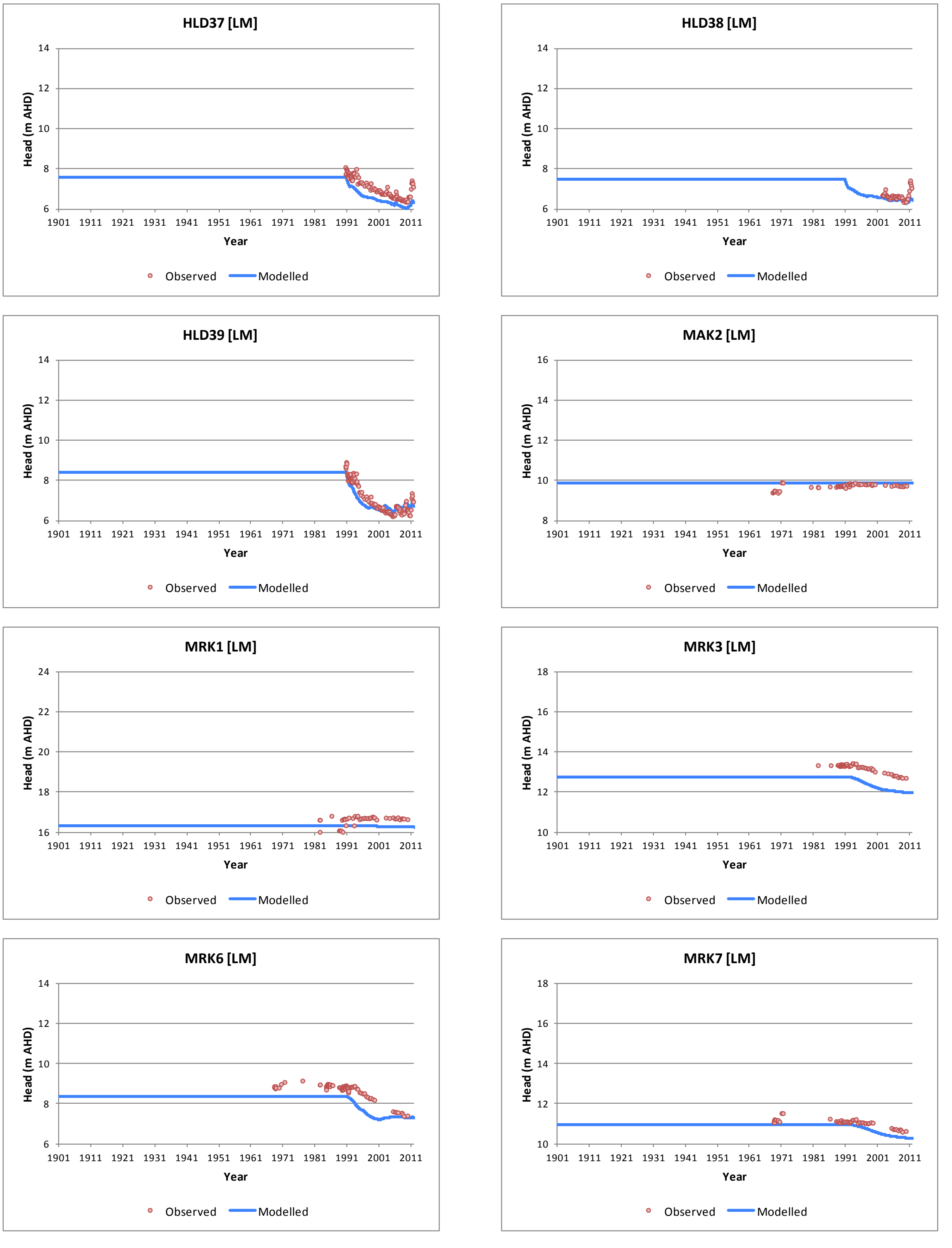


Figure 4.5(c). **Hydrograph comparison between observed and modelled for Woolpunda (Lower Mannum Formation)**

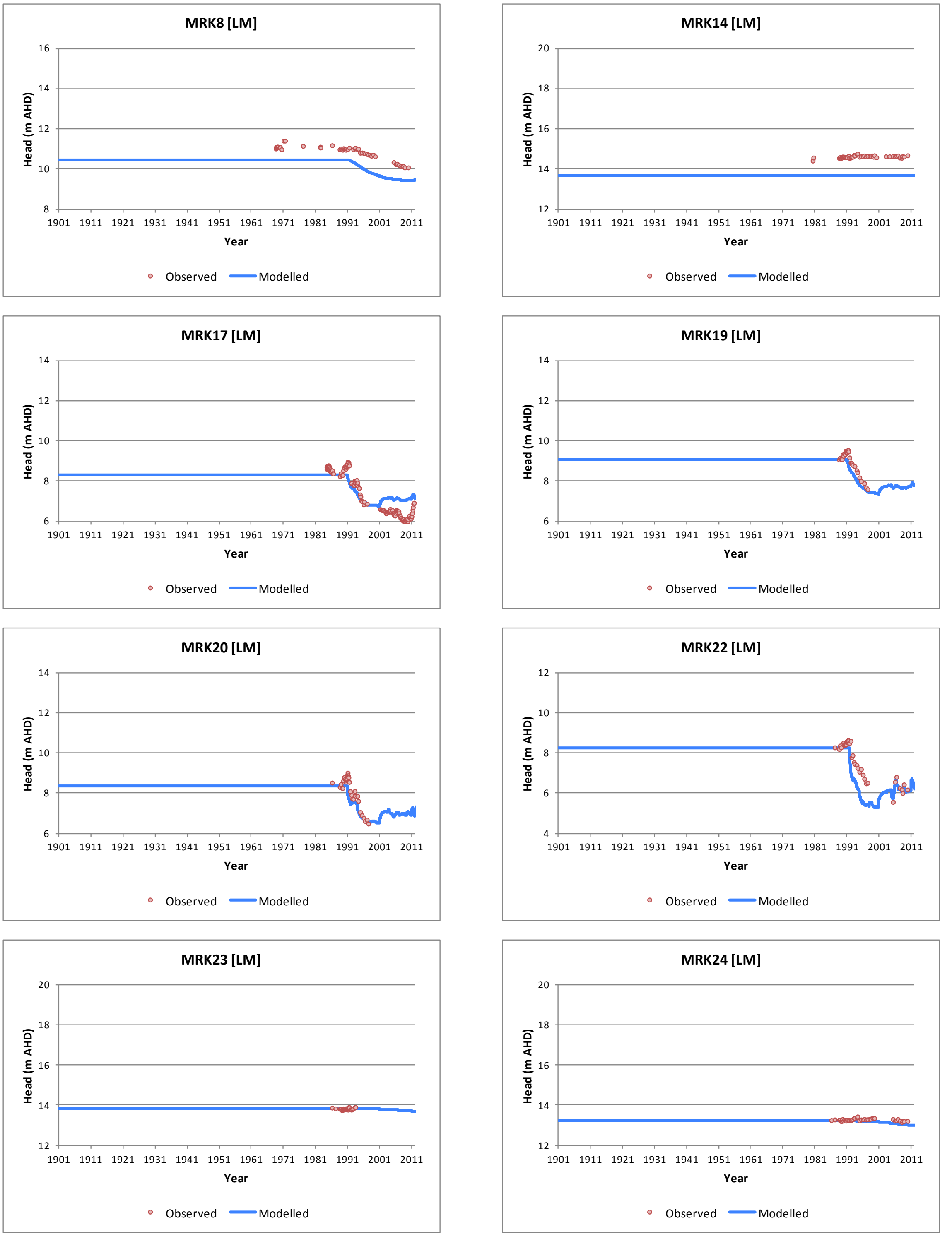


Figure 4.5(d). Hydrograph comparison between observed and modelled for Woolpunda (Lower Mannum Formation)

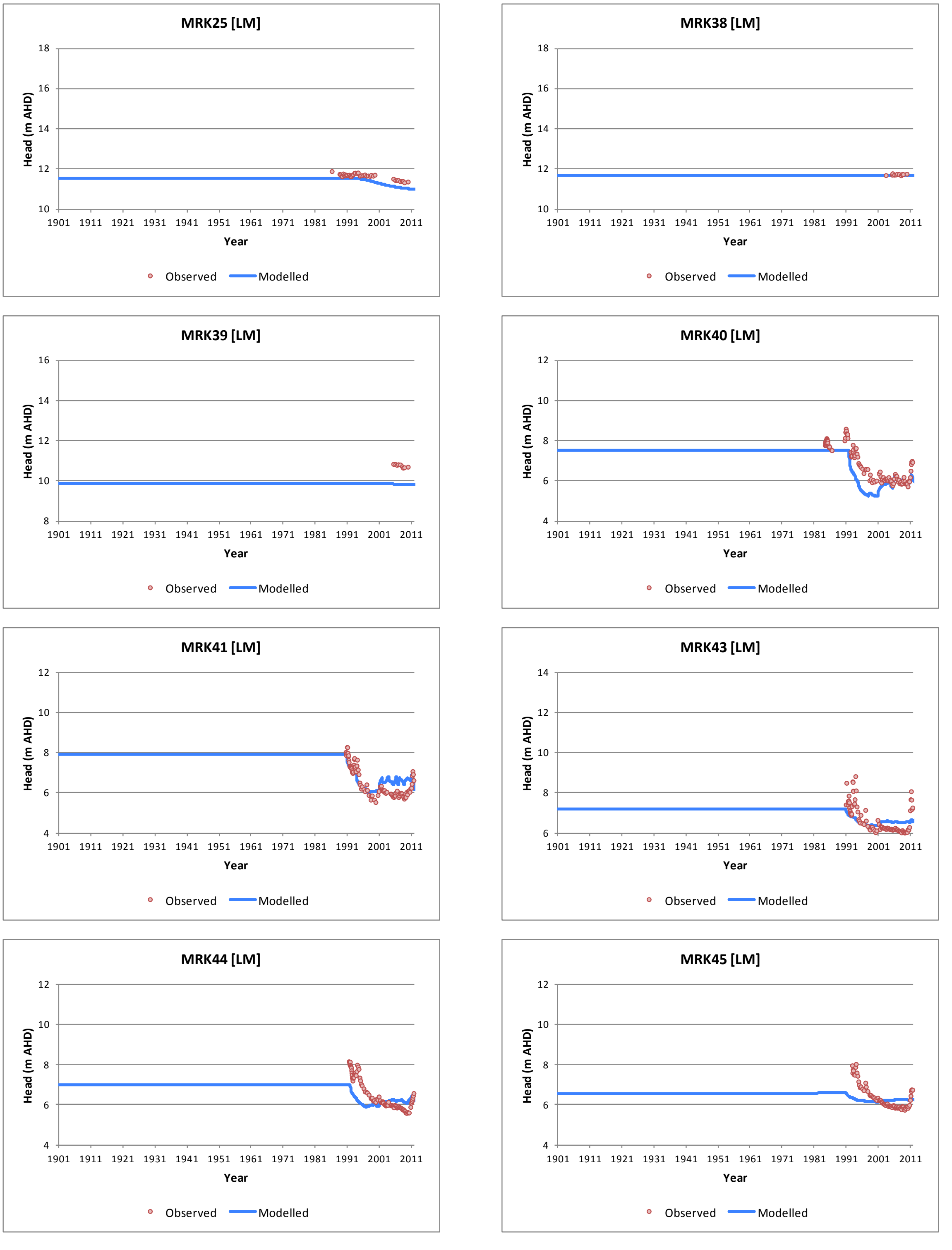


Figure 4.5(e). Hydrograph comparison between observed and modelled for Woolpunda (Lower Mannum Formation)

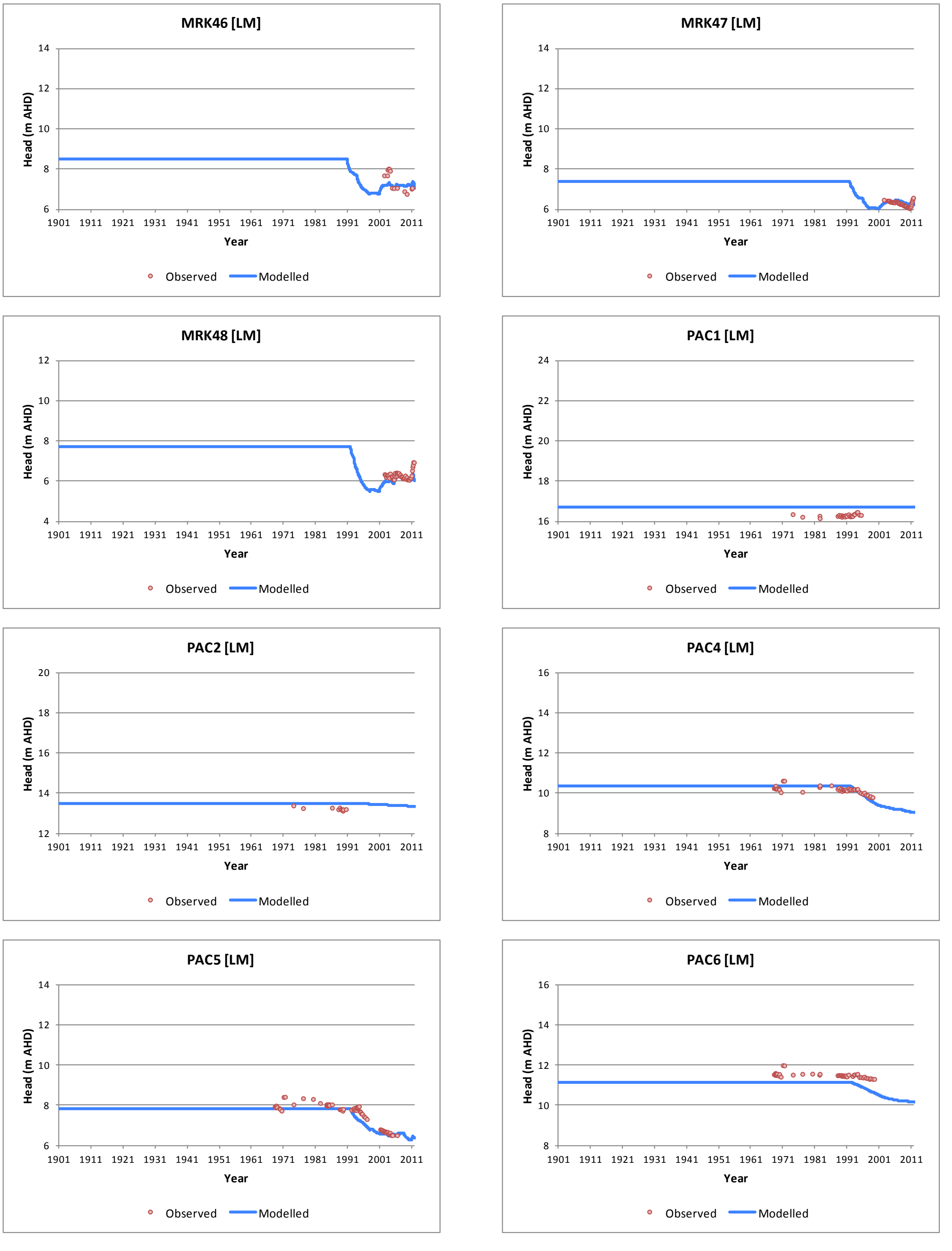


Figure 4.5(f). **Hydrograph comparison between observed and modelled for Woolpunda (Lower Mannum Formation)**

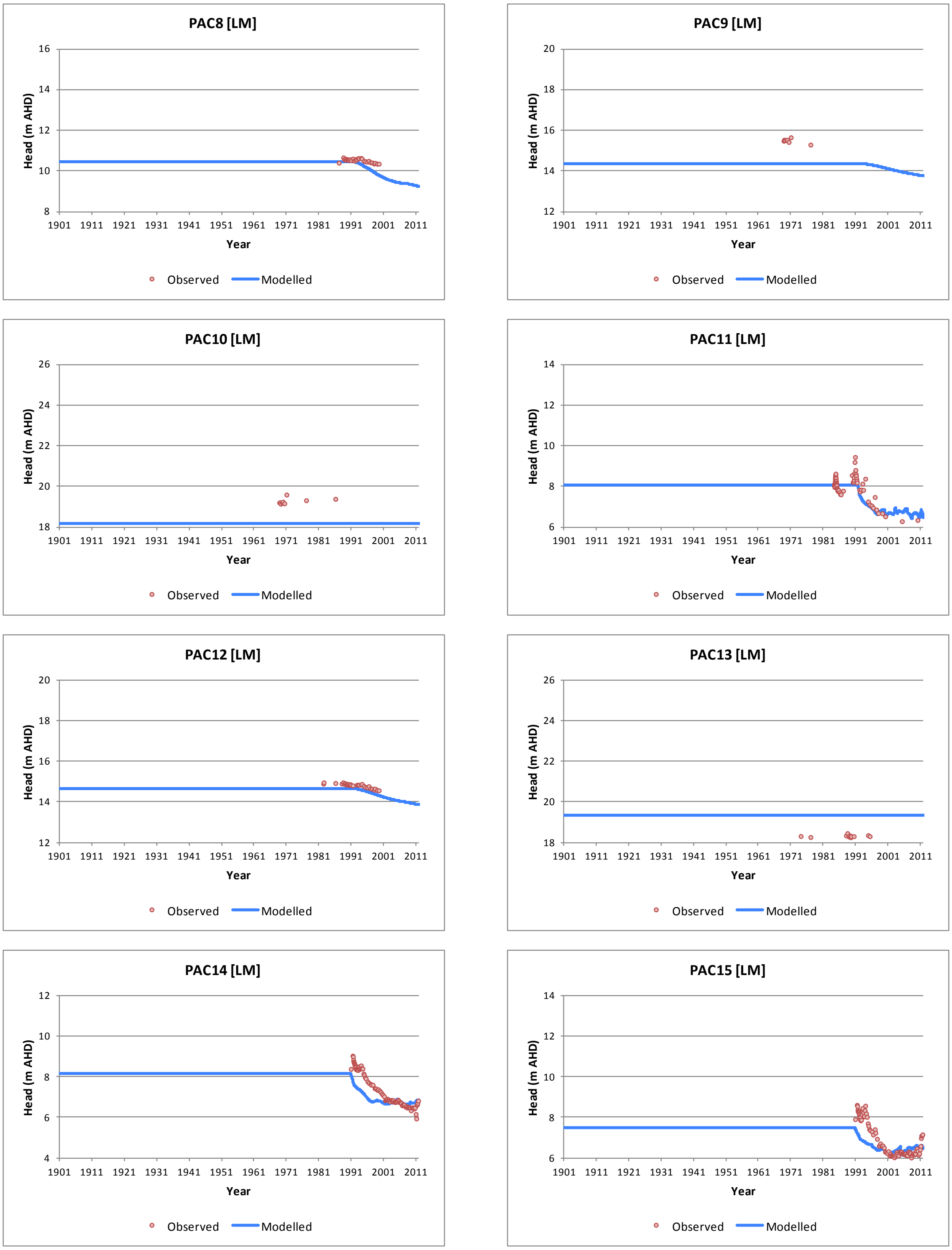


Figure 4.5(g). **Hydrograph comparison between observed and modelled for Woolpunda (Lower Mannum Formation)**

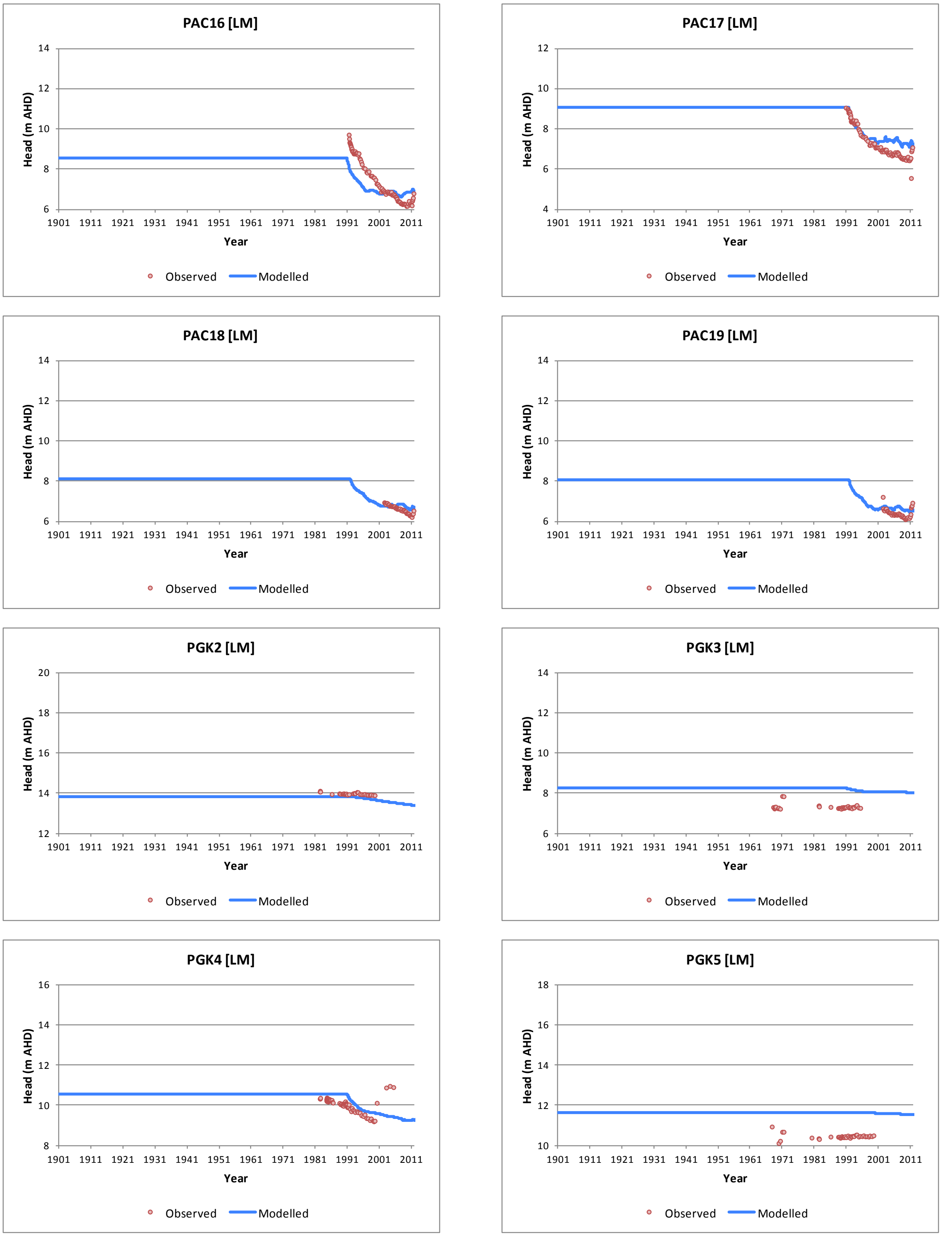


Figure 4.5(h). Hydrograph comparison between observed and modelled for Woolpunda (Lower Mannum Formation)

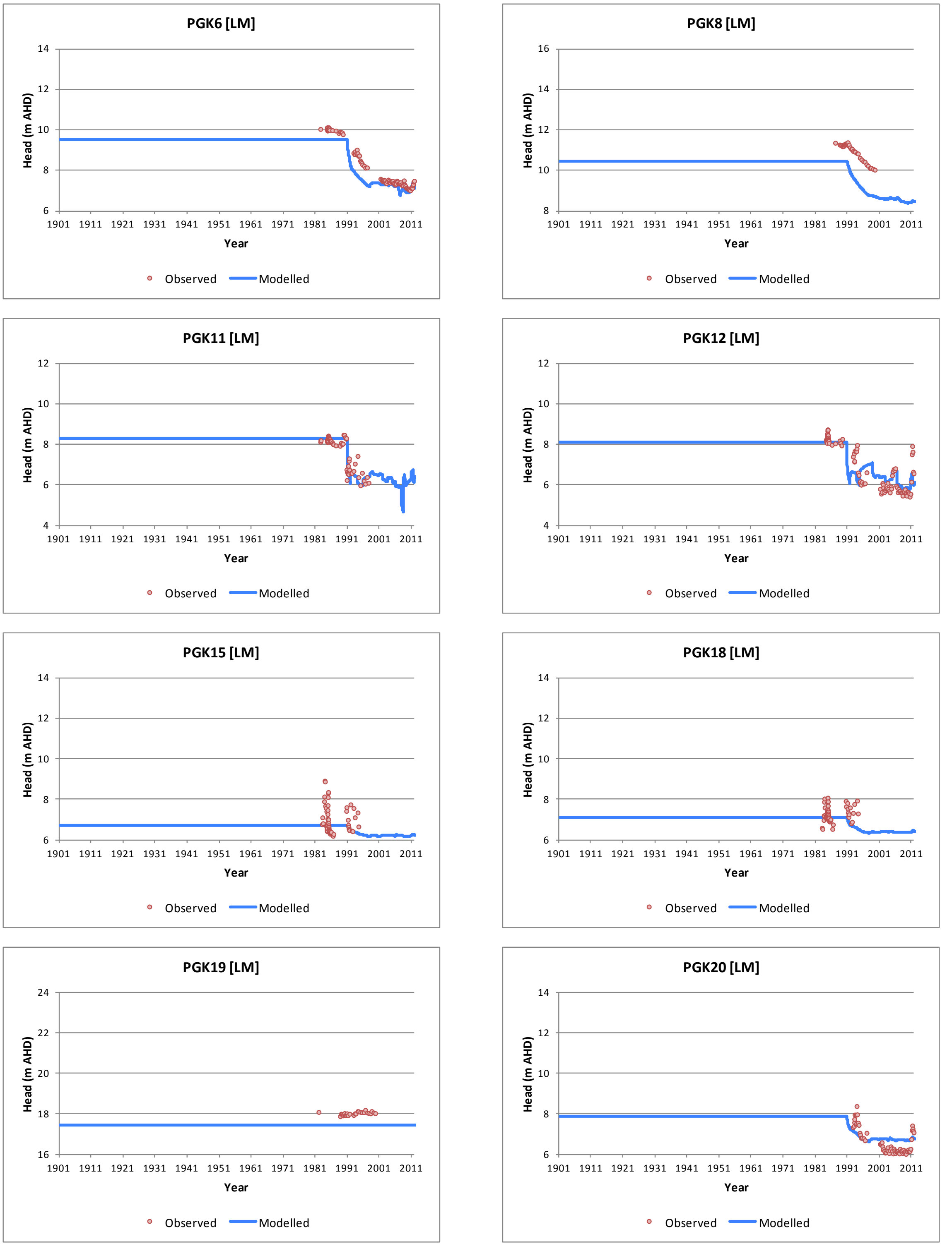


Figure 4.5(i). Hydrograph comparison between observed and modelled for Woolpunda (Lower Mannum Formation)

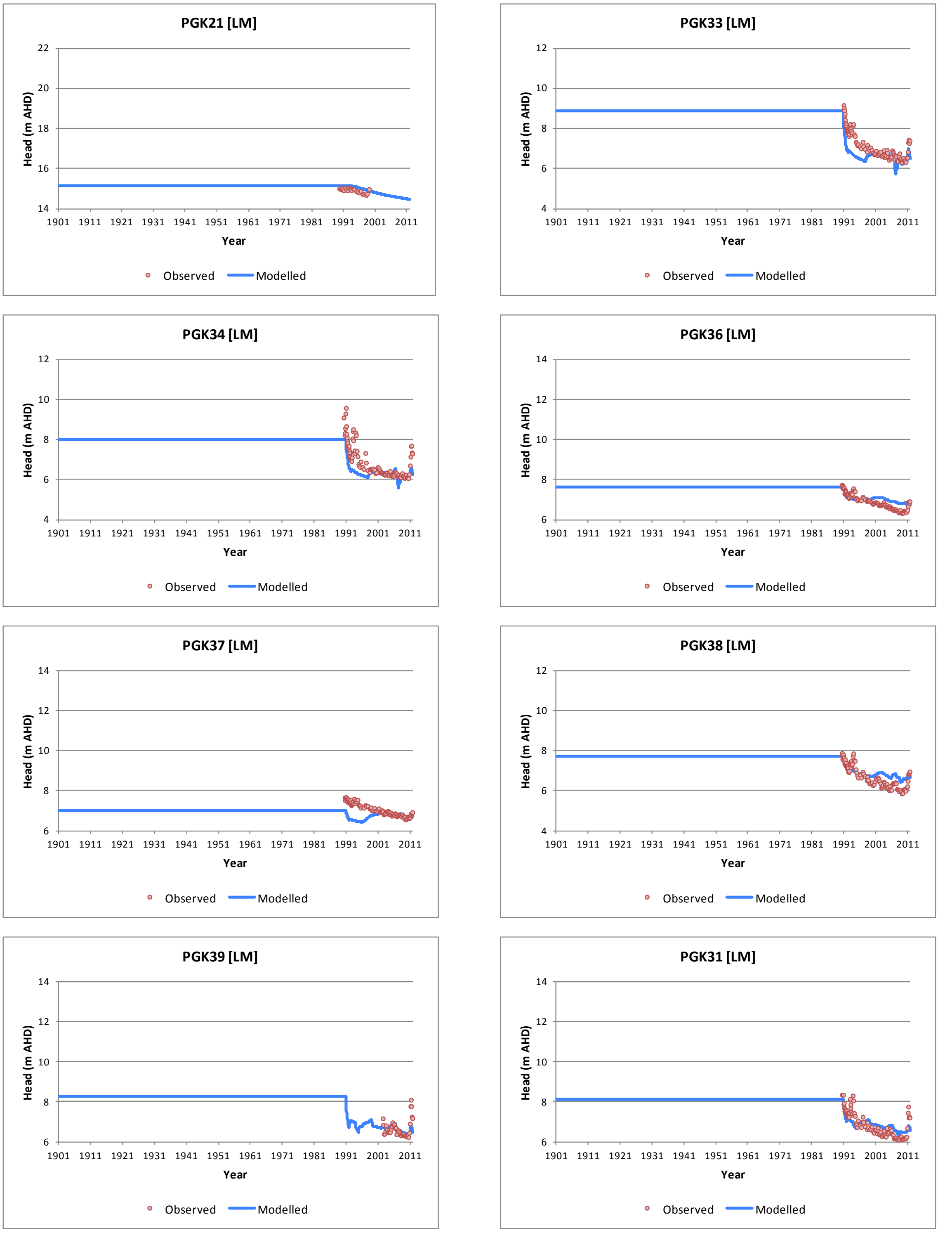
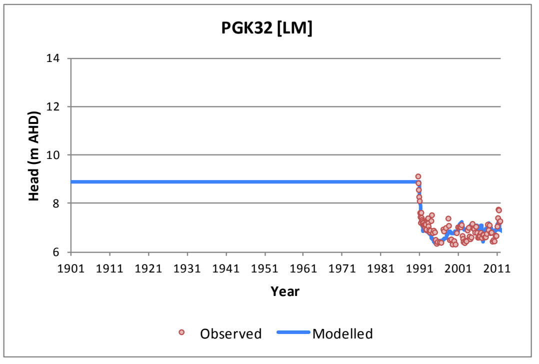


Figure 4.5(j). **Hydrograph comparison between observed and modelled for Woolpunda (Lower Mannum Formation)**



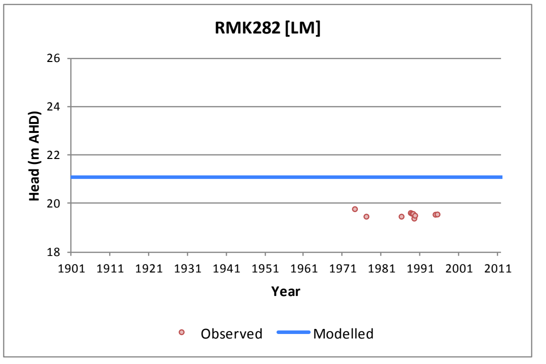


Figure 4.5(k). Hydrograph comparison between observed and modelled for Woolpunda (Lower Mannum Formation)

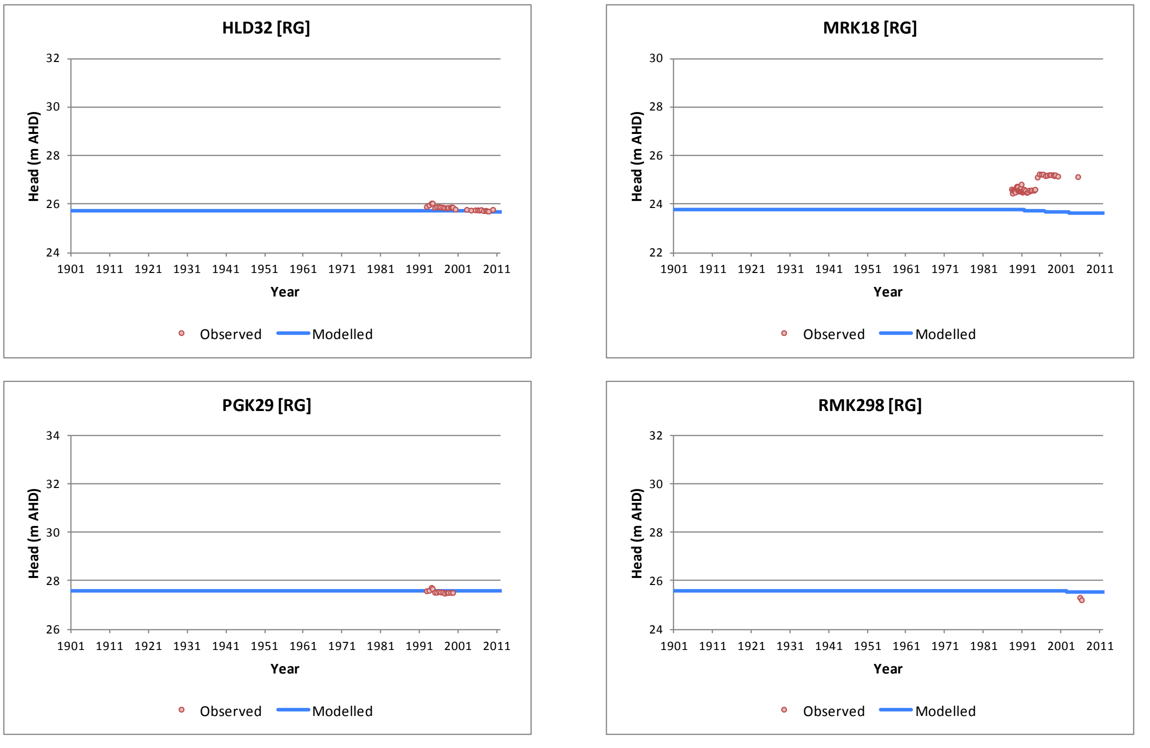


Figure 4.6. **Hydrograph comparison between observed and modelled for Woolpunda (Renmark Group)**

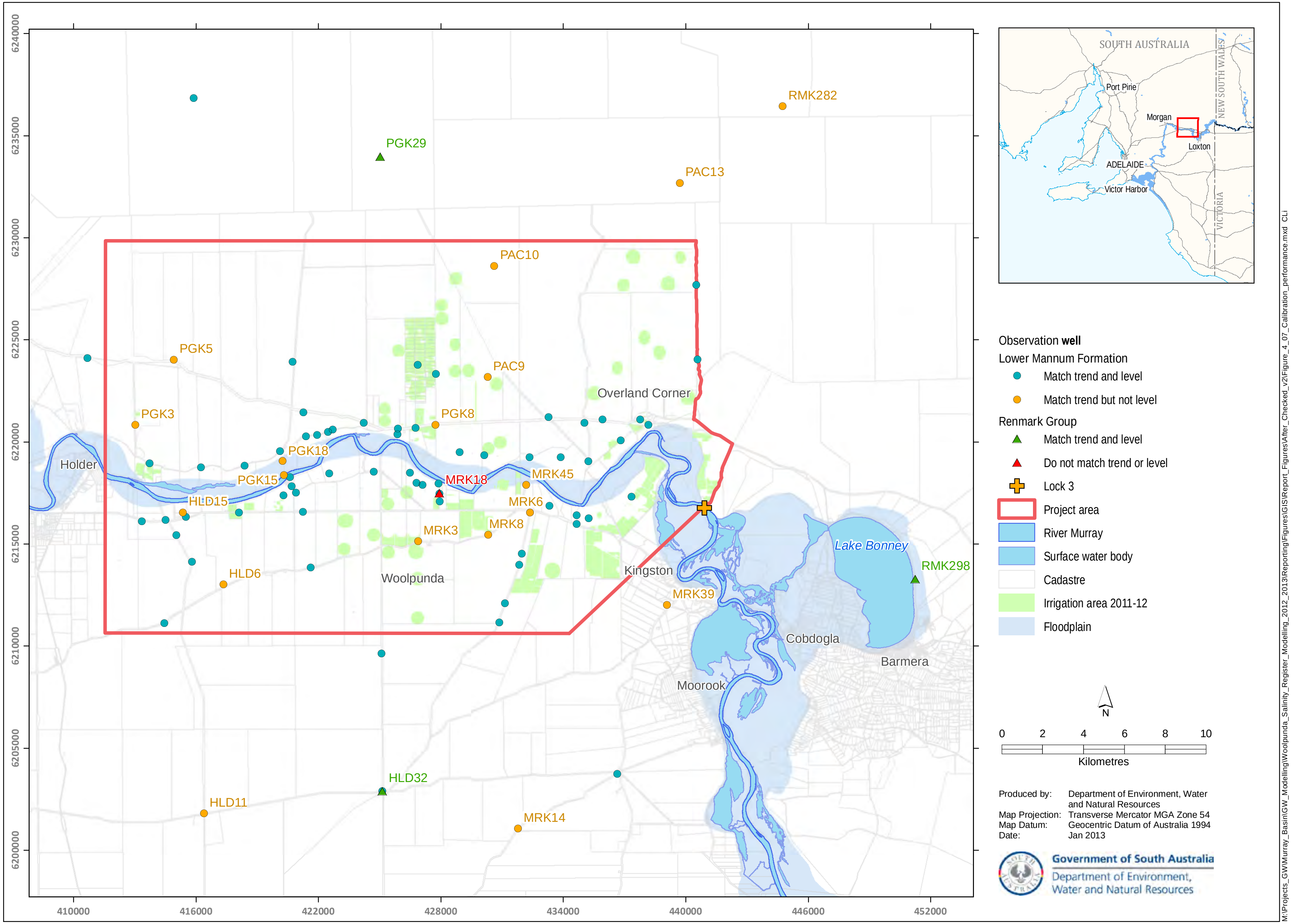


Figure 4.7. Hydrograph calibration performance spatial distribution

Figure 4.7 shows the spatial distributions of hydrograph calibration performance. It is found that 78% of hydrographs (67 wells) show a good match in trend and level (i.e. within 0.5 m of observed head, with correct trend), 21% (18 wells) show a good match in trend but not the level, and only 1% (1 well – MRK018) does not show a match in trend or level.

4.3.3 CALIBRATION RESULTS – ITERATION RESIDUAL ERROR

The SRMS error between observed and modelled heads was calculated for the years 1990, 2009 and 2012. These years span the period during which data are available and represent three different hydrogeological conditions:

- 1990 was before the commencement of the SIS
- 2009 was a time of lowered irrigation recharge, due to improved efficiency and drought restrictions
- 2012 represents current irrigation development and climate.

Figures 4.8 to 4.10 plot observed head against modelled head for the years 1990, 2009 and 2012 respectively. The SRMS is:

- 1990: 3.0%
- 2009: 2.9%
- 2012: 3.2%

The SRMS values are within the commonly-used criteria of below 5% SRMS. Given that most of the observation wells lie close to the Murray and hence provide a reasonable guide to the gradient between the groundwater and the river, these SRMS values indicate a good fit between modelled and observation data over the simulation period.

4.3.4 CALIBRATION RESULTS – WATER BALANCE ERROR

The model water balance error is less than 1% at all times. This is within the criteria defined in the *Groundwater Flow Modelling Guideline* (MDBC 2001) and *Australian Groundwater Modelling Guidelines* (NWC 2012).

4.4 MODEL CONFIRMATION

The calibration has been achieved with the refined hydraulic conductivity values remaining consistent with the available hydrogeological information. While this minimises uncertainty, confirmation through alternative evidence is also needed.

Model results are compared with observed salt loads (Run-of-River), in-stream electrical resistivity (NanoTEM), estimates of accession water volumes and estimated actual groundwater ET rates. These data provide qualitative and quantitative information on groundwater fluxes and the water balance.

4.4.1 SALT LOADS

The salt load entering the River Murray is calculated using the modelled groundwater flux and groundwater salinity for each model flow budget zone (Section 3.8). The resulting calculations of the salt load for the calibrated model are given in detail in Appendices B-3 to B-5.

Groundwater flux to river and salt load are estimated for the Woolpunda reach (river km 393.5–425). Model results for sample years are given in Table 4.1.

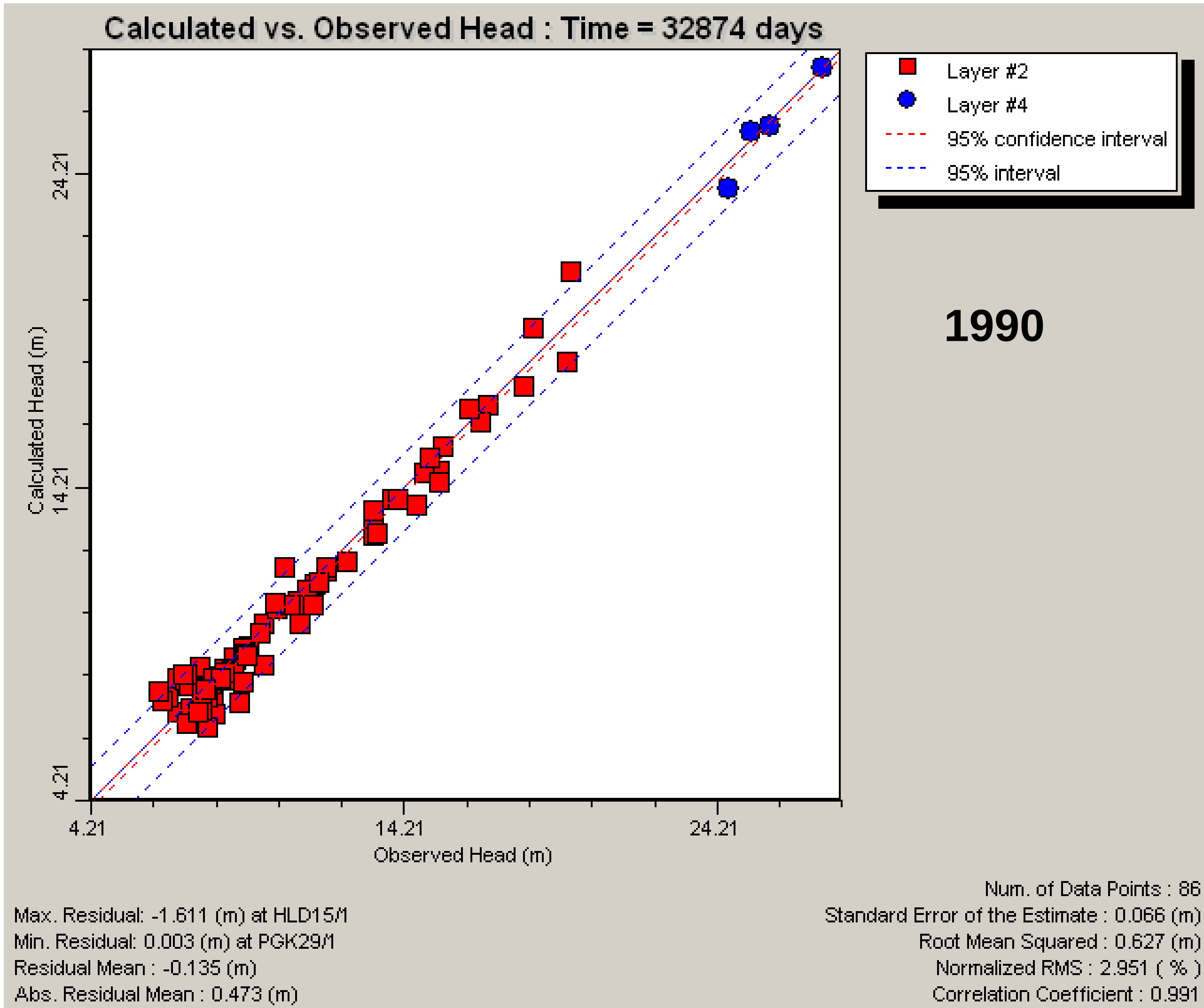


Figure 4.8. Scaled Root Mean Square (SRMS) at 1990

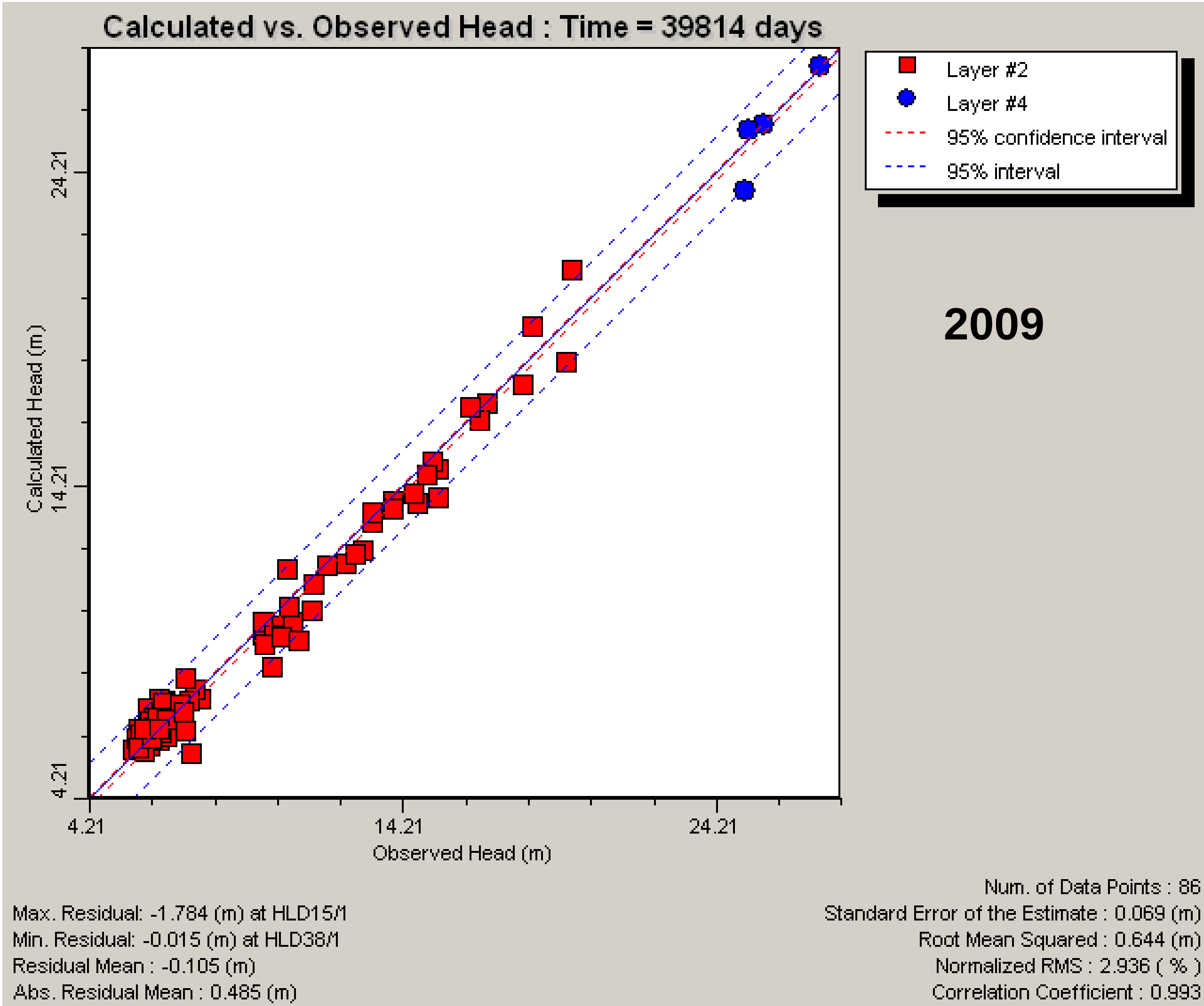


Figure 4.9. Scaled Root Mean Square (SRMS) at 2009

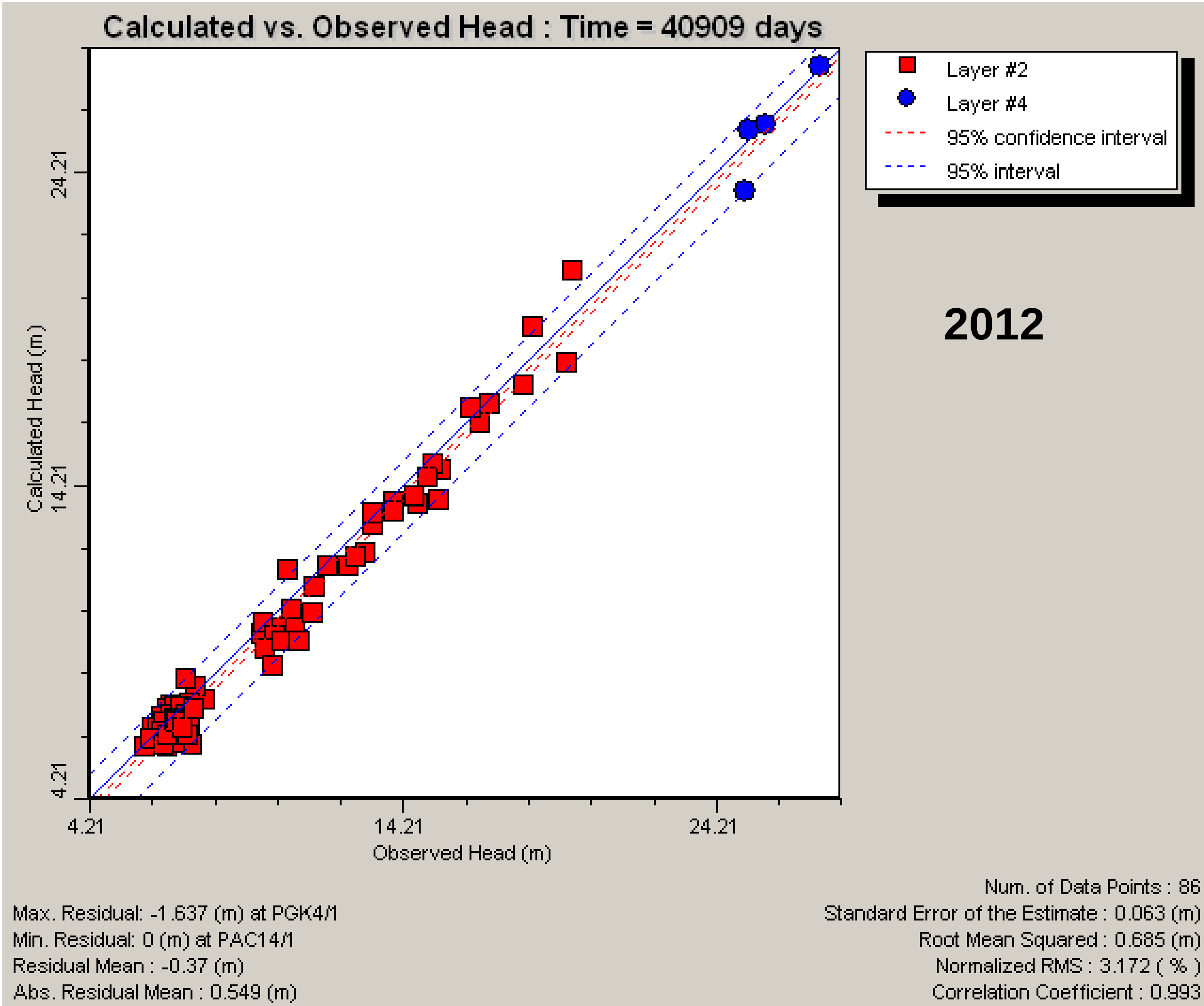


Figure 4.10. Scaled Root Mean Square (SRMS) at 2012

Table 4.1 Modelled groundwater flux and salt load in the Woolpunda calibrated model

Groundwater flux and salt load	Year		
	Steady-state	1990	2012
Flux to river (m^3/d)	8856	8875	1203
Salt load to river (t/d)	190.9	191.3	26.3

Figures 4.11 to 4.13 show the spatial distribution of modelled salt load of the Woolpunda reach for the years 1990, 2005 and 2012. In 1990 prior to the start of the SIS, the zones with the highest salt load are zones 17 to 34. This corresponds to the area where the gradient between the LMF groundwater mound and the river level is steepest (Figure 2.5). This also includes the area where the UMF is not present under the Monoman Formation (the cyan-coloured zone in Figure 3.10).

The Woolpunda SIS commenced in 1991. By 2005, salt loads have reduced sharply near the Woolpunda SIS. Zones upstream of the Woolpunda SIS (zones 43 to 48) show less of a decline in salt loads. These trends continue from 2005 to 2012, except that zones 17 to 19, 31 to 34, and 45 to 48 have slightly increased salt loads. Zones showing an increase in salt load over time lie close to irrigation areas, where short initial lag times mean that recharge has started to reach the watertable.

Figure 4.14 compares Run-of-River estimates of salt loads with modelled salt loads for the Woolpunda reach. While the RoR results exhibit a great deal of variation (as discussed in Section 2.4.1.2), the modelled results show an excellent match to values and trends, especially after the commencement of SIS. There has been a steep decline since the early 1990s due to SIS pumping.

4.4.2 GAINING AND LOSING REACHES

Geophysical surveys of riverbed resistivity (NanoTEM surveys, Section 2.4.1.1) provide information on which parts of the River Murray are gaining or losing reaches. Model results are compared to the 2004 survey (Telfer *et al.* 2005) as representative of “average” conditions where the river is at pool level. Later surveys are affected by severe drought or floods which the model does not aim to simulate.

If the model is simulating salt loads well, there should be a pattern of high observed riverbed resistivity in reaches of low modelled salt load and vice versa. The 2004 NanoTEM data (Figure 2.11) shows the riverbed resistivity and Figure 4.12 shows the 2004 modelled salt load. A comparison is provided in Table 4.2. The correct pattern is seen in all river reaches except for one reach, where the results are equivocal. The comparison increases confidence in the model results.

Table 4.2 Comparison of 2004 observed riverbed resistivities with modelled salt load

River kilometres of reach	Observed riverbed resistivity	Modelled salt load (t/d)	In agreement?
395 – 399	High	Typically 0 Zones 17 and 18 have higher salt loads of 0.3 and 0.9	Yes
400 to 416	Moderate	0.5 to 3.8	Yes
417 to 421	High	0 to 0.1	Yes
422 to 426	Moderate	Typically 0 Zones 41 and 42 have higher salt loads of 1.1 and 1.5	Not clear
427 to Lock 3	Very low	1.3 to 8.9	Yes

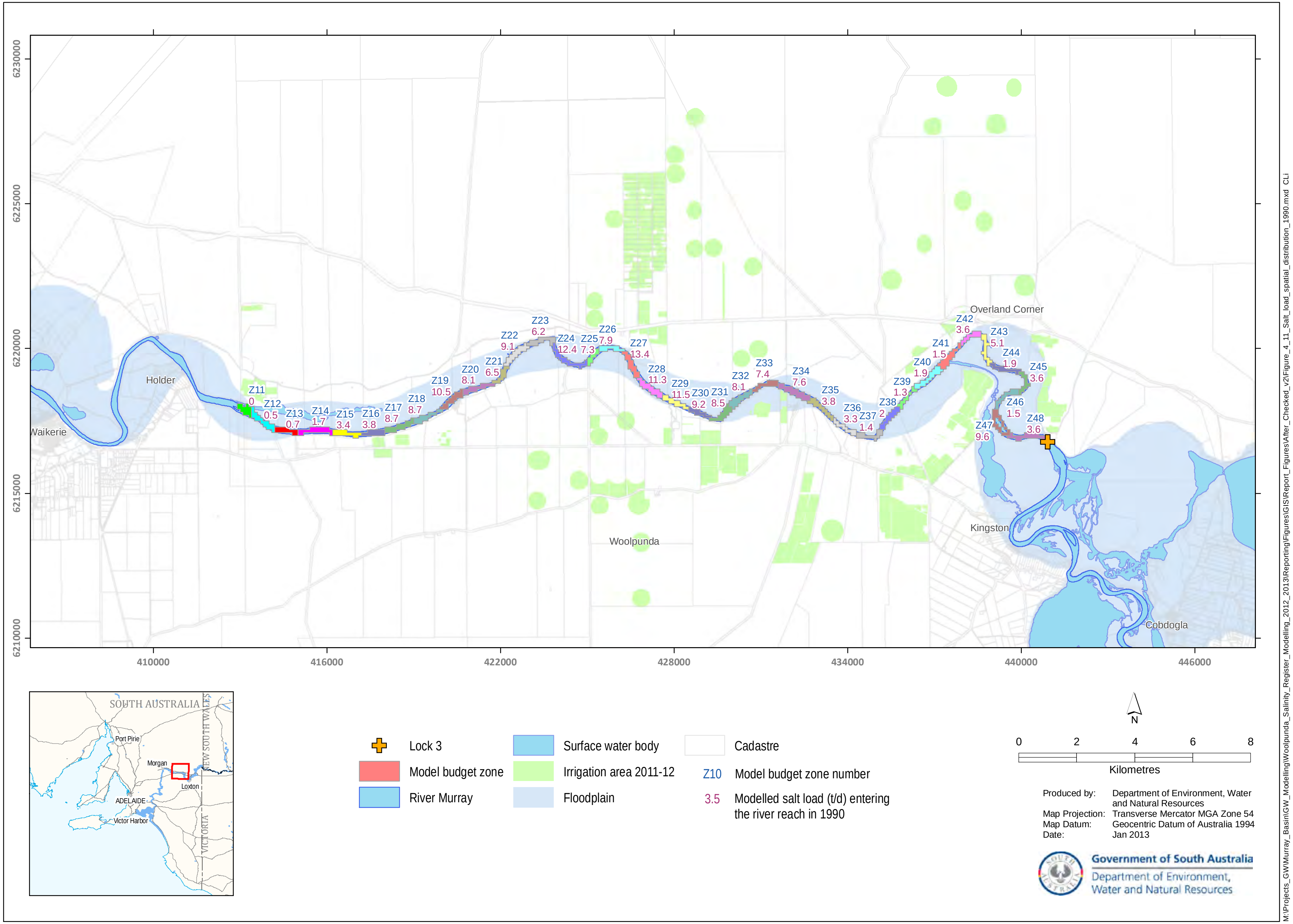


Figure 4.11. Modelled salt load spatial distribution at 1990

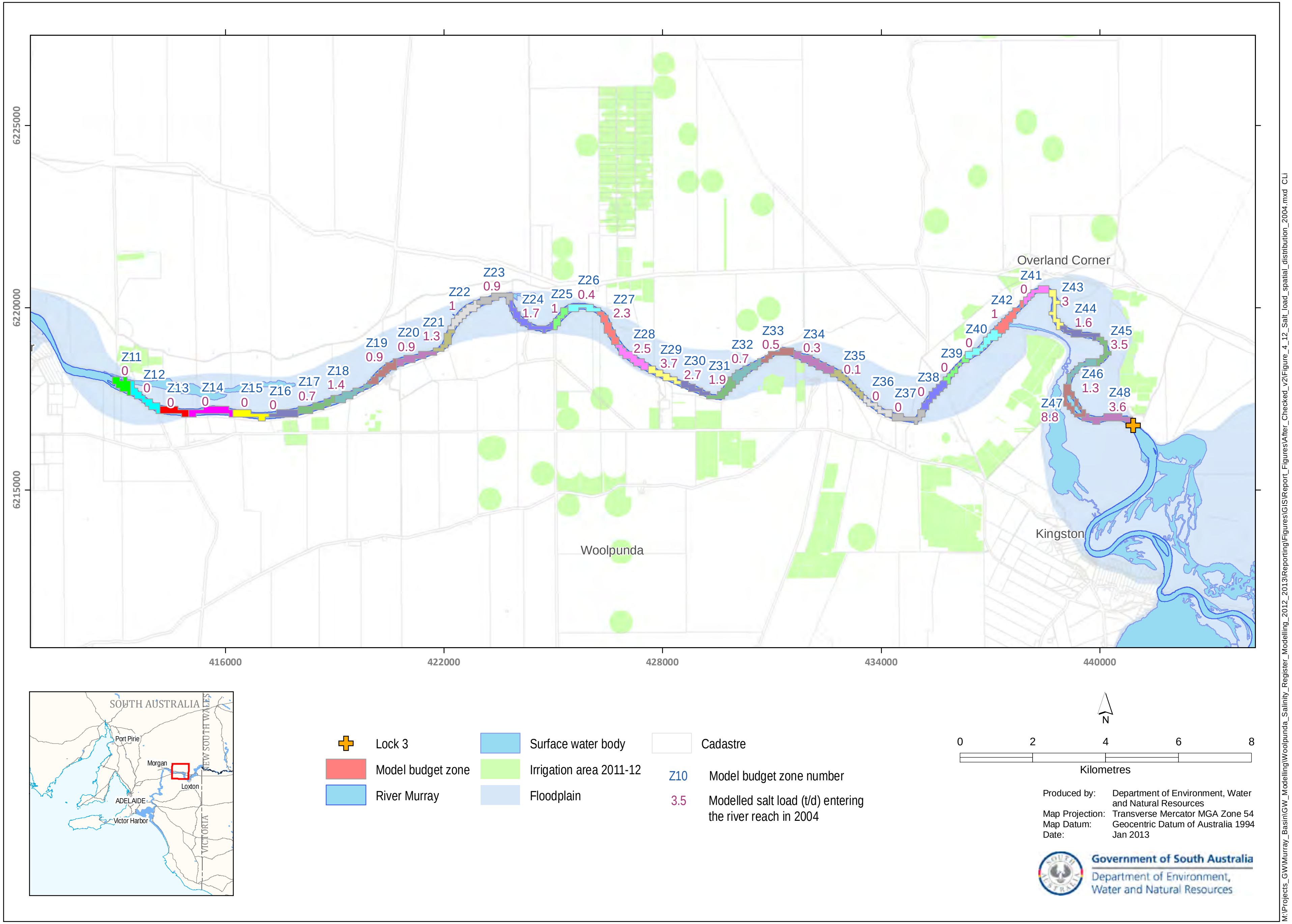


Figure 4.12. Modelled salt load spatial distribution at 2004

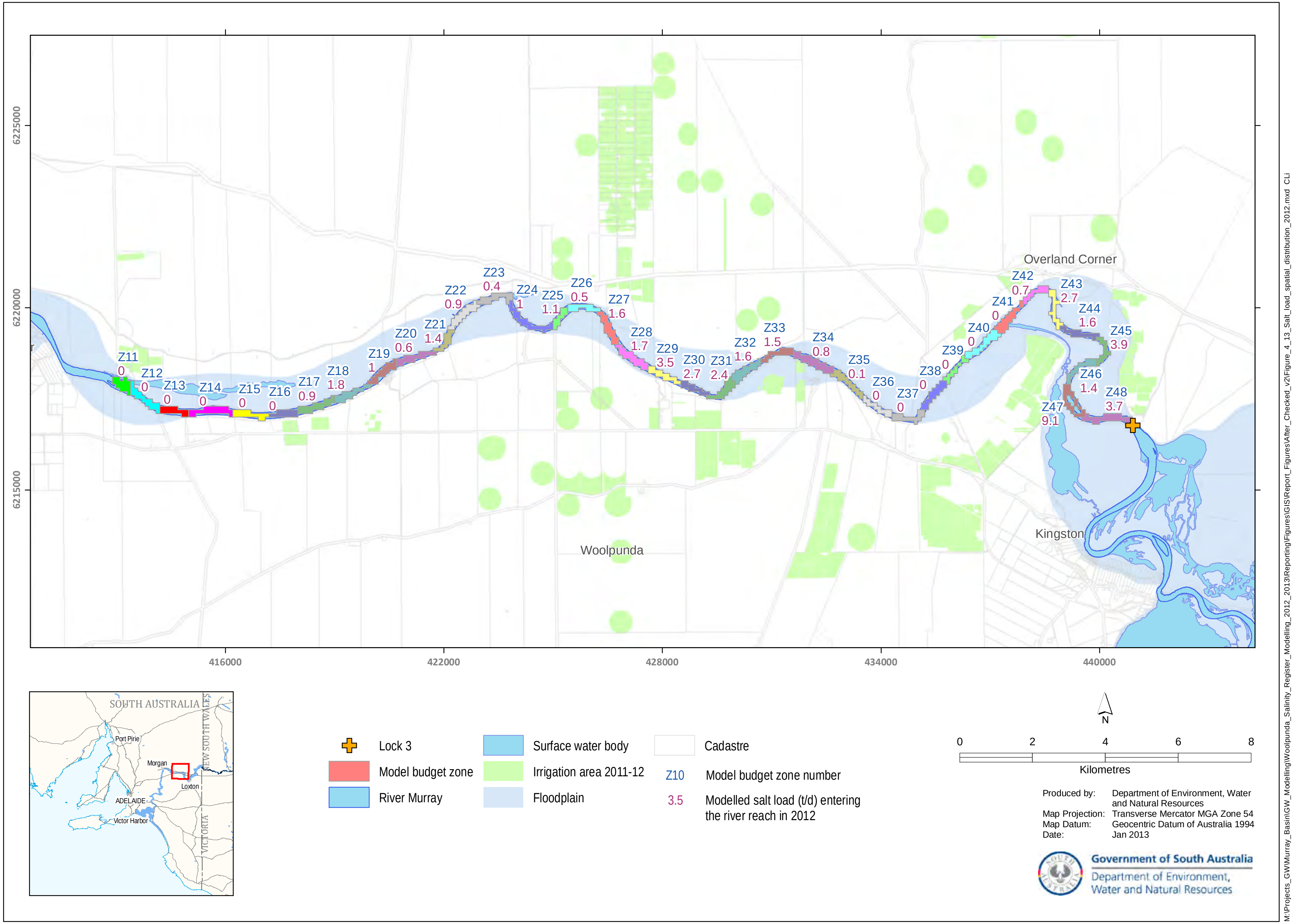


Figure 4.13. Modelled salt load spatial distribution at 2012

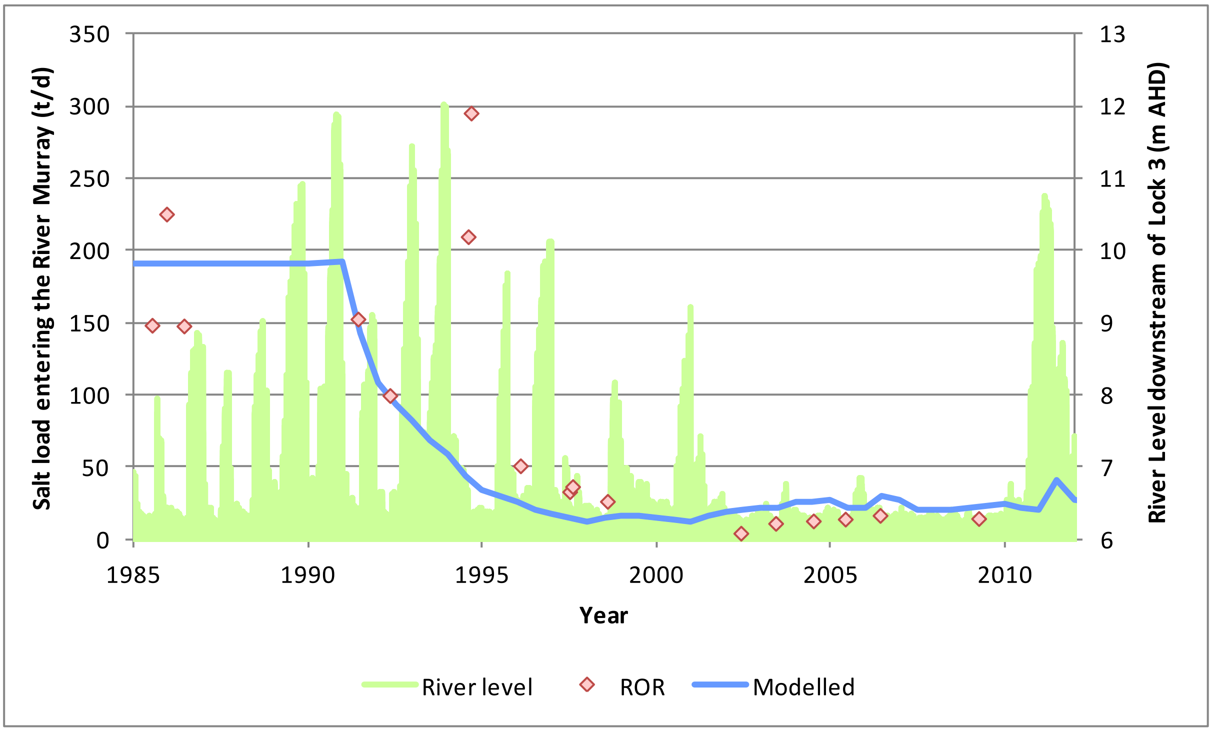


Figure 4.14 **Salt load comparison between Run-of-River measurements and the calibrated model outputs for Woolpunda**

4.4.3 RECHARGE VOLUMES

Some previous reports on Salinity Register models have compared independent estimates of accession water volumes with modelled recharge rates (e.g. Yan, Li and Woods 2012). The modelled recharge rates were selected during calibration, i.e. determined through inverse modelling, so this check was helpful in assessing the success of the calibration.

The recharge rates adopted for the Woolpunda model scenarios are not based on calibration (Section 4.3). Instead they are derived from the accession estimates (Vears 2013, in Appendix C-1) except that the decrease during the drought years 2005 – 2010 is omitted. For each cell which becomes irrigated, the initial lag time at that location between irrigation at the ground surface and the arrival of recharge to the watertable is based on SIMRAT model estimates (Section 3.7.3.3). The sum of the accession water recharging the watertable can then be calculated for each timestep. A comparison between the accession estimates and the total modelled recharge rates for the Woolpunda model will show them to be consistent by definition, but the total modelled recharge will not have exactly the same curve over time as the total accession estimates. This is because the lag time varies spatially and recharge from irrigation areas starting in a given year will not all reach the watertable at the same time.

Figures 4.15 and 4.16 compare the irrigation accession estimates of Vears (2013) and modelled recharge volume for permanent and pivot irrigation, respectively. The time axes of the figures extend far beyond the end of the historical calibration period (2012) to show the rising trend of modelled recharge volume in the future years. This implies that though the impact of irrigation on recharge is currently minimal, it can become more pronounced in the future.

The difference between the accession estimates and the modelled recharge is due to (i) the lag times applied to different irrigation areas and (ii) the fact that the decrease during the drought years is not modelled. Permanent irrigation began in 1972 and recharge commenced between 1980 and 2012, while pivot irrigation began in the 1990s and recharge commenced between 2025 and 2035.

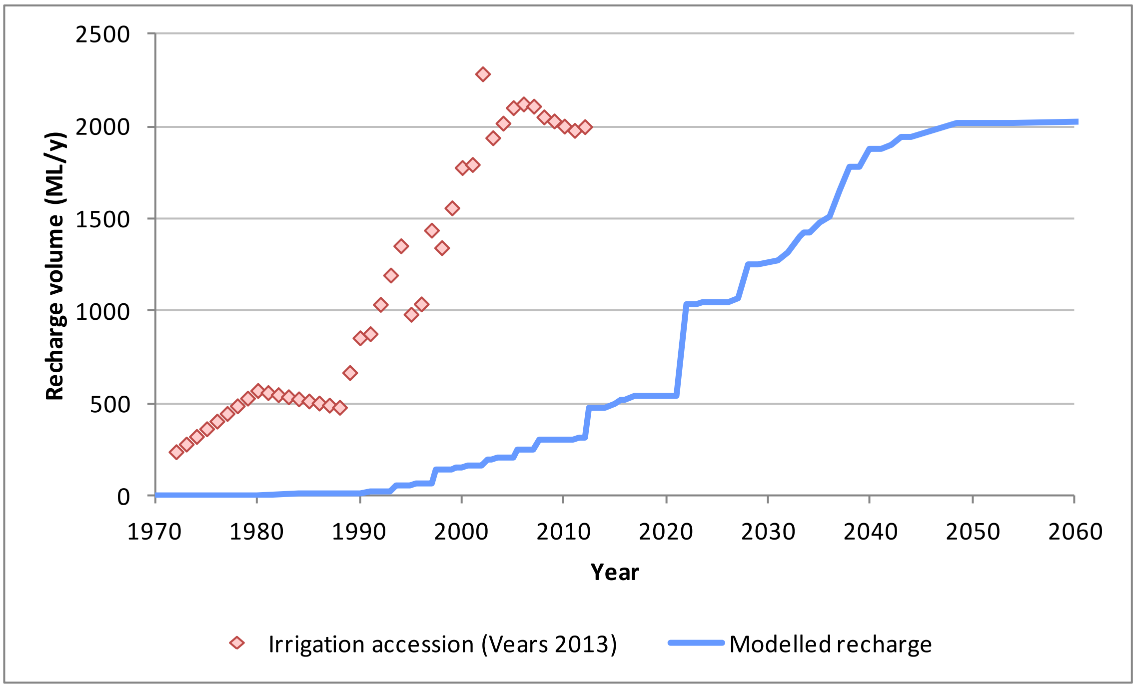


Figure 4.15 Comparison between calculated accession estimates (Vears 2013) and the calibrated modelled recharge volume for permanent irrigation

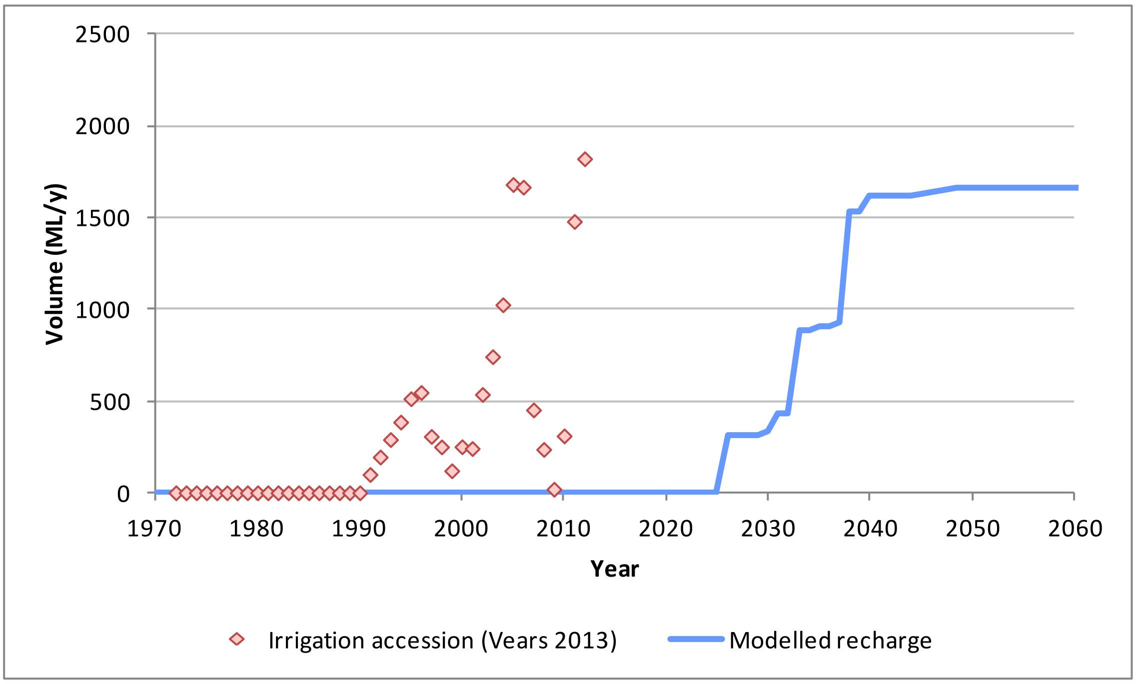


Figure 4.16 Comparison between calculated accession estimates (Vears 2013) and the calibrated modelled recharge volume for pivot irrigation

4.4.4 GROUNDWATER EVAPOTRANSPIRATION

There has been no research undertaken in the project area on groundwater ET on the floodplain area. CSIRO has investigated groundwater ET rates in Rilli's Floodplain at Loxton and the Bookpurnong floodplain (Holland *et al*. 2001; Doody *et al*. 2009). A recent unpublished study indicates that average actual groundwater ET rates on floodplains may be in the range of 60–80 mm/y, assuming that woodland covers 30 to 40% of the floodplain (K Holland, CSIRO, 2011, pers. comm.).

The calibrated model has a specified maximum (i.e. potential) groundwater ET rate of 250 mm/y and an extinction depth of 1.5 m, which are consistent with previous studies (Yan *et al.* 2005; Yan and Stadter 2008). The model result (Figure 4.17) shows that about 88 mm/y of groundwater is lost as ET (i.e. actual groundwater ET) in the floodplain within the model domain. This is very close to the floodplain ET in CSIRO's Loxton – Bookpurnong study. Groundwater ET depends on soil type, plant cover, groundwater salinity, depth to the watertable, climate and other factors which may differ from site to site. The sensitivity of the model to groundwater ET parameters is explored in Section 6.

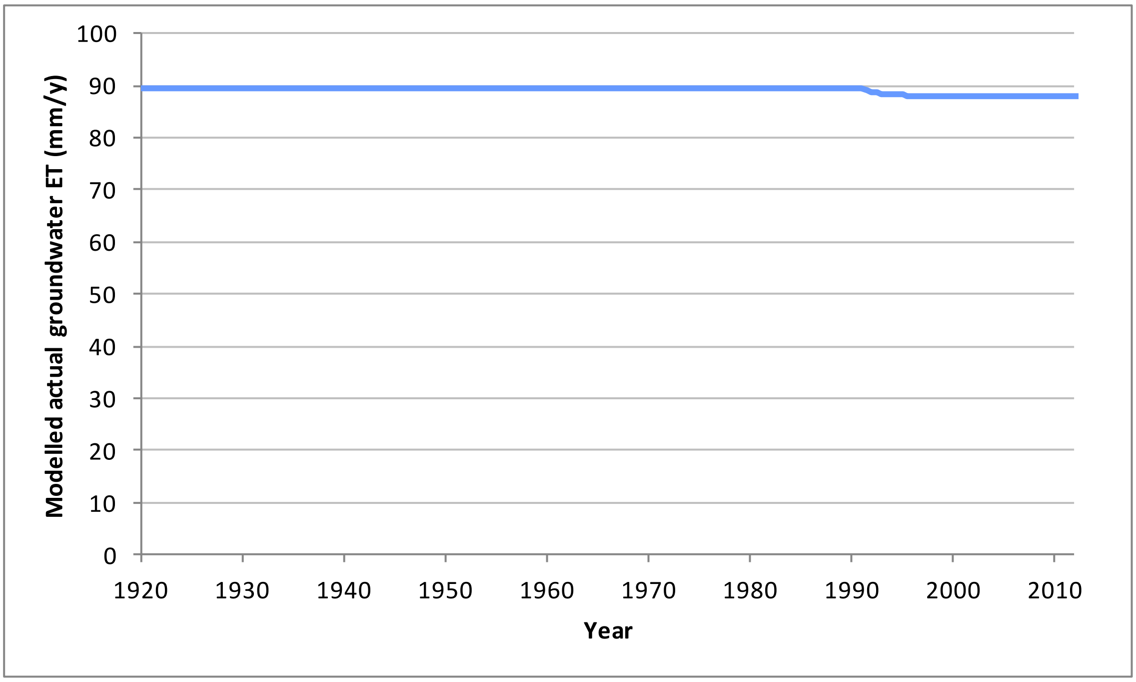


Figure 4.17 Modelled actual groundwater evapotranspiration

4.5 MODEL WATER BALANCE

Table 4.3 reports the water balance for the Woolpunda project area in model Layer 1 (Upper Mannum, Loxton Sand and Monoman Formations) and Layer 2 (Lower Mannum Formation and undifferentiated Murray Group). The water balance of the Ettrick Formation and Renmark Group is presented as a source of water to the Mannum Formation. The details of flow are given for the steady-state period (prior to irrigation), the beginning of 1990 (prior to SIS) and 2012 (latest year in the calibration period and including SIS).

Under the natural conditions of the steady-state model, most of the flows into the aquifers were from the vertical flux from the Renmark Group (13.78 ML/d) and lateral regional flow into the project area

(5.14 ML/d). Recharge from rainfall and river leakage adds relatively a minor 0.14 ML/d and 0.94 ML/d, respectively. Outflow from the aquifers was dominated by discharge to river (12.37 ML/d) and groundwater ET (6.58 ML/d). The other outflow from the aquifers was lateral regional flow (1.04 ML/d).

The water balance of 1990 is very similar to that of the steady-state conditions, as there are no significant changes in the major system drivers during that period, and the impact of irrigation on recharge has just started to increase slowly to 0.17 ML/d.

By 2012, the SIS has been operational for more than two decades. Upward vertical flux from the Renmark Group to the Lower Mannum Formation has increased by 0.82 ML/d to 14.60 ML/d, as the head in the Lower Mannum Formation has been lowered by SIS pumping, creating a steeper hydraulic gradient between the two aquifers. River leakage has also increased by 1.38 ML/d to 2.32 ML/d. This is because SIS pumping has caused more river reaches to become losing stream. Recharge from irrigation has increased by 0.85 ML/d since irrigation began to 0.99 ML/d. Outflow from the aquifers was dominated by SIS pumping (17.34 ML/d), which has significantly reduced the saline water discharge from the aquifer to the river (4.51 ML/d, a reduction of 7.86 ML/d). As the head in the floodplain was lowered by SIS, ET has decreased slightly to 6.02 ML/d. Regional lateral flow has reduced by 0.1 ML/d to 0.94 ML/d.

In summary, the natural and 1990 water balances were dominated by inflows from upward flux from the Renmark Group and regional flow; outflow was mainly into gaining reaches of the river. Since the SIS had commenced, the groundwater flux entering the River Murray had declined substantially, as designed. The impact of irrigation on recharge is still minimal up to the present day. These model results are consistent with the hydrogeological understanding of the region.

Table 4.3 Water balance for the Woolpunda area

Water Balance Component INFLOW to the aquifer	Water volume (ML/d)		
	Steady-state	1990	2012
Release from storage	0.00	0.00	5.72
Recharge from irrigation and rainfall	0.14	0.17	0.99
River leakage (river losses to the aquifer)	0.94	0.93	2.32
Lateral flow (into the project area)	5.18	5.13	5.35
Vertical flow (into the Murray Group)	13.78	13.78	14.60
Total IN	**20.00**	**20.00**	**29.00**

Water Balance Component OUTFLOW to the aquifer	Water volume (ML/d)		
	Steady-state	1990	2012
Flow to storage	0.00	0.00	0.17
SIS pumping	0.00	0.00	17.34
ET	6.58	6.58	6.02
River leakage (discharge to the river)	12.37	12.39	4.51
Lateral flow (outward from the project area)	1.04	1.04	0.94
Total OUT	**20.00**	**20.00**	**29.00**

5 MODEL SCENARIOS AND PREDICTIONS

The calibrated historical model is used as a basis for estimating past and future salt loads to the River Murray under various scenarios. A standard suite of scenarios has been developed for the SA Salinity Register models and the scenarios used for the Woolpunda study area are consistent with this suite.

The standard suite of SA scenarios has been developed progressively in consultation with DEWNR and MDBA staff. Most of the model scenarios are those required for the MDBA's BSMS Salinity Register, such as estimating how salt loads vary due to mallee clearance, irrigation and the SIS. Some standard scenarios assist decisions on salinity management, such as Scenarios 5 and 8C, which simulate the impacts of new irrigation developments. The aims are to:

- Provide estimated salt loads entering the River Murray under different accountable development and management actions (100-year predictions from current year) for use as Salinity Register entries, specifically:
  - Mallee clearance
  - Irrigation development
  - Improved irrigation practice
  - Salt Interception Scheme
- determine the State and Federal responsibility for cost sharing
- assist with the broad-scale planning for state groundwater management schemes (e.g. SIS)
- satisfy the reporting requirements of:
  - Schedule B to Schedule 1 of the Water Act 2007
  - the Basin Salinity Management Strategy Operational Protocols 2005.

The standard suite of SA Salinity Register modelling scenarios adopted in this study is summarised in Table 5.1.

All scenarios are discussed in detail in the following sections. The model names, e.g. WP2013_S3A, refer to the MODFLOW files preserved in the SA Groundwater Model Warehouse, following the protocol given in Appendix C-4.

To prevent the over-estimation of salinity credits, future scenarios presume that irrigation drainage will be similar to that of 2005, prior to the water restrictions imposed during the drought years of 2006 to 2010. The recharge rate is set conservatively at 100 mm/y for permanent irrigation (except Scenario 3A) and 60 mm/y for pivot irrigation The impact of the Millennium Drought is not considered and this is consistent with the MDBA approach that the Salinity Register entries should not include the impact of climate sequence features such as drought.

To satisfy the MDBA Salinity Register requirements, the annual salt load (t/d) from 1988 up to CY100 (current year + 100 years) is reported in a summary section and detailed values are in Appendix B-1. The results include values for the River Murray reach between Holder and Lock 3. The results will be input into MSM-BIGMOD by the MDBA to calculate the in-river EC impact at Morgan.

Table 5.2 provides definitions for terms used for South Australian numerical models for Salinity Register estimates. There are some definitions included in the table that are not used in the current project.

All scenarios have the same spatial discretisation, convergence criteria, parameters and boundary conditions as those adopted in the calibrated transient historical model described in Section 3, except as noted in Sections 5.2 to 5.10 below.

Table 5.1 Summary of the standard SA Salinity Register model scenarios and conditions

Scenario	Description	Simulated period	Irrigation development area	IIP	SIS
Calibrated model	Historical	1920-CY	Footprint of irrigation history	Yes	Yes
Scenario 1	Natural system	Steady-state	None	-	No
Scenario 2	Mallee clearance	1920-CY100	None (but includes Mallee clearance area)	-	No
Scenario 3A	Pre-1988, no IIP or RH	1988-CY100	Pre-1988	No	No
Scenario 3C	Pre-1988, with IIP and RH	1988-CY100	Pre-1988	Yes	No
Scenario 4	Current Irrigation	1988-CY100	Pre-1988 + Post-1988	Yes	No
Scenario 5	Current plus future irrigation	1988-CY100	Pre-1988 + Post-1988 + Future development	Yes	No
Scenario 8A	Current irrigation plus constructed SIS	1988-CY100	Pre-1988 + Post-1988	Yes	Yes
Scenario 8B	Pre-1988, with IIP and with RH plus constructed SIS	1988-CY100	Pre-1988	Yes	Yes
Scenario 8C	Current plus future irrigation plus constructed SIS	1988-CY100	Pre-1988 + Post-1988 + Future development	Yes	Yes

IIP: Improved Irrigation Practices SIS: Salt Interception Scheme CY: Current Year

Table 5.2 Definitions of conditions for scenarios

Recharge	Irrigation drainage and/or rainfall infiltration reaching the groundwater table
Initial lag time (New irrigation development)	Time (years) taken for recharge to reach the groundwater table at a new irrigation site. Lag time is affected by depth to groundwater table and the presence and properties of aquitards. As predicted by SIMRAT, initial lag time can be several decades.
Late lag time (Existing irrigation area with water mound)	Time (years) taken for recharge to reach the groundwater table in an existing irrigation area where the irrigation water wetting front has already reached the watertable. This will therefore apply to irrigation areas where an irrigation water mound exists. According to recent research, late lag time can be shorter than a couple of months.
Current year (CY)	e.g. 2013
Current year + 100 (CY100)	100 years from the current year (e.g. if current year is 2013 , then CY100 = 2113)
Pre-1988 irrigation	Irrigation development area and drainage that occurred prior to 01/01/1988
Post-1988 irrigation	Irrigation development area and drainage that occurred between 01/01/1988 and the current year

Future development	Future irrigation development area and drainage resulting from activation of already allocated water that is assumed to occur after the current year (2013).
Mallee clearance	Clearance of natural vegetation commencing during the 1920s, resulting in increased recharge to the groundwater table in dry-land (non-irrigated) areas. No major clearing of native vegetation occurred after 1988.
Improved Irrigation Practices (IIP)	Irrigation efficiency improved over time as sprinkler and drip systems replaced flood irrigation via earth channels. In this report, IIP means the greatly improved technology, monitoring soil system and management of irrigation systems after 1988.
Rehabilitation (RH)	Replacement of leaky concrete water distribution channels with pipelines after 1988 resulted in reduced water transportation losses which are reflected by reduced recharge to the groundwater table. Rehabilitation in pre-1988 irrigation areas is explicitly omitted from Salinity Register scenarios.
Concept Design SIS	The Concept Design SIS designed to intercept the maximum groundwater flux and salt load resulting from all past, present and future irrigation development, or the naturally occurring groundwater flux where this is large and must be intercepted and used in the MDBA Approval Submission process to determine the: cost-benefit ratio sharing of costs between the State and the MDBA total SIS well field flux for pipeline design. The Concept Design SIS may not be able to control 100% of the salt load due to technical or economic constraints. The modelled Concept Design SIS may not represent the actual numbers of production wells that are eventually constructed.
Revised Design SIS	During the investigation and construction phase of an SIS, expectations regarding the effectiveness of the SIS, or its extent, may be revised due to technical issues that arise, resulting in the Revised Design SIS. The Revised Design SIS represents the current view of what the final constructed and operating SIS is most likely to be. The Revised Design SIS may change, as issues that have arisen are resolved. The Revised Design SIS may not be able to control 100% of the salt load due to technical or economic constraints. The modelled Revised Design SIS may not represent the actual number of production wells that are eventually constructed.
As-constructed SIS	Model representation of the on-ground As constructed SIS infrastructure using historical pumping rates and forward projections that may or may not be constrained by production well pumping capacity or pipeline capacity or disposal basin capacity. Significant differences to the Concept or Revised SIS may result in the need to recalibrate the model at the time of the 5 year review. The As-constructed SIS may not be able to control 100% of the salt load due to technical or economic constraints. The modelled As-constructed SIS may result in the need for model recalibration and re-accreditation, if the actual numbers of on-ground wells are different to those that have been applied in the Concept and Revised Design SIS.
Modelled result	Output from the calibrated model (e.g. potentiometric head distribution) that can be compared to observed data.
Predicted result	Output from the prediction model has been used to determine the future result of a particular scenario.

5.1 RECHARGE APPLIED IN IRRIGATION SCENARIOS

The following areas and rates are used in the scenarios intended to simulate the impact of accountable irrigation actions on groundwater salt loads to the River Murray:

- for pre-1988 irrigation: two scenarios, each using the irrigation area at 1988 to define the recharge area, with one scenario adopting a recharge rate of 100 mm/y and the other adopting a recharge rate of 120 mm/y (the 'do nothing' scenario). Comparison of these two scenarios will provide the benefit gained by reduction in recharge rates attributed to improved irrigation practices. Note that there was no pivot irrigation for the pre-1988 period.
- for post-1988 irrigation: the post-1988 irrigation areas will be used to define the recharge area and a recharge rate of 100 mm/y is used for permanent irrigation and 60 mm/y for pivot irrigation to define the current average condition (representing average conditions prior to water restrictions).

More detail is given in the descriptions of the individual scenarios which follow.

5.2 SCENARIO 1: NATURAL CONDITION

Scenario 1 estimates the baseline groundwater flux and salt load entering the River Murray post-river regulation but prior to irrigation development and the construction of the SIS.

The following conditions are applied to the model:
- the model is steady-state
- River Murray levels are post-regulator (i.e. the river locks are included)
- there is no land clearance
- there is no irrigation development
- recharge rates everywhere are 0.1 mm/y, based on CSIRO studies of uncleared mallee
- the SIS are not included.

This scenario is identical to the steady-state model used during calibration to provide initial conditions for the transient historical model.

Table 5.3 gives the modelled flux and salt load entering the River Murray in the Woolpunda area for Scenario 1 (see Section 4.4.1 for the definition of the Woolpunda reach).

Table 5.3 Predicted groundwater flux and salt load – Scenario 1: Natural Condition

Groundwater flux and salt load	Steady-state
Flux to river (m^3/d)	8856
Salt load to river (t/d)	190.9

5.3 SCENARIO 2: MALLEE CLEARANCE

Scenario 2 simulates the clearance of the native mallee vegetation and subsequent increase in recharge rates. It estimates the resulting hydrological changes, groundwater flux and salt load entering the River Murray.

The following conditions are applied to the transient model (WP2013_S2):
- the simulated time period is 1920 to CY100
- land clearance prior to 1920 is assumed to have occurred in 1920
- recharge due to mallee clearance is represented by zones and rates estimated by CSIRO and provided by the former DENR. These recharge rates are greater than or equal to 0.1 mm/y,

increasing in some areas to ~10 mm/y, with changes occurring every 10 years. The rates and zones are given in Appendix A-1

- the vegetation outside the cleared zones is mallee, so a recharge rate of 0.1 mm/y is applied
- there is no irrigation development
- the annual salt loads for 1988 to CY100 are reported as required by the MDBA for the Salinity Register.

Table 5.4 summarises the predicted flux and salt load entering the River Murray in the Woolpunda area. Further results are given Appendixes B-1 to B-2. The starting values in 1920 are those given for Scenario 1 in Table 5.3.

Table 5.4 Predicted groundwater flux and salt load – Scenario 2: Mallee clearance

Groundwater flux and salt load	Year						
	1988	2000	2013	2015	2050	2100	2113
Flux to river (m^3/d)	8881	8887	8903	8904	8959	9373	9592
Salt load to river (t/d)	191.5	191.6	191.9	191.9	193.1	201.8	206.4

5.4 SCENARIO 3A: PRE-1988 IRRIGATION WITHOUT IMPROVED IRRIGATION PRACTICES OR REHABILITATION

Scenario 3A simulates what would have happened if irrigation development and practices had remained unchanged from 1988. This scenario is used in conjunction with Scenario 3C to estimate the salinity benefits of improvements in irrigation practice after 1988. It estimates the resulting hydrological changes, groundwater flux and salt load entering the River Murray.

The following conditions are applied to the transient model (WP2013_S3A):

- the simulated time period is from 1920 to CY100
- the recharge zones for 1988 to CY100 are based on the 1988 irrigation development area
- recharge rates are assigned as follows and are given in Appendices A-2 and A-5:
    - The irrigation recharge rates at 1988 cannot be estimated from observations (i.e. inverse modelling) as the observation hydrographs have not shown any responses to irrigation recharge yet. Hence an irrigation recharge rate of 120 mm/y is assumed for this scenario, based on Vears (2013) in Appendix C, to reflect the impact of the absence of improved irrigation practice
    - there are irrigation areas planted before 1988 where the lag time means that root zone drainage has not yet reached the watertable by 1988. In those areas, recharge rates may still increase after 1988 to reflect the delay. Recharge becomes constant no more than lag time years after 1988
    - in areas where irrigation did not exist in 1988, the mallee recharge rate of 0.1 mm/y is adopted
- the annual salt loads for 1988 to CY100 are reported as required by the MDBA for the Salinity Register.

Table 5.5 summarises the predicted flux and salt load entering the River Murray in the Woolpunda area. Further results are given in Appendixes B-1 to B-2. The starting values in 1920 are those given for Scenario 1 in Table 5.3.

Table 5.5 Predicted groundwater flux and salt load – Scenario 3A: Pre-1988 irrigation, no IIP or RH

Groundwater flux and salt load	Year						
	1988	2000	2013	2015	2050	2100	2113
Flux to river (m^3/d)	8879	9009	9199	9241	9372	9387	9388
Salt load to river (t/d)	191.4	194.1	198.2	199.1	201.9	202.2	202.3

5.5 SCENARIO 3C: PRE-1988 IRRIGATION WITH IMPROVED IRRIGATION PRACTICES AND REHABILITATION

Scenario 3C simulates what would have happened if the irrigation development area had remained unchanged from 1988, but improvements in irrigation practice had still occurred. This scenario is used in conjunction with Scenario 3A to estimate the salinity benefits of improvements in irrigation practice after 1988. It estimates the resulting hydrological changes, groundwater flux and salt load entering the River Murray.

The following conditions are applied to the transient model (WP2013_S3C):

- the simulated time period is from 1920 to CY100
- the model is identical to the calibrated historical model until 1 January 1988
- the recharge zones for 1988 to CY100 are based on the 1988 irrigation development area
- recharge rates are assigned as follows and are given in Appendices A-2 and A-5:
  - The irrigation recharge rates at 1988 cannot be estimated from observations (i.e. inverse modelling) as the observation hydrographs have not shown any responses to irrigation recharge yet. Hence an irrigation recharge rate of 100 mm/y is assumed for permanent irrigation and 60 mm/y for pivot irrigation for this scenario, to reflect the impact of improved irrigation practice
  - This study does not consider the impact of the Millennium Drought on groundwater recharge as the Salinity Register scenarios should not include climate sequence impacts. Therefore the recharge rate is held constant once the irrigation recharge has reached the watertable.
  - in areas where irrigation did not exist in 1988, the mallee recharge rate of 0.1 mm/y is adopted
- the annual salt loads for 1988 to CY100 are reported as required by the MDBA for the Salinity Register.

Table 5.6 summarises the predicted flux and salt load entering the River Murray in the Woolpunda area. Further results are given in Appendices B-1 to B-2. The starting values in 1920 are those given for Scenario 1 in Table 5.3.

Table 5.6 Predicted groundwater flux and salt load – Scenario 3C: Pre-1988, with IIP and with RH

Groundwater flux and salt load	Year						
	1988	2000	2013	2015	2050	2100	2113
Flux to river (m^3/d)	8875	8982	9140	9175	9284	9294	9295
Salt load to river (t/d)	191.3	193.5	196.9	197.7	200.0	200.3	200.3

5.6 SCENARIO 4: CURRENT IRRIGATION

Scenario 4 simulates what would have happened if the current irrigation development and practices had continued indefinitely without the construction of the SIS. In conjunction with Scenario 8A, it can be used to estimate SIS benefits. It estimates the resulting hydrological changes, groundwater flux and salt load entering the River Murray. As the Salinity Register entries should not include the impact of climate sequence, the model does not simulate the contraction of irrigation area and reduction in recharge rates due to drought restrictions from 2006 to 2010.

The following conditions are applied to the transient model (WP2013_S4):

- the simulated time period is from 1920 to CY100
- the model recharge rates are identical to the calibrated historical model
- the recharge zones for 2006 to CY100 include all areas irrigated in 2005 and all newer irrigation areas which began after 2005 (i.e. the scenario does not simulate any reductions in irrigation area which occurred in the drought-restricted years 2006 to 2010)
- recharge rates are assigned as follows and are given in Appendices A-2 and A-5:
  - The irrigation recharge rates at 1988 cannot be estimated from observations (i.e. inverse modelling) as the observation hydrographs have not shown any responses to irrigation recharge yet. Hence an irrigation recharge rate of 100 mm/y is assumed for permanent irrigation and 60 mm/y for pivot irrigation for this scenario, to reflect the impact of improved irrigation practice
  - in areas where irrigation did not occur, the mallee recharge rate of 0.1 mm/y is adopted
- the annual salt load for 1988 to CY100 are reported as required by the MDBA for the Salinity Register.

Table 5.7 summarises the predicted flux and salt load entering the River Murray in the Woolpunda area. Further results of the predicted flux of saline groundwater and salt load are given in Appendices B-1 to B-2.

Table 5.7 Predicted groundwater flux and salt load – Scenario 4: Current irrigation

Groundwater flux and salt load	Year						
	1988	**2000**	**2013**	**2015**	**2050**	**2100**	**2113**
Flux to river (m^3/d)	8875	9066	9262	9337	11122	12552	12693
Salt load to river (t/d)	191.3	195.4	199.6	201.2	239.3	269.7	272.7

5.7 SCENARIO 5: CURRENT, PLUS FUTURE EXPANSION OF IRRIGATION

Scenario 5 simulates what would have happened if the SIS had not been constructed but irrigation development continued after 2013. It is identical to Scenario 4 except that irrigation development continues after 2013, so it is used to estimate the salinity impact of future (post-2013) irrigation development. It estimates the resulting hydrological changes, groundwater flux and salt load entering the River Murray. Note that this scenario is not required by the MDBA for the Salinity Registers but informs State policy.

The following conditions are applied to the transient model (WP2013_S5):

- the simulated time period is from 1920 to CY100
- the model is identical to the Scenario 4 model until 1 January 2043
- the recharge zones and rates for 2043 to CY100 are identical to Scenario 4 except that additional irrigation recharge zones are included, based on potential new development areas estimated by

DEWNR and the PIRSA Policy and Planning Group (Figure 2.15). All new zones are permanent irrigation and a recharge rate of 100 mm/y is applied. Lag time for the new irrigation areas are estimated using SIMRAT, which estimates that drainage from post-CY irrigation areas will not reach the watertable until 2043
- the recharge rates are given in Appendices A-2 and A-3.

Table 5.8 summarises the predicted flux and salt load entering the River Murray in the Woolpunda area. Further results of the predicted flux of saline groundwater and salt load are given in Appendices B-1 to B-2.

Table 5.8 Predicted groundwater flux and salt load – Scenario 5: Current plus future irrigation

Groundwater flux and salt load	Year						
	1988	**2000**	**2013**	**2015**	**2050**	**2100**	**2113**
Flux to river (m^3/d)	8875	9066	9262	9337	11183	13345	13533
Salt load to river (t/d)	191.3	195.4	199.6	201.2	240.6	286.6	290.7

5.8 SCENARIO 8A: CURRENT IRRIGATION WITH AS-CONSTRUCTED SIS

Scenario 8A simulates what will happen if the current irrigation development and practices continue indefinitely and the SIS continues to operate as currently constructed and continues to meet the current mid-point water level criteria into the future, an approach developed by the Five Year Review Modelling for Salinity Registers Project Team. It is identical to Scenario 4 except that it includes the SIS, so the two scenarios can be compared to estimate SIS benefits. It estimates the resulting hydrological changes, groundwater flux and salt load entering the River Murray. As with Scenario 4, Scenario 8A does not simulate the impact of the 2006 to 2010 drought restrictions and the irrigation areas for future years are based on those of 2005.

The following conditions are applied to the transient model (WP2013_S8A):
- the simulated time period is from 1920 to CY100
- the model is identical to the Scenario 4 model except that the SIS is included
- the production wells are simulated using the Drain Package so that the SIS continues to operate for the duration of the model run as it currently operates with respect to the control of mid-point water levels under all scenarios (note that the calibrated historical model employed the Well Package). Drain cells are used rather than fixed pump rates, as the SIS operators will vary pump rates over time to achieve target heads at the midpoint observation wells. Different drain elevation and conductance values were trialled until the model achieved the target heads. To achieve the middle point level equal to or slightly lower than the river level and pumping rates within the actual recorded pumping rates, the adopted drain elevations in the model are mostly 6.1 m AHD while some can be up to 7 m AHD, and the conductance is 1000 m^2/d. Appendices A-6 and A-7 provide further detail
- the results for 1988 to CY100 are reported as required by the MDBA for the Salinity Register.

Figure 5.1 shows how the SIS is simulated in Scenarios 8A, 8B and 8C.

Table 5.9 summarises the predicted flux and salt load entering the River Murray in the Woolpunda area. Further results of the predicted flux of saline groundwater and salt load are given in Appendices B-1 to B-2. The salt loads are significantly lower than those of Scenario 4.

Table 5.9 Predicted groundwater flux and salt load – Scenario 8A: Current irrigation plus Woolpunda SIS

Groundwater flux and salt load	Year						
	1988	2000	2013	2015	2050	2100	2113
Flux to river (m^3/d)	8877	686	684	686	738	762	764
Salt load to river (t/d)	191.3	15.1	15.0	15.1	16.2	16.7	16.8

5.9 SCENARIO 8B: PRE-1998 IRIGATION WITH AS-CONSTRUCTED SIS

Scenario 8B simulates what would have happened if the irrigation development area had remained unchanged from 1988, but improvements in irrigation practice had still occurred and the SIS had been constructed. It is identical to Scenario 3C except that it includes the SIS, so the two scenarios can be compared to estimate SIS benefits for cost-sharing calculations. It estimates the resulting hydrological changes, groundwater flux and salt load entering the River Murray.

The following conditions are applied to the transient model (WP2013_S8B):

- the simulated time period is from 1920 to CY100
- the model is identical to the Scenario 3C model except that the SIS is included
- the SIS is simulated using the same methodology as Scenario 8A. Appendices A-6 and A-7 provide further detail
- the results for 1988 to CY100 are reported as required by the MDBA for the Salinity Register.

Table 5.10 summarises the predicted flux and salt load entering the River Murray in the Woolpunda area. Further results of the predicted flux of saline groundwater and salt load are given in Appendices B-1 to B-2. The salt loads are significantly lower than those of Scenario 3C.

Table 5.10 Predicted groundwater flux and salt load – Scenario 8B: Pre-1988 irrigation plus Woolpunda SIS

Groundwater flux and salt load	Year						
	1988	2000	2013	2015	2050	2100	2113
Flux to river (m^3/d)	8875	653	647	647	641	636	635
Salt load to river (t/d)	191.3	14.3	14.2	14.2	14.1	14.0	13.9

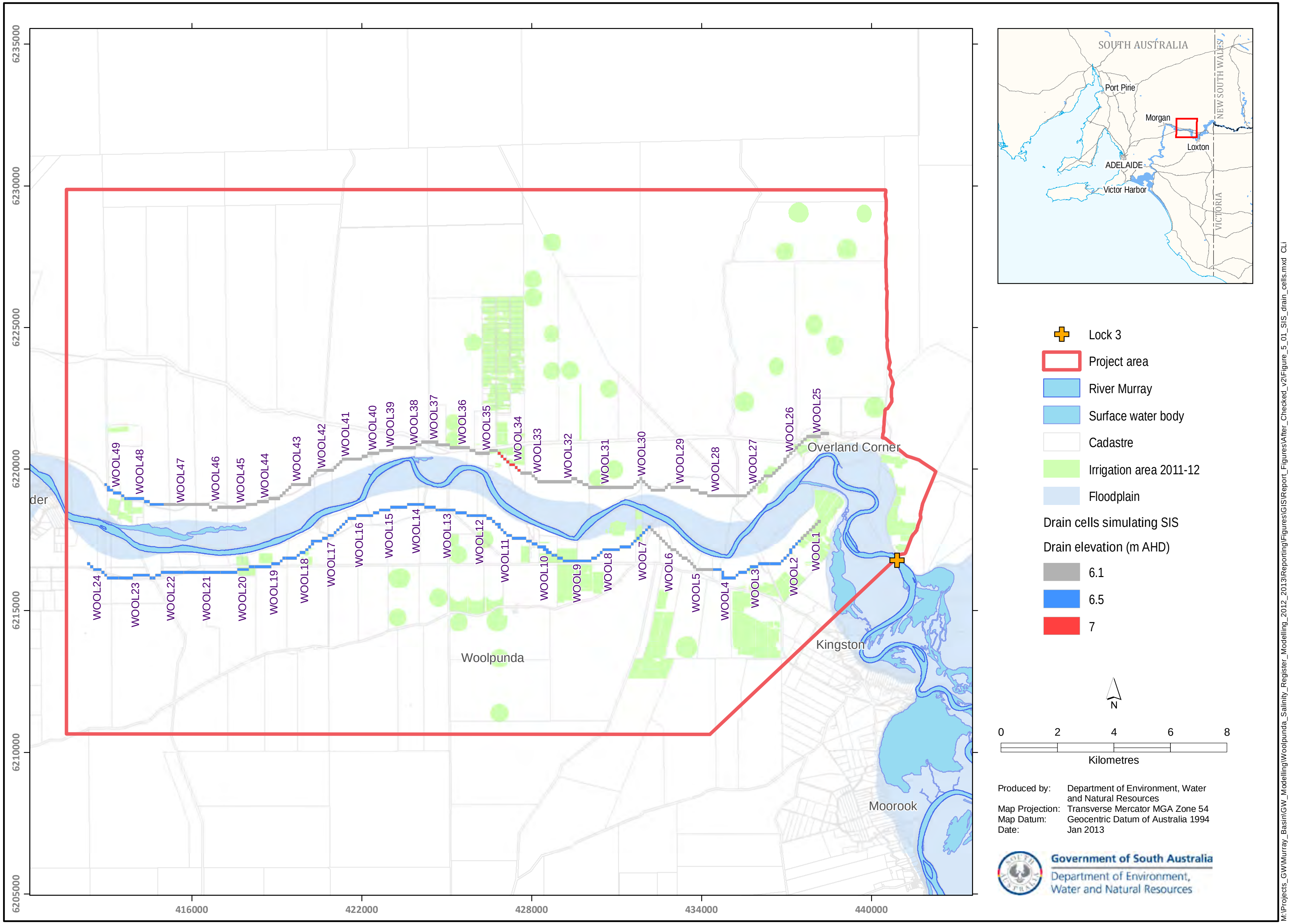


Figure 5.1. Modelled SIS in the prediction models

5.10 SCENARIO 8C: FUTURE IRRIGATION WITH AS-CONSTRUCTED SIS

Scenario 8C simulates what will happen if irrigation development continues after 2013 and the SIS continues to operate as constructed. It is identical to Scenario 5 except that it includes the SIS, so the two scenarios can be compared to estimate SIS benefits. It estimates the resulting hydrological changes, groundwater flux and salt load entering the River Murray. Note that this scenario is not required by the MDBA for the Salinity Registers but informs State policy.

The following conditions are applied to the transient model (WP2013_S8C):

- the simulated time period is from 1920 to CY100
- the model is identical to the Scenario 5 model except that the SIS is included
- the SIS is simulated using the same methodology as Scenario 8A. Appendices A-6 and A-7 provide further detail.

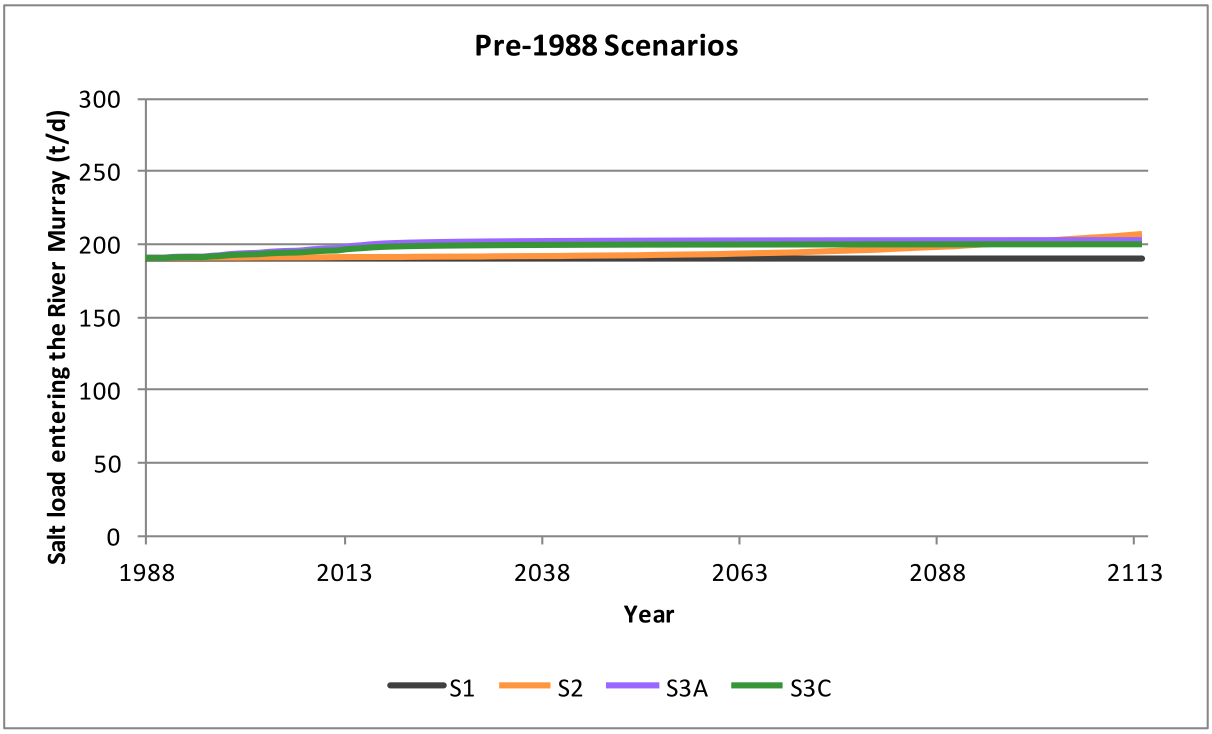
Table 5.11 summarises the predicted flux and salt load entering the River Murray in the Woolpunda area. Further results of the predicted flux of saline groundwater and salt load are given in Appendices B-1 to B-2. The salt loads are significantly lower than those of Scenario 5.

Table 5.11 Predicted groundwater flux and salt load – Scenario 8C: Future irrigation plus Woolpunda SIS

Groundwater flux and salt load	Year						
	1988	2000	2013	2015	2050	2100	2113
Flux to river (m^3/d)	8875	686	684	686	741	778	781
Salt load to river (t/d)	191.3	15.1	15.0	15.1	16.3	17.1	17.1

5.11 COMPARISON OF SCENARIO SALT LOADS

Figures 5.2 and 5.3 display the annual salt loads from 1988 to 2113 for all scenarios for the Woolpunda reach. Details of the model results (both flux and salt load) for all scenarios are given in Appendix B.



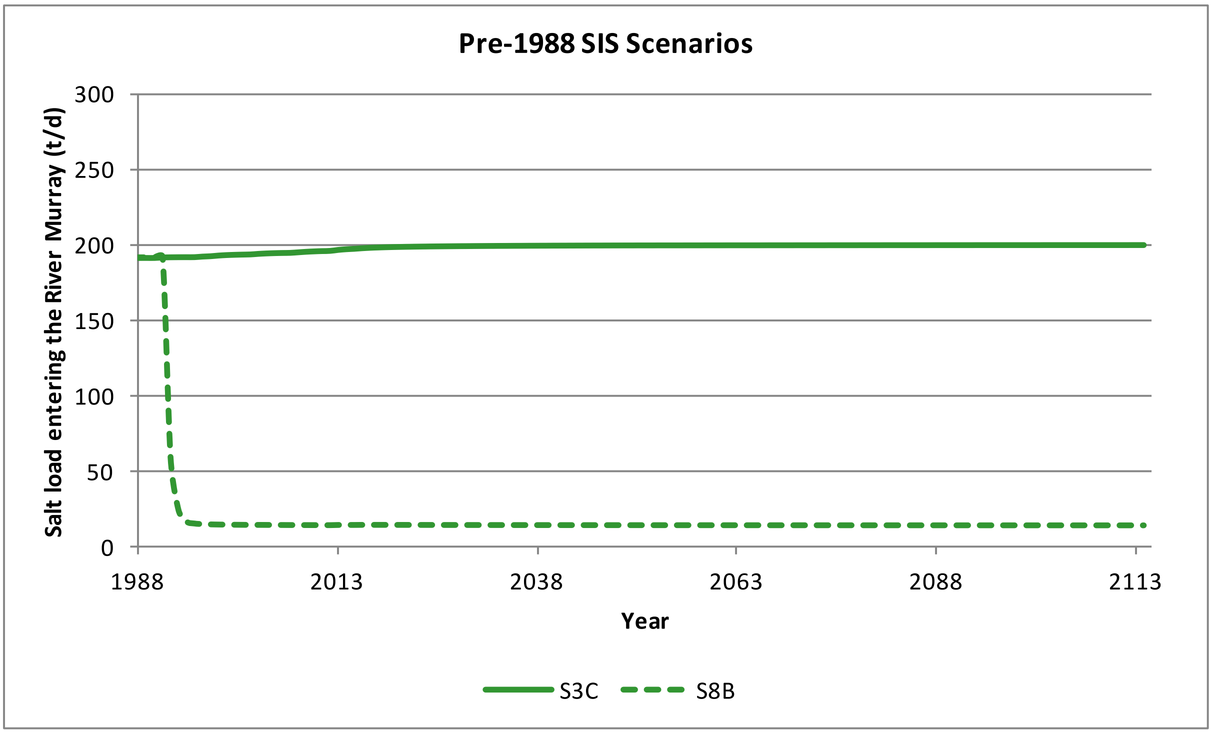
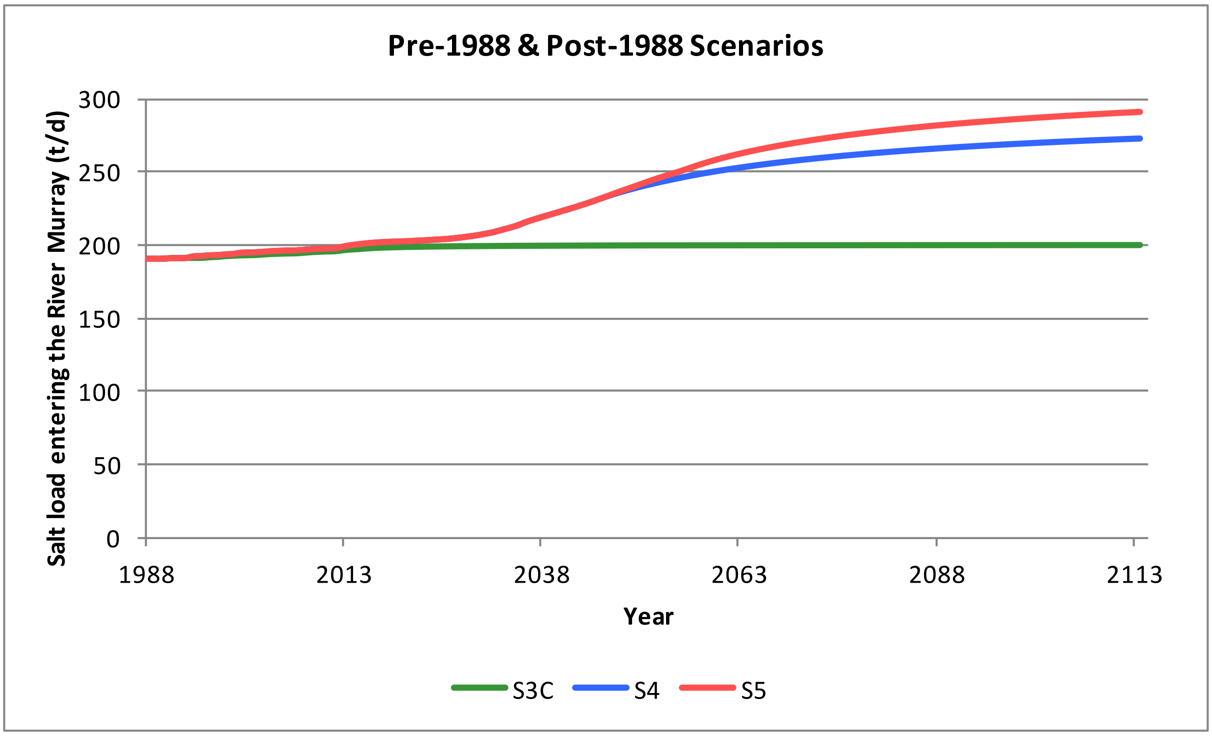


Figure 5.2 Predicted total salt loads entering the River Murray from the Woolpunda Reach for Pre-1988 scenarios



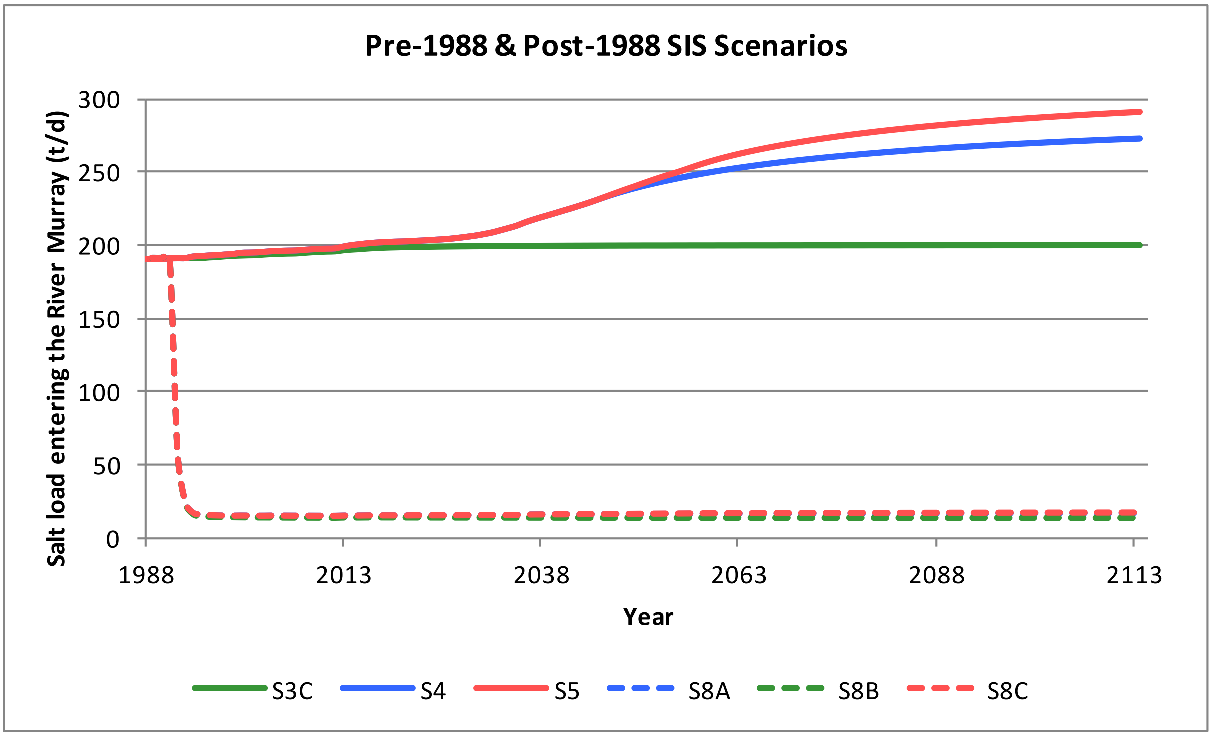


Figure 5.3 Predicted total salt loads entering the River Murray from the Woolpunda Reach for Pre-1988 and Post-1988 scenarios

6 SENSITIVITY AND UNCERTAINTY ANALYSIS

Sensitivity analysis is a procedure for quantifying the impact of an incremental variation in aquifer hydraulic parameters or stresses on modelled responses (MDBC 2001). The *Groundwater Flow Modelling Guideline* (MDBC 2001) recommends for high complexity models such as the Woolpunda model, "only a limited sensitivity analysis (not violating the calibration conditions) after calibration is completed, in order to indicate qualitatively the impact of key parameters in critical areas."

A manual sensitivity analysis is performed. This requires changing a single model parameter, re-running the model to obtain a new set of predicted heads and fluxes and observing the effect of the change and the emphasis is on determining how sensitive the model is to each parameter (NWC 2012).

As the model is well calibrated, the aim of the sensitivity analysis for the Woolpunda model is to improve confidence in the calibrated historical model by checking whether other reasonable model inputs provide a better or worse calibration. The tested parameters are those with representative regional values which are not known with certainty. As the model is calibrated to potentiometric head observations and its results are confirmed through comparison to Run-of-River estimates of salt loads, the sensitivity results are presented in terms of the SRMS to head observations and also salt load.

The model inputs below are varied for the sensitivity analysis:

- groundwater ET rate
- groundwater ET extinction depth
- River Murray riverbed conductance
- Ettrick Formation vertical hydraulic conductivity
- Renmark Group horizontal hydraulic conductivity
- Lower Mannum Formation horizontal hydraulic conductivity
- Lower Mannum Formation specific storage
- Upper Mannum Formation specific yield.

Although calibration and sensitivity analysis were undertaken together, sensitivity analysis is reported separately in this Section to be consistent with previous Salinity Register modelling reports.

Uncertainty analysis is a broader term, encompassing the estimation of uncertainty in model results due to poorly known parameter distributions, observation errors and simplified model assumptions such as omitted processes. Within Australian groundwater modelling, there is no industry-wide agreed approach to uncertainty analysis. The *Groundwater Flow Modelling Guideline* (MDBC 2001) and *Australian Groundwater Modelling Guidelines* (NWC 2012) outline some options, such as worst-case scenario modelling, Monte Carlo simulations, alternative conceptualisations and predictive analysis. Handbooks such as that of Hill & Tiedeman (2007) are yet to be adopted for widespread Australian use.

The aim of the uncertainty analysis for the Woolpunda model is to gauge the confidence of the salt load predictions and the impact of different assumptions and inputs on these predictions.

The model inputs below were varied for the uncertainty analysis:

- River Murray level
- irrigation recharge

- permanent irrigation recharge rate
- pivot irrigation recharge rate
- lag time
- impact of mallee clearance.

Other model inputs are important, but their values are more easily and reliably observed, e.g. SIS pump rates, or are expected to be less heterogeneous and therefore robustly interpolated from observations, e.g. potentiometric heads along model boundaries.

Scenario 4 is simulated for all but one uncertainty analysis. Scenarios 4 and 8A are the closest representation of reality, but because 8A includes the SIS which will minimise changes in salt load over time, Scenario 4 is the better option for determining differences due to uncertainty. Scenario 2 is used to examine uncertainty due to the impact of mallee clearance, as this is the scenario which includes this process.

6.1 SENSITIVITY ANALYSIS

The baseline simulation is the calibrated historical model. In each sensitivity analysis simulation, a single input parameter is changed.

6.1.1 PARAMETERS AND VALUES

The parameters investigated for the sensitivity analysis are those where there is a degree of uncertainty of their value and where their importance to model calibration is not immediately clear. Parameters are varied to robustly check their impact on key model outputs as described below. In keeping with recommendations from the *Australian Groundwater Modelling Guidelines* (NWC 2012), each parameter is adjusted by an amount commensurate with its likely range. Table 6.1 gives the values of the parameters in the calibrated model and other values considered in the sensitivity simulations.

Groundwater evapotranspiration rate and extinction depth are included in the sensitivity analysis as it is difficult to establish regionally representative values based on fieldwork: ET can be measured in the field but may be highly variable within small areas. The two groundwater ET rates considered in the sensitivity test are 200 mm/y, which is the lower bound of the areal actual ET, and 1100 mm/y, which is the upper bound of the areal potential evaporation for the Woolpunda area (Section 2.4.4). The groundwater ET extinction depth is varied by 0.5 m from the value of 1.5 m used in the calibrated model.

Riverbed conductance depends on riverbed sediment thickness and hydraulic conductivity, neither of which has been sampled within the project area. The conductance is the product of the riverbed vertical conductivity and the grid cell area divided by the thickness of the riverbed. The thickness of the riverbed is not known. The calibrated model's riverbed conductance of 500 m^2/d is equivalent to a vertical conductivity of 0.05 m/d for a riverbed thickness of 1 m. The sensitivity test considers two other conductance values, 50 and 5000 m^2/d, which are equivalent to vertical conductivities of 0.005 and 0.5 m/d respectively, for a riverbed thickness of 1 m.

The vertical hydraulic conductivity of the Ettrick Formation is varied by an order of magnitude (i.e. multiplied by 10 and divided by 10) during the sensitivity analysis. This is because the vertical hydraulic conductivity of the Ettrick Formation has not been estimated by any aquifer tests and is only informed from previous modelling studies (Watkins 1993; Rural Solutions 2005). The horizontal hydraulic conductivity of the Ettrick Formation is adjusted to be the same as the vertical hydraulic conductivity.

The horizontal hydraulic conductivity of the Renmark Group has been estimated from aquifer tests in the Chowilla Floodplain (Magarey and Howles 2009) but nowhere else. The sensitivity analysis considers two other values: 1 m/d, which was used in the Morgan to Wellington numerical groundwater model (Yan *et al.* 2010); and 25 m/d, which was used in a preliminary unpublished model of Woolpunda developed by AWE. The vertical hydraulic conductivity is scaled to be one tenth of the horizontal hydraulic conductivity.

The horizontal hydraulic conductivity and specific storage of the Lower Mannum Formation are included in the sensitivity analysis. The horizontal hydraulic conductivity of the Lower Mannum Formation has been estimated from aquifer tests (see Table 2.2). For sensitivity analysis, the two altered values considered are 1 m/d and 5 m/d, which are the lower and higher values in the reasonable range. The vertical hydraulic conductivity is scaled to be one tenth of the horizontal hydraulic conductivity. There are no aquifer test data for the specific storage of the Lower Mannum Formation, hence its value is varied by an order of magnitude during the sensitivity analysis.

Similarly, the Upper Mannum Formation specific yield has not been estimated by any aquifer tests and hence it is varied to 0.05 and 0.3 during the sensitivity analysis, which are considered to be the lower and higher value of the reasonable range for specific yield based on its texture, respectively.

Table 6.1 Sensitivity test parameter values

Parameter	Lower value	Calibrated model	Higher value
ET rate (mm/y)	200	250	1100
ET extinction depth (m)	1	1.5	2
River conductance (m^2/d)	50	500	5000
Ettrick Formation Kv (m/d)	× 1/10	see Figure 3.12	× 10
Renmark Group Kh (m/d)	1	10	25
Lower Mannum Formation Kh (m/d)	1	2	5
Lower Mannum Formation Ss (/m)	5.0E-5	5.0E-4	5.0E-3
Upper Mannum Formation Sy (-)	0.05	0.1	0.3

6.1.2 RESULTS

Figure 6.1 shows the sensitivity of the calibration fit (SRMS of the difference between modelled and observed potentiometric head) to the sensitivity parameters for 1990, 2009 and 2012. Positive values indicate a better fit to observation data than the calibrated model, negative values indicate a worse fit.

Some of the selected parameters make negligible difference to the calibration fit, indicating that they do not substantially alter modelled potentiometric heads at observation well locations. The SRMS values are not sensitive to groundwater ET rate and extinction depth, and river conductance, perhaps because there are few observation wells in the floodplain, where these parameters will have the most influence on potentiometric head.

The calibration fit is clearly affected by the vertical hydraulic conductivity of the Ettrick Formation and the horizontal hydraulic conductivity of the Renmark Group and Lower Mannum Formation. The fit is significantly worse for the altered values than for the calibrated model, except where the horizontal hydraulic conductivity of the Renmark Group is 25 m/d. This value is not adopted in the calibrated model as it is considered too high and only contributes to a relatively minor improvement in calibration fit in the later years of the calibration period.

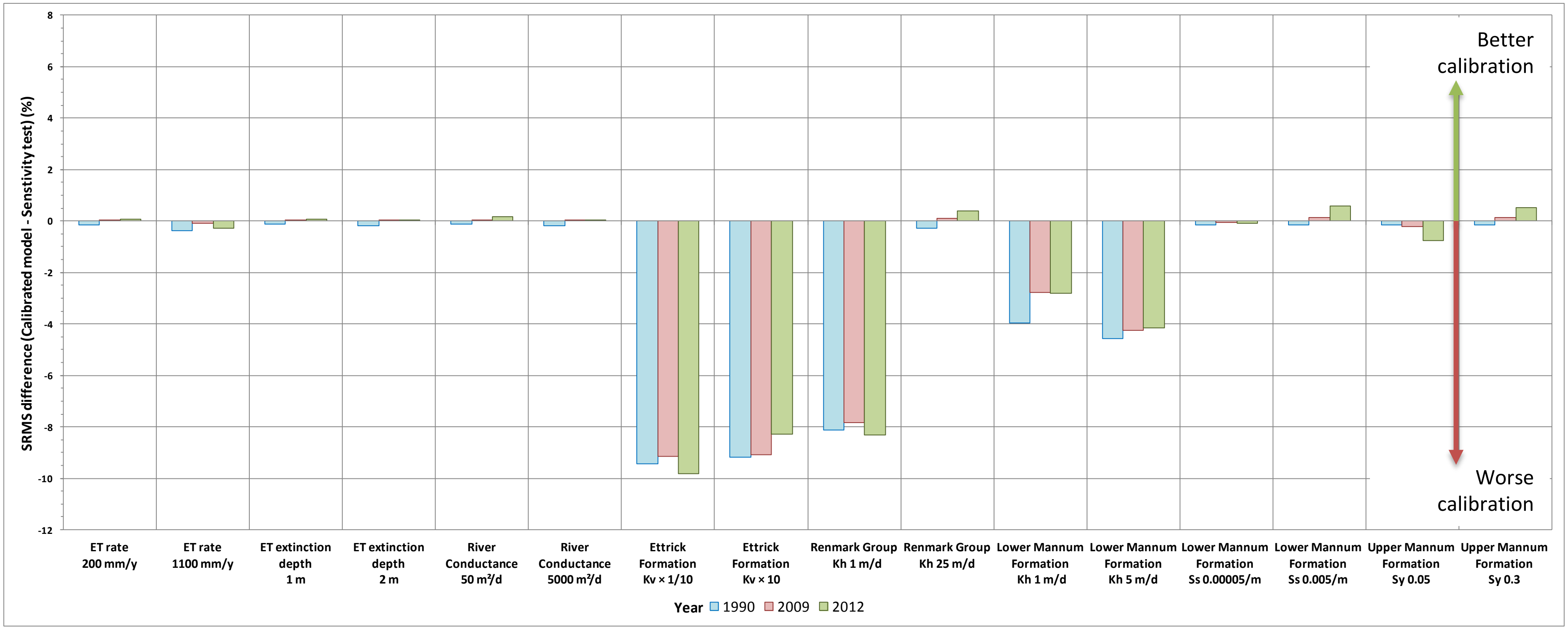


Figure 6.1. **Sensitivity of calibration fit to observed heads (SRMS)**

For storage of the Lower and Upper Mannum Formations, although Figure 6.1 indicates that a better calibration fit is possible, their altered values are not adopted after comparing their modelled salt loads with the RoR data. Figure 6.2 shows the sensitivity of the modelled salt load to the River Murray in the Woolpunda reach to the sensitivity parameters. Salt loads are not sensitive to the lower groundwater ET rate, groundwater ET extinction depth, riverbed conductance and the higher Renmark Group horizontal hydraulic conductivity. The higher groundwater ET rate, lower Ettrick Formation vertical hydraulic conductivity and the lower Renmark Group horizontal hydraulic conductivity cause the modelled salt load to be unrealistically low, while the higher Ettrick Formation vertical hydraulic conductivity and the higher Lower Mannum Formation horizontal hydraulic conductivity lead to an overestimation of modelled salt load compared to the RoR data. The altered values of the Upper Mannum Formation specific yield and the higher value of Lower Mannum Formation specific storage lead to a worse match to the RoR data. The lower Lower Mannum Formation horizontal hydraulic conductivity may result in a better match to the RoR data, but Figure 6.1 clearly shows that this will significantly worsen the calibration fit.

6.2 UNCERTAINTY ANALYSIS

The approach for uncertainty analysis is to select input parameters that are poorly known and/or highly heterogeneous which have a significant impact on key scenario outputs. The parameters are varied within reasonable bounds, based on available data and current knowledge. Predicted salt loads for Scenario 4 are compared.

The model inputs below are varied for the uncertainty analysis:

- River Murray level
- irrigation recharge
    - permanent irrigation recharge rate
    - pivot irrigation recharge rate
    - lag time
- impact of mallee clearance.

Groundwater salinity is not included in the uncertainty analysis, as explained below.

6.2.1 GROUNDWATER SALINITY

The groundwater system in the Woolpunda area is driven by upward leakage from the Renmark Group through the Lower Mannum Formation to the Monoman Formation. The adopted salinities for calculating modelled salt load are based on the salinity observations for the Lower Mannum Formation as there are very few salinity observations from the Monoman Formation. It is anticipated that the Lower Mannum Formation salinities will not change significantly over time, as head observations indicate that the irrigation recharge has not yet reached the watertable. Therefore groundwater salinity is not included in the uncertainty analysis.

Although not included in the analysis, groundwater salinity does contribute a considerable uncertainty to modelled salt load. This is because the model only calculates groundwater flow but does not simulate groundwater salinity changes either using observed values or solute transport modelling. The salt loads for each reach are estimated externally to the MODFLOW model, by multiplying the modelled flux value by the selected salinity zone value.

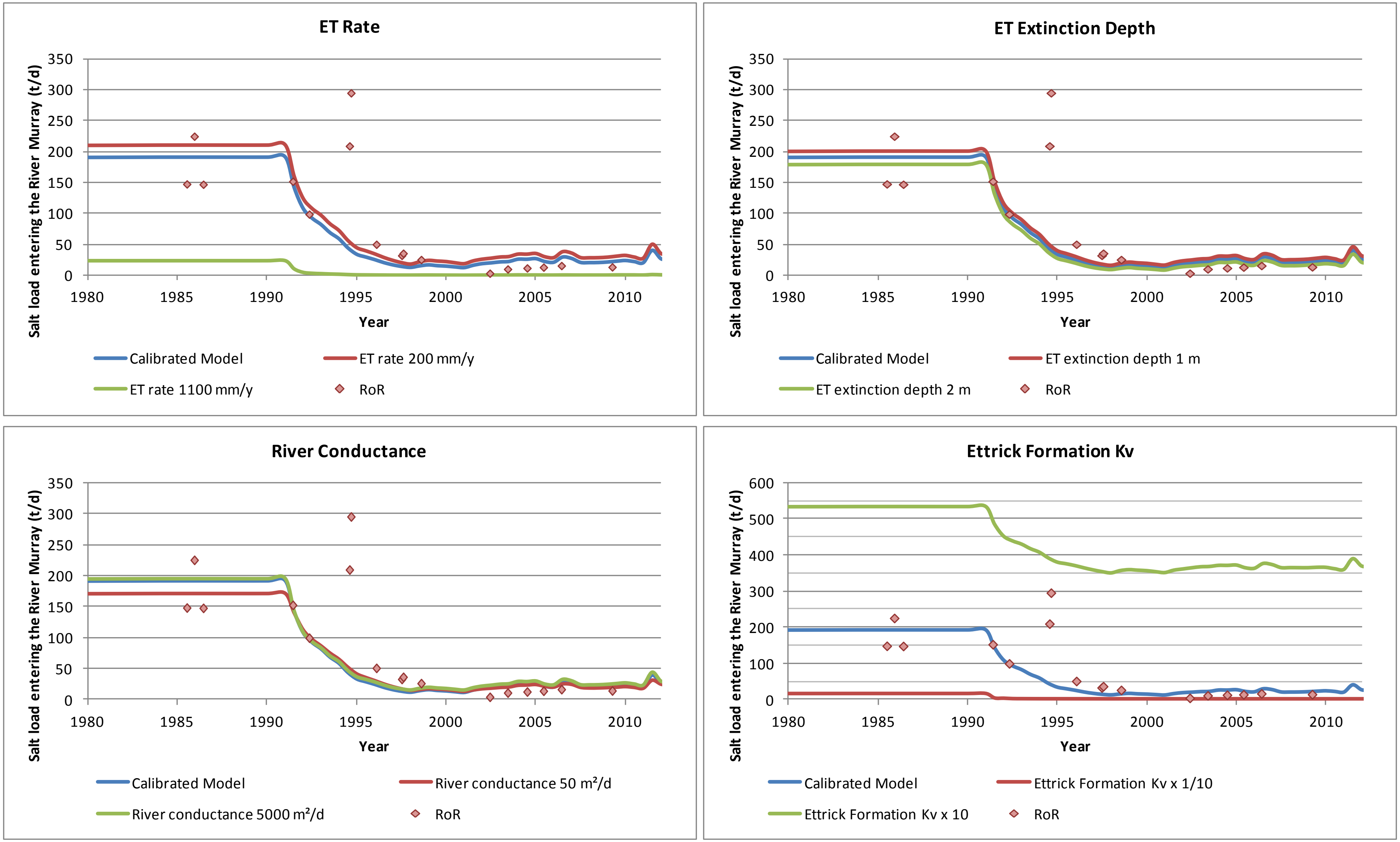


Figure 6.2(a). **Sensitivity of salt loads for the Woolpunda reach**

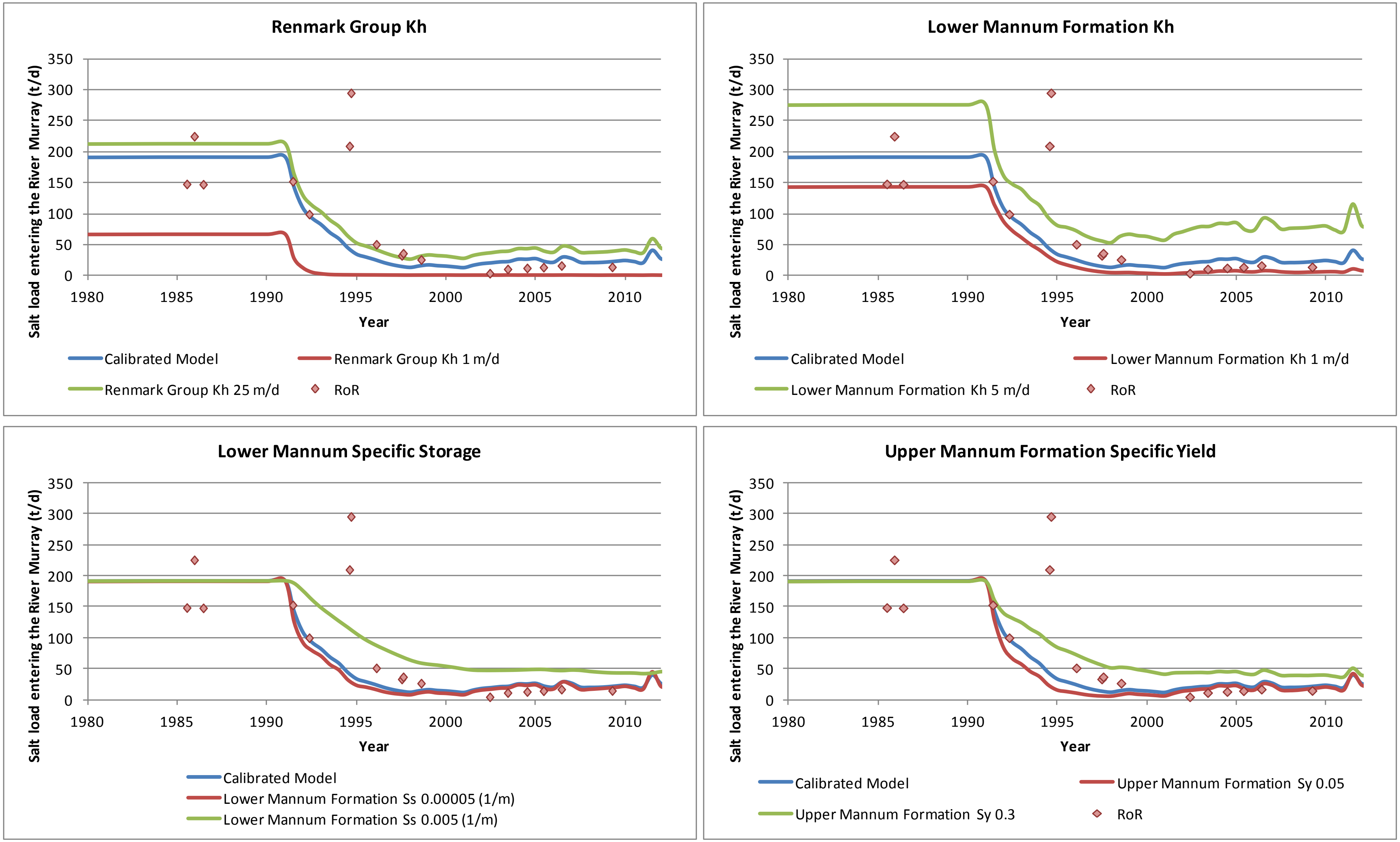


Figure 6.2(b). **Sensitivity of salt loads for the Woolpunda reach**

Therefore the uncertainty of salinity in modelled salt load can be easily explored as salinity is directly proportional to modelled salt load, meaning that a certain percentage change in salinity will lead to the same percentage change in modelled salt load.

6.2.2 RIVER LEVEL

River levels are extensively monitored, but as the model does not simulate changes in river level over time, the question is how the river level impacts the model outputs. In the calibrated model, the river level can be considered “average” or representative of constant-climate conditions. An analysis of river levels downstream of Lock 3 recorded from 1975 to 2011 was conducted. It was found that downstream of Lock 3, where the pool level is 6.10 m AHD, the 75th percentile river level from 1975 to 2012 is 7.39 m AHD, which is adopted for the river level uncertainty analysis.

Figure 6.3 shows the modelled salt loads for the river level uncertainty analysis. Salt loads from the 75th percentile river level are approximately 75 t/d lower than the salt loads from the currently adopted pool level. This is because a higher river level (the 75th percentile) will decrease the hydraulic gradient towards the river, hence reducing groundwater discharge and salt loads to the river. While their salt load magnitude is different, their trend is almost identical.

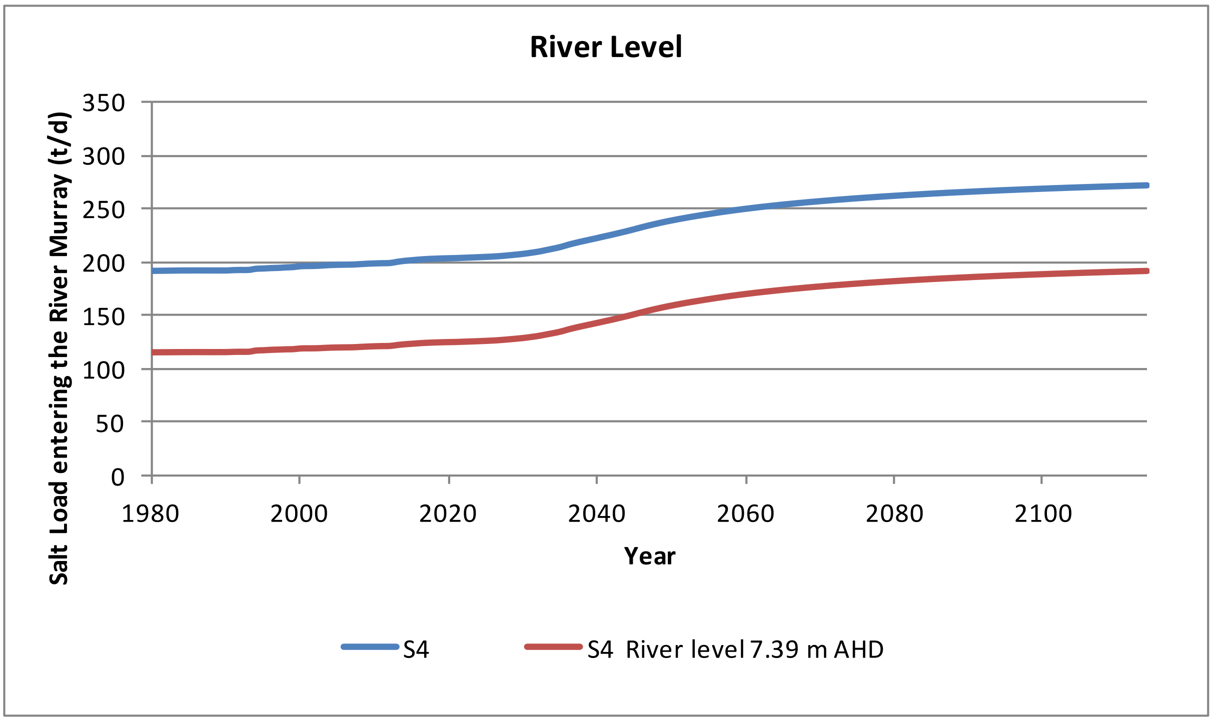


Figure 6.3 Uncertainty of river level in salt loads for the Woolpunda reach

6.2.3 IRRIGATION RECHARGE

Irrigation recharge rates and lag times are not estimated by inverse modelling as head observations indicate that most of the irrigation recharge has not yet reached the watertable. Hence a constant value of recharge rate and lag times from SIMRAT are applied for the permanent and pivot irrigation. The impact of irrigation recharge on the modelled salt loads can be significant, and therefore its uncertainty needs to be analysed.

Three irrigation recharge parameters are varied:

- the permanent irrigation recharge rate,
- the pivot irrigation recharge rate and
- the initial lag time between irrigation at the ground surface and recharge to the watertable.

6.2.3.1 PERMANENT IRRIGATION RECHARGE RATE

The recharge rate for permanent irrigation is 100 mm/y in the majority of the scenarios (Section 5). For the uncertainty analysis, rates of 70 mm/y and 140 mm/y are considered, based on advice from T Meissner (Laroona Environmetrics, 2013, pers. comm.). The rate of 70 mm/y corresponds to an application rate of 7 ML/ha/y which is typical for vines and vegetables with 90% irrigation efficiency. The 140 mm/y rate corresponds to an 80% efficiency rate. This assumes that there is no major change in crop type (e.g. tree crops may require 9.5 ML/ha/y).

Figure 6.4 shows the modelled salt loads for the permanent irrigation recharge rate uncertainty analysis. Salt loads from a permanent irrigation recharge rate of 70, 100 and 140 mm/y are highly similar until approximately 2030. The difference increases over subsequent decades. By 2113, salt loads from a recharge rate of 140 mm/y are higher than salt loads from a recharge rate of 100 mm/y by around 20 t/d, while salt loads from a recharge rate of 70 mm/y are lower than salt loads from a recharge rate of 100 mm/y by about 15 t/d. Therefore the uncertainty associated with permanent irrigation recharge rate can be quantified to be up to ± 20 t/d.

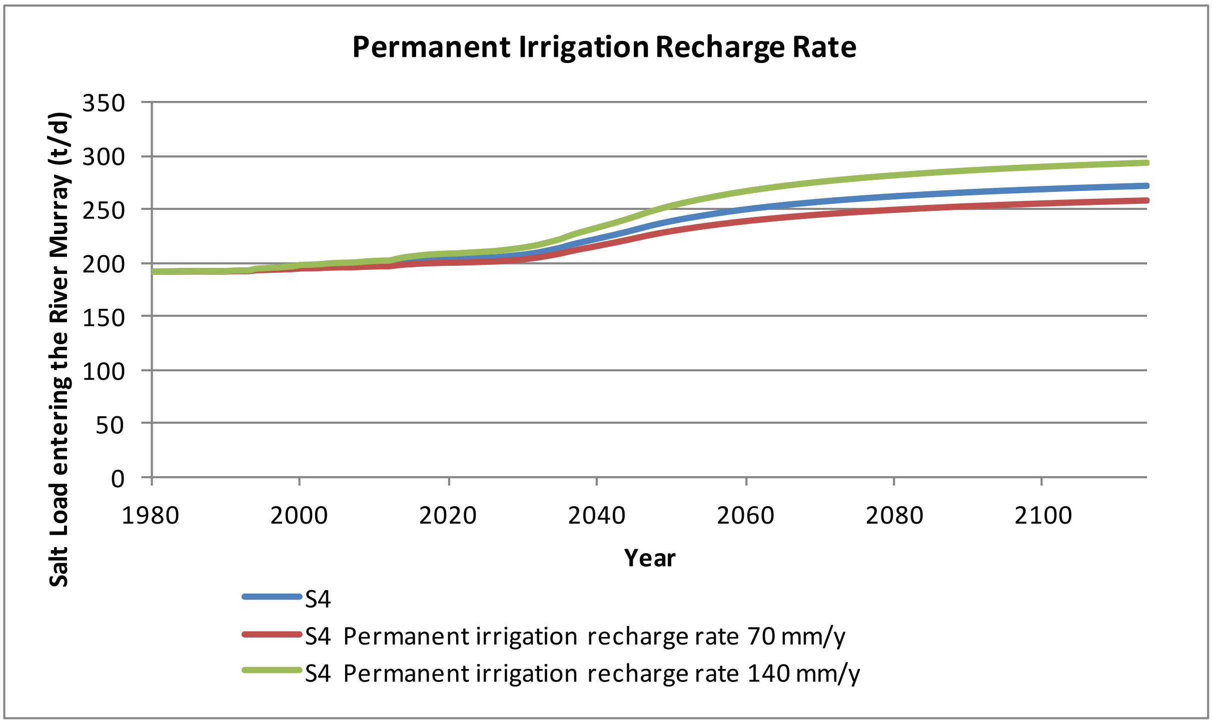


Figure 6.4 Uncertainty of permanent irrigation recharge rate in salt loads for the Woolpunda Reach

6.2.3.2 PIVOT IRRIGATION RECHARGE RATE

A recharge rate of 60 mm/y is applied for the pivot irrigation which is based on the current understanding (Vears 2013 in Appendix C). However, the fact that pivot irrigation is only temporary means that the adopted recharge rate is likely to be an overestimation. This is a conservative approach but at the same time introduces uncertainty to the modelled salt loads. It is possible that the pivot irrigation root zone drainage may reach the watertable very slowly due to long initial lag times caused by its non-continuous nature and relatively low application rates. This hypothesis is tested during the uncertainty analysis by changing the pivot irrigation recharge rate to 0 mm/y.

Figure 6.5 shows the modelled salt loads for the pivot irrigation recharge rate uncertainty analysis. Salt loads from a simulation without pivot irrigation starts to deviate from salt loads a simulation with pivot irrigation at approximately 2050. The difference increases over time. At 2113, the difference is around 15 t/d, hence the uncertainty associated with pivot irrigation recharge rate can be quantified to be up to -15 t/d.

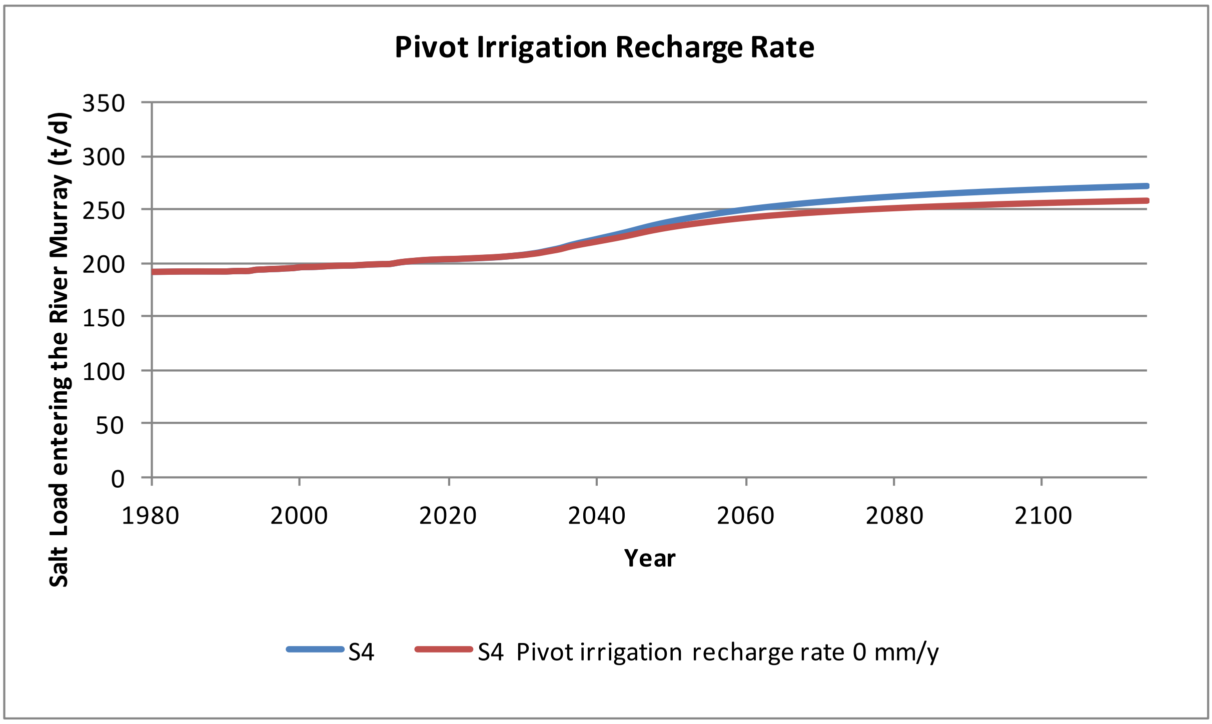


Figure 6.5 Uncertainty of pivot irrigation recharge rate in salt loads for the Woolpunda Reach

6.2.3.3 LAG TIME

Lag times for irrigation recharge are estimated using SIMRAT, assuming a continuous irrigation root zone drainage rate of 100 mm/y. While this is consistent with the assumptions for the permanent irrigation, the temporary pivot irrigation is non-continuous and its adopted recharge rate is only 60 mm/y. Hence the lag times for the pivot irrigation areas may be underestimated. Also the SIMRAT lag time estimates are based on assumed properties of the unsaturated zone sediments which are themselves uncertain. As there are no observation data to verify the lag times, there is a considerable amount of uncertainty of lag times.

For the uncertainty analysis, three cases are compared:

- Scenario 4 with the currently adopted lag times
- Scenario 4 with lag times of at least 40 years, any currently adopted lag times longer than 40 years are unchanged
- Scenario 4 with lag times of 20 years or less, any currently adopted lag times shorter than 20 years are unchanged.

Figure 6.6 shows the modelled salt loads for the irrigation recharge lag time uncertainty analysis. The change of lag times affects when the modelled salt loads begin to rise, as expected. Salt loads from lag times of 20 years or less start to increase the earliest, at around 2020. Its difference from salt loads from the currently adopted lag times peak at approximately 25 t/d at around 2035. Salt loads from lag times of at least 40 years are similar to salt loads from the currently adopted lag times, indicating the currently adopted lag times are relatively closer to 40 years than to 20 years. In the long-term, the difference in salt loads due to different lag times is minimal.

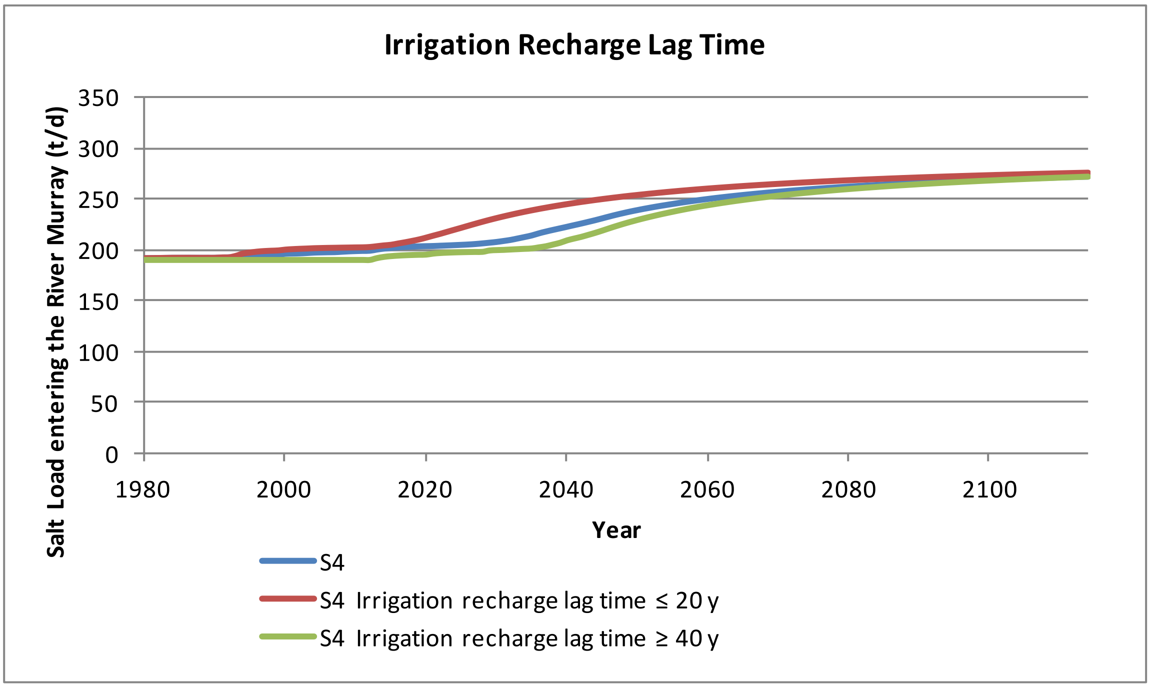


Figure 6.6 Uncertainty of irrigation recharge lag time in salt loads for the Woolpunda Reach

6.2.3.4 IMPACT OF MALLEE CLEARANCE

For simplicity, the impact of mallee clearance on groundwater recharge is not simulated in any future prediction scenarios except Scenario 2. This raises the concern whether the boundary conditions at the north and south would remain constant over time if the impact of mallee clearance is included in the other scenarios. The boundary conditions at the east and west are not considered in this uncertainty analysis as they are more affected by SIS and irrigation recharge, which has been discussed in Section 3.6.1.

Figure 6.7 shows the hydrographs close to the north and south model domain boundaries for Scenario 2 from 1970 until 2012. The location of the hydrographs can be found in Figure 2.10. The observed potentiometric head is compared with modelled values from Scenario 2. The trend for both observed and modelled potentiometric head is flat, indicating that mallee clearance has had little impact on potentiometric head to the present day. The boundary conditions do not need to be altered for that time period.

The impact of mallee clearance in the future is estimated by Scenario 2. The land clearance increases recharge, which increases potentiometric head and hence groundwater flux to the river. Scenario 2 estimates the increase in salt load to the River Murray as 15.5 t/d by 2114. Hence the model uncertainty due to mallee clearance for the other scenarios is up to 15.5 t/d.

6.3 CONCLUSIONS

The inputs used in the calibrated historical model are based on currently available data. Properties which are difficult to measure in the field have been used in sensitivity tests and varied within reasonable ranges in the model to determine the impact on model calibration. The modelled salt loads are most sensitive to the vertical hydraulic conductivity of the Ettrick Formation. The altered values of the Ettrick Formation vertical hydraulic conductivity lead to poorer calibration to observed heads, indicating that the model is well-calibrated. The model is not sensitive to groundwater ET rate and extinction depth, and river conductance, perhaps because there are few observation wells in the floodplain, where these parameters will have the most influence on potentiometric head.

In all sensitivity tests, the input values adopted for the calibrated model provide a better (or equal) overall calibration to groundwater head observations (SRMS) and Run-of-River salt load estimates.

The uncertainty analysis considers the range of salt load predictions when assumptions concerning river level, recharge and mallee clearance are changed. Modelled salt loads will be lowered by up to 75 t/d if the 75th percentile river level is used instead of the pool level. Uncertainty from the permanent irrigation recharge rate can lead to a change in salt loads by up to ± 20 t/d, while salt loads will be reduced by up to 15 t/d if the pivot irrigation root-zone drainage never reaches the watertable. Irrigation lag times affect when the modelled salt load start to increase, but the salt load difference in the long-term is minimal. The impact of mallee clearance on the area near the north and south model domain boundaries on groundwater level is negligible. These tests indicate that there is a considerable uncertainty about predicted future salt loads entering the River Murray, depending on model assumptions and irrigation efficiency.

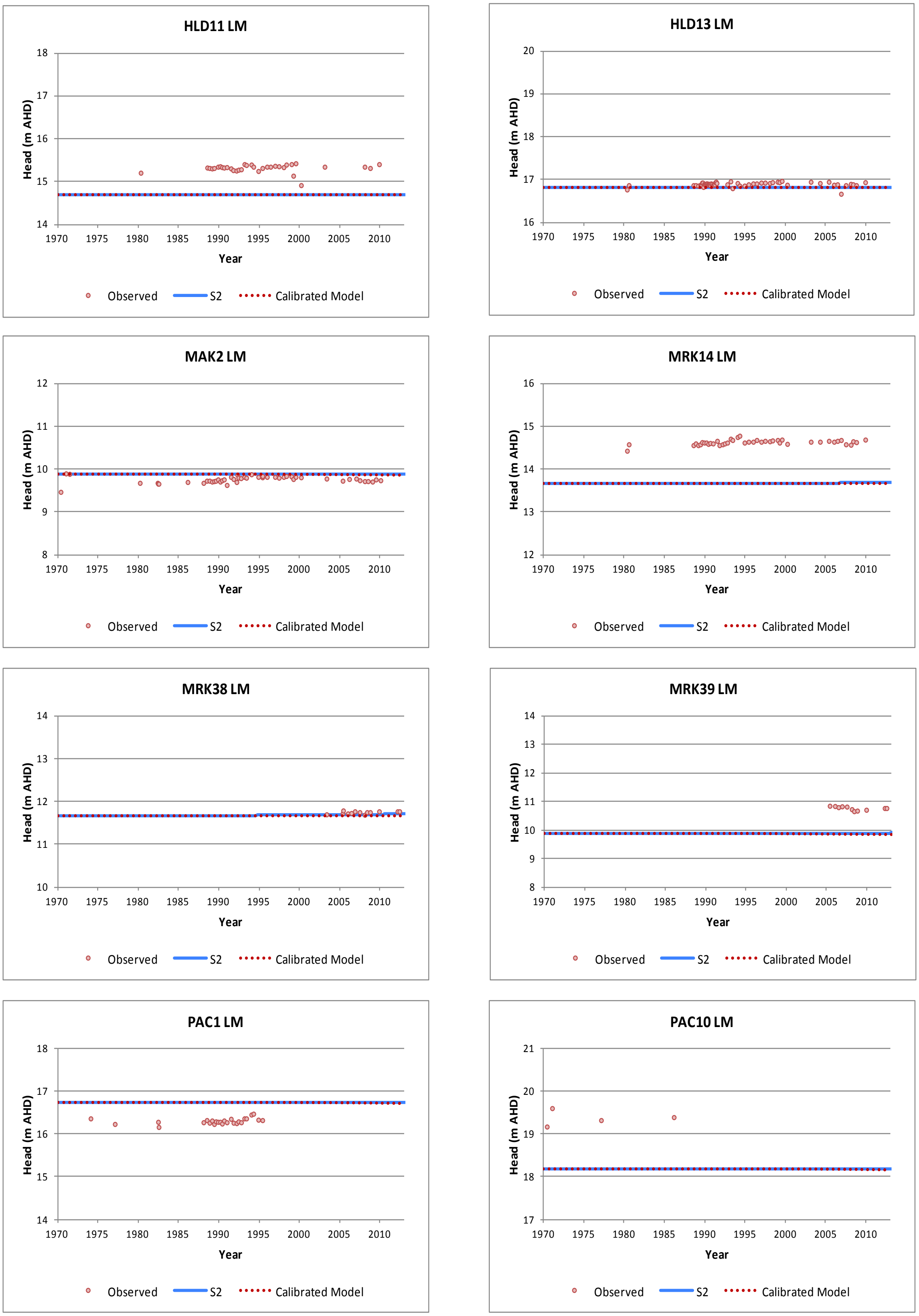
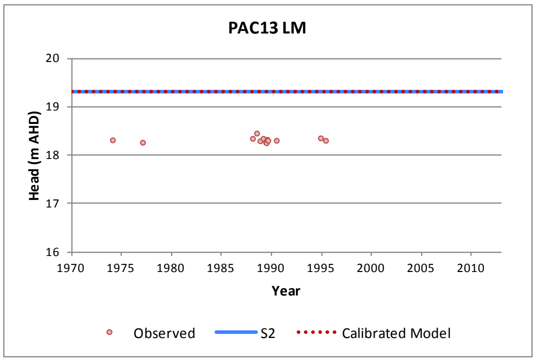
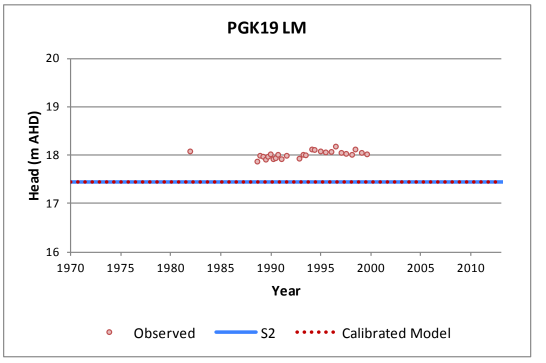


Figure 6.7(a). **Hydrographs near the north and south boundaries for Scenario 2 (Lower Mannum Formation)**





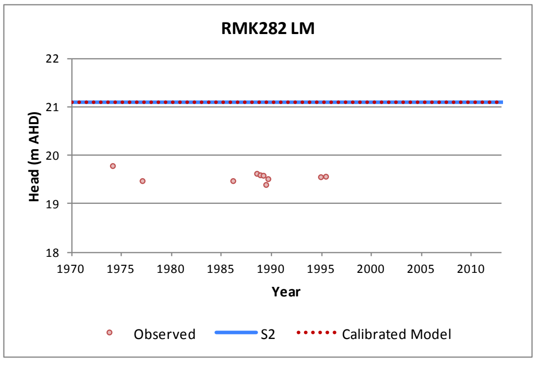


Figure 6.7(b). Hydrographs near the north and south boundaries for Scenario 2 (Lower Mannum Formation)

7 MODEL CAPABILITIES AND LIMITATIONS

The *MDBC Groundwater Modelling Guideline* (2001) states 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 improve. 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.*

The *NWC Australian Groundwater Modelling Guidelines* (2012) state that*: the capabilities and limitations section is intended to explicitly describe the capabilities and limitations of the model. This section states what the model should and should not be used for, so that expectations of the model can be managed. Limitations of data and code, the reliability of different outcomes of the model and how further data collection or research may improve reliability should be described.*

The range of possible uses of a model, its capabilities and limitations, reflect a number of factors. Firstly, there is the model's purpose, as model assumptions and design decisions depend crucially on this: e.g. the choice of processes simulated, spatial scale, time period, calibration criteria and recorded outputs. Secondly, data availability and accuracy shape the possible uses of the model. Thirdly, there may be limitations in the available science, for example, if there is no agreed and accurate description/equation of a process such as groundwater evapotranspiration. Computational issues may also constrain model use, if simulation times are slow or numerical methods are unstable and/or inaccurate.

Section 3.9 details model simplifications in representing the conceptual model. Section 6.2 describes the model uncertainties due to uncertainties in key input parameters, which may serve as a guide for where improvements could be made in the future with the availability of additional data or with the improvement of hydrogeological understanding.

The model has limitations due to gaps in both the current knowledge and existing information, and the special requirements of estimating salt loads for the Salinity Register. Some hydrogeological and hydrological features are simplified to reflect the needs of the Register. If the model were to be adapted for other purposes, the assumptions below may require alteration:

1. Fine detail of hydrogeological units is not included, as this level of detail is not available, not required for the Salinity Register and cannot be included in a regional numerical model.
2. The model has made a number of simplifications for the area to the east of Hamley Fault. Consequently the model results for that area should not be used for Salinity Register purposes. Model upgrades for inclusion of the Overland Corner area can be considered when required.
3. As the Salinity Register salt loads are about average the long term impact from accountable (human activity) actions, it does not include climate sequence impacts or river level fluctuations, so salt loads in effect assume average conditions in future predictions. Short-term changes in groundwater level and salt load are not simulated.
4. Groundwater salinities are assumed to remain constant when predicting future salt loads entering the river. However, groundwater salinity will most likely change in the future in response to accessions from brackish irrigation drainage, groundwater evapotranspiration, SIS pumping freshwater from the river into groundwater and flood interactions. This limitation is related to the current knowledge, existing information and current technical capacity for

monitoring of groundwater salinity changes for solute transport modelling. The model can be used to run a solute transport model when the groundwater salinity changes under irrigation area and floodplain area are fully understood and observed groundwater salinity data (detailed salinity distribution and changes horizontally and vertically) are available.

5. Although model recharge zones, rates and lag times are based on the best estimates and available information, the model uncertainties due to irrigation recharge is high as near the irrigation areas, there are either no observation wells or the observation wells are no longer monitored to confirm it. Therefore it is recommended that groundwater level data, which may be considered crucial for the next Five-Year Review, be collected in areas where none are currently available.

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 MODEL IMPROVEMENTS

The Woolpunda Numerical Groundwater Flow Model 2013 has been developed as part of the review of the SIS and Salinity Register entries. It is based on a prior model accredited by the MDBC, the Lock 3 to Morgan model of Rural Solutions (2005). The Lock 3 to Morgan model spans a region that includes two distinct hydrogeological regimes which are now represented by two separate models, each simulating a different area: the Waikerie to Morgan model 2012 (Yan *et. al* 2012) and the Woolpunda 2013 model.

The model was upgraded based on new information from hydrogeological investigations, particularly irrigation data and SIS operations. Following modelling guidelines (MDBC 2001; NWC 2012), the modified model was recalibrated using long-term observed (historical) regional potentiometric heads from SIS observation wells. Its results have been confirmed using RoR data, geophysical surveys and other information. The model was used to estimate salt loads to the River Murray for different scenarios required for the Salinity Register. As specified by the Guidelines (MDBC 2001; NWC 2012), sensitivity and uncertainty tests were undertaken to aid risk assessment in management and policy decisions.

The modelled salt loads and calibration performance are compared between the Rural Solutions 2005 model and the Woolpunda 2013 model in Table 8.1 and Table 8.2, respectively. In Table 8.1, the modelled salt loads from the Woolpunda 2013 model show a much closer match to the ROR salt loads than those of the Rural Solutions 2005 model. Table 8.2 shows that the number of observation wells used for calibration in the Woolpunda 2013 model is about four times higher than the Rural Solutions 2005 model. The calibration statistics (i.e. SRMS, a lower value indicates a better calibration) for the Woolpunda 2013 model are much lower than the Rural Solutions 2005, indicating a significant calibration improvement.

Table 8.1 Modelled salt load comparison between the Rural Solutions 2005 model and the Woolpunda 2013 model

Year	Salt load (t/d)		
	Run-of-River	Rural Solutions 2005 model	Woolpunda 2013 model
1988	201	253	191
1998	14	41	12
2001	14	58	12
2003	13	76	21

Table 8.2 Calibration performance comparison between the Rural Solutions 2005 model and the Woolpunda 2013 model

Model	Number of observation wells in Woolpunda	SRMS	
		1988	2000
Rural Solutions 2005 model	19	5.00%	7.80%
Woolpunda 2013 model	86	2.80%	2.70%

Model files are organised (structure and name convention) using a structure following the protocol from the SA Groundwater Model Warehouse. The files are shown in Appendix C-4. This includes collated data, model files, model input and output files and output analyses.

8.2 MODELLING RESULTS

The model is an 'impact assessment model of high complexity' in the terminology of the MDBC Guideline (MDBC 2001) with a confidence level mainly meeting Class 3 criteria (but sometimes limited to Class 2 due to a lack of data), according to the classification criteria of the *Australian Groundwater Modelling Guidelines* (NWC 2012). The modelling work has resulted in an improved understanding of the hydrogeology of the aquifer system in the Woolpunda area. The upgraded model was used to predict the flux of saline groundwater (salt load) entering the River Murray under different irrigation practices and development scenarios. Comparison of scenario modelling results (salt loads) can be seen in Figures 5.2 to 5.3 and in Table 8.3. The annual salt loads and groundwater flux entering the River Murray for each scenario are given in Figures 8.1 to 8.2.

Table 8.3 Summary of predicted salt load (t/d) Entering the River Murray – Woolpunda

Woolpunda	Year simulated	Salt load required by Salinity Registered						
		1988	2000	2013	2015	2050	2100	2113
Calibrated historical model	**1920-2013**	191.3	14.5	25.8	25.2	-	-	-
Scenario 1	**Steady-state**	190.9	190.9	190.9	190.9	190.9	190.9	190.9
Scenario 2	**1920 – 2114**	191.5	191.6	191.9	191.9	193.1	201.8	206.4
Scenario 3A	**1920 – 2114**	191.4	194.1	198.2	199.1	201.9	202.2	202.3
Scenario 3C	**1920 – 2114**	191.3	193.5	196.9	197.7	200.0	200.3	200.3
Scenario 4	**1920 – 2114**	191.3	195.4	199.6	201.2	239.3	269.7	272.7
Scenario 5	**1920 – 2114**	191.3	195.4	199.6	201.2	240.6	286.6	290.7
Scenario 8A	**1920 – 2114**	191.3	15.1	15.0	15.1	16.2	16.7	16.8
Scenario 8B	**1920 – 2114**	191.3	14.3	14.2	14.2	14.1	14.0	13.9
Scenario 8C	**1920 – 2114**	191.3	15.1	15.0	15.1	16.3	17.1	17.1

8.3 RECOMMENDATIONS FOR FUTURE WORK

The numerical model is required to be reviewed at intervals of not more than seven years by Schedule B. The Register entries derived from the model are to be reviewed every five years. The model review process considers new information, knowledge and landscape-scale changes. Taking the uncertainty analysis results into account, the following recommendations are made so the quality of each aspect of the model is maintained or improved over time.

8.3.1 MONITORING AND DATA COLLECTION

The following recommendations are for monitoring, field work and data collection:

- ontinue collection of irrigation data. Application volumes, irrigation area, crop type and drainage volumes recorded and collated to provide estimates of root zone drainage over time. This information provides higher confidence on model recharge

- continue the current monitoring of potentiometric head and salinity in Obswell and SIS wells to continue for model validation in the next Five-Year Review
- groundwater level data near irrigation areas could be collected through the drilling of new wells and/or recommencing the monitoring at abandoned wells. This would assist in determining the volume of irrigation drainage which has reached the watertable to recharge the Mannum Formation aquifer
- conduct aquifer tests to estimate the vertical conductivity of the Ettrick Formation and the horizontal conductivity of the Renmark Group aquifer
- continue RoR surveys as they are used for model confirmation which increases model output confidence
- monitoring groundwater head and salinity in the Monoman Formation over time may improve salt load calculations.

8.3.2 ADDITIONAL MODEL FEATURES AND PROCESSES

It is recommended that the following numerical model improvements be considered during the next Five-Year Review. The usefulness and feasibility of each item listed below will depend on the future requirements and assumptions of the Salinity Registers, the state of scientific knowledge and data availability.

Features requiring additional model development:

- improving simulation of groundwater recharge from irrigation, if more information becomes available
- more detailed representation of the Overland Corner area, should the model be required to simulate salt loads for that region
- improving simulation of evapotranspiration from groundwater, if more information becomes available
- possibly improving calibration in the floodplain area against flood events, such as fluctuations in river level over time, when data becomes available (e.g. detailed pool level and inundation area).

8.3.3 POTENTIAL WORK FOR FUTURE

The following works could improve the quality of the numerical model results but may not be necessary for the next Five Year Review process:

- investigation of riverbed hydraulic conductivity
- AEM data will improve salt load calculations. These data will be useful if solute transport modelling is included in future models
- improved understanding of flow in the unsaturated zone, including perched aquifers, to inform recharge rates and areas
- consideration of groundwater salinity changes over time in salt load calculations when valid information becomes available. This will affect salt loads and calculation of salt loads by either:
  - multiplying groundwater flux to the river by salinity that varies with time for each reach, or
  - full solute transport simulation.

Time (y)	S-1 (t/d)	S-2 (t/d)	S-3A (t/d)	S-3C (t/d)	S-4 (t/d)	S-5 (t/d)	S-8A (t/d)	S8B (t/d)	S-8C (t/d)
1988	190.9	191.5	191.4	191.3	191.3	191.3	191.3	191.3	191.3
1989	190.9	191.5	191.4	191.3	191.3	191.3	191.4	191.3	191.3
1990	190.9	191.5	191.4	191.3	191.3	191.3	191.4	191.3	191.3
1991	190.9	191.5	191.8	191.7	191.7	191.7	191.7	191.7	191.7
1992	190.9	191.6	192.0	191.8	191.8	191.8	58.6	58.6	58.6
1993	190.9	191.6	192.0	191.8	191.8	191.8	23.9	23.9	23.9
1994	190.9	191.6	192.0	191.9	192.9	192.9	17.0	16.5	17.0
1995	190.9	191.6	192.1	191.9	193.2	193.2	15.7	15.2	15.7
1996	190.9	191.6	192.6	192.3	193.6	193.6	15.3	14.8	15.3
1997	190.9	191.6	192.8	192.5	193.8	193.8	15.2	14.6	15.2
1998	190.9	191.6	193.4	193.0	194.3	194.3	15.1	14.5	15.1
1999	190.9	191.6	193.8	193.3	194.6	194.6	15.0	14.4	15.0
2000	190.9	191.6	194.1	193.5	195.4	195.4	15.1	14.3	15.1
2001	190.9	191.7	194.2	193.7	195.6	195.6	15.0	14.3	15.0
2002	190.9	191.7	194.4	193.8	195.7	195.7	15.0	14.3	15.0
2003	190.9	191.7	194.9	194.2	196.1	196.1	15.0	14.2	15.0
2004	190.9	191.7	195.2	194.5	196.5	196.5	15.0	14.2	15.0
2005	190.9	191.7	195.4	194.7	196.7	196.7	15.0	14.2	15.0
2006	190.9	191.7	195.6	194.8	196.9	196.9	15.0	14.2	15.0
2007	190.9	191.8	195.7	194.9	197.0	197.0	15.0	14.1	15.0
2008	190.9	191.8	196.2	195.3	197.4	197.4	15.0	14.1	15.0
2009	190.9	191.8	196.6	195.6	197.8	197.8	15.0	14.1	15.0
2010	190.9	191.8	196.9	195.9	198.1	198.1	14.9	14.1	14.9
2011	190.9	191.8	197.2	196.1	198.3	198.3	14.9	14.1	14.9
2012	190.9	191.9	197.4	196.3	198.4	198.4	14.9	14.1	14.9
2013	190.9	191.9	198.2	196.9	199.6	199.6	15.0	14.2	15.0
2014	190.9	191.9	198.7	197.4	200.6	200.6	15.1	14.2	15.1
2015	190.9	191.9	199.1	197.7	201.2	201.2	15.1	14.2	15.1
2016	190.9	192.0	199.6	198.1	201.8	201.8	15.1	14.3	15.1
2017	190.9	192.0	199.9	198.4	202.3	202.3	15.2	14.3	15.2
2018	190.9	192.0	200.2	198.6	202.6	202.6	15.2	14.3	15.2
2019	190.9	192.0	200.4	198.8	202.8	202.8	15.2	14.3	15.2
2020	190.9	192.0	200.6	198.9	203.0	203.0	15.2	14.3	15.2
2021	190.9	192.1	200.7	199.0	203.2	203.2	15.2	14.2	15.2
2022	190.9	192.1	200.8	199.1	203.5	203.5	15.2	14.2	15.2
2023	190.9	192.2	200.9	199.2	203.7	203.7	15.2	14.2	15.2
2024	190.9	192.2	201.0	199.3	204.0	204.0	15.2	14.2	15.2
2025	190.9	192.2	201.1	199.4	204.4	204.4	15.2	14.2	15.2
2026	190.9	192.2	201.2	199.4	204.7	204.7	15.2	14.2	15.2
2027	190.9	192.2	201.2	199.5	205.2	205.2	15.3	14.2	15.3
2028	190.9	192.2	201.3	199.5	205.8	205.8	15.3	14.2	15.3
2029	190.9	192.2	201.3	199.6	206.5	206.5	15.3	14.2	15.3
2030	190.9	192.3	201.4	199.6	207.3	207.3	15.3	14.2	15.3
2031	190.9	192.3	201.4	199.6	208.3	208.3	15.3	14.2	15.3
2032	190.9	192.4	201.5	199.7	209.3	209.3	15.4	14.2	15.4
2033	190.9	192.5	201.5	199.7	210.8	210.8	15.4	14.2	15.4
2034	190.9	192.5	201.5	199.7	212.2	212.2	15.4	14.1	15.4
2035	190.9	192.5	201.6	199.8	213.8	213.8	15.5	14.1	15.5
2036	190.9	192.5	201.6	199.8	215.9	215.9	15.7	14.1	15.7
2037	190.9	192.6	201.6	199.8	217.7	217.7	15.8	14.1	15.8
2038	190.9	192.6	201.7	199.8	219.4	219.4	15.8	14.1	15.8
2039	190.9	192.6	201.7	199.9	220.9	220.9	15.9	14.1	15.9
2040	190.9	192.6	201.7	199.9	222.5	222.5	15.9	14.1	15.9
2041	190.9	192.7	201.7	199.9	224.1	224.1	15.9	14.1	15.9
2042	190.9	192.8	201.8	199.9	225.7	225.7	16.0	14.1	16.0
2043	190.9	192.8	201.8	199.9	227.4	227.4	16.0	14.1	16.0
2044	190.9	192.9	201.8	200.0	229.1	229.1	16.0	14.1	16.0
2045	190.9	192.9	201.8	200.0	231.0	231.0	16.1	14.1	16.1
2046	190.9	192.9	201.8	200.0	232.8	232.9	16.1	14.1	16.1
2047	190.9	193.0	201.9	200.0	234.6	234.9	16.1	14.1	16.1
2048	190.9	193.0	201.9	200.0	236.3	236.8	16.2	14.1	16.2
2049	190.9	193.0	201.9	200.0	237.8	238.7	16.2	14.1	16.2
2050	190.9	193.1	201.9	200.0	239.3	240.6	16.2	14.1	16.3
2051	190.9	193.2	201.9	200.1	240.6	242.5	16.2	14.1	16.3
2052	190.9	193.3	201.9	200.1	241.9	244.4	16.3	14.1	16.4
2053	190.9	193.4	202.0	200.1	243.2	246.1	16.3	14.1	16.4
2054	190.9	193.4	202.0	200.1	244.3	247.8	16.3	14.1	16.4
2055	190.9	193.5	202.0	200.1	245.4	249.5	16.3	14.1	16.5
2056	190.9	193.6	202.0	200.1	246.5	251.2	16.3	14.1	16.5
2057	190.9	193.6	202.0	200.1	247.6	253.0	16.3	14.1	16.5
2058	190.9	193.7	202.0	200.1	248.6	254.8	16.4	14.0	16.6
2059	190.9	193.7	202.0	200.1	249.5	256.5	16.4	14.0	16.6
2060	190.9	193.8	202.0	200.1	250.4	258.1	16.4	14.0	16.6
2061	190.9	193.9	202.1	200.1	251.3	259.6	16.4	14.0	16.6
2062	190.9	194.1	202.1	200.1	252.1	260.9	16.4	14.0	16.7
2063	190.9	194.2	202.1	200.1	252.9	262.2	16.4	14.0	16.7
2064	190.9	194.3	202.1	200.1	253.7	263.5	16.4	14.0	16.7
2065	190.9	194.4	202.1	200.1	254.4	264.6	16.5	14.0	16.7
2066	190.9	194.5	202.1	200.1	255.2	265.7	16.5	14.0	16.7
2067	190.9	194.6	202.1	200.1	255.8	266.8	16.5	14.0	16.7
2068	190.9	194.7	202.1	200.1	256.5	267.8	16.5	14.0	16.8
2069	190.9	194.8	202.1	200.1	257.1	268.8	16.5	14.0	16.8
2070	190.9	194.9	202.1	200.2	257.7	269.7	16.5	14.0	16.8
2071	190.9	195.1	202.1	200.2	258.3	270.6	16.5	14.0	16.8
2072	190.9	195.3	202.1	200.2	258.9	271.4	16.5	14.0	16.8
2073	190.9	195.5	202.1	200.2	259.4	272.2	16.5	14.0	16.8
2074	190.9	195.7	202.1	200.2	260.0	273.0	16.6	14.0	16.8
2075	190.9	195.8	202.2	200.2	260.5	273.8	16.6	14.0	16.9
2076	190.9	196.0	202.2	200.2	261.0	274.5	16.6	14.0	16.9
2077	190.9	196.2	202.2	200.2	261.5	275.2	16.6	14.0	16.9
2078	190.9	196.3	202.2	200.2	262.0	275.9	16.6	14.0	16.9
2079	190.9	196.5	202.2	200.2	262.4	276.5	16.6	14.0	16.9
2080	190.9	196.6	202.2	200.2	262.9	277.2	16.6	14.0	16.9
2081	190.9	196.9	202.2	200.2	263.3	277.8	16.6	14.0	16.9
2082	190.9	197.1	202.2	200.2	263.7	278.4	16.6	14.0	16.9
2083	190.9	197.4	202.2	200.2	264.1	279.0	16.6	14.0	16.9
2084	190.9	197.6	202.2	200.2	264.5	279.5	16.6	14.0	16.9
2085	190.9	197.8	202.2	200.2	264.9	280.1	16.6	14.0	17.0
2086	190.9	198.1	202.2	200.2	265.3	280.6	16.6	14.0	17.0
2087	190.9	198.3	202.2	200.2	265.7	281.1	16.7	14.0	17.0
2088	190.9	198.5	202.2	200.2	266.0	281.6	16.7	14.0	17.0
2089	190.9	198.7	202.2	200.2	266.4	282.1	16.7	14.0	17.0
2090	190.9	198.9	202.2	200.2	266.7	282.6	16.7	14.0	17.0
2091	190.9	199.2	202.2	200.2	267.0	283.0	16.7	14.0	17.0
2092	190.9	199.5	202.2	200.2	267.4	283.5	16.7	14.0	17.0
2093	190.9	199.8	202.2	200.2	267.7	283.9	16.7	14.0	17.0
2094	190.9	200.1	202.2	200.2	268.0	284.3	16.7	14.0	17.0
2095	190.9	200.4	202.2	200.3	268.3	284.7	16.7	14.0	17.0
2096	190.9	200.7	202.2	200.3	268.6	285.1	16.7	14.0	17.0
2097	190.9	201.0	202.2	200.3	268.9	285.5	16.7	14.0	17.0
2098	190.9	201.3	202.2	200.3	269.2	285.9	16.7	14.0	17.1
2099	190.9	201.5	202.2	200.3	269.4	286.3	16.7	14.0	17.1
2100	190.9	201.8	202.2	200.3	269.7	286.6	16.7	14.0	17.1
2101	190.9	202.1	202.2	200.3	270.0	287.0	16.7	14.0	17.1
2102	190.9	202.5	202.2	200.3	270.2	287.3	16.7	14.0	17.1
2103	190.9	202.9	202.2	200.3	270.5	287.7	16.7	14.0	17.1
2104	190.9	203.2	202.2	200.3	270.7	288.0	16.7	14.0	17.1
2105	190.9	203.6	202.2	200.3	270.9	288.3	16.7	14.0	17.1
2106	190.9	203.9	202.2	200.3	271.2	288.6	16.7	14.0	17.1
2107	190.9	204.2	202.2	200.3	271.4	289.0	16.8	14.0	17.1
2108	190.9	204.5	202.2	200.3	271.6	289.3	16.8	14.0	17.1
2109	190.9	204.9	202.2	200.3	271.9	289.6	16.8	14.0	17.1
2110	190.9	205.1	202.3	200.3	272.1	289.8	16.8	14.0	17.1
2111	190.9	205.5	202.3	200.3	272.3	290.1	16.8	13.9	17.1
2112	190.9	206.0	202.3	200.3	272.5	290.4	16.8	13.9	17.1
2113	190.9	206.4	202.3	200.3	272.7	290.7	16.8	13.9	17.1
2114	190.9	206.8	202.3	200.3	272.9	290.9	16.8	13.9	17.1

Figure 8.1. Modelled salt load entering the River Murray for all scenarios for the Woolpunda reach

Time	S-1	S-2	S-3A	S-3C	S-4	S-5	S-8A	S8B	S-8C
(y)	(t/d)	(t/d)	(t/d)	(t/d)	(t/d)	(t/d)	(t/d)	(t/d)	(t/d)
1988	8856	8881	8879	8875	8875	8875	8877	8875	8875
1989	8856	8881	8879	8875	8875	8875	8877	8875	8875
1990	8856	8881	8879	8875	8875	8875	8877	8875	8875
1991	8856	8884	8899	8892	8892	8892	8894	8892	8892
1992	8856	8885	8907	8898	8898	8898	2751	2751	2751
1993	8856	8886	8910	8901	8901	8901	1104	1104	1104
1994	8856	8886	8911	8902	8950	8950	773	750	773
1995	8856	8887	8912	8903	8962	8962	715	691	715
1996	8856	8887	8935	8922	8981	8981	698	673	698
1997	8856	8887	8948	8933	8990	8990	690	664	690
1998	8856	8887	8977	8956	9012	9012	685	660	685
1999	8856	8887	8997	8973	9028	9028	681	656	681
2000	8856	8887	9009	8982	9066	9066	686	653	686
2001	8856	8890	9019	8990	9075	9075	683	651	683
2002	8856	8892	9027	8997	9082	9082	681	649	681
2003	8856	8893	9048	9014	9100	9100	681	649	681
2004	8856	8894	9064	9027	9119	9119	684	648	684
2005	8856	8894	9074	9036	9129	9129	683	646	683
2006	8856	8895	9082	9042	9137	9137	682	645	682
2007	8856	8895	9087	9047	9142	9142	681	644	681
2008	8856	8895	9108	9064	9160	9160	681	643	681
2009	8856	8895	9128	9081	9178	9178	680	643	680
2010	8856	8895	9143	9093	9190	9190	679	642	679
2011	8856	8899	9153	9102	9200	9200	678	641	678
2012	8856	8901	9162	9109	9207	9207	678	640	678
2013	8856	8903	9199	9140	9262	9262	684	647	684
2014	8856	8904	9225	9162	9307	9307	686	647	686
2015	8856	8904	9241	9175	9337	9337	686	647	686
2016	8856	8905	9263	9193	9365	9365	689	649	689
2017	8856	8905	9280	9207	9387	9387	690	650	690
2018	8856	8905	9292	9217	9402	9402	690	650	690
2019	8856	8906	9302	9225	9414	9414	690	649	690
2020	8856	8906	9309	9232	9423	9423	690	649	690
2021	8856	8910	9316	9237	9430	9430	689	648	689
2022	8856	8913	9321	9241	9444	9444	692	648	692
2023	8856	8915	9326	9245	9456	9456	692	647	692
2024	8856	8916	9330	9249	9470	9470	692	647	692
2025	8856	8916	9333	9252	9485	9485	693	647	693
2026	8856	8917	9337	9255	9501	9501	693	646	693
2027	8856	8918	9340	9257	9523	9523	694	646	694
2028	8856	8918	9343	9259	9552	9552	695	646	695
2029	8856	8919	9345	9261	9584	9584	696	645	696
2030	8856	8919	9347	9263	9620	9620	697	645	697
2031	8856	8923	9349	9265	9666	9666	698	645	698
2032	8856	8927	9351	9267	9716	9716	699	644	699
2033	8856	8929	9353	9268	9783	9783	701	644	701
2034	8856	8930	9355	9270	9851	9851	702	644	702
2035	8856	8931	9357	9271	9924	9924	703	644	703
2036	8856	8932	9358	9272	10023	10023	715	643	715
2037	8856	8933	9359	9273	10107	10107	719	643	719
2038	8856	8934	9361	9275	10184	10184	721	643	721
2039	8856	8935	9362	9276	10258	10258	722	643	722
2040	8856	8936	9363	9277	10333	10333	723	642	723
2041	8856	8941	9364	9277	10409	10409	725	642	725
2042	8856	8944	9365	9278	10484	10484	726	642	726
2043	8856	8947	9366	9279	10563	10563	728	642	728
2044	8856	8949	9367	9280	10644	10644	729	642	729
2045	8856	8951	9368	9281	10731	10731	731	641	731
2046	8856	8953	9369	9281	10818	10823	732	641	733
2047	8856	8954	9370	9282	10902	10915	734	641	735
2048	8856	8956	9371	9283	10980	11007	736	641	737
2049	8856	8957	9372	9283	11054	11096	737	641	739
2050	8856	8959	9372	9284	11122	11183	738	641	741
2051	8856	8964	9373	9284	11186	11272	739	640	743
2052	8856	8969	9374	9285	11247	11360	740	640	745
2053	8856	8973	9374	9285	11305	11444	741	640	747
2054	8856	8976	9375	9285	11359	11524	742	640	748
2055	8856	8979	9375	9285	11412	11601	743	640	749
2056	8856	8982	9376	9286	11464	11682	744	640	751
2057	8856	8985	9377	9286	11513	11768	745	639	753
2058	8856	8988	9377	9286	11560	11852	745	639	754
2059	8856	8991	9378	9287	11605	11931	746	639	755
2060	8856	8994	9378	9287	11647	12005	747	639	757
2061	8856	9000	9379	9287	11688	12074	747	639	758
2062	8856	9007	9379	9288	11727	12138	748	639	759
2063	8856	9013	9379	9288	11765	12200	749	639	759
2064	8856	9018	9380	9288	11801	12257	749	639	760
2065	8856	9024	9380	9288	11835	12312	750	638	761
2066	8856	9029	9381	9288	11869	12363	750	638	762
2067	8856	9034	9381	9288	11901	12413	751	638	763
2068	8856	9038	9381	9289	11932	12460	751	638	763
2069	8856	9043	9382	9289	11961	12506	752	638	764
2070	8856	9048	9382	9289	11990	12549	752	638	765
2071	8856	9057	9382	9289	12018	12590	753	638	765
2072	8856	9066	9383	9290	12045	12630	753	638	766
2073	8856	9075	9383	9290	12071	12668	754	638	767
2074	8856	9083	9383	9290	12096	12705	754	638	767
2075	8856	9091	9384	9290	12120	12740	754	637	768
2076	8856	9099	9384	9290	12144	12775	755	637	768
2077	8856	9106	9384	9290	12167	12808	755	637	769
2078	8856	9114	9384	9291	12189	12840	755	637	769
2079	8856	9121	9384	9291	12211	12871	756	637	770
2080	8856	9128	9384	9291	12232	12901	756	637	770
2081	8856	9140	9385	9292	12252	12930	757	637	771
2082	8856	9152	9385	9292	12272	12958	757	637	771
2083	8856	9164	9385	9292	12291	12985	757	637	772
2084	8856	9176	9385	9292	12310	13011	758	637	772
2085	8856	9187	9385	9292	12328	13037	758	637	772
2086	8856	9197	9385	9292	12346	13061	758	636	773
2087	8856	9208	9386	9292	12363	13086	758	636	773
2088	8856	9218	9386	9292	12380	13109	759	636	774
2089	8856	9227	9386	9293	12396	13132	759	636	774
2090	8856	9237	9386	9293	12412	13154	759	636	774
2091	8856	9251	9386	9293	12428	13175	760	636	775
2092	8856	9267	9386	9293	12443	13196	760	636	775
2093	8856	9282	9387	9293	12458	13216	760	636	775
2094	8856	9297	9387	9293	12472	13236	760	636	776
2095	8856	9310	9387	9294	12486	13255	760	636	776
2096	8856	9324	9387	9294	12500	13274	761	636	776
2097	8856	9337	9387	9294	12514	13293	761	636	777
2098	8856	9349	9387	9294	12527	13311	761	636	777
2099	8856	9361	9387	9294	12540	13328	761	636	777
2100	8856	9373	9387	9294	12552	13345	762	636	778
2101	8856	9390	9387	9294	12564	13362	762	635	778
2102	8856	9409	9387	9294	12576	13378	762	635	778
2103	8856	9426	9387	9294	12588	13394	762	635	778
2104	8856	9443	9388	9294	12600	13409	762	635	779
2105	8856	9460	9388	9294	12611	13424	763	635	779
2106	8856	9475	9388	9294	12622	13439	763	635	779
2107	8856	9491	9388	9295	12633	13453	763	635	779
2108	8856	9505	9388	9295	12643	13467	763	635	780
2109	8856	9520	9388	9295	12653	13481	763	635	780
2110	8856	9534	9388	9295	12663	13495	764	635	780
2111	8856	9553	9388	9295	12673	13508	764	635	780
2112	8856	9573	9388	9295	12683	13521	764	635	781
2113	8856	9592	9388	9295	12693	13533	764	635	781
2114	8856	9611	9388	9295	12702	13546	764	635	781

Figure 8.2. Modelled groundwater flux entering the River Murray for all scenarios for the Woolpunda reach

UNITS OF MEASUREMENT

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

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

Shortened forms

~	approximately equal to
bgs	below ground surface
EC	electrical conductivity (µS/cm)
K	hydraulic conductivity (m/d)
pH	acidity
pMC	percent of modern carbon
ppb	parts per billion
ppm	parts per million
ppt	parts per trillion
w/v	weight in volume
w/w	weight in weight

GLOSSARY

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

Anabranch — A branch of a river that leaves the main channel

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

Aquifer, confined — Aquifer in which the upper surface is impervious (see 'confining layer') and the water is held at greater than atmospheric pressure; water in a penetrating well will rise above the surface of the aquifer

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

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

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

Basin — The area drained by a major river and its tributaries

Benchmark condition — Points of reference from which change can be measured

BoM — Bureau of Meteorology, Australia

Bore — See 'well'

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

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

Confining layer — A rock unit impervious to water, which forms the upper bound of a confined aquifer; a body of impermeable material adjacent to an aquifer; see also 'aquifer, confined'

CSIRO — Commonwealth Scientific and Industrial Research Organisation

DEH — former Department for Environment and Heritage (Government of South Australia)

DENR — former Department of Environment and Natural Resources (Government of South Australia)

DES — Drillhole Enquiry System; a database of groundwater wells in South Australia, compiled by the Department of Environment, Water and Natural Resources

DEWNR — Department of Environment, Water and Natural Resources (Government of South Australia)

DFW — former Department for Water (Government of South Australia)

Dryland salinity — The process whereby salts stored below the surface of the ground are brought close to the surface by the rising watertable. The accumulation of salt degrades the upper soil profile, with impacts on agriculture, infrastructure and the environment.

d/s — Downstream

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

EC — Electrical conductivity; 1 EC unit = 1 micro-Siemen per centimetre (µS/cm) measured at 25°C; commonly used as a measure of water salinity as it is quicker and easier than measurement by TDS

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

Floodplain — Of a watercourse means: (1) floodplain (if any) of the watercourse identified in a catchment water management plan or a local water management plan; adopted under the Act; or (2) where (1) does not apply — the floodplain (if any) of the watercourse identified in a development plan under the *Development (SA) Act 1993*; or (3) where neither (1) nor (2) applies — the land adjoining the watercourse that is periodically subject to flooding from the watercourse

Flow regime — The character of the timing and amount of flow in a stream

Fully-penetrating well — In theory this is a wellhole that is screened throughout the full thickness of the target aquifer; in practice, any screen that is open to at least the mid 80% of a confined aquifer is regarded as fully-penetrating

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

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

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

Hydraulic conductivity (K) — A measure of the ease of flow through aquifer material: high K indicates low resistance, or high flow conditions; measured in metres per day

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

Hydrography — The discipline related to the measurement and recording of parameters associated with the hydrological cycle, both historic and real time

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

Impact — A change in the chemical, physical, or biological quality or condition of a water body caused by external sources

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

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

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

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

m AHD — Defines elevation in metres (m) according to the Australian Height Datum (AHD)

MDBA — Murray-Darling Basin Authority

MDBC — former Murray-Darling Basin Commission

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

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

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

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

Observation well — A narrow well or piezometer whose sole function is to permit water level measurements

Obswell — Observation Well Network

Percentile — A way of describing sets of data by ranking the dataset and establishing the value for each percentage of the total number of data records. The 90th percentile of the distribution is the value such that 90% of the observations fall at or below it.

Perennial streams — Permanently inundated surface stream courses. Surface water flows throughout the year except in years of infrequent drought.

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

Phreatophytic vegetation — Vegetation that exists in a climate more arid than its normal range by virtue of its access to groundwater

Piezometer — A narrow tube, pipe or well; used for measuring moisture in soil, water levels in an aquifer, or pressure head in a tank, pipeline, etc

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

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

Precautionary principle — Where there are threats of serious or irreversible environmental damage, lack of full scientific certainty should not be used as a reason for postponing measures to prevent environmental degradation

Production well — The pumped well in an aquifer test, as opposed to observation wells; a wide-hole well, fully developed and screened for water supply, drilled on the basis of previous exploration wells

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

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

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

Seasonal watercourses or wetlands — Those watercourses or wetlands that contain water on a seasonal basis, usually over the winter–spring period, although there may be some flow or standing water at other times

Specific storage (S_s) — Specific storativity; the amount of stored water realised from a unit volume of aquifer per unit decline in head; it is dimensionless

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

State Water Plan — Policy document prepared by the Minister that sets the strategic direction for water resource management in the State and policies for achieving the objects of the *Natural Resources Management (SA) Act 2004*

(S) — Storativity; storage coefficient; the volume of groundwater released or taken into storage per unit plan area of aquifer per unit change of head; it is dimensionless

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

T — Transmissivity; a parameter indicating the ease of groundwater flow through a metre width of aquifer section (taken perpendicular to the direction of flow), measured in m^2/d

TDS — Total dissolved solids, measured in milligrams per litre (mg/L); a measure of water salinity

Tertiary aquifer — A term used to describe a water-bearing rock formation deposited in the Tertiary geological period (1–70 million years ago)

Transmissivity (T) — A parameter indicating the ease of groundwater flow through a metre width of aquifer section

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

u/s — Upstream

USGS — United States Geological Survey

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

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

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

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

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