Pike-Murtho Numerical Groundwater Model 2014

Volume 1: Report and Figures

DEWNR Technical report 2014/05

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

PIKE-MURTHO NUMERICAL GROUNDWATER MODEL 2014

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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The following people are acknowledged for their contribution to the project:

- Linda Vears of DEWNR as the project manager advised on policy, assisted with irrigation data and coordinated the Five Year Review Modelling Registers Project Team
- Vanessa Peat of DEWNR compiled irrigation application data from DEWNR database system
- Tony Meissner of Laroona Environmetrics provided consultation report for irrigation data and estimated irrigation accession volumes for the Pike-Murtho area
- Peter Forward of SA Water provided Salt Interception Scheme data and observation wells' reference elevation.

Representatives from various disciplines formed a Five Year Review Modelling Registers Project Team, with emphasis on filling in data and knowledge gaps and providing policy advice. Members of the team include:

- 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 Hugh Middlemis of RPS.

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SUMMARY

The Pike-Murtho area is located in the Riverland region of South Australia on the eastern side of the River Murray near Renmark and the SA-Vic border. The Pike and Murtho irrigation areas have rapidly expanded in recent decades and are continuing to expand, especially at Central Murtho. The additional drainage is expected to increase groundwater gradients to the River, significantly increasing groundwater salt loads to the River Murray due to the natural high salinity of the groundwater (Yan et al., 2006). However, there is a considerable depth to water, so there are long lag times for drainage from the root zone to reach the watertable. Hence there have been limited increases in salt load to the river to date, but substantial impacts are expected in future.

To mitigate the salt load impacts, two Salt Interception Schemes (SIS) have been commissioned. The Pike SIS was commissioned in 2012 and consists of four production wells pumping approximately 30 L/s. The Murtho SIS was commissioned in 2014 and consists of 23 production wells pumping approximately 100 L/s. The SIS pumps groundwater from the Loxton Sands Formation, to lower the watertable and reduce the saline groundwater flux to the River Murray.

To meet obligations to the Murray-Darling Basin Authority (MDBA) Basin Salinity Management Strategy (BSMS), South Australia maintains and updates the accredited MODFLOW groundwater models to estimate the salt entering the River Murray and provide entries for the BSMS Salinity Registers. The modelling work is undertaken by the Science, Monitoring and Knowledge Branch (SMK) of the Department of Environment, Water and Natural Resources (DEWNR), in liaison with the MDBA.

The aim of each Salinity Register model is to simulate the regional aquifer system in its project area such that the model:

- Improves understanding of the hydrogeology of the regional aquifer system and processes
- Provides estimated fluxes of saline groundwater and salt load 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 (SIS)
- Assists with 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 Pike-Murtho project area lies within the domain of the Border to Lock 3 SA Salinity Register model, which was developed in 2003 (Yan et al. 2005). This simulates the eastern Riverland region, from the SA–Vic border to downstream of Lock 3 (Figure 1.1). In 2006 DWLBC refined the Border to Lock 3 model in the Pike-Murtho area (Yan et al., 2006). The Pike-Murtho sub-zone model was reviewed by MDBA as “fit for purpose given current data availability” (Salient Solutions, 2006) and the model was accredited for Salinity Register entry and assisting the conceptual design of SIS in the Pike-Murtho area.

This modelling project (2013/2014) reviews and upgrades the Border to Lock 3 model in the Pike-Murtho area as part of a five yearly review process for the Salinity Register and the SIS. The model was upgraded based on new information and knowledge from hydrogeological investigations conducted during SIS construction and from a detailed review of irrigation data.

SUMMARY

The calibration has been improved by including additional long-term observation data. The model was successfully recalibrated to head observations and its results confirmed through comparison to Run of River (RoR) salt load, geophysical surveys, groundwater ET and irrigation accession information. A sensitivity analysis considered how model parameters, when varied within reasonable ranges, impacted the model calibration, providing increased confidence in the results.

The upgraded model was used to re-run scenarios under the conditions required for the Salinity Register entries. 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 scenario salt load results are summarised in Tables S-1 and S-2. An uncertainty analysis evaluated how input parameters which are poorly known and/or highly heterogeneous may impact key scenario outputs. Recommendations are made for future work to improve data collection and model design.

This report documents the technical information, as well as the model and model inputs/results for the accreditation process. The report includes comprehensive information on the model design, model inputs and estimated annual salt loads for the different scenarios.

A further, separate document will be developed by DEWNR’s Murray Darling Basin Policy and Strategy Team 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 BSMS 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 – Pike

Pike					Year/Salt load (t/d)							
Scenario	**Name**	**Irrigation development area**	**IIP[1]**	**SIS[2]**	**1880**	**1988**	**2000**	**2013**	**2015**	**2050**	**2100**	**2113**
Calibrated model	Historical irrigation, IIP & SIS	Irrigation history	Yes	Yes	31.6	103.4	109.3	79.3	-	-	-	-
Scenario 1	Natural System (Steady State since 1920)	None	–	–	31.6	31.6	31.6	31.6	31.6	31.6	31.6	31.6
Scenario 2	Mallee Clearance	None	–	–	31.6	33.8	34.9	36.4	36.7	41.9	50.9	53
Scenario 3A	Irrigation Pre-1988, no IIP	Pre-1988	No	No	31.6	103.4	119.4	127	127.6	143.3	146.5	146.9
Scenario 3C	Irrigation Pre-1988, with IIP	Pre-1988	Yes	No	31.6	103.4	105.6	85.2	84	93.1	95.1	95.3
Scenario 4	Current irrigation (business as usual)	Pre-1988 + Post-1988	Yes	No	31.6	103.4	109.3	88.9	87.6	119.5	127.5	128.4
Scenario 5	Current plus future irrigation	Pre-1988 + Post-1988 + Future development	Yes	No	31.6	103.4	109.3	88.9	87.6	128.2	142.1	143.3
Scenario 7A	Current irrigation plus revised and constructed SIS	Pre-1988 + Post-1988	Yes	Yes	31.6	103.4	109.3	78.4	73.3	95.7	101.6	102.2
Scenario 7B	Pre-1988, with IIP plus revised and constructed SIS	Pre-1988	Yes	Yes	31.6	103.4	105.6	75.1	70.2	74.1	75.3	75.4
Scenario 7C	Current plus future irrigation plus revised and constructed SIS	Pre-1988 + Post-1988 + Future development	Yes	Yes	31.6	103.4	109.3	78.4	73.3	108.9	123.5	124.5

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

Table S-2 Summary of Predicted Salt Load (t/d) entering the River Murray – Murtho

Murtho					Year/Salt load (t/d)							
Scenario	**Name**	**Irrigation development area**	**IIP[1]**	**SIS[2]**	**1880**	**1988**	**2000**	**2013**	**2015**	**2050**	**2100**	**2113**
Calibrated model	Historical irrigation, IIP & SIS	Irrigation history	Yes	Yes	20.5	56.1	83.2	56.0	-	-	-	-
Scenario 1	Natural System (Steady State since 1920)	None	–	–	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
Scenario 2	Mallee Clearance	None	–	–	20.5	20.8	20.8	20.9	20.9	21.2	22.8	23.6
Scenario 3A	Irrigation Pre-1988, no IIP	Pre-1988	No	No	20.5	56.1	86.2	104.4	105.5	152.6	161.0	161.8
Scenario 3C	Irrigation Pre-1988, with IIP	Pre-1988	Yes	No	20.5	56.1	83.2	52.9	51.7	89.6	96.5	97.1
Scenario 4	Current irrigation (business as usual)	Pre-1988 + Post-1988	Yes	No	20.5	56.1	83.2	56.0	55.3	162.8	200.8	204.4
Scenario 5	Current plus future irrigation	Pre-1988 + Post-1988 + Future development	Yes	No	20.5	56.1	83.2	56.0	55.3	169.3	233.2	238.7
Scenario 7A	Current irrigation plus revised and constructed SIS	Pre-1988 + Post-1988	Yes	Yes	20.5	56.1	83.2	56.0	28.6	67.5	101.6	104.9
Scenario 7B	Pre-1988, with IIP plus revised and constructed SIS	Pre-1988	Yes	Yes	20.5	56.1	83.2	52.9	25.8	18.1	19.1	19.2
Scenario 7C	Current plus future irrigation plus revised and constructed SIS	Pre-1988 + Post-1988 + Future development	Yes	Yes	20.5	56.1	83.2	56.0	28.6	71.0	120.8	125.2

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

1 INTRODUCTION

River salinity is 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) 2001–15 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 Pike-Murtho area of the SA Riverland affects the salinity of the River Murray and its impact is expected to rise significantly in future years (Yan et al., 2006). 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 aquifer systems of the Riverland region.

The aim of this project is to redevelop the Pike-Murtho area within the SA Border to Lock 3 groundwater flow model (Yan et al., 2006, Yan et al., 2011). The model is designed to calculate salt loads as Salinity Register entries for the following accountable actions along the Pike-Murtho river reaches:

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

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.

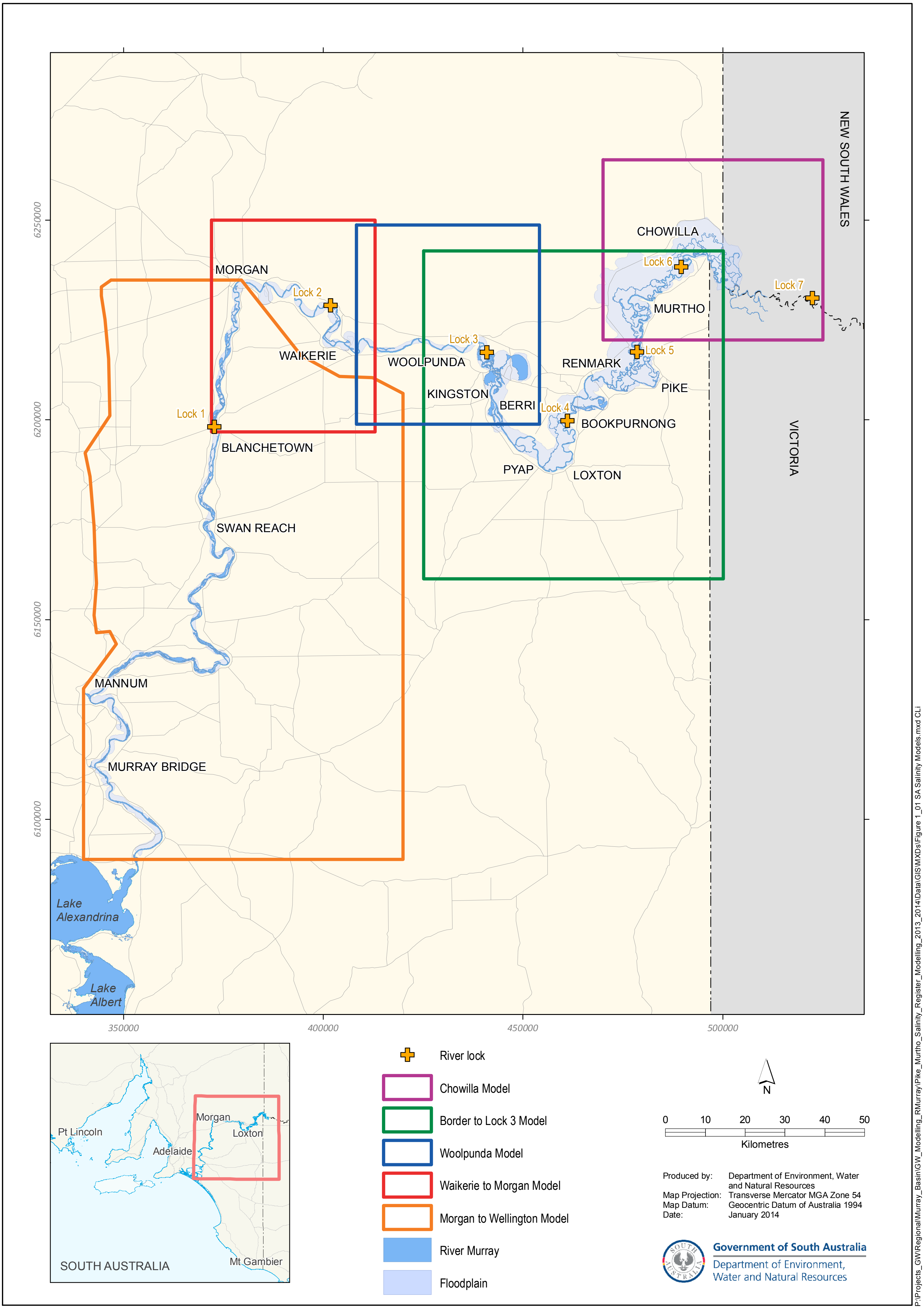


Figure 1.1. Numerical groundwater models developed in South Australia for the Salinity Registers

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 et al., 2005)
- SA Border to Lock 3 (Yan et al., 2006, Yan et al., 2007, Yan and Stadter, 2008, Yan et al., 2011)
- Woolpunda (Woods et al., 2013)
- Waikerie to Morgan (Yan et al., 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.

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 Commission 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 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 PIKE-MURTHO AREA

The Pike-Murtho area is located in the Riverland region of South Australia near Renmark (Section 2.1). It lies on the eastern side of the River Murray, extending from Salt Creek and Lyrup upstream to the Victorian border, within a region with wide floodplains and extensive anabranches. It encompasses the irrigation areas of North Murtho, Central Murtho, South Murtho, Upper Pike, Mid Pike, Simarloo and Lyrup. Water pumped from the River Murray is used for irrigation in the area.

Root zone drainage, from rainfall and irrigation, passes through the unsaturated zone to recharge the groundwater table. Higher watertable levels significantly increase the flux of saline groundwater entering the river valley and therefore salt load entering the River Murray. The timing of salinity impacts varies by irrigation area. Some Murtho irrigation areas have a depth to water of up to 70 m and a Blanchetown Clay thickness of up to 22 m, so the time taken for root zone drainage to reach the watertable can be decades (Fuller et al., 2005). Consequently, while a groundwater mound has developed at the older, established irrigation area at Lyrup, the watertable is still rising beneath Murtho irrigation areas.

To reduce the saline groundwater accessions to the River Murray, improvements have been made to irrigation practices and two SIS have been constructed. Pumping at the Pike SIS commenced in 2012 and at the time of writing, the Murtho SIS is intended to be operational by the end of 2013. The extraction wells are designed to 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 Pike-Murtho reach.

1.3 PREVIOUS GROUNDWATER MODELS OF THE PIKE-MURTHO AREA

1.3.1 PRIOR TO THE BORDER TO LOCK 3 MODEL

The Pike-Murtho area was included in a numerical groundwater flow model which spanned the eastern half of the River Murray in SA (Barnett et al., 2001). The purpose of the model was to estimate the salinity impacts of land clearance. The Pike-Murtho area was not represented in detail, although historical recharge rates were estimated for the irrigation areas.

The first numerical groundwater flow model to focus on the Pike-Murtho region was developed by REM in 2002 (REM, 2002a, REM, 2002b). It was based on detailed investigations of the surface and groundwater systems of the Pike and Murtho region which commenced in the mid- to late 1990s (Yan et al., 2006).

Murtho was selected as one of six case study locations used to test the SIMRAT model, which is implemented within a Geographical Information System (GIS) framework (Fuller et al., 2005). SIMRAT employs two analytical equations to estimate the salt load impact of new irrigation areas on the River Murray. Parameters from the equations are obtained from a data atlas.

1.3.2 THE BORDER TO LOCK 3 MODEL

The Border to Lock 3 model is the accredited Salinity Register model which includes the Pike-Murtho area. The model domain is designed to cover the entire eastern Riverland area for use with various projects and to avoid potential model-boundary effects interfering with model results within the project area (Yan et al., 2011). The major irrigation districts included are Loxton, Bookpurnong, Pike, Murtho, Berri, Renmark, Pyap, New Residence, Moorook and Kingston.

The Border to Lock 3 model has been developed and revised in a number of stages, initially based on work undertaken by Australian Water Environments (AWE 2003) and further developed by the Department of Water, Land and Biodiversity Conservation (DWLBC) from late 2003. An initial version had eight layers (Yan, Howles & Hill 2005) but a subsequent revision reduced this to five layers, modelling the lower aquitards implicitly via vertical hydraulic conductivity (Yan et al. 2005).

The Border to Lock 3 model provides a unified hydrogeological description of the eastern Riverland and contains a number of Salinity Register project areas. Each project area includes a group of irrigation areas and, where present, SIS. The assumption is that irrigation recharge and SIS pumping within a project area will not substantially impact the potentiometric head in other project areas, so that the Border to Lock 3 model need only simulate these features within one project area at a time. Since its initial development, the Border to Lock 3 model has been revised incrementally by project area. The hydrogeology, hydrology and land use of the project area is reviewed and revisions are made to the Border to Lock 3 model. The model is recalibrated against data from within the project area. All hydrogeological changes to the model are retained for subsequent projects. The sub-model will be named as:

- BL3_PM – Border to Lock 3 model Pike-Murtho sub-zone modelling project
- BL3_RB – Border to Lock 3 model Renmark-Berri sub-zone modelling project
- BL3_PK – Border to Lock 3 model Pyap to Kingston sub-zone modelling project
- BL3_LB – Border to Lock 3 model Loxton-Bookpurnong sub-zone modelling project

In late 2004 DWLBC commissioned Resource and Environmental Management (REM) and Aquaterra to refine the Border to Lock 3 model in the Pike-Murtho project area (Yan et al., 2006). The work was undertaken to assist the conceptual design of SIS in the Pike and Murtho regions of the SA Riverland. The refined model provided quantitative estimates of salt loads entering the River Murray under a range of past and future land and water use conditions (REM-Aquaterra, 2005a, REM-Aquaterra, 2005b). An independent review (Salient Solutions, 2005) recommended further work be conducted to address:

(i) calibration performance in the Lyrup, Simarloo and Mid-Pike areas
(ii) salt loads in terms of the long-term averages as seen in the River
(iii) modelling recommendations made by REM and Aquaterra (2005b).

DWLBC further developed the model to address those concerns and to incorporate the results of further field investigations (Yan et al., 2006). Consequently, the Border to Lock 3 model was reviewed as “fit for purpose given current data availability” (Salient Solutions, 2006) and accredited in the Pike-Murtho project area.

The Border to Lock 3 model was revised further in the Berri-Renmark project area in 2007 (Yan et al., 2007), in the Pyap-Kingston project area in 2007 (Yan & Stadter 2008) and in the Loxton-Bookpurnong project area in 2011 (Yan et al., 2011). The DWLBC Unit that developed the model became part of the Department for Water (DFW) upon its establishment in 2010, then joined the Department of Environment, Water and Natural Resources (DEWNR) on its founding in 2012.

1.3.3 RECENT STUDIES

Substantial fieldwork in the unconfined aquifers and modelling studies have been conducted since 2006, when the Pike-Murtho project area of the Border to Lock 3 model was last revised. The studies support the design and construction of the Pike River SIS and the Murtho SIS. Hydrological, hydrogeological and other information has been compiled in two atlases (AWE, 2012a, AWE, 2012b). Australian Water Environments (AWE) developed a numerical groundwater flow model of the Pike area in 2010 (AWE, 2010b) which was used to evaluate SIS wellfield designs in 2011 (AWE, 2011b). A model of the Murtho region was also developed for SIS design (AWE, 2010a, AWE, 2011a). This estimated future groundwater salt loads to the River Murray under different conceptual models. River levels were either (i) fixed at constant, low-flow conditions or (ii) varied over time according to historical observations, including the simulation of overbank flooding. Groundwater salinity was either (i) constant over time or (ii) varied over time due to mixing with floodwaters, freshening from irrigation recharge, and evapotranspiration (ET). Minor modifications of the AWE model of Murtho were made in 2013 so that it could calculate the salinity benefits of the SIS (AWE, 2013). Aquifer properties and groundwater salinity zones were simplified, irrigation recharge rates and SIS pump rates were updated, and river levels and groundwater salinity were assumed to be constant over time.

This project aims to refine the Border to Lock 3 groundwater flow model to incorporate recent hydrogeological information from the Pike-Murtho area. This report presents the revisions made to the Pike-Murtho area in the Border to Lock 3 model. The model uses assumptions and methods consistent with other SA Salinity Register models.

1.4 AIMS OF THE 2014 PIKE-MURTHO MODEL

This work refines the existing Border to Lock 3 groundwater flow model in the Pike-Murtho project area. This study captures new knowledge within the modelling platform. The updated model provides improved estimates of salinity impacts from the Pike-Murtho reaches under the various accountable actions, and hence leads to refinement and improvement in the Salinity Registers.

The aim is to develop a model capable of simulating the regional aquifer system in the Pike-Murtho 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

        - Recharge estimates based on application volumes and other data (Laroona Environmetrics (2014); see Appendix C)
    - Review of near-river groundwater salinity
    - Compilation of data for 2007 – 2013 where available, principally:
        - Potentiometric head in observation wells
        - SIS pump rates
        - RoR salt load estimates
- Refinement of Model Design and Construction
    - Extended the model domain to the north to include the entire Murtho Land and Water Management Plan (LWMP) region
    - Updated model layer structural contours, particularly for the upper surface of the Loxton-Clay-Bookpurnong Formation aquitard
    - Updated hydraulic conductivity values for the Loxton Sands, based on aquifer tests conducted since 2006
    - Improved representation of the River Murray and its anabranches
    - Adjusted recharge rates, areas and lag times to reflect the irrigation data review
    - Inclusion of SIS pump rates and head observations for 2007 – 2013
    - Revised model flow budget zones, which are used for salt load calculation
    - Revised groundwater salinities used for salt load calculation
- Model Calibration and Confirmation
    - Increased number of observation wells and hydrographs used for calibration
    - Improved calibration to potentiometric head, especially in areas adjacent to the River Murray and SIS
    - Confirmation of model inputs and parameters against independent estimates of irrigation accessions and actual groundwater evapotranspiration
    - Confirmation of the model results by comparing to the RoR salt load estimates and instream geophysics.
- Running scenarios for Salinity Register entry
    - Modelling of SIS to represent the operating guidelines of each scheme
    - Additional scenarios, including Scenario 8a (current irrigation + SIS) and Scenario 8b (pre-1988 irrigation + 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
    - Salt load details for each scenario in Appendix B

The scenario definitions are included in Appendix A.

2 HYDROGEOLOGY AND HYDROLOGY OF THE PIKE-MURTHO AREA

The Pike-Murtho 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 Kellet (1989), Barnett (1991), Drexel and Preiss (1995), Lukasik and James (1998), and McLaren et al. (2011).

The hydrogeology of the Pike-Murtho region is described in Yan et al. (2006), AWE (2008), DWLBC (2006) and DWLBC (2009). Early studies of the region estimated drainage and mapped soil types (PIRSA, 1995, Woodward-Clyde, 1998). Groundwater-surface water interaction has been inferred from a series of geophysical NanoTEM surveys and mapped (Telfer et al., 2005, AWE, 2011e, AWE, 2013a). Further information is available from numerical model reports of the region, which include data reviews and hydrogeological conceptual models. Numerical model reports spanning regions including Pike-Murtho are Miles et al. (2001), Barnett et al. (2001), REM (2002b), REM (2002c), REM-Aquaterra (2005), Fuller et al. (2005), Yan et al. (2006), AWE (2010b), AWE (2011b), and AWE (2011c).

Considerable fieldwork has been conducted in the last few years to support the design and construction of the Pike River SIS and the Murtho SIS, providing more data on the region, such as SKM (2008). Hydrological, hydrogeological and other information has been summarised in two atlases (AWE, 2012a, AWE, 2012b). Data includes information from DEWNR and PIRSA databases and prior studies. DEWNR has since compiled a further major dataset: historical irrigation data (Appendix C). Run of River (RoR) salt loads from groundwater baseflow to the River Murray are reviewed in AWE (2013c).

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 Pike-Murtho project area is defined to include the LWMP areas for Pike and Murtho, which occupy approximately700 km^2 from the Old Customs House near Chowilla in the north, to Gordon Road below Gurra Gurra Lakes in the south. The project area is bounded by the River Murray to the west and the South Australian–Victorian border to the east. Figure 2.1 shows the location and key hydrological features. The project area includes the River Murray between the Border to Lock 4, extending from river kilometres 637.5 to 537 (note: river kilometres give the distance from the river mouth when following the main river channel upstream). It encompasses the irrigation areas of North Murtho, Central Murtho, South Murtho, Upper Pike, Mid Pike, Simarloo and Lyrup.

The project area can be divided into highland and floodplain regions. The highland regions are at an elevation of approximately 30 to 130 m AHD, through which the River Murray has carved a floodplain valley with a ground elevation between -2 and 30 m AHD (AWE, 2012a, AWE, 2012b). Cliffs are present at the boundary between the floodplain and highland for most of the reach.

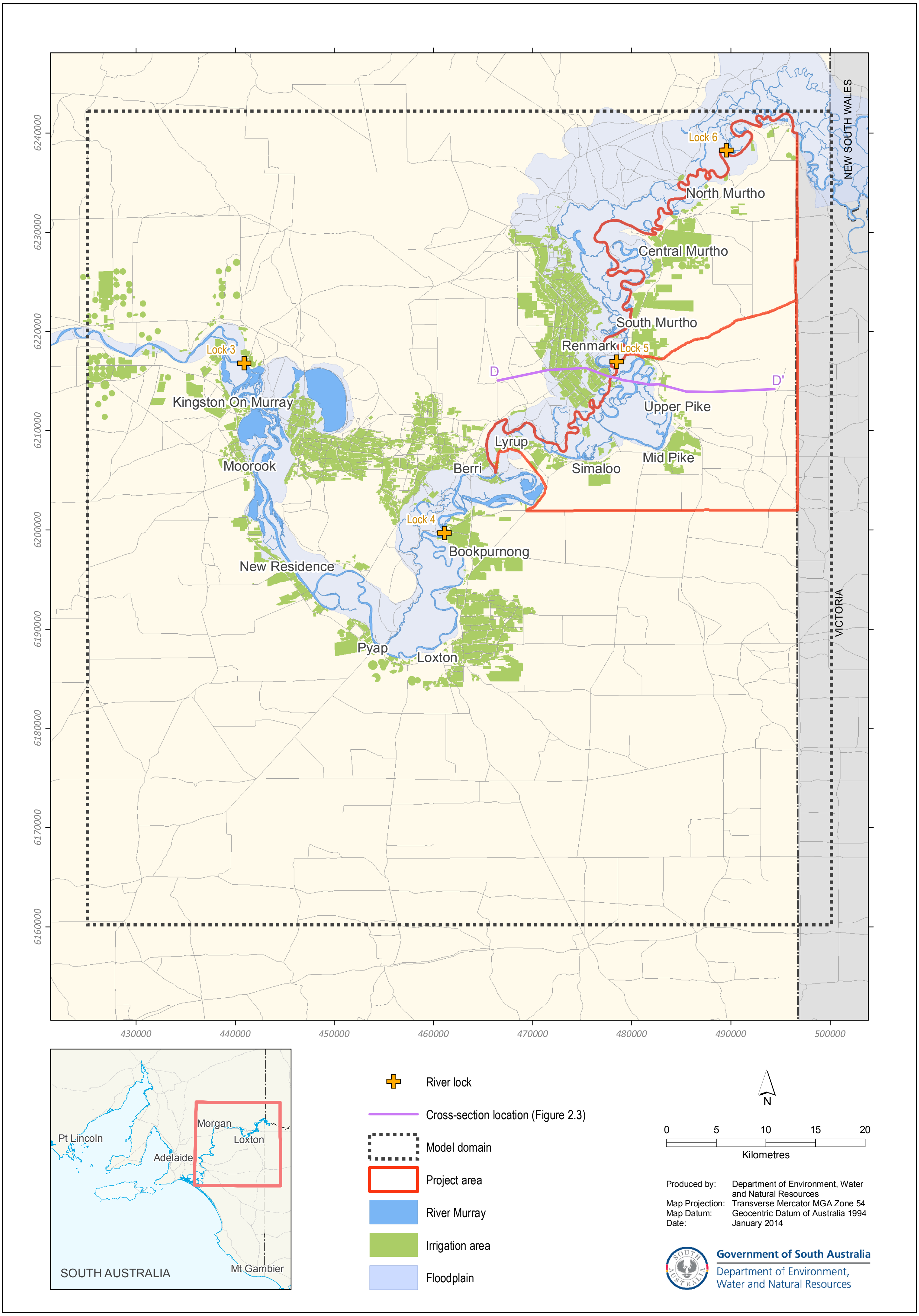


Figure 2.1. Project site map and model domain

The project area has wide floodplains and extensive anabranches. On the eastern side of the River Murray are the Woolenook Bend Complex and Pike-Mundic floodplains, extending up to six km from the main river channel. On the western side, outside the Pike-Murtho area, are the Renmark and Chowilla floodplains. Major anabranches flowing into the River Murray include Chowilla Creek, Monoman Creek, Ral Ral Creek, Bookmark Creek and Pike River.

2.2 CLIMATE

The climate is characterised by hot dry summers and cool, wetter winters. At Renmark Irrigation Station 024003, which is on the western bank of the river near river kilometre 568, the average annual rainfall is 252 mm (Bureau of Meterology, 2013b). At Lyrup, the mean annual rainfall is 241 mm (Bureau of Meterology, 2013b). The closest station recording evapotranspiration (ET) is the Loxton Research Centre Station 024024, south of the project area, with a potential ET of 1898 mm/y (Bureau of Meterology, 2013a). Table 2.1 provides monthly averages for rainfall and ET. Rainfall is slightly 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 2.6.4).

Table 2.1 Average monthly rainfall at Renmark Irrigation 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)	17	18	13	18	23	22	25	24	24	25	21	20	252
Potential ET (mm)	295	235	198	120	71	51	53	84	123	183	225	267	1898

2.3 HYDROGEOLOGY

2.3.1 REGIONAL SETTING

The Murray-Darling Basin (MDB) 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 near 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 Pike-Murtho region lies within the Renmark Trough, a transitional zone between the thicker sediments of the Western Central Depocentre to the east, where sediments are greater than 500 m thick, and the basement high lying west of the Hamley Fault, where sediments are less than 200 m thick (Brown, 1989, Barnett, 1991). This change of sediment thickness forces groundwater upwards (Yan et al., 2011). The groundwater is highly saline and contributes significant quantities of salt when it flows into the River Murray.

The Pike-Murtho reach has a basement elevation between approximately -450 and -550 m AHD, dipping towards the north-east (Barnett, 1991). Above the basement are three major aquifer systems: the Renmark Group sands and gravels, the Murray Group limestone sediments, and the Loxton Sands (also known as the Pliocene Sands). The regional watertable lies within the Loxton Sands but a perched water table can occur within the Woorinen Formation above the Blanchetown Clay (Yan et al., 2006). The Murray Group has been subdivided stratigraphically by Lukasik and James (1998) with three sub- aquifers recognized (Mannum, Glenforslan and Pata/Bryant Creek). Figure 2.3 is a cross-section through the Pike-Mundic floodplain, illustrating the upper stratigraphy of the Pike-Murtho reach.

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 Loxton Sands is generally juxtaposed with the Monoman Formation and hence the watertable aquifer within the Loxton Sands hydraulically connects with the watertable aquifer in the Monoman Sands. In some floodplain areas, such as the Pike-Mundic floodplain, the Woolenook Bend Complex and north of Woolenook, the watertable can occur within the overlying sediments of the Coonambidgal Formation (Yan et al., 2006). At some sites in the Pike and Renmark floodplains, the base of the Monoman Formation is underlain by a thin section of Lower Loxton Sands (AWE, 2012a, AWE, 2012b). Below the Monoman Formation (and the Lower Loxton Sands, where present) are the Lower Loxton Clay and the Bookpurnong Beds, which form an aquitard which separates the Monoman Formation aquifer from the underlying Murray Group Limestone aquifer.

Table 2.2 summarises aquifer and aquitard properties reported in previous studies. Most aquifer tests have been conducted near the edge of the floodplain and highland (AWE, 2012a, AWE, 2012b, REM, 2002c, REM, 2002b, REM, 2005, Stadter et al., 2008, URS, 2000).

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

The characteristics of each hydrogeological unit in the project area are discussed briefly in order of elevation, deeper sediments first, in this section.

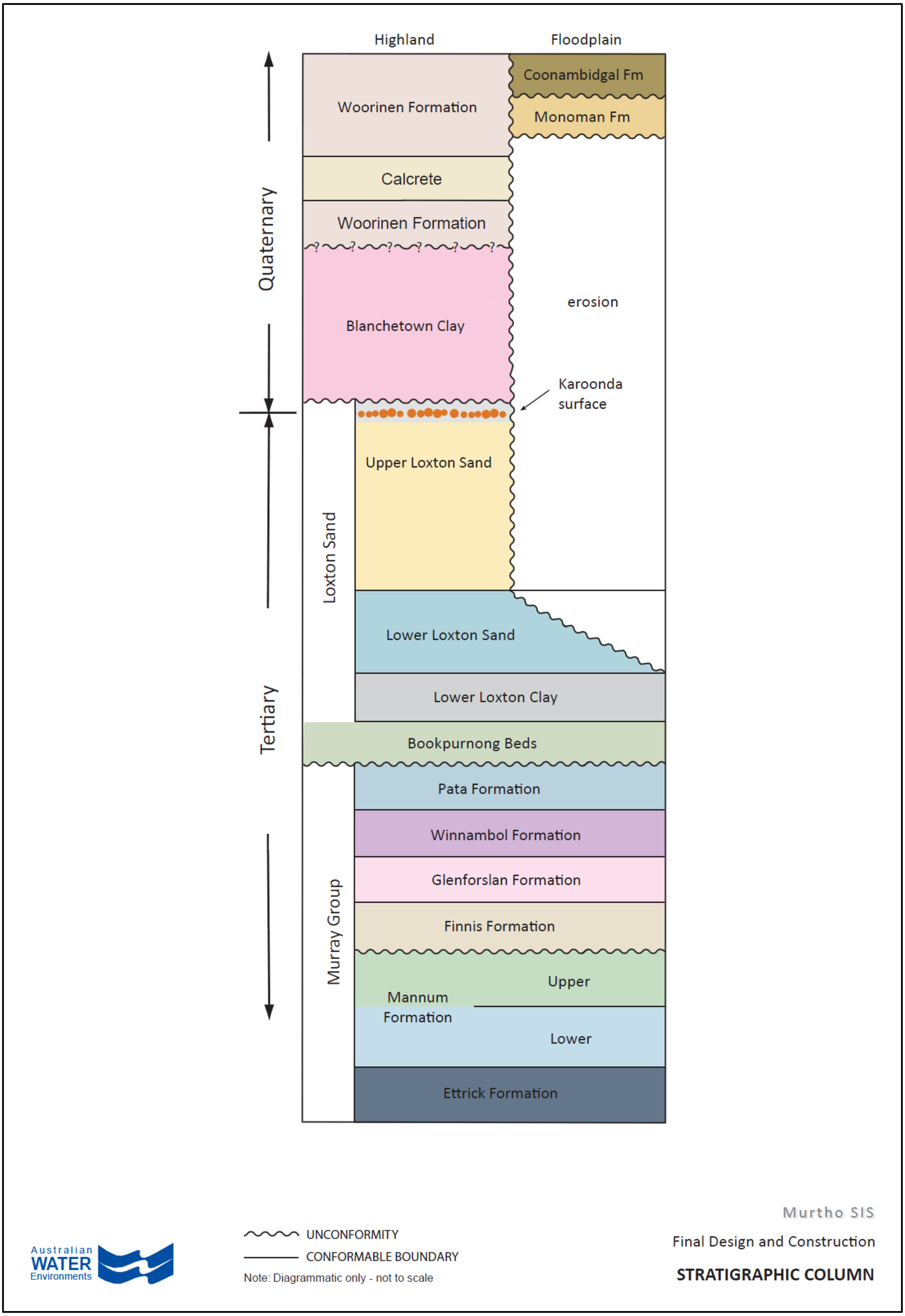


Figure 2.2. Stratigraphic column (AWE 2012a)

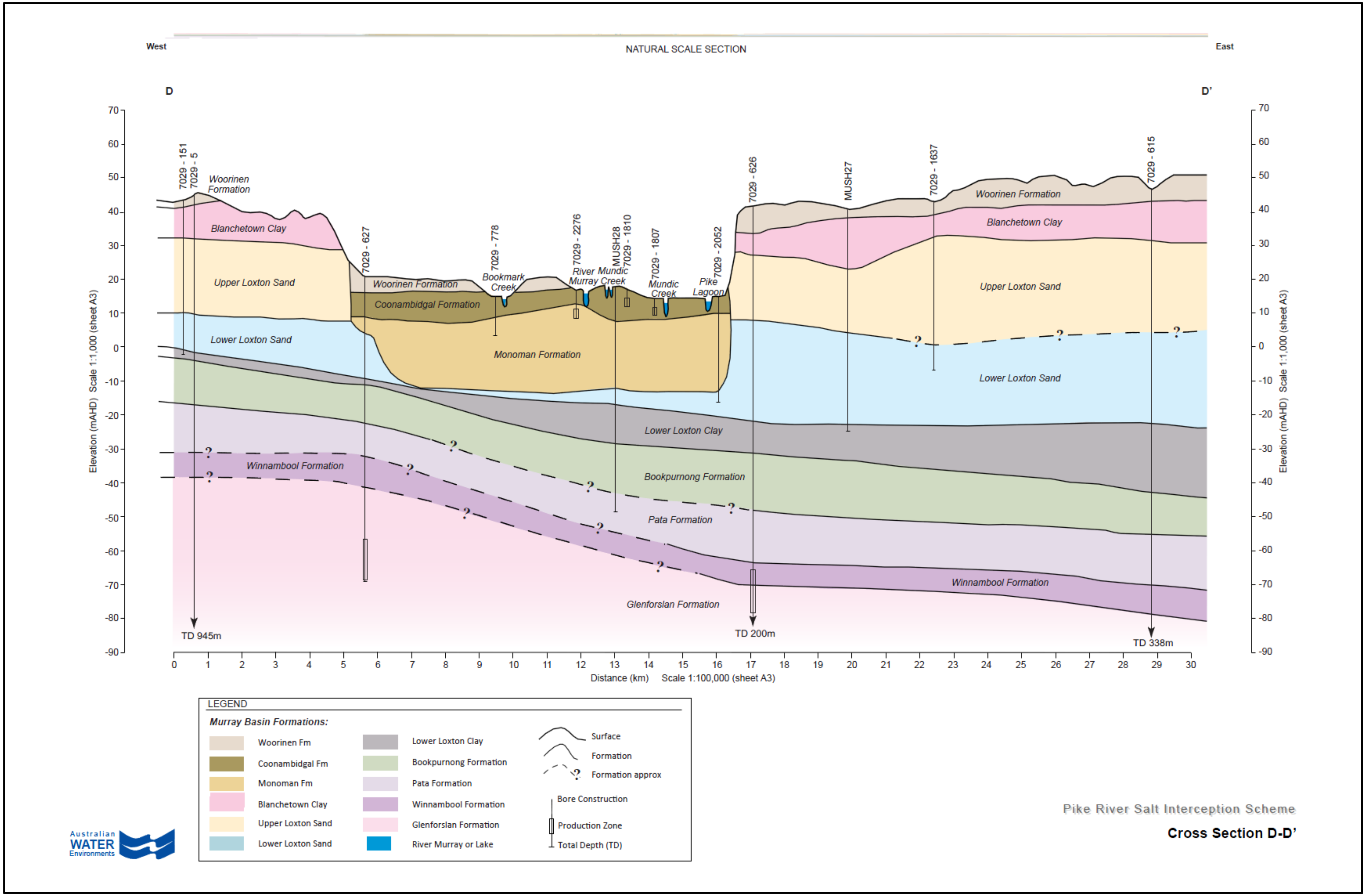


Figure 2.3. Cross-section (AWE 2012b)

Table 2.2 Summary of hydraulic parameters for Pike-Murtho area

Hydrogeological Unit		Hydraulic conductivity (m/d)		Transmissivity (m²/d)	Storage (-)		Source
		K_h	K_v	T	$S^{(1)}$	Sy	
Woorinen Formation							
Coonambidgal Formation							
Monoman Formation		2 – 19			4×10^{-4}		URS (2000) REM (2002b) REM (2002a)
		25 – 33		500 – 655	5×10^{-3}		AWE (2012a) AWE (2012b)
Blanchetown Clay			3×10^{-4}				REM (2002b)
Loxton Sands		0.3 – 5.8		26 – 121	2×10^{-4} – 2×10^{-3}	0.06 – 0.13	REM (2002b) REM (2002a) REM (2005)
		3 – 59		79 – 1470	5×10^{-6} – 0.275		AWE (2012a) AWE (2012b)
Lower Loxton Clay and Shells							
Bookpurnong Formation			6×10^{-4} – 1.6				REM (2002b) REM (2002a)
Murray Group Limestone	Pata Formation	0.05 – 0.1			1×10^{-3}		REM (2002b)
	Winnambool Formation						
	Glenforslan Formation						
	Mannum Formation	0.05 – 0.1					URS (2000)

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

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 base of the group lies at approximately -550 to -450 m AHD in the Pike-Murtho area (Barnett, 1991). The sediments are approximately 350 m thick (Barnett, 1991) and of Eocene origin (Brown, 1989). Geochemical investigations suggest that the Renmark Group was last recharged 30 000 years ago (Harrington et al., 2006).

2.3.3 ETTRICK FORMATION

The Ettrick Formation consists of grey-green glauconitic and fossiliferous marl. Hydrogeologically, the Ettrick Formation separates the Renmark Group from the aquifers of the Murray Group. The thickness of the Ettrick Formation within the study area is approximately 25 to 40 m, based on three well-logs. In the Pike-Murtho study area, the head difference between the Renmark Group and Murray Group aquifers is 10 to 15 m upwards indicating that the Ettrick Formation acts as an effective confining aquitard (Barnett, 1991).

2.3.4 MURRAY GROUP LIMESTONE

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). The Murray Group exhibits variable thickness due to erosion of its upper surface but in the study area may be approximately150 m thick (Barnett, 1991). The sediments dip towards the north-east, with the top elevation at -22 m AHD near Gurra Gurra Lakes and below -66 m AHD near Lock 6 (AWE, 2012a).

On a regional scale, the Murray Group Limestone may be considered as a single unit but on a local scale sub aquifers with intervening aquitards are recognised. 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.

In the study area, the geological sequence (Figure 2.2) includes three sub unit aquifers (AWE, 2000). The limestones (Pata, Glenforslan and Mannum Formations) are separated by marl aquitards (Winnambool and Finniss Formations).

The median potentiometric surface for the Murray Group aquifer at 2012 is shown in Figure 2.4, interpolated from the median of all measurements for each well. There are only a few observations in the project area and they do not differentiate the subunits. Hence this figure shows the potentiometric surface for the Murray Group Limestone as a whole. The groundwater flow direction is from the north-east (25 m AHD) to the south-west (18 m AHD). The hydrographs are reported in Section 4 and they show a steady trend in both the Pike and Murtho areas.

Groundwater salinities for the Murray Group Limestone recorded by DEWNR (2013), AWE (2012a) and AWE (2012b) range from 10700 to 92395 mg/L, with a median of 21535 mg/L.

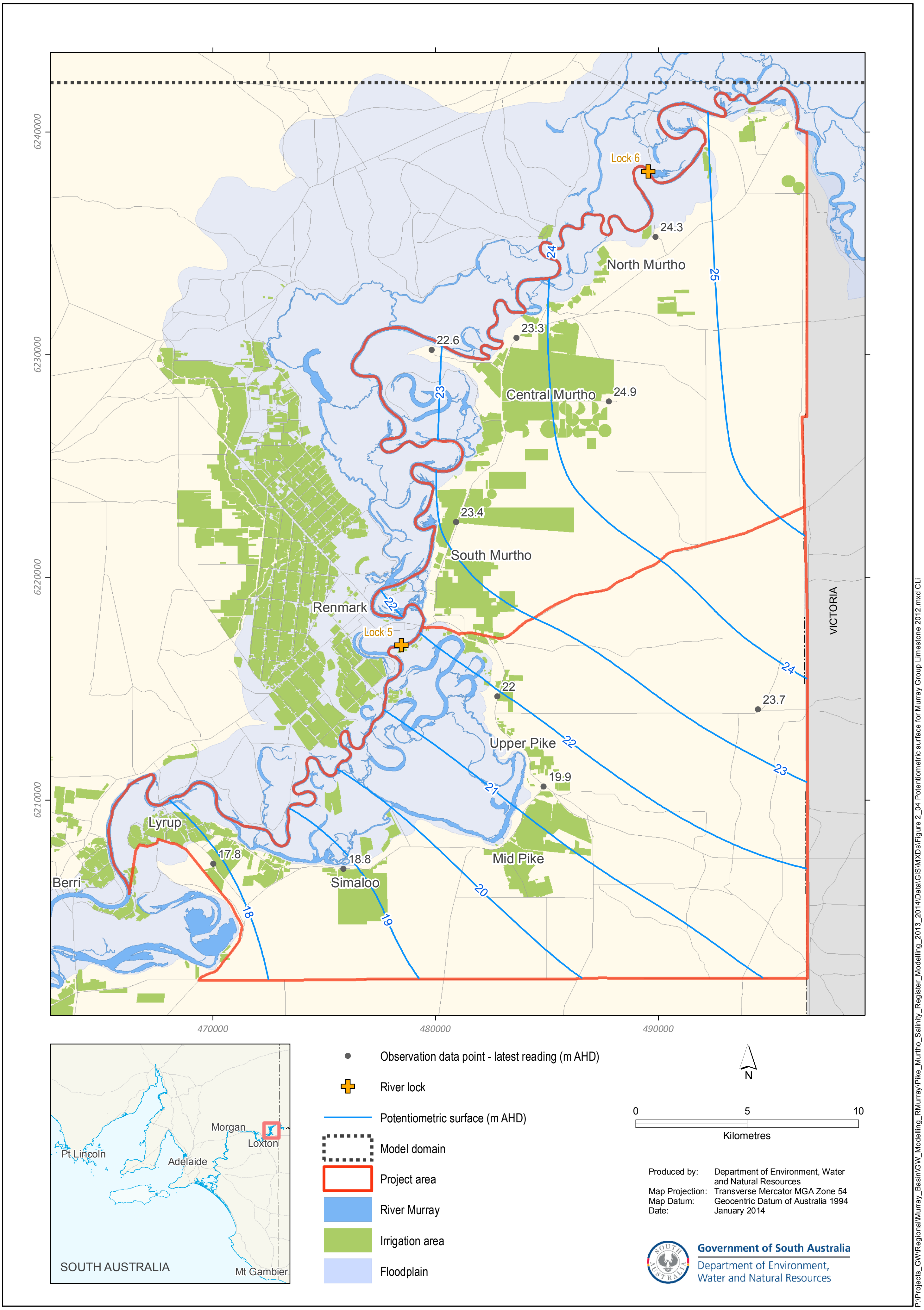


Figure 2.4. Potentiometric surface for the Murray Group Limestone

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 (AWE, 2011d). It is confined in the Pike-Murtho area but is unconfined in other Riverland regions to the west, such as Woolpunda (Barnett, 1991).

Two aquifer tests undertaken by URS (2000) for the Mannum Limestone within the project area yielded a hydraulic conductivity of 0.05–0.1 m/d. No aquifer test data are available for the storativity of the Lower Mannum Formation in the Pike-Murtho area, but aquifer tests from Waikerie and Qualco show that the storativity values can be from 2.5 x 10^{-4} to 10^{-3} (AWE, 2011f).

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). This unit dips to the north-east, but is difficult to distinguish from the underlying Lower Mannum Formation in some areas (Yan and Stadter, 2008).

No aquifer test data is available for the Upper Mannum Formation within the study area, but the aquifer tests undertaken in Waikerie gave estimates of vertical hydraulic conductivity of the order of 6 x 10^{-3} m/d (AWE, 2011f).

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 (Yan et al., 2005). Although no data are available within the project area, the thickness of the Finniss Formation is found to be between 2 and 14 m thick in the adjacent Loxton-Bookpurnong area, with a median of 2.8 m (AWE, 2011a). At some locations in the Loxton-Bookpurnong area, there is a steep vertical gradient for potentiometric head through the Finniss Formation of more than 0.2 m/m, indicating that the Finniss aquitard must have a low vertical hydraulic conductivity, given that it is a thin unit (AWE, 2011a).

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 bryozoans and shell fragments (Lukasik and James, 1998). It is a confined aquifer within the project area and closely resembles the Pata Formation, with the exception that it contains occasional fine-grained hard bands (Yan et al., 2005). No thickness data are available for the Glenforslan Formation within the Pike-Murtho area. In the adjacent Loxton-Bookpurnong area, it varies in thickness from 16 to 30 m, with a median thickness of 26 m (AWE, 2011a).

No aquifer test data are available for the Glenforslan Formation within the study area. In the Loxton area, two aquifer tests yielded estimates of 0.14 and 0.56 m/d for hydraulic conductivity and and 2 x 10^{-4} for the storage coefficient (AWE, 2011a).

2.3.4.5 WINNAMBOOL FORMATION

The Winnambool Formation aquitard comprises grey to pale green calcareous clay (marl) and silty clay (Yan et al., 2005). No data is available for the Winnambool Formation within the Pike-Murtho area. In the Loxton-Bookpurnong area this unit has a median thickness of 7 m and varies from 2 to

14 m (AWE, 2011a). At Loxton, the Winnambool Formation is known to provide an effective aquitard between the Pata and Glenforslan Formations (Yan et al., 2011).

2.3.4.6 PATA FORMATION

The Pata Formation is a poorly consolidated bryozoal limestone with interbedded friable sand layers that occurs throughout the Pike-Murtho area (Yan et al., 2005). This unit crops out to the south of Loxton, outside the study area, where it is exposed at river pool level downstream from the Loxton Caravan Park (Yan et al., 2005). The top surface elevation is approximately -20 to -50 m AHD in Pike and -50 to -65 in Murtho (AWE, 2012a). Although described as a limestone, the unit is a poor aquifer due to the presence of marl. Aquifer tests conducted by REM (2002b) in the Pike-Murtho area give hydraulic conductivity values between 0.05 and 0.1 m/d and a storativity of 10^{-3}.

2.3.5 LOXTON CLAY, LOXTON SHELLS AND THE BOOKPURNONG FORMATION

Between the Murray Group and the overlying Loxton Sands aquifer is an aquitard consisting of the Bookpurnong Formation, the Loxton Clay and Loxton Shells. The Bookpurnong Formation consists of poorly consolidated plastic silts and shelly clays that are differentiated from the Lower Loxton Clays and Shells (grey in colour) on the basis of colour (light to dark khaki) and increased plasticity (Yan et al., 2005). The lateral extent of the Lower Loxton Shells is difficult to confirm and is not necessarily continuous across the project area (Yan et al., 2005).

This confining bed primarily dips gently along a south-west/north-east axis. At Lyrup, its surface reaches 7 m AHD while near North Murtho it deepens to -24 m AHD (AWE, 2012a). Its thickness increases to the north-east, ranging approximately 20 m thick near Lyrup to around 50 m thick near Central Murtho (AWE, 2012a).

Aquifer tests conducted for the Bookpurnong Formation within the project area by REM (2002b) give a wide range of vertical hydraulic conductivity of 6×10^{-4} m/d to 1.6 m/d.

2.3.6 LOXTON SANDS FORMATION

The Loxton Sands, a highly heterogeneous unconfined aquifer, is the uppermost regional watertable aquifer in the highland area of Pike-Murtho. In the Murray valley, most of this unit has been eroded and the Monoman Formation deposited in its stead (Yan et al., 2005).

The Loxton-Parilla Sands were initially defined by Brown and Stephenson (1991) as a single sand sheet, deposited in a complex strand plain 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-Parilla 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 sands occur at the top of the sequence within the Upper Loxton Sand member and the least permeable fine sands occur at the base of the succession within the Lower Loxton Sand member (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, 2011a). Although the Lower Loxton Sands as a whole are generally considered to be a less permeable unit than the Upper Loxton Sands, in the Pike-Murtho region the upper part of the Lower Loxton Sands contains well-sorted marginal marine sands (REM-Aquaterra, 2005).

Its surface occurs at 17 to 72 m AHD on the highland in the Pike Murtho area (AWE, 2012a). Unlike the units below it, there is no consistent and obvious dip.

The thickness of the Loxton Sands ranges between 10 m at Lyrup and up to 90 m to the east of Central Murtho (AWE, 2012a).

Seven aquifer tests conducted by REM (2005), REM (2002a) and REM (2002b) for the Loxton Sands within the project area give hydraulic conductivity values of 0.3–5.8 m/d (Table 2.2). Approximately thirty aquifer tests reported in AWE (2012a) and AWE (2012b) give hydraulic conductivity values generally in the range 3 to 20 m/d, with a median of 13 m/d, and outlier values of 32 to 59 m/d.

The potentiometric surface for the Loxton Sands and Monoman Formation are shown together in Figure 2.5 as they are in hydraulic connection. It clearly shows the irrigation mound at Lyrup and elevated water table at Central Murtho and Simarloo. The groundwater flow direction at Murtho is predominantly to the west, whilst to the south of Paringa, it is generally towards the nearest discharge point, being the Pike River, River Murray or Gurra Gurra Lakes.

Water level trends depend on the observation well location. The hydrographs are shown in Section 4 and the location of the observation wells are shown in Figure 2.6. In Lyrup, the irrigation induced groundwater mound is evident and can be as high as approximately 20 m AHD (PAG041). This is approximately7 m higher than the pool level of 13.2 m AHD. A number of hydrographs (e.g. PAG050 and PAG055) show a decline since 2005, probably due to the Millennium Drought. In Simarloo, although the groundwater mounding is not as obvious as Lyrup, the hydrographs show an elevated watertable, which can be up to 16 m AHD (e.g. PAG033 and PAG035). This is approximately3 m higher than the pool level. Some hydrographs also show a slight decline since 2005 due to the water restrictions (e.g. PAG043 and PAG053). There are only a few observation wells in Mid-Pike, Upper-Pike, South Murtho and North Murtho, which show a steady trend, except that some wells show a slight increase after 2011 (e.g. PAG006, PAG097, MTH025 and MTH014). The hydrographs in Central Murtho show an elevated groundwater level of approximately 17 m AHD, which is approximately 1 m higher than the pool level of 16.3 m AHD. The hydrographs do not appear to respond to the water restrictions around 2005 (e.g. MTH008 and MTH019).

Groundwater salinities in the Loxton Sands vary dramatically across the study area, reflecting the impact of low salinity irrigation recharge and river water on the saline native groundwater.Figure 2.7 shows the groundwater salinities for the Loxton Sands from DEWNR (2013), AWE (2012a), AWE (2012b) and AWE (2011b). The values in this figure are based on the earliest available readings, as these are believed to be more representative of the regional groundwater salinity, compared to the more recent readings which may have been influenced by irrigation freshening.Figure 2.7 shows the salinities to vary from ~2700 to 79000 mg/L (with a median of 34000 mg/L) at Pike and ~1500 to 40000 mg/L (with a median of 29000 mg/L) at Murtho. The lower salinity values may be due to mixing with relatively fresh irrigation returns.

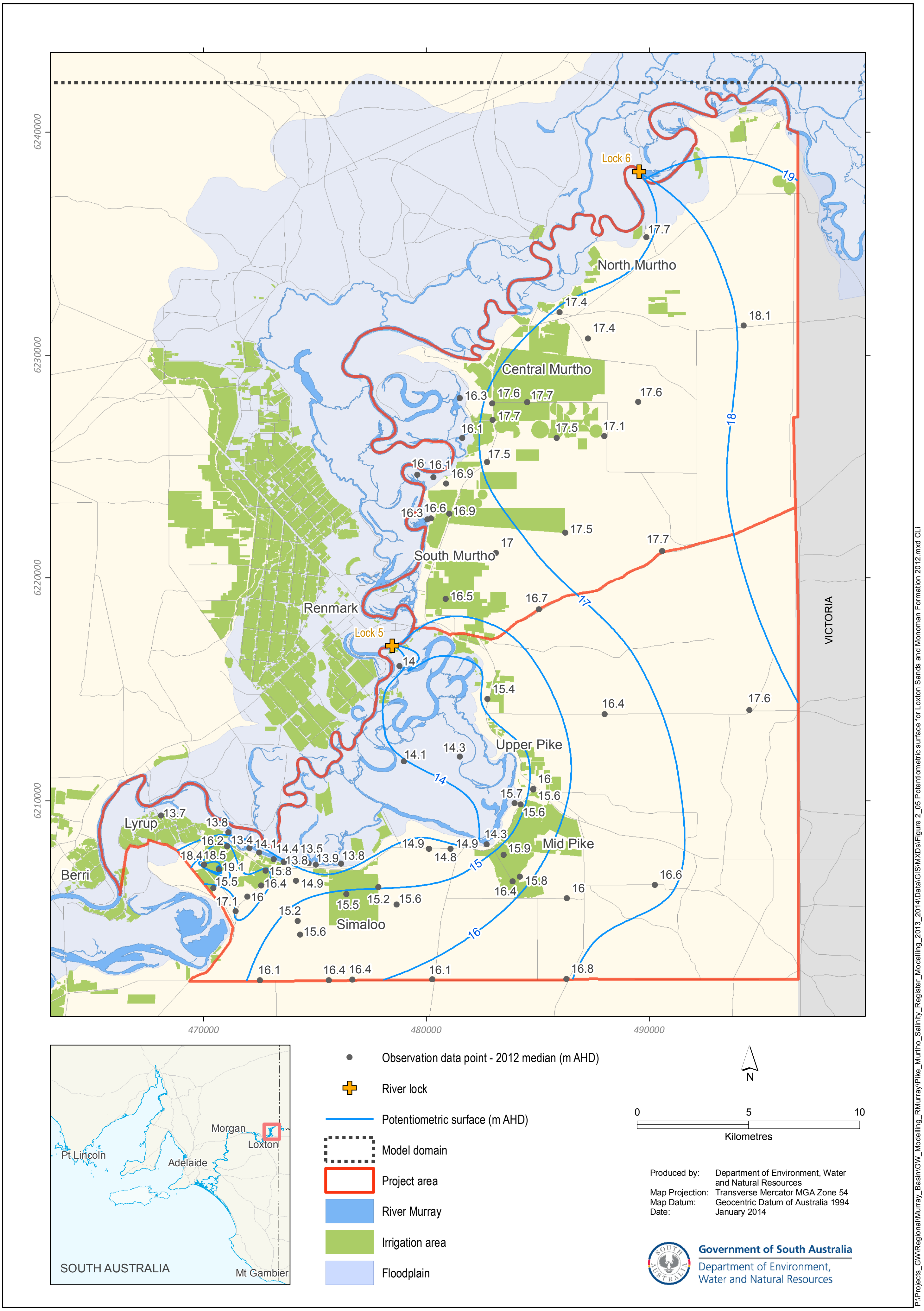


Figure 2.5. Potentiometric surface for the Loxton Sands and Monoman Formation at 2012

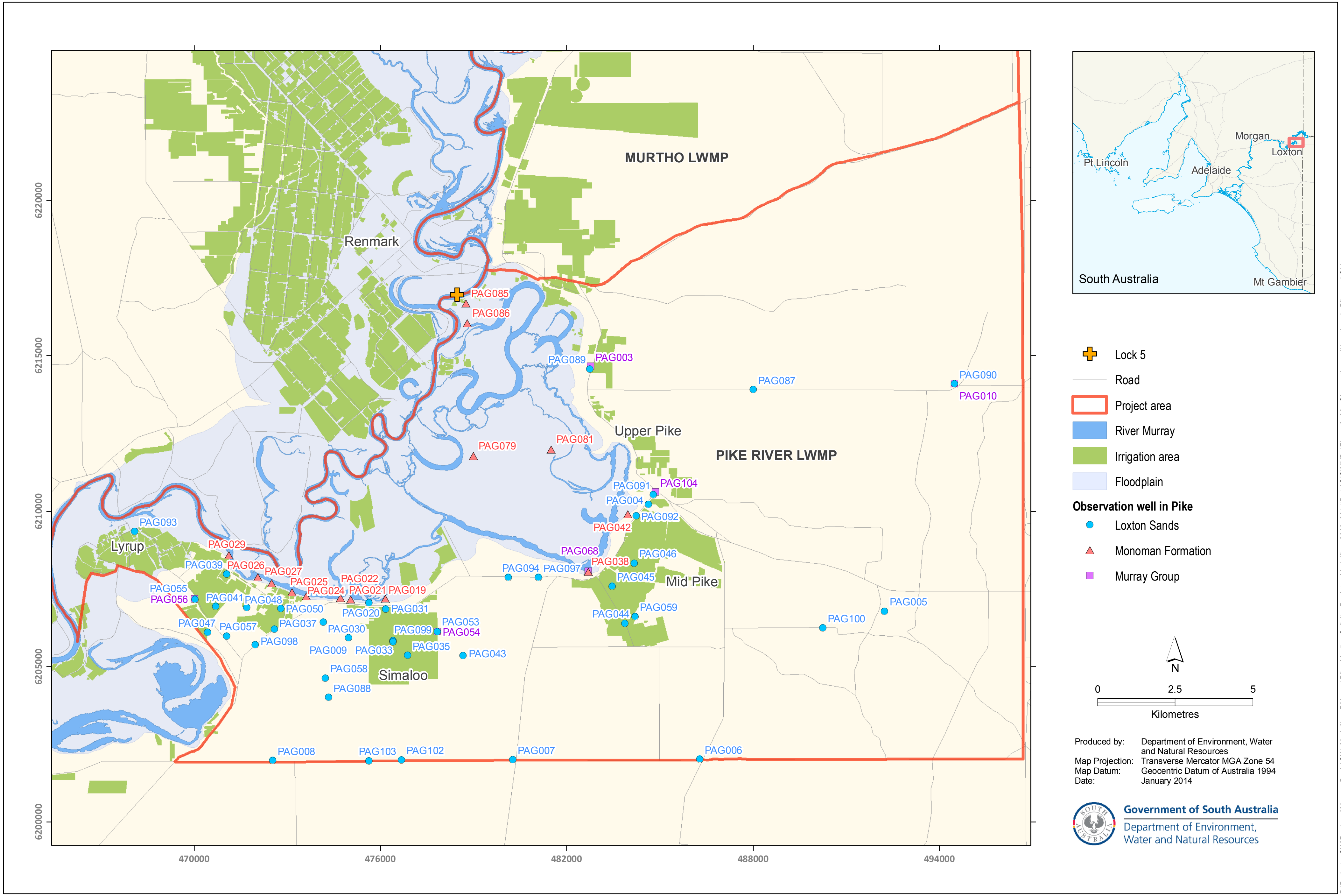


Figure 2.6a. Observation well locations in the Pike area

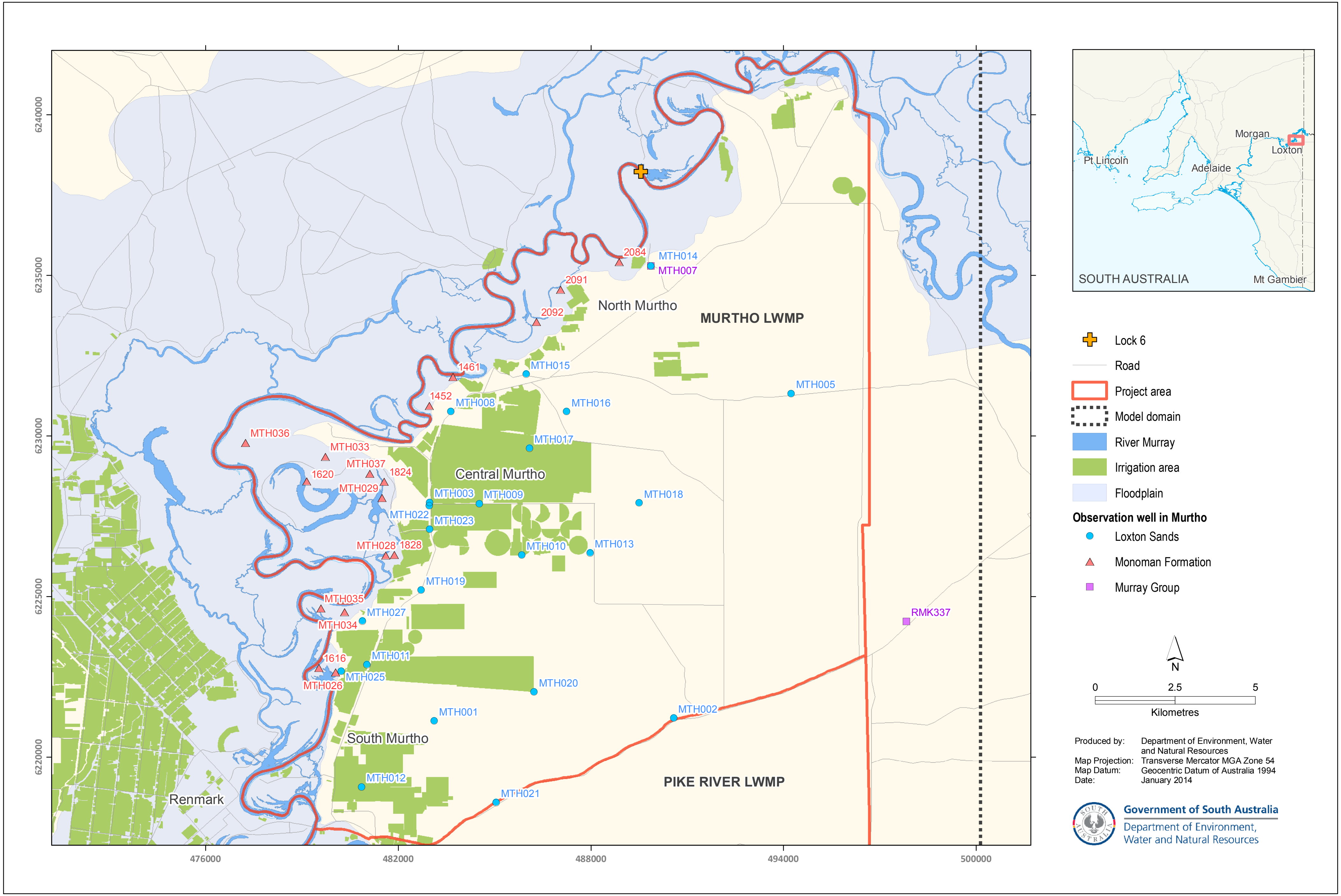


Figure 2.6b Observation well locations in the Murtho area

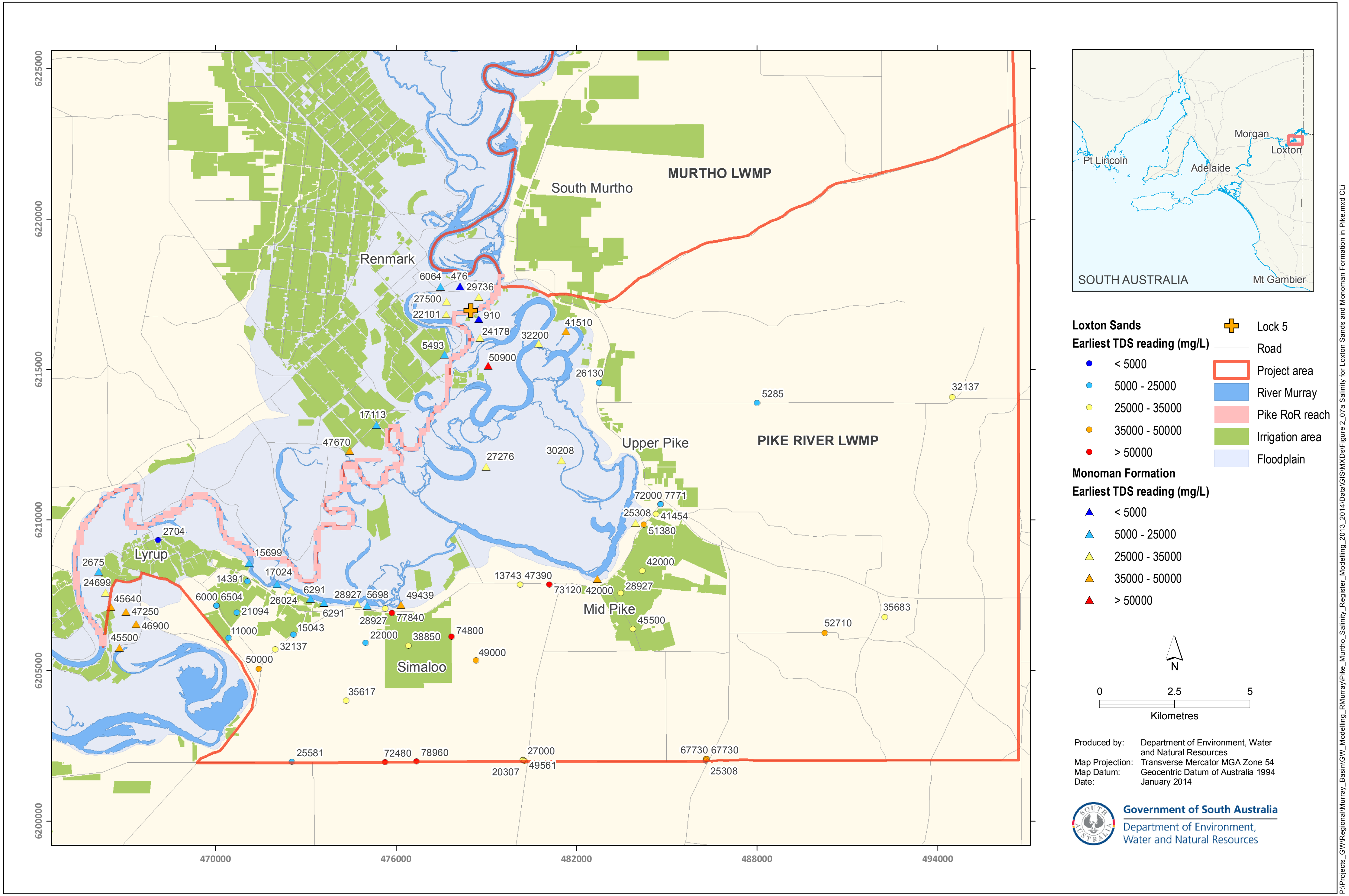


Figure 2.7a Groundwater salinities for the Loxton Sands and Monoman Formation in the Pike area (after AWE 2012a and AWE 2012b)

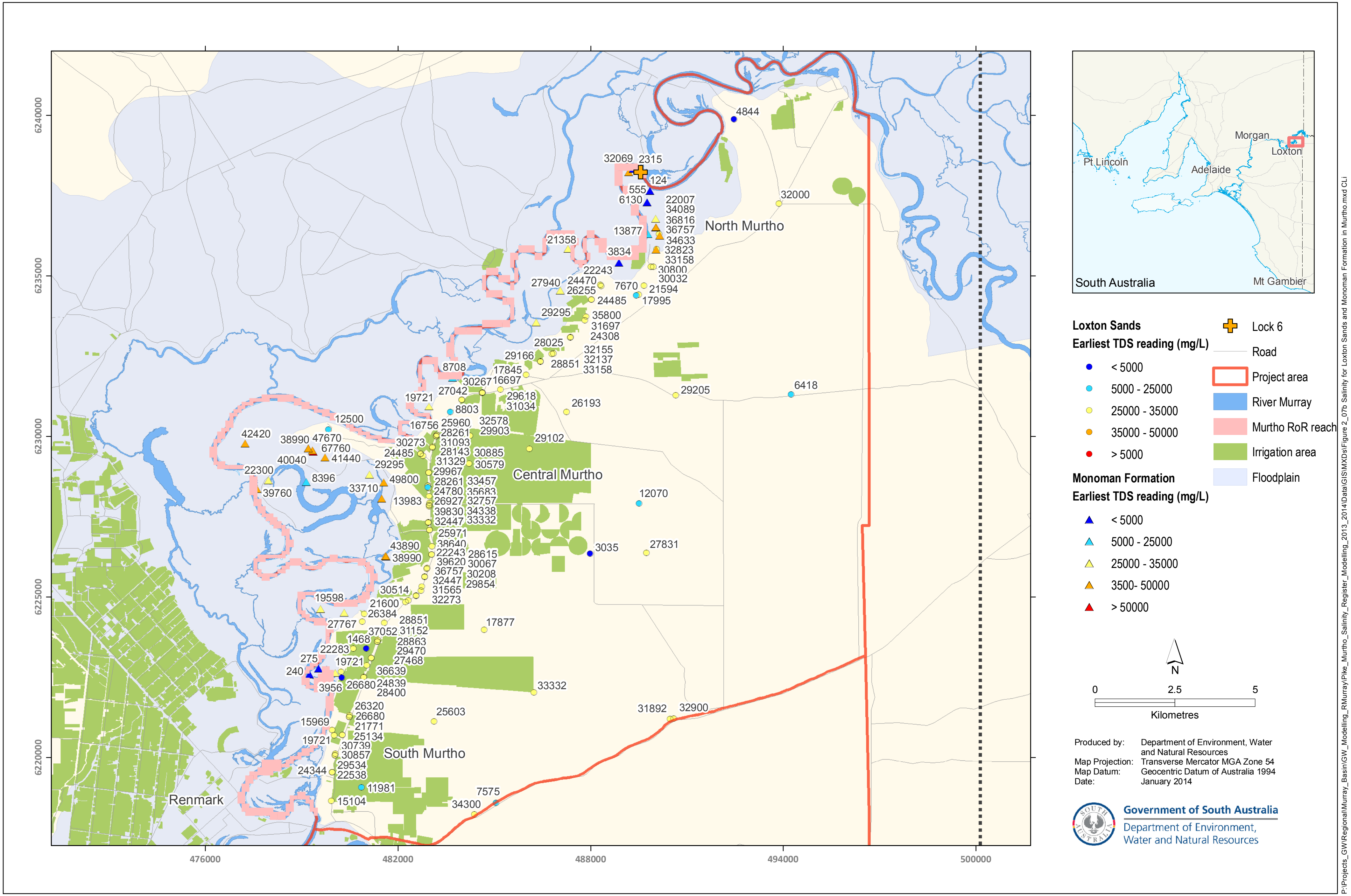


Figure 2.7b Groundwater salinities for the Loxton Sands and Monoman Formation in the Murtho area (after AWE 2012a and AWE 2012b)

2.3.7 MONOMAN FORMATION

In the incised River Murray erosive trench, the alluvial infill deposit of the floodplain is the Monoman Sands. It lies beneath the clays of the Coonambidgal Formation and above the regional aquitard of the Lower Loxton Clay/Bookpurnong Beds. At some locations, the Lower Loxton Sands is present between the Monoman Formation and the regional aquitard, and the Lower Loxton Sands and Monoman Formation form a combined aquifer (AWE, 2012a, AWE, 2012b).

The Monoman Formation 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). As a consequence of the depositional environment, the Monoman Formation is likely to have highly variable transmissivity (Yan et al., 2005). Floodplain air-core drilling carried out by REM in December 2004 included the Pike-Mundic, Woolenook Bend, and Gurra Gurra floodplains. Drilling revealed that the thickness of the Monoman Formation ranges between 7–19 m (REM-Aquaterra, 2005a). The more recent hydrogeological investigations undertaken by AWE (2012a) and AWE (2012b) show that the floodplain aquifer thickness is mostly between 15 and 30 m in the study area (including the Lower Loxton Sands where present). The Monoman Formation tends to become thicker towards the north, coupled with the possibility of an increase in the likelihood of the Monoman Formation being directly on top of the Lower Loxton Sands. This would thereby increase the total aquifer thickness upstream, however it is noted that visually it is very difficult to identify the boundary at the bottom of the Monoman Formation (Yan et al., 2006).

The Monoman Formation forms a semi-confined aquifer (AWE, 2012a, AWE, 2012b). It is juxtaposed with the Loxton Sands Formation and is in hydraulic connection. As groundwater moves laterally towards the River Murray it either transfers to the Monoman aquifer or directly discharges to the River at the base of the cliffs. Median potentiometric head values observed in the Monoman Formation and Loxton Sands in 2012 are shown together in Figure 2.5 as they are in hydraulic connection. Although not shown explicitly in the figure, above Lock 5 the groundwater level in the Monoman Formation is lower than the river pool level of 16.3 m AHD, causing losing stream conditions, as indicated by NanoTEM data (see Section 2.6.1.1).

The hydrographs (Section 4) show a strong response to the River Murray levels (e.g. Well 1452) and Pike River levels (e.g. PAG019). Their overall trends are relatively steady. There are no detailed historical readings available for this aquifer. Most of the wells started monitoring in the 1990s, while the others started in the 2000s. Some of the wells show a decline during the drought between 2005 and 2010 (e.g. PAG025). An increase in heads is observed in some wells near 2010 (e.g. PAG086) due to the high rainfall. The location of the observation wells are shown in Figure 2.6 and the hydrographs are shown along with the modelled heads in Section 4.

Aquifer tests undertaken by AWE (2012a), AWE (2012b), REM (2002a), REM (2002b) and URS (2000) show that the hydraulic conductivity of the Monoman Formation in the study area can be highly variable, ranging from 2 to 33 m/d, with a median of 19 m/d, while the storage coefficient values can be between $4x10^{-4}$ and $5x10^{-3}$. 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, 2013d).

Salinity data are presented in Figure 2.7 and are sourced from AWE (2012a), AWE (2012b) and DEWNR (2013). Groundwater salinities vary from ~900 to 51000 mg/L in Pike, with a median of ~27000 mg/L, and vary from ~1400 to 68000 mg/L in Murtho, with a median of 29000 mg/L. 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.

2.3.8 COONAMBIDGAL FORMATION

The Quaternary Coonambidgal Formation forms a local floodplain aquitard and confining bed which overlies the Monoman Formation aquifer. The Coonambidgal Formation comprises clay and silts deposited during periods of episodic flooding (Brown and Stephenson, 1991). This unit has been re-worked in part by the meandering River Murray; the re-worked sediments can be more permeable.

Floodplain air-core drilling carried out by REM in December 2004 indicated that whilst the unit was commonly 2–4 m thick, it could vary in thickness anywhere from 1–9 m across the Pike-Mundic and Woolenook floodplains (Yan et al., 2006). It is likely that, similar to floodplains in the Loxton and Bookpurnong regions, the greater thicknesses would be observed at or near the break in slope between the floodplain and highland. The more recent hydrogeological investigations undertaken by AWE (2012a) and AWE (2012b) show that the thickness is between 2 and 10 m in the project area. The higher values are obtained from the wider floodplains, with up to 10 m observed in the Pike-Mundic floodplain and up to 7 m in the Woolenook floodplain.

No data are available on the hydrogeological properties of the Coonambidgal Formation in the study area.

2.3.9 BLANCHETOWN CLAY

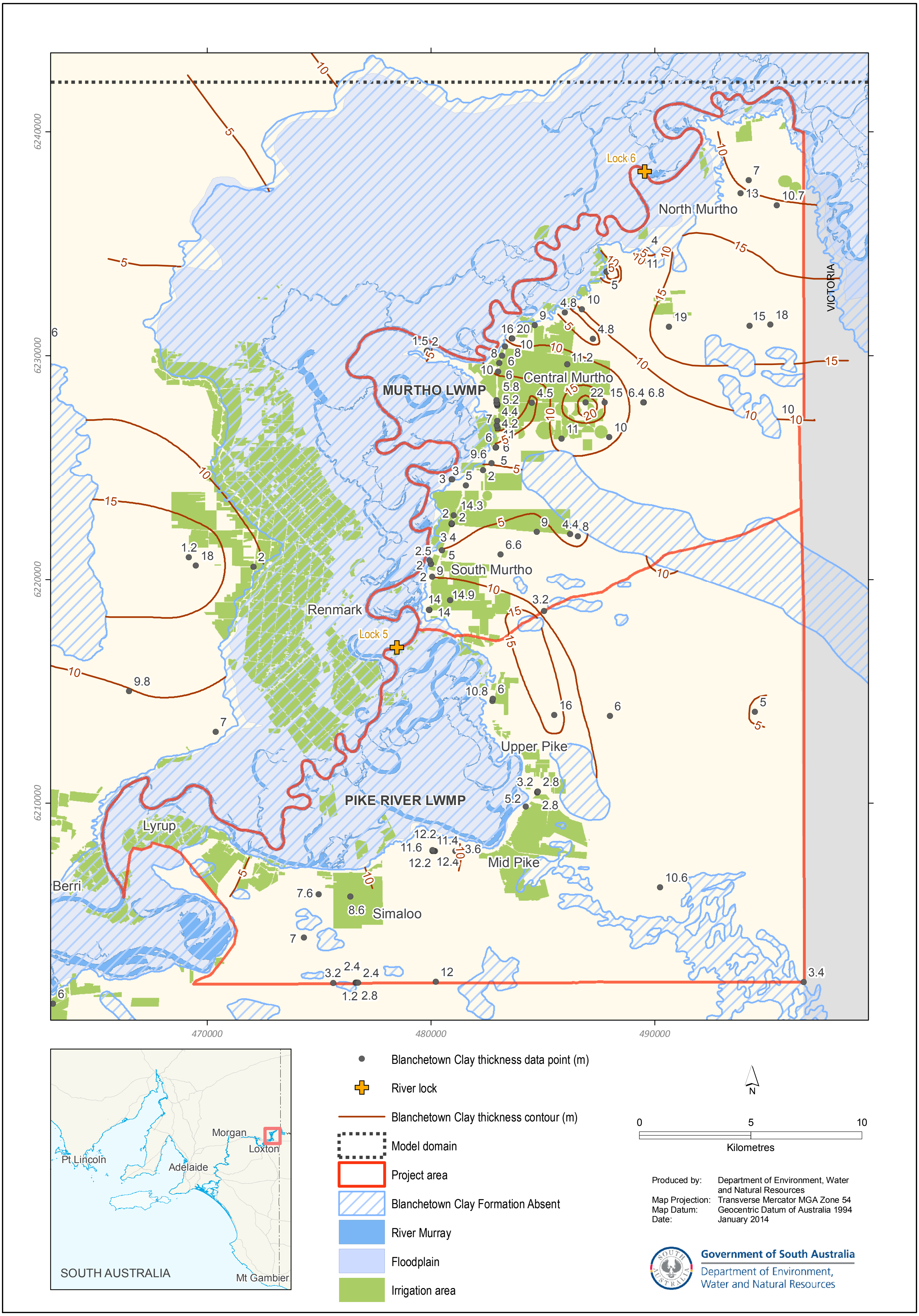
The Blanchetown Clay Formation forms a discontinuous regional aquitard on the highland that can cause local perching of shallow groundwater and influence irrigation-induced recharge rates. It is the main depositional unit of Lake Bungunnia, a paleolake of the Plio-Pleistocene (McLaren et al, 2009). It is predominantly composed of a thick sequence of green-grey clay comprised of kaolinite and illite. Two other, thinner, members have been identified at some locations: a basal well-sorted sand with interbedded clay (Chowilla Sand) and a finely laminated silt and silty clay (Nampoo Member) (McLaren et al, 2009).

The thickness of the Blanchetown Clay is shown in Figure 2.8. The Blanchetown Clay is absent across the floodplain and in large areas to the south-west of mid-Pike and west of South Murtho. The clay is also absent in discrete pockets along the eastern side of the River. The thickness of the Blanchetown Clay, where present, ranges from 1.2 to 22 m, thickest east of Woolenook Bend. The time taken for root zone drainage to reach the watertable depends in part on the thickness of the Blanchetown Clay.

2.3.10 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). In highland areas, the Woorinen Formation regularly contains multiple hard horizons of the Bakara Calcrete (Yan et al., 2006). 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, 2013d).

The Woorinen Formation provides a thin capping of Quaternary sediments across the highlands of the project area between 2–5 m thick (REM-Aquaterra, 2005). Sequences of roughly the same thickness have been deposited due to aeolian deposition on the Pike-Mundic Floodplain, on top of existing Coonambidgal Formation clay. Whilst the Woorinen Formation may experience localised perched groundwater tables, predominantly in areas with a reasonably thick sequence of Blanchetown Clay and higher recharge rates due to irrigation, the extent of perching has not been studied. It may delay and reduce the volume of infiltrated water that will reach the watertable in the Loxton Sands aquifer.



P:\Projects_GW\Regional\Murray_Basin\GW_Modelling_RMurray\Pike_Murtho_Salinity_Register_Modelling_2013_2014\Data\GIS\MXDs\Figure 2_08 Blanchetown Clay thickness.mxd CLi

Figure 2.8. Blanchetown Clay thickness (after AWE 2012a and AWE 2012b)

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 such as irrigation.

The two main aquifer systems in contact with the River Murray in the Pike-Murtho area are the unconfined Loxton Sands aquifer and the semi-confined Monoman Formation aquifer.

The Loxton Sands aquifer is the regional watertable aquifer on the highland. The regional lateral flow at Murtho is generally to the south-west, whilst at Pike it is generally towards to the nearest discharge point, being the Pike River, River Murray or Gurra Gurra Lakes. Irrigation recharge has altered groundwater flow in this aquifer. An irrigation induced groundwater mound of up to 18 m AHD at Lyrup and an elevated watertable of around 17 m AHD at Central Murtho have been observed. This steeper hydraulic gradient will result in an increased groundwater flux to the Monoman Formation and ultimately to the River Murray. At Pike, groundwater can discharge from the Loxton Sands directly to the Pike River, which flows into the River Murray. At some locations groundwater in the Loxton Sands can enter the River Murray directly via cliff seepage.

The River Murray has carved a valley through the landscape, into which the Monoman Formation has been deposited. The head in the Monoman Formation aquifer responds to short-term fluctuations in river level and its backwaters. Where the heads are higher than the river level, groundwater will discharge from the Monoman Formation to the river. Due to the shallow watertable in the floodplain, the Monoman Formation aquifer is also influenced by ET from groundwater, which may lower heads to below river level and cause losing stream conditions in some areas, especially above Lock 5.

Upward leakage from the underlying Murray Group into the floodplain aquifer is believed to be relatively minor due to the low hydraulic conductivity of the intervening aquitard of the Lower Loxton Clays and Bookpurnong Beds (REM-Aquaterra, 2005). This has been tested in the adjacent Loxton-Bookpurnong area by Yan et al. (2005) where the calibrated model shows that the Murray Group Limestone only contributes 3% of the overall salt load. This study has conducted a similar test for the Pike-Murtho area and the results are reported in Section 4.

In addition to the main aquifer systems, there are also local perched aquifers in the Woorinen Formation above the Blanchetown Clay in the main irrigation areas. These perched aquifers can delay and reduce the volume of infiltrated water that will reach the watertable in the Loxton Sands aquifer.

2.5 GROUNDWATER LEVEL MONITORING

There are 362 observation wells that monitor groundwater levels within the study area, most of which monitor the Loxton Sands and Monoman Formation aquifers. A few observation wells monitor the Murray Group Limestone but they do not differentiate the subunits. A selection of 101 wells is presented in this report for comparison with model results. The wells are well distributed within the 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 DEWNR (2013). Hydrograph data are presented along with calibrated model results in Section 4. Observation well locations in the Pike-Murtho area are presented in Figure 2.6.

2.6 HYDROLOGY

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

2.6.1 THE RIVER MURRAY

The River Murray floodplain acts as a groundwater sink in the Pike area, while in the Murtho area NanoTEM data indicate that most of the river reach is losing stream (see Section 2.6.1.1). The project area lies between Lock 6 to Lock 4, where the river pool level is:

- 16.3 m AHD between Lock 6 and 5
- 13.2 m AHD between Lock 5 and 4.

The locks 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 Pike-Murtho groundwater mounds: the average head difference between river level and pool level since 2000 ranges from 0.03 m upstream of Lock 5 to 0.5 m downstream of Locks 5 and 6.

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, Tan et al., 2007, Telfer et al., 2005). River bed resistivity can also be influenced by river depth as groundwater normally exhibits decreasing resistivity (i.e. is more saline) with increasing depth beneath the river.

Figure 2.9 shows NanoTEM data collected in 2004 for sediments immediately below the river bed (Telfer et al., 2005). Figure 2.9 indicates that most of the reach above Lock 5 is a losing stream, except immediately downstream of Lock 6 and above and below the Woolenook Bend floodplain, where groundwater can discharge directly from the Loxton Sands to the river. Below Lock 5, the river is mostly gaining stream. Figure 2.9 also indicates that the Pike River is a strongly gaining stream.

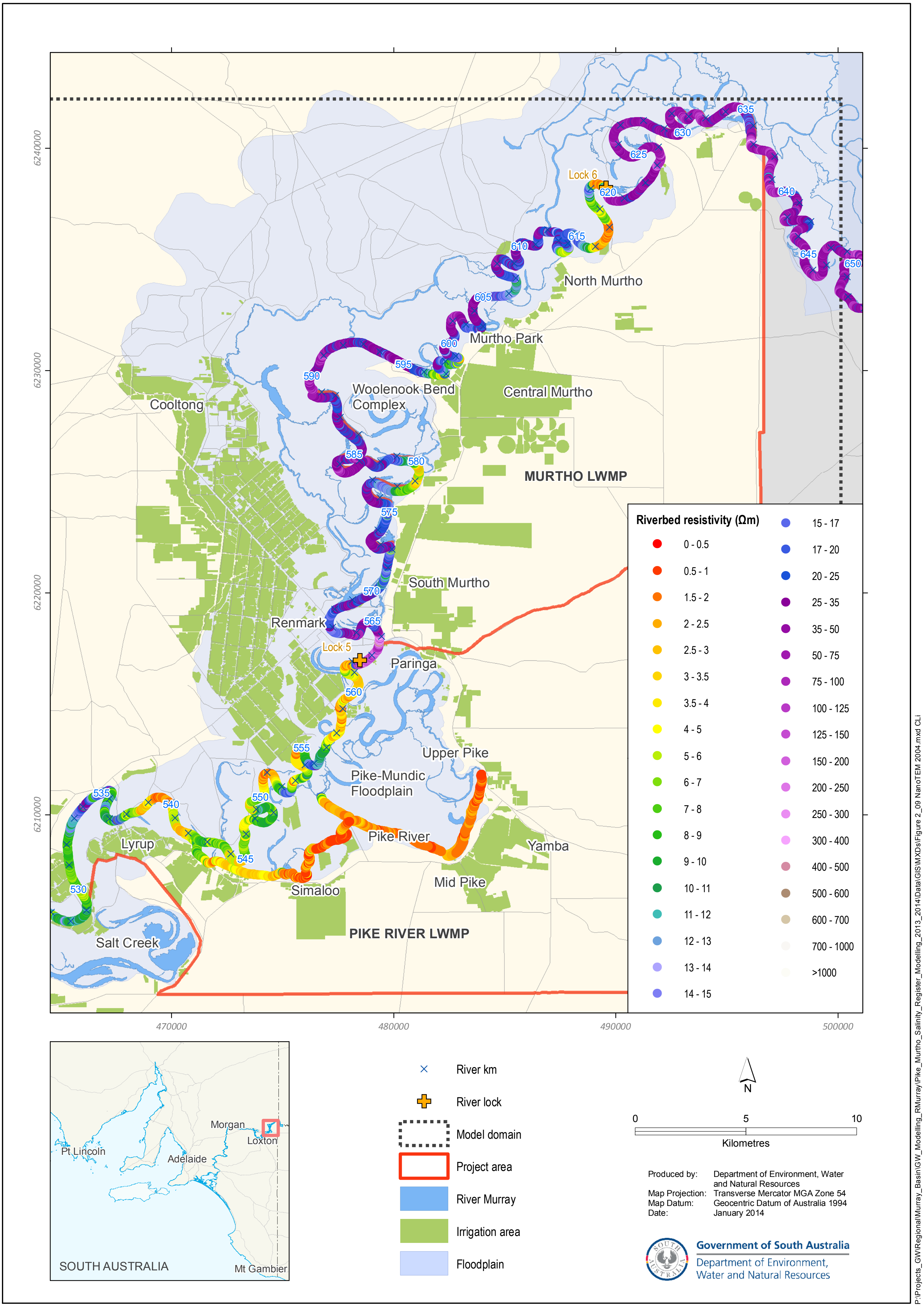


Figure 2.9. NanoTEM 2004 (Telfer et al. 2005)

2.6.1.2 RUN OF RIVER

Run-of-River (RoR) analysis results are presented in Figure 2.10. The Pike reach spans river km 530 to 562 while the Murtho reach spans river km from 563 to 621. No measurements were taken between 2010 and 2012 due to the high river flows (P Forward (SA Water) 2013, pers. comm., 28 July).

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 2.10 shows different salt load trends for the Pike and Murtho reaches. Before 2009, Murtho shows a generally declining trend while Pike shows a variable trend. The exceptionally high RoR salt load values at 2013 for both Pike and Murtho are due to the recent flood recessions after the 2010/11 high river levels.

The RoR results do not reflect the impact of Murtho SIS as it has not yet been commissioned. The Pike SIS was commissioned in 2011, but its impact was diminished by the recent flood recessions.

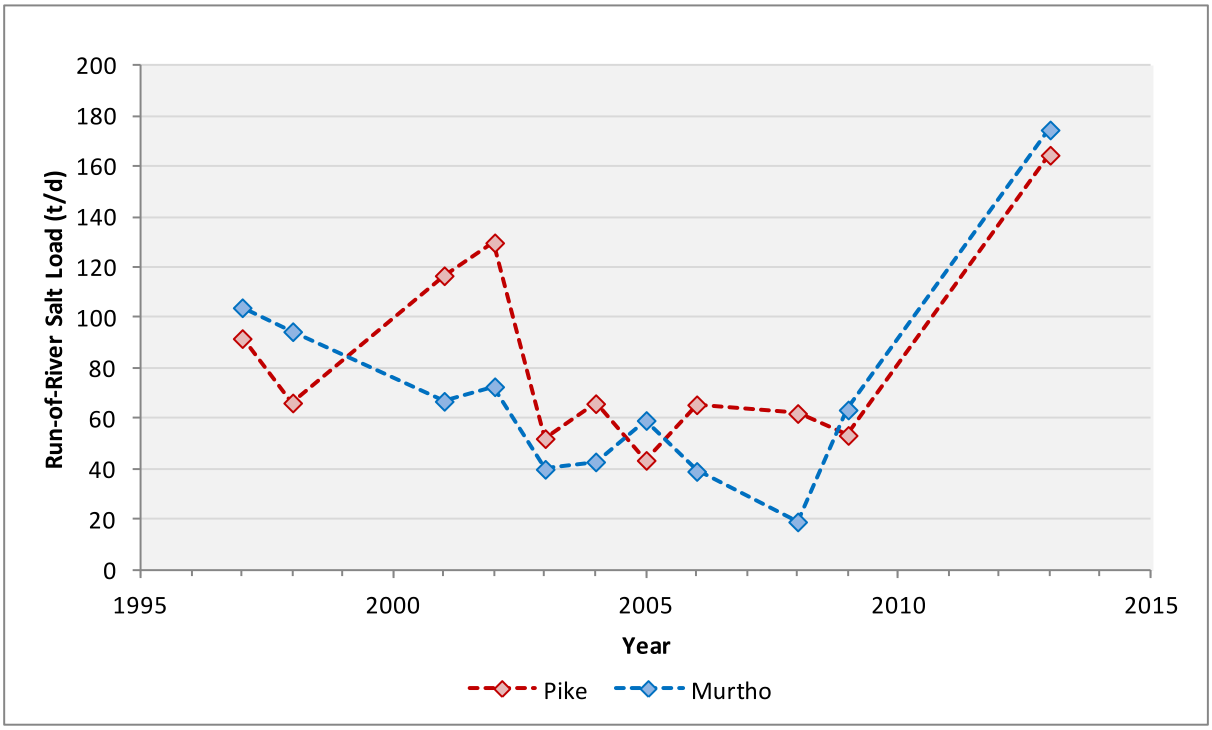


Figure 2.10 Salt load entering the River Murray from RoR Analysis

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 2.11 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 (AWE, 2012c).

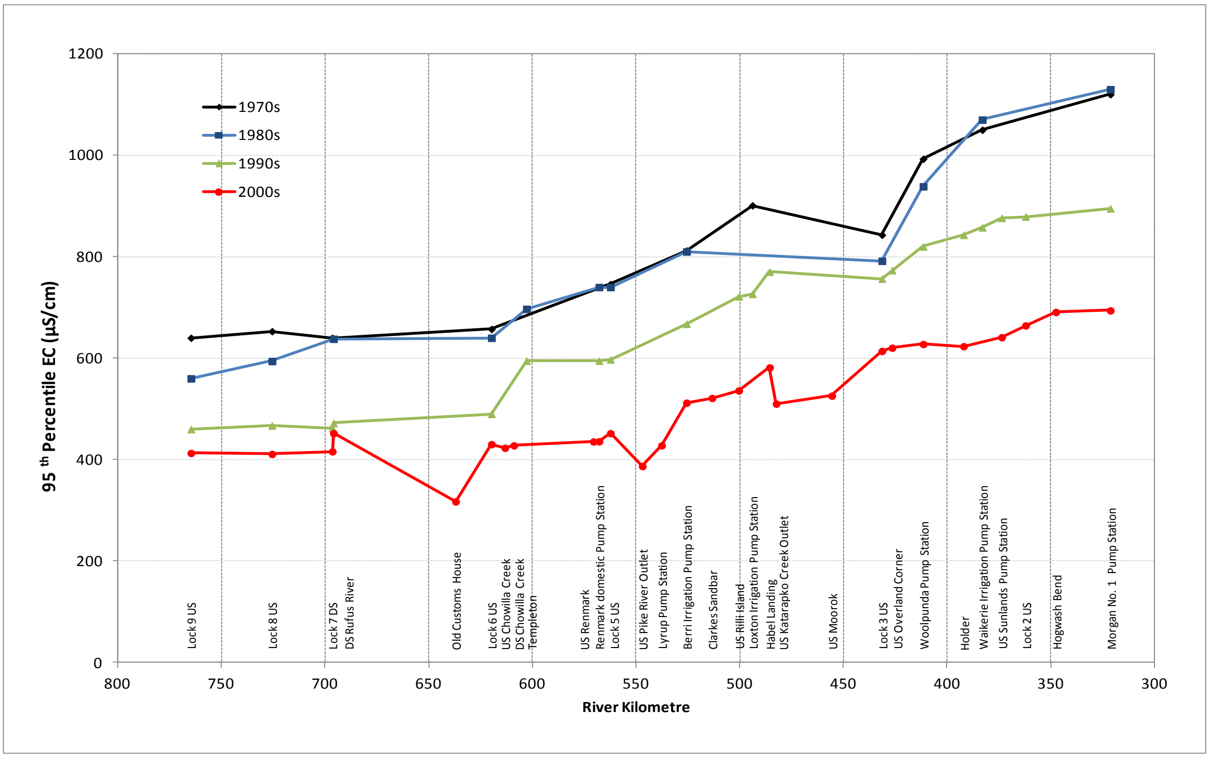


Figure 2.11 In-stream salinity 95 percentile versus river km for selected flows (AWE, 2012c)

2.6.2 OTHER SURFACE WATER BODIES

The project area includes anabranches of the River Murray. Groundwater flowing into anabranches will add to the overall groundwater salt load of the River Murray. Lakes, lagoons, wetlands and ephemeral surface water bodies also occur. These surface water bodies may influence groundwater flows and river salinity by adding saline surface water, particularly during flood recessions. Some may have a significant but only temporary impact on salt loads to the River Murray. When their water levels are high, they add additional salt load to the River Murray for a short period of time. Surface water features that may be of significance to this study are shown in Figure 2.12.

The Pike-Mundic floodplain is located to the south-east of Renmark. It includes a complex network of anabranches, lagoons and backwaters within an area of approximately 50 km^2. The transition between floodplain and the highland (denoted as being above the 1956 flood level or approximately 25 m AHD) can be steep where cliffs have formed along the Pike River. Surface water features of the Pike-Mundic floodplain include:

- Pike River
- Mundic Creek
- Pike Lagoon
- Tanyaca Creek

- Snake Creek
- Rumpagunyah Creek

Most of these are permanent, except Snake Creek which has been shallow or dry in the last few years (AWE, 2010a). A series of weirs and banks were constructed to control the stage level in these backwaters for irrigation purposes. The regulated stage levels were reported by REM-Aquaterra (2005) and range from 13.3 to 14.8 m AHD.

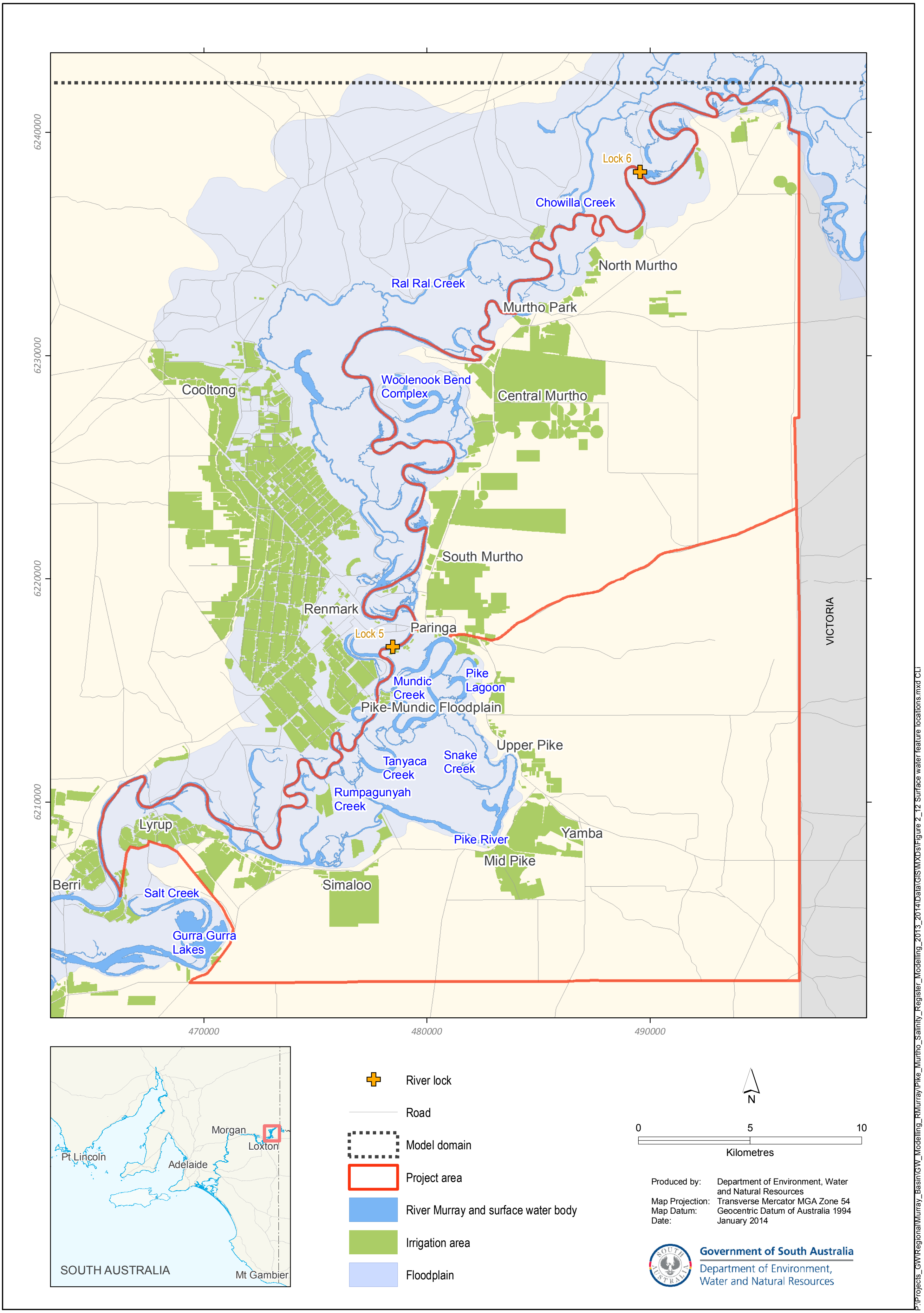
The Pike River is an anabranch of the River Murray which begins just above Lock 5 near Paringa and rejoins the main river below Lock 5 near Lyrup. NanoTEM data in Figure 2.9 indicate that the Pike River is mostly gaining stream. Salt loads from Pike River are delivered to the River Murray near Lyrup (river km 542).

Salt Creek and Gurra Gurra Lakes are located downstream of Lyrup and are also within the model domain. However, Yan et al. (2006) found that surface water features in the area do not have a direct connection with the River Murray under regular flow regimes, based on information from the local management committee and aerial photos. Salts in this area are stored in the floodplain and are only delivered to the River Murray during high flow or flood events.

In Murtho, surface water features that may be important for groundwater-surface water interaction and salt loads include:

- Woolenook Bend complex
- Ral Ral Creek
- Chowilla Creek

The geomorphology in Murtho is similar to Pike, with the Woolenook Bend Complex being the major floodplain of significance locally (Stadter, 2005). Stage height of these features largely depends on the level of the River Murray.



P:\Projects_GW\Regional\Murray_Basin\GW_Modelling_RMurray\Pike_Murtho_Salinity_Register_Modelling_2013_2014\Data\GIS\MXDs\Figure 2_12 Surface water feature locations.mxd CLi

Figure 2.12. Surface water feature locations

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 et al. (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 are given in Cook et al. (2004).

2.6.3.2 IRRIGATION DEVELOPMENT

Irrigation in the Pike-Murtho study area is mostly confined to highland areas except Lyrup where some of the irrigation area is on the floodplains. DEWNR commissioned Laroona Environmetrics to collate, summarise and verify irrigation data for the Pike-Murtho area, including changes in irrigation area over time and volume of water applied to crops (Laroona Environmetrics, 2013). The details are included as Appendix C-1. A brief summary is provided below.

Figure 2.13 shows the irrigation areas and their commencement years for the Pike-Murtho area. Irrigation was first established in Lyrup in 1894 while irrigation in most of the other areas started in the 1940s, except for North Murtho which started in the 1950s.

Irrigation areas are relatively small in North Murtho and Upper Pike, being less than 500 ha for all times. In Lyrup, Simarloo and Mid Pike, there was a steady increase in irrigation areas from the 1950s to the early 2000s, when the area was approximately 750 Ha. However, during the Millennium Drought between 2005 and 2010, there was a noticeable contraction in irrigation areas, probably due to the water restrictions.

Major irrigation developments are at Central and South Murtho. In South Murtho, irrigation areas began to increase from the 1950s, reaching approximately1500 Ha at 1999 and remaining steady until the drought, when the irrigation area was slightly reduced to 1400 Ha. In Central Murtho, irrigation areas expanded very rapidly to approximately3500 Ha at 2008 and did not contract during the drought.

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 Pike-Murtho 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 Blanchetown Clay, a perched aquifer may form. Localised perched aquifers can occur within the Woorinen Formation above the Blanchetown Clay on the highland in the study area, predominantly in areas with a thicker sequence of the Blanchetown Clay and higher recharge rates from irrigation (Yan et al., 2006). However, these locations have not been monitored or mapped.

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 (AWE, 2011d, Fuller et al., 2005). Estimates of lag time under irrigation areas in the Pike-Murtho region vary greatly, ranging from 0 to 85 years, depending on location (Fuller et al., 2005), assuming a steady root zone drainage rate of 120 mm/y (Figure 2.13 and Figure 2.14). The lag times in this area are relatively longer than other areas in the Riverland such as Loxton-Bookpurnong as this area has a thicker sequence of the Blanchetown Clay and a greater depth to the watertable (i.e. thicker unsaturated zone).

As the root zone drainage starts to reach the watertable, potentiometric heads in the Loxton Sands increase. This is the cause of the groundwater mounds at Lyrup and Simarloo and is presumably responsible for the approximately1 m rise in the watertable at Central Murtho. At locations with long lag times and recently-commenced irrigation, only a small proportion of irrigation drainage may have reached the watertable so far.

Irrigation within the model domain but outside the project area has not been included. This is primarily the Pyap to Kingston, Loxton-Bookpurnong and Berri-Renmark regions. It is expected that irrigation activities in these regions will not impact the potentiometric heads in the Loxton Sands at Pike-Murtho as they are at a reasonable distance from the project area or are on the opposite side of the River Murray.

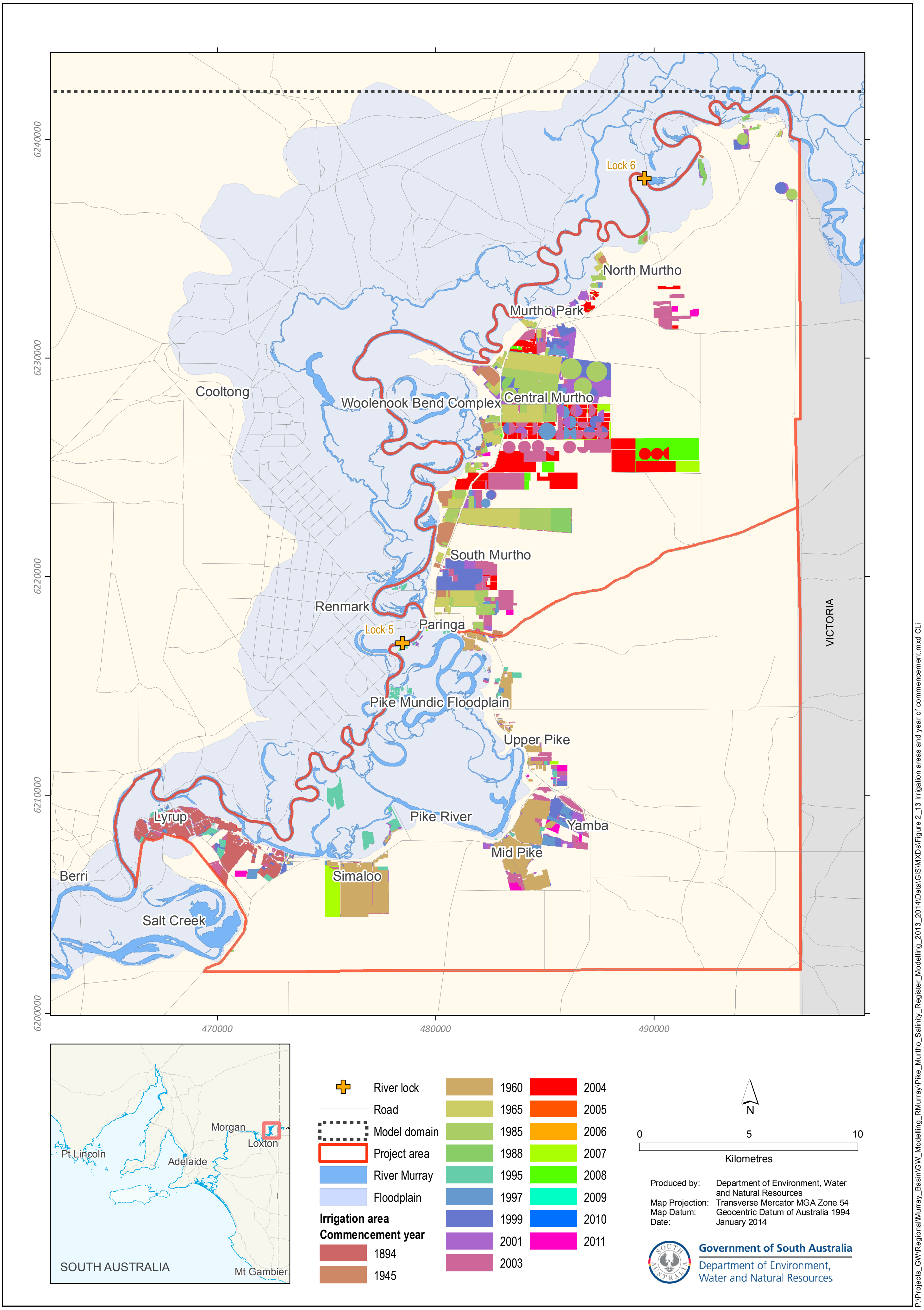


Figure 2.13. Irrigation areas and year of commencement

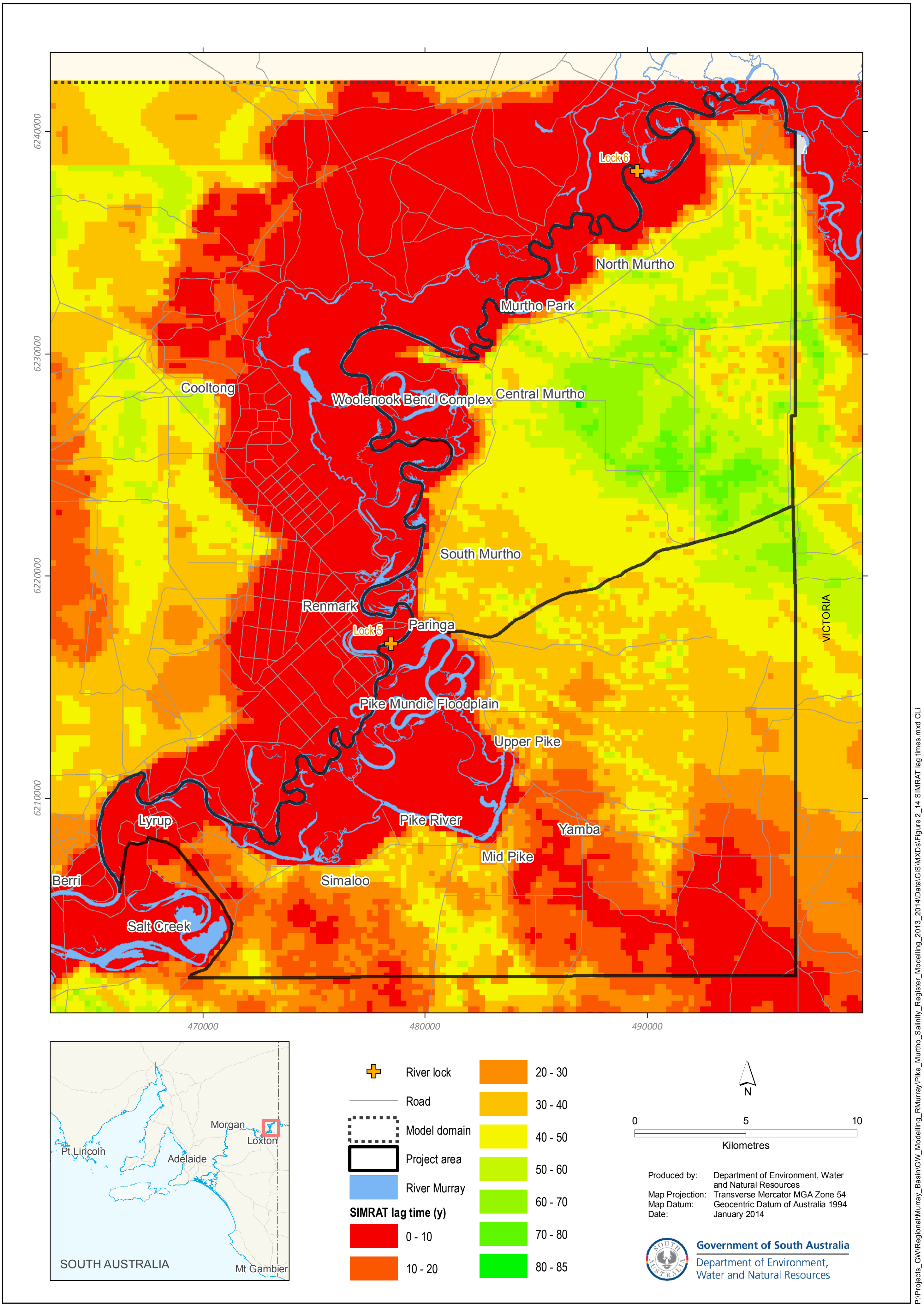


Figure 2.14. SIMRAT lag times based on an accession rate of 120 mm/y (Fuller et al. 2005)

2.6.3.3 DRAINS AND DRAINAGE WELLS

There are drainage wells in the Central Murtho and South Murtho areas. In most cases drainage wells were drilled as a solution to water-logging problems caused by perched aquifers. These wells can greatly reduce the estimated lag times for the irrigation accessions to reach the watertable.

Drainage wells existed in Central Murtho since 1975 and in South Murtho since 1970, based on DEWNR (2013). Yan et al. (2006) estimated the drainage rates to be 1–1.5 L/s in Central Murtho and 0.5–1 L/s in South Murtho through groundwater model calibration. It is assumed that all wells were sealed and disused by 2002 (P Hasslett (Local Farmer) 2006, pers. comm. January).

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 Meterology, 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 Pike-Murtho 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 Meterology, 2012).

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.

Holland et al. (2011) 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 Pike-Murtho floodplain areas, the woodland generally covers 40–45% of the total floodplain, suggesting an overall floodplain average groundwater ET of approximately80 to 90 mm/y.

2.6.5 CLIFF SEEPAGE

Anecdotal evidence indicates that only minor seepage occurs from cliff faces in the study area (Yan et al., 2006).

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 Pike and Murtho SIS (Figure 2.15) is to reduce in-stream salt loads by reducing groundwater heads, thereby flattening or slightly reversing the horizontal groundwater gradients. This is achieved by pumping groundwater from the Loxton Sands.

The Pike SIS consists of four production wells spaced approximately 1000 m apart and located 100–400 m inland from the edge of the river valley along the southern bank of the River Murray near river km 545. The scheme was commissioned in 2012 and pumps approximately30 L/s. The scheme aims to maintain a potentiometric head of approximately river pool level at the mid-point observation wells.

The Murtho SIS consists of 23 production wells spaced 500–1000 m apart and located approximately 500 m inland from the edge of the river valley along the eastern bank of the River Murray between river km 570 and 618. Pumping commenced in 2014. This scheme differs from other schemes in SA in that its pumping volume is limited by the pipeline capacity and the pumping volume may not be sufficient to lower the groundwater level at mid-point wells to the pool level in the long-term, when all the accession drainage from the current and future irrigation areas have reached the watertable. The total design flow rate of the scheme is 100 L/s and is provided by SA Water. The saline groundwater from the schemes is pumped from the Loxton Sands aquifer via a collector pipeline to the Noora Plain Disposal Basin.

2.8 CONCEPTUAL MODEL

The conceptual model describes the known hydrogeological features of the Pike-Murtho project area. Chapter 3 describes the simplified version adopted for the numerical model.

2.8.1 OVERVIEW

The key features of the Pike-Murtho hydrogeological model are presented in Figure 2.16. It illustrates the major aquifers and confining layers, recharge and discharge processes 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 Pike-Murtho model area consists of a series of Quaternary and Tertiary sediments underlain by basement. The River Murray channel is incised into the upper sediments. The principal hydrostratigraphic sequence in the Pike-Murtho 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 aquifers may occur locally beneath irrigation districts, this is not documented and has not been incorporated into the model. The perched aquifers and the thickness of the Blanchetown Clay will affect the lag times for the irrigation accessions to reach the watertable.

On the highland, the watertable resides within the Loxton Sands Aquifer. The Loxton Sands is underlain by the Lower Loxton Clays and Shells and the Bookpurnong Formation, which together act as an effective aquitard separating the Loxton Sands from the underlying Murray Group Limestone. Previous studies have shown that the impact of the Murray Group Limestone on salt loads to the River Murray is minimal in regions close to the study area (Yan et al., 2006, Yan et al., 2005). However, sub-units of the Murray Group are modelled as they are important in other areas within the model domain:

- the Pata Formation (aquifer)
- Winnambool Formation (aquitard)
- Glenforslan Formation (aquifer)
- Finniss Formation (aquitard)
- Mannum Formation (aquifer)

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). 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 Monoman Formation is hydraulically connected to the Loxton Sands in the project area.

The Monoman Formation hosts the River Murray and a number of surface water bodies, including anabranches and wetlands within the Pike-Mundic and Woolenook Complex floodplains, which can interact with the groundwater system. The stage level of the River Murray depends on the river locks and flow rate. In the study area most of the River Murray upstream of Lock 5 is losing stream while most of the river below Lock 5 is gaining stream (Figure 2.9). The stage level of the Pike River anabranch system is controlled by a series of weirs and banks. In the Pike-Mundic floodplain the saline groundwater mainly discharges at the Pike River, which flows into the River Murray. The stage level of the anabranches in the Woolenook Complex floodplain mainly depends on the level of River Murray.

Regionally, the dominant direction of lateral groundwater flow in the Loxton Sands within the project area is from east to west towards the River Murray, as driven by distant recharge sources (Barnett, 1991). The other major driver of this aquifer is recharge. Within the study area, recharge of the Loxton Sands 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 et al., 2004). Land clearance increases root zone drainage by roughly one to two orders of magnitude, but the time lag between clearance and recharge to the watertable is of the order of many decades in the Pike-Murtho area (Cook et al., 2004) so the additional water is yet to fully impact the hydrogeology.

Irrigation in the Pike-Murtho area first started at 1880 and has expanded considerably since the 1950s. Irrigation can significantly increase root zone drainage and hence aquifer recharge. Elevated watertables have been observed under Central and South Murtho, Lyrup and Simarloo. In Lyrup the groundwater mound can be as high as 18 m AHD, which is higher than the pool level of 13.2 m AHD by approximately 5 m. This creates a steep hydraulic gradient that increases saline groundwater discharge to the River Murray. The impact of irrigation on aquifer recharge is delayed by lag times, which depends on factors such as irrigation application rates and thickness of the Blanchetown Clay. Lag times are generally higher in Murtho than in Pike, due to the greater depth to the watertable and thicker sequence of the Blanchetown Clay in Murtho. Lag times in the Pike-Murtho area can be up to 85 years for a root zone drainage rate of 120 mm/y (Fuller et al., 2005). This means that while the more recent irrigation areas have little altered recharge to date, there may be substantial impacts in the future.

There are irrigation drainage wells targeting the Loxton Sands in the Central and South Murtho areas. The wells were constructed in the 1970s and can significantly shorten the lag times. They are assumed to cease operation and sealed by 2002 (P Hasslett (Local Farmer) 2006, pers. comm. January).

Irrigation in the Pyap to Kingston, Loxton-Bookpurnong and Berri-Renmark regions are outside the project area but within the model domain. They are neglected as it is not anticipated to substantially affect the potentiometric head in the Loxton Sands at Pike-Murtho.

To mitigate the salt load impacts of the Pike-Murtho groundwater mounds, the Pike and Murtho SIS have been constructed. The Pike SIS commenced operation in 2012 while the Murtho SIS commenced in 2014. Production wells within the SIS target the Loxton Sands and intercept discharge flux from this aquifer before it enters the floodplain aquifer (Monoman Formation) and/or the River Murray. For the Pike SIS, the aim of pumping from this aquifer is to reduce mid-point groundwater heads to pool level, thereby flattening or reversing (slightly) horizontal groundwater gradients and the pattern of discharge towards the floodplain. However, the pumping volume of the Murtho SIS is limited by the capacity of the pipeline and disposal basin, hence it may not be able to lower the groundwater level to pool level in the long-term even pumping at the maximum rate. The diverted saline groundwater from Pike-Murtho is discharged to the Noora Disposal Basin, to the south of Pike. There are no other groundwater extractions in the area as the groundwater is too saline for crop irrigation, stock or potable use.

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 or inflows from saline surface water bodies.

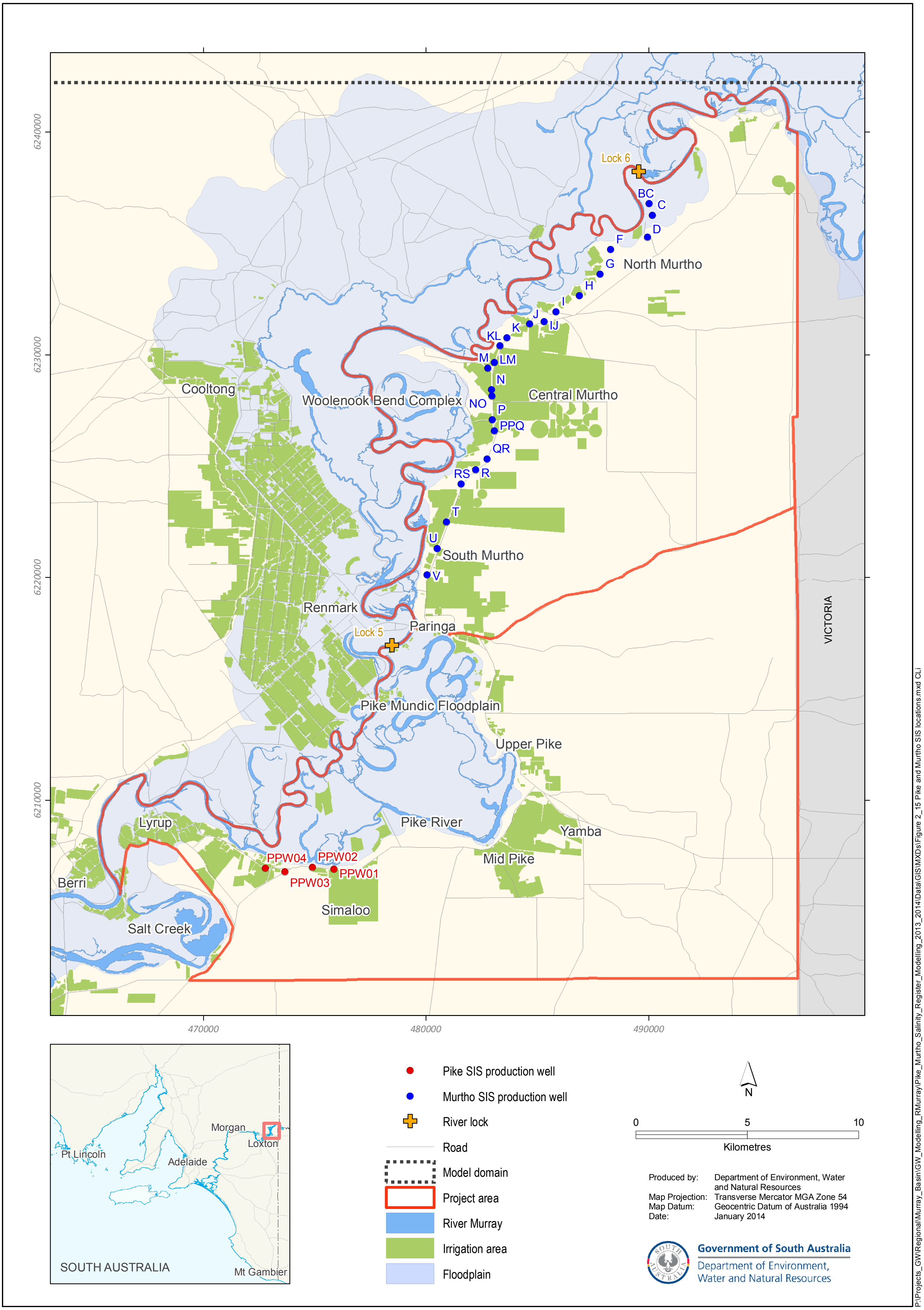


Figure 2.15. Pike and Murtho SIS locations

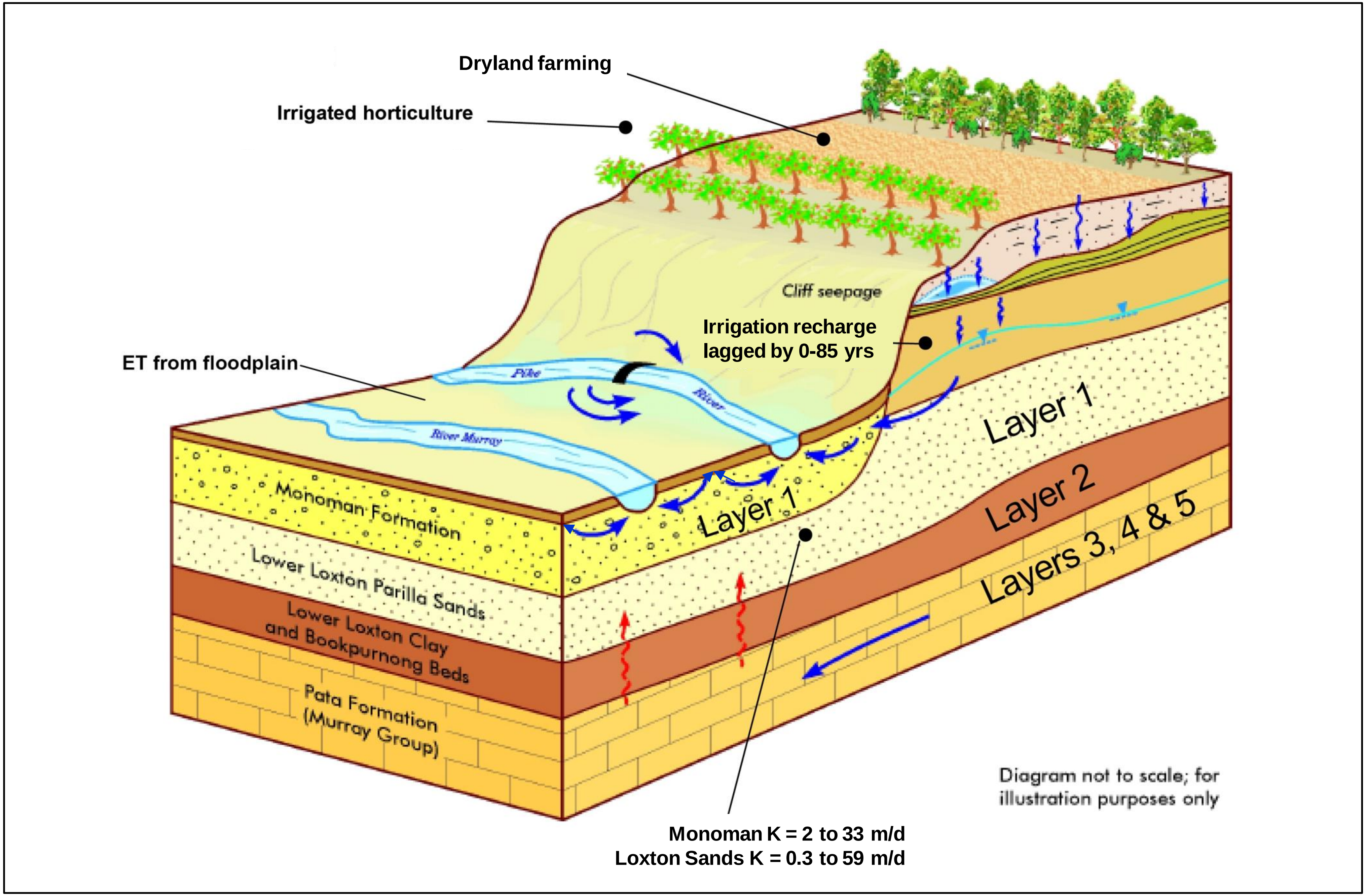


Figure 2.16. Hydrogeological conceptual model (after Yan et al. 2006)

2.8.2 PATHWAYS FOR SALT TO THE RIVER MURRAY

Under natural conditions before river regulation and irrigation, there would have been a small 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.

The natural conditions have been modified over time. Fluxes to and from the river were changed by irrigation developments, which began from the 1890s, changing local watertable levels and hence groundwater gradients and fluxes to and from the river. Locks and weirs were constructed on the River Murray in the 1920s and 1930s to regulate the flow, changing the river level. The recently constructed Pike and Murtho SIS will also alter the hydrogeological system.

Saline groundwater now enters the River Murray, including its tributaries and anabranches, by the following mechanisms in the Pike-Murtho area:

- discharge from the Monoman Formation that acts as a conduit for lateral flow from the Loxton Sands
- discharge from the Monoman Formation that acts as a conduit for upward leakage from the underlying confined Murray Group aquifer system
- direct inflow, or via seepage from exposed Loxton Sands at or near the base of cliffs adjacent to the River Murray
- discharge during and after periods of flood from the Monoman Formation, localised hypersaline lakes (salinas) and mobilised salt from the unsaturated zone.

Salt loads from groundwater also enter the River Murray via the following surface water features:

- the creek system in the Pike-Mundic Floodplain, especially the Pike River, can receive saline groundwater discharge and deliver the salt loads to the River Murray upstream of Lyrup
- the creek system in the Woolenook Bend Complex can receive saline groundwater discharge and transport the salt loads to the River Murray
- salt loads from the Chowilla Floodplain above Lock 6 can enter the River Murray below Lock 6 via the Chowilla Creek at river km 610–611 km.

3 MODEL CONSTRUCTION

3.1 SALINITY REGISTERS AND MODEL CONTEXT

The purpose of this model is to estimate groundwater salt loads entering the River Murray from the Pike-Murtho 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 Salinity Registers compare the relative impacts of anthropogenic accountable actions, not including climate change. Other processes, such as changes in river level due to flood or drought, may alter River Murray salinity, but these are not simulated for the Salinity Register. If those processes were included in the model, numerous simulations would be required to distinguish the contribution to river salinity from those of accountable actions. Hence the current models for SA Salinity Register employ simplifying assumptions which have been agreed with the MDBA. River levels and evapotranspiration rates are constant over time. Seasonal changes are not simulated. Floodplain processes are simulated relatively simply. Groundwater salinity values are selected such that the impact of river locks is included but that any subsequent changes to salinity due to irrigation and SIS are not. The models do not estimate future salinity impacts due to climate sequences, such as changes in river level due to flood events, or changes in irrigation due to drought.

The Border to Lock 3 model covers a large region that includes the Pike-Murtho study area. The model domain is designed to cover the SA Riverland area, including the major irrigation districts of Loxton, Bookpurnong, Pike, Murtho, Berri, Renmark, Pyap, New Residence, Moorook and Kingston.

The Border to Lock 3 model was first developed in 2005 (Yan et al., 2005b, Yan et al., 2004). Since then it has been used for a number of projects and revised each time in the region of project interest — at Loxton-Bookpurnong (Yan et al. 2005), Pike-Murtho (Yan et al. 2006), Berri-Renmark (Yan et al., 2007b, Aquaterra et al., 2006), Pyap-Kingston (Yan & Stadter 2008) and Loxton-Bookpurnong (Yan et al., 2011). Section 1.3 provides a detailed model history. It is an impact assessment model capable of simulating the regional aquifer system. The model and results for the Pike-Murtho project area were reviewed and accredited for Register use by the MDBC in 2006.

The revised model for the Pike-Murtho project area is based on the most recent prior revision of the Border to Lock 3 model, that of Loxton-Bookpurnong 2011 (Yan et al., 2011), but the hydrogeology of the Pike-Murtho project area has been refined. The principal revisions are listed in Section 1.4 and include an extended model domain to cover the entire Murtho LWMP area, updated structural contours, revised hydraulic parameters and boundary conditions and more detailed salinity zones. Further data were also collected for comparison with model results during calibration and confirmation (Section 4).

The figures presented in this Section show the full extent of the Border to Lock 3 model, its parameters and boundary conditions. However, the text concentrates on the Pike-Murtho study area. Detailed discussions of parameter and boundary condition choices in other areas are given in the prior model reports (Yan et al., 2007a, Yan and Stadter, 2008, Yan et al., 2011). The model upgrading, calibration and predictions were undertaken within the project area only, also referred to as the regional model "sub-zone". This "sub-zone by sub-zone" approach is appropriate in South Australia as there are minimal impacts from land use changes in neighbouring irrigation districts, due to the hydrogeological separation from the project area by hydraulic boundaries such as the River Valley, large floodplain, creek systems and groundwater dividing lines. The validity of this assumption for the Pike-Murtho project area is tested as part of the sensitivity and uncertainty analysis of Section 6.

3.2 MODFLOW AND VISUAL MODFLOW

MODFLOW-2000 (Harbaugh et al., 2000) was selected as the numerical code for the Border to Lock 3 model. It was chosen for reasons of reliability and consistency, as it is the industry standard groundwater flow code and the other SA Salinity Register models 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 the explicit simulation of 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 3.10). 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 simulating 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 0.01 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 2011.1 Pro (Schlumberger Water Services, 2011) was selected as a pre- and post-processor platform for quick generation of data files for MODFLOW. 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.

3.3 MODEL DOMAIN AND GRID

Previous versions of the Border to Lock 3 model, such as Yan et al. (2011), did not include a small area of the northern part of the Murtho LWMP area (upstream of Lock 6). The current model domain has been extended northward about (4km) to include the entire Murtho LWMP area. The whole model domain simulates an area 75 km east-west by 82 km north-south. The bounding GDA 1994 coordinates of the model domain are E425122 N6160180 in the south-west and E500122 N6242212 in the north-east (Figure 3.1 and Figure 3.2). The grid is orientated north-south. The domain spans the River from river kilometre 648.5 in Victoria to river kilometre 408 downstream of Lock3.

The Pike-Murtho project area is located on the eastern side of the River Murray, from the Border (river km 648.5) to Salt Creek. As the model was developed to simulate a number of adjacent Riverland regions for various projects, the model domain is much larger than the Pike-Murtho study area. The selection of a large model domain that incorporates the smaller study area is consistent with good modelling practice, as the model domain boundaries are set at a sufficient distance so that they should not be influenced by the behaviour of the aquifer system in the study area over the modelled time period. One drawback of the large model extent is that computing times are greater than those of a model simulating a smaller area with the same grid resolution. The large model extent also means that the model design must reflect the hydrogeology of a large region, rather than detailing local conditions: for example, different hydrogeological units are important in different model regions, which could affect layer choice.

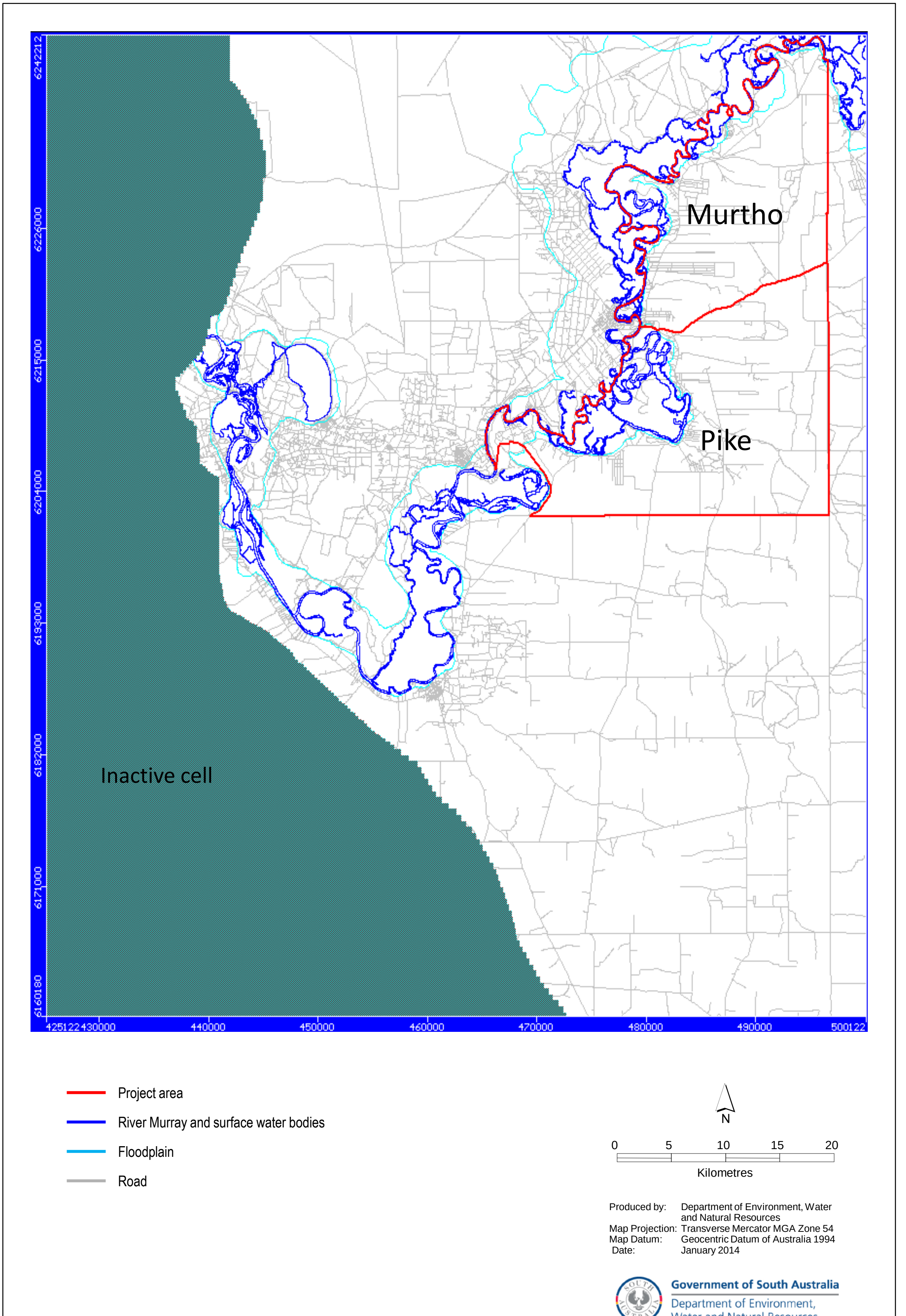


Figure 3.1 Regional model domain and project area

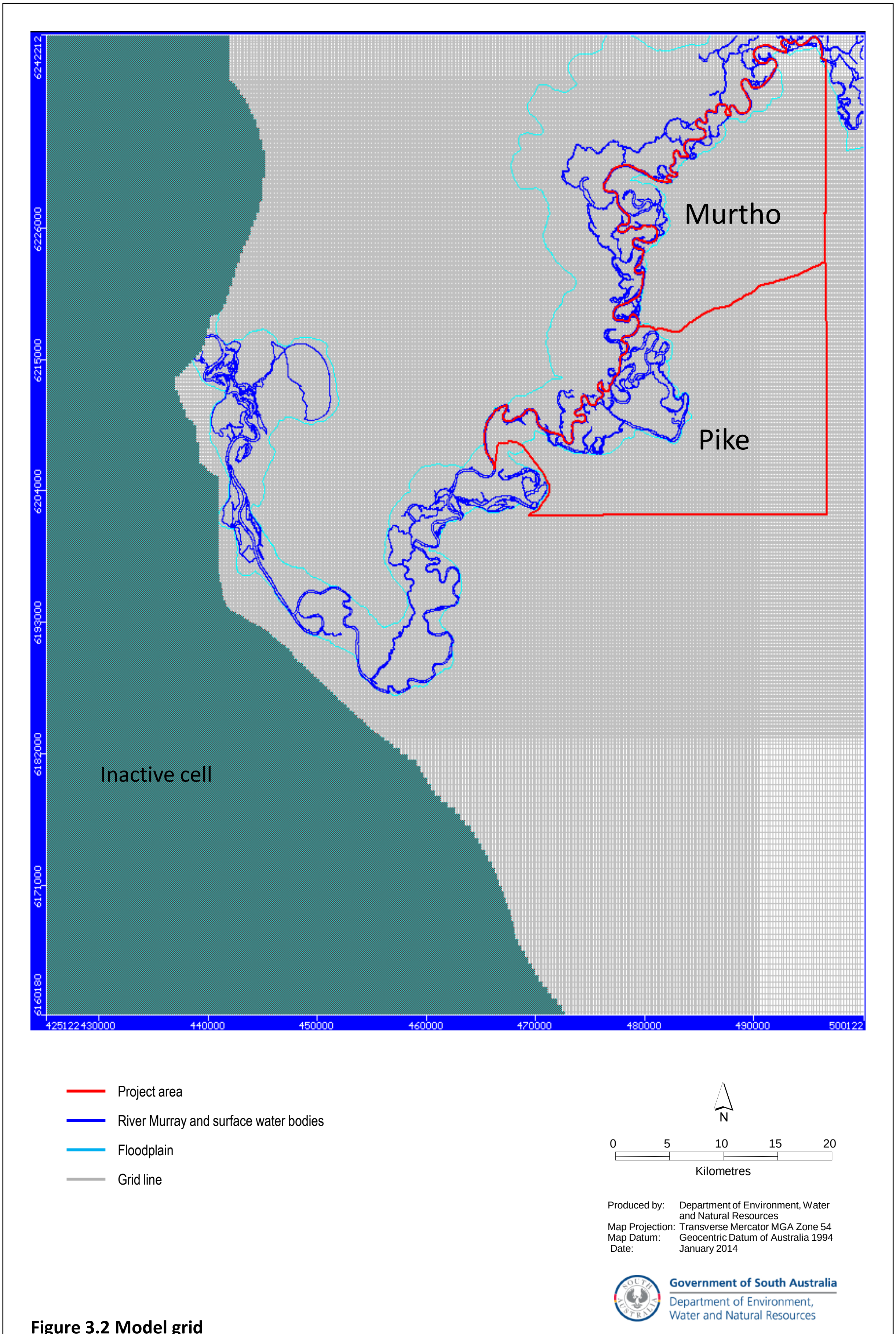


Figure 3.2 Model grid

The rectangular model grid is divided into 500 columns and 518 rows. Applied to five layers, this resulted in a total of 1 295 000 finite difference cells. The cell size is approximately 125 x 125 m in most of the Pike-Murtho area, including the SIS locations and major irrigation areas, and other irrigation districts (Berri-Renmark, Loxton-Bookpurnong and Pyap to Kingston). The remaining model area has a coarser grid size of up to 500 x 375 m.

An east-west cross-section of the model grid in Pike near Lock 5 is shown in Figure 3.3. The selection of model layers is discussed in Section 3.5.

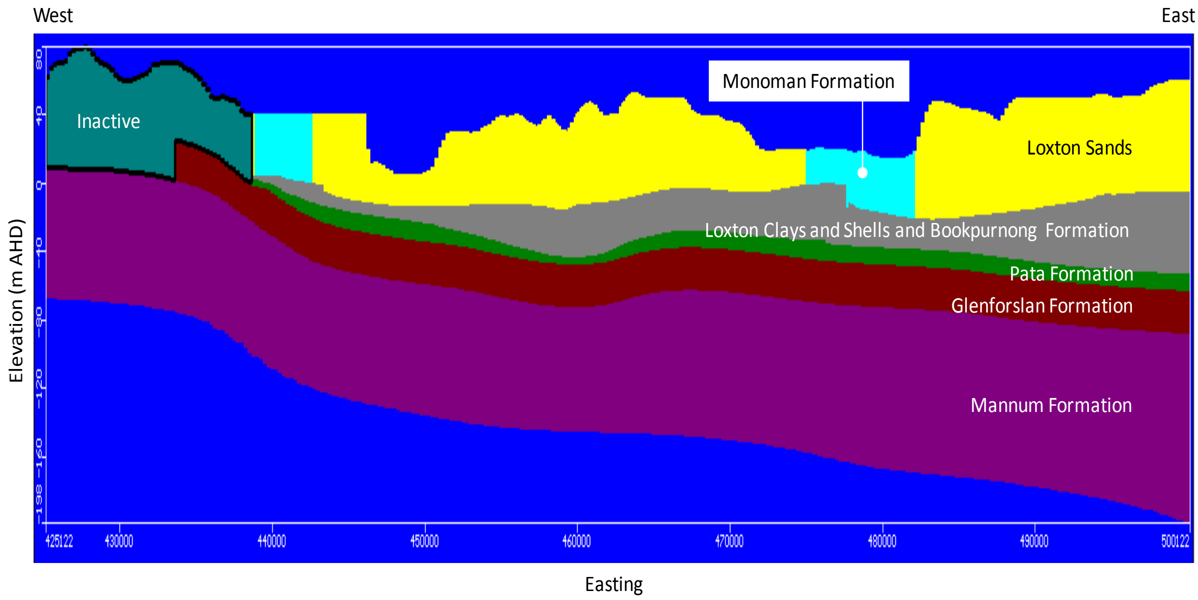


Figure 3.3 Model layers (east-west cross-section through model row 217, N6215000)

3.4 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 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 models are used to simulate the historical period and future predictions. The historical transient model simulates 1880 to 2014 with a total of 52 stress periods. The scenario simulations run from 1880 to 2114, with 152 stress periods (Appendix B). To reduce computational effort, the stress periods of the transient models are five years in length at the beginning of the simulation and reduced to two years between 1980 and 1988. From 1988 onwards, the stress periods are one year in length, as annual salt loads from 1988 to 2114 are required by the MDBA for the Salinity Register but simulation of seasonal changes is not desired. Each stress period of the transient models has 10 time steps and a time step multiplier of 1.2.

3.5 MODEL LAYERS IN THE PIKE-MURTHO AREAS

3.5.1 3.5.1 LAYER STRUCTURE

The Border to Lock 3 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
- intervening aquitards.

In the Border to Lock 3 model area, these units comprise the Monoman Formation aquifer, the Loxton Sands aquifer, the Loxton Clay and Shells and Bookpurnong Formation aquitard, the Pata Formation aquifer, the Winnambool Formation aquitard, the Glenforslan Formation aquifer, the Finniss Formation aquitard and the Mannum Formation aquifer.

The Border to Lock 3 model represents the key hydrogeological units within five layers (Figure 3.3). The layering chosen reflects the regional hydrogeology to the best of current knowledge based on interpreted data. The hydrostratigraphic units assigned to the model layers in the Pike-Murtho project area are given in Table 3.1.

Table 3.1 Model layer aquifers and aquitards

Layer	Hydrogeological unit	Aquifer/Aquitard	MODFLOW layer type
1	Loxton Sands regionally, Monoman Formation in the river valley	Aquifers	Unconfined (type 1)
2	Lower Loxton Clay and Shells, Bookpurnong Formation	Aquitards	Confined/Unconfined (type 3)
3	Pata Formation	Aquifer	Confined/Unconfined (type 3)
-	Winnambool Formation	Aquitard	Simulated as vertical leakage
4	Glenforslan Formation	Aquifer	Confined (type 0)
-	Finniss Formation	Aquitard	Simulated as vertical leakage
5	Mannum Formation	Aquifer	Confined (type 0)

Where possible, a hydrogeological unit is represented by a single model layer. Within the Pike-Murtho project area, the only exception is that the Murray Valley has cut through the Loxton Sands, so layer 1 represents the Loxton Sands aquifer regionally and the Monoman Formation aquifer within the valley.

The Woorinen Formation and the Blanchetown Clay are not included in the model. Perched aquifers can form in the Woorinen Formation above the Blanchetown Clay, reducing and delaying irrigation accession from reaching the watertable in the Loxton Sands. Although not explicitly simulated in the model, this impact is accounted for by controlling the time lag and recharge rate to the Loxton Sands during model calibration, based on the information provided by SIMRAT (Fuller et al., 2005) and Laroona Environmetrics (2014).

The Coonambidgal Formation occurs 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., 2005b). This approach ensures that the salinity impact is not underestimated and is also consistent with other Salinity Register models.

The combined aquitard of the lower Loxton Clay and Shells plus the Bookpurnong Formation is represented explicitly by a layer (Layer 2) in the model. Murray Group Limestone aquifers were simulated in three model layers. The aquitards within the Murray Group Limestone aquifer is simulated as vertical leakage between aquifers without an actual layer in the model, provided that storage in the aquitard is not important (McDonald and Harbaugh, 1988), for example, where the aquitard layers are relatively thin and fairly uniformly distributed. This approach reduces the number of model layers and the input data set requirements and speeds up the model calculation process. These aquitards have been merged into the underlying/overlying aquifers and the vertical hydraulic conductivity values of those aquifer layers modified to control the vertical leakage between the aquifers.

The Renmark Group aquifer is not simulated. The impact of the Renmark Group is communicated to the River Murray via the three overlying aquifers of the Murray Group and the watertable aquifer of the Loxton Sands and Monoman Formation. Accurate simulation of the four aquifers overlying the Renmark Group should be sufficient for the timescales simulated.

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

The layer elevations for the base of the Loxton Sands and Monoman Formation have been revised from those of Yan et al. (2011) within the Pike-Murtho project area. The revised elevations are based on new data provided in the Pike and Murtho data atlases (AWE, 2012a, AWE, 2012b). Data were obtained and interpreted from geological and geophysical logs for the project area. Structure contours were hand drawn to reflect both the data and other structural information, such as the edge of the Murray Valley. Both the well data and structure contours were used to interpolate values. In some areas where there were minimal data, the initial interpolations had to be adjusted, for example, if they led to negative thickness in areas where the unit was known to exist.

The new interpolated values within the Pike-Murtho project area were inset within the larger model domain and boundaries between the two data sets were smoothed across the overlap to form a merged whole. Areas outside the project area retain the same elevations as in the previous version of the model (Yan et al., 2011).

As discussed earlier, the model domain has been extended northwards to cover the entire Murtho LWMP area. In the extended area, the top of Loxton Sands and Monoman Formation is based on the same DEM data as the remaining area, while the base is derived from the AWE atlases (AWE, 2012a, AWE, 2012b). Elevations for the other layers are simply extended northwards from the edge of the original domain, due to lack of data and the expectation that their impact on the model results should be small.

3.5.2 LAYER 1: LOXTON SANDS AND MONOMAN FORMATION AQUIFERS

Layer 1 represents the Loxton Sands unconfined/semi-unconfined aquifer on the highland and the Monoman Formation semi-unconfined/semi-confined aquifer in the floodplain.

Ground elevation from the former Department of Environment and Natural Resources (DENR; now part of DEWNR) is adopted as the top of layer 1. This is reasonable wherever the Loxton Sands and Monoman Formation aquifers are unconfined and is a simplification elsewhere. The Loxton Sands aquifer represented within Layer 1 is 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. Again, this is a conservative approach in that it ensures the salinity impact is not underestimated. The simulation of these units would have no material impact on the result due to the Monoman and Coonambidgal aquifer thickness is so small.

The top of layer 1 is shown in Figure 3.4 and ranges between 17 to 92 m AHD on the highland and generally 15 to 20 m AHD in the floodplain within the project area. The base of layer 1 is the top of the Loxton Clay and Shells and Bookpurnong Formation aquitard. Its thickness ranges between 10 m and 100 m in the project area.

3.5.3 LAYER 2: LOWER LOXTON CLAY AND SHELLS AND BOOKPURNONG FORMATION AQUITARDS

Layer 2 represents the Lower Loxton Clay and Shells and Bookpurnong Formation aquitards in the project. The top of layer 2 occurs between -25 to 6 m AHD in the project area (Figure 3.5). The top of layer 2 was revised in the Pike-Murtho project area based on data from the Pike and Murtho data atlases (AWE, 2012a, AWE, 2012b). The base of layer 2 is the top of the Pata Formation. Layer 2 has a thickness of 11 to 47 m in the project area.

3.5.4 LAYER 3: PATA FORMATION AQUIFER

Layer 3 represents the regionally-distributed Upper Murray Group Limestone aquifer (e.g. Pata Formation in Loxton area), which is modelled as a semi-confined low permeability aquifer. The top of layer 3 in the Pike-Murtho area was revised based on data from the Pike and Murtho data atlases (AWE, 2012a, AWE, 2012b). The top of layer 3 occurs between -53 and -14 m AHD in the project area (Figure 3.6). The base elevation of layer 3 is the top of the Layer 4 which are unchanged from the previous version of the Border to Lock 3 model (Yan et al., 2011). Layer 3 is 7 to 11 m thick in the project area.

3.5.5 WINNAMBOOL FORMATION AQUITARD

The Winnambool Formation vertical hydraulic conductivity was applied to the Pata Formation (layer 3) and the Glenforslan Formation (layer 4) to allow calculation of the leakage between these aquifers. The modelling method simulates the effect of the Winnambool Formation at a lower computational cost than required for explicit simulation.

3.5.6 LAYER 4: GLENFORSLAN FORMATION AQUIFER

Layer 4 represents the regionally-distributed part of Murray Group Limestone (e.g. Glenforslan Formation in Loxton area), which is a semi-confined, low permeability aquifer. The top elevation of layer 4 was interpreted from geological and geophysical logs and extrapolation of these values and by examination of the cross-section given in REM-Aquaterra (2005b). The (top of layer 4) occurs between -62 to -24 m AHD in the project area (Figure 3.7). The layer is assumed to be 25 m thick, unchanged from the previous version of the Border to Lock 3 model (Yan et al., 2011).

3.5.7 FINNISS FORMATION AQUITARD

The Finniss Formation vertical hydraulic conductivity was applied to the Glenforslan Formation (layer 4) and is combined with the specified vertical hydraulic conductivity of the Mannum Formation (layer 5) to allow calculation of vertical leakage between these aquifers. This modelling method simulates the effect of mainly vertical flow through the Finniss Formation.

3.5.8 LAYER 5: MANNUM FORMATION AQUIFER

Layer 5 represents the regionally-distributed Mannum Formation, which is a confined, moderate permeability aquifer. The top elevation of layer 5 occurs between -87 to -49 m AHD in the project area (Figure 3.8). Layer 5 has a thickness of 79 to 107 m and a base elevation of -138 to -191 m AHD in the project area, unchanged from the previous version of the Border to Lock 3 model (Yan et al., 2011) (Figure 3.9).

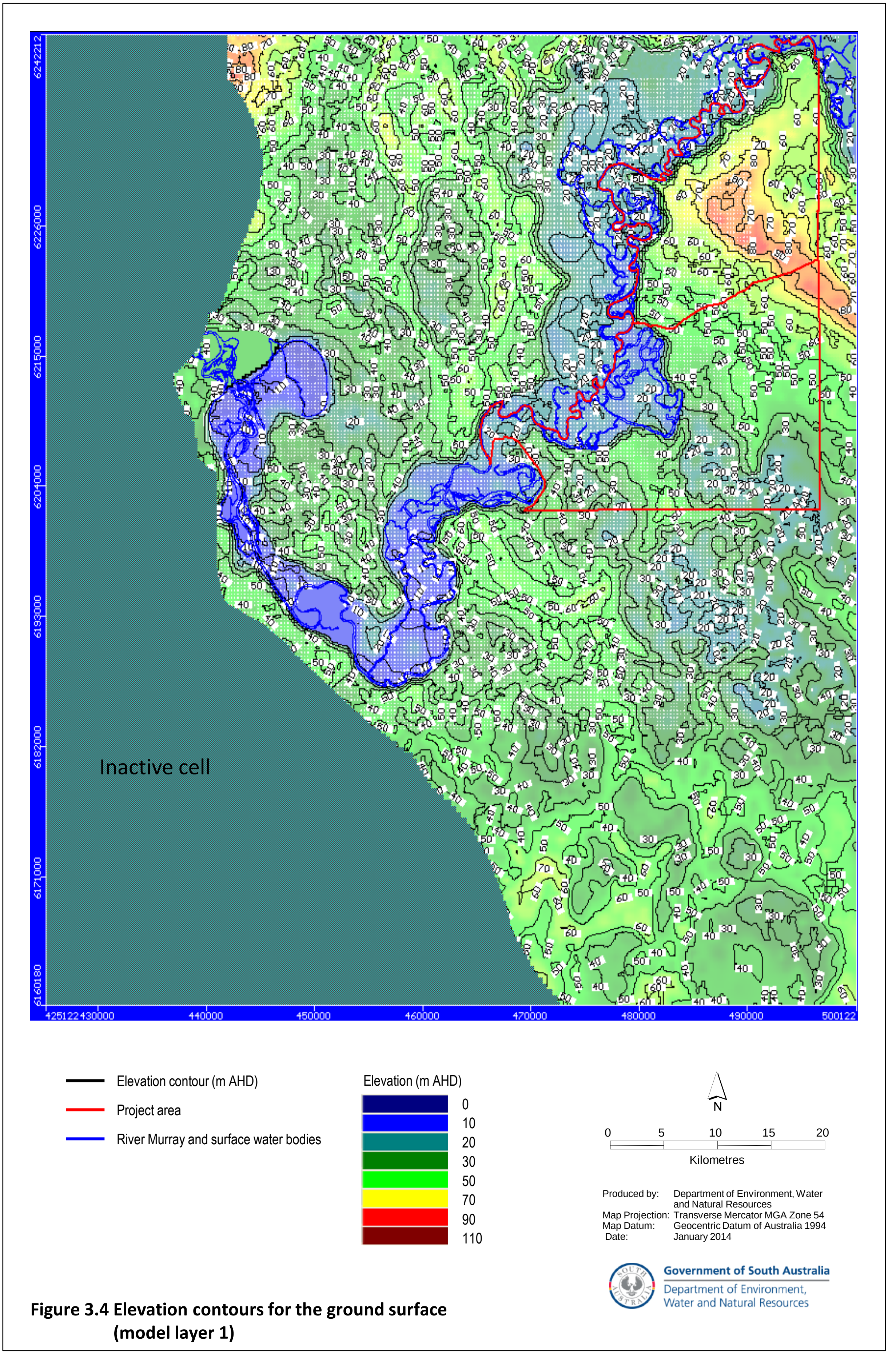
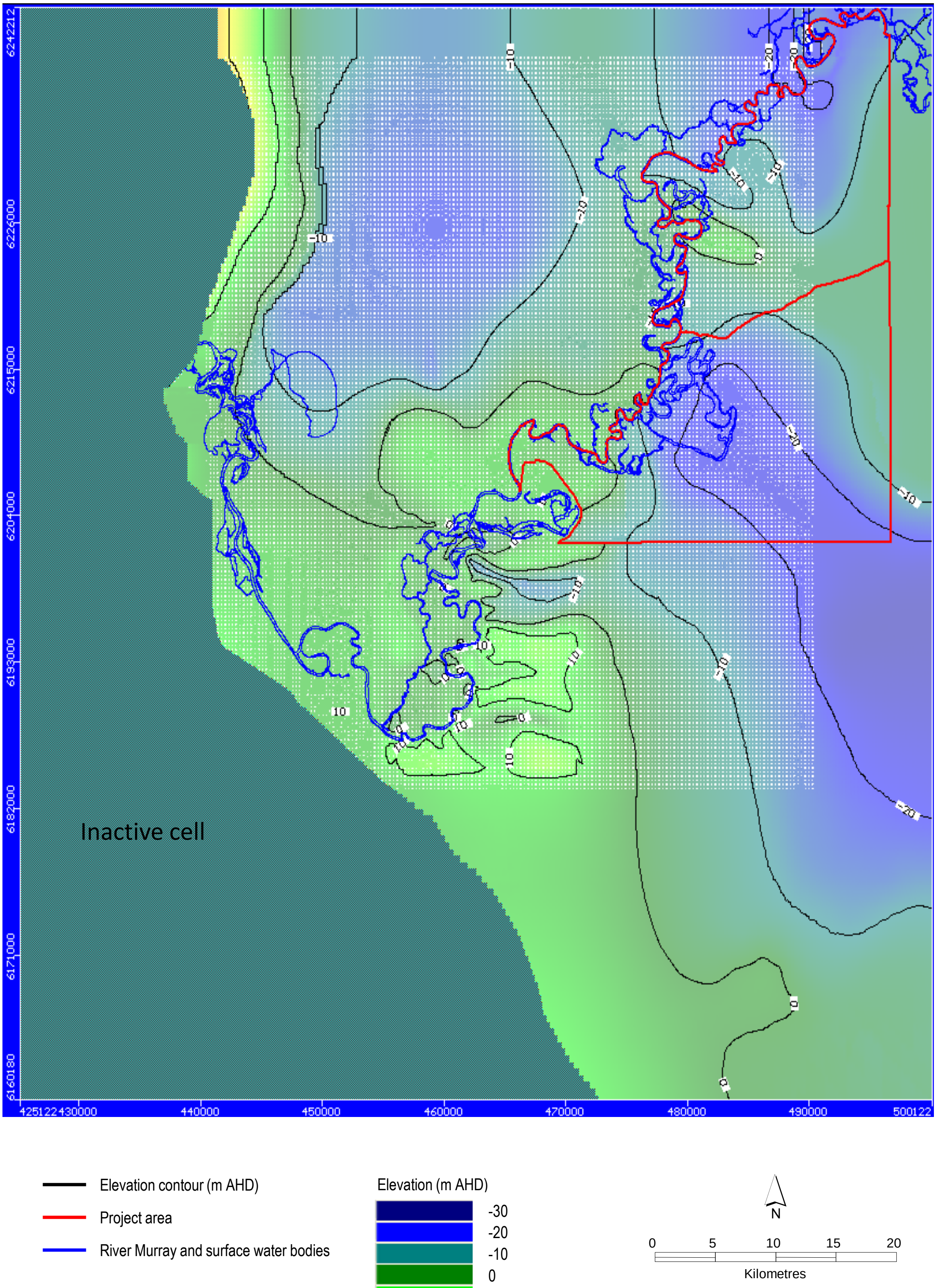


Figure 3.4 Elevation contours for the ground surface (model layer 1)



Produced by: Department of Environment, Water and Natural Resources
Map Projection: Transverse Mercator MGA Zone 54
Map Datum: Geocentric Datum of Australia 1994
Date: January 2014

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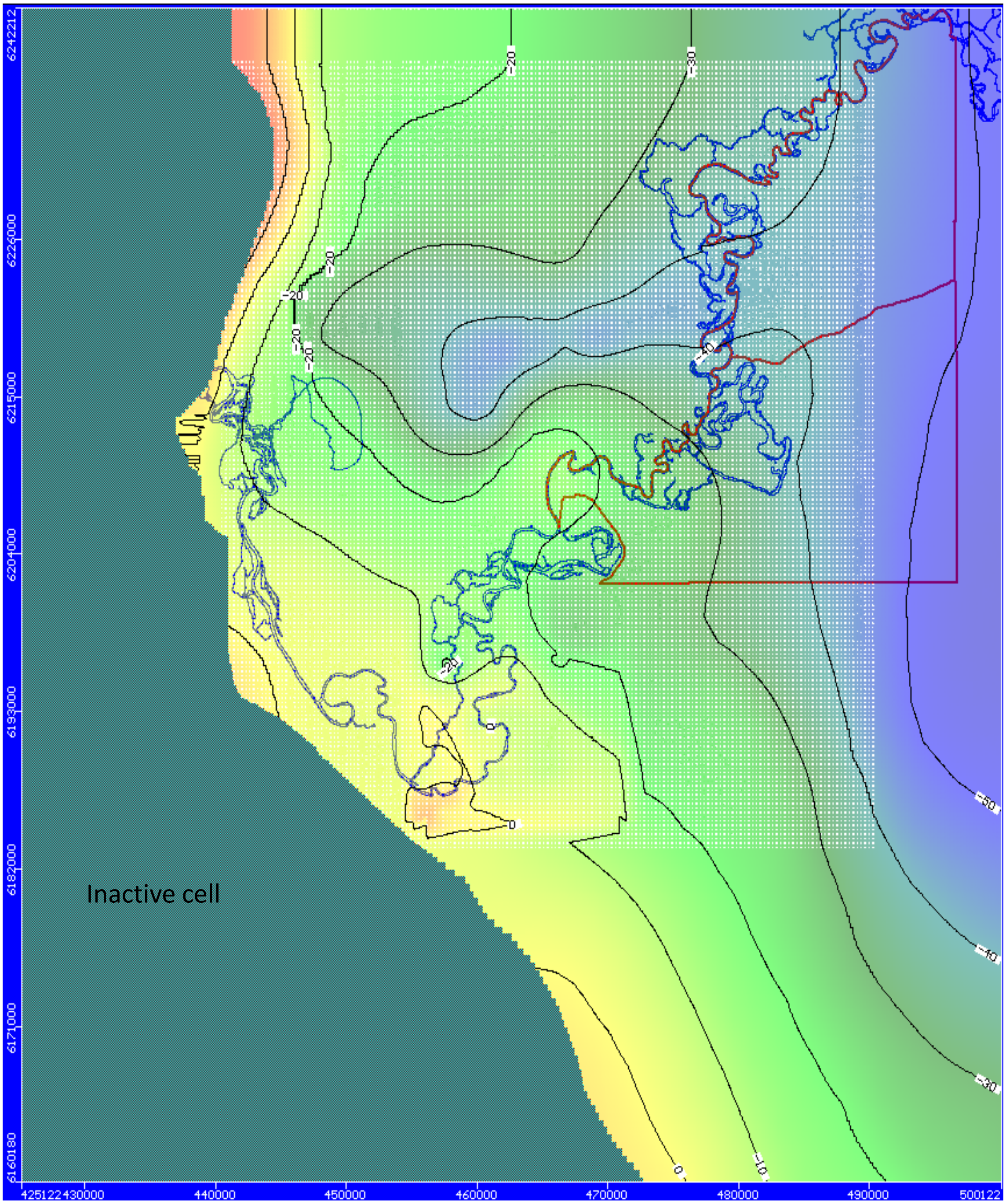
Figure 3.5 Elevation contours for the top of Loxton Clay and Shells and Bookpurnong Formation (model layer 2)



Elevation contour (m AHD)
Project area
River Murray and surface water bodies

Elevation (m AHD)

	-60
	-50
	-40
	-30
	-20
	0
	20
	40

N

0 5 10 15 20

Kilometres

Produced by: Department of Environment, Water and Natural Resources
Map Projection: Transverse Mercator MGA Zone 54
Map Datum: Geocentric Datum of Australia 1994
Date: January 2014

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Figure 3.6 Elevation contours for the top of Pata Formation (model layer 3)

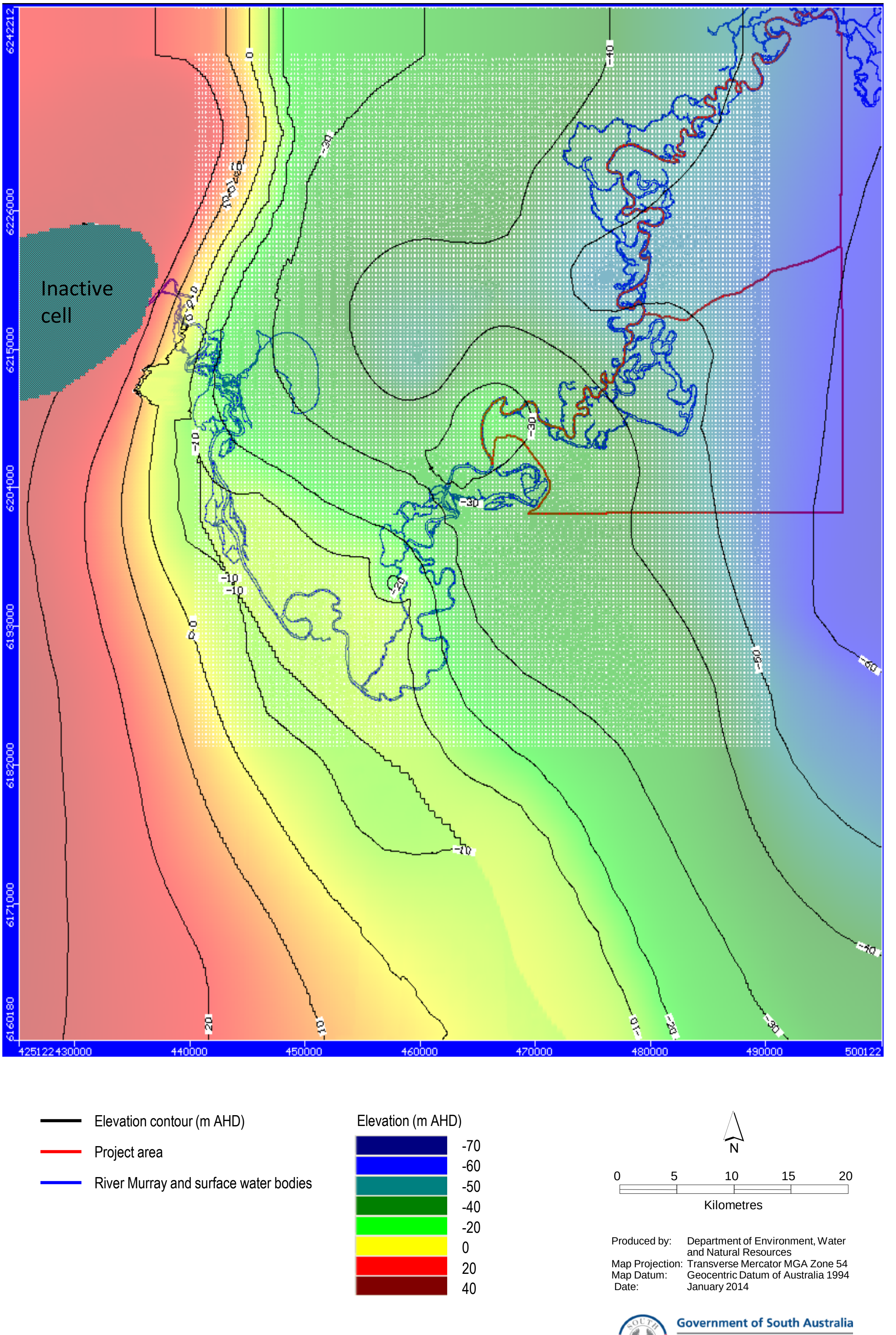

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Figure 3.7 Elevation contours for the top of Glenforslan Formation (model layer 4)

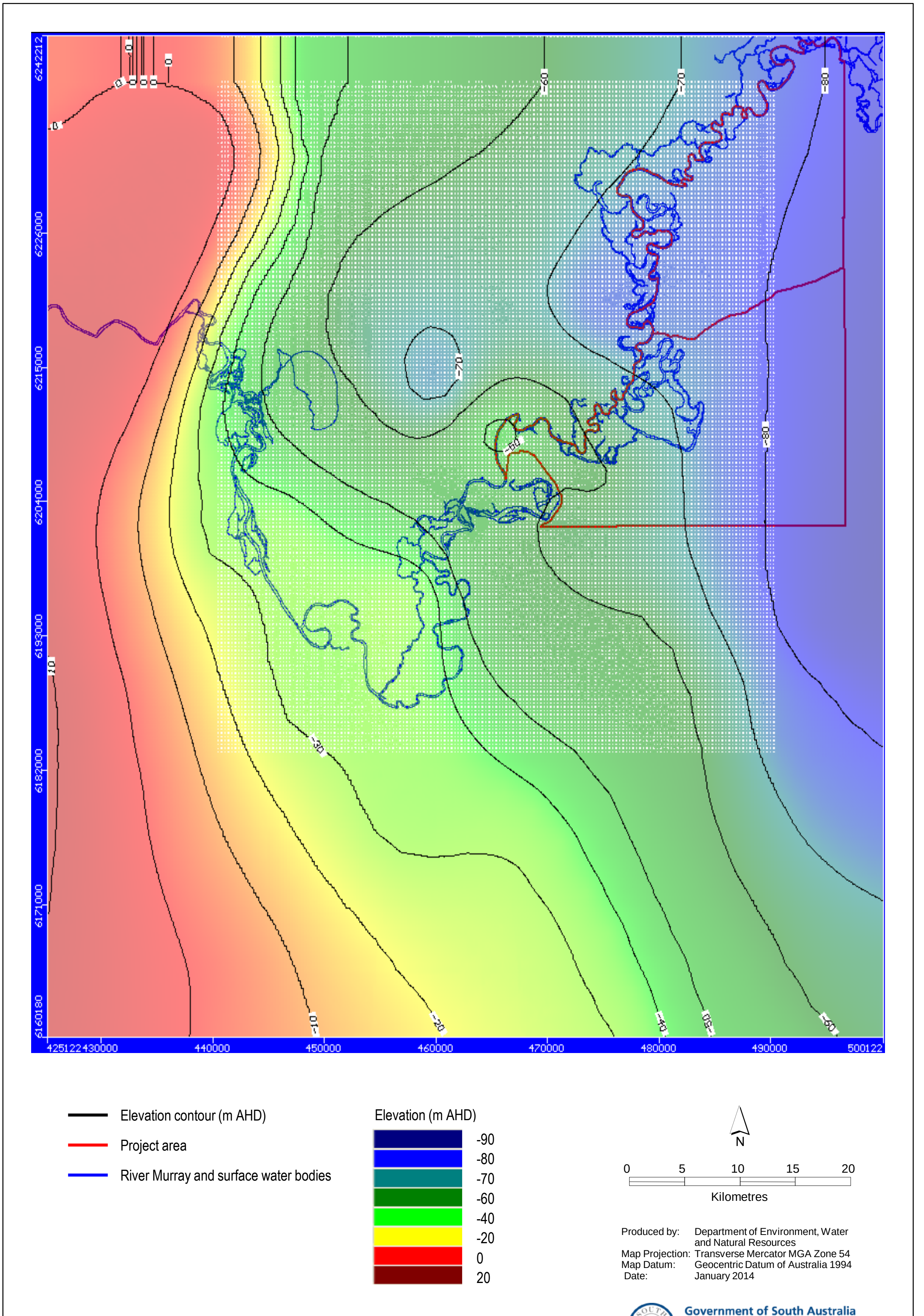

Figure 3.8 Elevation contours for the top of Mannum Formation (model layer 5)

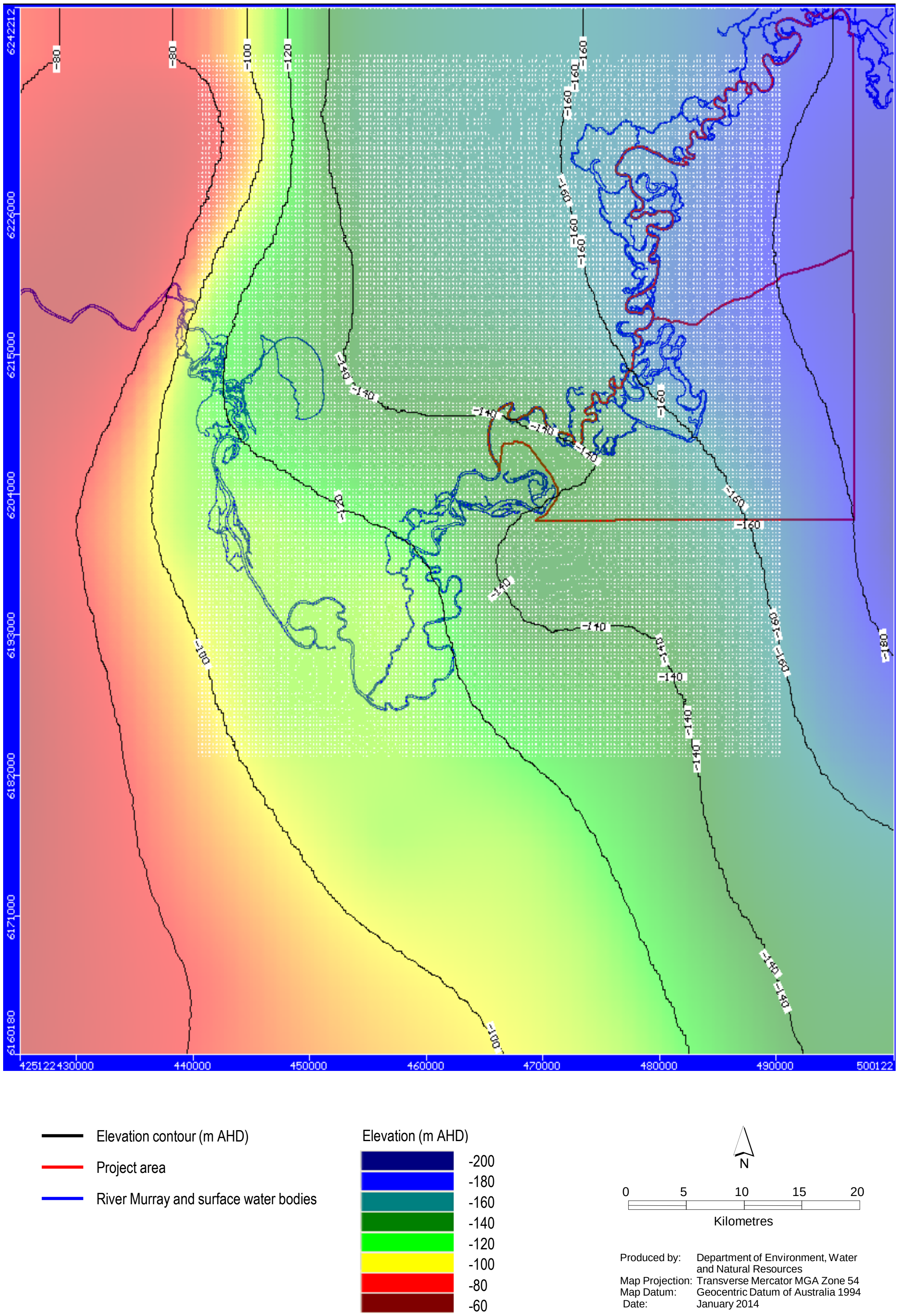

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Figure 3.9 Elevation contours for the base of Mannum Formation (model layer 5)

3.6 MODEL HYDRAULIC PARAMETERS

In order to constrain the model calibration, a physically realistic range of aquifer and aquitard hydraulic parameters for the Pike-Murtho project area were derived from previous reports and new data (Table 2.2). Hydraulic parameter zones and values from Yan et al. (2011) were modified based on previous studies and the Pike and Murtho data atlases (AWE, 2012a, AWE, 2012b). For example, the extent of the near-river hydraulic conductivity zones in the Loxton Sands aquifer are based on aquifer tests and on cross-sections showing variations in texture. These initial zones and values were varied in the project area during calibration (see Section 4 for further details).

The parameters adopted for layers 3, 4 and 5 are unchanged from the previous version of the Border to Lock 3 model (Yan et al., 2011) as there is no new aquifer test information and the calibration was insensitive to their aquifer and aquitard parameters.

Due to the representation of the Monoman Formation in the model as an unconfined aquifer, confined storage coefficient values determined from pumping tests are not applicable.

The adopted parameters are generally within the measured ranges given in Table 2.2. The horizontal hydraulic conductivity for the Pata and Mannum Formations and the vertical hydraulic conductivity for the Loxton Lower Clay and Shells and Bookpurnong Formation are slightly outside the observed range in Table 2.2 but are reasonable values given the heterogeneity of the sediments and the limited data available. Aquifer tests in neighbouring areas support the values chosen for the model: the horizontal hydraulic conductivity of the Pata Formation has been estimated as 0.1 to 0.7 m/d in the adjacent Loxton-Bookpurnong area (AWE, 2011) while the horizontal hydraulic conductivity of the Mannum Formation is 0.5 to 5 m/d in Woolpunda area (Woods et al., 2013).

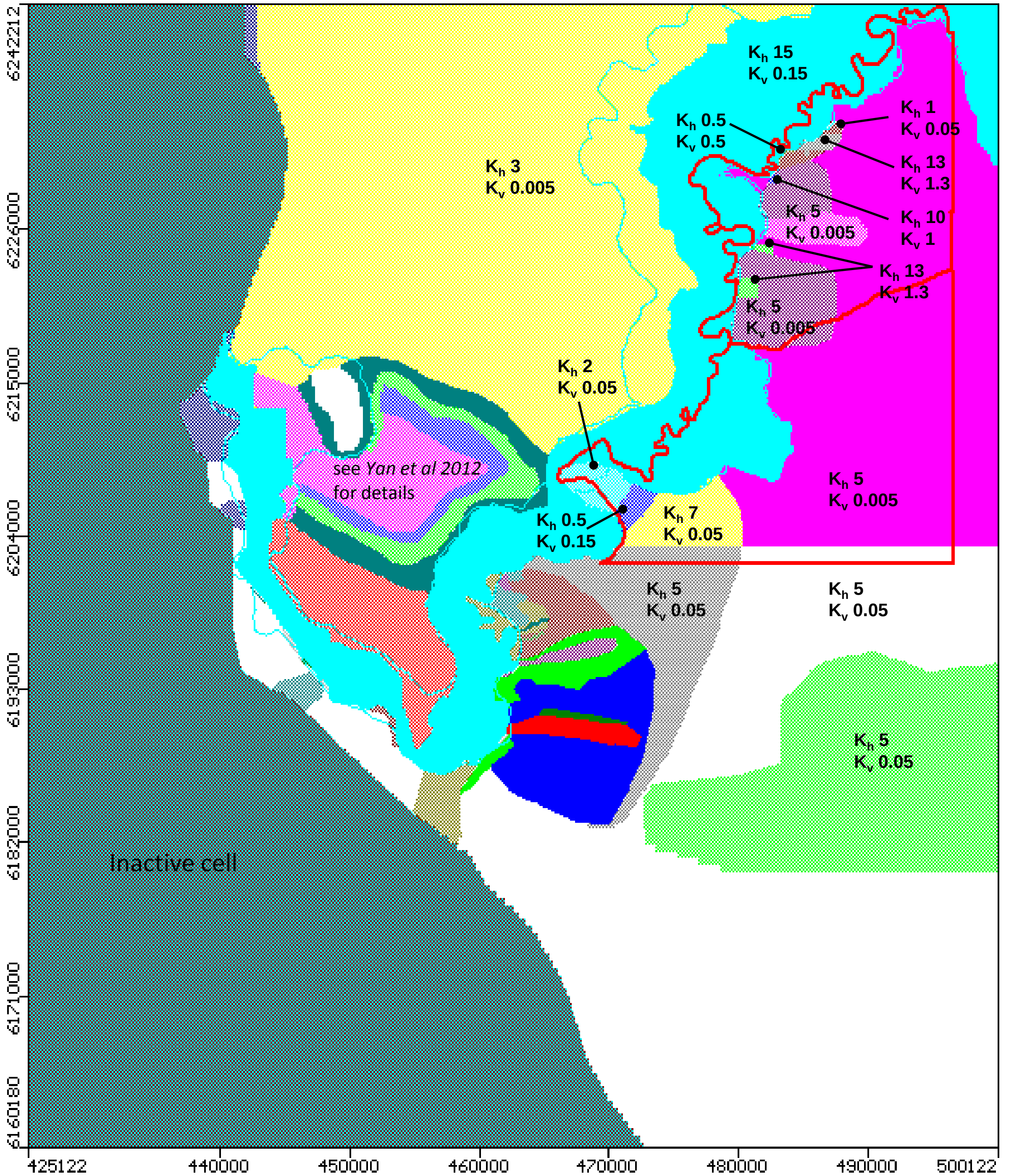
The aquitard within the Murray Group Limestone is modelled as vertical leakance rather than as a layer. The effective vertical hydraulic conductivity of the vertical hydraulic conductivity adopted for layers 3 and 4, i.e. $1x10^{-5}$ to $2x10^{-4}$ m/d. Similarly, the effective vertical hydraulic conductivity for layers 4 and 5 is $5x10^{-6}$ to $2x10^{-4}$ m/d in the study area.

The adopted aquifer and aquitard hydraulic parameters for the Pike-Murtho project area are given in Table 3.1.

Figure 3.10 to Figure 3.14 show the spatial distribution of the parameters through the entire extent of the Border to Lock 3 model.

Table 3.1 Adopted aquifer and aquitard hydraulic parameters in the Pike-Murtho project area

Hydrogeological unit	Model layer	Hydraulic conductivity		Storage	
		Kh (m/d)	Kv (m/d)	Ss (-/m)	Sy (-)
Monoman Formation	1	15	0.15	0.0001	0.15
Loxton Sands	1	0.5 - 13	0.005 - 1.3	0.0001 - 0.0005	0.1 - 0.15
Lower Loxton Clay and Shells/Bookpurnong Formation	2	0.006	1×10^{-5} - 0.002	0.0001	0.15
Pata Formation	3	0.5	1×10^{-5} - 0.0002	0.0001	0.15
Glenforslan Formation	4	1.5 - 2	0.0002 - 0.0005	0.0001	0.15
Mannum Formation	5	0.5 - 2	5×10^{-6} - 0.001	5×10^{-5}	0.15



Kh Horizontal hydraulic conductivity (m/d)

Kh Vertical hydraulic conductivity (m/d)

Project area

Floodplain

N

0 5 10 15 20

Kilometres

Produced by: Department of Environment, Water and Natural Resources

Map Projection: Transverse Mercator MGA Zone 54

Map Datum: Geocentric Datum of Australia 1994

Date: January 2014

Government of South Australia

Department of Environment, Water and Natural Resources

Figure 3.10 Model hydraulic parameters for layer 1 Loxton Sands and Monoman Formation

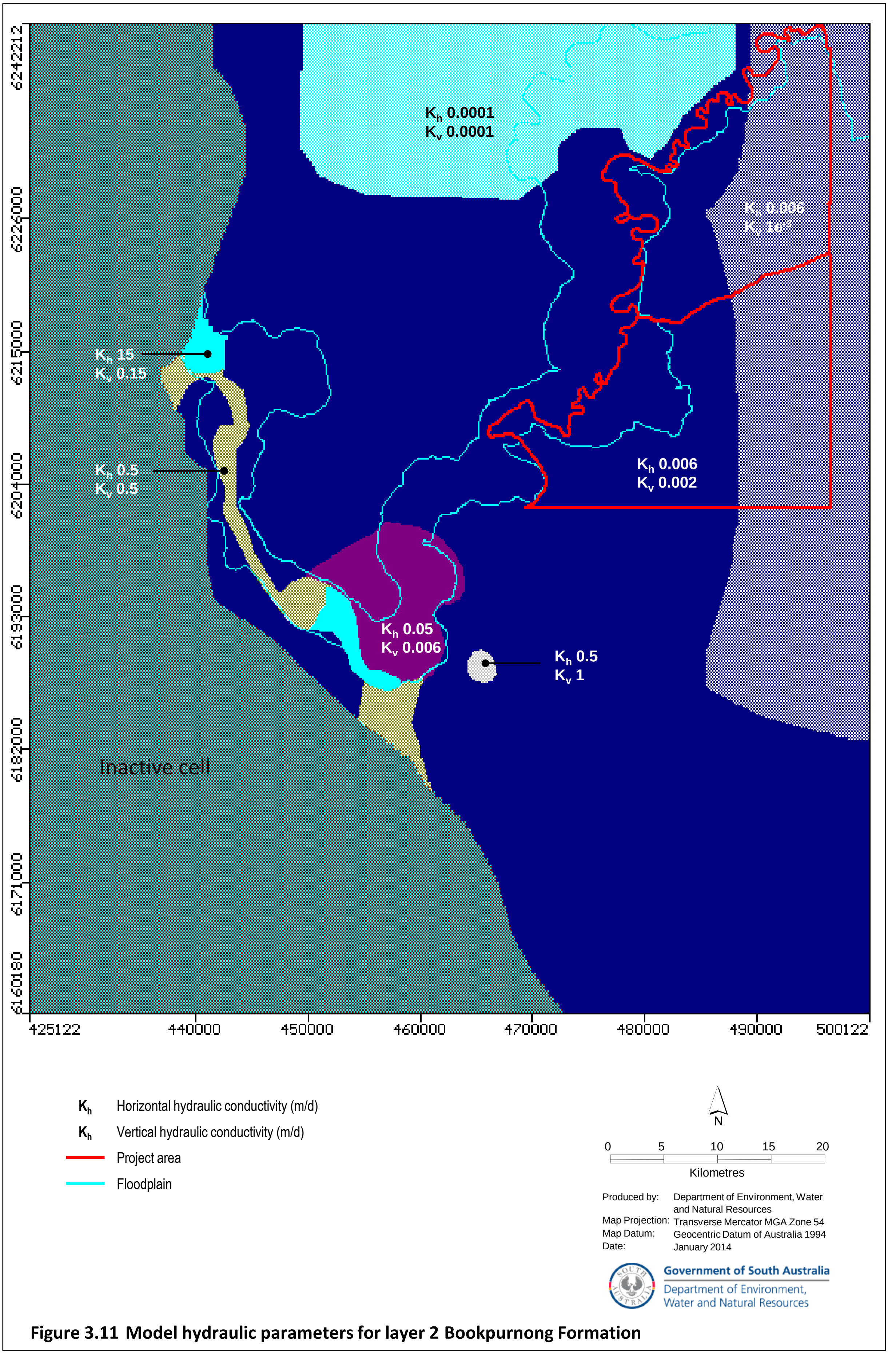


Figure 3.11 Model hydraulic parameters for layer 2 Bookpurnong Formation

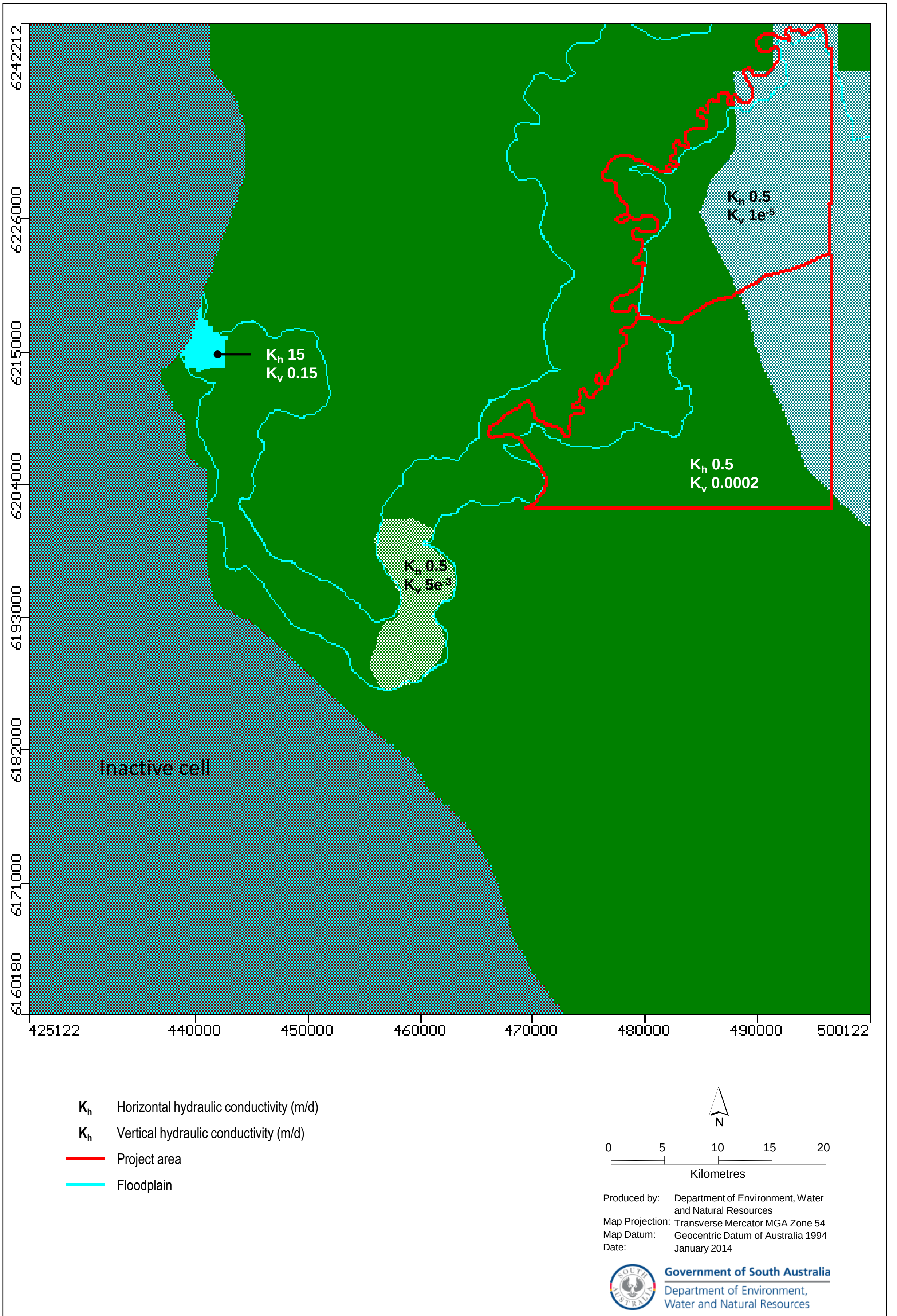


Figure 3.12 Model hydraulic parameters for layer 3 Pata Formation

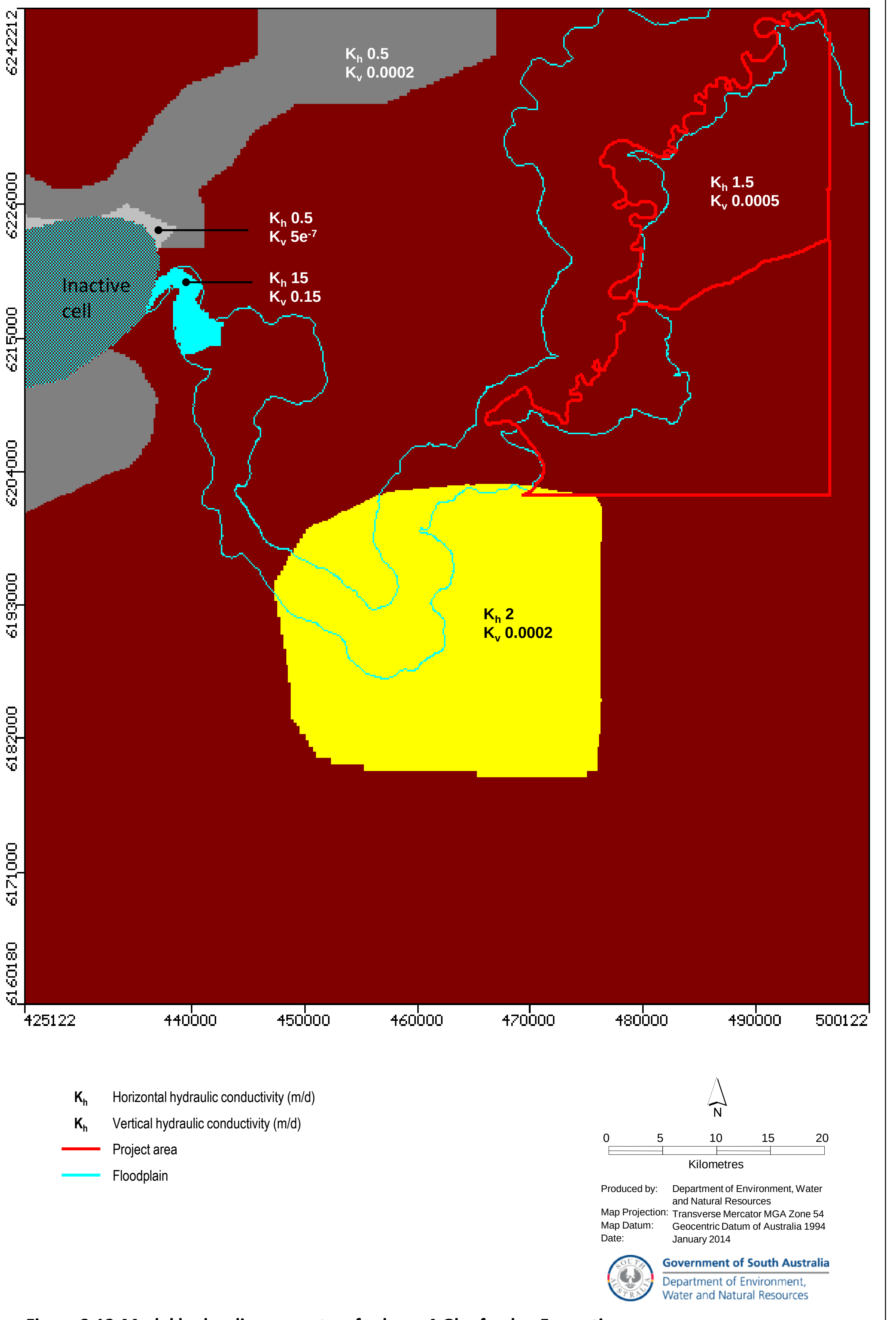


Figure 3.13 Model hydraulic parameters for layer 4 Glenforslan Formation

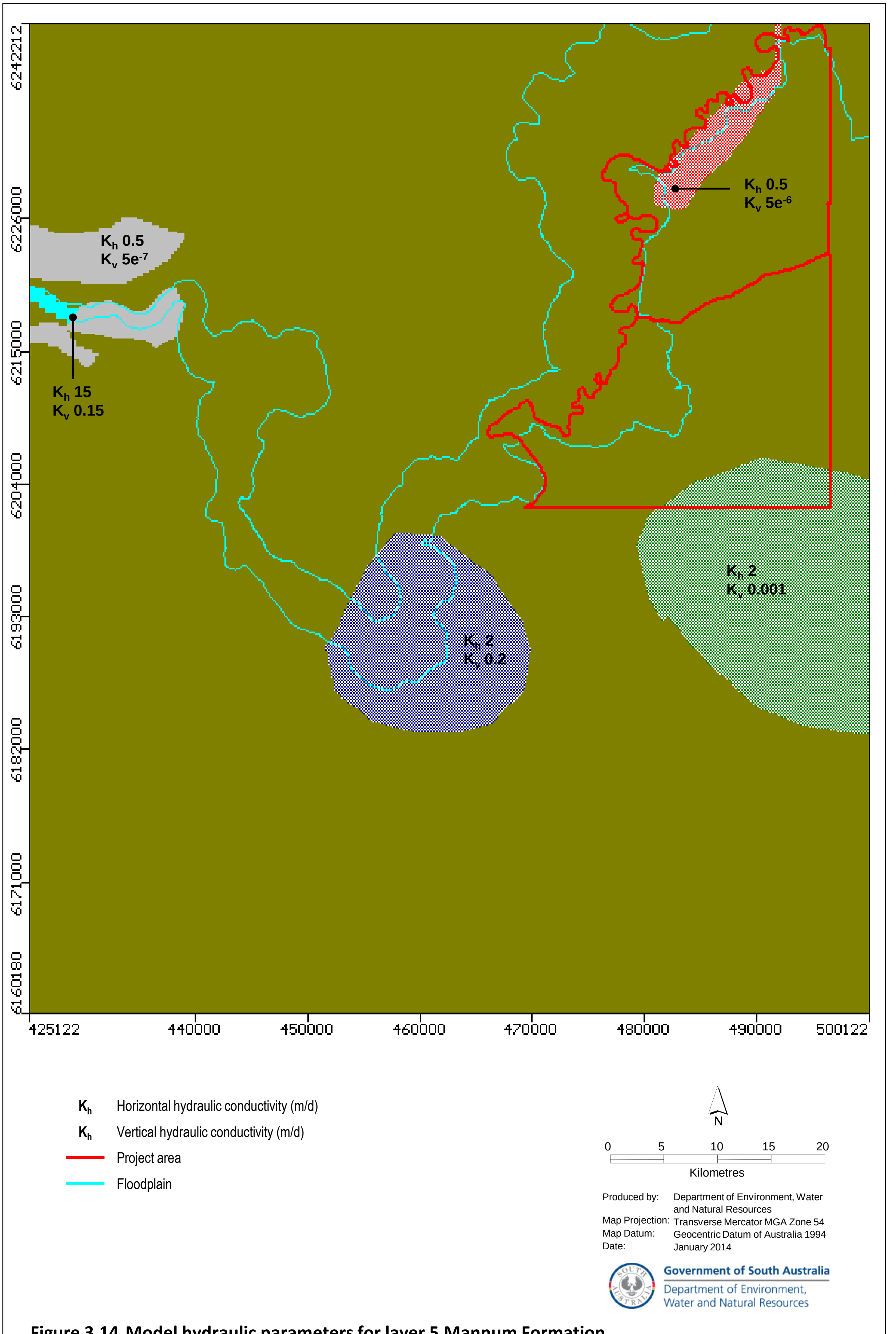


Figure 3.14 Model hydraulic parameters for layer 5 Mannum Formation

3.7 MODEL BOUNDARIES

This section describes the numerical model's representation of all boundary conditions in the Pike-Murtho project area except aquifer recharge, which is described separately in Section 3.8. This section includes:

- regional flow in and out of the model domain
- surface water features including the River Murray
- cliff seepage
- drainage schemes and wells
- the Salt Interception Schemes Operation
- groundwater evapotranspiration

The model boundary conditions are summarised for each layer in Figure 3.15 to Figure 3.19. Areas that are expected to be dry for all scenarios are represented as inactive cells.

3.7.1 REGIONAL FLOW

The regional groundwater flow in the Pike-Murtho area is generally from east to west. This is simulated using general head boundary (head-dependent flow) cells along the edges of the model domain within the layers representing aquifers. The assigned head values for the general head boundary are based on observed heads, e.g. from Barnett (1991). The potentiometric surface from Yan et al. (2005a) is also used to assign head values for the general head boundary for the Murray Group Limestone aquifer in the Chowilla area.

Little data is available to distinguish changes in potentiometric head with depth within the aquifer units of the Murray Group, so at a specified location, the same potentiometric head at the boundariey is assigned to layers 3, 4 and 5.

The conductance for GHB was varied during calibration until a good match to the observed heads was achieved regionally. The conductance is 100 m^2/d, except as follows (Figure 3.15 to Figure 3.19):

- along the southern boundary in layers 1,3,4 and 5, the 24 to 26 m AHD boundary has a conductance of 20 m^2/d
- along the northern boundary in layer 3, the 22 m AHD boundary and the 20 m AHD boundary have a conductance of 50 to 100 m^2/d
- along the northern boundary in layers 4 and 5, the 18 to 22 m AHD boundary has a conductance of 10 to 100 m^2/d
- along the inactive cell boundary to the west in layers 2 and 3, where the conductance of the 10.7 m AHD boundary is 1000 m^2/d.

Where the groundwater flow is parallel to the model edge, a no-flow boundary is assigned.

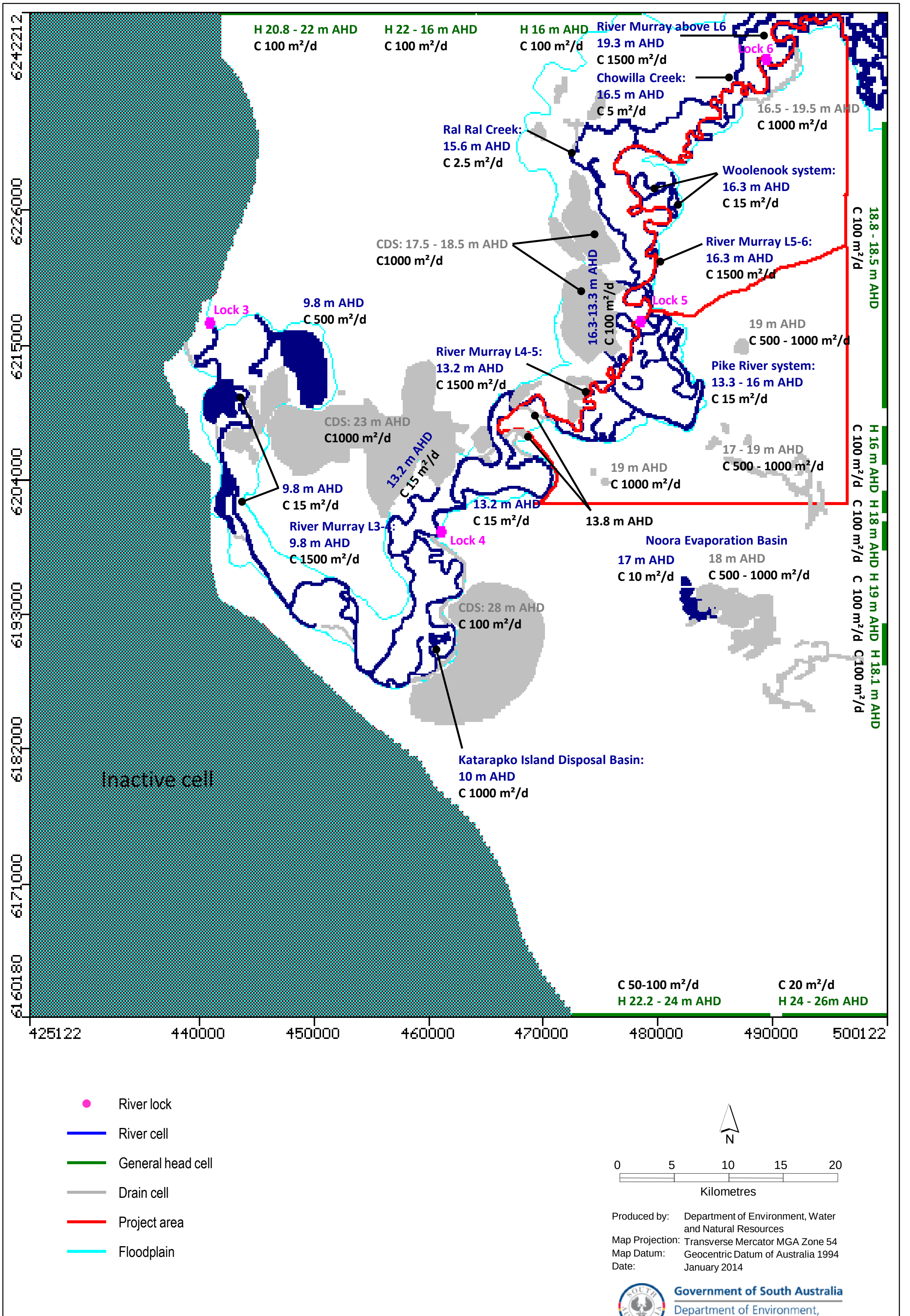


Figure 3.15 Model boundary conditions for layer 1

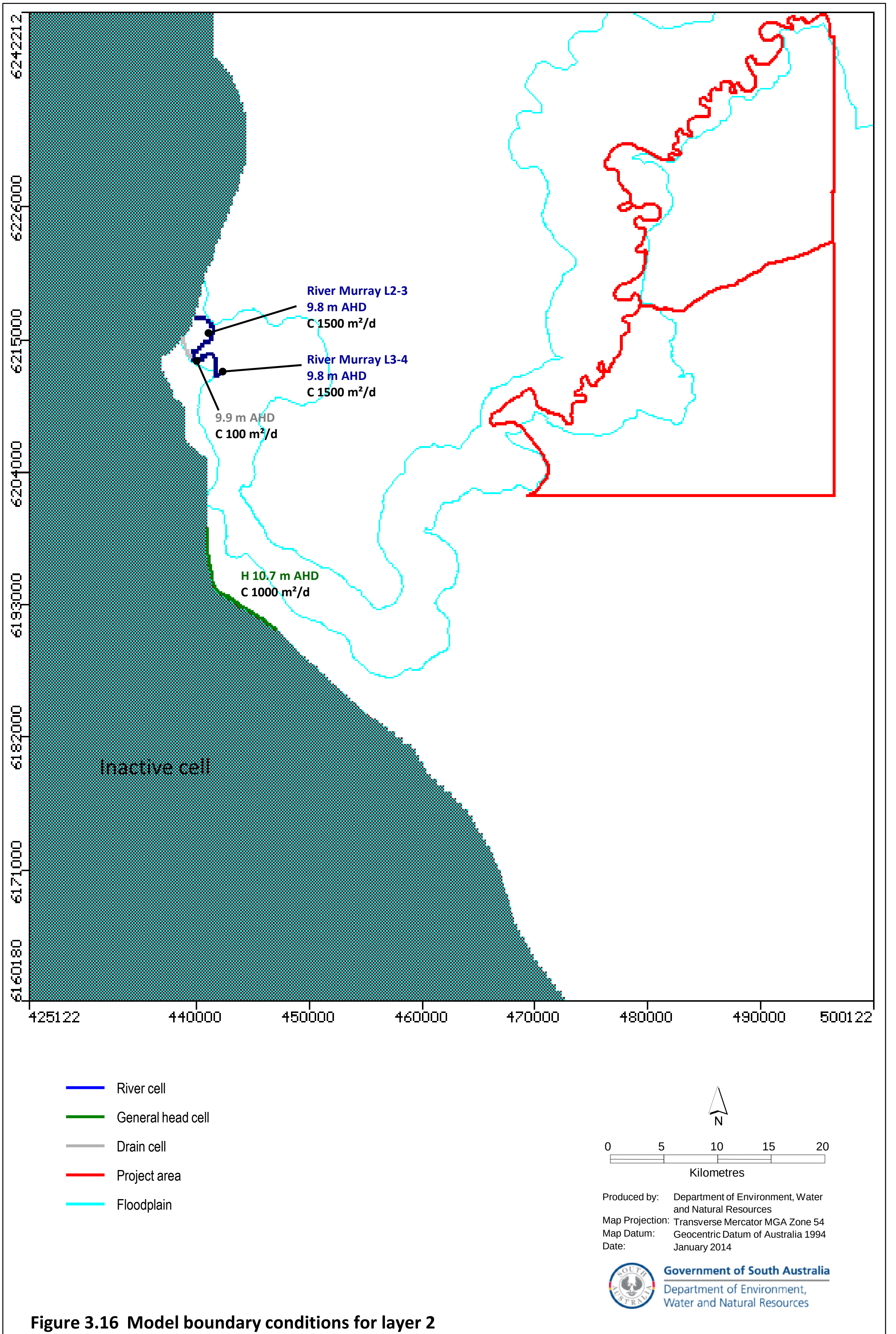


Figure 3.16 Model boundary conditions for layer 2

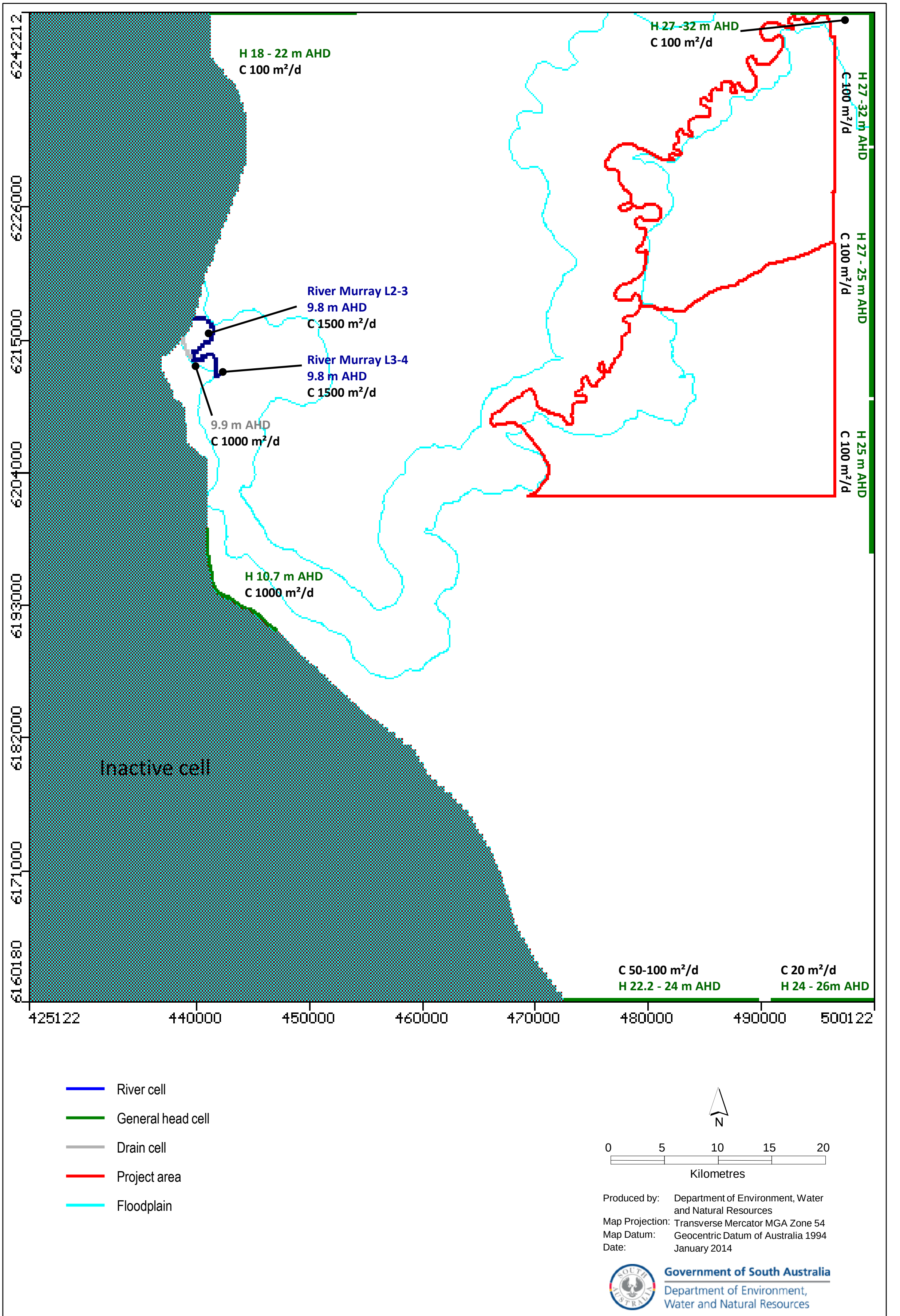


Figure 3.17 Model boundary conditions for layer 3

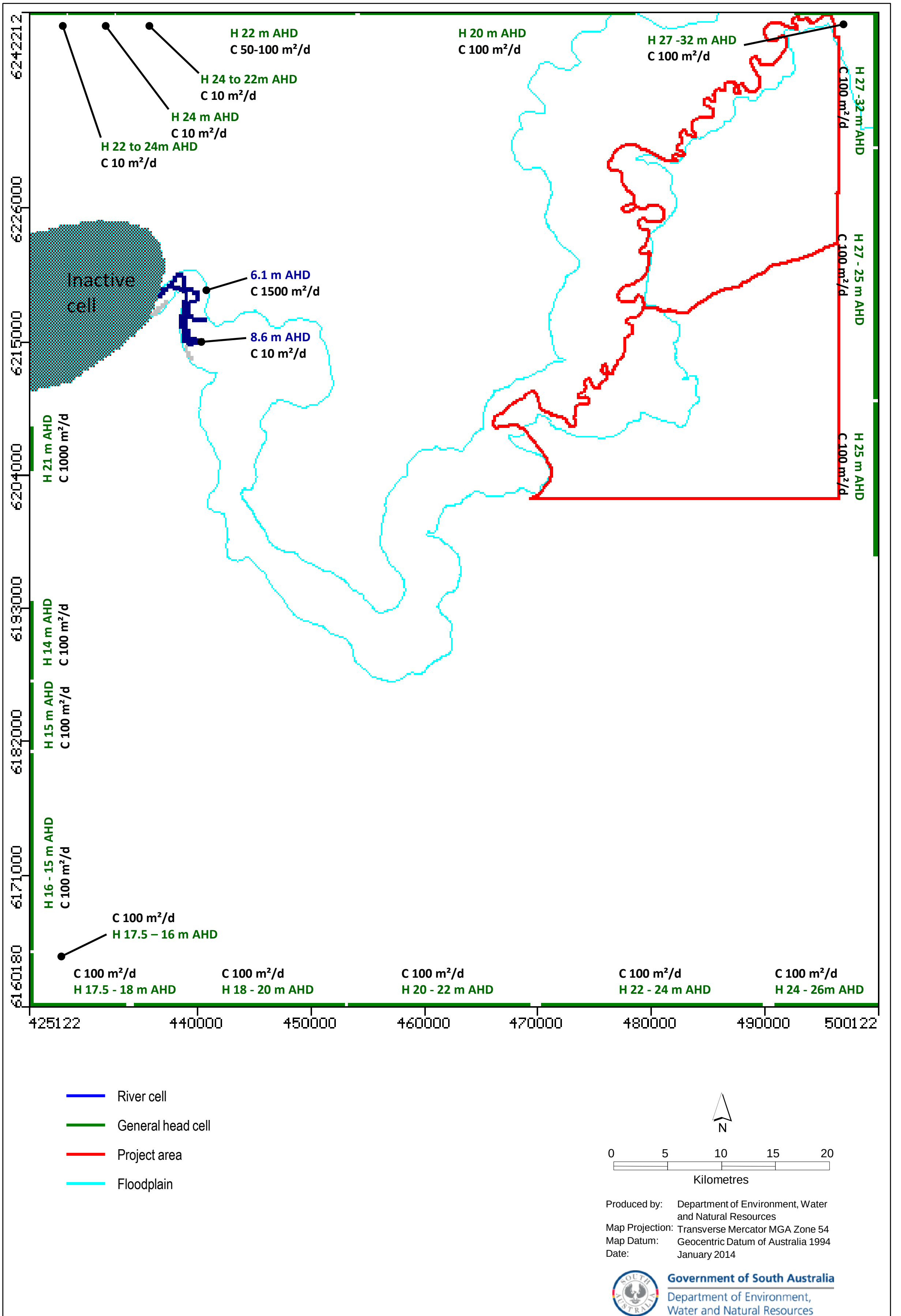


Figure 3.18 Model boundary conditions for layer 4

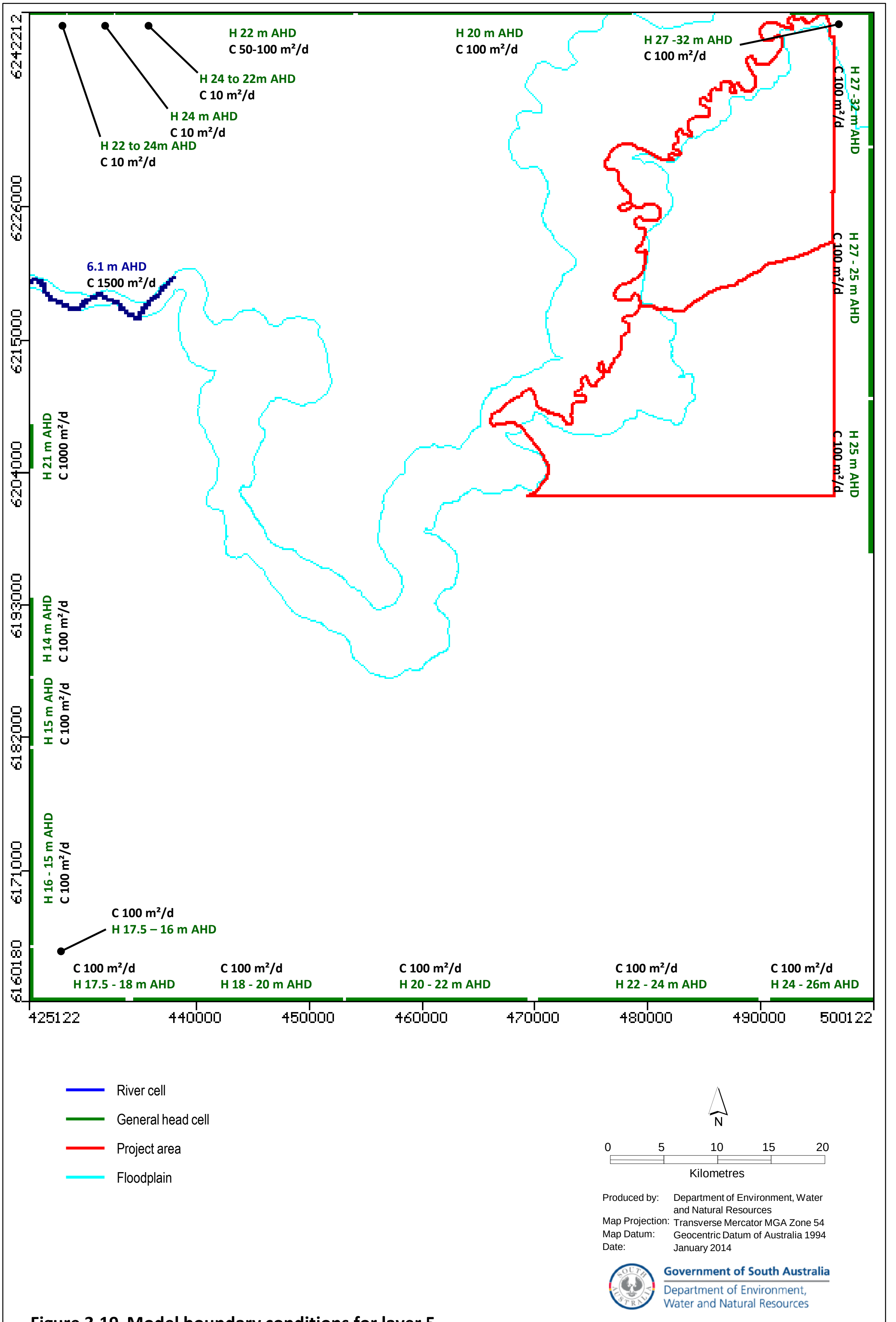


Figure 3.19 Model boundary conditions for layer 5

3.7.2 SURFACE WATER FEATURES

3.7.2.1 RIVER MURRAY MAIN CHANNEL

The River Murray, including its anabranches, is simulated using MODFLOW river cells. In early versions of the Border to Lock 3 model (Yan et al., 2006), it was simulated using constant head 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. This should provide a better approximation of the interaction between the River Murray and groundwater. However, sources of groundwater discharge to the River Murray (e.g. from the Pike-Murtho side, Renmark side and vertical fluxes) cannot be distinguished using river cells and this is a model limitation.

In the Pike-Murtho project area, the River Murray occurs in layer 1 and the riverbed elevation is based on bathymetry data, with an average depth of 3 m. Riverbed elevation only alters MODFLOW calculations when the groundwater level is below the riverbed elevation. There are no known locations in the Pike-Murtho project area where this occurs, and SIS pumping is monitored so that it will not lower the watertable significantly below the river pool level. It is anticipated that the groundwater level will be higher than the riverbed elevations for all modelling cases and hence the riverbed elevations will not have any impacts on the modelling results. The river stage is held constant at pool level. This is a simplification of the real system dynamics which is consistent with the purpose of the Salinity Registers.

The river stages for the River Murray in the Pike-Murtho project area are as follows:

- 19.3 m AHD upstream of Lock 6
- 16.3 m AHD between Lock 6 and Lock 5
- 13.2 m AHD between Lock 5 and Lock 4

Conductance values for MODFLOW river cells were obtained during calibration. The main river channel has a conductance of 1500 m^2/d, which is consistent with other Salinity Register models such as Yan et al. (2011).

3.7.2.2 ANABRANCHES AND OTHER SURFACE WATER FEATURES

Anabranches are represented by river cells. Their locations are shown in Figure 2.12 and the boundary conditions applied are summarised in Figure 3.15.

The anabranch creek system in the Pike-Mundic floodplain is modelled based on the information provided in REM-Aquaterra (2005a). The model settings for the major surface water features in this floodplain are shown in Table 3.2 below.

Table 3.2 Model settings for the surface water features in the Pike floodplain

Surface water feature	River stage (m AHD)	Riverbed elevation (m AHD)	Conductance (m^2/d)
Upper Pike River	14.6 - 14.8	13.2 - 13.5	15
Mid Pike River	14.3	13.2	15
Lower Pike River	13.3 - 13.4	11.3 - 12.5	15
Mundic Creek	15.6	13.8	15
Pike Lagoon	15.2	13.7	15
Tanyaca Creek	13.4	12.4	15
Snake Creek	14.4 - 15	12.8 - 13	15
Rumpabunyah Creek	13.4	12	15

The Salt Creek is simulated as river cells with a river stage of 13.2 m AHD, a depth of 2 m and a conductance of 100 m^2/d. However, as explained in Section 2.6.2, these surface water features do not have a direction connection with the River Murray under regular flow regimes (Yan et al., 2006) and hence are not included in salt load calculations for Salinity Register purpose. The anabranches in the Woolenook Complex floodplain are assigned a river stage of 16.3 m AHD (same as pool level), a depth of 1 m and a conductance of 15 m^2/d. The river stage and depth were adopted from Yan et al. (2006) while the conductance was adjusted during model calibration.

An anabranch between river kilometres 605 and 614 (near Lock 6) has been added to the Border to Lock 3 model since Yan et al. (2011), based on satellite images. A conductance of 15 m^2/d and a depth of 1 m were adopted with river level set to 16.3 m AHD.

The Chowilla anabranch creek system was not included in the previous simulations of the Pike-Murtho study area (Yan et al., 2006) but part of it has been included in this study as the model domain has been extended northward to cover the full extent of the Murtho LWMP area. A level of 15.6–19.2 m AHD, a depth of 0.6–5 m and a conductance of 2.5–5 m^2/d were adopted based on Chowilla model.

3.7.3 DRAINAGE WELLS

Drainage wells are present in the Central and South Murtho areas as a solution to water-logging problems caused by perched aquifers. Most are included in the model using MODFLOW's Well package and inject water into the Loxton Sands aquifer (layer 1). Their locations and pumping rates (1–1.5 L/s for Central Murtho and 0.5–1 L/s for South Murtho) are adopted from Yan et al. (2006). All the drainage wells are assumed to be sealed and disused by 2002 (P Hasslett (Local Farmer) 2006, pers. comm. January).

The drainage well locations will be shown along with the irrigation recharge zones in Section 3.8.3.

3.7.4 SALT INTERCEPTION SCHEMES SIMULATION IN THE CALIBRATED MODEL

The Pike SIS commenced in 2012 while the Murtho SIS commenced in 2014. As such, only the Pike SIS is included in the transient calibrated model. Its production wells are simulated by MODFLOW's Well package. The pumping rates adopted in the model are based on annual volumes provided by SA Water. The pumping well locations for the Pike SIS are shown in Figure 2.15.

The Pike SIS is simulated differently in the prediction models, which will be discussed in more detail along with the Murtho SIS in Section 5.

The water intercepted by the Pike and Murtho SIS is disposed at the Noora Disposal Basin. The watertable at Noora area is generally within 2 m of the ground surface, discharging groundwater via evapotranspiration. Only a relatively small area has constantly held disposed water for the last 40 years. The current water level in the ponding area is around 17.5 m AHD, similar to the watertable level, indicating that evapotranspiration acts strongly to control the water balance.

The Noora Disposal Basin is represented in model layer 1 by MODFLOW's River package and Drain package. In area where disposed water is constantly held, the River package is used. The river cells have a stage of 17.5 m AHD, a conductance of 10 m^2/d and a depth of 0.5 m, based on Heneker (2007) and Hodgkin et al. (2007). The drain package is used for the general lowland area. The drain cells have an elevation of 18 m AHD and a conductance of 500–1000 m^2/d.

3.7.5 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. In the Pike-Murtho project area, the maximum groundwater ET rate is set at 1100 mm/y and the extinction depth is set at 2 m, based on Bureau of Meterology (2001) and Holland et al. (2001). The ET parameters were confirmed during calibration against actual ET rates observed in the field (Section 4). ET is most likely to occur on the floodplains and in some lowland areas where the watertable is shallow.

3.7.6 SEEPAGE AND LOWLAND AREAS

Groundwater can discharge at the cliff interface between the highland and floodplain as cliff seepage. Most of the cliff seepage is simulated using MODFLOW's drain cells with a drain elevation of 13.8 m AHD) and a conductance of 100 m^2/d in Lyrup, and a drain elevation of 16.5–19.5 m AHD and a conductance of 1000 m^2/d near Lock 6. The drain elevation is the average ground surface elevation of the floodplains. These cells are represented in model layer 1.

Similarly, groundwater can discharge at lowland areas outside the floodplain near Simarloo, Mid Pike and Upper Pike. This is simulated using MODFLOW drain cells with a drain elevation of 17–19 m AHD and a conductance of 1000 m^2/d. These cells are represented in model layer 1.

3.7.7 GROUNDWATER ALLOCATION AND USE

There is no allocation of groundwater or known groundwater use in the Pike-Murtho area.

3.8 MODEL RECHARGE

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

3.8.1 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.

In all transient simulations except Scenario 2 for Mallee Clearance, 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. This simplification has been agreed to in discussion with the MDBA and is discussed further in Section 6.

3.8.2 RECHARGE DUE TO MALLEE CLEARANCE

Scenario 2 (see Section 5) simulates the impact of mallee clearance on River Murray salt loads. The recharge zones and rates are specified by the former DENR (now part of DEWNR) and are based on studies by CSIRO (Cook et al., 2004) and the former DENR using SIMRAT and SIMPACT models. 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. The mallee clearance is assumed to have started in 1920. There are 40 recharge zones and rates vary from 0.1 to 11 mm/y. The details of recharge zones shown in Figure 3.20 and rates are given in Appendix A-1.

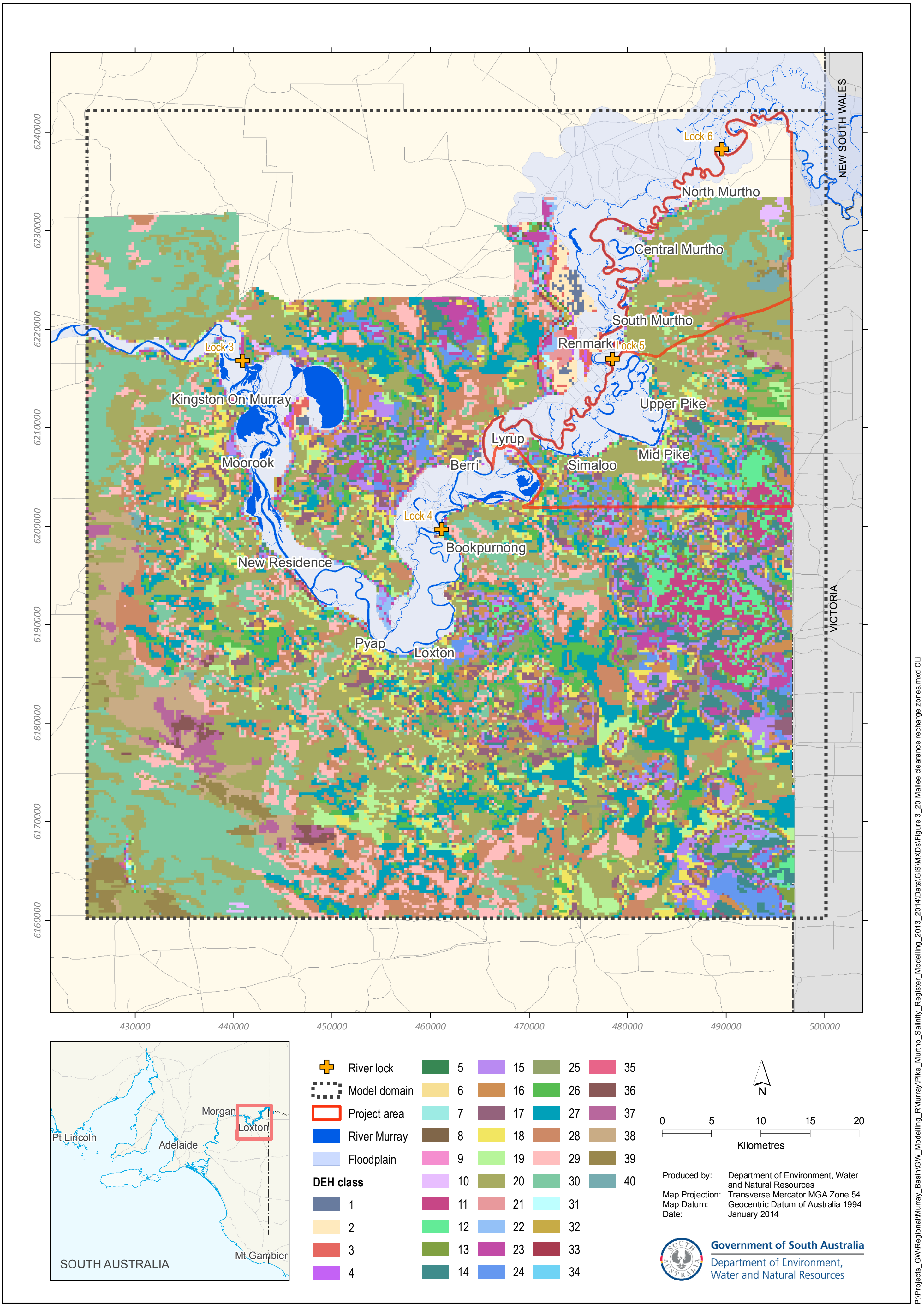


Figure 3.20. Mallee clearance model recharge zones

3.8.3 RECHARGE DUE TO IRRIGATION: OVERVIEW

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 et al., 2011), as described below.

The total spatial extent of recharge for a given year is based on irrigation footprint and commencement year data from the former DENR and Mapping Services Australia. The irrigated areas are divided into zones based on irrigation commencement year, initial lag time and estimated recharge rates. During calibration, the recharge zones, initial lag time and recharge rates are adjusted within reasonable ranges until the modelled water level and trend consistently approximates the observed water level and trend. Further details on the methodology are given in Section 3.8.4.

The difficulty of this approach is non-uniqueness. That is, there may be more than one combination of input parameters that will provide a reasonable match to available data. In particular, modelled head levels depend on hydraulic conductivity and the recharge rate. As there is a degree of uncertainty about both aquifer hydraulic conductivity and the recharge rates, it is unlikely that the recharge estimates derived from inverse modelling are unique. However, a careful approach has been adopted to minimise the uncertainty and to improve the likelihood that recharge estimates are within acceptable known knowledge range of their true values.

The main aspects of the approach are:

- calibration begins with a numerical model incorporating the best available hydrogeological data and an up-to-date conceptual model, at scales appropriate for the project aims
- recharge zones are determined by recharge areas, rates, commencement year and lag times that are based on the best available data and the latest scientific research, such as a variably-saturated groundwater flow model conducted by Lisdon Associates (2010)
- during calibration, the recharge rate of each zone is varied within a reasonable range appropriate for irrigation practices at the time of application (i.e. taking into account the lag time to the watertable). If this leads to a poor match to observed heads, the aquifer properties are also varied within reasonable ranges, provided that the hydrogeological data supports such changes.
- to confirm the validity of the model parameters, lag times, recharge estimates and salt load results, the following are compared to available data sources, including:
    - a comparison of recharge estimates with known historical practices and an independent assessment of accession water by Laroona Environmetrics (2014)
    - a comparison of estimated salt loads with historical monitoring sites, NanoTEM and RoR data
    - a comparison of estimated groundwater evapotranspiration with field estimates from CSIRO (Holland et al., 2011).
- sensitivity and uncertainty analyses are performed to estimate model uncertainty.

3.8.4 MODEL IRRIGATION RECHARGE SETTINGS AND ASSUMPTIONS

The process in developing modelled recharge is described in detail below.

3.8.4.1 RECHARGE AREA

The areas of recharge in the model are assumed to be the irrigation areas in the Pike-Murtho project area. Irrigation areas outside the project area are omitted as part of the “sub-zone” approach discussed earlier, except where applied as part of sensitivity and uncertainty analysis (Section 6).

The model recharge areas are based on the irrigation footprint GIS data provided by the former DENR and Mapping Services Australia. The spatial extent of irrigation development at specific milestones (1894, 1930, 1940, 1945, 1950, 1960, 1965, 1970, 1975, 1980, 1985, 1988, 1990, 1995, 1997, 1999, 2000, 2001, 2003 to 2011 yearly data) was used to generate recharge areas over time. The location of irrigation areas and starting years as provided by the former DENR and Mapping Services Australia are indicated in Figure 2.13.

As the irrigation footprint data indicate that irrigation areas expand with time (Figure 2.13), the GIS files were used to assign model recharge areas with different starting years. As irrigation continues to develop, more model irrigation recharge areas become active to simulate the irrigation area expanding. The year that an irrigation zone becomes active depends on the commencement year of irrigation and on the initial lag time, which is discussed later. The recharge zones and lag time used in the calibrated model for the Pike and Murtho areas are given in Figure 3.21.

Within a recharge zone, there may be properties or paddocks that are irrigated in some years but not others. These small fluctuations in irrigation area within a zone are not simulated directly, but are represented as changes in recharge rate.

Lateral movement in the unsaturated zone, e.g. within perched aquifers, may occur in the project area but there is insufficient data to implement this directly in the model. Potential localised lateral movement of accession water from zone to zone is addressed indirectly by varying recharge during calibration.

3.8.4.2 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.

The SIMRAT model was developed to provide quick impact assessment for future irrigation developments and estimates the initial lag time (Fuller et al., 2005). The lag times estimated by SIMRAT are shown in Figure 2.14. SIMRAT makes a number of simplifying assumptions that may not apply everywhere within the Pike-Murtho project area — for example, that the water moves vertically and not laterally and that the irrigation accession rate is 100 mm/y which is lower than estimated rates for early irrigation. The assumptions and input information in SIMRAT could lead to estimates that are significantly different to the true historical lag time. However, SIMRAT is currently the only available data source for estimating lag time. Therefore, the initial lag time from SIMRAT was only considered as the starting point in model development and it was altered with other model input parameters to achieve the closest match to observed hydrographs and other data.

3.8.4.3 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 1990 and 1995 were simulated by two different model recharge zones.

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.

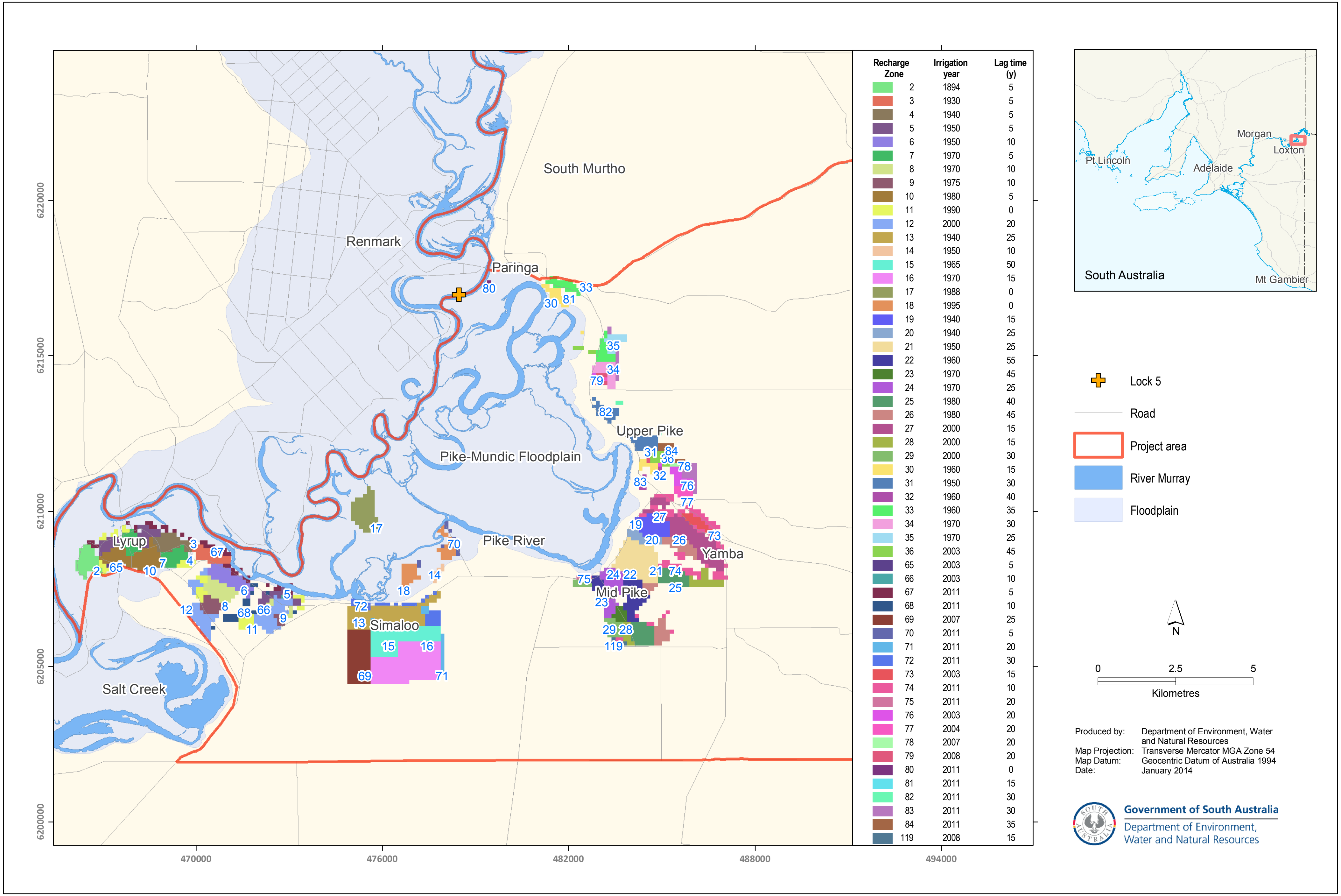
Recharge rate

Recharge rate was the last aspect to be considered during the model recharge zoning process. If a recharge zone contained more than one observation wells, it was possible that the observation wells showed different groundwater levels or trends; hence the recharge rates needed to achieve calibration for those wells would be different. In this situation, the recharge zone was separated into smaller model recharge zones as each zone could only have one set of recharge rates. Recharge rate of each zone is varied within a reasonable range appropriate for irrigation practices at the time of application. In the early years, recharge rate was generally high and decreasing once the irrigation improvement method is adopted. In the historical transient model, initial recharge rates were up to 520 mm/y in early 1900s when flood irrigation were applied in the Pike-Murtho area, falling to around 100 m/y in recent years when irrigation efficiency have been improved. The model derived rates and areas are listed in Appendix A.

3.8.4.4 LATE LAG TIME

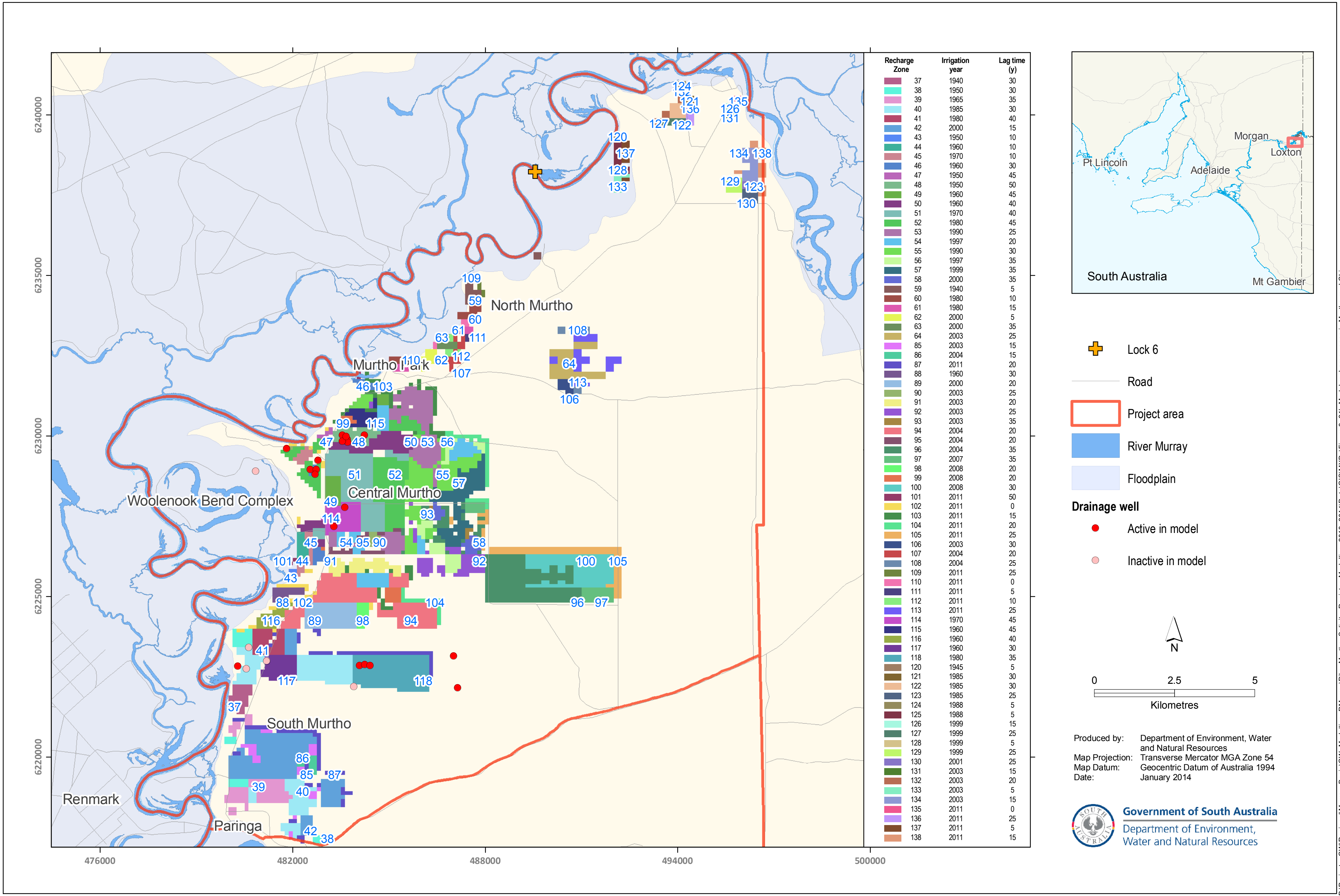
Late lag time is the time taken for changes in root zone drainage to alter recharge to the watertable in an existing irrigation area where the irrigation water's wetting front has already reached the watertable. This will therefore apply to irrigation areas where an irrigation groundwater mound exists.

The independent study by Lisdon Associates (2010) for the adjacent Loxton area utilised a variably-saturated cross-section model (SUTRA) that also estimated the late lag time. The simulations show that after the wetting front has reached the watertable, the time taken for changes in irrigation practice to impact on the recharge to the watertable can be within a few months. This result is supported by observed responses in hydrographs following changes to the irrigation activities. This is an important outcome to assist in defining the recharge, particularly the appropriate recharge rates for scenario modelling to distinguish impacts from irrigation activities.



P:\Projects_GW\Regional\Murray_Basin\GW_Modelling_RMurray\Pike_Murtho_Salinity_Register_Modelling_2013_2014\Data\GIS\MXDs\Figure 3_21a Model recharge zones in Pike.mxd CLi

Figure 3.21a. Model recharge zones and lag time in the Pike area



Recharge Zone	Irrigation year	Lag time (y)
37	1940	30
38	1950	30
39	1965	35
40	1985	30
41	1980	40
42	2000	15
43	1950	10
44	1960	10
45	1970	10
46	1960	30
47	1950	45
48	1950	50
49	1960	45
50	1960	40
51	1970	40
52	1980	45
53	1990	25
54	1997	20
55	1990	30
56	1997	35
57	1999	35
58	2000	35
59	1940	5
60	1980	10
61	1980	15
62	2000	5
63	2000	35
64	2003	25
85	2003	15
86	2004	15
87	2011	20
88	1960	30
89	2000	20
90	2003	25
91	2003	20
92	2003	25
93	2003	35
94	2004	20
95	2004	20
96	2004	35
97	2007	35
98	2008	20
99	2008	20
100	2008	30
101	2011	50
102	2011	0
103	2011	15
104	2011	20
105	2011	25
106	2003	30
107	2004	20
108	2004	25
109	2011	25
110	2011	0
111	2011	5
112	2011	10
113	2011	25
114	1970	45
115	1960	45
116	1960	40
117	1960	30
118	1980	35
120	1945	5
121	1985	30
122	1985	30
123	1985	25
124	1988	5
125	1988	5
126	1999	15
127	1999	25
128	1999	5
129	1999	25
130	2001	25
131	2003	15
132	2003	20
133	2003	5
134	2003	15
135	2011	0
136	2011	25
137	2011	5
138	2011	15

P:\Projects_GW\Regional\Murray_Basin\GW_Modelling_RMurray\Pike_Murtho_Salinity_Register_Modelling_2013_2014\Data\GIS\MXDs\Figure 3_21b Model recharge zones in Murtho.mxd CLi

Figure 3.21b. Model recharge zones and lag time in the Murtho area

3.9 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 et al. (2005).

All flow budget zones correspond to a single river kilometre reach. 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.

The salinity value assigned to a zone is based on the nearest salinity value on the Pike-Murtho side of the river, choosing the higher value to be conservative. The only exception is near Lock 6 where the groundwater downstream of Lock 6 has been freshened by river water inflows due to the change in pool level between upstream and downstream of Lock 6.

The location of the model budget zones and the associated groundwater salinity values are shown in Figure 3.22. For the Salinity Register, salt loads are calculated for Murtho between river kilometres 620 to 565 and for Pike between river kilometres 564 to 530. Note that the river reach above Lock 6 is within the project area but not included in salt load calculations.

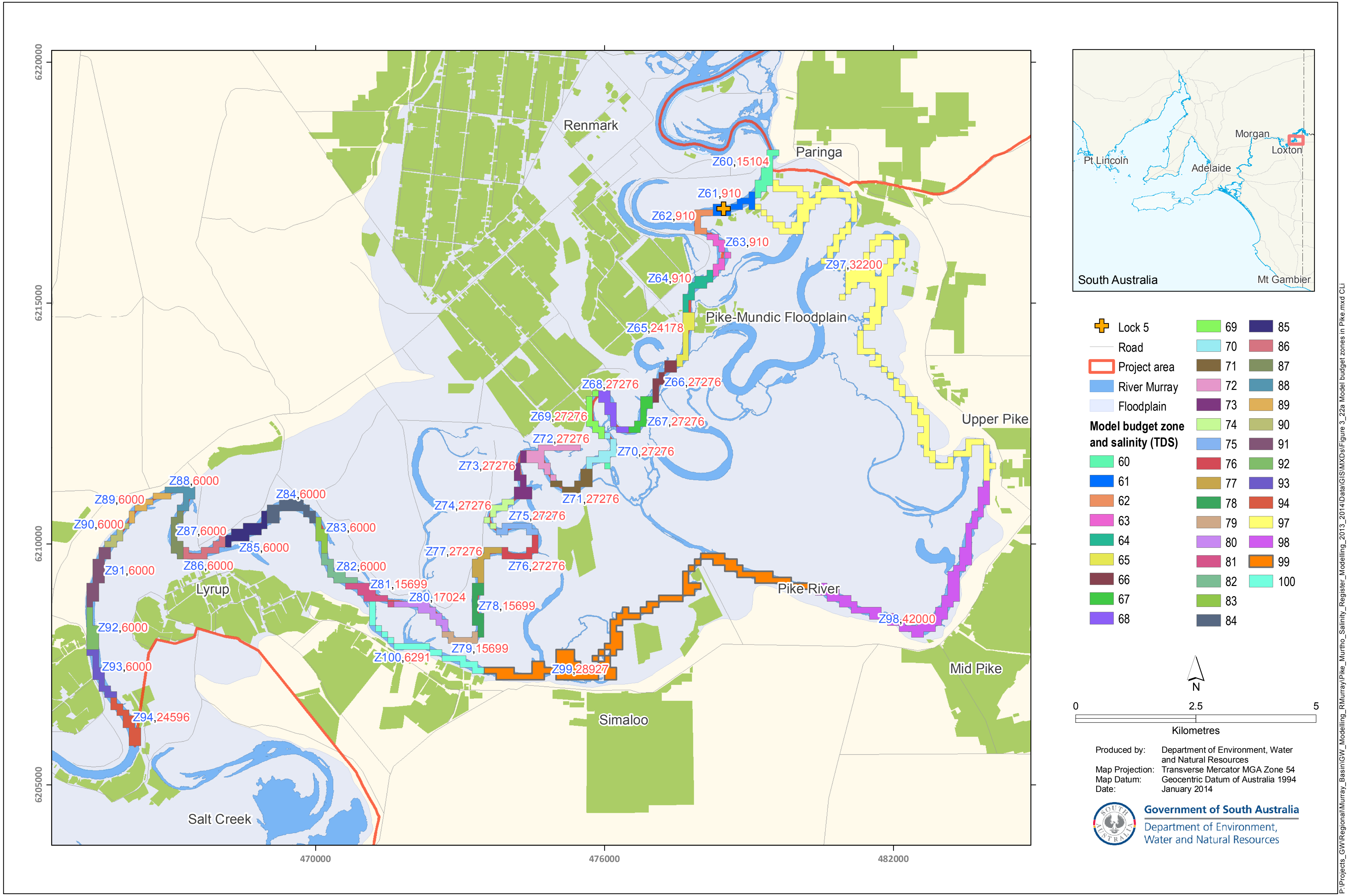


Figure 3.22a. Model budget zones in Pike

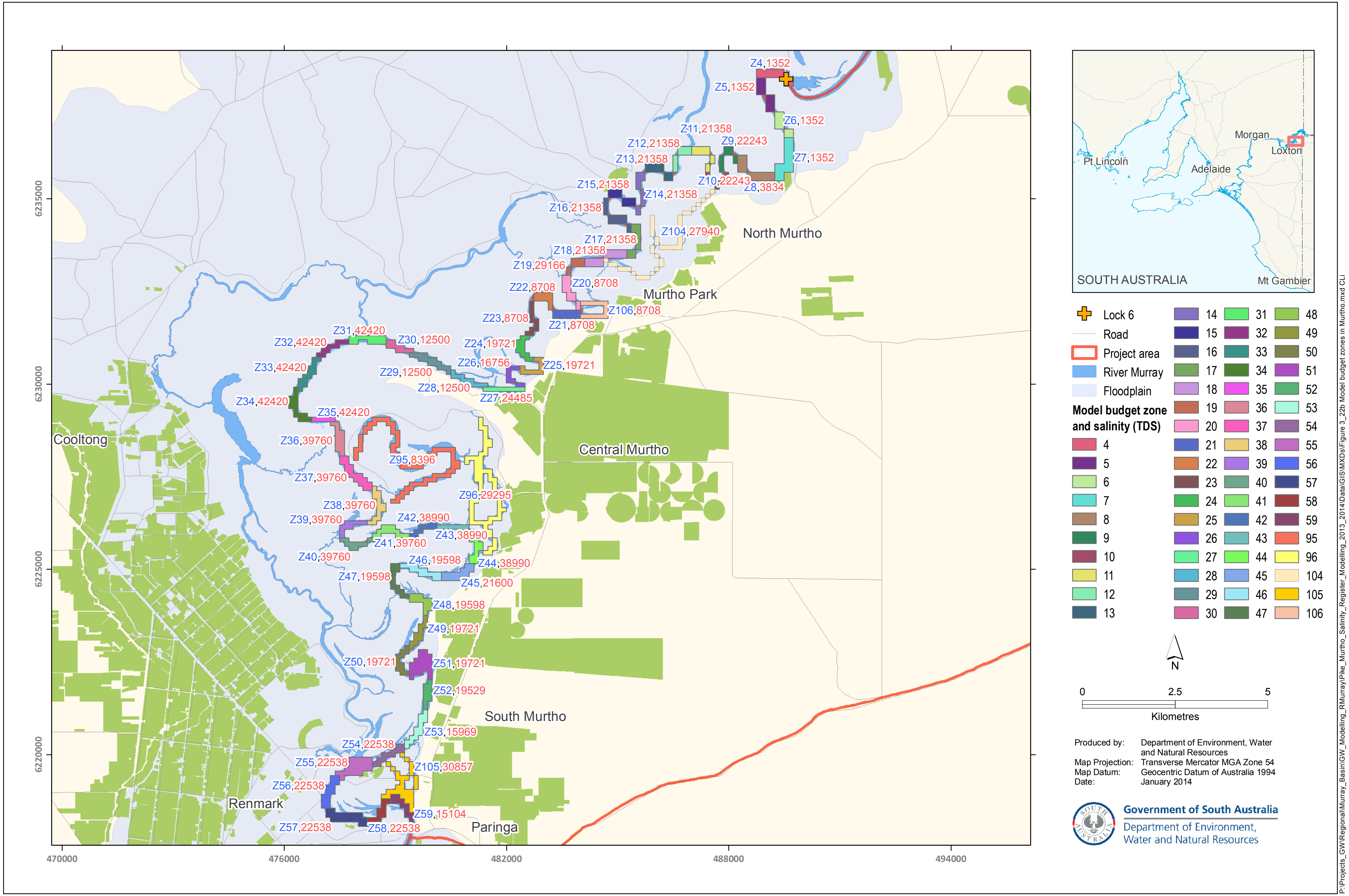


Figure 3.22b. Model budget zones in Murtho

3.10 MODEL SIMPLIFICATION

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

3.10.1 SIMULATION PROCESSES

- The model does not estimate future impacts due to climate sequence, such as changes in river level, changes in evapotranspiration, and changes to irrigation areas due to drought, 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 based on SIMRAT and modified by calibration.

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.

3.10.2 SPATIAL AND TEMPORAL DISCRETISATION

- Due to limited data availability, the model layer elevations are necessarily approximate and will not reflect the full heterogeneity of the system (this limitation is true for all numerical models).
- 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.
- Due to insufficient data, the sub-units of the Murray Group Limestone aquifer cannot be clearly defined in the project area. The surfaces of the sub-units are interpolated and extended to the project area from other areas (e.g. Loxton and Bookpurnong) and may not represent the real conditions.

3.10.3 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.
- Limited 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.

3.10.4 MODEL BOUNDARY CONDITIONS

- Irrigation and SIS within the model domain, but outside the project area, e.g. the Loxton-Bookpurnong and the Berri-Renmark areas, are not simulated. As these irrigation districts are at a reasonable distance from the project area, their impact on the potentiometric heads in the project area is expected to be negligible (this is partially tested in Section 6).
- 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 except where 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* (Barnett, et al. 2012):

- scattergraph of modelled heads plotted against observed heads
- a simple statistic measuring goodness of fit: the scaled root mean square (SRMS) 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 cm, 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 comparing model inputs and outcomes with estimates and information on water and solute fluxes (Section 0):

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

Calibration of the Pike-Murtho 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 is undertaken to develop a broad-scale hydraulic conductivity distribution and basic 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.

Hydraulic conductivities and model boundary conditions are varied within reasonable limits. Due to the absence of pre-irrigation head data, the results from the steady-state model are compared with the potentiometric surface developed in previous investigations which is believed to be the best available estimate of pre-development equilibrium hydraulic conditions in the project area.

Barnett (1991) provides estimated potentiometric contours for the regional watertable based on limited data available. The contours are modified so that they reflect the post-river regulation and pre-irrigation conditions and are comparable to the steady-state model results (Figure 4.1 left).

There is a good match between the estimated and modelled potentiometric surfaces for the Loxton Sands and Monoman Formation aquifers in most areas (Figure 4.1), but there are discrepancies in some other areas. It may be due to the model limitations and uncertainties in the estimation of the historic surface.

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 parameter changes made to the transient model will be automatically applied to the steady-state model.

4.3 TRANSIENT MODEL CALIBRATION

Transient calibration is undertaken on an iterative basis by adjusting hydraulic parameters, recharge rates and boundary conditions until a satisfactory match with observed data is obtained. The output from a steady-state model with matching parameters and boundary conditions provides the initial conditions for transient model runs. The historical period from 1880 to 2013 was simulated.

Hydraulic conductivities and boundary conditions were altered within known ranges and reasonable limits to achieve a good match to observed heads. Irrigation recharge was the main parameter varied during transient calibration to achieve a good match between observed and modelled groundwater trends, as the trends were mainly driven by irrigation recharge in the project area. Irrigation recharge rates were altered within known ranges and reasonable limits until a satisfactory match with observed groundwater level trends was obtained. The total input recharge cannot be easily estimated from existing information and data, but can be checked whether it is within the estimated ranges of irrigation accessions.

In the Pike-Murtho project area, the majority of salt loads entering the River Murray are from lateral groundwater flux through the Loxton Sands and Monoman Formation as a result of raised watertable from irrigation water. Matching observed water level trends in the Loxton Sands was therefore considered imperative during calibration.

The head level in the Murray Group Limestone aquifer has also been considered in the calibration exercise because of the potential for upward leakage from the underlying aquifers driven by these heads. The observation wells in the Murray Group Limestone aquifer within the project area target different depths of the aquifer. Most of these wells are more than 150 m deep and therefore they are implemented in model layer 5. Two wells (PAG054 and PAG068) are less than 80 m deep, but their measured water levels are similar to the modelled water levels in layer 5. This raises a question that whether the sub-units of the Murray Group Limestone aquifer are clearly separated by aquitards, as observed in other areas such as Loxton.

4.3.1 CALIBRATION RESULTS – POTENTIOMETRIC HEAD CONTOURS

The major processes that affect the heads in the Loxton Sands are irrigation development. The SIS impact is expected to be relatively small in the project area as the Pike SIS only commenced near the end of the calibration period in 2012 and its scale is relatively small with only four wells. The Murtho SIS commenced in 2014 which is outside the calibration period (1880 – 2013).

4.3.1.1 LAYER 1: LOXTON SANDS AND MONOMAN FORMATION

Modelled potentiometric head contours for the Loxton Sands and Monoman Formation aquifers were compared with potentiometric head values in 2012 (Figure 4.2). The model contour shapes were also compared with contours developed from 2012 observations in Figure 2.5. Both the head elevations and the flow directions were evaluated.

In general, the modelled contours match very well with the observed data in both Pike and Murtho. The modelled contours show some small and localised cones of depression around the Pike SIS pumping wells. In Lyrup, the modelled groundwater mound shows a good match to the observations except the highest observed value of 19 m AHD. There are no observations to compare against for the elevated modelled watertable at Simarloo (16 m AHD) and Central Murtho (18 m AHD). The match is less satisfactory in the regional areas but its impact on the key model outcome (i.e. groundwater flux to the River Murray) is expected to be small given their distance from the river.

4.3.1.2 LAYER 3-5: MURRAY GROUP LIMESTONE AQUIFER

There is little information available for comparison with the modelled Murray Group Limestone potentiometric heads. Within the project area, there are only seven observation wells for this aquifer in the model.

As no SIS pumping wells target this aquifer within the project area and the impact from recharge is minimal (due to its depth), it is expected that the Murray Group Limestone potentiometric surface does not change significantly with time. This is further supported by the observation wells in this layer, which show minor changes in heads. As such, the modelled contours are compared against the latest available observations instead of observations from a particular year.

Modelled contours from layer 5 are used in this comparison because most Murray Group Limestone observation wells were implemented in this layer, as explained in Section 4.3. Also, most of the observation wells used for developing the potentiometric surface for the Murray Group Limestone aquifer are more than 150 m deep, so it is appropriate to compare observed data to model layer 5.

Figure 4.3 compares modelled contours with the latest available observations made at the monitoring wells. The match is generally good, except for some wells in Pike where the discrepancy can be up to approximately 2 m (PAG003). This may be due to the uncertainty in which sub-unit these wells are screening. As vertical leakage is expected to be small within the project area, this discrepancy is considered acceptable.

4.3.2 CALIBRATION RESULTS – HYDROGRAPHS

There are many observation wells in the model area, so a subset of 101 wells was chosen (see Section 2.5). 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 2.6.

A comparison of modelled and observed (historical) potentiometric heads in the Loxton Sands (Figure 4.4 and Figure 4.7) and Monoman Formation (Figure 4.5 and Figure 4.8) indicate a close match in most wells 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. PAG019 and PAG021).

Some hydrographs in the regional areas (e.g. PAG006, PAG007 and PAG008) match the trend but not the level. However, given their distance from the River Murray, their impact on the model results (i.e. groundwater flux to the river) should be minimal.

For the Murray Group Limestone, Figure 4.6 and Figure 4.9 show that the model hydrographs match well with the observed hydrographs in Murtho while the match is less satisfactory for some of the wells in Pike. As explained in Section 4.3.1.2, this is likely to be due to the uncertainty in which sub-unit these wells are screening. Again, their impact on the model results (i.e. groundwater flux to the river) should be minimal as vertical leakage in the project area is expected to be small.

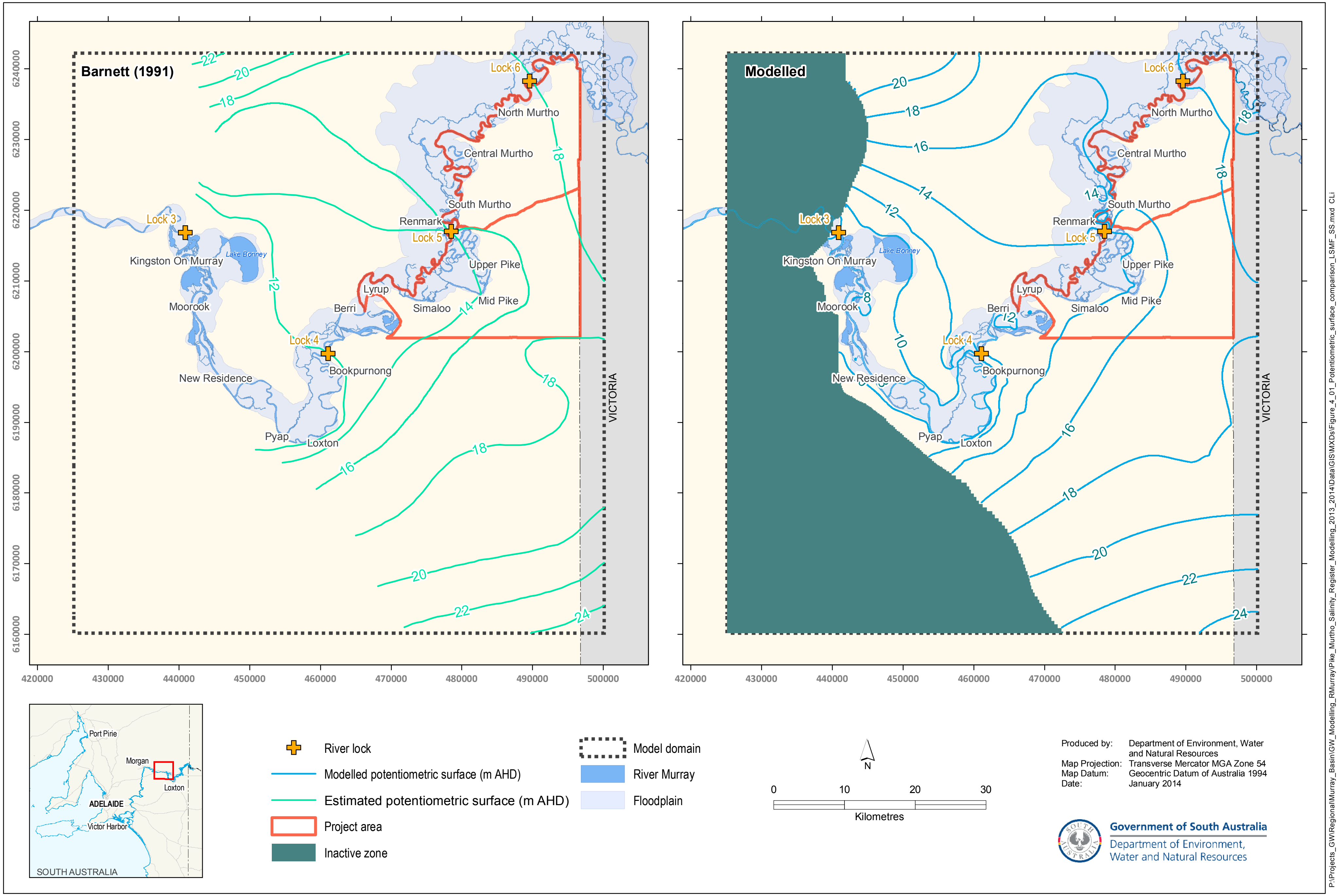


Figure 4.1. Comparison of estimated (Barnett 1991) and modelled potentiometric surface for model layer 1 (Loxton Sands and Monoman Formation in steady-state conditions)

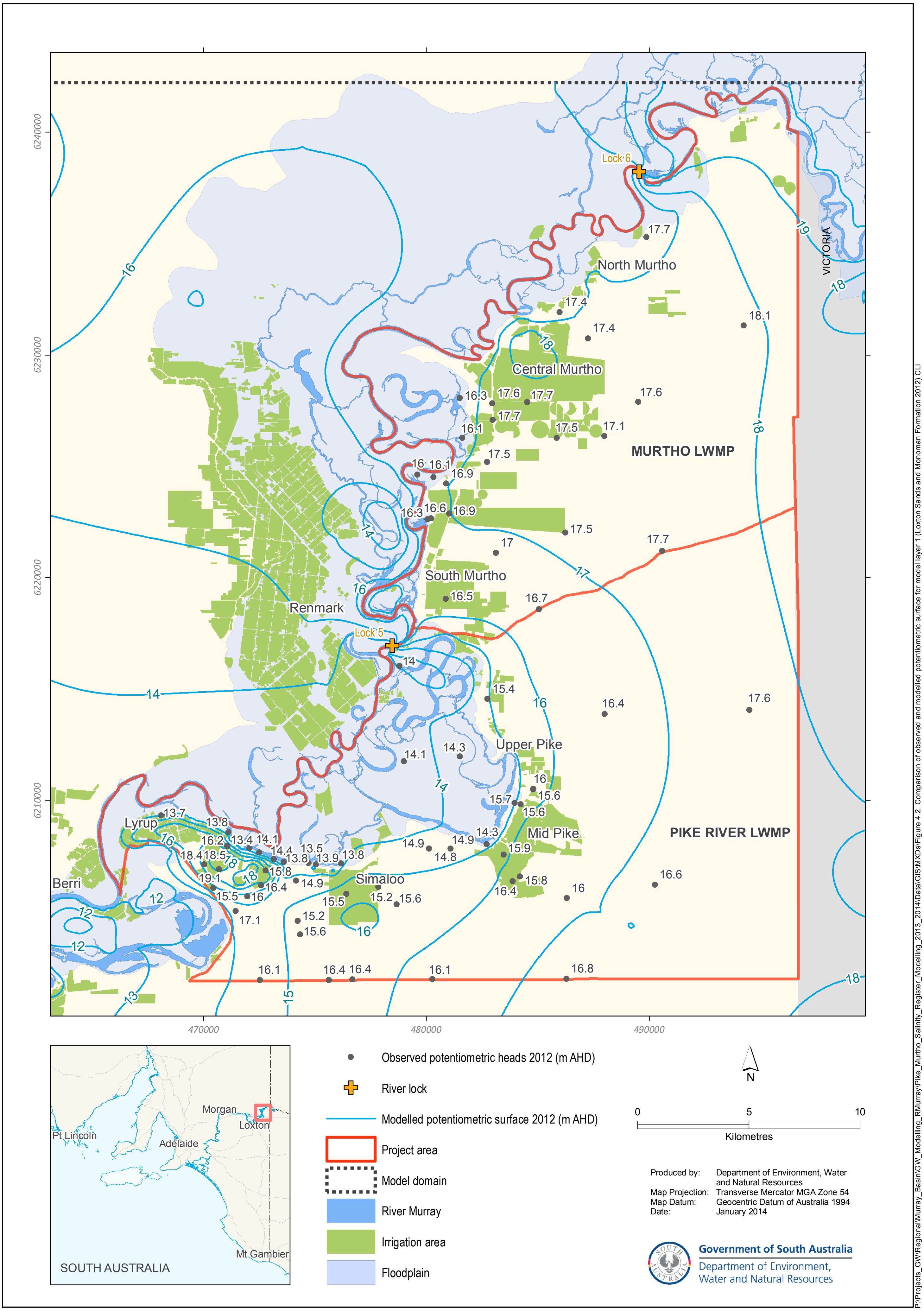
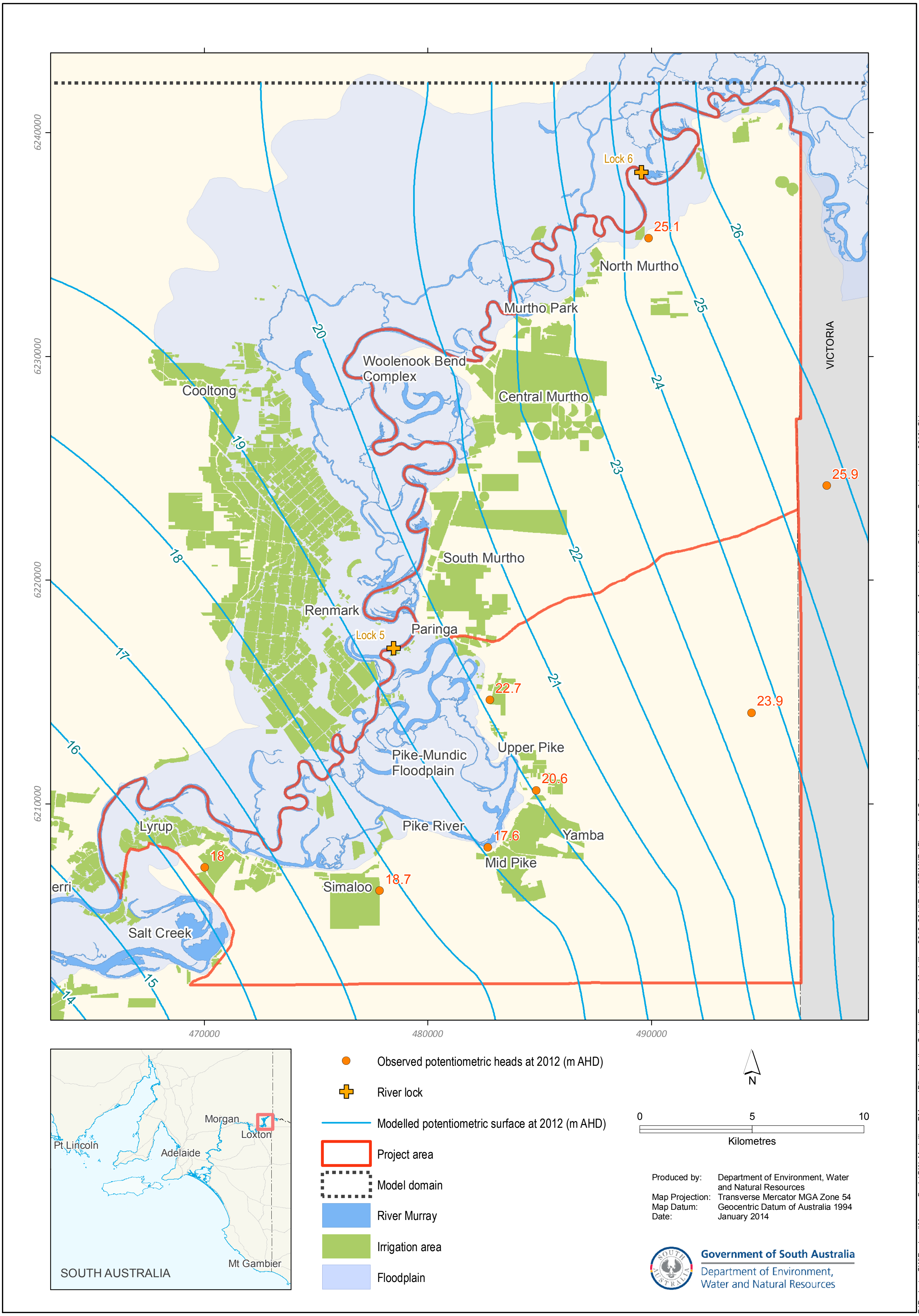


Figure 4.2. Comparison of observed and modelled potentiometric surface for model layer 1 (Loxton Sands and Monoman Formation 2012)



P:\Projects_GW\Regional\Murray_Basin\GW_Modelling_RMurray\Pike_Murtho_Salinity_Register_Modelling_2013_2014\Data\GIS\MXDs\Figure 4.3. Comparison of observed and modelled potentiometric surface for model layer 5 (Murray Group Limestone 2013) CLi

Figure 4.3. Comparison of observed and modelled potentiometric surface for model layer 5 (Murray Group Limestone 2012)

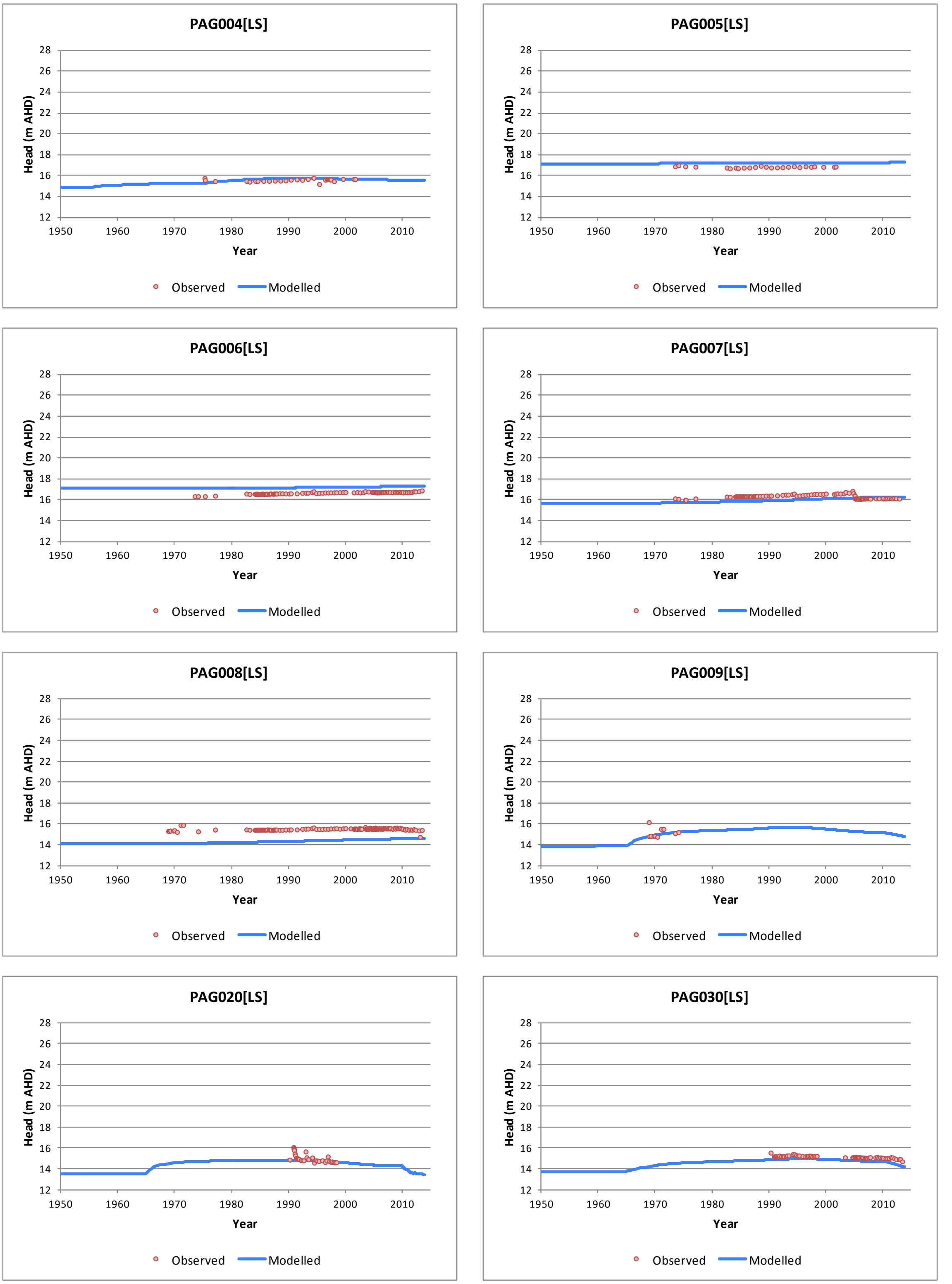


Figure 4.4(a). Hydrograph comparison between observed and modelled for Pike (Loxton Sands-Layer 1)

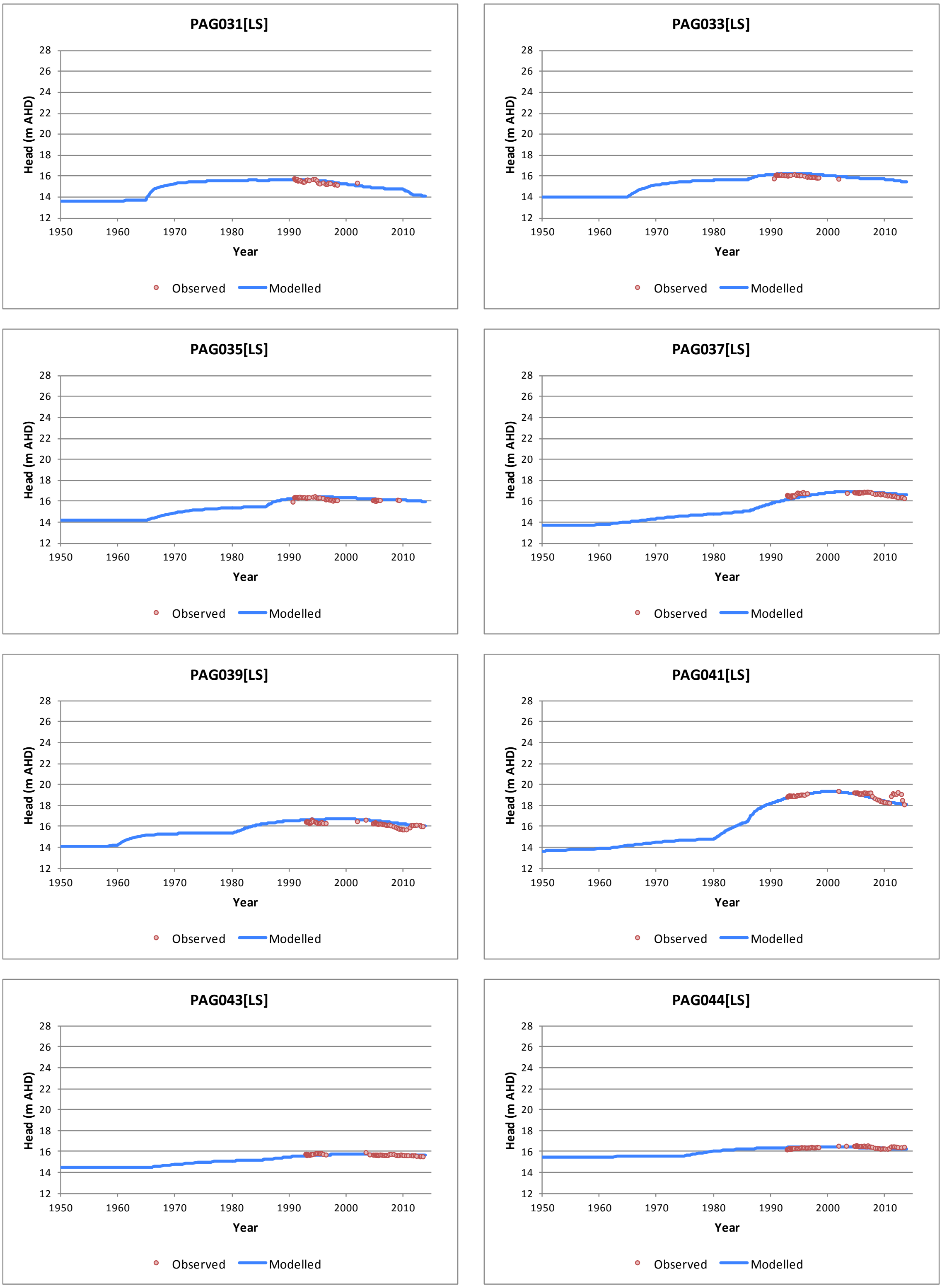


Figure 4.4(b). Hydrograph comparison between observed and modelled for Pike (Loxton Sands-Layer 1)

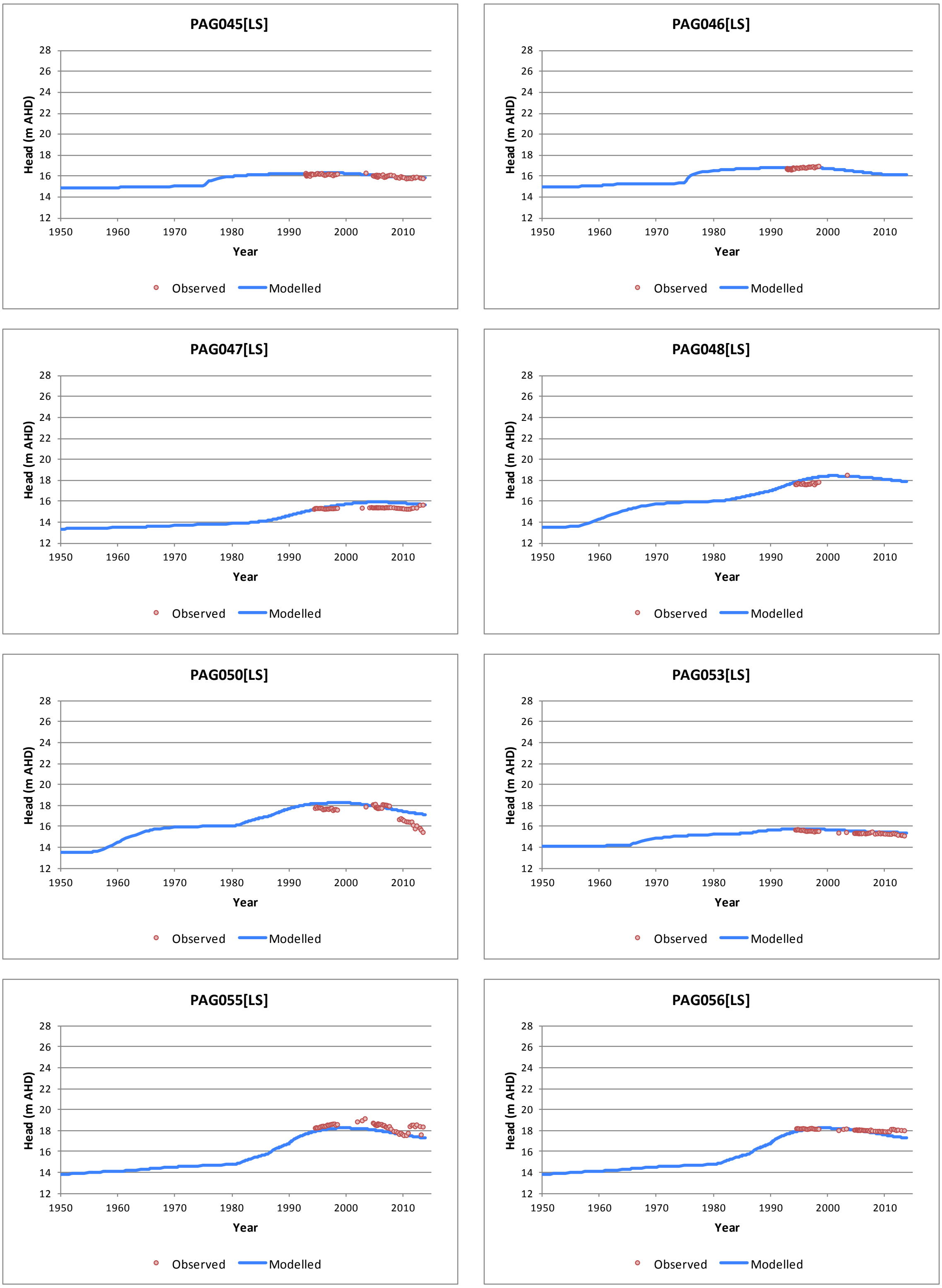


Figure 4.4(c). Hydrograph comparison between observed and modelled for Pike (Loxton Sands-Layer 1)

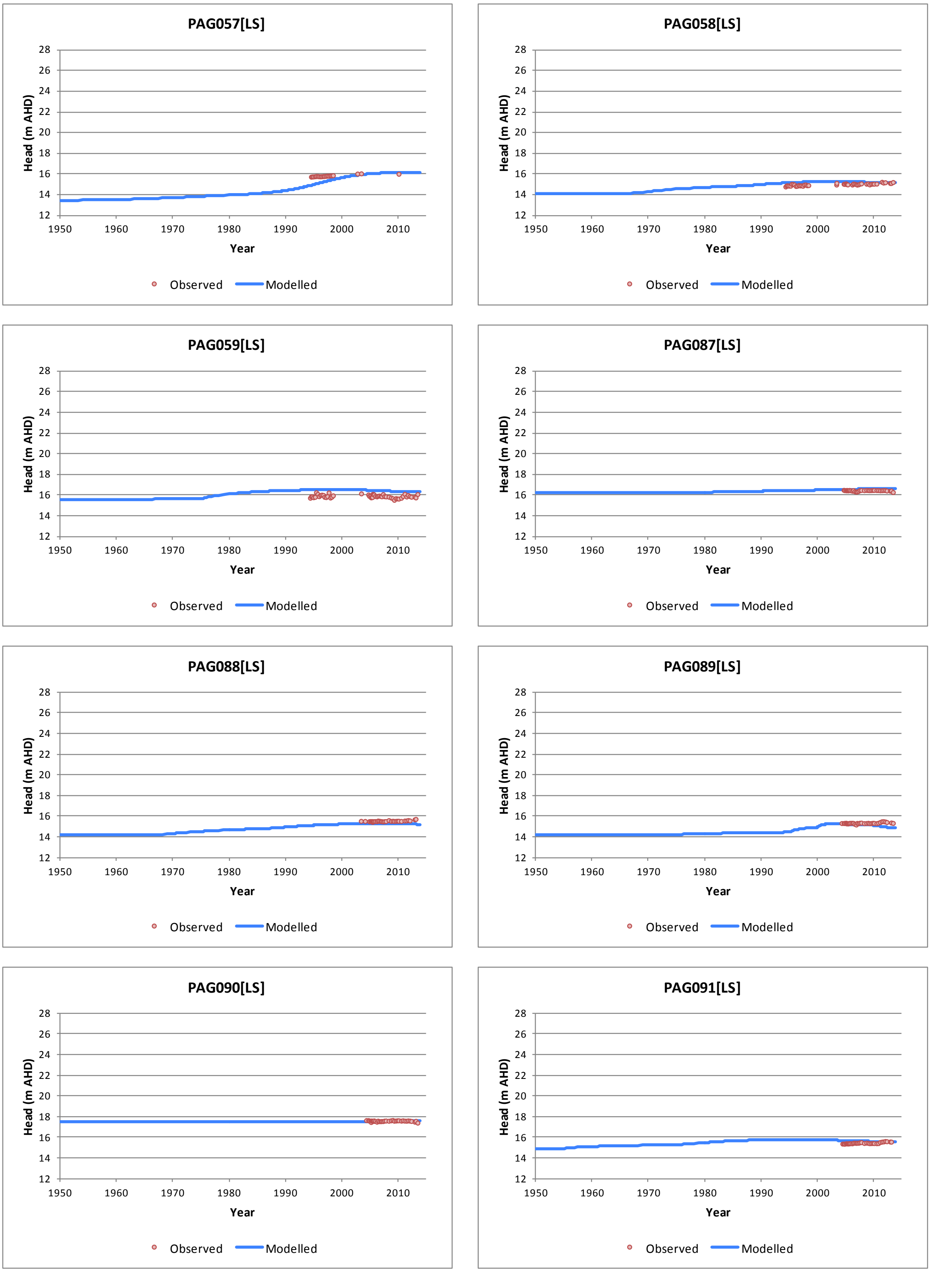


Figure 4.4(d). **Hydrograph comparison between observed and modelled for Pike (Loxton Sands-Layer 1)**

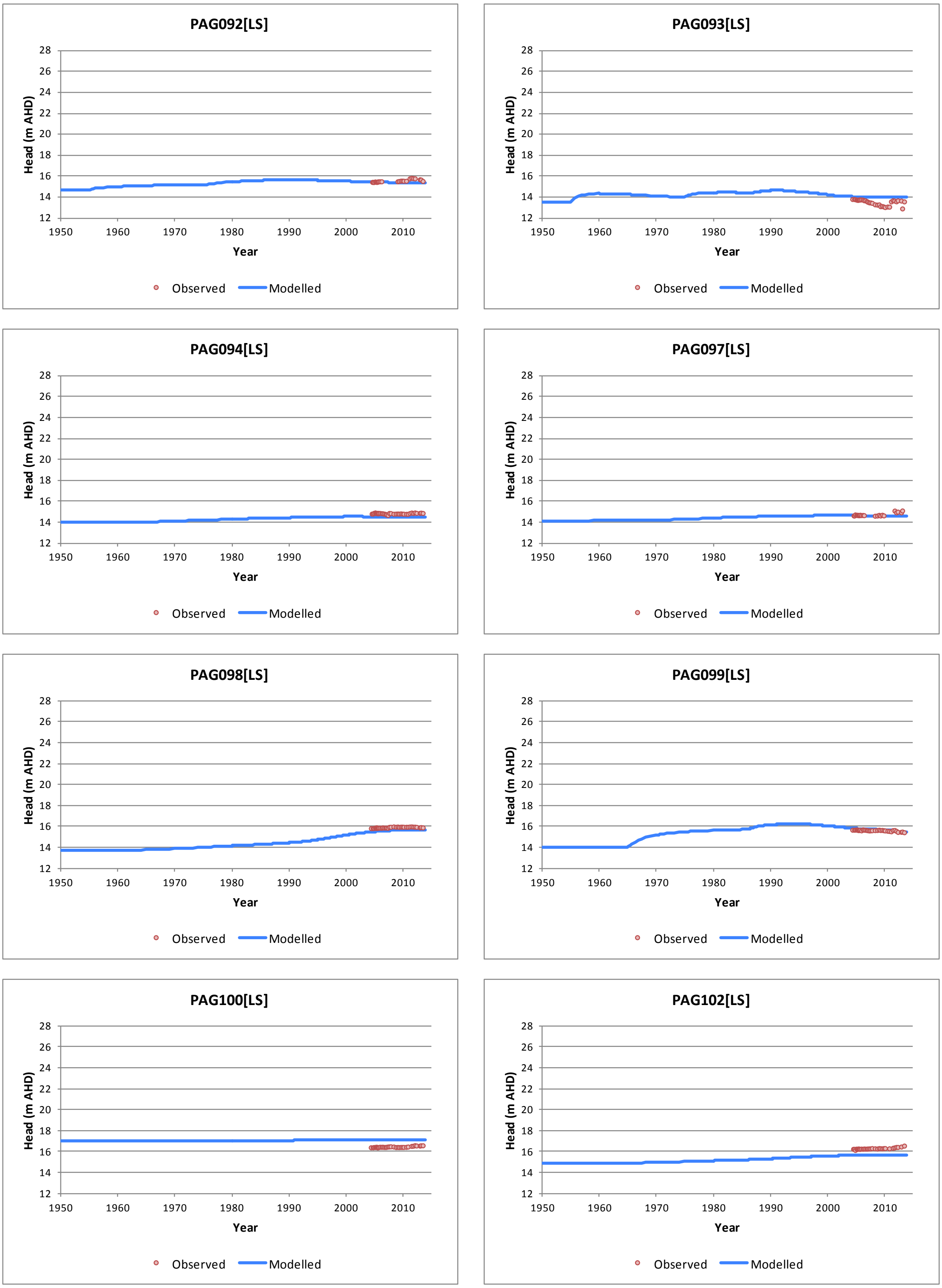


Figure 4.4(e). Hydrograph comparison between observed and modelled for Pike (Loxton Sands-Layer 1)

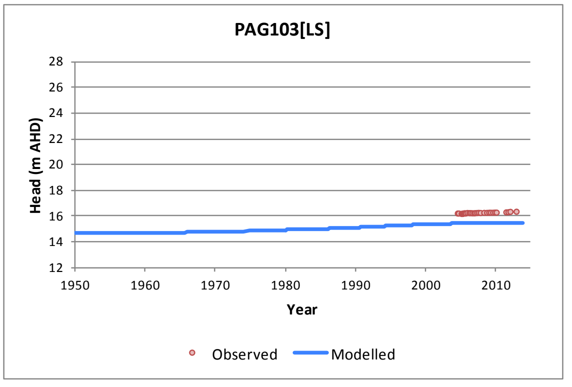


Figure 4.4(f). Hydrograph comparison between observed and modelled for Pike (Loxton Sands-Layer 1)

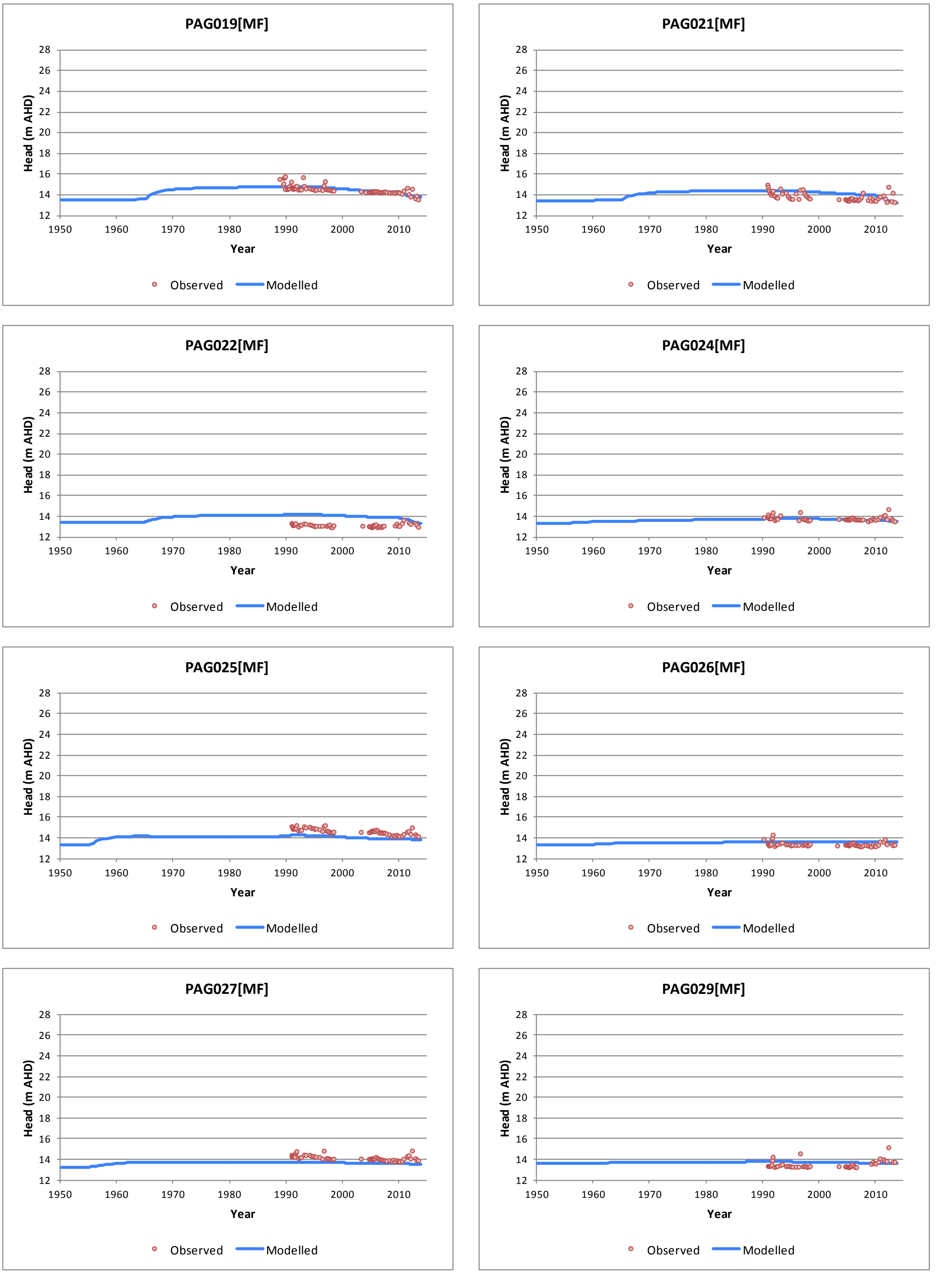


Figure 4.5(a). Hydrograph comparison between observed and modelled for Pike (Monoman Formation-Layer 1)

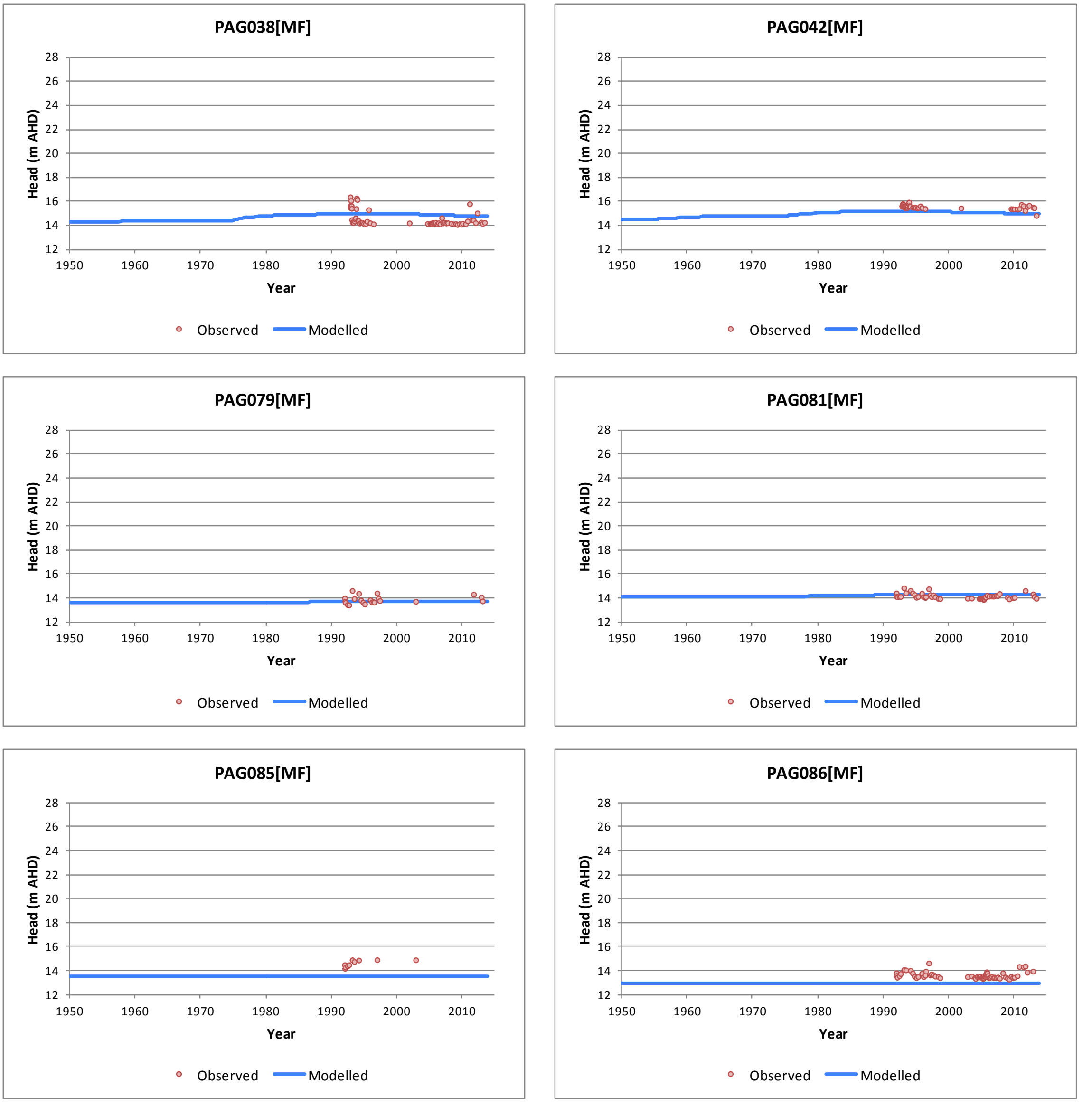


Figure 4.5(b). Hydrograph comparison between observed and modelled for Pike (Monoman Formation-Layer 1)

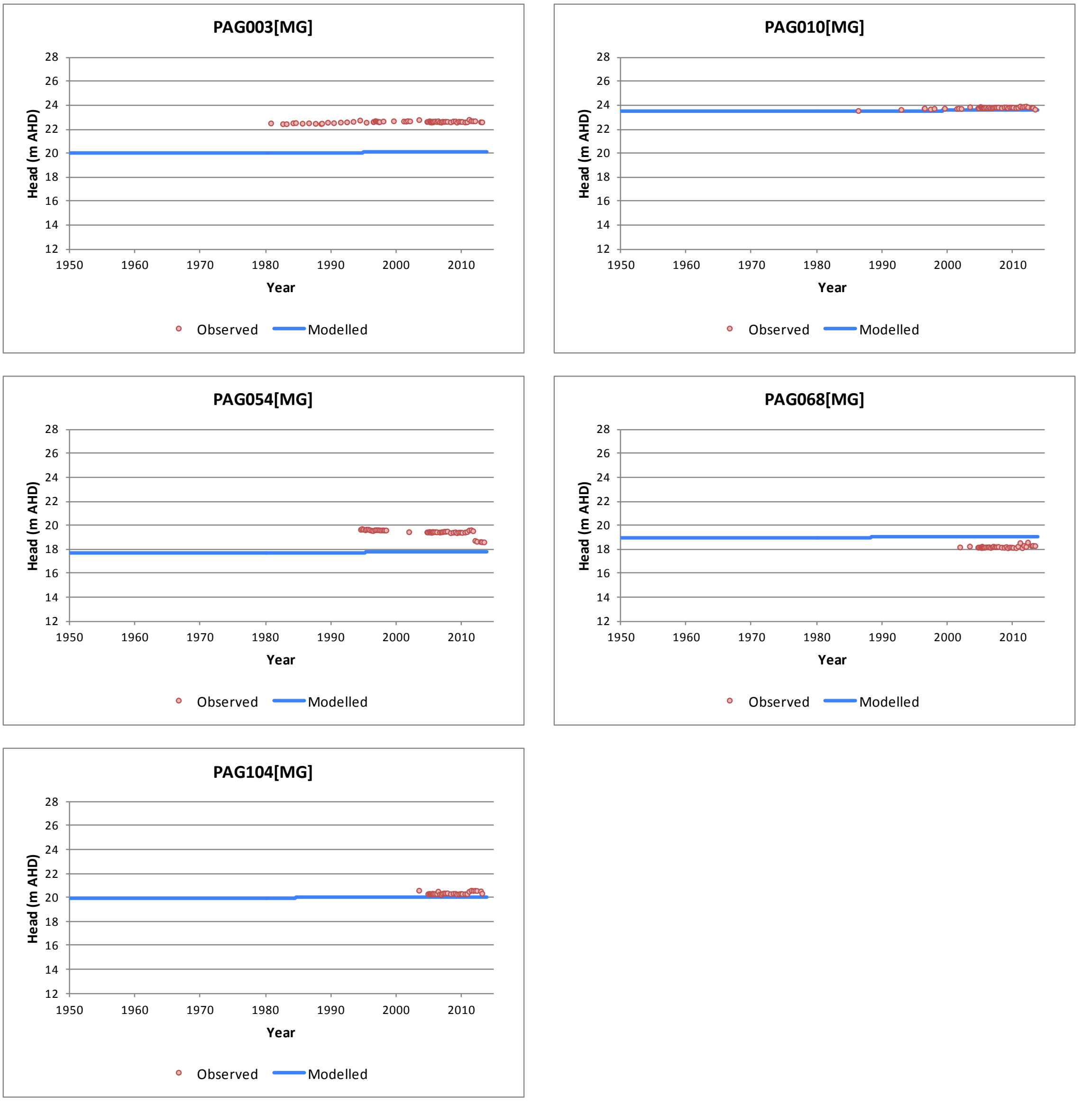


Figure 4.6. **Hydrograph comparison between observed and modelled for Pike (Murray Group-Layer 5)**

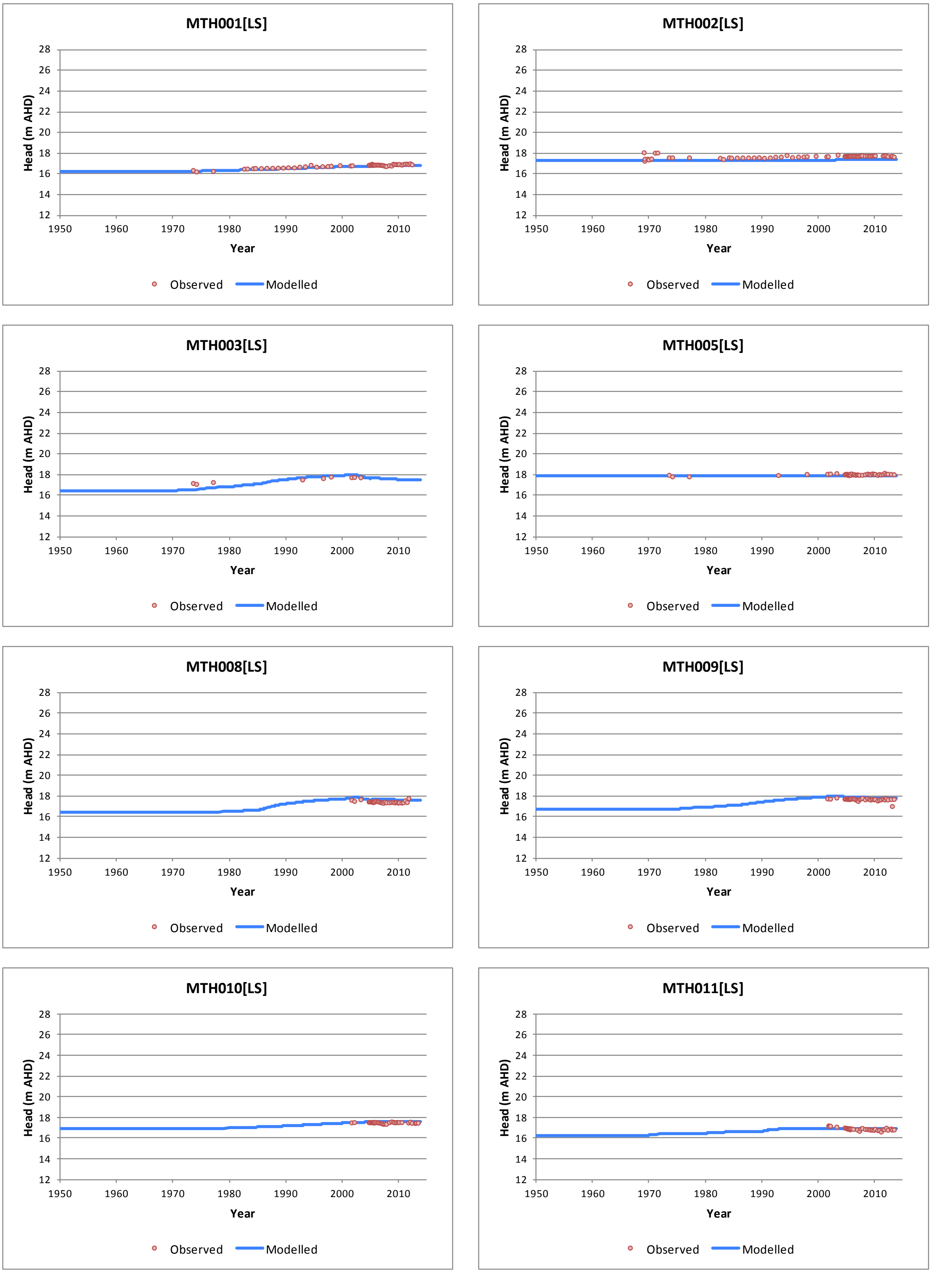


Figure 4.7(a). Hydrograph comparison between observed and modelled for Murtho (Loxton Sands-Layer 1)

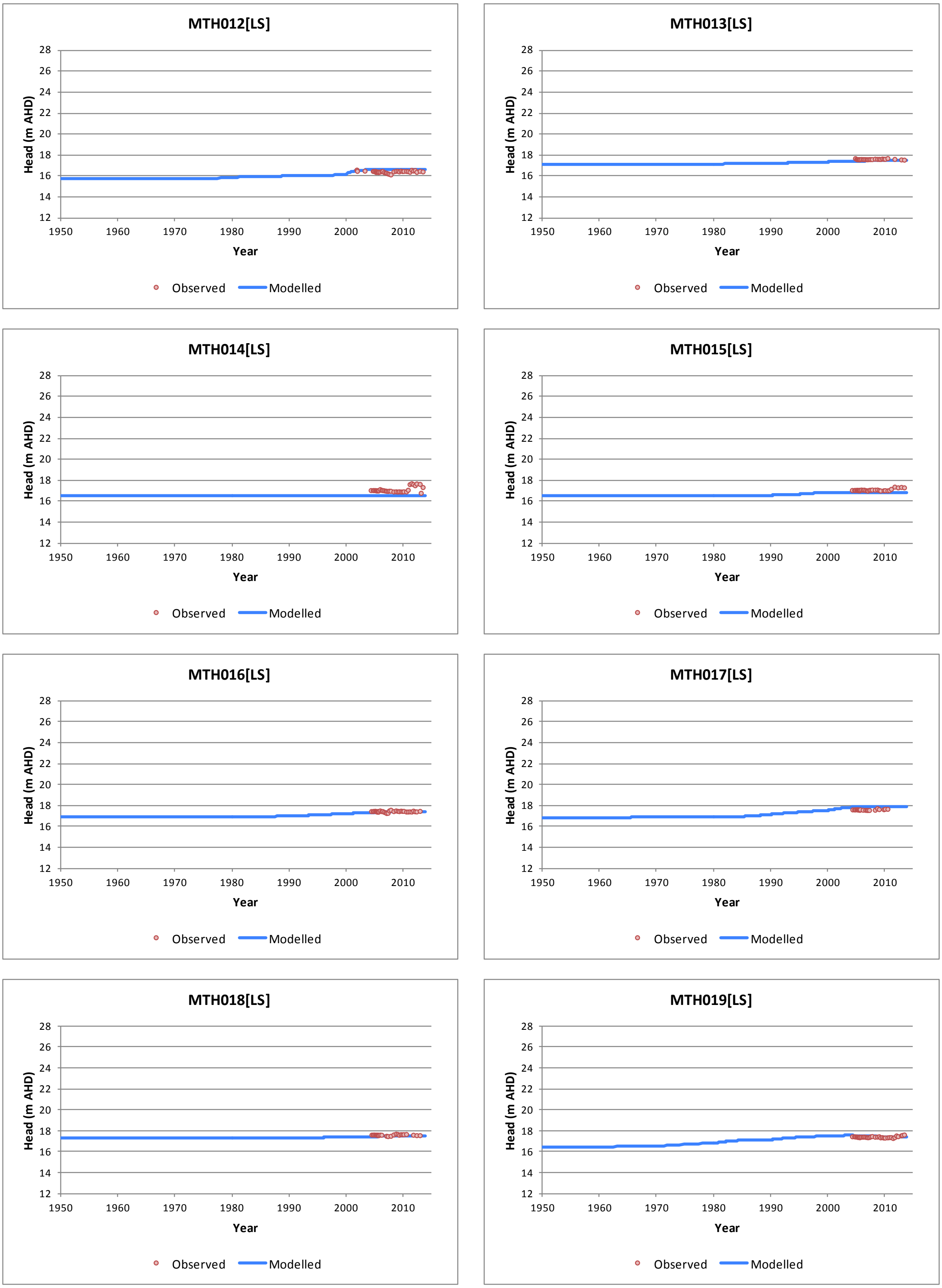


Figure 4.7(b). Hydrograph comparison between observed and modelled for Murtho (Loxton Sands-Layer 1)

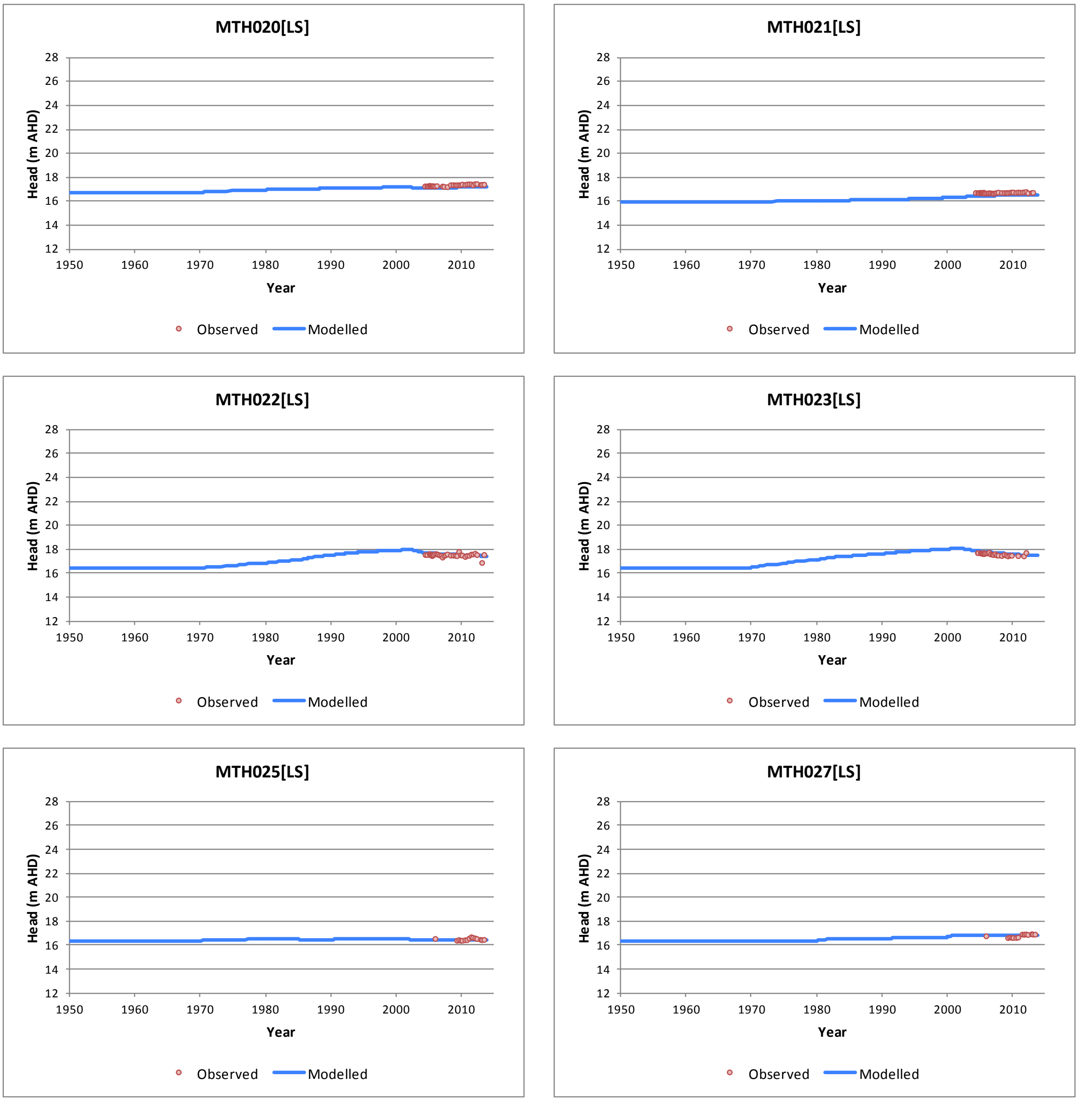


Figure 4.7(c). Hydrograph comparison between observed and modelled for Murtho (Loxton Sands-Layer 1)

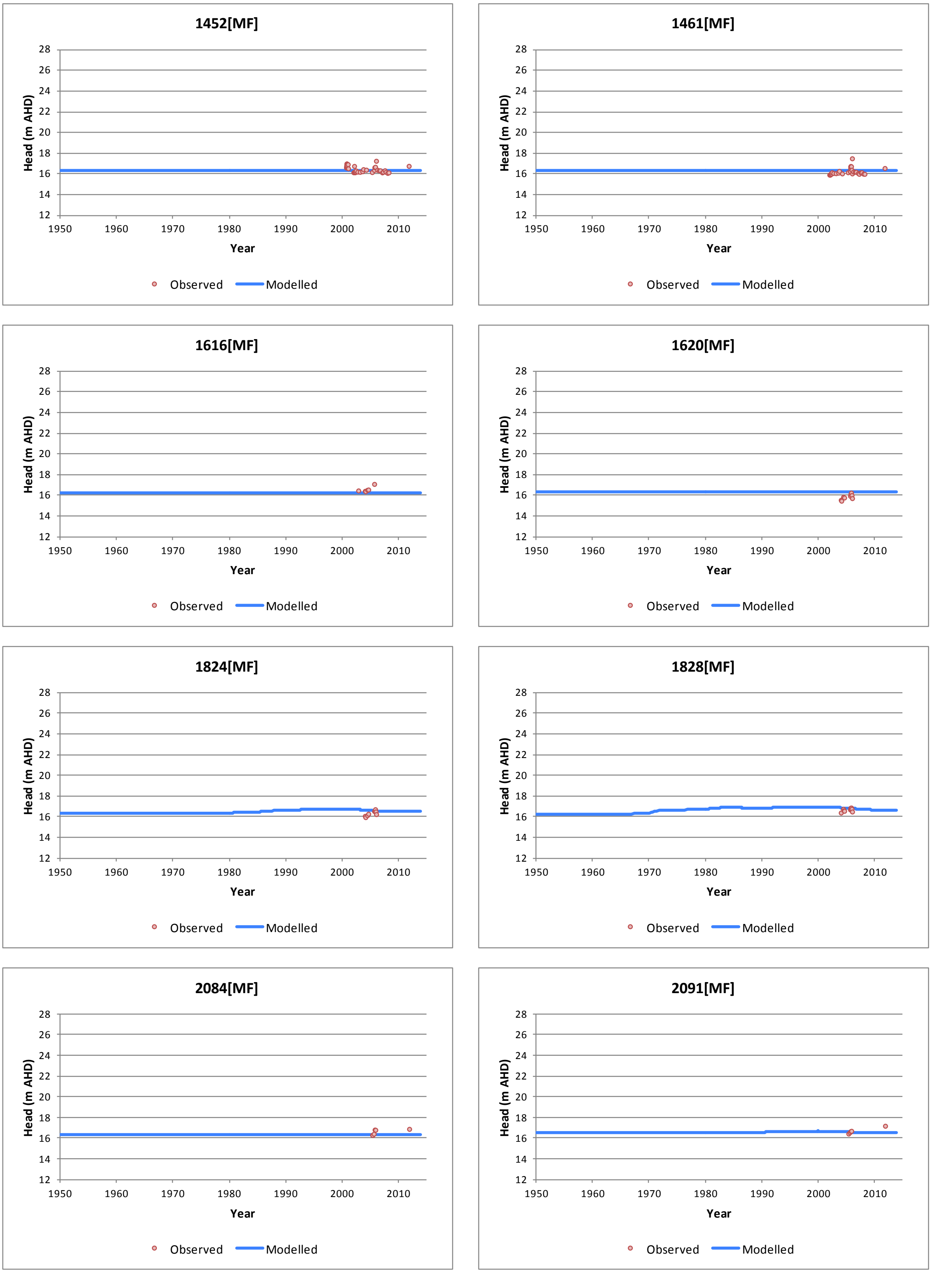


Figure 4.8(a). Hydrograph comparison between observed and modelled for Murtho (Monoman Formation-Layer 1)

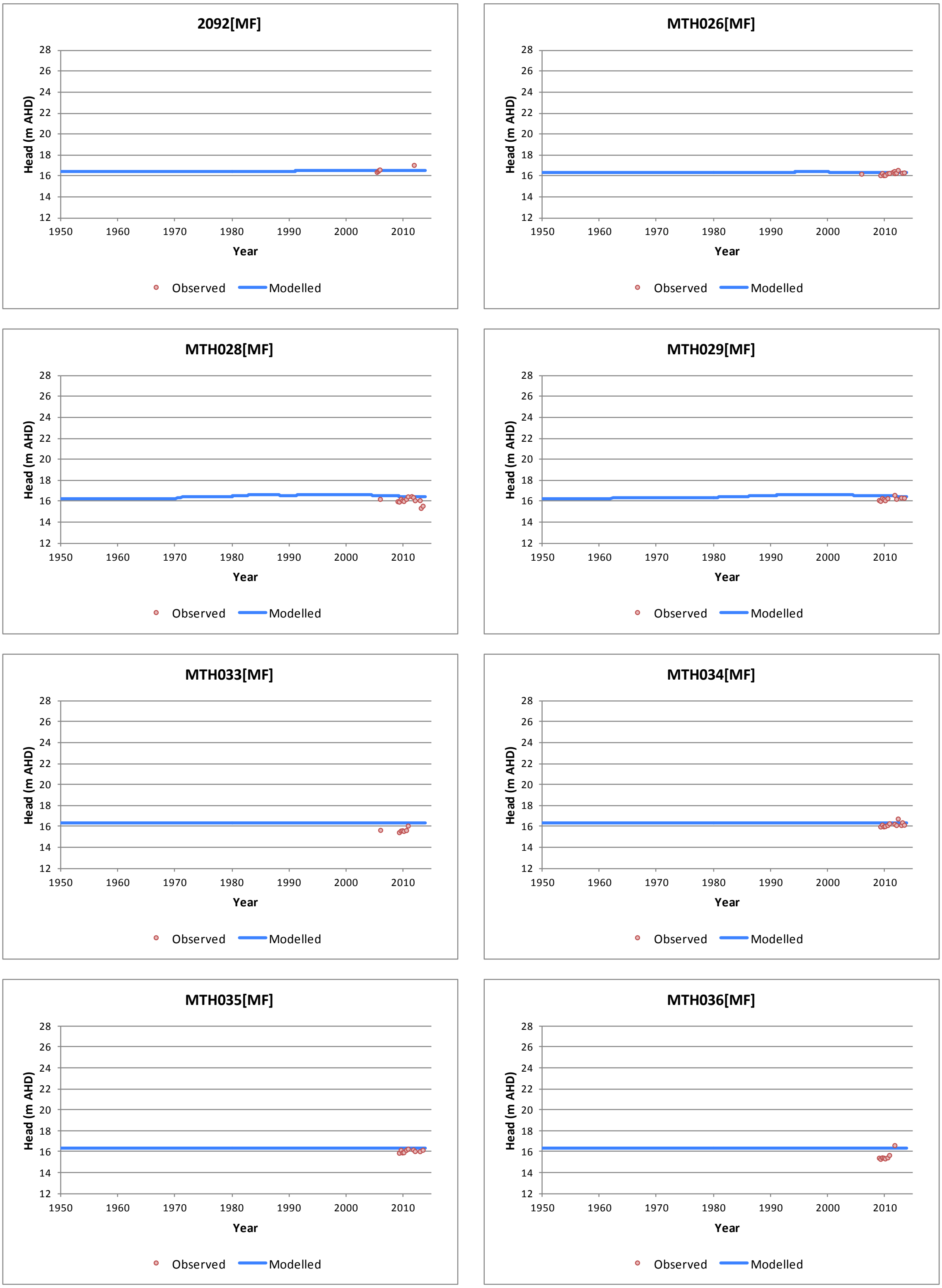


Figure 4.8(b). **Hydrograph comparison between observed and modelled for Murtho (Monoman Formation-Layer 1)**

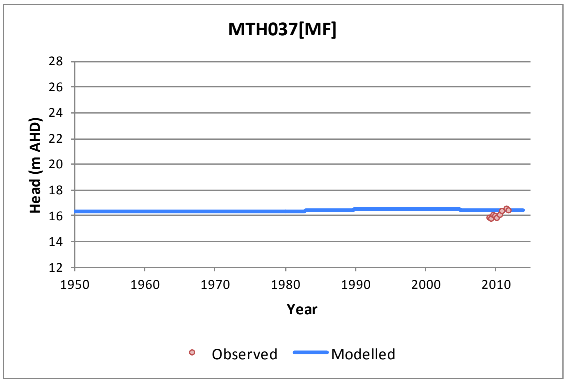
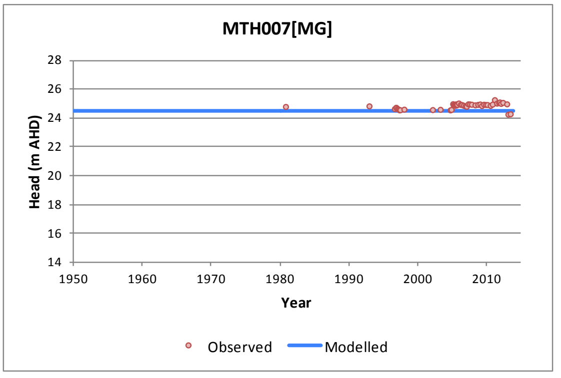


Figure 4.8(c). **Hydrograph comparison between observed and modelled for Murtho (Monoman Formation-Layer 1)**



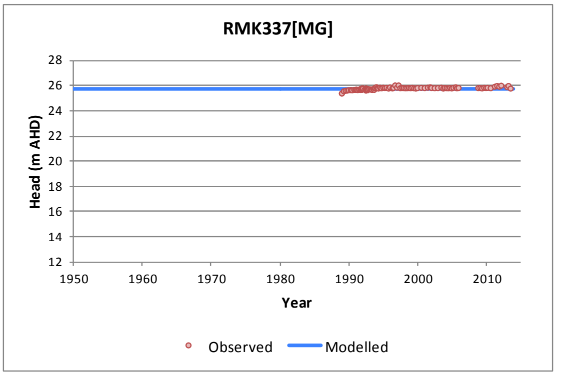


Figure 4.9. Hydrograph comparison between observed and modelled for Murtho (Murray Group-Layer 5)

Figure 4.10 shows the spatial distribution of hydrograph calibration performance for the Loxton Sands, Monoman Formation and Murray Group Limestone aquifers in the Pike-Murtho area. The figure indicates that the observation wells with a less satisfactory match are mainly located in Pike. Most of these wells are in the Murray Group Limestone.

The calibration performance is also summarised in Table 4.1. Most hydrographs show a good match between observed and modelled, except the observed fluctuations in head in the near-river wells. Table 4.1 indicates that most wells in the Loxton Sands and Monoman Formation show a good match in level (within ± 0.5 m) while two of the Murray Group Limestone wells show a less satisfactory match (more than ± 1 m).

Table 4.1 Hydrograph calibration performance

Aquifer	Number of observation wells			
	Good match in level (<±0.5 m)	Moderate match in level (±0.5 - 1 m)	Less satisfactory match in level (>±1 m)	Total
Loxton Sands	61	2	0	63
Monoman Formation	26	5	0	31
Murray Group	4	1	2	7
Total	91	8	2	101

4.3.3 CALIBRATION RESULTS – ITERATION RESIDUAL ERROR

The SRMS error between observed and modelled heads was calculated for the years 1986, 2005 and 2013. These years span the period during which data are available and represent three different hydrogeological conditions:

- 1986 represents the pre-1988 conditions
- 2005 was before the commencement of the SIS and a time of lowered irrigation recharge, due to improved efficiency and drought restrictions
- 2013 was after the commencement of the Pike SIS and represents current irrigation development and climate.

Figure 4.11 to Figure 4.13 plot observed head against modelled head for the years 1986, 2005 and 2013 respectively. The SRMS is:

- 1986: 6.65%
- 2005: 3.86%
- 2013: 4.30%

The SRMS values are within the criteria of 5% - 10% SRMS as suggested by Middlemis et al (2001). 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* (Middlemis et al, 2001) and *Australian Groundwater Modelling Guidelines* (Barnett, et al. 2012).

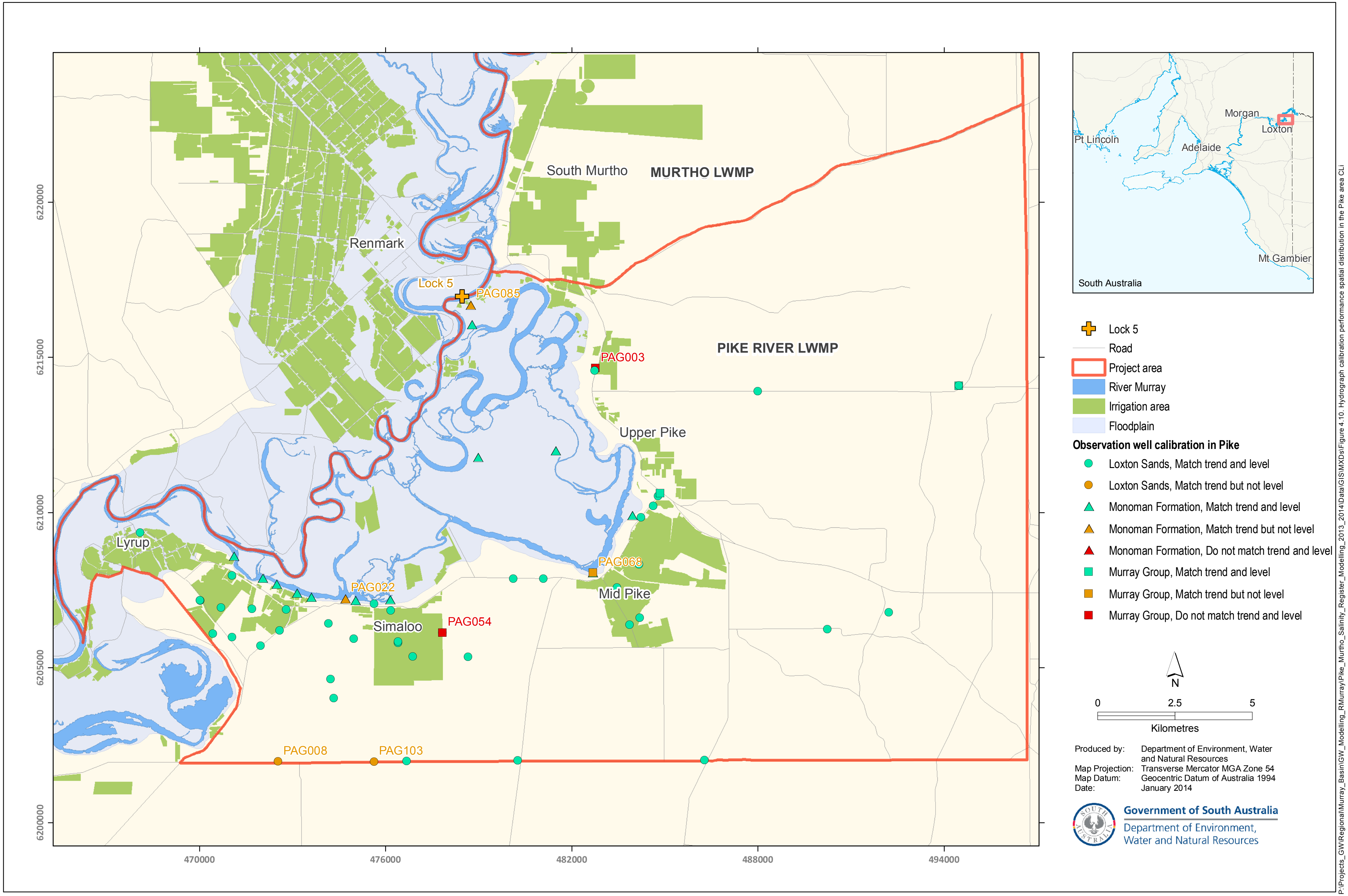


Figure 4.10a. Hydrograph calibration performance spatial distribution in the Pike area

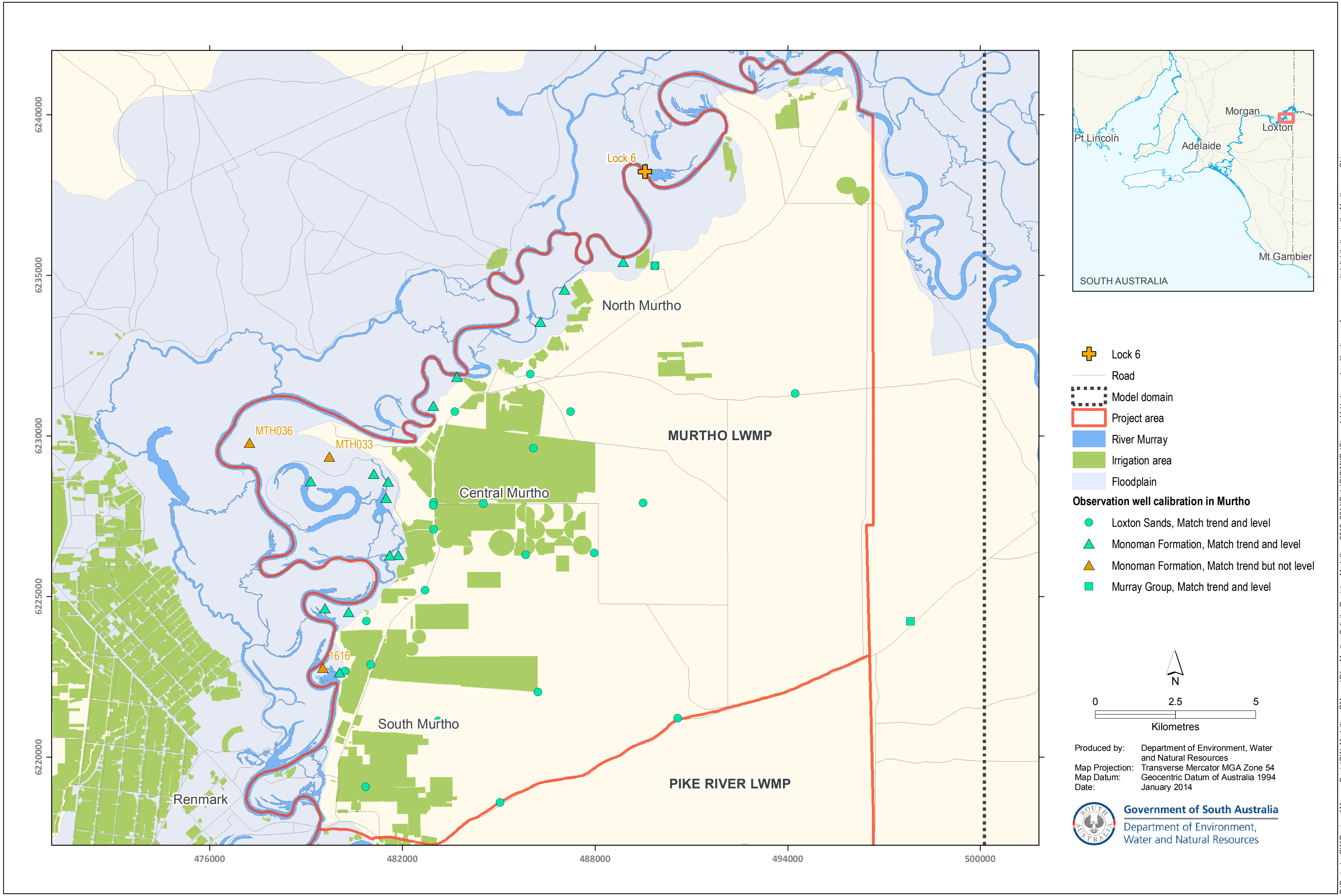


Figure 4.10b. Hydrograph calibration performance spatial distribution in the Murtho area

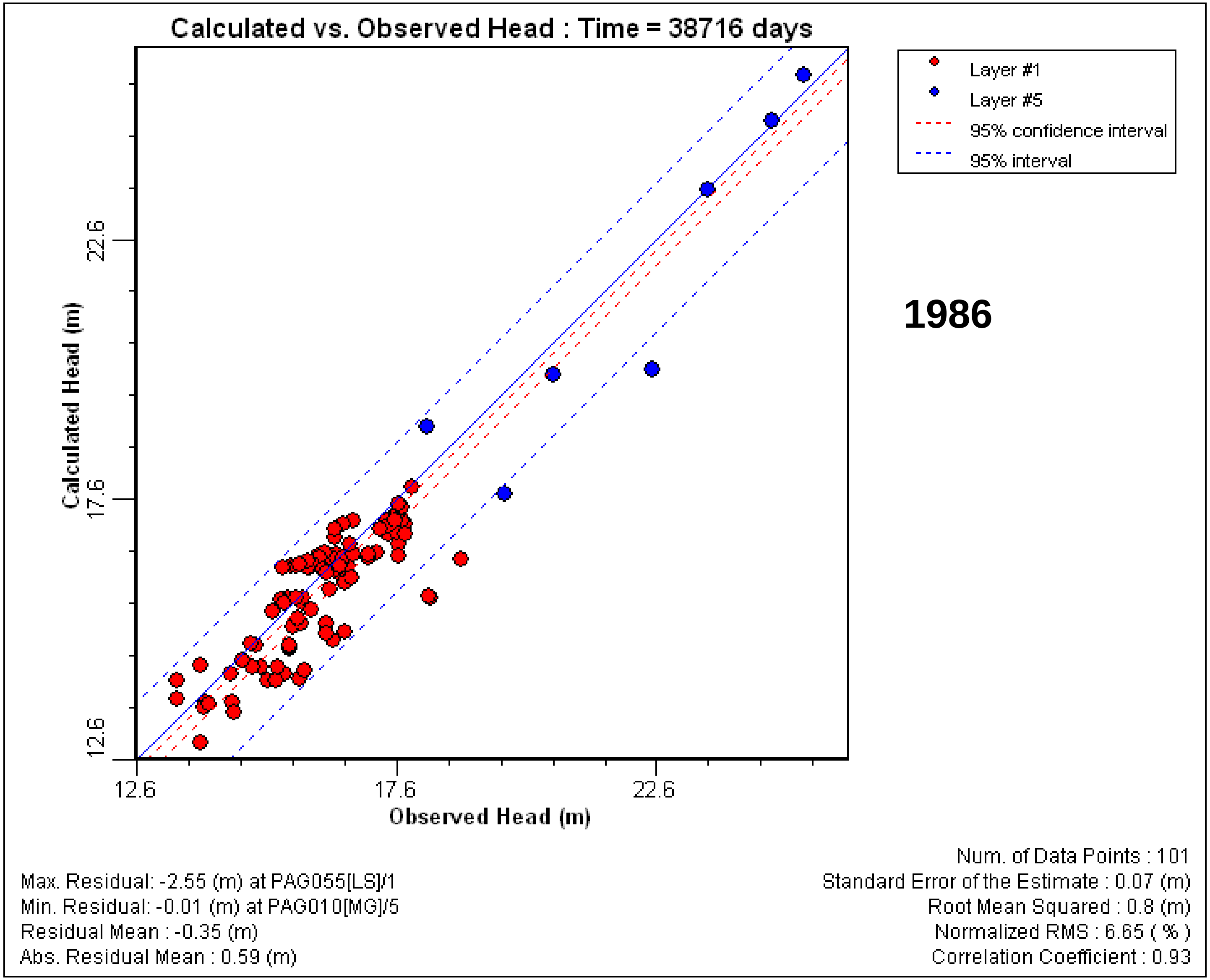


Figure 4.11.Scaled Root Mean Square (SRMS) at 1986

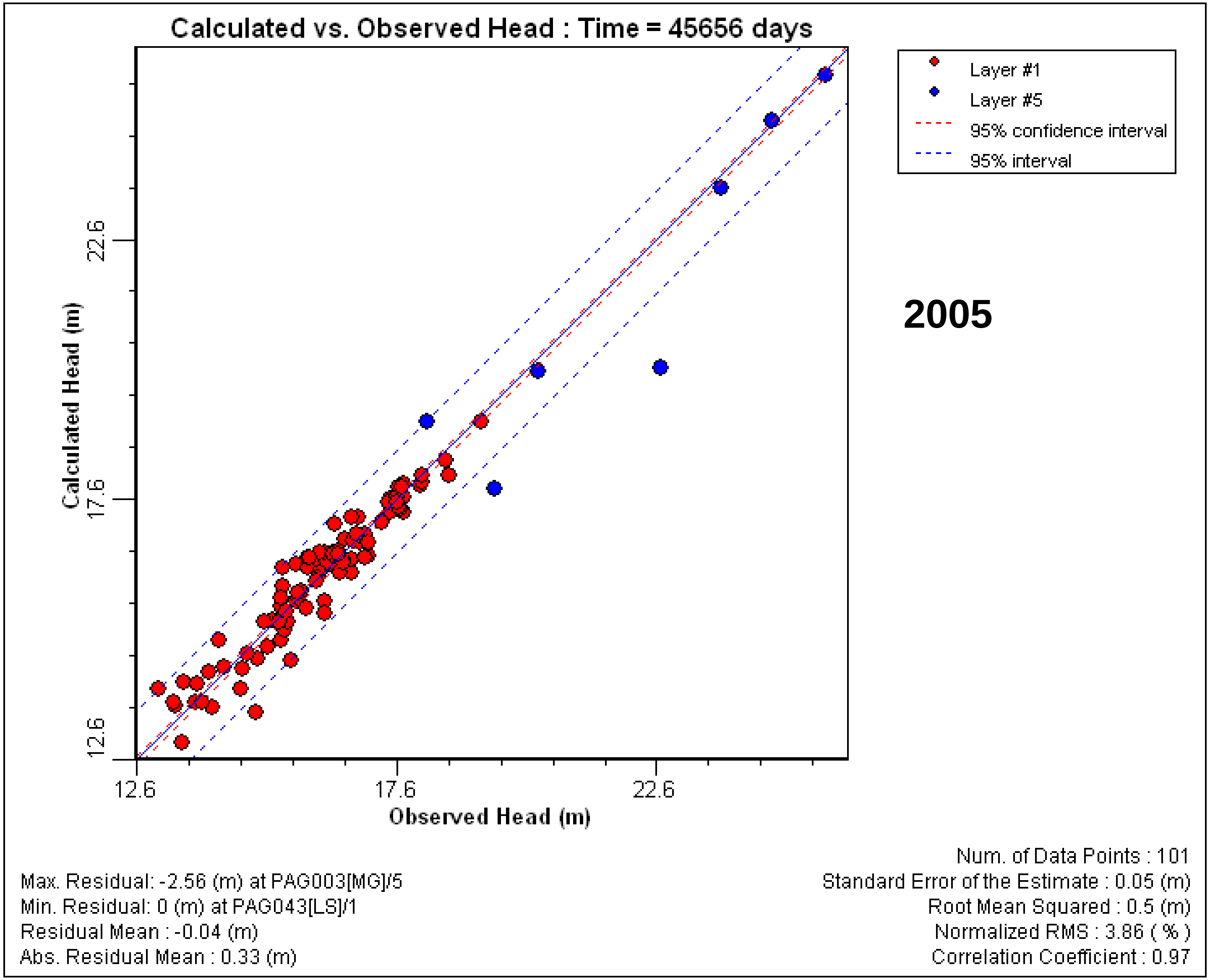


Figure 4.12.Scaled Root Mean Square (SRMS) at 2005

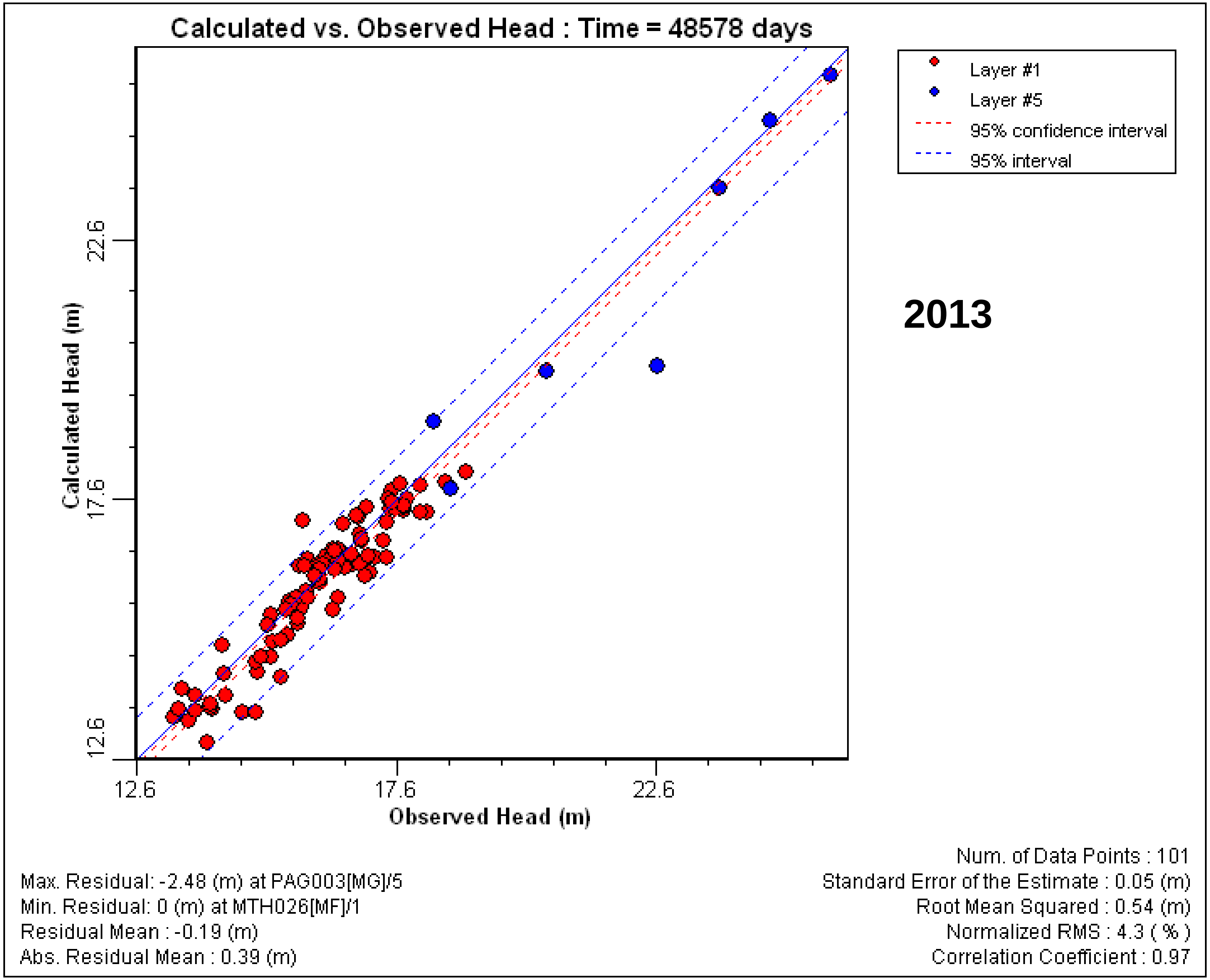


Figure 4.13.Scaled Root Mean Square (SRMS) at 2013

4.4 MODEL CONFIRMATION

The calibration has been achieved with the refined recharge, hydraulic conductivity and boundary condition values remaining consistent with the available 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 Appendix B.

Groundwater flux to river and salt load are estimated for the Pike (from Lyrup to lock 5) and Murtho (from Lock 5 to Lock 6) reaches. Model results for sample years are given in Table 4.2.

Table 4.2 Modelled groundwater flux and salt load in the Pike-Murtho calibrated model

Reach	Stress period	Flux to river (m^3/d)	Salt load to river (t/d)
Pike	Steady-state	2099	31.6
	1986	5475	101.2
	2005	5230	99.7
	2013	4397	79.2
Murtho	Steady-state	6568	20.5
	1986	7955	51.7
	2005	8745	67.1
	2013	8250	56.4

Figure 4.14 to Figure 4.19 show the spatial distribution of modelled salt load of the Pike and Murtho reaches for the years 1986, 2005 and 2013.

In Pike, due to the wide Pike-Mundic floodplain between the River Murray and the Pike River, salt load that enters the River Murray directly is relatively small and appears to be insensitive to irrigation activities in Pike.

In Murtho, most of the river reach is in losing stream condition. There is a considerable amount of salt load entering the river downstream of Lock 6 due to the approximately3 m river stage difference between upstream and downstream of the Lock 6.

Another reach with noticeable salt load is the reach to the north-west of Central Murtho (Zone 25 in the figures), which is likely due to its proximity to the edge of the floodplain. The Woolenook anabranch creek (Zone 96) also collects a significant amount of salt load and delivers it to the River Murray (Zone 44). From 1986 to 2005, overall salt load has slightly increased and there is no particular reach that shows a significant change.

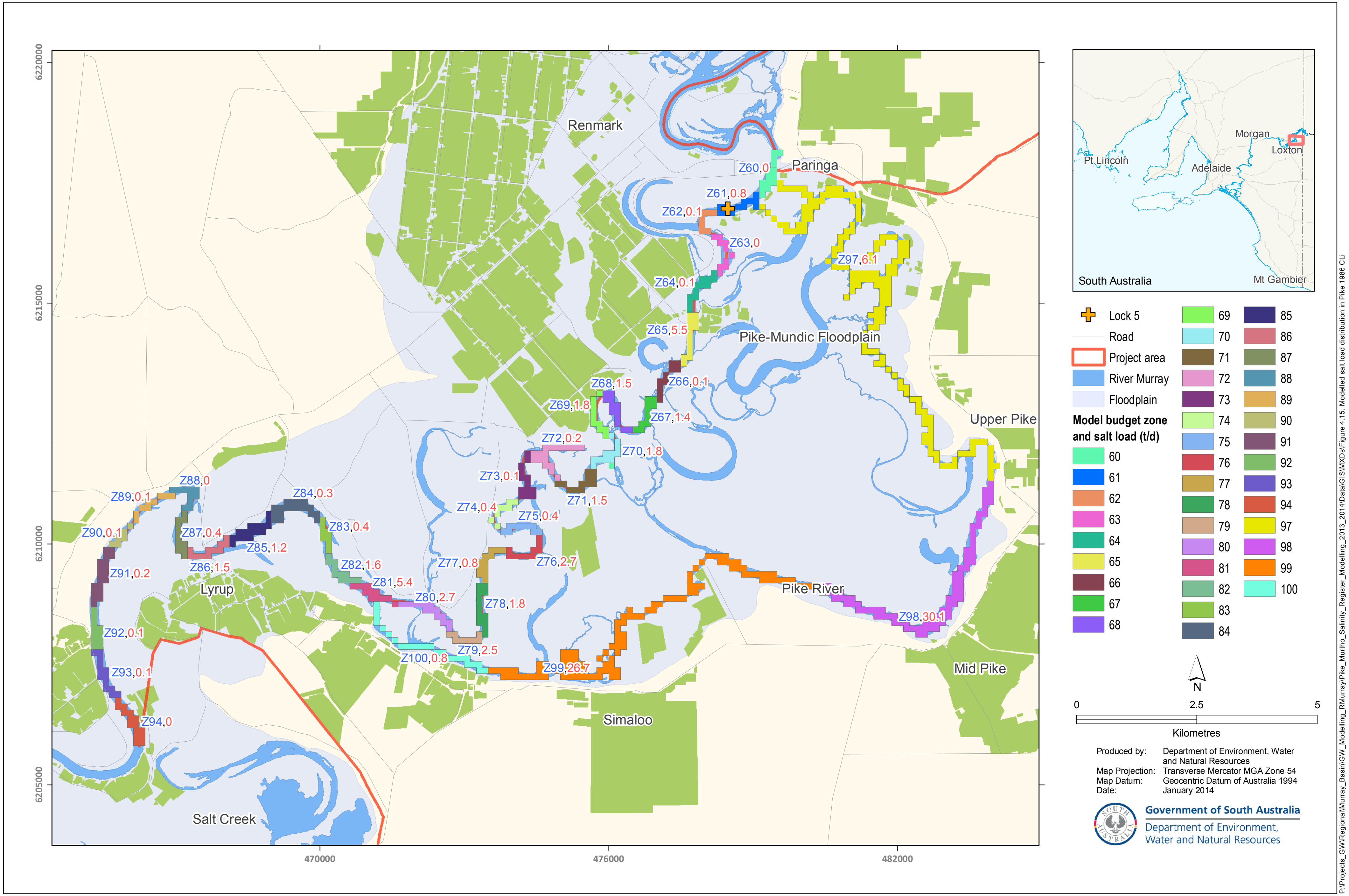


Figure 4.14. Modelled salt load distribution in Pike at 1986

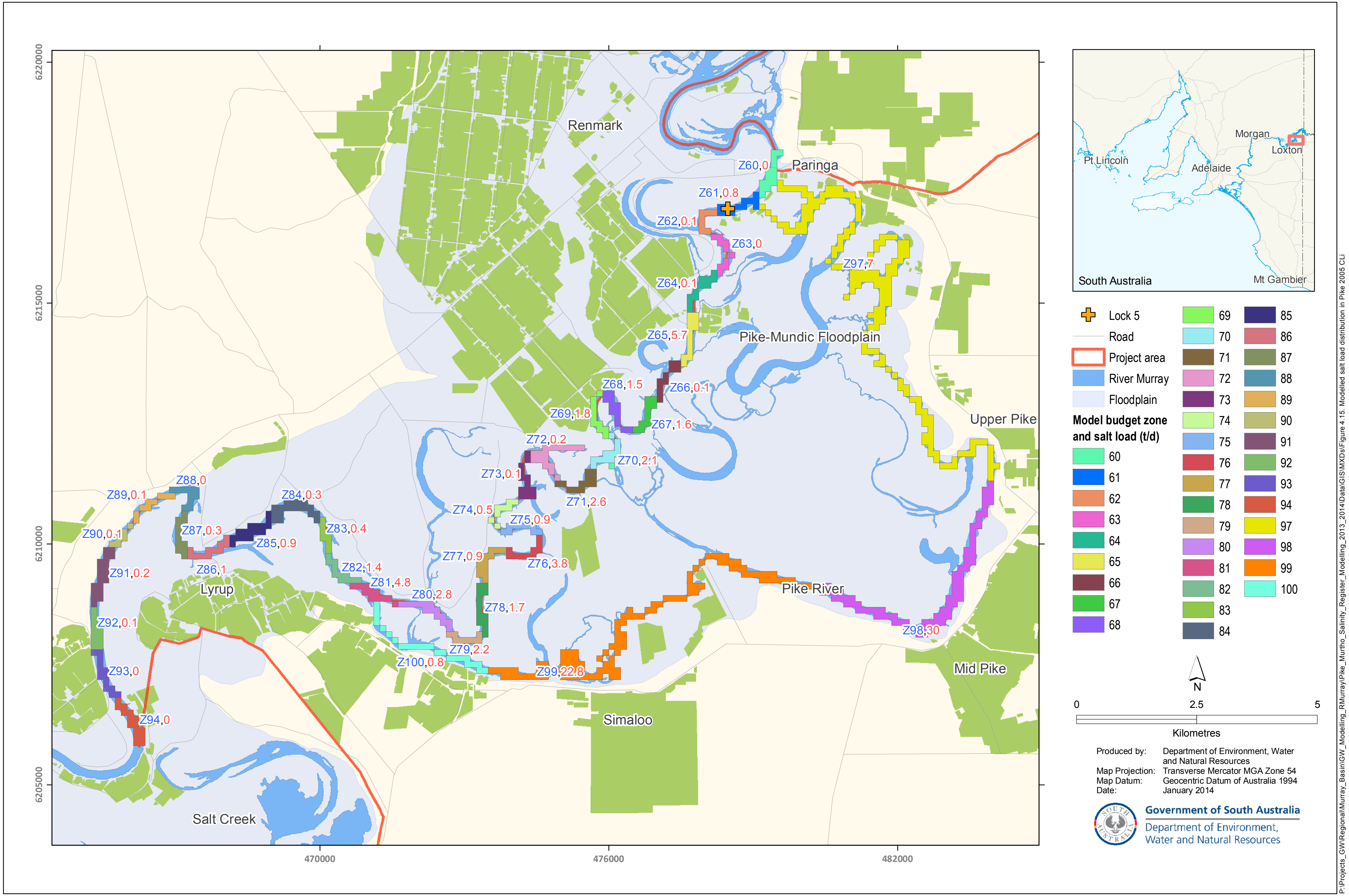


Figure 4.15. Modelled salt load distribution in Pike at 2005

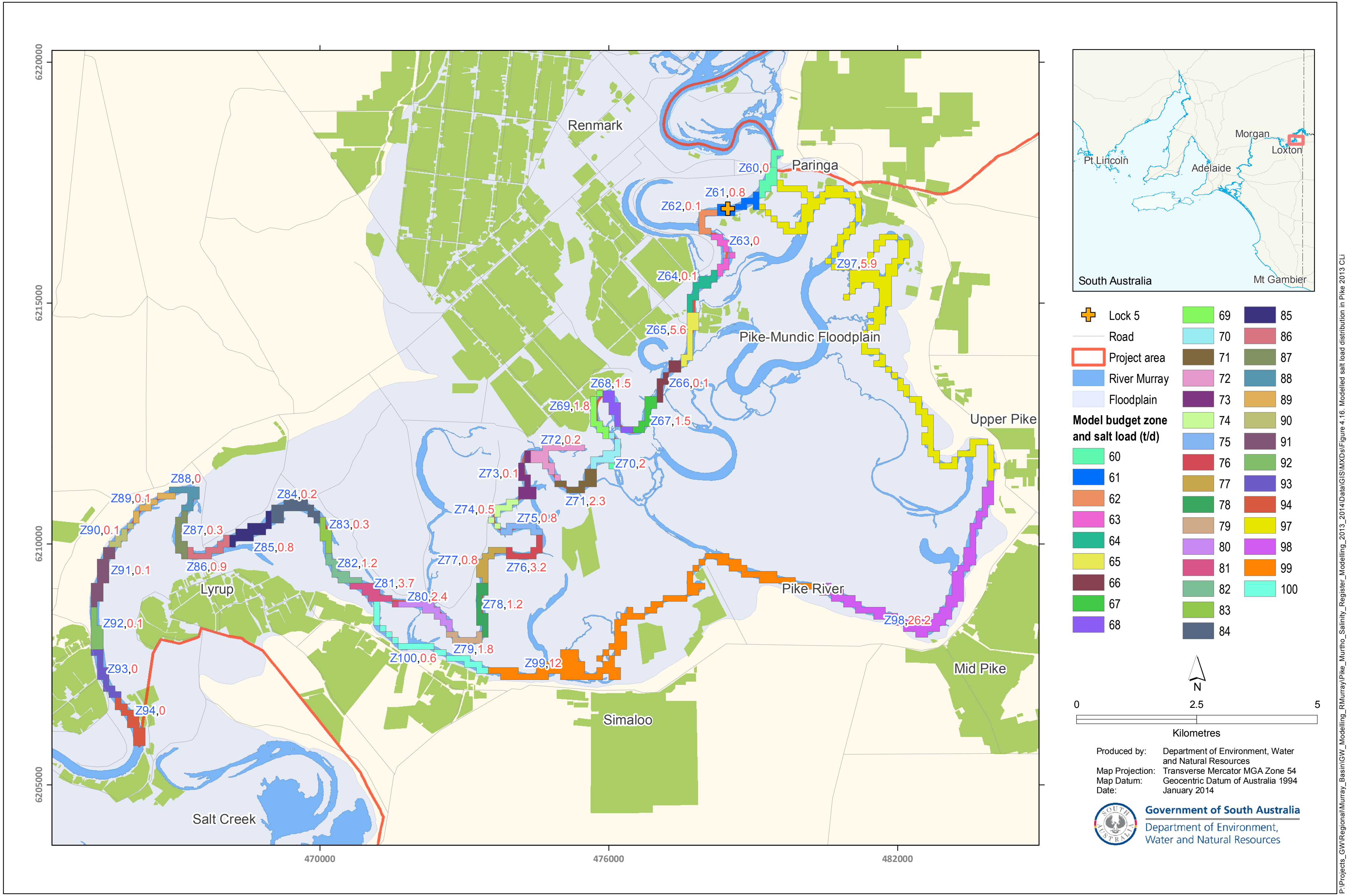


Figure 4.16. Modelled salt load distribution in Pike at 2013

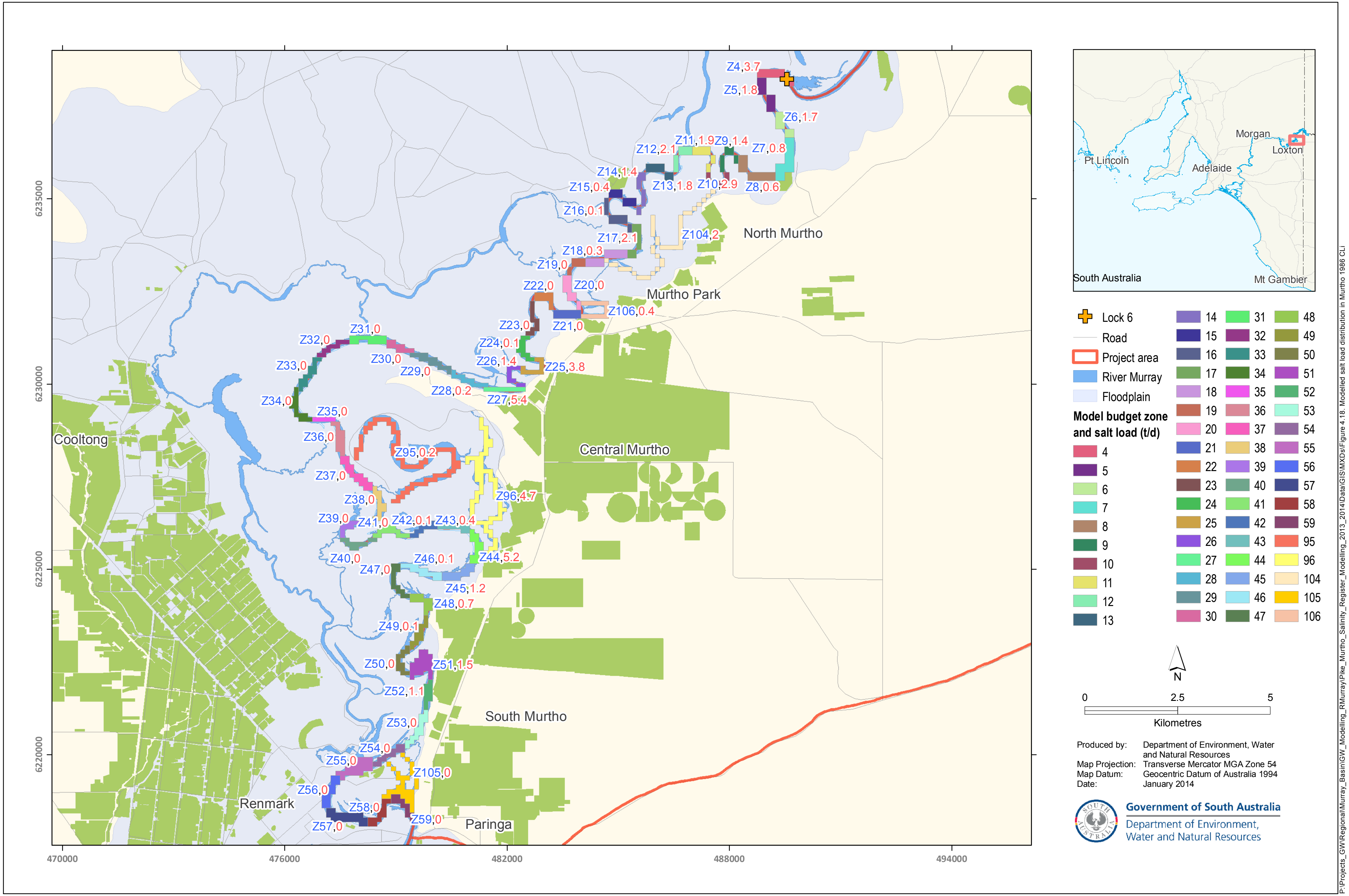
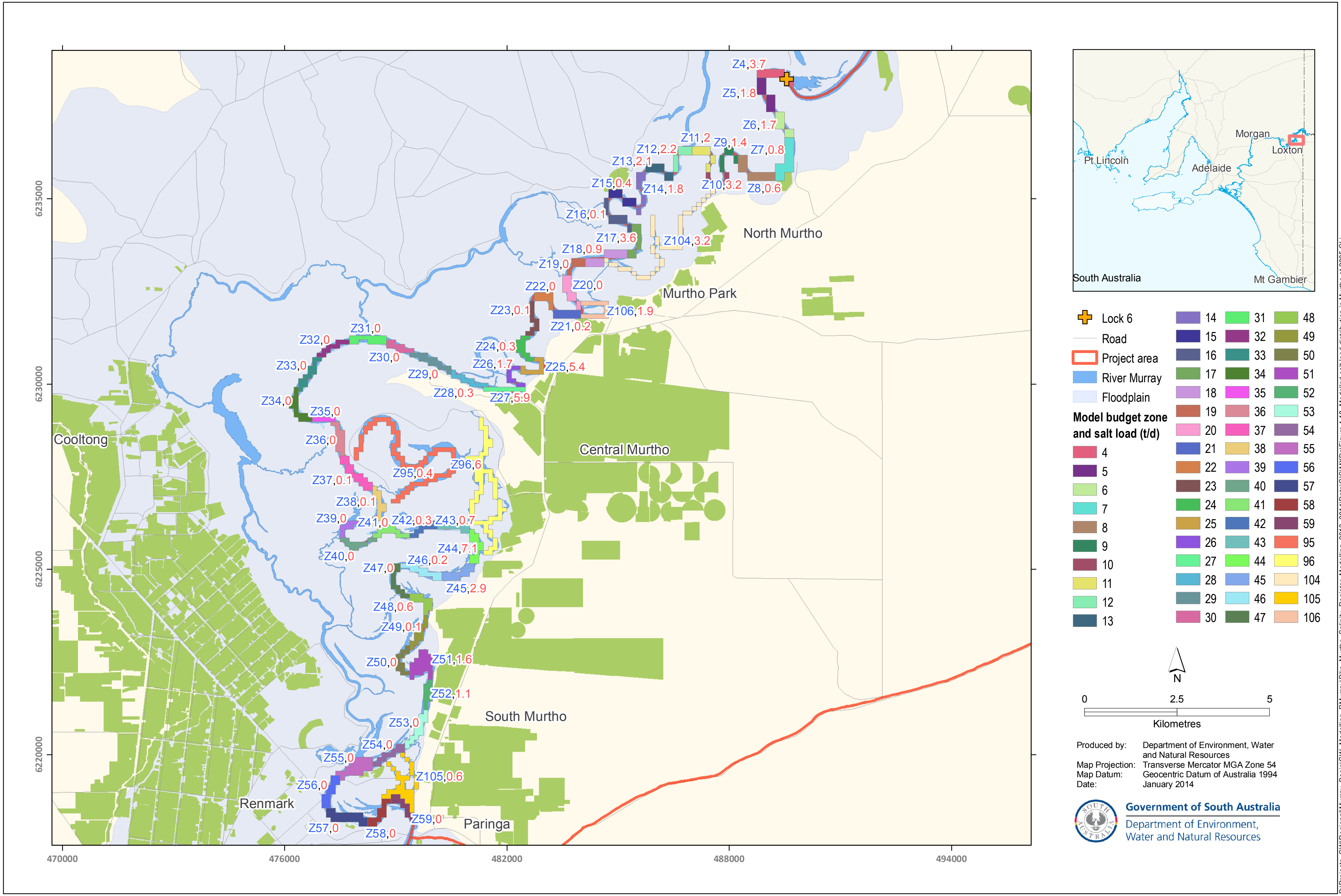


Figure 4.17. Modelled salt load distribution in Murtho at 1986



P:\Projects_GW\Regional\Murray_Basin\GW_Modelling_RMurray\Pike_Murtho_Salinity_Register_Modelling_2013_2014\Data\GIS\MXDs\Figure 4.18. Modelled salt load distribution in Murtho at 2005 CLi

Figure 4.18. Modelled salt load distribution in Murtho at 2005

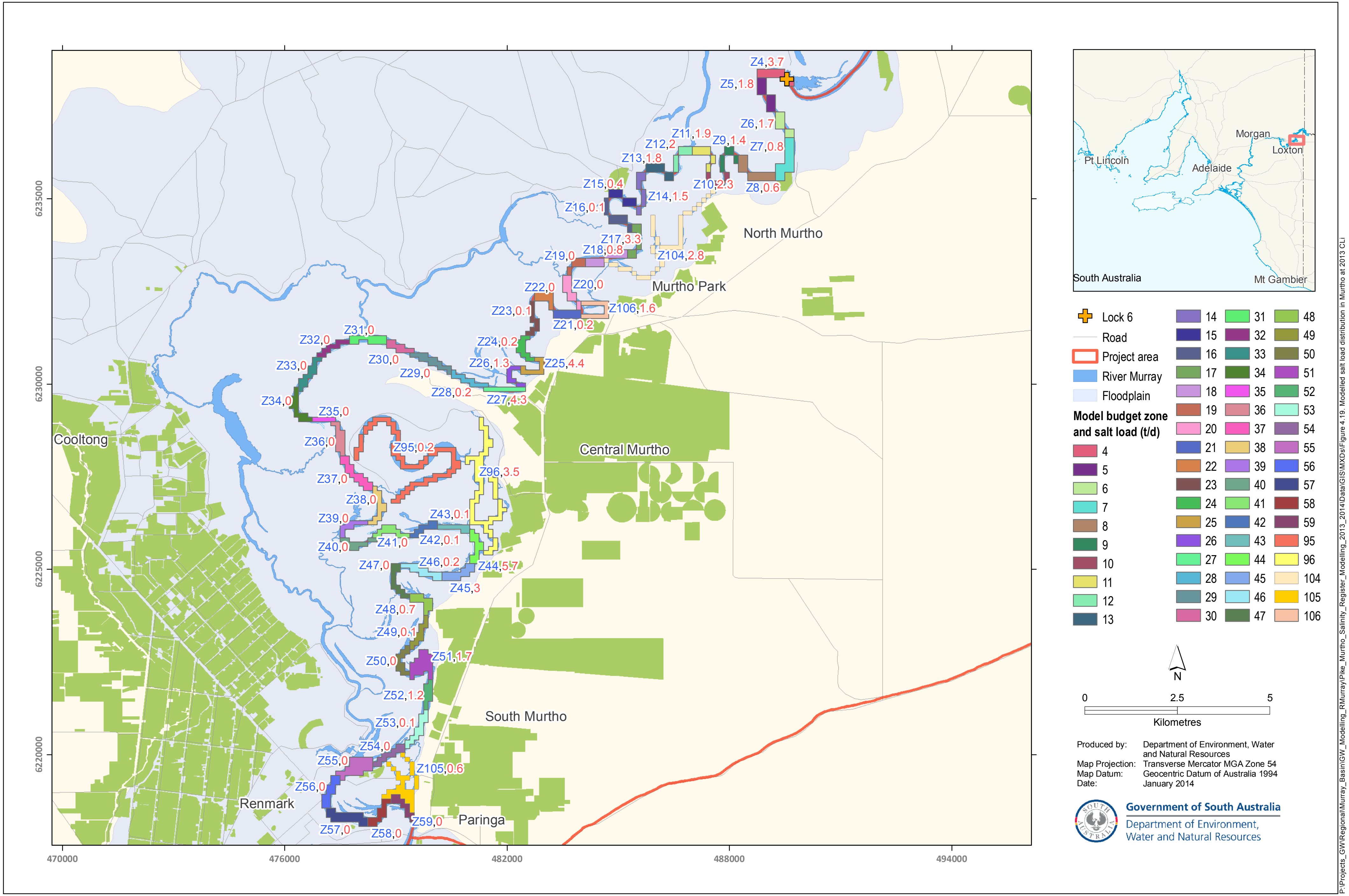
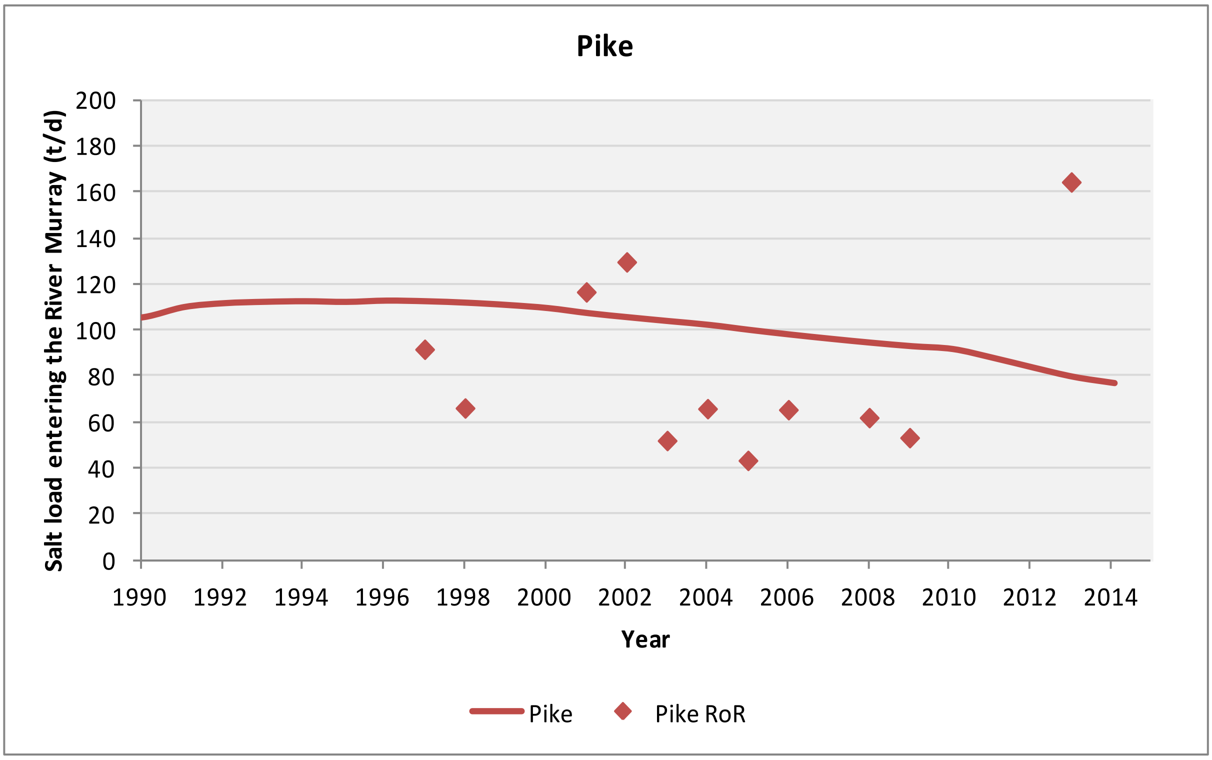


Figure 4.19. Modelled salt load distribution in Murtho at 2013



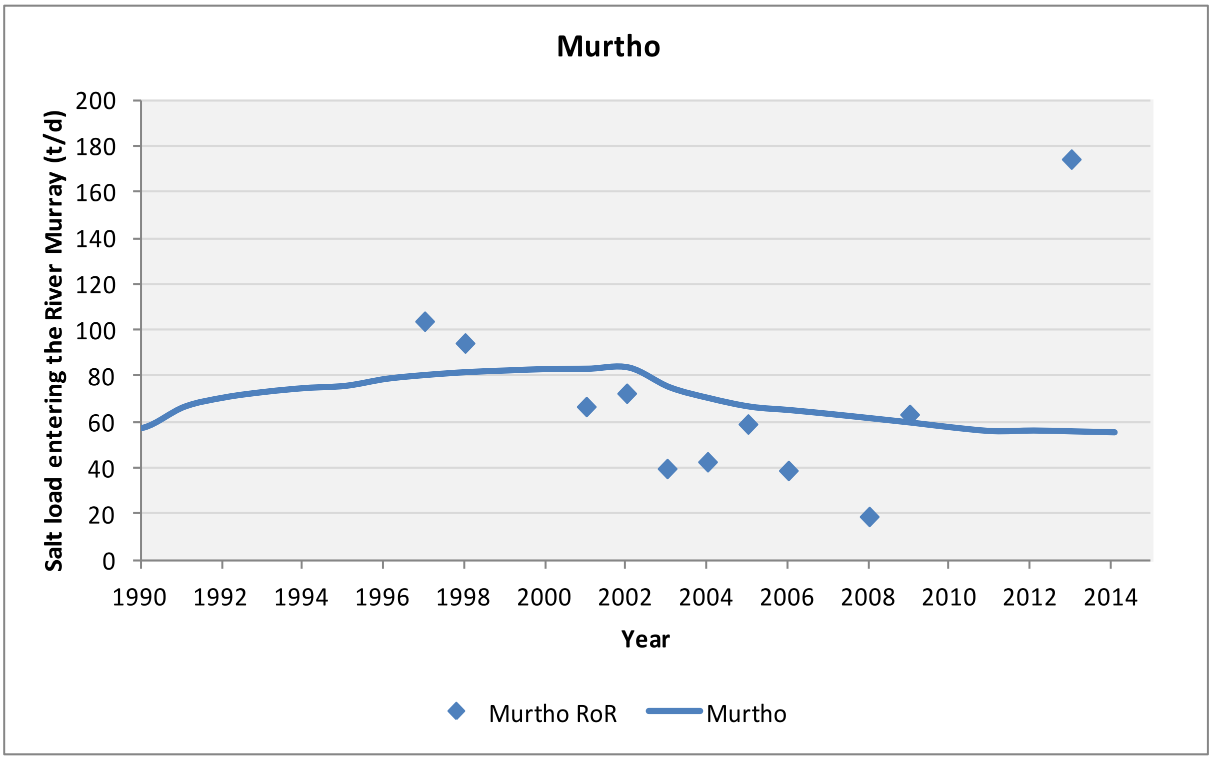


Figure 4.20 Salt load comparison between Run-of-River measurements and the calibrated model outputs from Pike-Murtho reaches

Figure 4.20 compares Run-of-River estimates of salt loads with modelled salt loads for the Pike-Murtho reach. Note that the RoR results exhibit a great deal of variation, as discussed in Section 2.6.1.2. In general the higher RoR estimates are caused by flood recessions while the lower RoR estimates are due to the Millennium Drought. As the model only simulates average climate conditions and does not take flooding or drought into account (i.e. the river stage is held constant), the model does not intend to match the higher or lower RoR estimates. The figure shows that the modelled salt load lies somewhere between the higher and lower RoR estimates, which is considered satisfactory.

4.4.2 GAINING AND LOSING REACHES

Geophysical surveys of riverbed resistivity (NanoTEM surveys, Section 2.6.1.1) 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. NanoTEM data from 2004 (Figure 2.9) shows the riverbed resistivity. Figure 4.11 and Figure 4.15 show the 2005 modelled salt load. A comparison is provided in Table 4.3. The correct pattern is seen in all river reaches except for one reach (river km 564–593 in Pike). The majority of salt load in this reach comes from Renmark, which the model does not intend to simulate in details. The comparison increases confidence in the model results.

Table 4.3 Comparison of 2004 observed riverbed resistivities with 2005 modelled salt load

Region	River km	Observed riverbed resistivity	Modelled salt load (t/d)	In agreement?
Pike	530 - 538	High	0 - 1	Yes
	564 - 593	Moderate	0 - 5.7	No. Most of the salt load in this reach comes from Renmark irrigation area, which the model does not simulate in details.
	Pike River	Low	22.1 - 29.5	Yes
Murtho	565 - 578	High	0 - 1.6	Yes
	579 - 580	Low	2.9 - 7.1	Yes
	581 - 596	High	0 - 0.7	Yes
	597 - 599	Generally low but high at river km 598	5.4 - 5.9 1.7 at river km 598 (zone 26)	Yes
	600 - 615	Generally high but low at river km 604 and 617	0 - 2.2 3.9 at river km 607 (zone 17) 3.1 at river km 614 (zone 10)	Yes
	616 - 620	Low	0.6 - 3.7	Yes

4.4.3 RECHARGE VOLUMES

The good match to groundwater trends indicates that the recharge rates estimated via inverse modelling (calibration) are consistent with available hydrogeological information. While this minimises uncertainty, confirmation through alternative evidence is also needed.

To seek confirmation of recharge estimates, an independent estimate of accession water volumes was undertaken by Laroona Environmetrics (2014) (Appendix C). The accession estimates are based on a review of irrigation and infrastructure information for both Pike and Murtho sourced from DEWNR and historical irrigation-trust records. A water balance method was employed in the calculation and the details are shown in Appendix C. The outputs of this work were compared with the total recharge applied in the calibrated model to confirm that the modelled recharge was within appropriate range. This comparison provides confidence that the total recharge applied in the model is within the reasonable range and is consistent with accession estimates.

Figure 4.21 compares the accession-water estimates of Laroona Environmetrics (2014) with the total recharge volume from the calibrated model. In most areas, including Upper and Mid Pike, Simarloo and North Murtho, once the initial lag time is considered there is close alignment in the increase in calculated accession volume and modelled recharge volume. The early gap may indicate the initial losses through the wetting front and lateral movement.

After the wetting front reaches the watertable, the trends become similar in both accession water and total recharge. As expected, the total recharge volume is lower than the accession water. There are exceptions in Upper Pike, North Murtho and Lyrup where the modelled recharge is sometimes slightly higher than the accession estimates, but these are considered acceptable given the uncertainty in the accession estimates. It is noted that accession water is not the same as the total recharge as in reality it may differ by volume, rate over time and footprint due to some of the accession water remaining in the pore spaces of the unsaturated zone and within perched aquifers; the remainder becomes watertable recharge. Additionally, the accession water rates differ from the recharge due to losses in the unsaturated zone through lateral movement, especially when there is an intervening clay layer and there is an initial wetting front loss as the accession water percolates towards the watertable.

In Lyrup, recharge responds very quickly to accession (i.e. very short lag time) as about half of the irrigation area is on the slope at the cliff side of floodplain where the watertable is shallow. In Central and South Murtho, recharge does not show an increasing trend by the end of the calibration period as the accession does. This is due to the long lag time in this area, as a result of deep watertable and thick Blanchetown Clay. It is expected that the recharge will show a similar increasing trend in the near future.

The confirmations provide confidence that the recharge applied in the model are a reasonable estimate of the true recharge rates and reproduce the observed impacts in the groundwater and the River Murray.

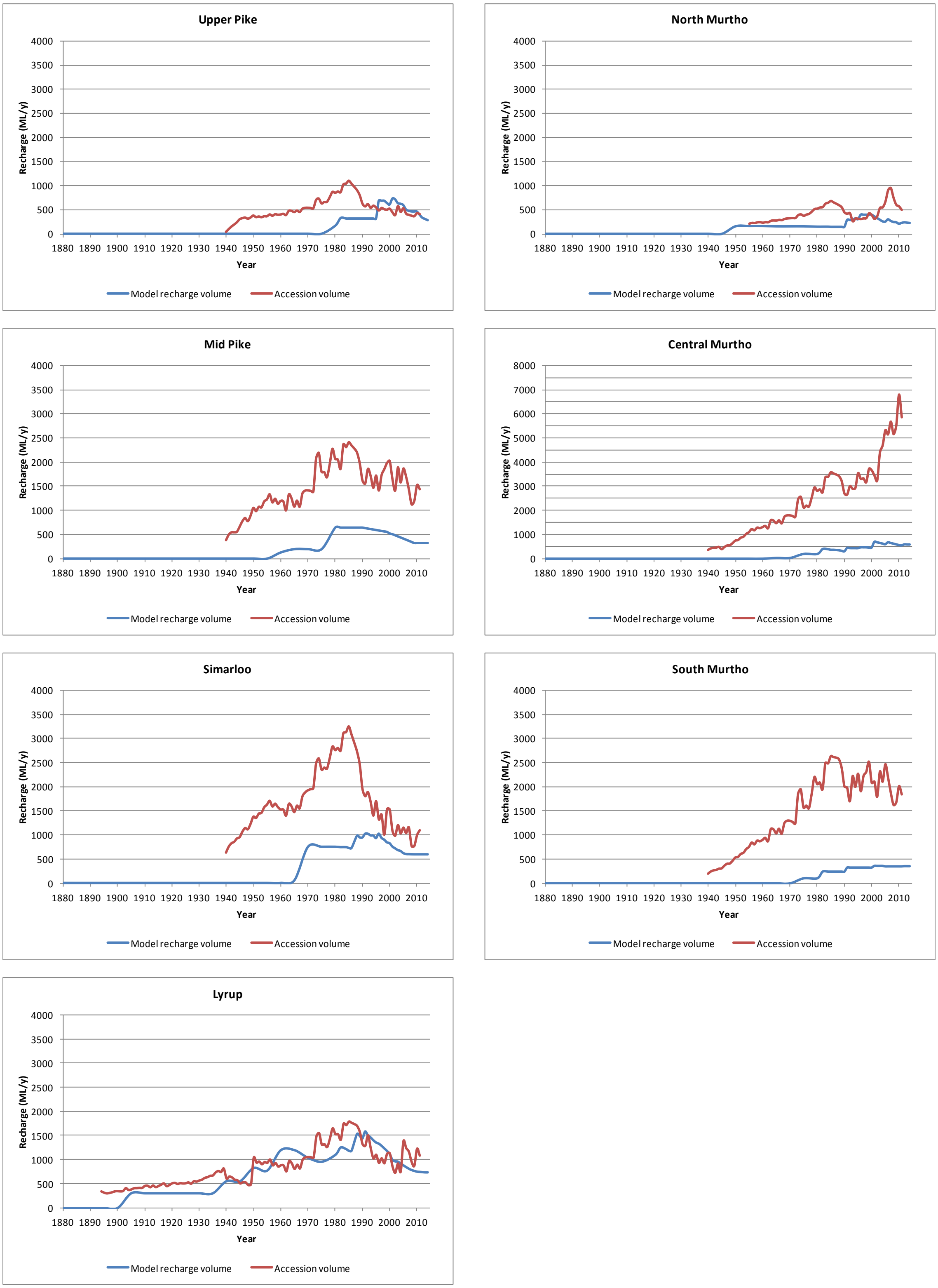


Figure 4.21 **Comparison between calculated accession estimates (Laroona Environmetrics, 2014) and the calibrate modelled recharge volume**

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 (Doody et al., 2009, Holland et al., 2001). Holland et al. (2011) and K Holland (CSIRO) 2013, pers. comm., 15 March) indicate 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.

The inputs for groundwater ET in the model have a specified maximum (i.e. potential) groundwater ET rate of 1100 mm/y and an extinction depth of 2 m, which are consistent with Yan et al. (2012). The model outputs (Figure 4.22) show that about 60 - 70 mm/y of groundwater is lost as ET (i.e. actual groundwater ET) in the floodplain within the Pike-Murtho area. This is well within 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.

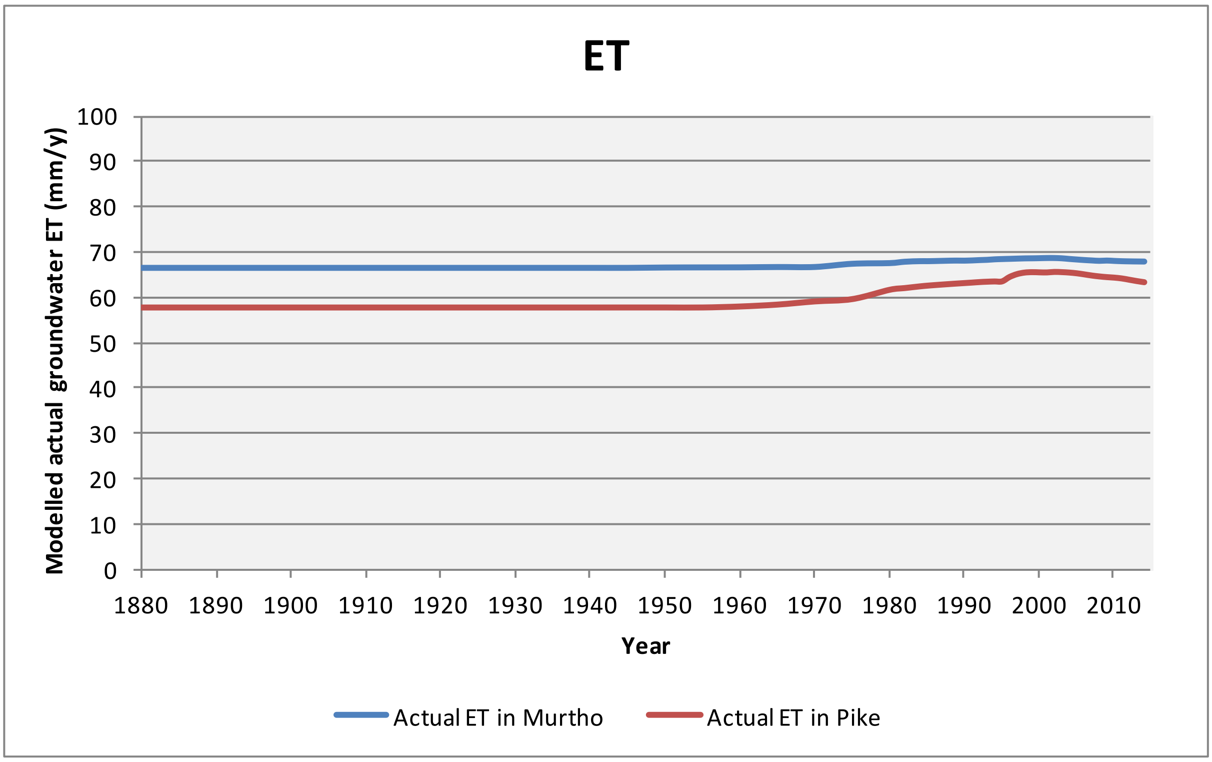


Figure 4.22 Modelled actual groundwater evapotranspiration in Pike and Murtho

4.5 MODEL WATER BALANCE

Table 4.4 reports the water balance for the Pike-Murtho project area in layer 1, i.e. the Monoman Sands and Loxton Sands aquifers which is in direct contact with the river valley or the River Murray. The details of flow are given for the steady-state period (prior to irrigation), 2005 (irrigation conditions before drought water restrictions) and 2013 (current irrigation conditions with Pike SIS).

Prior to irrigation developments (the steady-state model), most of the flows into the aquifers are from losing-stream reaches of the river (23.8 ML/d) which were mainly in Murtho between Locks 5 and 6. Total regional flow is 7 ML/d, including 5 ML/d of lateral flow and 2 ML/d of vertical leakage from the Murray Group. Recharge is solely from rainfall and is minimal (0.2 ML/d). The main outflows from the aquifers are groundwater ET (20.6 ML/d), due to the extensive floodplain systems in the Pike-Murtho area. Most of the lateral outflow (5.1 ML/d) is expected to travel from the Pike-Murtho area across the River Murray as throughflow to the floodplain area on the western side of the River and where it is lost to evaporation. There is also a considerable amount of groundwater discharge to the River Murray (5.5 ML/d), which includes both groundwater from the highland and fluxes from upstream to downstream of a lock due to the steep hydraulic gradient.

The water balance results for 2005 show that inflows to the aquifers have increased considerably. It may be due to increasing recharge from irrigation (10.5 ML/d). Flow from losing reaches of the Murray is decreased by 1.3 ML/d due to the higher watertable which decreases the gradient from the river. The increase in inflows leads to an increase in flow to the River Murray's gaining reaches (10.4 ML/d, an increase of 4.9 ML/d from steady-state), regional lateral flow (6.6 ML/d), to the Murray Group via downward leakage (0.7 ML/d) and into storage where the watertable is still rising (1 ML/d). Groundwater ET on the floodplain is increased by 1.8 ML/d to 22.4 ML/d.

The water balance results for 2013 show that total recharge has declined which may be due to a combination of irrigation efficiency improvement and water restriction during drought. The recharge has declined by 1.7 ML/d to 8.8 ML/d. The Pike SIS has been commissioned from 2012 and the SIS extracts 1 ML/d in 2013. Groundwater flow entering the River Murray (gaining) declines by 1.3 ML/d to 9.1 ML/d. There is a small decrease in groundwater ET on floodplain.

In summary, the natural water balance is dominated by river leakage into/out of the aquifers and groundwater ET on the floodplains. As irrigation developed, there was an increase in irrigation recharge, which resulted in an increase in groundwater discharge to the River Murray. In recent years, the Pike SIS and decreasing irrigation recharge reduced groundwater discharge to the river. These model results are consistent with the hydrogeological understanding of the region.

Table 4.4 Water balance for the Pike-Murtho area

Water Balance Component INFLOW to the aquifer	Water volume (ML/d)		
	Steady-state	2005	2013
Release from storage	0.0	1.2	1.4
Recharge from irrigation and rainfall	0.2	10.5	8.8
River leakage (river losses to the aquifer)	23.8	22.5	22.5
Lateral flow (into the project area)	5.4	5.1	5.1
Vertical flow (Upward from the Murray Group)	1.8	1.9	1.9
Total IN	**31.2**	**41.2**	**39.7**
Water Balance Component OUTFLOW to the aquifer	Water volume (ML/d)		
	Steady-state	2005	2013
Flow to storage	0.0	1.0	0.5
SIS wells	0.0	0.0	1.0
ET (include horizontal drainage wells and cliff toe drains)	20.6	22.4	22
River leakage (discharge to the river)	5.5	10.4	9.1
Lateral flow (Outward from the project area)	5.1	6.6	6.4
Vertical flow (Downward to the Murray Group)	0.1	0.7	0.6
Total OUT	**31.2**	**41.2**	**39.7**
Total IN-Total OUT	**0.0**	**0.0**	**0.0**
Percent discrepancy	**0.0**	**0.0**	**0.0**

5 MODEL SCENARIOS AND PREDICTIONS

5.1 SCENARIO SUITE

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 Pike-Murtho 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 7C, 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 Schemes
- 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. PM2014_S4, refer to the MODFLOW files preserved in the SA Groundwater Model Warehouse, following the protocol given in Appendix C-2.

To prevent the over-estimation of salinity credits, future scenarios presume that recharge due to irrigation will be similar to 2005 rates, prior to the water restrictions imposed during the drought years of 2006 to 2010. The minimum recharge rate is set conservatively at 100 mm/y (except Scenario 3A). This means that the impacts of improved irrigation practices and rehabilitation are also not over-estimated. 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 Lyrup to Lock 6. 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	1880-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 irrigation without IIP or RH	1988-CY100	Pre-1988	No	No
Scenario S3B	Pre-1988 irrigation with IIP, no RH	Not applicable	Pre-1988	Yes	No
Scenario 3C	Pre-1988 irrigation 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 6	Concept Design SIS	Not applicable	Pre-1988+Post-1988+Future development	Yes	Yes
Scenario 7A	Current irrigation plus revised and constructed SIS	1988-CY100	Pre-1988 + Post-1988	Yes	Yes
Scenario 7B	Pre-1988 irrigation with IIP and RH plus revised and constructed SIS	1988-CY100	Pre-1988	Yes	Yes
Scenario 7C	Current plus future irrigation plus revised and constructed SIS	1988-CY100	Pre-1988 + Post-1988 + Future development	Yes	Yes
Scenario S8	As constructed SIS	Not applicable	Pre-1988+Post-1988+Future development	Yes	Yes

IIP: Improved Irrigation Practices   RH: Rehabilitation   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. 2014
Current year + 100 (CY100)	100 years from the current year (e.g. if current year is 2014 , then CY100 = 2114)
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.
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 and 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, 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.

5.2 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 the varying recharge rates as provided by calibration and the other maintaining the calibrated recharge rate at 1988 into the future (the 'do nothing' scenario). Comparison of these two scenarios will provide the benefit gained by reduction in recharge rates attributed to improved irrigation practices and rehabilitation.
- for post-1988 irrigation: the post-1988 irrigation areas will be used to define the recharge area and the calibrated recharge rates at 2005 are used to define the current average condition (representing average conditions prior to water restrictions).
- for future irrigation: shorter lag time is applied in areas where an irrigation water mound exists and an initial lag time is applied if the new developed area is located away from existing irrigation water mounds.

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

5.3 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 Pike-Murtho area for Scenario 1 (see Section 3.8 for the definition of the Pike-Murtho reach).

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

Groundwater flux and salt load	Steady-state	
	Pike	Murtho
Flux to river (m^3/d)	2100	6473
Salt load to river (t/d)	31.6	20.5

5.4 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 (PM2014_S2):

- the simulated time period is 1880 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 approximately10 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 SIS are not included
- 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 Pike-Murtho area. Further results are given Appendices B-1 to B-2. The starting values in 1880 are those given for Scenario 1 in Table 5.3.

The existing mallee clearance recharge data do not cover a small area in the northernmost part of the Murtho LWMP area. The most common value in the Murtho area is applied to this area. The impact of this area on salt load has been tested and is found to be negligible (less than 0.1 t/d).

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

Pike Groundwater flux and salt load	Year						
	1988	2000	2014	2015	2050	2100	2114
Flux to river (m^3/d)	2191	2231	2296	2301	2505	2878	2977
Salt load to river (t/d)	33.8	34.9	36.5	36.7	41.9	50.9	53.2

Murtho Groundwater flux and salt load	Year						
	1988	2000	2014	2015	2050	2100	2114
Flux to river (m^3/d)	6489	6492	6496	6496	6508	6592	6643
Salt load to river (t/d)	20.8	20.8	20.9	20.9	21.2	22.8	23.7

5.5 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 and the rehabilitation of irrigation infrastructure 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 (PM2014_S3A):

- the simulated time period is from 1880 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 for 1988 to CY100 are assigned as follows and are given in Appendices A-2 and A-3:
  - in established irrigation areas, it is assumed that there is negligible lag time for recharge to pass from the irrigation drainage root zone to the groundwater table, so the recharge rates from 1988 in the historical model are applied
  - there are irrigation areas planted before 1988 where the lag time indicates that root zone drainage water has not yet reached the watertable by 1988. In those areas, recharge rates may still increase after 1988 to reflect the delay. Recharge rate becomes constant and no more - 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 SIS are not included
- the results 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 Pike-Murtho area. Further results are given Appendix B-1. The starting values in 1880 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

Pike **Groundwater flux and salt load**	**Year**						
	1988	**2000**	**2014**	**2015**	**2050**	**2100**	**2114**
Flux to river (m^3/d)	5591	6295	6576	6586	7080	7184	7196
Salt load to river (t/d)	103.4	119.4	127.3	127.6	143.3	146.5	146.9

Murtho **Groundwater flux and salt load**	**Year**						
	1988	**2000**	**2014**	**2015**	**2050**	**2100**	**2114**
Flux to river (m^3/d)	8091	9581	10449	10473	12594	12985	13026
Salt load to river (t/d)	56.1	86.2	105.0	105.5	152.6	161.0	161.8

5.6 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 and rehabilitation of infrastructure had still occurred. This scenario is used in conjunction with Scenario 3A to estimate the salinity benefits of improvements in irrigation practice and the rehabilitation of irrigation infrastructure 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 (PM2014_S3C):

- the simulated time period is from 1880 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 for 1988 to CY100 are assigned as follows and are given in Appendices A-2 and A-3:
  - the rates from the calibrated model are used to reflect best estimates of the impact of rehabilitation and improved irrigation practice
  - zones with a calibrated recharge rate greater than or equal to 100 mm/y are assumed to benefit from improved irrigation practices; recharge rates decline gradually to 100 mm/y from the current year CY to late lag time years after CY
  - For newer irrigation developments, the recharge rate will rise to a maximum of 100 mm/y at lag time years after the commencement year
  - in areas where irrigation did not exist in 1988, the mallee recharge rate of 0.1 mm/y is adopted
- the SIS are not included
- the results 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 Pike-Murtho area. Further results are given Appendix B-1. The starting values in 1880 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

Pike Groundwater flux and salt load	Year						
	1988	2000	2014	2015	2050	2100	2114
Flux to river (m^3/d)	5591	5502	4514	4487	4703	4764	4772
Salt load to river (t/d)	103.4	105.6	84.6	84.0	93.1	95.1	95.4

Murtho Groundwater flux and salt load	Year						
	1988	2000	2014	2015	2050	2100	2114
Flux to river (m^3/d)	8091	9467	7990	7965	9660	9985	10017
Salt load to river (t/d)	56.1	83.2	52.2	51.7	89.7	96.5	97.2

5.7 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 7A, 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 irrigation areas and rates for future years are based on those of 2005.

The following conditions are applied to the transient model (PM2014_S4):

- the simulated time period is from 1880 to CY100
- the model is identical to the calibrated historical model until 1 January 2014
- the recharge zones for 2006 to CY100 are based on the 2005 irrigation development area
- recharge rates for 2006 to CY100 are assigned as follows and are given in Appendices A-2 and A-3:
    - from 2006 until 2014 (CY), the calibrated rates from the historical model are adopted
    - zones with a calibrated recharge rate greater than or equal to 100 mm/y are assumed to benefit from improved irrigation practices; recharge rates decline gradually to 100 mm/y from the current year CY to late lag time years after CY
    - For newer irrigation developments, the recharge rate will rise to a maximum of 100 mm/y lag time years after the commencement year
    - in areas where irrigation did not exist in 2005, the mallee recharge rate of 0.1 mm/y is adopted
- the SIS are not included
- the results 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 Pike-Murtho area. Further results of the predicted flux of saline groundwater and salt load are given in Appendix B-1. The results are discussed further in Section 5.12.

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

Pike **Groundwater flux and salt load**	**Year**						
	1988	**2000**	**2014**	**2015**	**2050**	**2100**	**2114**
Flux to river (m^3/d)	5591	5716	4717	4691	5808	6072	6099
Salt load to river (t/d)	103.4	109.3	88.2	87.6	119.5	127.5	128.4

Murtho **Groundwater flux and salt load**	**Year**						
	1988	**2000**	**2014**	**2015**	**2050**	**2100**	**2114**
Flux to river (m^3/d)	8094	9467	8139	8122	13001	14780	14963
Salt load to river (t/d)	56.1	83.2	55.6	55.3	163.0	200.8	204.7

5.8 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 2014. It is identical to Scenario 4 except that irrigation development continues after 2014, so it is used to estimate the salinity impact of future (post-2014) 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 (PM2014_S5):

- the simulated time period is from 1880 to CY100
- the model is identical to the Scenario 4 model until 1 January 2014
- the recharge zones and rates for 2014 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 2.13). A recharge rate of 100 mm/y is applied in the new zones. Shorter lag time is applied in the new irrigation areas as they are located in or immediately adjacent to existing irrigation areas. Lag times are based on SIMRAT estimates using an accession rate of 100 mm/y.
- the recharge rates are given in Appendices A-2 and A-3
- the SIS are not included
- the results for 1988 to CY100 are reported for the Salinity Register.

Table 5.8 summarises the predicted flux and salt load entering the River Murray in the Pike-Murtho area. Further results of the predicted flux of saline groundwater and salt load are given in Appendix B-1. The results are discussed further in Section 5.12.

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

Pike Groundwater flux and salt load	Year						
	1988	2000	2014	2015	2050	2100	2114
Flux to river (m^3/d)	5591	5716	4716	4691	6094	6549	6591
Salt load to river (t/d)	103.4	109.3	88.2	87.6	128.2	142.1	143.4

Murtho Groundwater flux and salt load	Year						
	1988	2000	2014	2015	2050	2100	2114
Flux to river (m^3/d)	8094	9467	8139	8122	13333	16315	16587
Salt load to river (t/d)	56.1	83.2	55.6	55.3	169.6	233.3	239.1

5.9 SCENARIO 7A: CURRENT IRRIGATION WITH REVISED AND CONSTRUCTED SIS

Scenario 7A simulates what will happen if the current irrigation development and practices continue indefinitely with the revised and constructed SIS. 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 7A does not simulate the impact of the 2006 to 2010 drought restrictions and the irrigation areas and rates for future years are based on those of 2005.

The following conditions are applied to the transient model (PM2014_S7A):

- the simulated time period is from 1880 to CY100
- the model is identical to the Scenario 4 model except that SIS are included
- the SIS are represented as follows:
  - the Pike SIS is simulated using the MODFLOW Drain Package (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 mid-point observation wells. Different drain elevation and conductance values were trialled until the model achieved the target heads. Where this resulted in pumping rates greater than SIS design limits, the conductance was lowered until the pumping rates were within design limits. 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 elevation in the model is 13 m AHD and the conductance is 1000 m^2/d. Appendices A-6 and A-7 provide further detail.
  - For the Murtho SIS, as discussed in Section 2.7.2, its pumping volume is constrained by the pipeline capacity 103 L/s, (P Forward (SA Water) 2014, pers. comm., 18 January) and the pumping volume may be insufficient to lower the watertable at mid-point wells to the pool level in the long term. Therefore to simulate the Murtho SIS the Well Package is used instead of the Drain Package. The pumping rates are adopted from SA Water and the pumping rates are remained constant from 2014 to 2114.
- 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 7A, 7B and 7C.

Table 5.9 summarises the predicted flux and salt load entering the River Murray in the Pike-Murtho area. Further results of the predicted flux of saline groundwater and salt load are given in Appendix B-1. The salt loads are significantly lower than those of Scenario 4, as discussed in Section 5.12.

Table 5.9 Predicted groundwater flux and salt load – Scenario 7A: Current irrigation plus Pike-Murtho SIS

Pike Groundwater flux and salt load	Year						
	1988	**2000**	**2014**	**2015**	**2050**	**2100**	**2114**
Flux to river (m^3/d)	5591	5716	4215	4139	4887	5071	5092
Salt load to river (t/d)	103.4	109.3	75.0	73.3	95.7	101.6	102.3

Murtho Groundwater flux and salt load	Year						
	1988	**2000**	**2014**	**2015**	**2050**	**2100**	**2114**
Flux to river (m^3/d)	8094	9467	8139	6003	7445	8721	8867
Salt load to river (t/d)	56.1	83.2	55.6	28.2	64.0	94.0	97.4

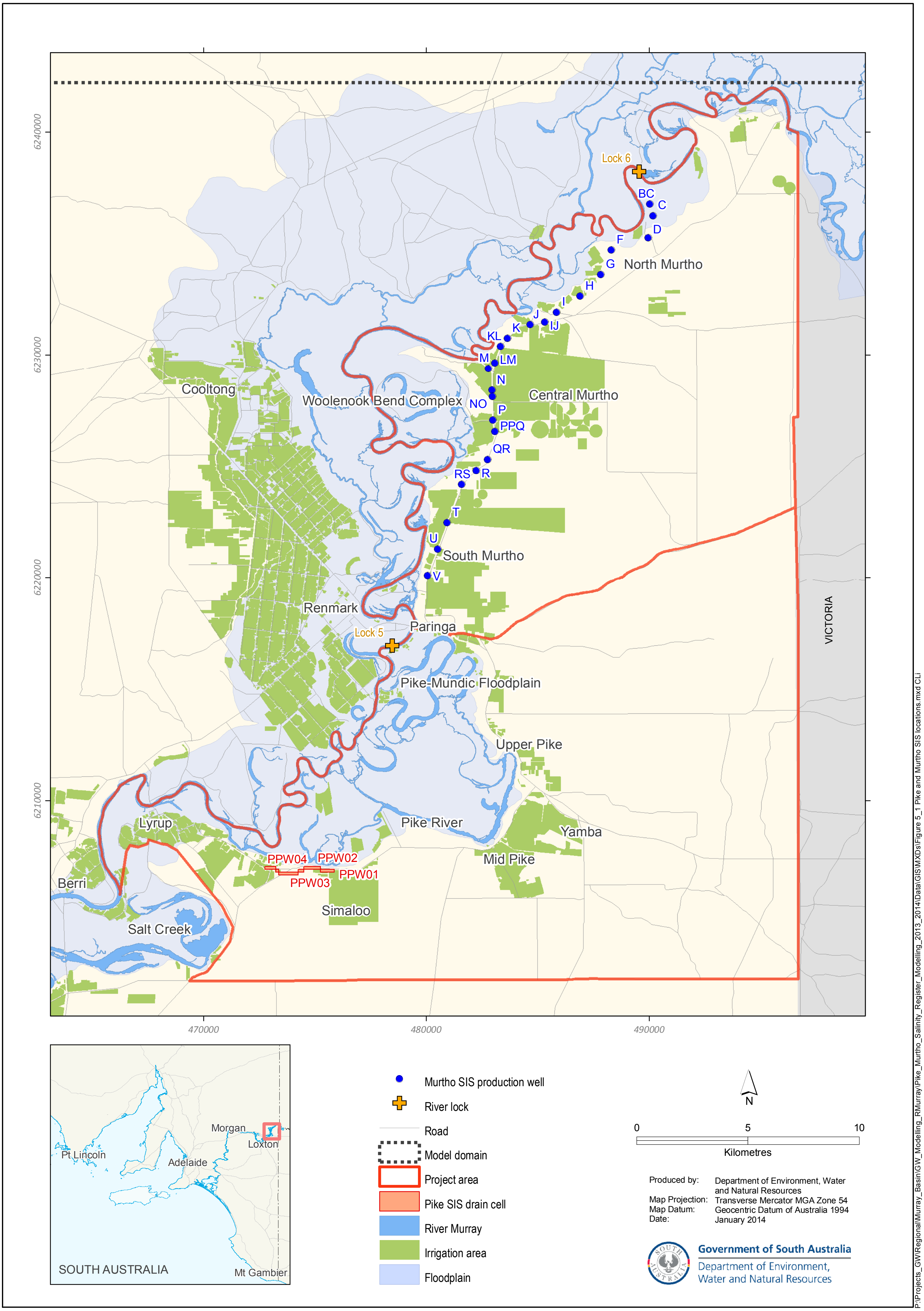


Figure 5.1. Pike and Murtho SIS locations in prediction model

5.10 SCENARIO 7B: PRE-1998 IRIGATION WITH REVISED AND CONSTRUCTED SIS

Scenario 7B simulates what would have happened if the irrigation development area had remained unchanged from 1988, but improvements in irrigation practice and rehabilitation of infrastructure had still occurred with the revised and constructed SIS. It is identical to Scenario 3C except that it includes the SIS, so the two scenarios can be compared to estimate SIS benefits and 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 (PM2014_S7B):

- the simulated time period is from 1880 to CY100
- the model is identical to the Scenario 3C model except that SIS are included
- the SIS are simulated using the same methodology as Scenario 7A. 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.

The results given in Table 5.10 summarise the predicted flux and salt load entering the River Murray in the Pike-Murtho area. Further results of the predicted flux of saline groundwater and salt load are given in Appendix B-1.

Table 5.10 Predicted groundwater flux and salt load – Scenario 7B: Pre-1988 irrigation plus Pike-Murtho SIS

Pike **Groundwater flux and salt load**	**Year**						
	1988	**2000**	**2014**	**2015**	**2050**	**2100**	**2114**
Flux to river (m^3/d)	5591	5502	4032	3957	3980	4010	4015
Salt load to river (t/d)	103.4	105.6	71.9	70.2	74.1	75.3	75.4

Murtho **Groundwater flux and salt load**	**Year**						
	1988	**2000**	**2014**	**2015**	**2050**	**2100**	**2114**
Flux to river (m^3/d)	8094	9467	7990	5901	5594	5635	5639
Salt load to river (t/d)	56.1	83.2	52.2	25.6	17.8	18.7	18.8

5.11 SCENARIO 7C: FUTURE IRRIGATION WITH REVISED CONSTRUCTED SIS

Scenario 7C simulates what will happen if irrigation development continues after 2014 with the revised and constructed SIS. 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 (PM2014_S7C):

- the simulated time period is from 1880 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 7A. 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 Pike-Murtho 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.

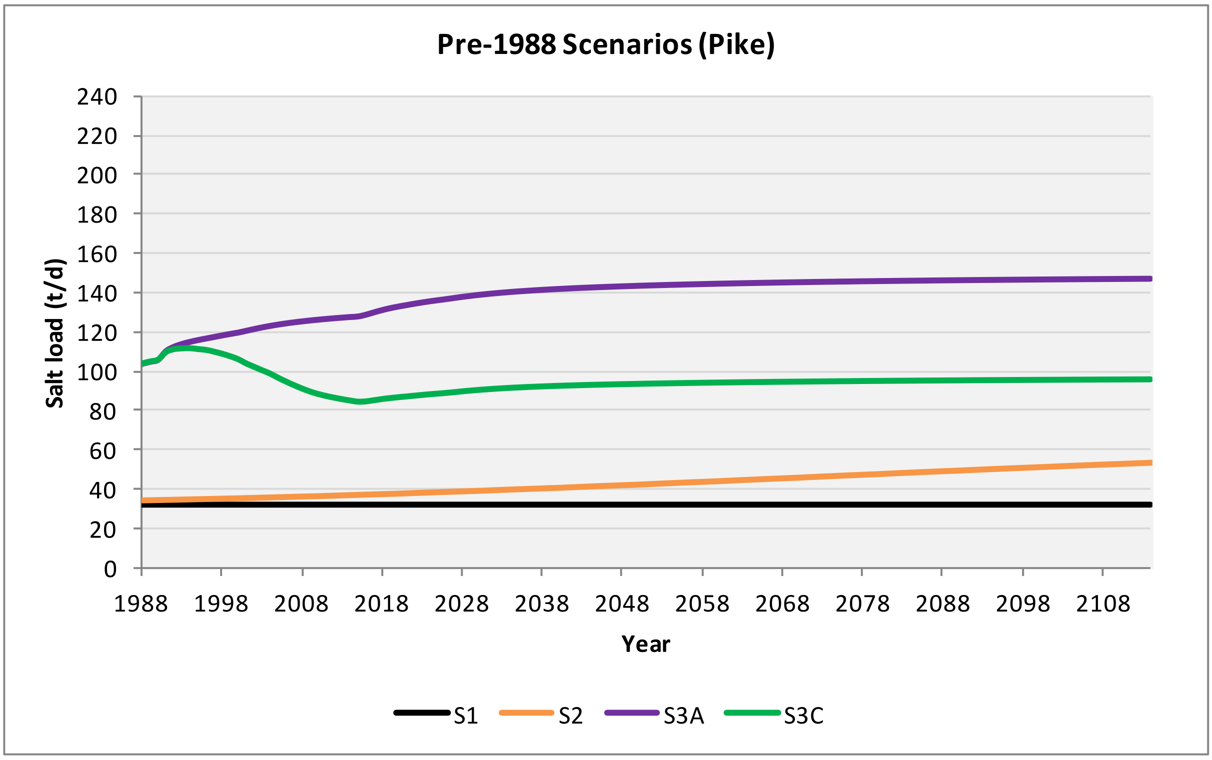
Table 5.11 Predicted groundwater flux and salt load – Scenario 7C: Future irrigation plus Pike-Murtho SIS

Pike **Groundwater flux and salt load**	**Year**						
	1988	**2000**	**2014**	**2015**	**2050**	**2100**	**2114**
Flux to river (m^3/d)	5591	5716	4215	4139	5125	5443	5475
Salt load to river (t/d)	103.4	109.3	75.0	73.3	103.1	113.4	114.4

Murtho **Groundwater flux and salt load**	**Year**						
	1988	**2000**	**2014**	**2015**	**2050**	**2100**	**2114**
Flux to river (m^3/d)	8094	9467	8139	6003	7606	10395	10682
Salt load to river (t/d)	56.1	83.2	55.6	28.2	67.6	128.3	134.3

5.12 COMPARISON OF SCENARIO SALT LOADS

Figure 5.2 to Figure 5.5 display the annual salt loads from 1988 to 2114 for all scenarios for the Pike-Murtho reach. Details of the model results (both flux and salt load) for all scenarios are given in Appendix B.



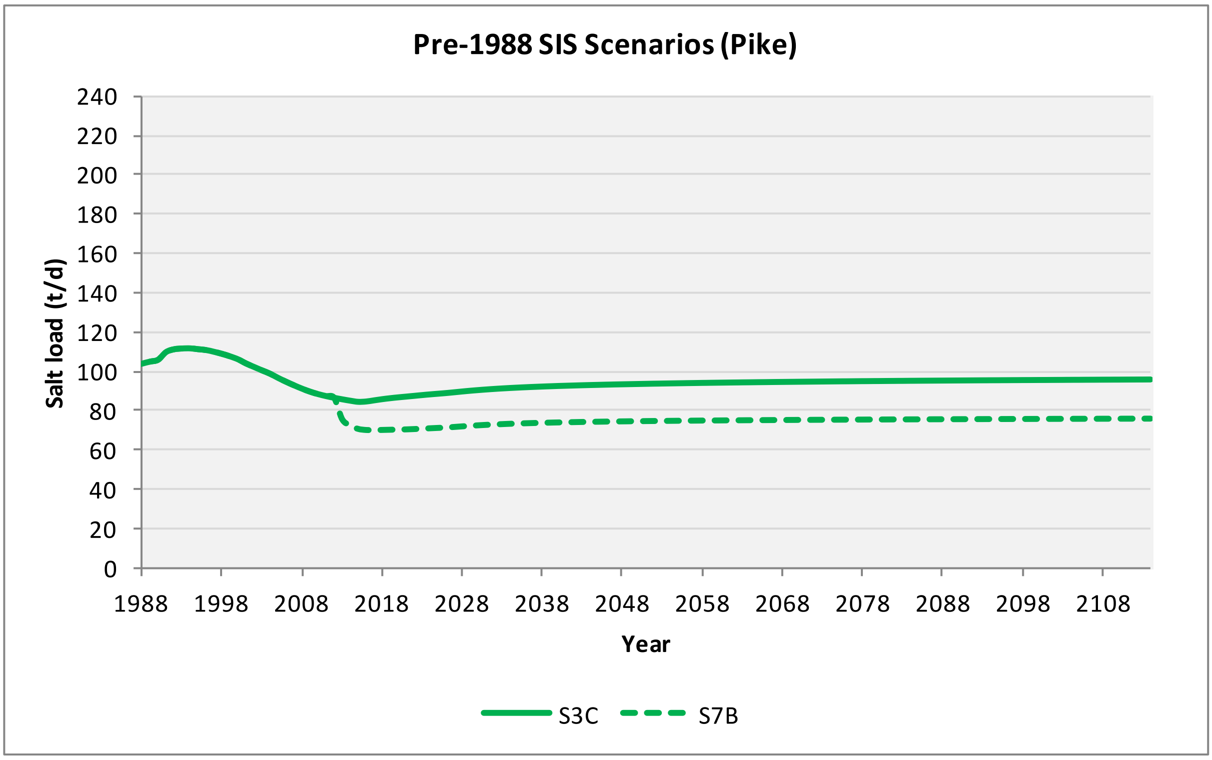
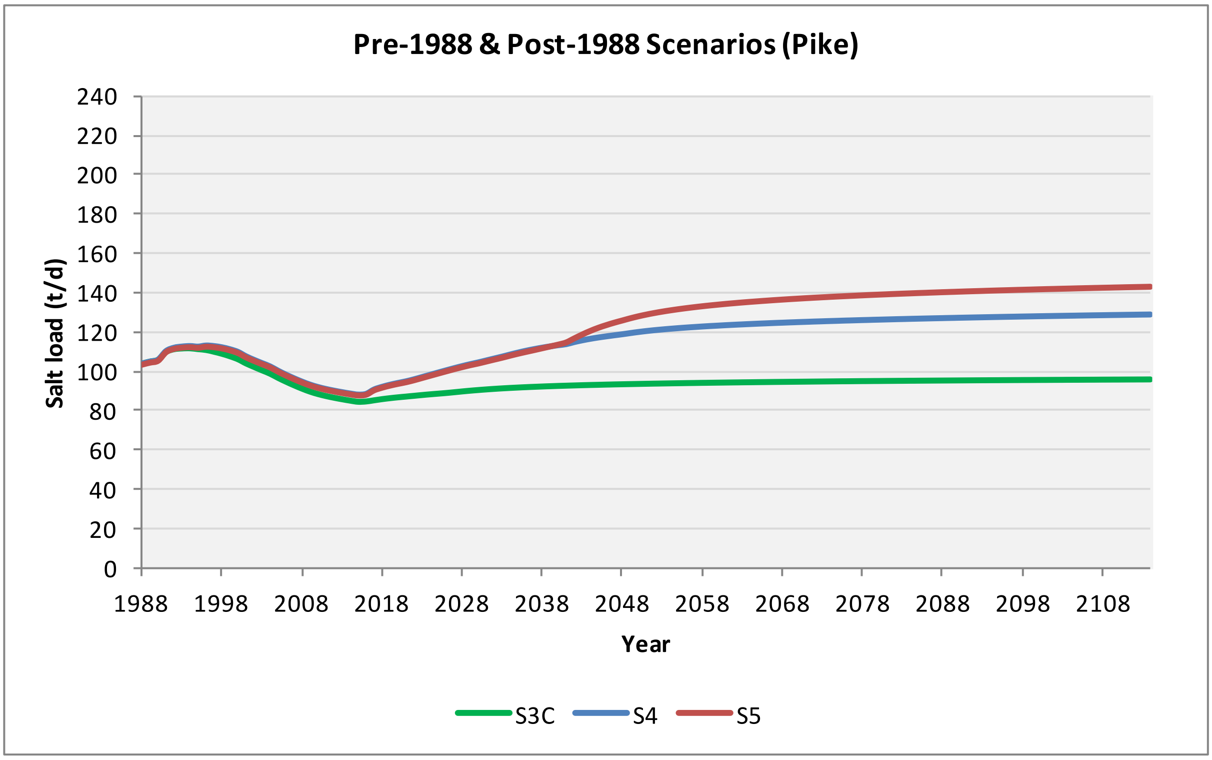


Figure 5.2 Predicted total salt loads entering the River Murray from the Pike Reach for Pre-1988 scenarios



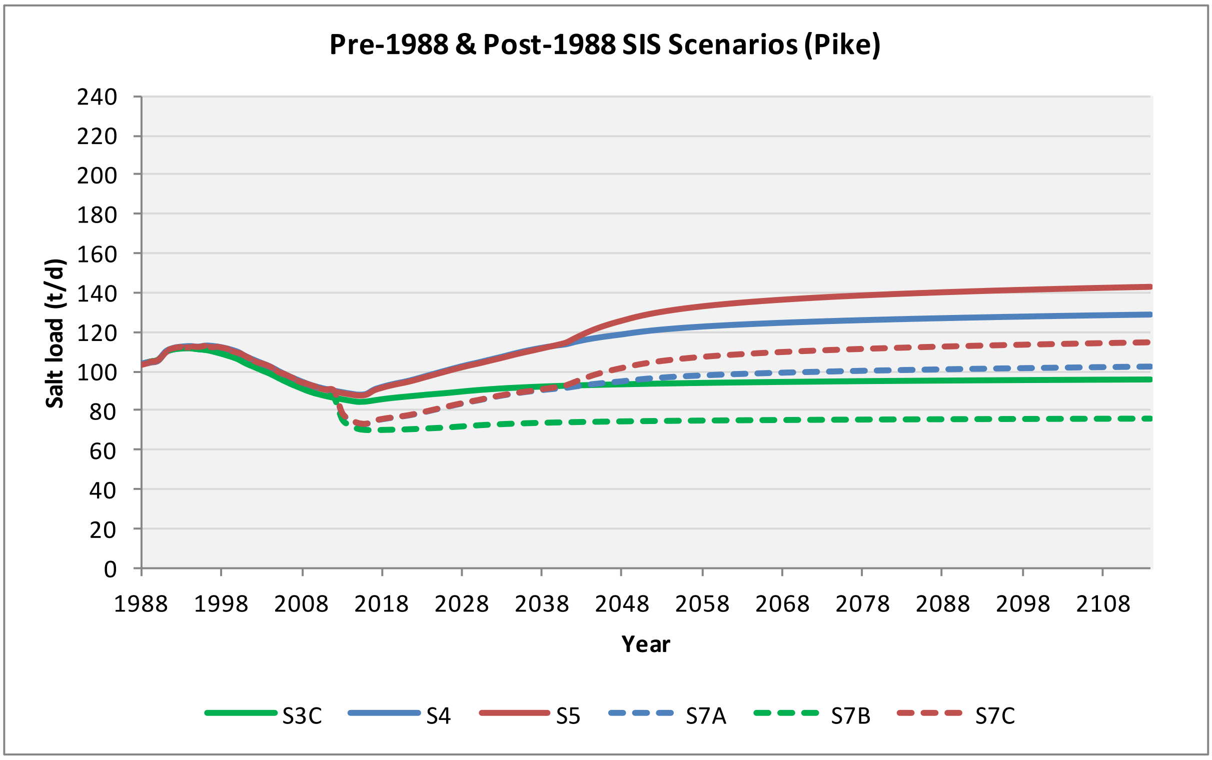
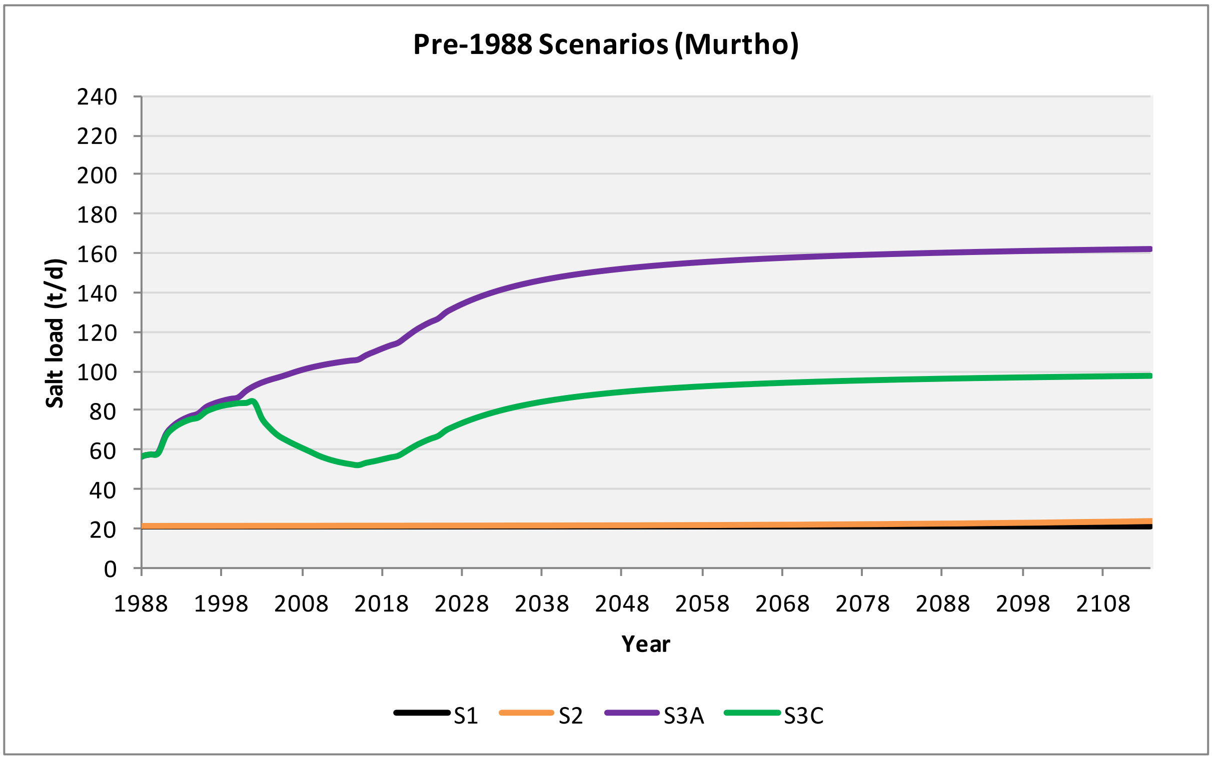


Figure 5.3 **Predicted total salt loads entering the River Murray from the Pike Reach for Pre-1988 and Post-1988 scenarios**



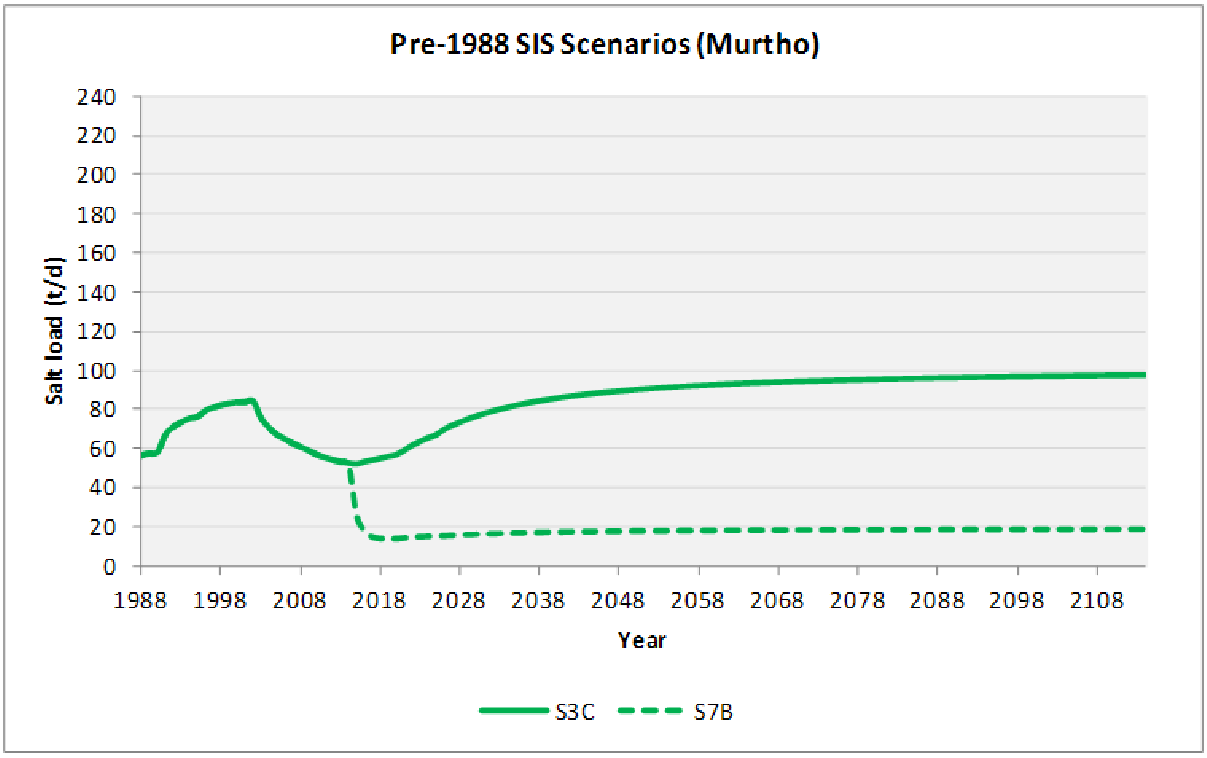
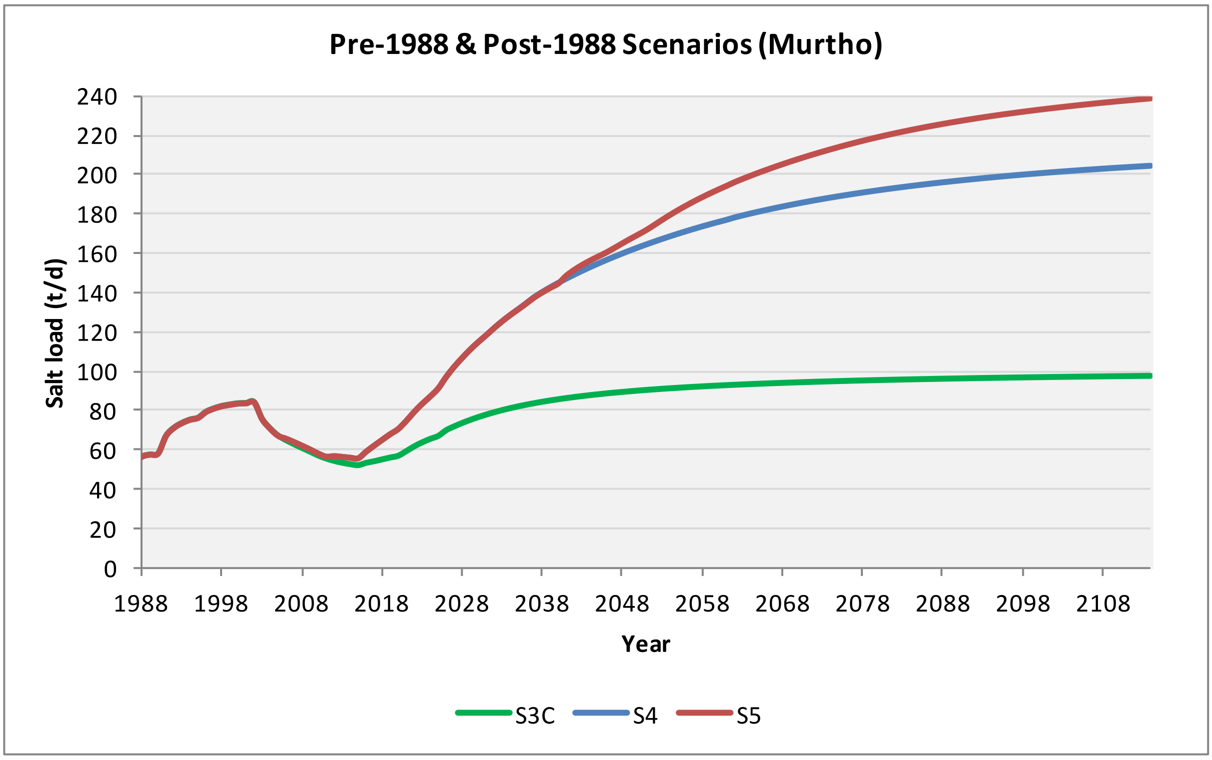


Figure 5.4 **Predicted total salt loads entering the River Murray from the Murtho Reach for Pre-1988 scenarios**



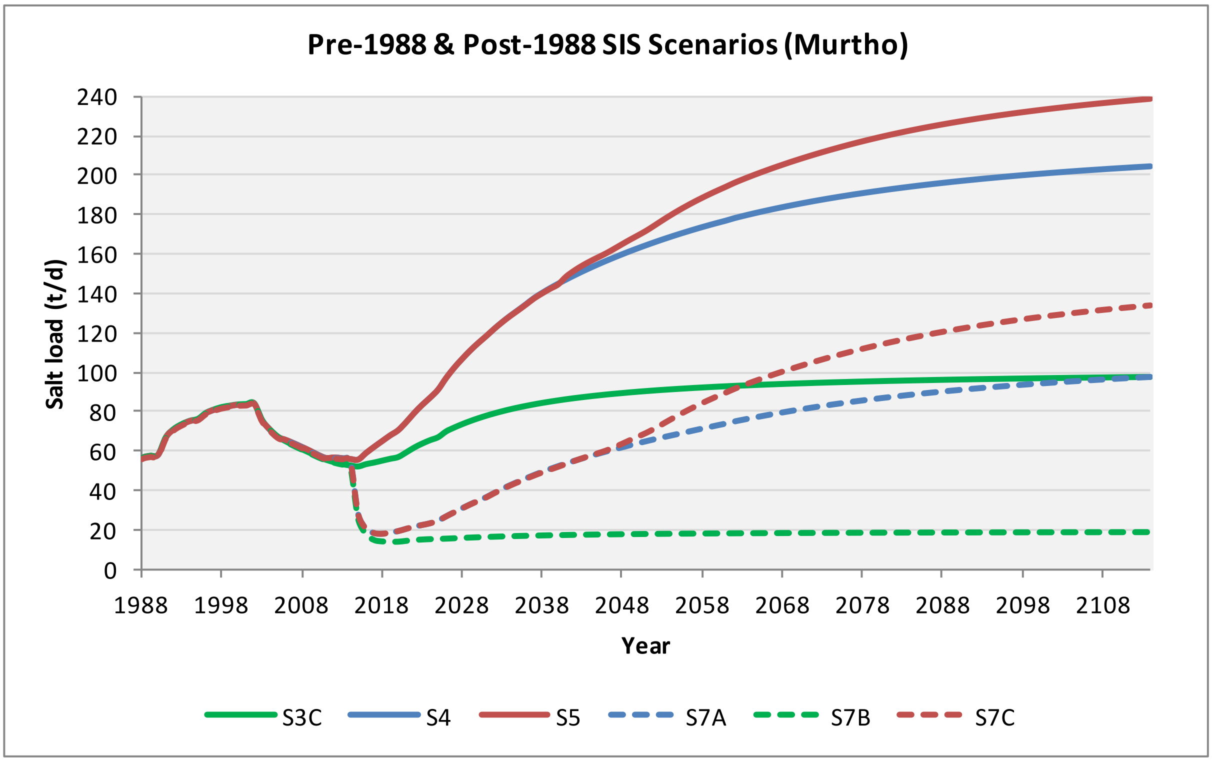


Figure 5.5 Predicted total salt loads entering the River Murray from the Murtho Reach for Pre-1988 and Post-1988 scenarios

6 SENSITIVITY AND UNCERTAINTY ANALYSIS

6.1 SENSITIVITY ANALYSIS

Sensitivity analysis is a procedure for quantifying the impact of an incremental variation in aquifer hydraulic parameters or stresses on modelled responses (Middlemis et al., 2001). The *Groundwater Flow Modelling Guideline* (Middlemis et al., 2001) recommends for high complexity models such as the Pike-Murtho 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.”

As the model is well calibrated, the aim of the sensitivity analysis for the Pike-Murtho 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.

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 (Barnett et al., 2012).

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

The model inputs below are varied for the sensitivity analysis:

- Loxton Sands horizontal hydraulic conductivity
- Loxton Sands specific yield
- Monoman Formation horizontal hydraulic conductivity
- Bookpurnong Formation vertical hydraulic conductivity
- potential groundwater ET rate
- groundwater ET extinction depth
- River Murray riverbed conductance
- Pike and Murtho anabranches riverbed conductance.

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.

6.1.1 SENSITIVITY TEST 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* (Barnett et al., 2012), each parameter is adjusted by an amount commensurate with its likely range.

Figure 6.1 shows the values of the parameters in the calibrated model and other values considered in the sensitivity simulations.

Table 6.1 Sensitivity test parameter values

Parameter	Lower value	Calibrated model	Higher value
Loxton Sands Kh (m/d)	x 1/2	0.5-13	x 2
Monoman Formation Kh (m/d)	10	15	20
Bookpurnong Formation Kv (m/d)	x 1/10	1×10^{-5} - 2×10^{-3}	x 10
Loxton Sands Sy (-)	0.05	0.15	0.2
Potential groundwater ET rate (mm/y)	250	1100	–
Groundwater ET extinction depth (m)	1	2	3
Riverbed conductance (River Murray) (m^2/d)	500	1500	4500
Riverbed conductance (anabranches) (m^2/d)	5	15	50

The horizontal hydraulic conductivity of the Loxton Sands has been estimated from aquifer tests and model calibration. The sensitivity analysis varies the hydraulic conductivity by a factor of 2 (i.e. multiplied by 2 and divided by 2). The hydraulic conductivity values in both the higher and lower cases are still within the knowledge range. The vertical hydraulic conductivity is scaled to be one tenth of the horizontal hydraulic conductivity.

The Loxton Sands specific yield was based on the general hydrogeological understanding of the area. It is varied to 0.05 and 0.2 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 and literature values.

Similarly, the Monoman Formation horizontal hydraulic conductivity is varied to 10 m/d and 20 m/d during the sensitivity analysis, which are considered to be the lower and upper bound of the knowledge range, respectively. The vertical hydraulic conductivity is scaled to be one tenth of the horizontal hydraulic conductivity.

The vertical hydraulic conductivity of the Bookpurnong 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 Bookpurnong Formation has been estimated by only a few aquifer tests and was mainly inferred from the aquifer tests in the Loxton area (Yan et al., 2006, Yan et al., 2005).

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 potential maximum groundwater ET rate (i.e. model input) considered in the sensitivity test is 250 mm/y, which is the lower bound of the value and is used in other modelling studies such as Yan et al. (2011) and Woods et al. (2013). A higher value is not tested as the ET rate applied in the calibration model is already 1100 mm/y, which is the upper bound of the value for the Pike-Murtho area (Section 2.6.4). This rate is also applied in other modelling studies such as Yan et al. (2012). The groundwater ET extinction depth is varied by 1 m from the value of 2 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 is 1500 m^2/d for the River Murray and is equivalent to a vertical conductivity of 0.1 m/d for a riverbed thickness of 1 m. The sensitivity test considers two other conductance values, 500 and 4500 m^2/d for the River Murray, which are equivalent to vertical conductivities of 0.03 and 0.3 m/d respectively, for assuming riverbed thickness of 1 m.

Anabranch riverbed conductance, including the Pike River, is 15 m^2/d in the calibrated model. Two values are considered in the sensitivity analysis: 5 m^2/d, which is adopted from the Chowilla 2004 model developed by Yan et al. (2004), and 50 m^2/d, which could be the upper bound of the value in the area.

6.1.2 SENSITIVITY TEST RESULTS

SRMS difference between modelled and observed potentiometric head was used to examine the sensitivity of the parameters. Figure 6.1 shows the changes of SRMS from the calibration for 1986, 2005 and 2013. Positive values indicate a better fit to observation data than the calibrated model, negative values indicate a worse fit.

Most of the selected parameters make negligible difference to the calibration fit (i.e. less than 1% SRMS difference), indicating that they do not substantially alter modelled potentiometric heads at observation well locations. In addition, the fit is worse for the altered values than for the calibrated model for most of these parameters.

Only three sensitivity tests cause a considerable difference to the calibration fit (i.e. more than 1% SRMS difference): the higher and lower cases of Loxton Sands horizontal hydraulic conductivity and the lower case of Loxton Sands specific yield. The higher and lower cases of Loxton Sands horizontal hydraulic conductivity clearly lead to a worse calibration fit and therefore are not considered.

The lower case of Loxton Sands specific yield shows a better calibration fit at 1986, minimal difference at 2005 and a worse fit at 2013. It may be due to the fact that model layer 1 is simulated as unconfined, while in reality the aquifers can be semi-confined in some area. Also, a specific yield of 0.1 – 0.15 is applied to the entire project area in the model, but it may actually be heterogeneous in the field. Furthermore, it indicates that the calibrated model better represents the long-term system which has reached a level of equilibrium. Therefore good calibration fit in later years is considered more imperative as it provides the starting point for future predictions. Therefore the currently adopted specific yield of 0.1–0.15 is considered suitable.

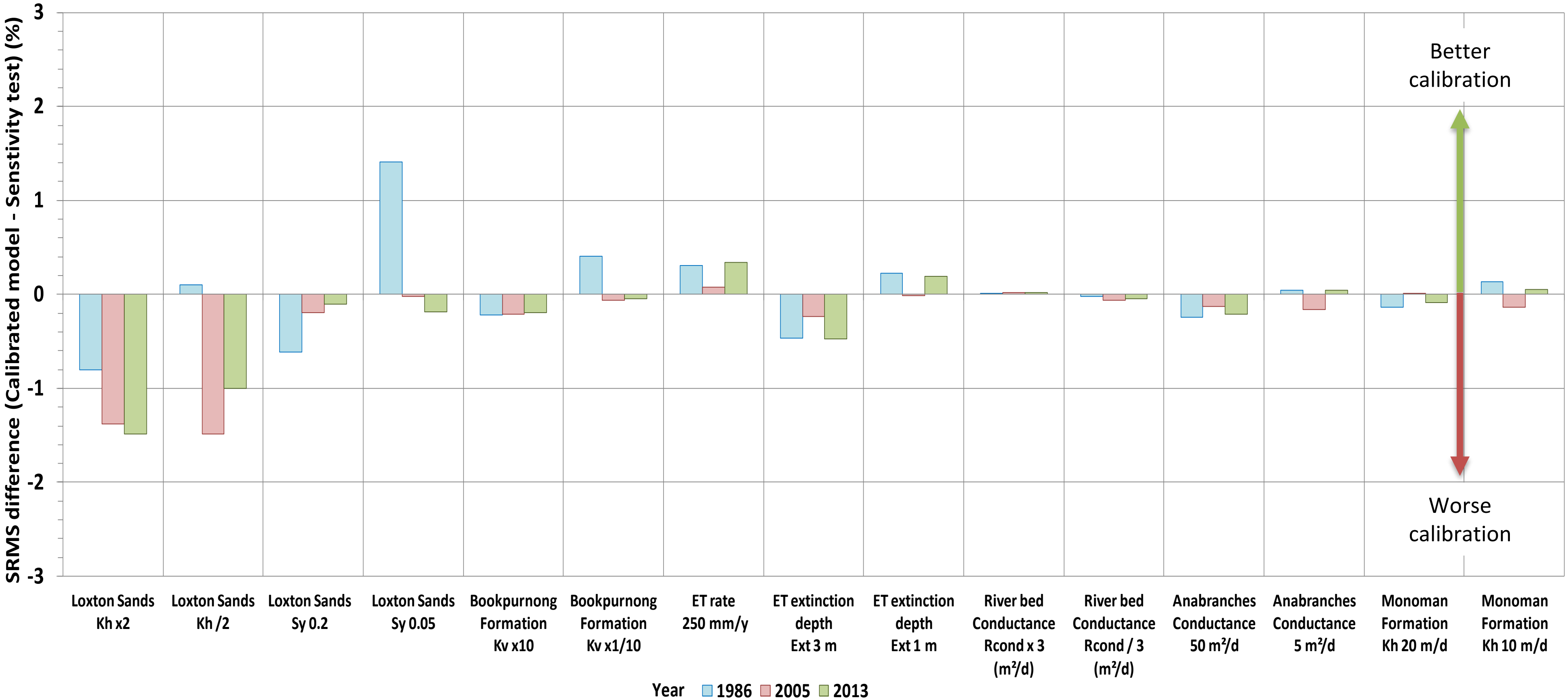


Figure 6.1. **Sensitivity of calibration fit to observed heads (SRMS)**

Modelled salt loads were used to measure how the parameters are sensitive to the model results. The test results also were compared to ROR data to measure its possibilities. Figure 6.2 and Figure 6.3 show the sensitivity of the modelled salt load to the River Murray in the Pike and Murtho reaches to the selected parameters. Salt loads are sensitive to potential groundwater ET rate and extinction depth in both Pike and Murtho. The lower groundwater ET rate and shallower ET extinction depth lead to an increase of modelled salt load but they are above the majority of RoR values. The deeper extinction depth results in a reduction in modelled salt load and matches the lower RoR values. The low values of RoR data were result of the drought conditions which is not included in this study for the Salinity Register modelling.

In Pike, salt loads are sensitive to anabranches conductance. This is because most highland groundwater discharges to the Pike River, rather than directly to the River Murray. The lower anabranch conductance leads the modelled salt loads to match the lower RoR values, again as discussed above the lower values of RoR are not considered to be appropriate to this study because of drought conditions. The higher anabranch conductance results in modelled salt loads much higher than the majority of RoR values and hence is not considered valid.

The lower Loxton Sands specific yield, which provides a better head calibration fit in early years, only causes a small difference in modelled salt loads in early years and very minor difference in later years (Figure 6.1). This supports the view that the currently adopted specific yield is appropriate for future predictions.

The modelled salt loads appear to be insensitive to changes in other selected parameters such as Bookpurnong Bed Kv (multiplied by 10 and divided by 10), Monoman Formation Kh (10 and 20 m/d) and Murray River bed conductance (3 times less or more which equivalent to vertical conductivities of 0.03 and 0.3 m/d).

Figure 6.2 Sensitivity of salt loads for the Pike reach

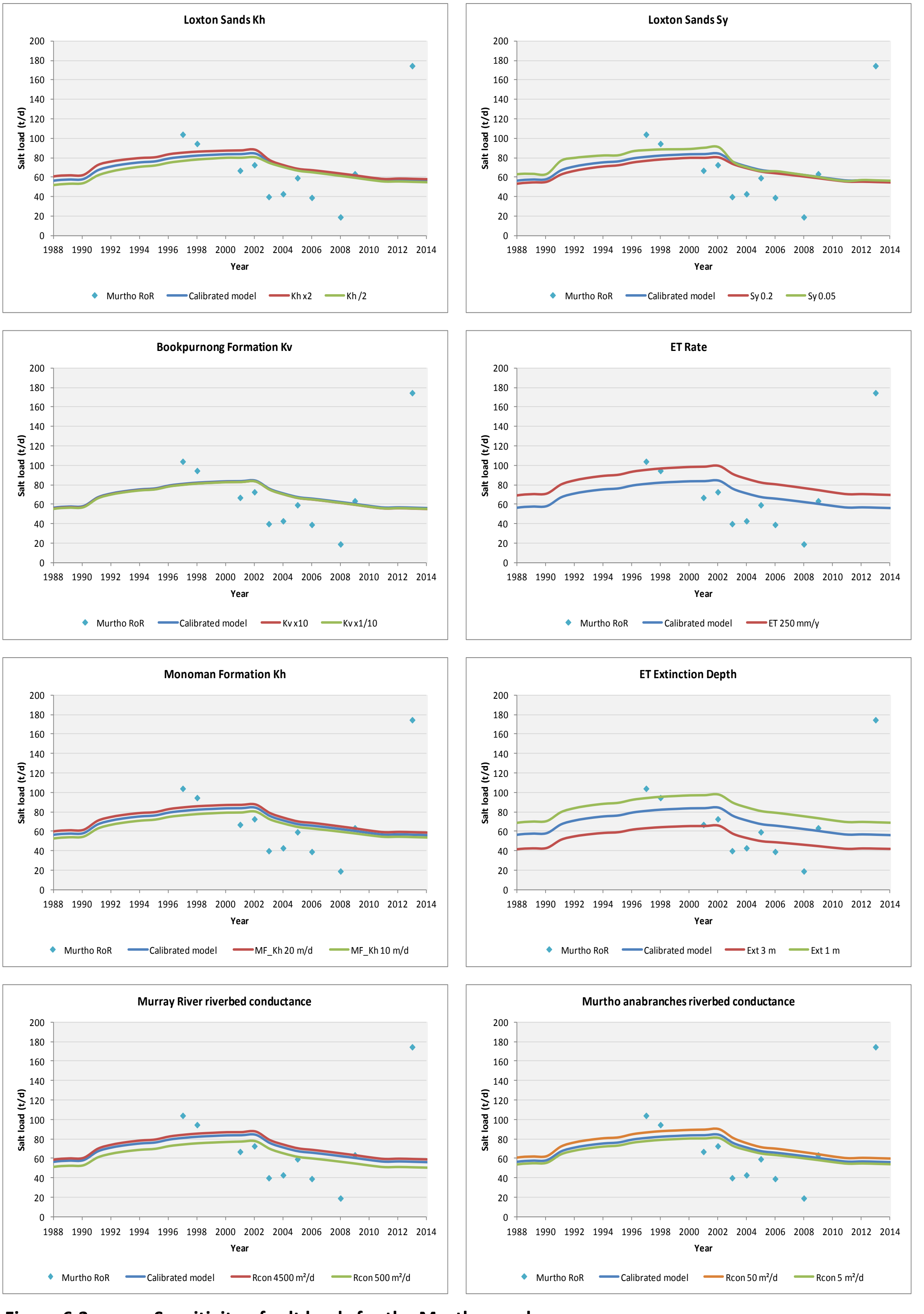


Figure 6.3 Sensitivity of salt loads for the Murtho reach

6.2 UNCERTAINTY ANALYSIS

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* (Middlemis et al., 2001) and *Australian Groundwater Modelling Guidelines* (Barnett et al., 2012) outline some options, such as worst-case scenario modelling, Monte Carlo simulations, alternative conceptualisations and predictive analysis. Handbooks such as Hill and Tiedeman (2007) are yet to be adopted for widespread Australian use.

The approach for uncertainty analysis is to select input parameters or conceptual assumptions that are poorly known and/or highly heterogeneous which may 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 aim of the uncertainty analysis for the Pike-Murtho 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:

- Groundwater salinity
- Irrigation recharge lag time
- Impact from excluding the Renmark irrigation area which is located on the western side of the River Murray and is outside the project area

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 uncertainty analysis. Scenarios 4 and 7A are the closest representation of reality, but because 7A includes the SIS which will minimise changes in salt load over time, Scenario 4 is the better option for determining differences due to uncertainty.

6.2.1 GROUNDWATER SALINITY

While much groundwater salinity data are available in some parts of the study area, salinity in a given aquifer may vary spatially, with location, depth and over time. The model calculates groundwater flow but does not simulate groundwater salinity changes 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. For the purposes of the Salinity Register, it is assumed that groundwater salinity is constant over time as the irrigation-derived groundwater mounds push regional groundwater into the river. This assumption is conservative which is consistent with BSMS requirement for the Salinity Registers.

Monitoring data show variations of groundwater salinity values between locations, with depth and over time in all sub-zone areas. It is most likely due to the natural hydrogeological processes, irrigation activities, wet/dry conditions and even method of sampling. This uncertainty analysis compares the salinity value used in salt load calculation with potential low and high observed groundwater salinities values in each sub-zone area (see Table 6.2). The percentage of groundwater salinity variation is a direct measure of the potential percentage changes in salt load. The calculation is a direct linear function.

The groundwater salinity range in Table 6.2 indicates that the groundwater salinity could be lower (e.g. 16% to 55%) or higher (e.g. 6% to 60%) the values used in calculation of the modelled salt load. The percentage is different between sub-zones. This means that the salt load could change up to 60% in the sub zone area. However, within the project area, a salt load change is limited to a range of RoR data.

Table 6.2 Ranges of groundwater salinity in Sub-zones (Loxton Sands aquifer)

Sub-Zone Area	Low Value (TDS mg/L)	*Percentage Low***	Applied* (TDS mg/L)	High Value (TDS mg/L)	*Percentage High***
North Murtho	17995	-16%	21358	32137	34%
Central Murtho	12500	-49%	24485	39840	39%
South Murtho	15104	-29%	21130	30857	32%
Upper Pike	26130	-19%	32200	34360	6%
Middle Pike	28927	-31%	42000	73120	43%
Simarloo	13743	-52%	28927	47390	39%
Lyrup	2700	-55%	6000	15043	60%

** Salinity values in salt load calculation are different from km to km (see Fig 3.22a-b). The applied values in the table are the most frequently occurring value in the sub-zone area*

*** Percentage difference to the applied value indicates effect on salt load calculation*

6.2.2 LAG TIME

The initial lag time from SIMRAT was used as starting point in the model and then it was altered with other model input parameters to achieve the closest match to observed hydrographs and other data. As there are no observation data to verify the lag times for new irrigation recharge, there is a considerable amount of uncertainty of lag times applied for future predictions.

For the uncertainty analysis, three cases are compared:

- Scenario 4 with the currently adopted lag times from calibrated model
- Scenario 4 with longer lag times for new irrigation recharge
    - at least 50 years,
    - any currently adopted lag times longer than 50 years are unchanged
- Scenario 4 with shorter lag times for new irrigation recharge
    - 10 years or less,
    - any currently adopted lag times shorter than 10 years are unchanged.

The test results of salt load due to using different lag times are shown in Figure 6.4 and Figure 6.5.
It is expected that the change of lag times affects when the modelled salt loads begin to rise. The shorter lag time case salt load starting to increase the earliest and peaksat around 2030. For the longer lag time case, salt load peaks at approximately around 2050. Salt loads from the shorter lag time case are similar to salt loads from the currently adopted lag times, indicating the currently adopted lag times are relatively closer to 10 years than to 50 years. In the long-term of 100 year prediction, the salt load difference due to lag times is minimal.

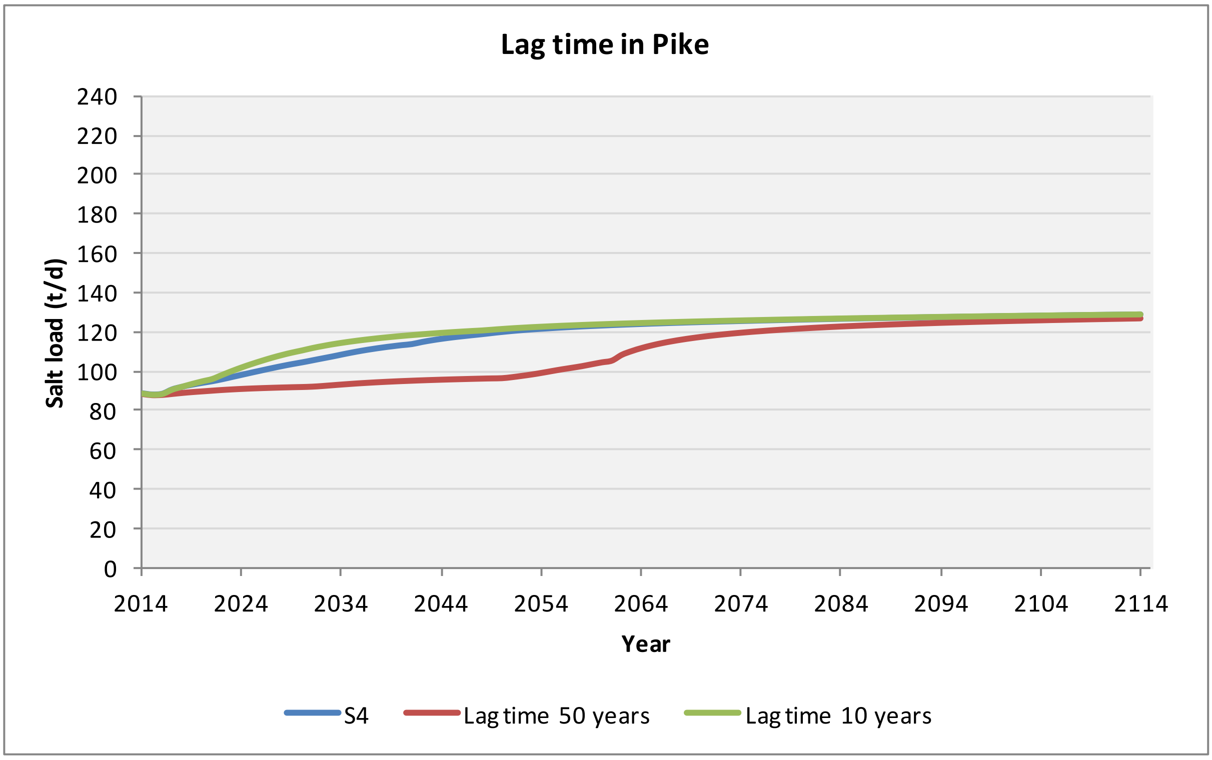


Figure 6.4 Uncertainty of irrigation recharge lag time in salt loads for the Pike Reach

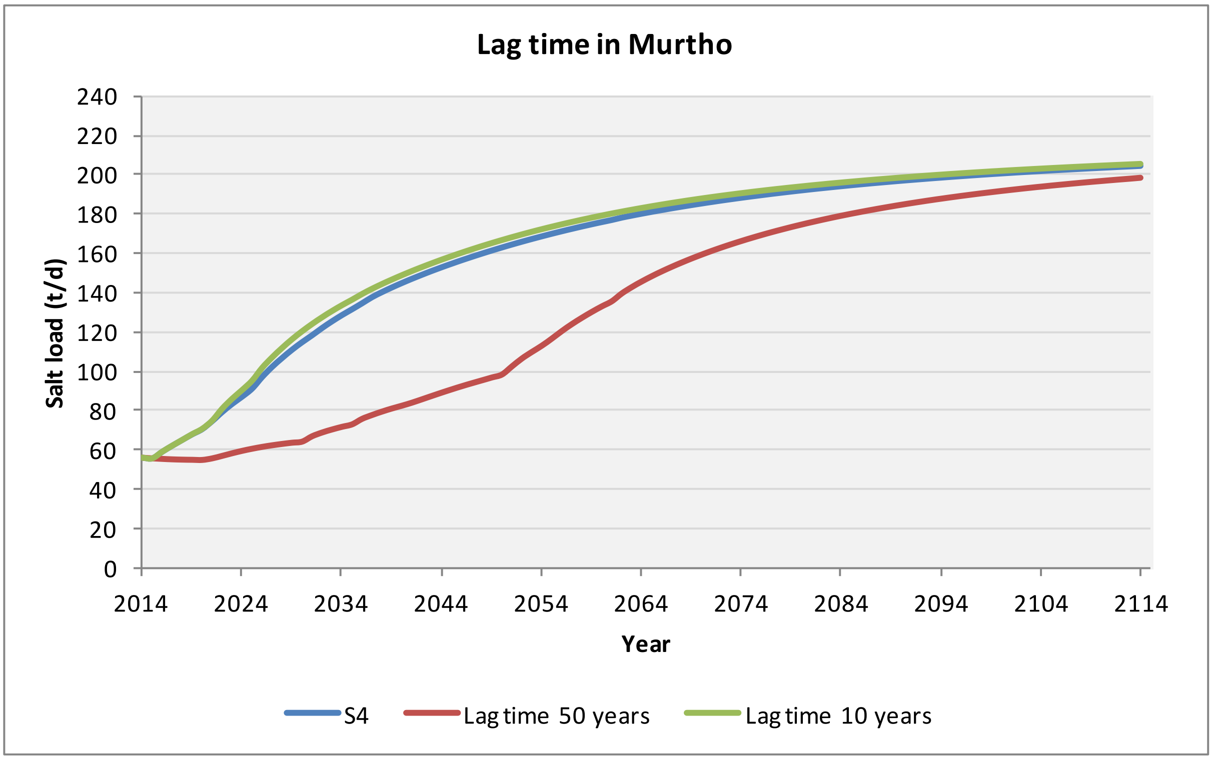


Figure 6.5 Uncertainty of irrigation recharge lag time in salt loads for the Murtho Reach

6.2.3 IMPACT OF RENMARK IRRIGATION RECHARGE

The Pike-Murtho project area resides in the regional Border to Lock 3 model, which also incorporates other irrigation districts such as Bookpunong-Loxton, Renmark-Berri and Pyap to Kingston. In this study, as discussed in Section 3 “sub-zone by sub-zone” approach, simulation of irrigation recharge changes are only applied within the Pike-Murtho project area. This approach is based on the assumption that the impacts of irrigation activities from the neighbouring districts on the Pike-Murtho project area is expected to be minimal due to the hydrogeological separation by hydraulic boundaries such as the River Valley, large floodplain, creek systems and groundwater dividing lines. The validity of this assumption for the Pike-Murtho project area is examined in this uncertainty analysis.

The Renmark irrigation area is on the western side of the project area (see Fig 2.1). Due to its proximity to the project area, there are concerns that the irrigation in the Renmark area may have an impact on the modelled results for the Pike-Murtho project area. To assess this impact, the groundwater mound in Renmark irrigation area was included in the test. Fixed head cells were used to simulate potentiometric surface contours 16 m AHD, 17 m AHD and 18 m AHD based on the 2000 condition from Yan et al. (2007). Assuming this is a conservative approach as the groundwater level in 2000 is relatively high and reflects the pre-drought conditions. The water levels are kept constant throughout the entire simulation.

Figure 6.6 shows the impact of Renmark irrigation on the modelled salt loads for Murtho. The maximum difference is approximately 10–15 t/d and it should be less based on lower groundwater level conditions in Renmark area. The test results show that the salt load difference for the Pike area is minor due to its distance from the Renmark area and large floodplain in between the areas.

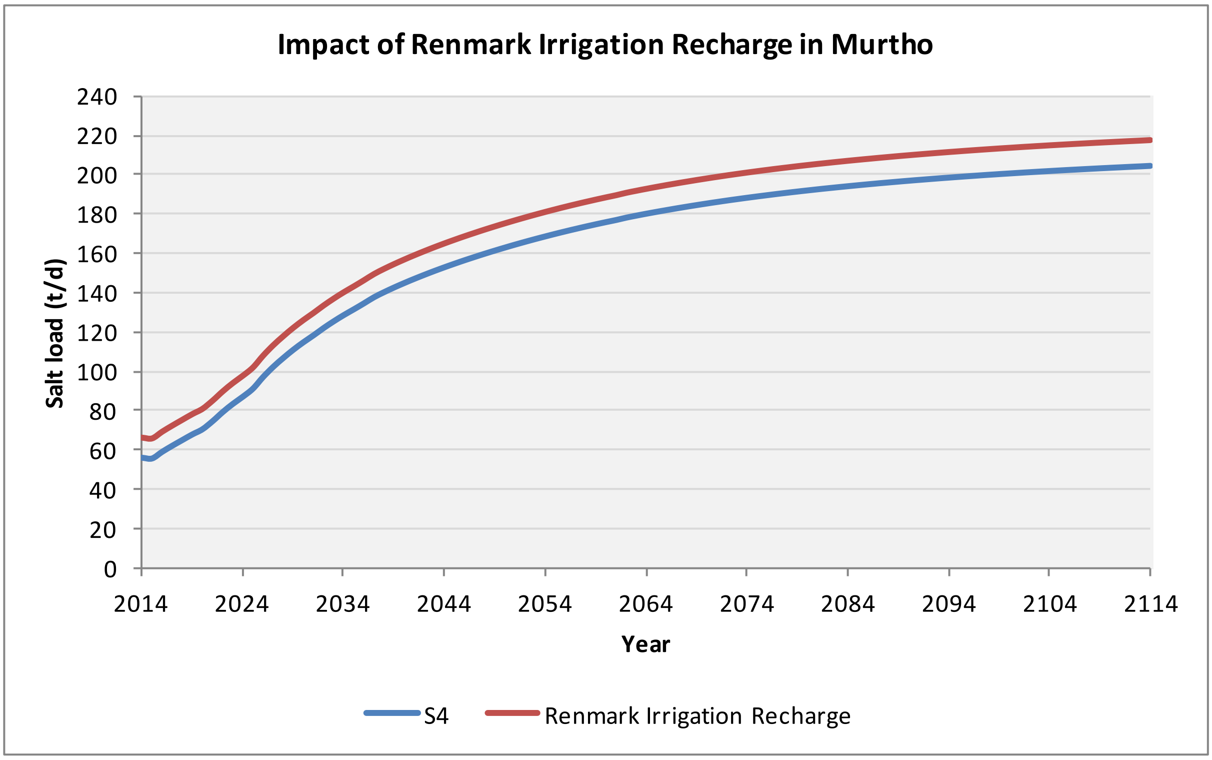


Figure 6.6 **Uncertainty of Renmark irrigation recharge in salt loads for the Murtho Reach**

7 MODEL CAPABILITIES AND LIMITATIONS

The Groundwater Flow Modelling Guideline (Middlemis et al., 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 Australian Groundwater Modelling Guidelines (Barnett et al., 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 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 and limitations below may require alteration:

1. Fine detail of local scaled 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. As the Salinity Register salt loads are about the long-term impact from accountable (human activity) actions, it does not include short term climate change impacts or river level fluctuations, as salt loads in effect assume baseline conditions in future predictions. Short-term changes (e.g. river dynamics) and actions causing changes in groundwater level and salt load are not simulated.
3. 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 detailed groundwater salinity changes temporarily (long term and short term) and spatially (horizontal and vertical). The current 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 and only if floodplain recharge and evaporation area substantially improved.

4. Model recharge zones and rates are based on the best available information, but are likely to be different in reality and differ in the future to those used in predictive modelling.
5. Groundwater levels in the floodplains are controlled by model input of ET rate and extinction depth and recharge. For extinction depth, the accuracy of model layer 1 top elevation is crucial. The elevation data are available DEM data, which can be at a finer resolution. When importing DEM data into the model, some of the details were lost due to the coarser size of the model cells and a steep change in nearby cells. This may result in reduced accuracy of modelled water levels near the edge of the floodplain. For detailed floodplain simulations, accuracy of ground surface representation in the model is required.

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 MODEL IMPROVEMENTS

The Border to Lock 3 numerical groundwater flow model has been reviewed and upgraded in the Pike-Murtho area as part of the Five-Year Review process of the SIS and Salinity Register entries. The model was upgraded based on new information and knowledge from hydrogeological investigations, groundwater modelling, particularly irrigation data and SIS investigation and construction. The upgrade includes the following features in Pike-Murtho area:

- compilation of detailed irrigation data, including irrigation footprints and accession estimates
- review of observed potentiometric head and near-river groundwater salinity
- compilation of data for 2007–13, including SIS pump rates and RoR salt load estimates
- extended model domain to the north to include the entire Murtho LWMP area
- updated model layer structural contours
- updated hydraulic conductivity values based on additional aquifer tests, information and knowledge
- improved representation of the River Murray and its anabranches
- updated groundwater ET on the floodplains to reflect the latest research findings
- revised model boundary conditions based on the current understanding of the conceptual model
- revised model flow budget zones, which are used for salt load calculations.

The model calibration has been improved by including additional long-term observed (historical) regional potentiometric heads from observation wells. The number of observation wells used for calibration in the Pike-Murtho 2014 model (101 wells) is about four times more than the Pike-Murtho 2006 model (25 wells). The calibration shows a better match to observed level and trends in most wells. The confirmation results show better match to RoR data, geophysical surveys, groundwater ET and irrigation accession information. The improved calibration and confirmation increase the confidence on the model results.

The improved model provides different results from the 2006 model and the comparison between the 2006 and 2014 models are show in Figure 8.1. The 2014 modelled salt loads show a better match to the RoR salt loads than the 2006 modelled salt loads. The 2014 modelled salt loads are lower than the 2006 modelled salt loads, which is mainly due to the improved understanding of groundwater ET in the floodplains from recent research findings by CSRIO. The total actual groundwater ET from floodplain has significantly increased from the 2006 model (7 ML/d) to the 2014 model (22 ML/d), which results in a reduction in groundwater flux entering the river from 20 ML/d in the 2006 model down to 10 ML/d in the 2014 model at year 2005.

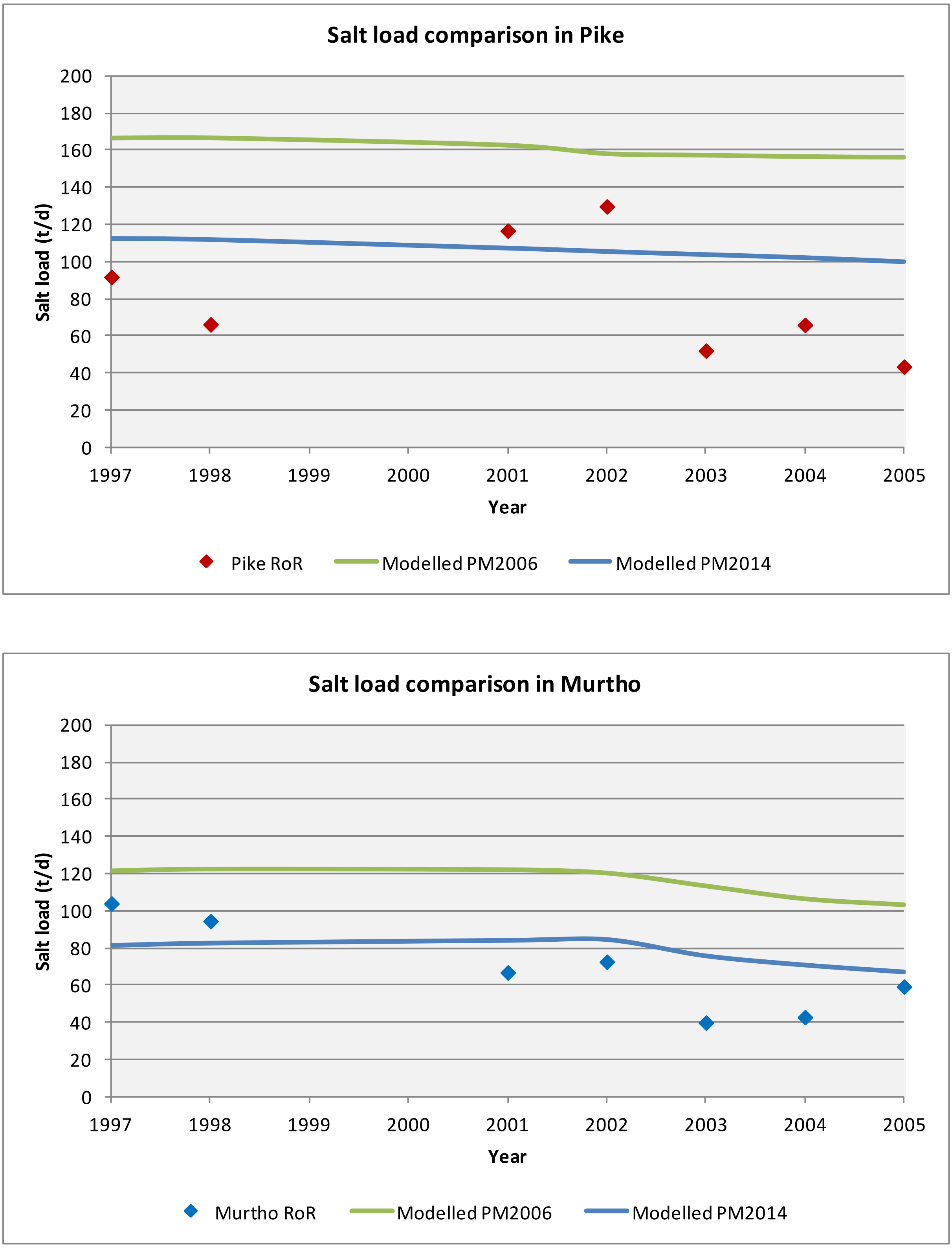


Figure 8.1 Salt load comparisons between RoR salt loads and the 2006 and 2014 modelled salt loads

The model is an 'impact assessment model of high complexity' in the terminology of the Middlemis et al. (2001) Modelling Guideline with a confidence level mainly meeting Class 2 criteria (but sometimes Class 3 in some elements), according to the classification criteria of the Barnett et al. (2012) Modelling Guidelines. The model was used to estimate salt loads to the River Murray for different scenarios required for the Salinity Register.

As specified by the Modelling Guidelines (Middlemis et al., 2001, Barnett et al., 2012), sensitivity and uncertainty tests were undertaken to aid risk assessment in future management and policy decisions.

Model files are organised (structure and name convention) using a structure following the protocol from the DEWNR Groundwater Model Warehouse. The filings are shown in Appendix C-2. This includes collated data, model files, model input and output files, results and reports.

8.2 MODELLING RESULTS

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 Figure 5.2 to Figure 5.5 and are summarised in Table 8.1 and Table 8.2. The annual salt loads and groundwater flux entering the River Murray for each scenario are given in Figure 8.2 and Figure 8.3 and for the Murtho in Figure 8.4 and Figure 8.5.

Table 8.1 Summary of predicted salt load (t/d) Entering the River Murray in Pike

Pike	Year simulated	Modelled salt load (t/d)						
		1988	2000	2014	2015	2050	2100	2114
Calibrated historical model	1880-2013	103.4	109.3	79.3	-	-	-	-
Scenario 1	Steady-state	31.6	31.6	31.6	31.6	31.6	31.6	31.6
Scenario 2	1880 – 2114	33.8	34.9	36.4	36.7	41.9	50.9	53.0
Scenario 3A	1880 – 2114	103.4	119.4	127.0	127.6	143.3	146.5	146.9
Scenario 3C	1880 – 2114	103.4	105.6	85.2	84.0	93.1	95.1	95.3
Scenario 4	1880– 2114	103.4	109.3	88.9	87.6	119.5	127.5	128.4
Scenario 5	1880 – 2114	103.4	109.3	88.9	87.6	128.2	142.1	143.3
Scenario 7A	1880 – 2114	103.4	109.3	78.4	73.3	95.7	101.6	102.2
Scenario 7B	1880 – 2114	103.4	105.6	75.1	70.2	74.1	75.3	75.4
Scenario 7C	1880 – 2114	103.4	109.3	78.4	73.3	108.9	123.5	124.5

Table 8.2 Summary of predicted salt load (t/d) Entering the River Murray in Murtho

Murtho	Year simulated	Modelled salt load (t/d)						
		1988	2000	2014	2015	2050	2100	2114
Calibrated historical model	1880-2013	56.1	83.2	56.0	-	-	-	-
Scenario 1	Steady-state	20.5	20.5	20.5	20.5	20.5	20.5	20.5
Scenario 2	1880 – 2114	20.8	20.8	20.9	20.9	21.2	22.8	23.6
Scenario 3A	1880 – 2114	56.1	86.2	104.4	105.5	152.6	161.0	161.8
Scenario 3C	1880 – 2114	56.1	83.2	52.9	51.7	89.6	96.5	97.1
Scenario 4	1880 – 2114	56.1	83.2	56.0	55.3	162.8	200.8	204.4
Scenario 5	1880 – 2114	56.1	83.2	56.0	55.3	169.3	233.2	238.7
Scenario 7A	1880 – 2114	56.1	83.2	56.0	28.6	67.5	101.6	104.9
Scenario 7B	1880 – 2114	56.1	83.2	52.9	25.8	18.1	19.1	19.2
Scenario 7C	1880 – 2114	56.1	83.2	56.0	28.6	71.0	120.8	125.2

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:

- continue collection of irrigation data which includes metering actual application volumes, mapping irrigated areas, recording crop types and drainage volumes. These data could provide estimates of root zone drainage over time and provides higher confidence on model recharge.
- continue the current monitoring of potentiometric head and salinity in Obswell and SIS wells for model validation in the next Five-Year Review
- conduct more aquifer tests to estimate the vertical conductivity of the Bookpurnong Formation and the horizontal conductivity of the Loxton Sands aquifer in the regional area
- continue RoR surveys as they are used for model confirmation which increases model output confidence
- improve quality of groundwater salinity data (e.g. distribution) in the Loxton Sands 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 are:

- improving simulation of groundwater recharge from irrigation, if more information becomes available
- improving simulation of evapotranspiration from groundwater on the floodplain areas, if more information becomes available
- improving model layering, especially the sub-units of the Murray Group Limestone aquifer in the Pike-Murtho area, based on detailed drillhole log analysis and additional Murray Group Limestone wells.
- 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)
- improving the understanding of floodplain-river connections in the 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 information about groundwater salinity. These data will be useful for salt load calculations and if solute transport modelling is included in future models
- improved understanding of flow in the unsaturated zone, including perched aquifers, to better inform recharge rates and lag time
- consideration of groundwater salinity changes over time in salt load calculations when valid information becomes available. This will affect estimating 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.
- Using LIDAR for floodplain

Pike								
Time	**S-1**	**S-2**	**S-3A**	**S3C**	**S-4**	**S-5**	**S-8A**	**S-8B**
(y)	*(t/d)*	*(t/d)*	*(t/d)*	*(t/d)*	*(t/d)*	*(t/d)*	*(t/d)*	*(t/d)*
1880	31.6	31.6	31.6	31.6	31.6	31.6	31.6	31.6
1885	31.6	31.6	31.6	31.6	31.6	31.6	31.6	31.6
1890	31.6	31.6	31.6	31.6	31.6	31.6	31.6	31.6
1895	31.6	31.6	31.6	31.6	31.6	31.6	31.6	31.6
1900	31.6	31.6	31.6	31.6	31.6	31.6	31.6	31.6
1905	31.6	31.6	32.3	32.3	32.3	32.3	32.3	32.3
1910	31.6	31.6	32.4	32.4	32.4	32.4	32.4	32.4
1915	31.6	31.6	32.5	32.5	32.5	32.5	32.5	32.5
1920	31.6	31.6	32.5	32.5	32.5	32.5	32.5	32.5
1925	31.6	31.7	32.5	32.5	32.5	32.5	32.5	32.5
1930	31.6	31.7	32.5	32.5	32.5	32.5	32.5	32.5
1935	31.6	31.7	32.5	32.5	32.5	32.5	32.5	32.5
1940	31.6	31.8	37.9	37.9	37.9	37.9	37.9	37.9
1945	31.6	31.9	38.5	38.5	38.5	38.5	38.5	38.5
1950	31.6	32.0	40.8	40.8	40.8	40.8	40.8	40.8
1955	31.6	32.2	40.7	40.7	40.7	40.7	40.7	40.7
1960	31.6	32.4	48.0	48.0	48.0	48.0	48.0	48.0
1965	31.6	32.6	53.8	53.8	53.8	53.8	53.8	53.8
1970	31.6	32.7	71.7	71.7	71.7	71.7	71.7	71.7
1975	31.6	33.0	77.0	77.0	77.0	77.0	77.0	77.0
1980	31.6	33.3	91.2	91.2	91.2	91.2	91.2	91.2
1982	31.6	33.4	95.9	95.9	95.9	95.9	95.9	95.9
1984	31.6	33.5	99.2	99.2	99.2	99.2	99.2	99.2
1985	31.6	33.6	100.3	100.3	100.3	100.3	100.3	100.3
1986	31.6	33.7	101.3	101.3	101.3	101.3	101.3	101.3
1988	31.6	33.8	103.4	103.4	103.4	103.4	103.4	103.4
1989	31.6	33.9	104.5	104.5	104.5	104.5	104.5	104.5
1990	31.6	34.0	105.5	105.4	105.4	105.4	105.4	105.4
1991	31.6	34.1	109.9	109.3	109.8	109.8	109.8	109.3
1992	31.6	34.1	112.1	110.7	111.5	111.5	111.5	110.7
1993	31.6	34.2	113.6	111.1	112.1	112.1	112.1	111.1
1994	31.6	34.3	114.7	111.2	112.3	112.3	112.3	111.2
1995	31.6	34.4	115.6	110.8	112.1	112.1	112.1	110.8
1996	31.6	34.5	116.4	110.3	112.6	112.6	112.6	110.3
1997	31.6	34.6	117.2	109.4	112.3	112.3	112.3	109.4
1998	31.6	34.7	117.9	108.4	111.7	111.7	111.7	108.4
1999	31.6	34.8	118.7	107.1	110.7	110.7	110.7	107.1
2000	31.6	34.9	119.4	105.6	109.3	109.3	109.3	105.6
2001	31.6	35.0	120.3	103.5	107.1	107.1	107.1	103.5
2002	31.6	35.1	121.2	101.7	105.3	105.3	105.3	101.7
2003	31.6	35.2	122.0	100.0	103.6	103.6	103.6	100.0
2004	31.6	35.3	122.8	98.3	102.0	102.0	102.0	98.3
2005	31.6	35.4	123.5	96.1	99.8	99.8	99.8	96.1
2006	31.6	35.6	124.1	94.2	97.8	97.8	97.8	94.2
2007	31.6	35.7	124.6	92.4	95.9	95.9	95.9	92.4
2008	31.6	35.8	125.1	90.7	94.2	94.2	94.2	90.7
2009	31.6	35.9	125.6	89.1	92.7	92.7	92.7	89.1
2010	31.6	36.0	126.0	87.9	91.5	91.5	91.5	87.9
2011	31.6	36.1	126.4	86.9	90.5	90.5	90.5	86.9
2012	31.6	36.3	126.7	86.0	89.6	89.6	89.6	86.0
2013	31.6	36.4	127.0	85.2	88.9	88.9	78.4	75.1
2014	31.6	36.5	127.3	84.5	88.2	88.2	75.0	71.9
2015	31.6	36.7	127.6	84.0	87.6	87.6	73.3	70.2
2016	31.6	36.8	128.5	84.1	88.0	88.0	72.9	69.6
2017	31.6	36.9	129.8	84.7	90.2	90.2	74.5	69.6
2018	31.6	37.0	130.9	85.3	91.6	91.6	75.3	69.7
2019	31.6	37.2	131.8	85.8	92.7	92.7	76.0	69.7
2020	31.6	37.3	132.7	86.2	93.6	93.6	76.5	69.8
2021	31.6	37.4	133.4	86.6	94.4	94.4	77.1	69.9
2022	31.6	37.6	134.1	87.0	95.4	95.4	77.8	70.1
2023	31.6	37.7	134.8	87.4	96.6	96.6	78.7	70.3
2024	31.6	37.9	135.4	87.8	97.7	97.7	79.7	70.5
2025	31.6	38.0	135.9	88.1	98.9	98.9	80.6	70.7
2026	31.6	38.2	136.5	88.4	100.0	100.0	81.5	70.9
2027	31.6	38.3	137.1	88.8	101.1	101.1	82.5	71.2
2028	31.6	38.4	137.6	89.2	102.1	102.1	83.4	71.5
2029	31.6	38.6	138.1	89.6	103.1	103.1	84.2	71.7
2030	31.6	38.7	138.6	90.0	104.0	104.0	85.0	72.0
2031	31.6	38.9	139.0	90.3	105.0	105.0	85.8	72.2
2032	31.6	39.1	139.4	90.5	106.0	106.0	86.7	72.4
2033	31.6	39.2	139.8	90.8	107.0	107.0	87.5	72.6
2034	31.6	39.4	140.1	91.0	108.0	108.0	88.1	72.8
2035	31.6	39.5	140.4	91.2	109.0	109.0	88.7	72.9
2036	31.6	39.7	140.7	91.4	110.0	110.0	89.3	73.1
2037	31.6	39.8	141.0	91.6	110.8	110.9	89.8	73.2
2038	31.6	40.0	141.2	91.8	111.5	111.8	90.3	73.3
2039	31.6	40.1	141.4	91.9	112.2	112.8	90.7	73.4
2040	31.6	40.3	141.6	92.0	112.8	113.7	91.0	73.5
2041	31.6	40.4	141.8	92.2	113.3	114.8	91.4	73.6
2042	31.6	40.6	142.0	92.3	114.4	116.9	92.0	73.6
2043	31.6	40.8	142.2	92.4	115.3	118.9	92.6	73.7
2044	31.6	41.0	142.4	92.5	116.0	120.7	93.1	73.8
2045	31.6	41.1	142.6	92.6	116.7	122.3	93.6	73.8
2046	31.6	41.3	142.7	92.7	117.3	123.7	94.0	73.9
2047	31.6	41.5	142.9	92.8	117.8	124.9	94.4	74.0
2048	31.6	41.6	143.0	92.9	118.4	126.1	94.8	74.0
2049	31.6	41.8	143.1	93.0	118.9	127.2	95.2	74.1
2050	31.6	41.9	143.3	93.1	119.5	128.2	95.6	74.1
2051	31.6	42.1	143.4	93.1	120.0	129.1	96.0	74.2
2052	31.6	42.3	143.5	93.2	120.4	129.9	96.4	74.2
2053	31.6	42.5	143.6	93.3	120.8	130.6	96.6	74.2
2054	31.6	42.7	143.7	93.4	121.1	131.3	96.9	74.3
2055	31.6	42.8	143.9	93.4	121.5	131.9	97.1	74.3
2056	31.6	43.0	144.0	93.5	121.8	132.4	97.4	74.4
2057	31.6	43.2	144.1	93.5	122.0	132.9	97.6	74.4
2058	31.6	43.3	144.2	93.6	122.3	133.4	97.8	74.4
2059	31.6	43.5	144.2	93.7	122.5	133.8	97.9	74.5
2060	31.6	43.7	144.3	93.7	122.8	134.2	98.1	74.5
2061	31.6	43.9	144.4	93.8	123.0	134.6	98.2	74.5
2062	31.6	44.1	144.5	93.8	123.2	135.0	98.4	74.6
2063	31.6	44.3	144.6	93.9	123.4	135.3	98.5	74.6
2064	31.6	44.4	144.7	93.9	123.6	135.6	98.7	74.6
2065	31.6	44.6	144.8	94.0	123.8	135.9	98.8	74.6
2066	31.6	44.8	144.8	94.0	123.9	136.2	98.9	74.7
2067	31.6	45.0	144.9	94.1	124.1	136.5	99.0	74.7
2068	31.6	45.1	145.0	94.1	124.3	136.8	99.1	74.7
2069	31.6	45.3	145.0	94.1	124.4	137.1	99.3	74.7
2070	31.6	45.5	145.1	94.2	124.5	137.3	99.4	74.8
2071	31.6	45.7	145.2	94.2	124.7	137.5	99.5	74.8
2072	31.6	45.9	145.2	94.3	124.8	137.8	99.6	74.8
2073	31.6	46.1	145.3	94.3	125.0	138.0	99.7	74.8
2074	31.6	46.3	145.4	94.4	125.1	138.2	99.8	74.8
2075	31.6	46.4	145.4	94.4	125.2	138.4	99.8	74.9
2076	31.6	46.6	145.5	94.4	125.3	138.6	99.9	74.9
2077	31.6	46.8	145.5	94.5	125.5	138.8	100.0	74.9
2078	31.6	47.0	145.6	94.5	125.6	139.0	100.1	74.9
2079	31.6	47.1	145.6	94.5	125.7	139.2	100.2	74.9
2080	31.6	47.3	145.7	94.6	125.8	139.3	100.3	75.0
2081	31.6	47.5	145.7	94.6	125.9	139.5	100.3	75.0
2082	31.6	47.7	145.8	94.6	126.0	139.7	100.4	75.0
2083	31.6	47.9	145.8	94.7	126.1	139.8	100.5	75.0
2084	31.6	48.1	145.9	94.7	126.2	140.0	100.6	75.0
2085	31.6	48.3	145.9	94.7	126.3	140.2	100.6	75.1
2086	31.6	48.4	146.0	94.7	126.4	140.3	100.7	75.1
2087	31.6	48.6	146.0	94.8	126.5	140.5	100.8	75.1
2088	31.6	48.8	146.0	94.8	126.6	140.6	100.8	75.1
2089	31.6	49.0	146.1	94.8	126.7	140.7	100.9	75.1
2090	31.6	49.1	146.1	94.9	126.8	140.9	101.0	75.1
2091	31.6	49.3	146.2	94.9	126.8	141.0	101.0	75.1
2092	31.6	49.5	146.2	94.9	126.9	141.1	101.1	75.2
2093	31.6	49.7	146.2	94.9	127.0	141.3	101.2	75.2
2094	31.6	49.9	146.3	95.0	127.1	141.4	101.2	75.2
2095	31.6	50.0	146.3	95.0	127.2	141.5	101.3	75.2
2096	31.6	50.2	146.4	95.0	127.2	141.6	101.3	75.2
2097	31.6	50.4	146.4	95.0	127.3	141.7	101.4	75.2
2098	31.6	50.5	146.4	95.0	127.4	141.8	101.5	75.2
2099	31.6	50.7	146.5	95.1	127.5	142.0	101.5	75.3
2100	31.6	50.9	146.5	95.1	127.5	142.1	101.6	75.3
2101	31.6	51.0	146.5	95.1	127.6	142.2	101.6	75.3
2102	31.6	51.2	146.5	95.1	127.7	142.3	101.7	75.3
2103	31.6	51.4	146.6	95.2	127.7	142.4	101.7	75.3
2104	31.6	51.6	146.6	95.2	127.8	142.5	101.8	75.3
2105	31.6	51.7	146.6	95.2	127.9	142.6	101.8	75.3
2106	31.6	51.9	146.7	95.2	127.9	142.7	101.9	75.3
2107	31.6	52.0	146.7	95.2	128.0	142.8	101.9	75.3
2108	31.6	52.2	146.7	95.2	128.1	142.9	102.0	75.4
2109	31.6	52.4	146.8	95.3	128.1	143.0	102.0	75.4
2110	31.6	52.5	146.8	95.3	128.2	143.1	102.1	75.4
2111	31.6	52.7	146.8	95.3	128.3	143.1	102.1	75.4
2112	31.6	52.8	146.8	95.3	128.3	143.2	102.2	75.4
2113	31.6	53.0	146.9	95.3	128.4	143.3	102.2	75.4
2114	31.6	53.1	146.9	95.4	128.4	143.4	102.3	75.4

Figure 8.2. Modelled salt load entering the River Murray for all scenarios for the Pike reach

Pike								
Time	S-1	S-2	S-3A	S3C	S-4	S-5	S-8A	S-8B
(y)	(m³/d)	(m³/d)	(m³/d)	(m³/d)	(m³/d)	(m³/d)	(m³/d)	(m³/d)
1880	2100	2101	2100	2100	2100	2100	2100	2100
1885	2100	2101	2100	2100	2100	2100	2100	2100
1890	2100	2100	2100	2100	2100	2100	2100	2100
1895	2100	2100	2100	2100	2100	2100	2100	2100
1900	2100	2100	2100	2100	2100	2100	2100	2100
1905	2100	2100	2209	2209	2209	2209	2209	2209
1910	2100	2100	2230	2230	2230	2230	2230	2230
1915	2100	2100	2236	2236	2236	2236	2236	2236
1920	2100	2100	2239	2239	2239	2239	2239	2239
1925	2100	2102	2241	2241	2241	2241	2241	2241
1930	2100	2103	2242	2242	2242	2242	2242	2242
1935	2100	2107	2242	2242	2242	2242	2242	2242
1940	2100	2110	2703	2703	2703	2703	2703	2703
1945	2100	2116	2764	2764	2764	2764	2764	2764
1950	2100	2120	3093	3093	3093	3093	3093	3093
1955	2100	2127	3095	3095	3095	3095	3095	3095
1960	2100	2133	3730	3730	3730	3730	3730	3730
1965	2100	2141	3973	3973	3973	3973	3973	3973
1970	2100	2149	4526	4526	4526	4526	4526	4526
1975	2100	2159	4649	4649	4649	4649	4649	4649
1980	2100	2169	5134	5134	5134	5134	5134	5134
1982	2100	2174	5292	5291	5291	5291	5291	5291
1984	2100	2179	5408	5407	5407	5407	5407	5407
1985	2100	2182	5442	5442	5442	5442	5442	5442
1986	2100	2185	5476	5476	5476	5476	5476	5476
1988	2100	2191	5591	5591	5591	5591	5591	5591
1989	2100	2193	5656	5656	5656	5656	5656	5656
1990	2100	2196	5717	5709	5709	5709	5709	5709
1991	2100	2199	5898	5860	5917	5917	5917	5860
1992	2100	2203	5993	5893	5973	5973	5973	5893
1993	2100	2206	6056	5884	5982	5982	5982	5884
1994	2100	2210	6103	5861	5972	5972	5972	5861
1995	2100	2213	6142	5820	5943	5943	5943	5820
1996	2100	2217	6175	5783	5945	5945	5945	5783
1997	2100	2221	6208	5729	5915	5915	5915	5729
1998	2100	2224	6239	5663	5865	5865	5865	5663
1999	2100	2227	6268	5587	5798	5798	5798	5587
2000	2100	2231	6295	5502	5716	5716	5716	5502
2001	2100	2236	6327	5388	5589	5589	5589	5388
2002	2100	2240	6358	5293	5491	5491	5491	5293
2003	2100	2245	6388	5206	5410	5410	5410	5206
2004	2100	2249	6415	5125	5329	5329	5329	5125
2005	2100	2253	6439	5031	5232	5232	5232	5031
2006	2100	2257	6460	4948	5144	5144	5144	4948
2007	2100	2262	6480	4868	5063	5063	5063	4868
2008	2100	2266	6497	4794	4989	4989	4989	4794
2009	2100	2270	6513	4728	4923	4924	4923	4728
2010	2100	2274	6527	4674	4869	4869	4869	4674
2011	2100	2280	6541	4627	4823	4823	4823	4627
2012	2100	2285	6553	4586	4787	4787	4787	4586
2013	2100	2290	6565	4548	4750	4750	4363	4174
2014	2100	2296	6576	4514	4717	4716	4215	4032
2015	2100	2301	6586	4487	4691	4691	4139	3957
2016	2100	2305	6614	4483	4693	4693	4111	3925
2017	2100	2310	6651	4495	4826	4826	4219	3913
2018	2100	2315	6687	4509	4878	4878	4251	3907
2019	2100	2320	6719	4521	4912	4912	4268	3904
2020	2100	2324	6746	4532	4938	4938	4282	3902
2021	2100	2331	6770	4541	4963	4963	4296	3901
2022	2100	2337	6793	4551	4996	4996	4318	3902
2023	2100	2343	6814	4560	5033	5033	4346	3904
2024	2100	2349	6833	4569	5071	5071	4375	3907
2025	2100	2354	6851	4576	5108	5108	4405	3909
2026	2100	2360	6868	4585	5145	5145	4434	3912
2027	2100	2365	6885	4594	5181	5181	4463	3918
2028	2100	2370	6902	4604	5214	5214	4491	3924
2029	2100	2375	6918	4613	5247	5247	4517	3929
2030	2100	2380	6932	4621	5277	5277	4541	3935
2031	2100	2387	6945	4629	5308	5308	4568	3939
2032	2100	2394	6957	4636	5340	5340	4594	3944
2033	2100	2400	6968	4642	5372	5372	4617	3947
2034	2100	2407	6978	4648	5408	5408	4639	3951
2035	2100	2412	6988	4653	5443	5443	4660	3954
2036	2100	2418	6997	4658	5476	5477	4678	3957
2037	2100	2424	7005	4663	5506	5509	4695	3959
2038	2100	2429	7013	4667	5532	5542	4711	3962

Pike								
Time	S-1	S-2	S-3A	S3C	S-4	S-5	S-8A	S-8B
(y)	(m³/d)	(m³/d)	(m³/d)	(m³/d)	(m³/d)	(m³/d)	(m³/d)	(m³/d)
2039	2100	2435	7020	4671	5556	5575	4725	3964
2040	2100	2440	7027	4675	5577	5608	4738	3966
2041	2100	2448	7034	4678	5597	5647	4749	3967
2042	2100	2455	7040	4682	5634	5717	4770	3969
2043	2100	2462	7046	4685	5665	5785	4790	3971
2044	2100	2469	7051	4688	5691	5846	4807	3972
2045	2100	2475	7057	4690	5714	5900	4822	3974
2046	2100	2481	7062	4693	5735	5946	4835	3975
2047	2100	2488	7067	4696	5753	5988	4848	3976
2048	2100	2494	7071	4698	5771	6025	4860	3978
2049	2100	2500	7076	4701	5790	6061	4874	3979
2050	2100	2505	7080	4703	5808	6094	4887	3980
2051	2100	2513	7084	4705	5824	6124	4899	3981
2052	2100	2521	7088	4707	5838	6150	4909	3982
2053	2100	2528	7092	4709	5851	6173	4918	3983
2054	2100	2535	7095	4711	5862	6194	4927	3984
2055	2100	2542	7099	4713	5873	6214	4934	3985
2056	2100	2549	7102	4715	5883	6232	4941	3986
2057	2100	2556	7105	4717	5892	6249	4947	3987
2058	2100	2563	7109	4719	5900	6264	4953	3988
2059	2100	2569	7112	4720	5908	6279	4959	3988
2060	2100	2575	7115	4722	5916	6292	4964	3989
2061	2100	2584	7117	4724	5923	6305	4969	3990
2062	2100	2592	7120	4725	5930	6317	4973	3991
2063	2100	2599	7123	4727	5937	6329	4978	3991
2064	2100	2607	7125	4728	5943	6339	4982	3992
2065	2100	2614	7128	4729	5949	6349	4986	3993
2066	2100	2622	7130	4731	5955	6359	4990	3994
2067	2100	2629	7133	4732	5960	6369	4993	3994
2068	2100	2636	7135	4734	5965	6378	4997	3995
2069	2100	2643	7137	4735	5970	6386	5000	3995
2070	2100	2650	7139	4736	5975	6394	5004	3996
2071	2100	2658	7141	4737	5980	6402	5007	3997
2072	2100	2666	7143	4739	5985	6410	5010	3997
2073	2100	2674	7145	4740	5989	6417	5013	3998
2074	2100	2682	7147	4741	5993	6424	5016	3999
2075	2100	2690	7149	4742	5997	6431	5019	3999
2076	2100	2697	7151	4743	6001	6437	5021	4000
2077	2100	2704	7153	4744	6005	6444	5024	4000
2078	2100	2712	7155	4745	6009	6450	5027	4001
2079	2100	2719	7156	4746	6013	6456	5029	4001
2080	2100	2726	7158	4747	6016	6462	5032	4002
2081	2100	2734	7160	4748	6019	6467	5034	4002
2082	2100	2742	7161	4749	6023	6473	5036	4003
2083	2100	2750	7163	4750	6026	6478	5039	4003
2084	2100	2758	7164	4751	6029	6483	5041	4004
2085	2100	2766	7166	4752	6032	6488	5043	4004
2086	2100	2773	7167	4753	6036	6493	5045	4005
2087	2100	2781	7168	4754	6039	6498	5047	4005
2088	2100	2788	7170	4755	6041	6502	5050	4006
2089	2100	2796	7171	4756	6044	6506	5051	4006
2090	2100	2803	7172	4756	6047	6511	5054	4006
2091	2100	2811	7174	4757	6050	6515	5055	4007
2092	2100	2819	7175	4758	6052	6519	5057	4007
2093	2100	2826	7176	4759	6055	6523	5059	4008
2094	2100	2834	7177	4760	6057	6527	5061	4008
2095	2100	2841	7178	4760	6060	6531	5063	4008
2096	2100	2849	7180	4761	6062	6535	5065	4009
2097	2100	2856	7181	4762	6065	6539	5066	4009
2098	2100	2864	7182	4763	6067	6542	5068	4010
2099	2100	2871	7183	4763	6069	6546	5070	4010
2100	2100	2878	7184	4764	6072	6549	5071	4010
2101	2100	2885	7185	4765	6074	6553	5073	4011
2102	2100	2893	7186	4765	6076	6556	5075	4011
2103	2100	2900	7187	4766	6078	6559	5076	4011
2104	2100	2907	7188	4766	6080	6563	5078	4012
2105	2100	2915	7189	4767	6082	6566	5079	4012
2106	2100	2922	7190	4768	6084	6569	5081	4012
2107	2100	2929	7191	4768	6086	6572	5082	4013
2108	2100	2936	7192	4769	6088	6575	5084	4013
2109	2100	2942	7192	4769	6090	6577	5085	4013
2110	2100	2949	7193	4770	6092	6580	5087	4013
2111	2100	2956	7194	4771	6094	6583	5088	4014
2112	2100	2963	7195	4771	6096	6586	5090	4014
2113	2100	2970	7196	4772	6098	6588	5091	4014
2114	2100	2977	7196	4772	6099	6591	5092	4015

Figure 8.3. Modelled groundwater flux entering the River Murray for all scenarios for the Pike reach

Murtho								
Time (y)	S-1 (t/d)	S-2 (t/d)	S-3A (t/d)	S3C (t/d)	S-4 (t/d)	S-5 (t/d)	S-8A (t/d)	S-8B (t/d)
1880	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
1885	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
1890	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
1895	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
1900	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
1905	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
1910	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
1915	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
1920	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
1925	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
1930	20.5	20.5	20.5	20.5	20.5	20.5	20.5	20.5
1935	20.5	20.6	20.5	20.5	20.5	20.5	20.5	20.5
1940	20.5	20.6	20.5	20.5	20.5	20.5	20.5	20.5
1945	20.5	20.6	20.5	20.5	20.5	20.5	20.5	20.5
1950	20.5	20.6	26.3	26.3	26.3	26.3	26.3	26.3
1955	20.5	20.7	26.6	26.6	26.6	26.6	26.6	26.6
1960	20.5	20.7	26.6	26.6	26.6	26.6	26.6	26.6
1965	20.5	20.7	27.2	27.2	27.2	27.2	27.2	27.2
1970	20.5	20.7	27.3	27.3	27.3	27.3	27.3	27.3
1975	20.5	20.7	33.6	33.6	33.6	33.6	33.6	33.6
1980	20.5	20.7	35.4	35.4	35.4	35.4	35.4	35.4
1982	20.5	20.8	44.3	44.3	44.3	44.3	44.3	44.3
1984	20.5	20.8	47.0	47.0	47.0	47.0	47.0	47.0
1985	20.5	20.8	47.2	47.2	47.2	47.2	47.2	47.2
1986	20.5	20.8	51.3	51.3	51.3	51.3	51.3	51.3
1988	20.5	20.8	56.1	56.1	56.1	56.1	56.1	56.1
1989	20.5	20.8	57.2	57.2	57.2	57.2	57.2	57.2
1990	20.5	20.8	58.1	57.7	57.7	57.7	57.7	57.7
1991	20.5	20.8	67.6	66.8	66.8	66.8	66.8	66.8
1992	20.5	20.8	72.2	70.9	70.9	70.9	70.9	70.9
1993	20.5	20.8	74.8	73.3	73.3	73.3	73.3	73.3
1994	20.5	20.8	76.7	75.0	75.0	75.0	75.0	75.0
1995	20.5	20.8	78.0	75.9	75.9	75.9	75.9	75.9
1996	20.5	20.8	81.3	79.0	79.0	79.0	79.0	79.0
1997	20.5	20.8	83.2	80.7	80.7	80.7	80.7	80.7
1998	20.5	20.8	84.5	81.9	81.9	81.9	81.9	81.9
1999	20.5	20.8	85.5	82.6	82.6	82.6	82.6	82.6
2000	20.5	20.8	86.2	83.2	83.2	83.2	83.2	83.2
2001	20.5	20.8	89.6	83.4	83.4	83.4	83.4	83.4
2002	20.5	20.8	92.0	83.8	83.8	83.8	83.8	83.8
2003	20.5	20.8	93.9	75.3	75.3	75.3	75.3	75.3
2004	20.5	20.8	95.3	70.4	70.4	70.4	70.4	70.4
2005	20.5	20.9	96.4	66.8	66.8	66.8	66.8	66.8
2006	20.5	20.9	97.7	64.4	65.3	65.3	65.3	64.4
2007	20.5	20.9	99.1	62.3	63.6	63.6	63.6	62.3
2008	20.5	20.9	100.3	60.4	61.7	61.7	61.7	60.4
2009	20.5	20.9	101.4	58.6	59.8	59.8	59.8	58.6
2010	20.5	20.9	102.3	56.6	57.7	57.7	57.7	56.6
2011	20.5	20.9	103.1	55.1	56.1	56.1	56.1	55.1
2012	20.5	20.9	103.8	53.9	56.4	56.4	56.4	53.9
2013	20.5	20.9	104.4	53.0	56.0	56.0	56.0	52.9
2014	20.5	20.9	105.0	52.2	55.6	55.6	55.6	52.2
2015	20.5	20.9	105.5	51.7	55.3	55.3	28.2	25.6
2016	20.5	20.9	107.8	52.9	58.7	58.7	20.7	17.8
2017	20.5	20.9	109.5	53.7	61.8	61.8	18.6	14.8
2018	20.5	20.9	111.1	54.7	64.7	64.7	18.2	14.1
2019	20.5	20.9	112.7	55.6	67.6	67.6	18.8	14.0
2020	20.5	20.9	114.1	56.5	70.2	70.2	19.6	14.0
2021	20.5	20.9	117.0	58.8	74.4	74.4	20.7	14.4
2022	20.5	20.9	120.0	61.3	79.0	79.0	21.8	14.8
2023	20.5	21.0	122.5	63.3	83.1	83.1	22.7	15.1
2024	20.5	21.0	124.6	65.1	86.8	86.9	23.5	15.3
2025	20.5	21.0	126.4	66.6	91.0	91.0	24.9	15.4
2026	20.5	21.0	129.6	69.5	96.9	96.9	27.0	15.5
2027	20.5	21.0	131.9	71.5	102.1	102.0	29.1	15.7
2028	20.5	21.0	133.8	73.2	106.6	106.6	31.1	15.9
2029	20.5	21.0	135.6	74.7	110.8	110.8	33.1	16.1
2030	20.5	21.0	137.2	76.2	114.6	114.6	34.9	16.2
2031	20.5	21.0	138.7	77.5	118.2	118.2	36.7	16.3
2032	20.5	21.0	140.0	78.6	121.9	121.8	38.8	16.5
2033	20.5	21.0	141.2	79.7	125.3	125.3	40.8	16.6
2034	20.5	21.0	142.3	80.7	128.5	128.4	42.7	16.7
2035	20.5	21.0	143.4	81.6	131.5	131.3	44.5	16.8
2036	20.5	21.0	144.3	82.5	134.5	134.3	46.2	16.9
2037	20.5	21.0	145.2	83.3	137.6	137.4	47.9	17.0
2038	20.5	21.0	146.0	84.0	140.2	140.0	49.4	17.1
2039	20.5	21.0	146.8	84.6	142.6	142.3	50.9	17.2
2040	20.5	21.1	147.5	85.3	144.9	144.5	52.3	17.3
2041	20.5	21.1	148.2	85.9	147.0	148.5	53.7	17.4
2042	20.5	21.1	148.8	86.4	149.1	151.5	55.0	17.4
2043	20.5	21.1	149.4	86.9	151.1	154.1	56.2	17.5
2044	20.5	21.1	149.9	87.4	153.0	156.3	57.5	17.5
2045	20.5	21.1	150.4	87.8	154.8	158.4	58.6	17.6
2046	20.5	21.1	150.9	88.2	156.5	160.4	59.7	17.6
2047	20.5	21.1	151.4	88.6	158.2	162.7	60.8	17.7
2048	20.5	21.1	151.8	89.0	159.9	165.0	61.9	17.7
2049	20.5	21.2	152.2	89.4	161.5	167.4	62.9	17.8
2050	20.5	21.2	152.6	89.7	163.0	169.6	64.0	17.8
2051	20.5	21.2	153.0	90.0	164.5	171.9	64.9	17.9
2052	20.5	21.2	153.3	90.3	165.9	174.4	65.9	17.9
2053	20.5	21.2	153.7	90.6	167.4	177.1	66.8	17.9
2054	20.5	21.2	154.0	90.9	168.7	179.7	67.7	18.0
2055	20.5	21.3	154.3	91.1	170.0	182.1	68.6	18.0
2056	20.5	21.3	154.6	91.4	171.3	184.4	69.5	18.0
2057	20.5	21.3	154.9	91.6	172.5	186.6	70.4	18.1
2058	20.5	21.3	155.1	91.8	173.7	188.7	71.3	18.1
2059	20.5	21.3	155.4	92.0	174.9	190.6	72.2	18.1
2060	20.5	21.3	155.7	92.2	176.0	192.5	73.1	18.2
2061	20.5	21.3	155.9	92.4	177.1	194.3	73.9	18.2
2062	20.5	21.4	156.1	92.6	178.3	196.2	74.9	18.2
2063	20.5	21.4	156.3	92.8	179.3	197.9	75.7	18.2
2064	20.5	21.4	156.5	93.0	180.3	199.5	76.5	18.2
2065	20.5	21.4	156.8	93.1	181.2	201.1	77.3	18.3
2066	20.5	21.5	156.9	93.3	182.1	202.6	78.0	18.3
2067	20.5	21.5	157.1	93.5	183.0	204.0	78.7	18.3
2068	20.5	21.5	157.3	93.6	183.9	205.4	79.5	18.3
2069	20.5	21.5	157.5	93.8	184.7	206.8	80.1	18.3
2070	20.5	21.5	157.7	93.9	185.5	208.1	80.8	18.4
2071	20.5	21.6	157.8	94.0	186.2	209.4	81.5	18.4
2072	20.5	21.6	158.0	94.1	187.0	210.7	82.1	18.4
2073	20.5	21.6	158.1	94.3	187.7	211.9	82.7	18.4
2074	20.5	21.7	158.3	94.4	188.4	213.0	83.3	18.4
2075	20.5	21.7	158.4	94.5	189.1	214.2	83.9	18.4
2076	20.5	21.7	158.6	94.6	189.7	215.3	84.4	18.5
2077	20.5	21.8	158.7	94.7	190.4	216.4	85.0	18.5
2078	20.5	21.8	158.8	94.8	191.0	217.4	85.5	18.5
2079	20.5	21.8	159.0	94.9	191.6	218.4	86.0	18.5
2080	20.5	21.8	159.1	95.0	192.2	219.4	86.5	18.5
2081	20.5	21.9	159.2	95.1	192.7	220.3	87.0	18.5
2082	20.5	21.9	159.3	95.2	193.3	221.2	87.5	18.5
2083	20.5	22.0	159.4	95.3	193.8	222.1	87.9	18.6
2084	20.5	22.0	159.6	95.4	194.3	222.9	88.4	18.6
2085	20.5	22.1	159.7	95.5	194.8	223.7	88.8	18.6
2086	20.5	22.1	159.8	95.6	195.3	224.5	89.2	18.6
2087	20.5	22.1	159.9	95.6	195.8	225.3	89.6	18.6
2088	20.5	22.2	160.0	95.7	196.2	226.0	90.0	18.6
2089	20.5	22.2	160.1	95.8	196.7	226.7	90.4	18.6
2090	20.5	22.2	160.2	95.9	197.1	227.4	90.8	18.6
2091	20.5	22.3	160.2	95.9	197.5	228.1	91.1	18.6
2092	20.5	22.4	160.3	96.0	197.9	228.7	91.5	18.6
2093	20.5	22.4	160.4	96.1	198.3	229.4	91.8	18.7
2094	20.5	22.5	160.5	96.1	198.7	230.0	92.2	18.7
2095	20.5	22.5	160.6	96.2	199.1	230.6	92.5	18.7
2096	20.5	22.6	160.7	96.3	199.4	231.1	92.8	18.7
2097	20.5	22.6	160.8	96.3	199.8	231.7	93.1	18.7
2098	20.5	22.7	160.8	96.4	200.1	232.2	93.4	18.7
2099	20.5	22.7	160.9	96.4	200.5	232.8	93.7	18.7
2100	20.5	22.8	161.0	96.5	200.8	233.3	94.0	18.7
2101	20.5	22.8	161.0	96.6	201.1	233.8	94.3	18.7
2102	20.5	22.9	161.1	96.6	201.4	234.2	94.6	18.7
2103	20.5	23.0	161.2	96.7	201.8	234.7	94.8	18.7
2104	20.5	23.0	161.3	96.7	202.1	235.2	95.1	18.7
2105	20.5	23.1	161.3	96.8	202.3	235.6	95.4	18.7
2106	20.5	23.2	161.4	96.8	202.6	236.0	95.6	18.8
2107	20.5	23.2	161.4	96.9	202.9	236.5	95.9	18.8
2108	20.5	23.3	161.5	96.9	203.2	236.9	96.1	18.8
2109	20.5	23.3	161.6	97.0	203.4	237.3	96.3	18.8
2110	20.5	23.4	161.6	97.0	203.7	237.6	96.5	18.8
2111	20.5	23.5	161.7	97.1	203.9	238.0	96.8	18.8
2112	20.5	23.5	161.7	97.1	204.2	238.4	97.0	18.8
2113	20.5	23.6	161.8	97.1	204.4	238.7	97.2	18.8
2114	20.5	23.7	161.8	97.2	204.7	239.1	97.4	18.8

Figure 8.4. Modelled salt load entering the River Murray for all scenarios for the Murtho reach

Murtho								
Time	S-1	S-2	S-3A	S3C	S-4	S-5	S-8A	S-8B
(y)	(m³/d)	(m³/d)	(m³/d)	(m³/d)	(m³/d)	(m³/d)	(m³/d)	(m³/d)
1880	6473	6473	6472	6473	6473	6474	6473	6473
1885	6473	6473	6472	6473	6473	6473	6473	6473
1890	6473	6473	6472	6473	6473	6473	6473	6473
1895	6473	6473	6472	6473	6473	6473	6473	6473
1900	6473	6473	6472	6473	6473	6473	6473	6473
1905	6473	6473	6472	6473	6473	6473	6473	6473
1910	6473	6473	6472	6473	6473	6473	6473	6473
1915	6473	6473	6472	6473	6473	6473	6473	6473
1920	6473	6473	6472	6473	6473	6473	6473	6473
1925	6473	6476	6472	6473	6473	6473	6473	6473
1930	6473	6476	6471	6473	6473	6473	6473	6473
1935	6473	6480	6471	6473	6473	6473	6473	6473
1940	6473	6480	6471	6473	6473	6473	6473	6473
1945	6473	6482	6471	6473	6473	6473	6473	6473
1950	6473	6482	6832	6834	6834	6834	6834	6834
1955	6473	6484	6852	6853	6853	6853	6853	6853
1960	6473	6484	6858	6859	6859	6859	6859	6859
1965	6473	6486	6868	6870	6870	6870	6870	6870
1970	6473	6486	6872	6873	6873	6873	6873	6873
1975	6473	6487	7108	7109	7109	7109	7109	7109
1980	6473	6487	7174	7176	7176	7176	7176	7176
1982	6473	6489	7549	7550	7550	7550	7550	7550
1984	6473	6489	7657	7658	7658	7658	7658	7658
1985	6473	6489	7669	7671	7671	7671	7671	7671
1986	6473	6489	7859	7861	7861	7861	7861	7861
1988	6473	6489	8091	8094	8094	8094	8094	8094
1989	6473	6489	8145	8148	8148	8148	8148	8148
1990	6473	6489	8192	8182	8182	8182	8182	8182
1991	6473	6490	8666	8638	8638	8638	8638	8638
1992	6473	6491	8885	8842	8842	8842	8842	8842
1993	6473	6491	9014	8961	8961	8961	8961	8961
1994	6473	6491	9101	9043	9043	9043	9043	9043
1995	6473	6491	9164	9087	9087	9087	9087	9087
1996	6473	6491	9345	9254	9254	9254	9254	9254
1997	6473	6491	9434	9338	9338	9338	9338	9338
1998	6473	6491	9497	9397	9397	9397	9397	9397
1999	6473	6491	9543	9435	9435	9435	9435	9435
2000	6473	6492	9581	9467	9467	9467	9467	9467
2001	6473	6493	9729	9456	9456	9456	9456	9456
2002	6473	6493	9835	9464	9464	9464	9464	9464
2003	6473	6493	9915	9058	9058	9058	9058	9058
2004	6473	6493	9980	8828	8828	8828	8828	8828
2005	6473	6493	10034	8657	8657	8657	8657	8657
2006	6473	6494	10095	8553	8597	8597	8597	8553
2007	6473	6494	10163	8459	8522	8522	8522	8459
2008	6473	6494	10223	8372	8438	8438	8438	8372
2009	6473	6494	10276	8286	8350	8350	8350	8286
2010	6473	6494	10320	8194	8252	8252	8252	8194
2011	6473	6495	10359	8124	8179	8179	8179	8124
2012	6473	6495	10392	8069	8183	8183	8183	8069
2013	6473	6496	10422	8025	8161	8161	8161	8025
2014	6473	6496	10449	7990	8139	8139	8139	7990
2015	6473	6496	10473	7965	8122	8122	6003	5901
2016	6473	6496	10582	8022	8277	8277	5696	5586
2017	6473	6496	10659	8055	8415	8415	5613	5469
2018	6473	6496	10732	8095	8547	8547	5603	5432
2019	6473	6496	10800	8135	8679	8679	5626	5422
2020	6473	6496	10861	8172	8797	8797	5658	5420
2021	6473	6498	10995	8278	8986	8986	5709	5441
2022	6473	6498	11129	8387	9194	9194	5761	5461
2023	6473	6498	11238	8476	9379	9379	5801	5473
2024	6473	6498	11330	8552	9543	9543	5839	5481
2025	6473	6499	11410	8617	9721	9721	5893	5488
2026	6473	6499	11553	8746	9974	9974	5973	5493
2027	6473	6499	11652	8833	10218	10218	6053	5500
2028	6473	6499	11741	8910	10420	10420	6131	5508
2029	6473	6499	11821	8980	10609	10608	6207	5515
2030	6473	6499	11893	9044	10780	10779	6278	5521
2031	6473	6501	11959	9102	10941	10938	6346	5527
2032	6473	6501	12020	9156	11112	11108	6433	5533
2033	6473	6502	12075	9205	11268	11262	6514	5539
2034	6473	6502	12126	9250	11412	11404	6590	5544
2035	6473	6502	12173	9291	11545	11534	6659	5549
2036	6473	6502	12216	9329	11682	11670	6727	5554
2037	6473	6503	12257	9365	11827	11812	6794	5558
2038	6473	6503	12294	9397	11946	11929	6856	5562

Murtho								
Time	S-1	S-2	S-3A	S3C	S-4	S-5	S-8A	S-8B
(y)	(m³/d)	(m³/d)	(m³/d)	(m³/d)	(m³/d)	(m³/d)	(m³/d)	(m³/d)
2039	6473	6503	12328	9428	12056	12036	6916	5565
2040	6473	6503	12361	9456	12160	12138	6973	5569
2041	6473	6504	12391	9483	12260	12366	7027	5572
2042	6473	6505	12419	9507	12355	12509	7080	5575
2043	6473	6506	12446	9531	12446	12629	7131	5578
2044	6473	6506	12471	9552	12534	12733	7180	5581
2045	6473	6507	12494	9573	12619	12829	7227	5583
2046	6473	6507	12517	9592	12700	12922	7273	5585
2047	6473	6507	12538	9611	12779	13025	7317	5588
2048	6473	6508	12558	9628	12855	13131	7359	5590
2049	6473	6508	12577	9644	12929	13234	7403	5592
2050	6473	6508	12594	9660	13001	13333	7445	5594
2051	6473	6510	12612	9675	13071	13443	7486	5595
2052	6473	6511	12628	9689	13138	13568	7526	5597
2053	6473	6512	12644	9702	13204	13695	7564	5599
2054	6473	6512	12658	9715	13267	13817	7602	5600
2055	6473	6513	12673	9727	13329	13931	7638	5602
2056	6473	6513	12686	9739	13388	14038	7676	5603
2057	6473	6514	12699	9750	13446	14140	7714	5605
2058	6473	6515	12711	9760	13502	14236	7751	5606
2059	6473	6515	12724	9771	13556	14328	7788	5607
2060	6473	6516	12735	9780	13608	14415	7824	5608
2061	6473	6517	12746	9790	13658	14499	7860	5610
2062	6473	6519	12757	9799	13717	14589	7903	5611
2063	6473	6520	12767	9807	13765	14666	7938	5612
2064	6473	6521	12777	9816	13811	14741	7971	5613
2065	6473	6522	12786	9824	13856	14813	8004	5614
2066	6473	6523	12795	9831	13898	14882	8035	5615
2067	6473	6524	12804	9839	13940	14949	8066	5616
2068	6473	6525	12813	9846	13980	15014	8096	5617
2069	6473	6526	12821	9853	14019	15078	8125	5617
2070	6473	6527	12829	9860	14056	15140	8154	5618
2071	6473	6529	12837	9866	14092	15200	8182	5619
2072	6473	6531	12844	9872	14128	15258	8209	5620
2073	6473	6533	12851	9878	14162	15314	8235	5621
2074	6473	6534	12858	9884	14194	15369	8260	5621
2075	6473	6536	12865	9889	14226	15422	8285	5622
2076	6473	6537	12871	9895	14257	15473	8309	5623
2077	6473	6539	12878	9900	14287	15523	8332	5624
2078	6473	6540	12884	9905	14316	15572	8355	5624
2079	6473	6541	12890	9910	14344	15618	8377	5625
2080	6473	6543	12896	9914	14371	15664	8398	5625
2081	6473	6545	12901	9919	14398	15708	8419	5626
2082	6473	6548	12907	9923	14423	15750	8439	5627
2083	6473	6550	12912	9927	14448	15791	8459	5627
2084	6473	6552	12917	9932	14472	15830	8477	5628
2085	6473	6555	12923	9936	14496	15868	8496	5628
2086	6473	6557	12927	9939	14519	15905	8514	5629
2087	6473	6558	12932	9943	14541	15941	8531	5629
2088	6473	6560	12937	9947	14562	15975	8549	5630
2089	6473	6562	12942	9951	14584	16009	8565	5630
2090	6473	6564	12946	9954	14604	16041	8581	5631
2091	6473	6567	12950	9958	14624	16072	8597	5631
2092	6473	6570	12954	9961	14643	16103	8612	5632
2093	6473	6573	12958	9964	14662	16132	8627	5632
2094	6473	6576	12962	9967	14680	16161	8642	5632
2095	6473	6579	12966	9970	14698	16188	8656	5633
2096	6473	6582	12970	9973	14715	16215	8670	5633
2097	6473	6585	12974	9976	14732	16241	8683	5634
2098	6473	6587	12978	9979	14749	16267	8696	5634
2099	6473	6589	12981	9982	14765	16291	8709	5634
2100	6473	6592	12985	9985	14780	16315	8721	5635
2101	6473	6596	12988	9987	14796	16338	8733	5635
2102	6473	6600	12991	9990	14810	16360	8745	5635
2103	6473	6604	12994	9993	14825	16382	8757	5636
2104	6473	6607	12998	9995	14839	16404	8768	5636
2105	6473	6611	13001	9997	14853	16424	8779	5636
2106	6473	6614	13004	10000	14866	16445	8790	5637
2107	6473	6617	13007	10002	14879	16464	8800	5637
2108	6473	6620	13010	10004	14892	16483	8810	5637
2109	6473	6623	13012	10007	14905	16502	8820	5638
2110	6473	6626	13015	10009	14917	16520	8830	5638
2111	6473	6630	13018	10011	14929	16537	8840	5638
2112	6473	6634	13021	10013	14940	16554	8849	5638
2113	6473	6639	13023	10015	14952	16571	8858	5639
2114	6473	6643	13026	10017	14963	16587	8867	5639

Figure 8.5. Modelled groundwater flux entering the River Murray for all scenarios for the Murtho 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

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.

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; units are [m^{-1}]

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*

Storativity (S) — 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

Transmissivity (T)— 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)

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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