TECHNICAL REPORT

WAIKERIE TO MORGAN NUMERICAL GROUNDWATER MODEL 2012

VOLUME 1: REPORT AND FIGURES

2012/18

Government of South Australia
Department for Water

WAIKERIE TO MORGAN NUMERICAL GROUNDWATER MODEL 2012

VOLUME 1: REPORT AND FIGURES

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FOREWORD

South Australia's Department for Water leads the management of our most valuable resource—water.

Water is fundamental to our health, our way of life and our environment. It underpins growth in population and our economy—and these are critical to South Australia's future prosperity.

High quality science and monitoring of our State's natural water resources is central to the work that we do. This will ensure we have a better understanding of our surface and groundwater resources so that there is sustainable allocation of water between communities, industry and the environment.

Department for Water scientific and technical staff continue to expand their knowledge of our water resources through undertaking investigations, technical reviews and resource modelling.

Allan Holmes
CHIEF EXECUTIVE
DEPARTMENT FOR WATER

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Vanessa Peat and Scott Evans of Australian Water Environments provided additional hydrogeological data and interpretation.

Shiva Tazehkand of the Department for Water assisted with the compilation of the Appendices.

Linda Vears of the Department for Water as the project manager advised on policy, assisted with irrigation data gathering and coordinated the Five Year Review Modelling Registers Project Team.

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

- Chris Wright, Linda Vears, Wei Yan and Juliette Woods (on secondment) of the Department for Water
- Phil Pfeiffer and Asitha Katupitiya of the Murray-Darling Basin Authority
- Peter Forward of SA Water.

The report was peer reviewed by Don Armstrong (Lisdon Associates) as an expert hydrogeologist, geologist and groundwater modeller and Steve Barnett as Principal Hydrogeologist in the Department for Water.

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

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EXECUTIVE SUMMARY

Significant volumes of salt from groundwater enter the River Murray within the Waikerie to Morgan reach each year. The regional groundwater is naturally highly saline and has been mobilised by land clearance and irrigation. In 1991, 172 t/d of salt from groundwater was estimated to reach the river from a Run of River (RoR) survey conducted from Waikerie to Hogwash. Subsequent actions including salt interception and improved irrigation practices have mitigated or offset these impacts. Groundwater models quantify the projected impacts of actions taken or under consideration.

To meet obligations under the Murray-Darling Basin Authority's (MDBA) Basin Salinity Management Strategy (BSMS), South Australia is developing a suite of accredited MODFLOW groundwater models to bring entries forward to the BSMS Salinity Registers. This work is undertaken by the Science, Monitoring and Information Division of the Department for Water (DFW) under the broad direction of the Policy and Strategy Division of DFW, in liaison with the MDBA. Through the groundwater modelling process, scenarios are established to assist in the determining the origin and volume of salt entering the River Murray from groundwater sources.

DFW has developed a MODFLOW numerical groundwater flow model of the Waikerie to Morgan reach. The objectives of the modelling project were to develop a model capable of simulating the regional aquifer system in the study area which could be used to:

- Improve the understanding of the hydrogeology of the regional aquifer system and processes
- 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
- Assist with the broad-scale planning for groundwater management schemes (e.g. salt interception schemes – SIS) that help to control the flux of saline groundwater and therefore salt load, entering the River Murray.

The fundamental objective of the modelling work undertaken has been to improve confidence in the model parameters and results to the level that will enable and assist:

- Accreditation of the model by the MDBA
- Use of modelled salt loads as Salinity Register entries for the following accountable actions along the Waikerie to Morgan reach:
    - Mallee clearance
    - Irrigation development
    - Improved irrigation practice
    - The Qualco-Sunlands Groundwater Control Scheme
    - The Waikerie I, Waikerie IIA and Waikerie Lock 2 Salt Interceptions Schemes.

The model is not designed to evaluate the accountable actions of Stockyard Plain.

The model previously used to simulate this reach was the Lock 3 to Morgan model, which spans two distinct hydrogeological regimes with different key aquifers and salt load mobilisation drivers. The Lock 3 to Morgan reach will in future be simulated by two separate models—the Waikerie to Morgan model, as described in this report, and a Woolpunda model which is currently under development.

EXECUTIVE SUMMARY

DFW commissioned prototype numerical models of the Waikerie to Morgan reach which were developed by AWE (2009a, 2010, 2011a). This project refines the prototype model of AWE (2011a). Substantial data reviews have been conducted, such as irrigation data, to inform the model inputs. The model has been updated with the latest data, including from the recently-constructed Waikerie Lock 2 SIS. The model was recalibrated to head observations and its results confirmed through comparison to RoR salt loads observations and new estimates of accession volumes in irrigation areas. The model is successfully calibrated.

The calibrated historical model estimates the pre-development base salt load entering the river to be 5.6 t/d from Holder to Lock 2, 13.5 t/d from Lock 2 to Hogwash and 4.6 t/d from Hogwash to Morgan. In the model, salt load peaks at 151.4 t/d in 1985 for Holder to Lock 2, 66.5 t/d in 2000 for Lock 2 to Hogwash and 22.6 t/d in 1990 for Hogwash to Morgan. The additional salt load results from an increased flux of saline groundwater due to the development of groundwater mounds induced by irrigation drainage. Salt loads have since decreased, due to improvements in irrigation practice (including rehabilitation of infrastructure), water restrictions and the construction of three SIS and a Groundwater Control Scheme (GCS). The model estimates that 37.0 t/d, 21.6 t/d and 14.0 t/d of salt enters the river in the Holder to Lock 2, Lock 2 to Hogwash and Hogwash to Morgan reaches respectively in 2011.

After calibration, the transient model was used to 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.

This report documents the numerical groundwater flow model, including comprehensive information on the model design, model inputs and estimated annual salt loads for different scenarios. The results of the model scenario runs are summarised in Tables ES-1 to ES-3.

This report delivers the technical information about the model and model results for the accreditation process. 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.

Table ES-1 Summary of Predicted Salt Load (t/d) entering the River Murray – Holder to Lock 2

Holder to Lock 2					Year/Salt load (t/d)						
Scenario	**Description**	**Irrigation development area**	**IIP[1] & RH[2]**	**SIS[3]**	**1920**	**1988**	**2000**	**2011**	**2015**	**2050**	**2111**
Calibrated historical model	Historical	Foot print of irrigation history	Yes	WAIK I + QSTGCS + WAIK IIA + WAIK Lk 2	6	151	35	37	-	-	-
S-1	Natural system	None	-	No	6	6	6	6	6	6	6
S-2	Mallee clearance	None (but includes mallee clearance area)	-	No	6	6	6	7	7	10	18
S-3a	Pre-1988, no IIP, no RH	Pre-1988	No	No	6	151	152	155	156	163	170
S-3c	Pre-1988, with IIP and RH	Pre-1988	Yes	No	6	151	120	97	90	78	78
S-4	Current irrigation	Pre-1988 + post-1988	Yes	No	6	151	120	103	100	98	101
S-8a(i)	Current irrigation plus constructed SIS	Pre-1988 + post-1988	Yes	WAIK I	6	151	50	41	39	40	42
S-8a(ii)	Current irrigation plus constructed SIS	Pre-1988 + post-1988	Yes	WAIK I + QSTGCS	6	151	50	40	37	35	36
S-8a(iii)	Current irrigation plus constructed SIS	Pre-1988 + post-1988	Yes	WAIK I + QSTGCS + WAIK IIA	6	151	50	26	25	22	22
S-8a(iv)	Current irrigation plus constructed SIS	Pre-1988 + post-1988	Yes	WAIK I + QSTGCS + WAIK IIA + WAIK Lk 2	6	151	50	26	25	22	22
S-8b(i)	Pre-1988, with IIP and RH plus constructed SIS	Pre-1988	Yes	WAIK I	6	151	50	35	32	27	27
S-8b(ii)	Pre-1988, with IIP and RH plus constructed SIS	Pre-1988	Yes	WAIK I + QSTGCS	6	151	50	34	30	22	22
S-8b(iii)	Pre-1988, with IIP and RH plus constructed SIS	Pre-1988	Yes	WAIK I + QSTGCS + WAIK IIA	6	151	50	24	21	17	16
S-8b(iv)	Pre-1988, with IIP and RH plus constructed SIS	Pre-1988	Yes	WAIK I + QSTGCS + WAIK IIA + WAIK Lk 2	6	151	50	24	21	17	16

[1]IIP: Improved Irrigation Practices *[2]RH: Rehabilitation of irrigation distribution networks* *[3]SIS: Salt Interception Scheme*

Table ES-2 Summary of Predicted Salt Load (t/d) entering the River Murray – Lock 2 to Hogwash

Lock 2 to Hogwash					Year/Salt load (t/d)						
Scenario	**Description**	**Irrigation development area**	**IIP[1] & RH[2]**	**SIS[3]**	**1920**	**1988**	**2000**	**2011**	**2015**	**2050**	**2111**
Calibrated historical model	Historical	Foot print of irrigation history	Yes	WAIK I + QSTGCS + WAIK IIA + WAIK Lk 2	13	57	67	22	-	-	-
S-1	Natural system	None	-	No	13	13	13	13	13	13	13
S-2	Mallee clearance	None (but includes mallee clearance area)	-	No	13	14	14	14	15	17	23
S-3a	Pre-1988, no IIP, no RH	Pre-1988	No	No	13	57	72	78	80	86	89
S-3c	Pre-1988, with IIP and RH	Pre-1988	Yes	No	13	57	67	60	59	58	60
S-4	Current irrigation	Pre-1988 + post-1988	Yes	No	13	57	67	68	72	79	82
S-8a(i)	Current irrigation plus constructed SIS	Pre-1988 + post-1988	Yes	WAIK I	13	57	67	68	72	79	82
S-8a(ii)	Current irrigation plus constructed SIS	Pre-1988 + post-1988	Yes	WAIK I + QSTGCS	13	57	67	51	53	54	55
S-8a(iii)	Current irrigation plus constructed SIS	Pre-1988 + post-1988	Yes	WAIK I + QSTGCS + WAIK IIA	13	57	67	51	52	52	53
S-8a(iv)	Current irrigation plus constructed SIS	Pre-1988 + post-1988	Yes	WAIK I + QSTGCS + WAIK IIA + WAIK Lk 2	13	57	67	27	26	26	27
S-8b(i)	Pre-1988, with IIP and RH plus constructed SIS	Pre-1988	Yes	WAIK I	13	57	67	60	59	58	60
S-8b(ii)	Pre-1988, with IIP and RH plus constructed SIS	Pre-1988	Yes	WAIK I + QSTGCS	13	57	67	45	42	36	36
S-8b(iii)	Pre-1988, with IIP and RH plus constructed SIS	Pre-1988	Yes	WAIK I + QSTGCS + WAIK IIA	13	57	67	44	42	35	35
S-8b(iv)	Pre-1988, with IIP and RH plus constructed SIS	Pre-1988	Yes	WAIK I + QSTGCS + WAIK IIA + WAIK Lk 2	13	57	67	24	20	18	18

[1]IIP: Improved Irrigation Practices *[2]RH: Rehabilitation of irrigation distribution networks* *[3]SIS: Salt Interception Scheme*

Table ES-3 Summary of Predicted Salt Load (t/d) entering the River Murray – Hogwash to Morgan

Hogwash to Morgan					Year/Salt load (t/d)						
Scenario	**Description**	**Irrigation development area**	**IIP[1] & RH[2]**	**SIS[3]**	**1920**	**1988**	**2000**	**2011**	**2015**	**2050**	**2111**
Calibrated historical model	Historical	Foot print of irrigation history	Yes	WAIK I + QSTGCS + WAIK IIA + WAIK Lk 2	5	22	20	14	-	-	-
S-1	Natural system	None	-	No	5	5	5	5	5	5	5
S-2	Mallee clearance	None (but includes mallee clearance area)	-	No	5	5	5	5	5	5	5
S-3a	Pre-1988, no IIP, no RH	Pre-1988	No	No	5	22	23	23	23	24	24
S-3c	Pre-1988, with IIP and RH	Pre-1988	Yes	No	5	22	15	9	8	8	8
S-4	Current irrigation	Pre-1988 + post-1988	Yes	No	5	22	20	15	14	14	15
S-8a(i)	Current irrigation plus constructed SIS	Pre-1988 + post-1988	Yes	WAIK I	5	22	20	15	14	14	15
S-8a(ii)	Current irrigation plus constructed SIS	Pre-1988 + post-1988	Yes	WAIK I + QSTGCS	5	22	20	15	14	14	14
S-8a(iii)	Current irrigation plus constructed SIS	Pre-1988 + post-1988	Yes	WAIK I + QSTGCS + WAIK IIA	5	22	20	15	14	14	14
S-8a(iv)	Current irrigation plus constructed SIS	Pre-1988 + post-1988	Yes	WAIK I + QSTGCS + WAIK IIA + WAIK Lk 2	5	22	20	14	13	13	13
S-8b(i)	Pre-1988, with IIP and RH plus constructed SIS	Pre-1988	Yes	WAIK I	5	22	15	9	8	8	8
S-8b(ii)	Pre-1988, with IIP and RH plus constructed SIS	Pre-1988	Yes	WAIK I + QSTGCS	5	22	15	9	8	7	7
S-8b(iii)	Pre-1988, with IIP and RH plus constructed SIS	Pre-1988	Yes	WAIK I + QSTGCS + WAIK IIA	5	22	15	9	8	7	7
S-8b(iv)	Pre-1988, with IIP and RH plus constructed SIS	Pre-1988	Yes	WAIK I + QSTGCS + WAIK IIA + WAIK Lk 2	5	22	15	8	8	7	7

[1]IIP: Improved Irrigation Practices *[2]RH: Rehabilitation of irrigation distribution networks* *[3]SIS: Salt Interception Scheme*

1. INTRODUCTION

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

Three major irrigation management areas, Waikerie, Qualco-Sunlands and Cadell, in the Waikerie to Morgan area of the SA Riverland, have affected the salinity of the River Murray. The salinity impact has previously been assessed using different groundwater numerical models. Since the models were developed, further hydrogeological investigations and studies have improved the understanding of the region’s aquifer systems. The aim of this project is to upgrade a prototype Waikerie to Morgan model recently developed by AWE. The upgraded model is used to evaluate salt loads resulting from local accountable actions such as land clearance, irrigation area development, changes in irrigation practice and the construction of Salt Interception Schemes (SIS). After the model has been reviewed by groundwater modelling experts and accredited by the Murray-Darling Basin Authority (MDBA), the model results may be used to calculate salt load entering the River Murray for Salinity Register entries.

The fundamental objective of the modelling work undertaken has been to improve confidence in the model parameters and results to the level that will enable and assist:

- Accreditation of the model by the MDBA
- Use of modelled salt loads as Salinity Register entries for the following accountable actions along the Waikerie to Morgan reach:
    - Mallee clearance
    - Irrigation development
    - Improved irrigation practice
    - The Qualco-Sunlands Groundwater Control Scheme
    - The Waikerie I, Waikerie IIA and Waikerie Lock 2 Salt Interceptions Schemes.

The model is not designed to evaluate the accountable actions of Stockyard Plain.

This report extensively documents the groundwater flow model in a format that will assist completion of the 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.

This report delivers the technical information about the model and model results for the accreditation process. 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 2008 (the Agreement) provides the legislative framework to manage and reduce the impacts of salinity in the MDB and the Basin Salt Management Strategy (BSMS) 2001–2015 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 an agreed climatic/hydrologic sequence (1 May 1975 to 30 April 2000), which is agreed as being representative.

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, such as new irrigation developments, to occur 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.

The impact of actions is typically assessed using a numerical groundwater flow model. Since the BSMS was agreed, South Australia has developed a series of four numerical groundwater models that have been accredited to estimate salinity debits and credits for the Registers. They cover the following reaches of the River Murray:

(i) Chowilla floodplain, including areas in New South Wales, South Australia and Victoria

(ii) SA Border to Lock 3

(iii) Lock 3 to Morgan

(iv) Morgan to Wellington.

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 C of the Murray-Darling Basin Agreement 1992 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. When an SIS is first proposed, the salinity impact of the Concept Design is estimated as part of the approval process for the MDBA, using a suitable model that is not necessarily one accredited for use for the Registers. If further SIS investigations are approved, the SIS design is likely to be refined as new information becomes available and the salinity impact of the resulting Revised Design is also estimated for the MDBA prior to construction of the scheme. Once constructed, the salinity impact must be included on the Salinity Registers. 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 Reviews of the schemes.

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 3.11 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

- undertaken transparent and accurate assessment of South Australia's salinity accountability.

These strategies have proved successful and South Australia is currently removing more salt than it is putting into the River Murray. As a result, the MDBA's Basin Salinity Management Strategy (BSMS) Salinity Registers currently assess South Australia as having a strong 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.

There remain some salinity management issues in South Australia that have not yet been thoroughly addressed. For example, the potential salt impacts from flooding are currently being estimated. There is also a need to develop salinity targets for the section of river below Morgan, from which Adelaide draws much of its water supply.

Numerical groundwater models assist with many of these South Australian policy goals. They are used to estimate salinity impacts of management options, for example in the design and optimisation of SIS works.

1.2. THE WAIKERIE TO MORGAN AREA

The Waikerie to Morgan area is located within the Riverland region of South Australia. It encompasses the irrigation areas of Waikerie (included Golden Heights and Ramco Heights), Qualco-Sunlands, Cadell and Taylorville (including Toolunka and Markaranka) which are small irrigation areas on the northern side of the river. Water pumped from the River Murray is used for irrigation in the area. Root zone drainage, from rainfall and irrigation, recharges the groundwater table and has developed two major groundwater mounds, beneath the Waikerie and Qualco-Sunlands irrigation areas. These mounds have significantly increased the flux of saline groundwater entering the river valley and therefore salt load, entering the River Murray.

To reduce the salt from groundwater that enters the River Murray, improvements have been made to irrigation practices and three SIS have been constructed in Waikerie and Qualco-Sunlands areas. These SIS use extraction bores to lower groundwater gradients to the river valley and therefore reduce salt load entering the River Murray. The Qualco-Sunlands area also contains a groundwater control scheme, namely the Qualco-Sunlands Trust Groundwater Control Scheme (QSTGCS) which controls the irrigation mound to reduce the problem of water logging in the Qualco-Sunlands area.

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

1.3. REVIEW OF PREVIOUS MODELS IN THE WAIKERIE TO MORGAN AREA

Early groundwater flow models of the study area include a steady-state simulation of the Murray Group's interaction with the River Murray at Waikerie (Watkins 1990c), a single-layer model of Qualco-Sunlands (Watkins, Teoh and Way 1995), a three-layer model of Qualco-Sunlands simulating the Loxton Sands, Cadell Formation and Murray Group (Rust PPK 1996) and an optimisation model for Waikerie SIS (AWE 2000a).

The present model is derived from three series of prior models of the study area, those of (i) Woodward Clyde (1998, 1999a, 1999b, 2000), (ii) Rural Solutions (2005) and Aquaterra (2007) and (iii) AWE (2009a, 2009c, 2010, 2011a).

In 1998 to 2000, Woodward-Clyde developed a series of models for the Waikerie and Qualco-Sunlands areas (Woodward Clyde 1998, 1999a, 1999b, 2000). The purpose of was to assist in the design of the Qualco-Sunlands Groundwater Control Scheme and to assess the impact due to water logging and salt load caused by irrigation and the Stockyard Plain Disposal Basin (Woodward-Clyde 2000). A cross-sectional model of the unsaturated zone was used to estimate recharge (Woodward-Clyde 1998) and a five-layer MODFLOW model of the saturated sediments was used to estimate flux and salt load to the River Murray. The MODFLOW model simulated the Loxton Sands, the Cadell Formation, Morgan Limestone, Finniss Clay and Mannum Formation (Woodward-Clyde 2000). The model had significant difficulties to run (i.e. matrix solver convergence) and also difficulty in accurately calculating heads and water balance as it employed a nonlinear rewetting process to simulate the perched (or partially-perched) aquifer in the Loxton Sands.

The Woodward-Clyde MODFLOW model provided a starting point for the development of the Lock 3 to Morgan 2005 model to provide Salinity Register entries. To meet BSMS requirements, Aquaterra was contracted by Rural Solutions to develop a model from Lock 3 to Morgan (Rural Solutions 2005). The seven-layer model was accredited in 2005 by the MDBA and used for assessment of salt load impact and benefit from SIS, since the accreditation. It was updated in 2007 to correct an error in salt load calculation (Aquaterra 2007).

The Lock 3 to Morgan reach simulated by the accredited Lock 3 to Morgan 2005 model of Rural Solutions (2005) spans two distinct hydrogeological regimes (Figure 1.1). In Woolpunda, the river valley is in contact with the Upper Mannum Formation (AWE 2007b). Irrigation in the area is relatively limited and groundwater salt loads to the river are mainly driven by natural upwelling from the Renmark Group due to thinner Ettrick Formation in the area. In the Waikerie to Morgan reach, the river valley is mainly in contact with the Glenforslan Formation. As the Ettrick Formation is generally thicker in the study area and the Renmark Group is separated from the River Murray by four large geological layers, the influence of the Renmark Group on the River Murray is very small and can be neglected. In the Waikerie to Morgan area, salt loads are driven by irrigation-induced groundwater mounds.

Based on the current understanding of the system and Salinity Register entries, the Department for Water (DFW) decided to develop two numerical models, one simulating the Woolpunda reach and one simulating the Waikerie to Morgan area.

Splitting the Lock 3 to Morgan model into two models is a better approach and should improve model quality as:

- a finer model grid can be used due to the smaller model areas
- the reduced number of model layers allows groundwater evapotranspiration (ET) on the floodplain to be easily simulated. This was difficult in the previous model as the Monoman Formation was simulated in layer 3 and most standard MODFLOW interfaces do not permit groundwater evapotranspiration (ET) in layers other than layer 1.
- it will be easier computationally to run the model, due to the reduced number of model layers and the omission of the perched aquifer (Loxton Sands), which is not in contact with the River Murray. The Lock 3 to Morgan 2005 model was very computationally unstable, due to the rewetting process involved in simulating the saturation of the Loxton Sands and had to be separated into six-step models from historical model to predictions.

In 2009, AWE was contracted by the MDBA through DFW, to develop a model covering the Waikerie Lock 2 area only (AWE 2009a). The model was used to confirm a revised conceptual model which demonstrated that reduced upward leakage from the Lower Mannum Formation potentially reduces the flux to the floodplain aquifer in the Waikerie Lock 2 reach. At the request of DFW and MDBA, the 2009 Waikerie Lock 2 model was expanded in 2010 to cover the Waikerie to Morgan area. The model was

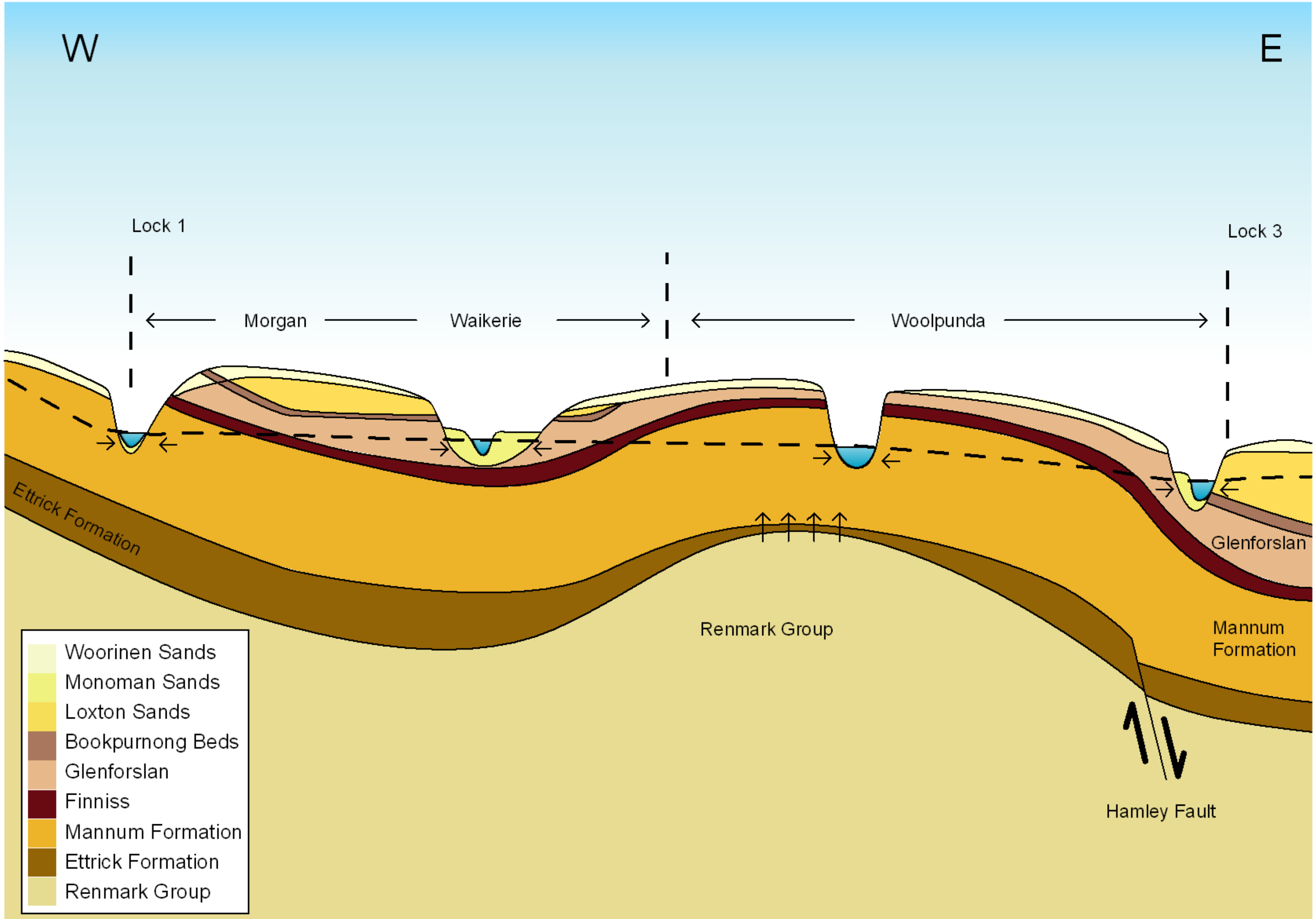


Figure 1.1 **Lock 3 to Morgan Hydrogeological Conceptual Model**

calibrated and demonstrated its capability to predict salt load impact from accountable activities including irrigation and SIS (AWE 2011a). As required by the MDBA accreditation process, the model and the model report needs to be further refined so that it can be accredited for Salinity Register use.

This project aims to refine the AWE (2011a) model and this report presents the revised Waikerie to Morgan 2012 model. The model has also been informed by data reviews (Section 2) and by numerical models spanning larger regions which include the study area.

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

1.4. CURRENT MODELLING EXERCISE

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

The upgrade includes the following features:

1. **Data Review**
    - Compilation of detailed irrigation data for areas within the model domain:
        - Irrigation footprints
        - Recharge estimates based on application volumes and other data, using the methodology of Laroona Associates (2011)
    - Review of near-river groundwater salinity, including trends over time
    - Compilation of data for 2009 and 2010 where available, principally:
        - Potentiometric head in observation bores
        - SIS pump rates.
2. **Refinement of Model Design and Construction**
    - Replacement of the constant head boundary cells at the model domain boundary with general head boundary cells, which will give a better control of flux into or out of the model through adjusting the conductance term.
    - Revised model flow budget zones, which are used for salt load calculation, to reflect Water Management Plan boundaries.
    - Improved simulation of Stockyard Plain Disposal Basin
    - Adjusted recharge rates and areas to reflect the irrigation data review
    - Inclusion of SIS pump rates and head observations for 2009 and 2010
    - Revised groundwater salinities used for salt load calculation.
3. **Model Calibration and Confirmation**
    - Improved calibration to potentiometric head, especially in areas adjacent to the River Murray and SIS, and in the irrigation areas
    - Confirmation of the model recharge by comparing to the newly collected irrigation accession estimates, as included in Appendix C-1
    - Confirmation of the model results by comparing to the Run of River (RoR) salt load estimates.
4. **Run scenarios for Salinity Register entry**
    - Revised SIS pump rates used for the future period (post-2012) to better represent the long-term average conditions

- The Stockyard Plain Disposal Basin is no longer simulated in scenarios without SIS
- Additional scenarios, including scenario 5 (current + future irrigation), scenario 8b (pre-1988 irrigation + SIS) and scenario 8c (scenario 5 + SIS).

5. **Sensitivity and Uncertainty tests**
   - Sensitivity and uncertainty tests to determine the confidence on the model outputs.
6. **Reporting**
   - Full report for the accreditation of Salinity Register model
   - More information and description on irrigation accession and model recharge
   - Documentation of how groundwater salinity values were chosen for each model flow budget zone
   - Scaled Root Mean Square (SRMS) error for selected years
   - Salt load details for each scenario in Appendix B.

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

The aim of this project is to upgrade the numerical groundwater model as a predictive management tool for determining salt loads entering the River Murray from the Waikerie to Morgan area. The revised model provides quantitative estimates of salt loads entering the River Murray under a range of past and future land and water use conditions that are required by MDBA Salinity Register entries.

2. HYDROGEOLOGY AND HYDROLOGY OF THE WAIKERIE TO MORGAN AREA

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

Rural Solutions (2005) provides a detailed literature review and history of investigations of the Waikerie to Morgan area for the years 1965 to 2005. In the past two decades, most hydrogeological studies of the area have related to the design and review of the Qualco-Sunlands Trust Groundwater Control Scheme (QSTGCS) and the Waikerie and Lock 2 Salt Interception Schemes (SIS) and so have focussed on the Qualco-Sunlands and Waikerie areas. Much less information is available on the regions downstream of Qualco, including the Cadell to Morgan reach.

Datasets and interpretations have been provided in numerous reports. The stratigraphy has been described in Watkins and Teoh (1995), Woodward Clyde (1998 and 2000) and was significantly reinterpreted in AWE (2003a) to match the reclassification made by Lukasik and James (1998) of Murray Group sub-units. Bore logs and aquifer tests are reported in Watkins (1990a 1990b), Clark (1992a 1992b), AWE (1999, 2003b, 2003c) for Waikerie and in Dennis (2000) for Qualco-Sunlands. Downhole geophysical data and groundwater chemistry is presented in EWS (1990a 1990b) and Watkins (1990c) respectively. In-stream salinity has been mapped in the NanoTEM studies (Telfer *et al*. 2005; AWE 2011b). Further data are available in the Government's online groundwater databases.

Data reviews and hydrogeological conceptual models form part of numerical model reports of the region. Numerical model reports of Qualco-Sunlands and/or Waikerie include Watkins (1990d), Watkins, Teoh and Way (1995), Rust PPK (1996), a staged series by Woodward Clyde (1998, 1999a, 1999b, 2000), Rural Solutions (2005) and AWE (2000a, 2009a, 2009c, 2010, 2011a). Numerical model reports spanning larger regions including Waikerie to Morgan are Miles *et al*. (2001), Barnett *et al*. (2002), Fuller *et al*. (2005), Rural Solutions (2005), Aquaterra (2007) and Yan *et al*. (2009).

From 2009 to 2011, DFW commissioned AWE to develop preliminary versions of a Waikerie to Morgan groundwater model (AWE 2009a; 2010; 2011a). This included the review and summary of available hydrogeological datasets collated by AWE in a series of earlier reports on the Waikerie SIS (AWE 2004; AWE 2007a; AWE 2008b) and Stockyard Plain Basin (AWE 2009b). The data included information from DFW and PIRSA databases and prior studies. These datasets have been used for the development of the Waikerie to Morgan model presented in this report. DFW has since compiled two further major datasets: GCS and SIS pump information from SA Water and irrigation data collated from numerous sources.

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 could be included in later versions.

2.1. LOCATION AND TOPOGRAPHY

The Waikerie to Morgan project area is defined as the Land and Water Management Plan areas for Waikerie, Qualco-Sunlands, Cadell and Taylorville North. It is in the north-western Riverland region of the South Australian part of the Murray Basin, extending from river kilometres 392 to 322. Figure 2.1 shows the location and key hydrological features such as irrigation areas and the Stockyard Plain Disposal Basin.

The principal irrigation districts within the project area are Waikerie, Qualco-Sunlands, Cadell and Taylorville North. The Waikerie irrigation area includes Golden Heights and Ramco Heights, while the Taylorville North area includes Toolunka and Markaranka (Section 2.4.3.2). The project area also includes the Waikerie, Waikerie IIA and Waikerie Lock 2 SIS and the QSTGCS (Section 2.4.6). Water diverted by the SIS and QSTGCS are pumped to Stockyard Plain Disposal Basin, which lies in a local depression in the landscape (Section 2.4.7).

The project area can be divided into 'highland' and floodplain regions. The highland regions are at an elevation of approximately 20 to 80 m AHD, through which the River Murray has carved a floodplain valley with a ground elevation between 0 and 24 m AHD (AWE 2011a). Cliffs may be present at the boundary between the floodplain and highland; for example, there are cliffs between river km 351 and 356 and the southern highland is in direct connection with the river, with potential for cliff seepage to occur (AWE 2011a).

2.2. CLIMATE

The climate is characterised by hot dry summers and cool winters. At Waikerie weather station 020028, the average annual rainfall is 262 mm with a potential evapotranspiration (ET) of 2120 mm/y (Bureau of Meteorology 2011; Table 2.1). Rainfall is higher in the winter months.

The potential ET exceeds rainfall, especially in the summer months where ET exceeds rainfall by an order of magnitude. This suggests that aquifer recharge from rainfall is likely to be minimal.

Table 2.1 Average monthly rainfall and potential groundwater evapotranspiration at Waikerie

	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Rainfall (mm)	15	24	14	19	18	23	22	19	25	26	29	31	262
Potential ET (mm)	322	252	214	132	84	63	65	102	150	202	240	295	2120

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

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

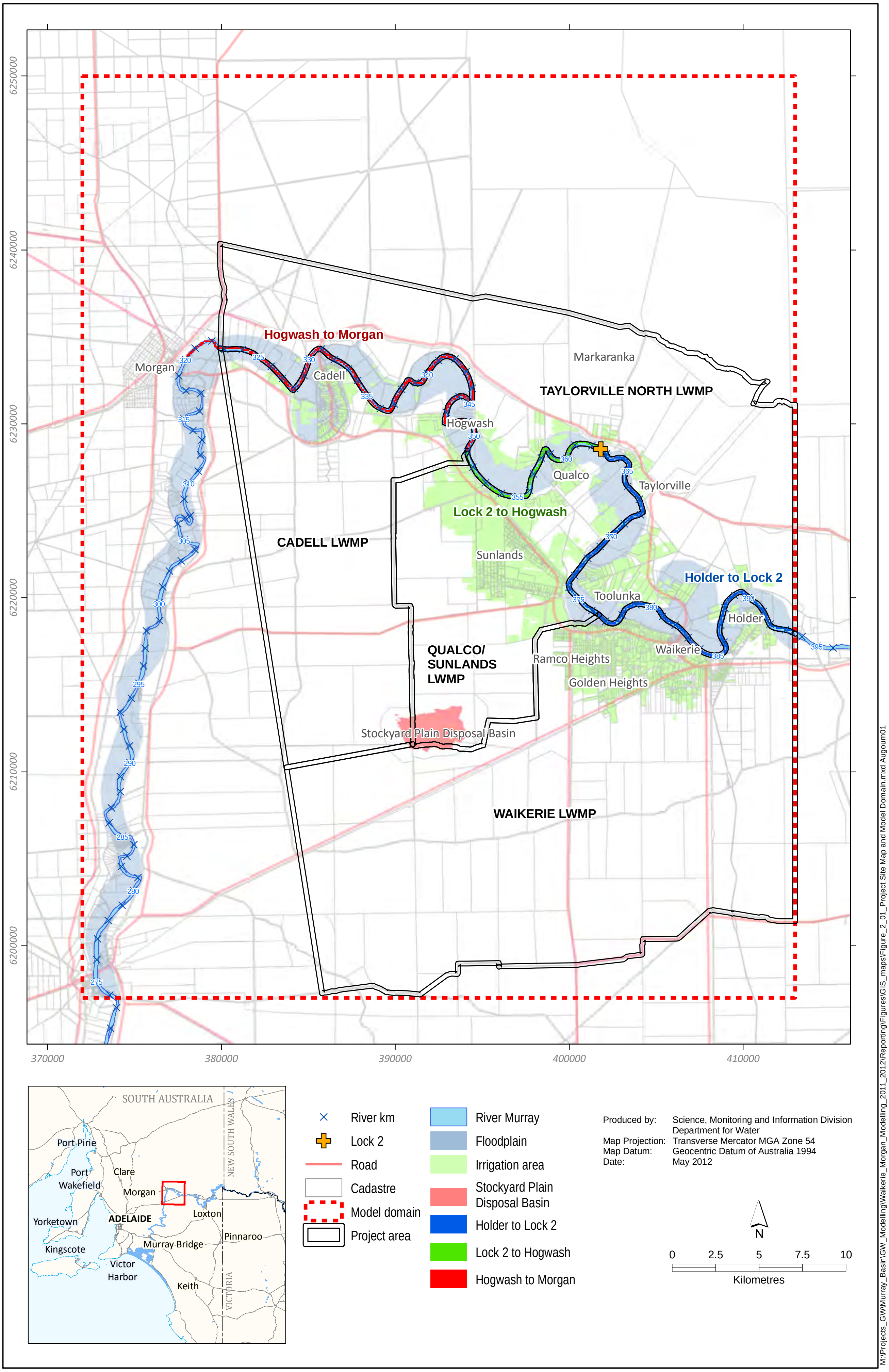


Figure 2.1 Project Site Map and Model Domain

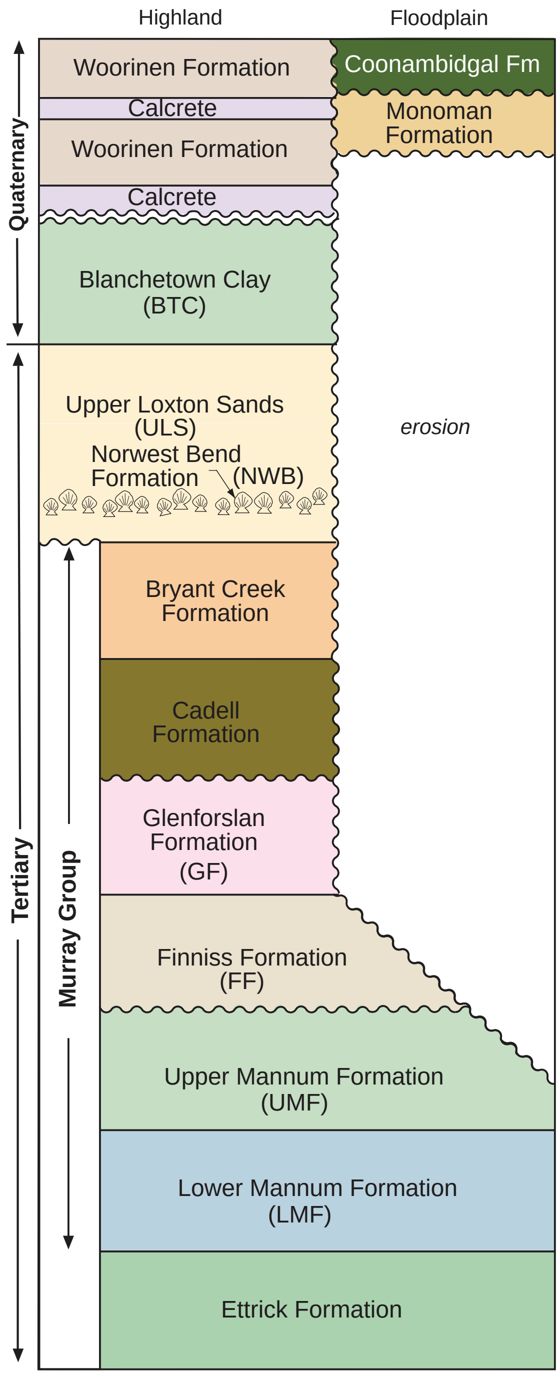
The hydrogeological units of the Waikerie to Morgan region are given in Figure 2.2 (AWE 2011a). The regional watertable lies within the Murray Group, but saturated areas (some of which are perched aquifers) have formed in upper sediments in areas of extensive irrigation (Woodward Clyde 1998). The River Murray has eroded a trench through the landscape, into which the floodplain sediments of the Monoman and Coonambidgal Formations have been deposited.

The characteristics of each hydrogeological unit in the project area are discussed briefly in this section.

Table 2.2 summarises aquifer and aquitard properties compiled and mapped in AWE (2011a). No new aquifer property data have become available since. Most aquifer tests have been conducted to test GCS and SIS pumping wells (e.g. Clark 1992a, 1992b, Dennis 2000, AWE 2003b), so the data are concentrated in the regions of Qualco and Waikerie (AWE 2011a).

Table 2.2 Hydrogeological units and calculated parameters from aquifer tests in the Waikerie to Morgan area (AWE 2011a)

Geological Unit	Region	Range in K_h (m/d)	Log mean K_h (m/d)	Range in K_v (m/d)	Log mean K_v (m/d)
Monoman Formation	Lock 2	6.48 – 10.92	8.41	-	-
Glenforslan Formation	Qualco	0.04 – 1.21	0.23	-	-
Finniss Formation / Upper Mannum Formation	Qualco (Finniss present)	-	-	4×10^{-4} – 3.33×10^{-3}	1.3×10^{-3}
Finniss Formation / Upper Mannum Formation	Qualco (Finniss absent)	-	-	6×10^{-3} – 6.7×10^{-3}	6.34×10^{-3}
Finniss Formation / Upper Mannum Formation	Lock 2 to km 381	-	-	6.5×10^{-4} – 5.53×10^{-3}	2.11×10^{-3}
Finniss Formation / Upper Mannum Formation	Upstream km 381	-	-	2.96×10^{-3} – 1.54×10^{-2}	6.39×10^{-3}
Lower Mannum Formation	Qualco	0.30 – 1.05	0.73	-	-
Lower Mannum Formation	Lock 2 to km 381	0.44 – 1.75	0.69	-	-
Lower Mannum Formation	Upstream km 381	0.86 – 9.24	2.25	-	-



Australian WATER Environments

UNCONFORMITY

CONFORMABLE BOUNDARY

Note: Diagrammatic only - not to scale

Waikerie to Morgan Groundwater Model

STRATIGRAPHIC COLUMN

Figure 2.2

2.3.2. RENMARK GROUP AND ETTRICK FORMATION

The Renmark Group aquifer overlies tectonically stable pre-Cainozoic basement rock (Brown 1989). Its sediments are Tertiary fluvio-lacustrine. It is overlain by the Ettrick Formation, a Tertiary marine marl (Barnett, 1991). Geochemical investigations suggest that the water in the Renmark Group aquifer is 30 000 years old, indicating slow movement and low interactions between aquifers. (Harrington, James-Smith & Love 2006).

Few observations have been made of the Renmark Group and Ettrick Formation in the Waikerie to Morgan region. There are data on formation depth and potentiometric head at Waikerie, but no data exists near the River Murray for the reach including Qualco, Cadell and Morgan (AWE 2008; Yan *et al*. 2009). The hydrograph from the reliable bore at Waikerie (Figure 2.3) shows little change over time despite significant changes within the Murray Group above, suggesting slow or minimal leakage between the aquifers. At Waikerie, head in the Renmark Group is approximately 25 m AHD.

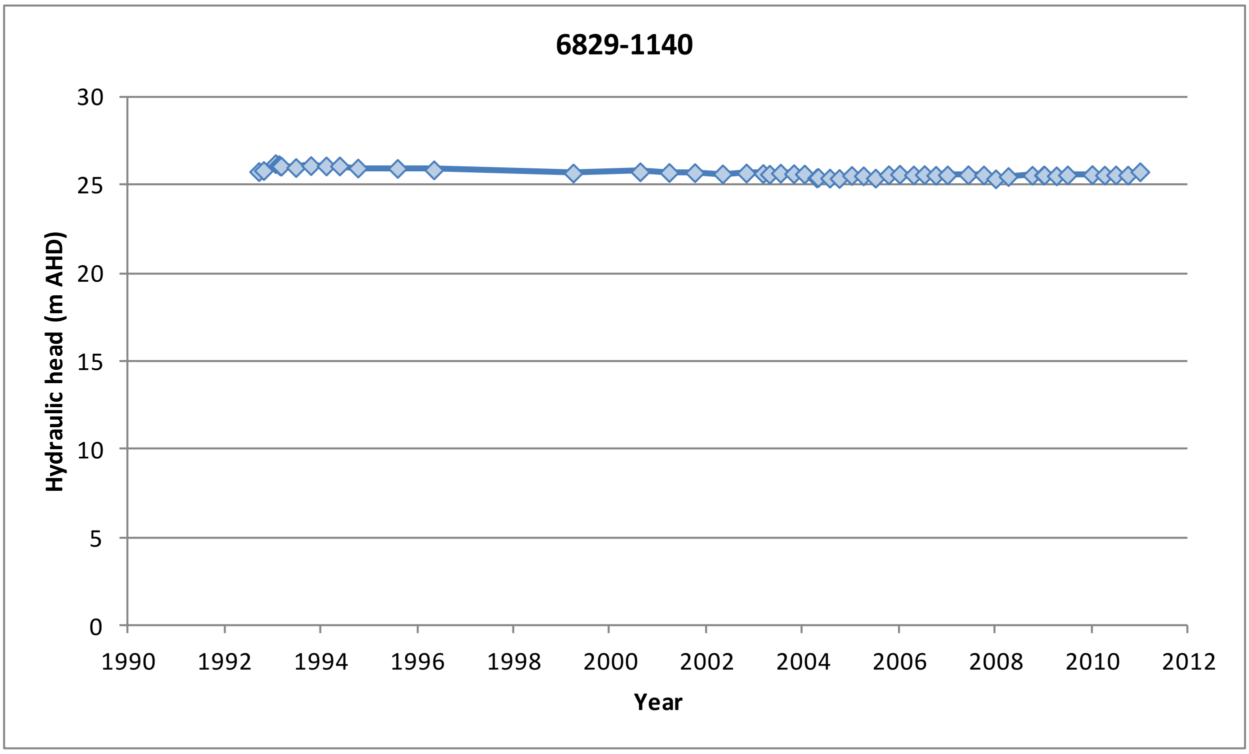


Figure 2.3 Hydrograph for Observation Bore 6829-1140 in the Renmark Group Aquifer at Waikerie

In the Waikerie to Morgan region, the Renmark Group is estimated to be 80 to 100 m thick (AWE 2008; Yan *et al*. 2009). The Ettrick Formation aquitard is up to 45 m thick at Waikerie but has been estimated to be less than 20 m thick from Lock 2 to Morgan (AWE 2008; Yan *et al*. 2009).

The head difference between the Renmark Group aquifer and the aquifers of the Murray Group is estimated to be between 15 and 25 m (Barnett 1991), indicating that the Ettrick Formation acts as an effective confining aquitard, but no data exists to confirm this for the reach downstream of Waikerie that includes Qualco, Cadell and Morgan, where the Ettrick aquitard may be thinner. In the Woolpunda reach immediately east of Waikerie, the Ettrick Formation thins to less than 15 m thick (Watkins 1993) and upwelling from the Renmark Group causes a natural groundwater mound in the Murray Group. However, there is no evidence of substantial upwelling in the Waikerie to Morgan study area.

2.3.3. MURRAY GROUP FORMATIONS

The Murray Group is a Tertiary Oglio-Miocene sequence of limestone aquifers and marl aquitards (Brown 1989, Lindsay and Barnett 1989). On a regional scale, the Murray Group Limestone may be considered as a single aquifer. Appendix E of Yan *et al*. (2009) summarises information on the Murray Group Limestone, considered as a single aquifer, over a region extending from Waikerie to Wellington which overlaps with the Waikerie to Morgan study area. Figure 2.4 shows the regional potentiometric head for 2008: flow is generally from the east to the west, but is influenced by the River Murray, irrigation areas and upward leakage from the groundwater mound at Woolpunda.

Within the study area, the characteristics of the Murray Group's separate units have a local impact on the hydrogeology. Murray Group sub-unit stratigraphy in the Riverland is described in Lindsay and Barnett (1989) but has since been reinterpreted by Lukasik and James (1998) and refined further by Wall (2001). Reports prior to 2000 typically use the older nomenclature or do not differentiate between the sub-units. The stratigraphy of the revised subunits has been interpreted and mapped in Waikerie, Qualco and some adjacent irrigation areas, but not in areas west of Qualco, where the Murray Group has been treated as a single aquifer. It is therefore not possible to present data on the properties of the sub-units outside the Waikerie-Qualco area. In the Waikerie to Morgan region, the Murray Group units include the Bryant Creek Formation, Cadell Formation, Glenforslan Formation, Finniss Formation and Upper and Lower Mannum Formations (AWE 2011a).

2.3.3.1. Lower Mannum Formation

The Lower Mannum Formation is a highly fossiliferous, sandy and weakly cemented limestone (Lukasik and James, 1998) that becomes finer and sandier with depth (AWE 2011a). The Lower Mannum Formation aquifer is confined in the Waikerie to Morgan reach (AWE 2011a) and unconfined to the east in Woolpunda (AWE 2007b). There is insufficient data on the sub-unit to determine whether it is unconfined to the west of Qualco. The Lower Mannum Formation is approximately 45 to 65 m thick in the Waikerie to Qualco reach (AWE 2011a). This aquifer is targeted for interception for the Waikerie, Waikerie IIA and Waikerie Lock 2 SIS.

Figure 2.5 shows transmissivity results from aquifer test estimates for the Lower Mannum Formation aquifer within the study area (AWE 2011a). The range of transmissivity values for the Qualco and Waikerie areas is presented in Figure 2.6. It can be seen that Qualco has a narrower range and lower median LMF transmissivity than Waikerie.

AWE (2011a) estimated the hydraulic conductivity as follows. Transmissivity values were grouped into three reaches: Qualco, the reach upstream of Lock 2 between river kilometres 381 and 362 and the east Waikerie reach between river kilometres 393 and 381. For each reach, the transmissivity range and logarithmic mean were calculated. As most of the bores only partially penetrate the aquifer, the aquifer thickness has not been measured at most of the test sites, so thicknesses were estimated from interpolated surfaces of the aquifer base and top (Section 3.4.3). It was found that the estimated aquifer thicknesses varied by less than 5 m within each reach. The hydraulic conductivity values for each reach were then calculated by dividing the logarithmic mean transmissivities by the estimated thickness.

For Qualco, reliable transmissivity estimates for the Lower Mannum Formation range from 18 to 63 m^2/d with a log mean of 44 m^2/d. The aquifer is estimated to be 60 m thick. For a saturated thickness of 60 m, the logarithmic mean transmissivity of 44 m^2/d is equivalent to a hydraulic conductivity of 0.73 m/d. For the reach upstream of Lock 2, transmissivity ranges from 22 to 87 m^2/d, the logarithmic mean transmissivity is 34 m^2/d and the estimated aquifer thickness is 50 m, giving a typical hydraulic conductivity of 0.7 m/d. Within the east Waikerie reach of the river between km 393 and 381, reliable transmissivity estimates for the Lower Mannum Formation range from 42.9 to 462 m^2/d, log mean

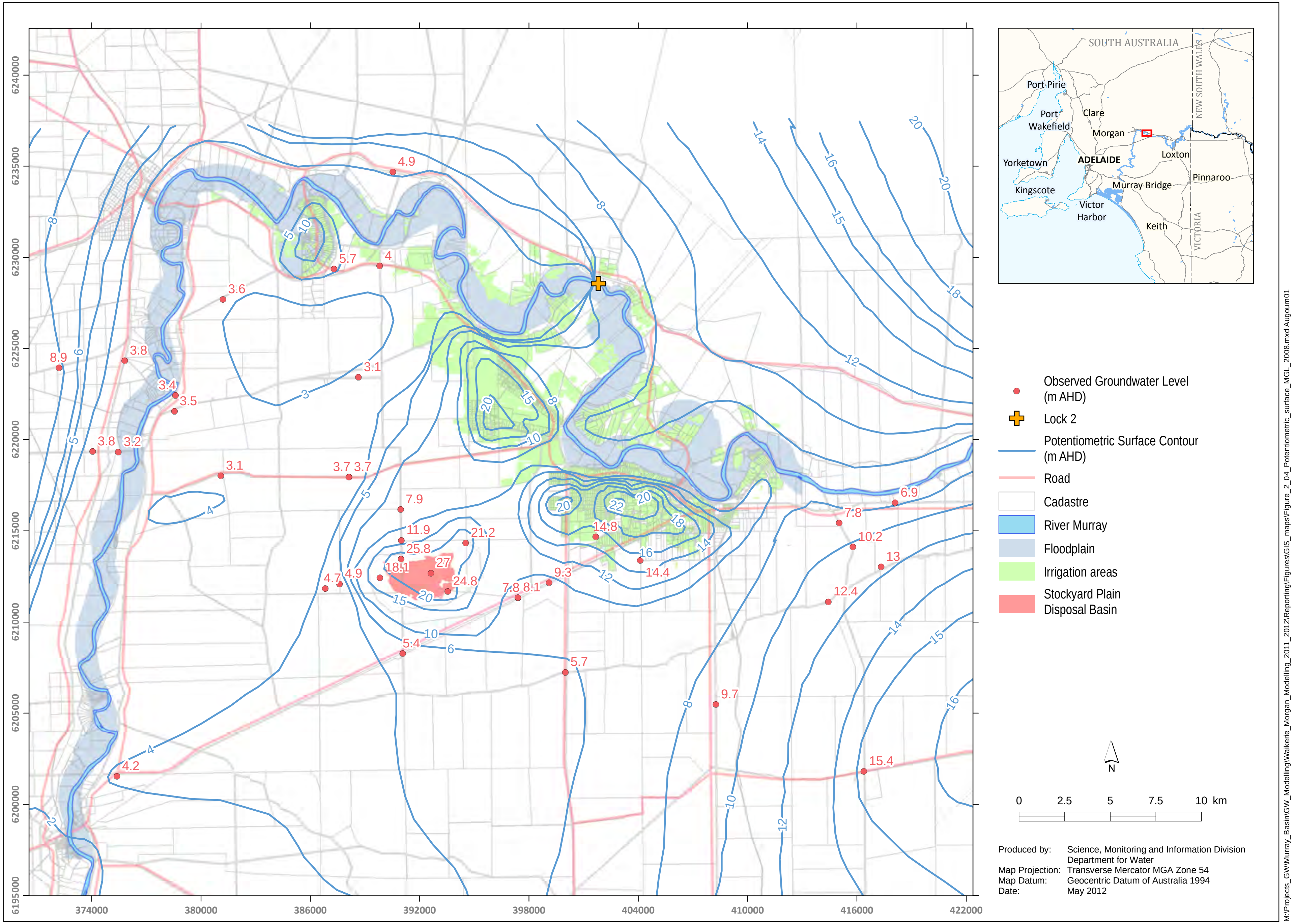


Figure 2.4 Potentiometric Surface for the Murray Group Limestone Aquifer 2008

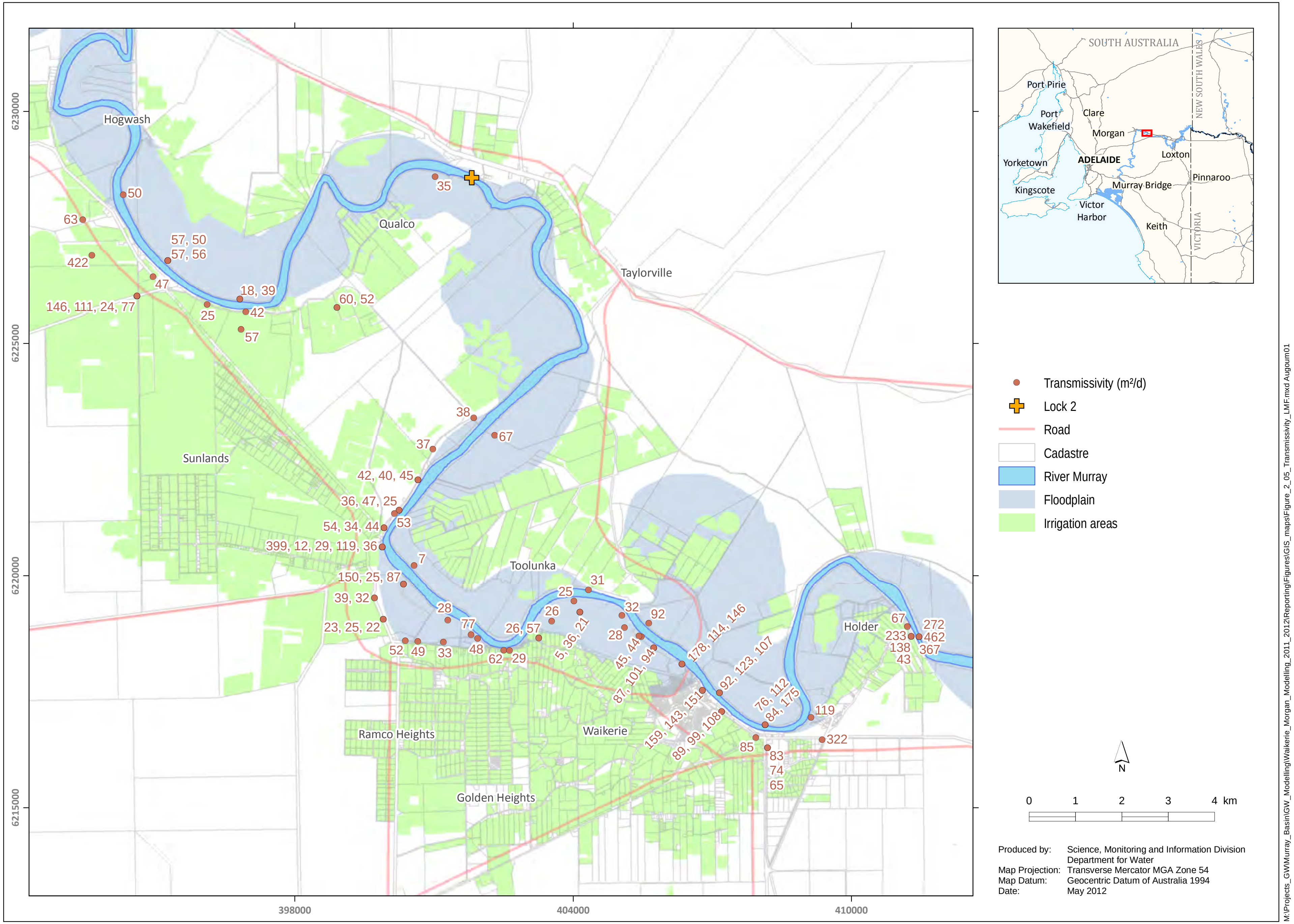


Figure 2.5 Transmissivity Estimates for the Lower Mannum Formation Aquifer

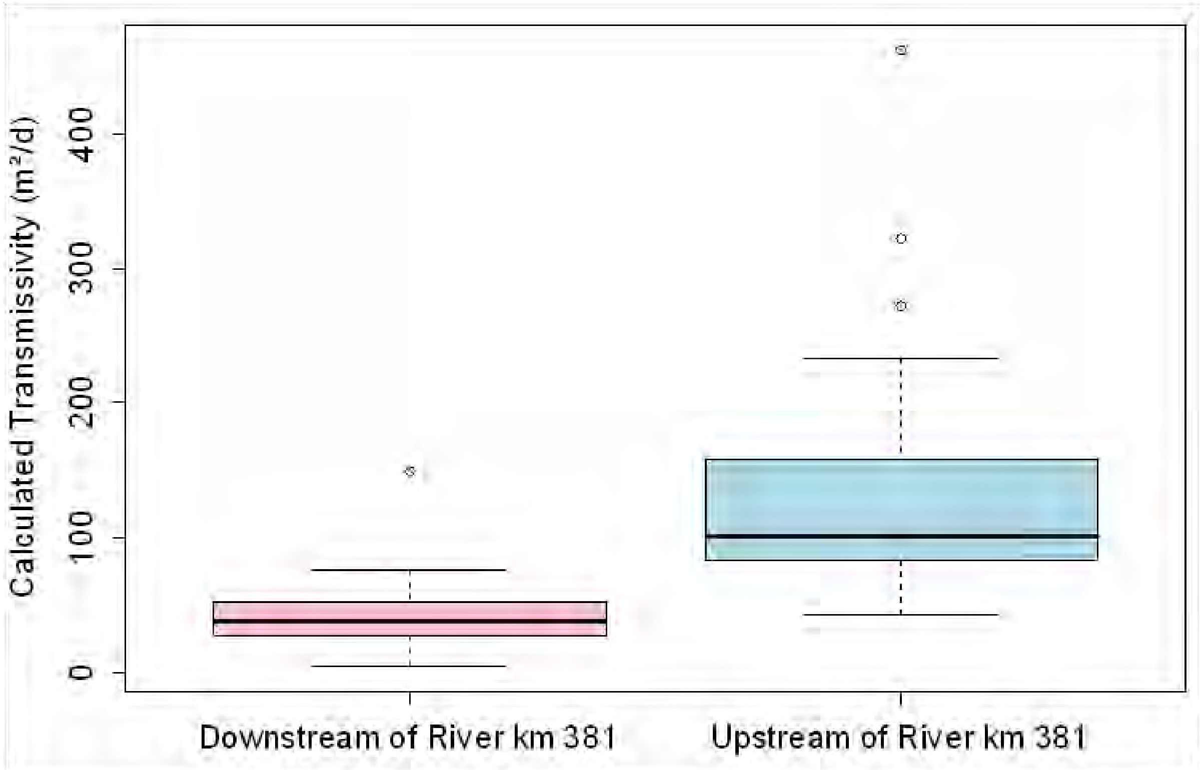


Figure 2.6 Box plot for the Calculated Transmissivities of the Lower Mannum Formation

transmissivity is 113 m^2/d and saturated thickness is 50 m which corresponds to a hydraulic conductivity of 2.25 m/d. The Lower Mannum Formation aquifer generally has much higher transmissivity than the Glenforslan Formation aquifer, due in part to the comparative thickness of the Lower Mannum Formation aquifer (AWE 2011a).

Storage in the Lower Mannum Formation aquifer has been estimated from aquifer tests at Waikerie and Qualco and all available values are shown in Figure 2.7. Values range from 2.5 x 10^{-4} to 10^{-3}, with a log mean of 5 x 10^{-4} (AWE 2011a).

The 2008 potentiometric head in the Lower Mannum Formation in the Waikerie-Qualco area is shown in Figure 2.8 (AWE 2011a). Groundwater mounds have developed beneath the Qualco-Sunlands and Ramco Heights and Golden Heights irrigation areas (the figure also includes speculative head contours beneath and adjacent to the SPDB).

Figure 2.9 displays measured salinity for the Lower Mannum Formation aquifer and includes some salinity values for bores intercepting the Murray Group where the subunit has not been identified. Salinity at Qualco is highly variable, ranging from 2000 to 39 000 mg/L, with a median value of 22 400 mg/L (AWE 2011a).

2.3.3.2. Finniss and Upper Mannum Formations

The Finniss Formation is a dark grey, medium to high plasticity clay with sparse aragonitic fossils (AWE 2011a) and the Upper Mannum Formation is a calcarenitic fossiliferous limestone, locally clay-rich to marly (Lukasik and James, 1998), weakly-cemented and low yielding (AWE 2011a). The Finniss and Upper Mannum Formations behave collectively as an aquitard that separates the Glenforslan Formation aquifer from the Lower Mannum Formation aquifer in the highland and from the Monoman Formation aquifer and Lower Mannum Formation aquifer in the floodplain.

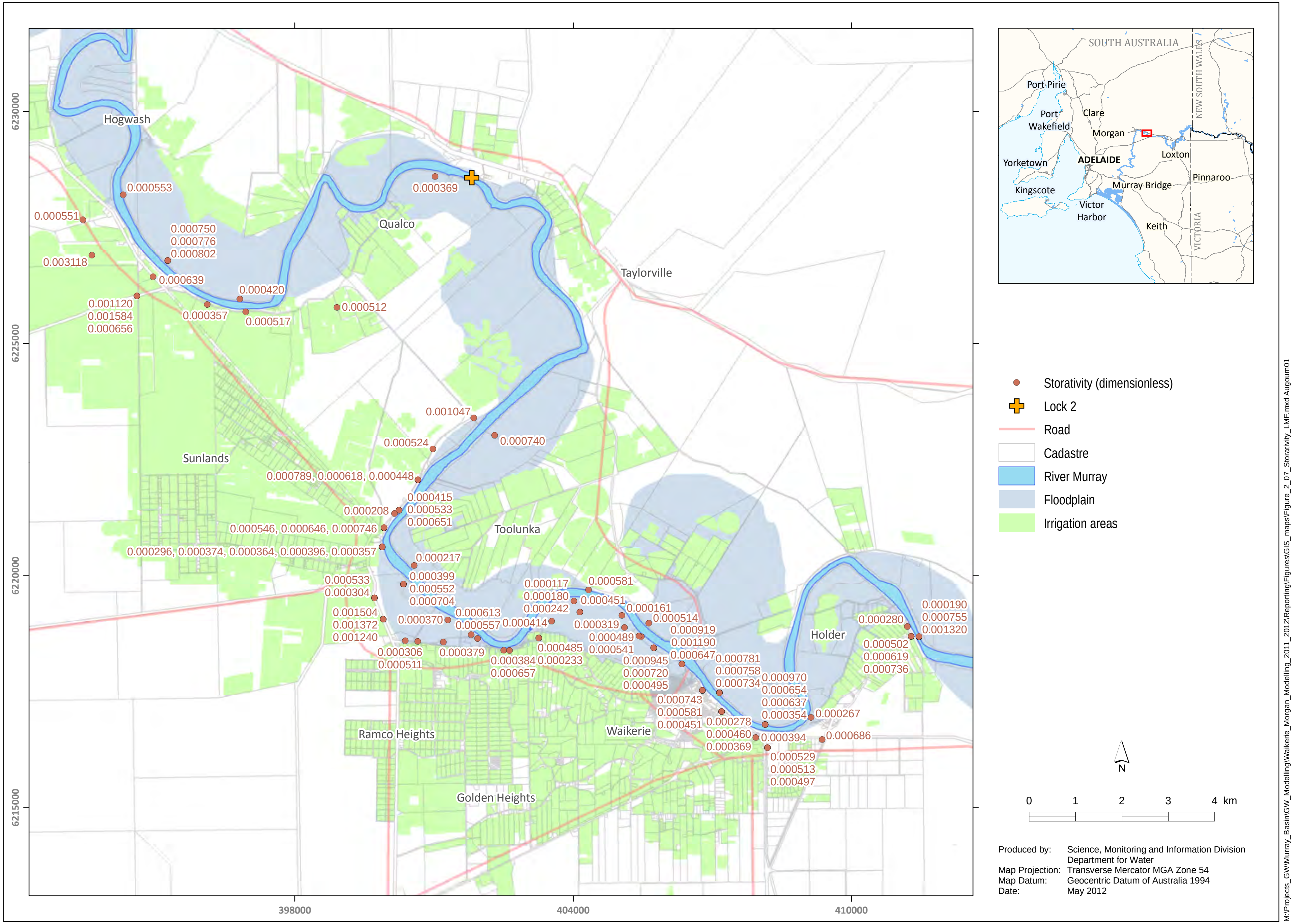


Figure 2.7 Storativity Estimates for the Lower Mannum Formation Aquifer

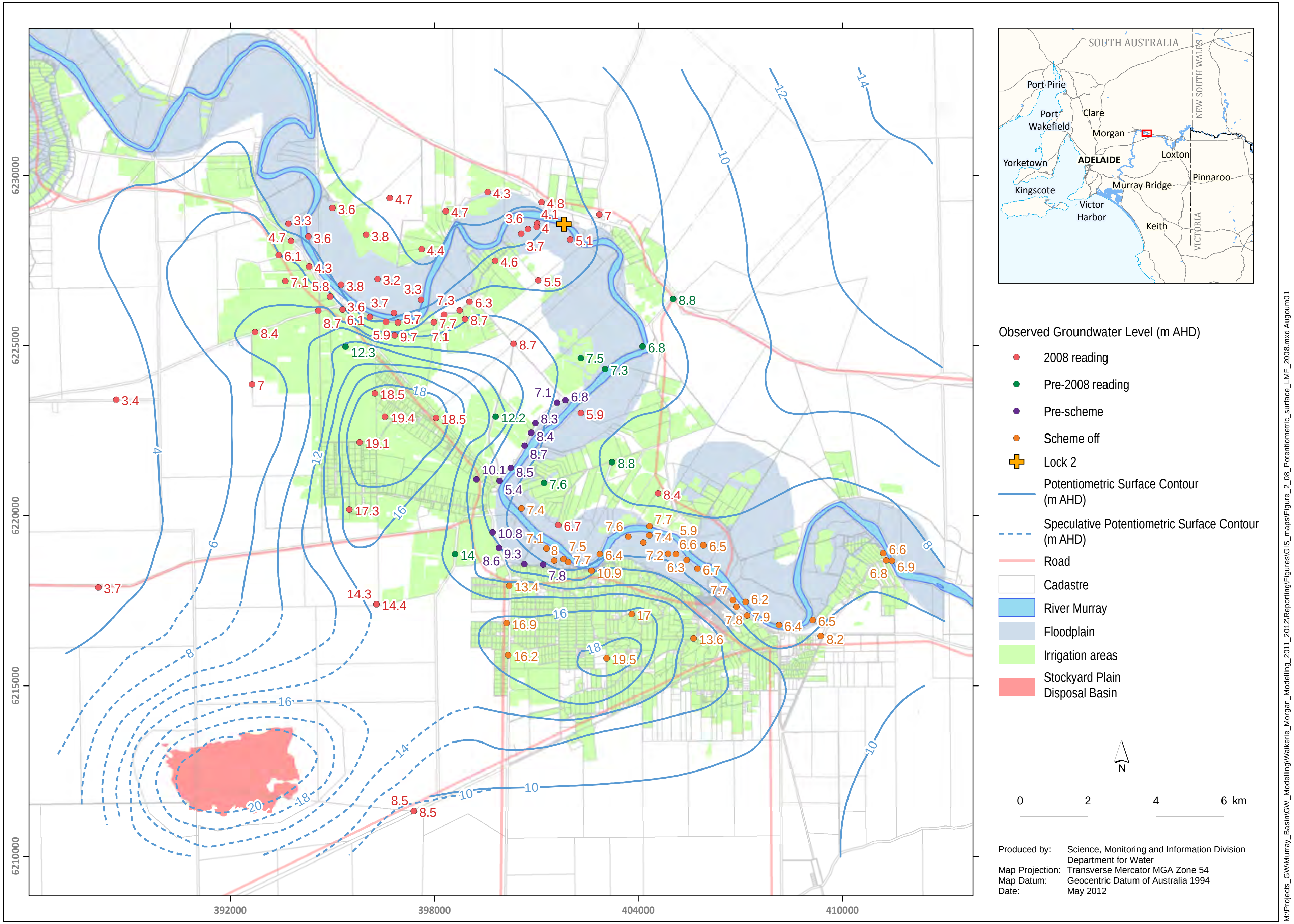


Figure 2.8 Potentiometric Surface for the Lower Mannum Formation Aquifer 2008

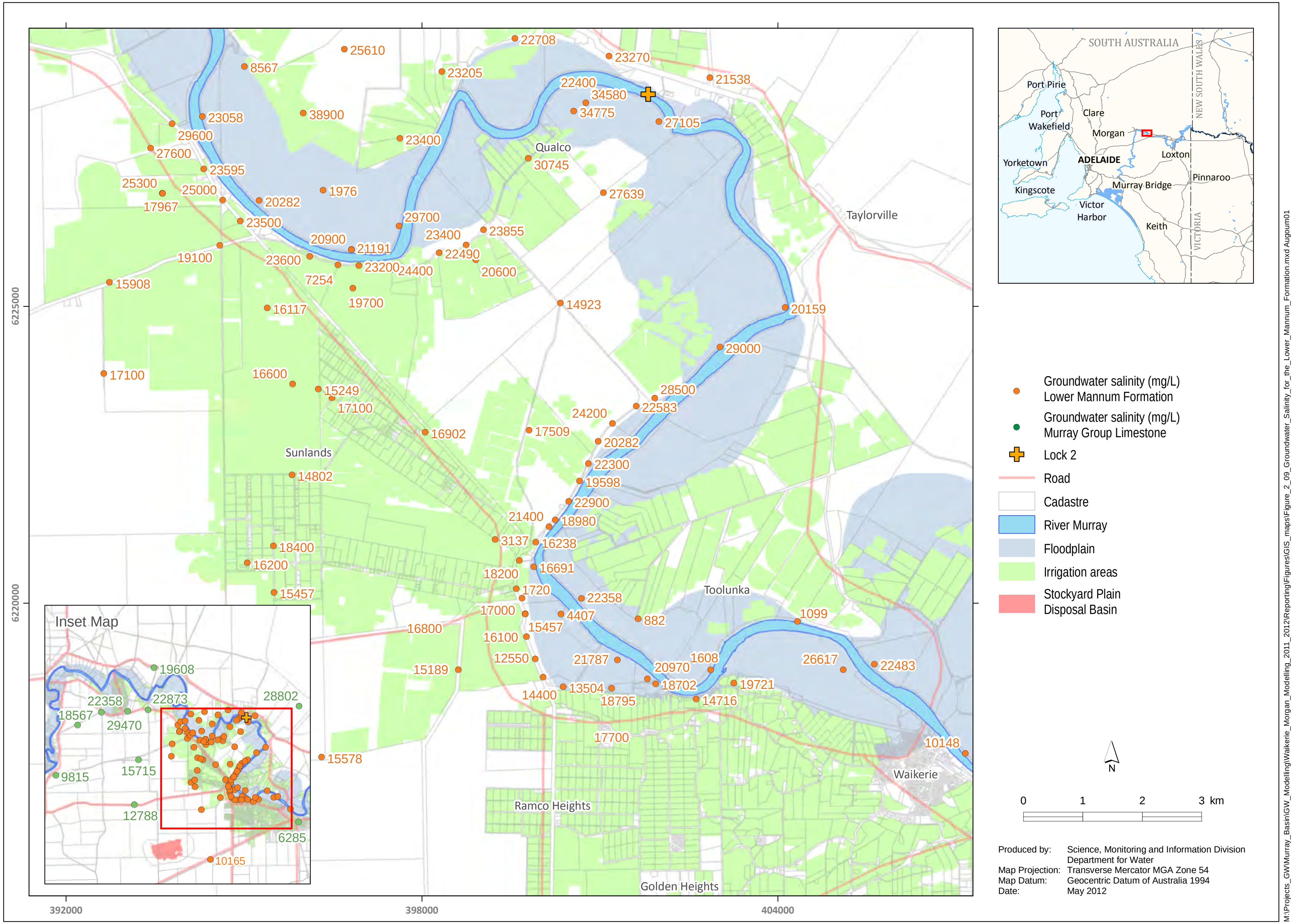


Figure 2.9 Groundwater Salinities for the Lower Mannum Formation and Murray Group Limestone Aquifers

The Finniss Formation is absent in sections of the floodplain (Figure 2.10). Aquifer tests demonstrate leakier aquifer responses in areas where the Finniss is absent when compared to areas where it is present (AWE 2004).

In the Cadell region and downstream of Cadell, the top elevation of the Finniss and Upper Mannum Formation in the highland is higher than the surface elevation in the floodplain, so the Monoman Formation aquifer is laterally juxtaposed against the Finniss and Upper Mannum Formation in this region (AWE 2005, 2011a).

Figure 2.10 shows the estimates of vertical hydraulic conductivity for the Finniss and Upper Mannum Formation aquitard (AWE 2011a). Vertical hydraulic conductivity estimates range from 4 x 10^{-4} to 3.3 x 10^{-3} m/d. Log mean vertical hydraulic conductivity in the Qualco highland region is 1.3 x 10^{-3} m/d (AWE 2011a). There are only two estimates of vertical hydraulic conductivity within the floodplain (where the Finniss Formation is known to be absent) and these are both within the high end range of vertical hydraulic conductivity, at 6 x 10^{-3} and 6.7 x 10^{-3} m/d respectively.

In the reach of river between river kilometres 381 and 362, vertical hydraulic conductivity estimates are lower than those upstream ranging from 6.5 x 10^{-4} to 5.53 x 10^{-3} m/d, with a log-mean vertical hydraulic conductivity of 2.11 x 10^{-3} m/d (AWE 2011a). Vertical hydraulic conductivity estimates range from 2.96 x 10^{-3} to 1.54 x 10^{-2} m/d, with a log mean of 6.39 x 10-3 m/d between kilometres 393 and 381.

2.3.3.3. Glenforslan Formation

The Glenforslan Formation was first defined in Lukasik and James (1998). It is a silty and sandy limestone formation with abundant bryozoan and shell fragments (Lukasik and James 1998; AWE 2011a). In some locations the Glenforslan Formation has developed secondary porosity and is karstic, e.g. the southwest corner of the Qualco-Sunlands irrigated area (AWE 2007a). It is unconfined in the Qualco-Sunlands area except in the river trench and under well-established irrigation areas. In the north and west, it is likely to be unsaturated, based on trends in base elevation, but little information is available on Murray Group subunits in those areas.

Aquifer tests of the Glenforslan Formation have been conducted in the Qualco-Sunlands area but not elsewhere. Figure 2.11 shows available data on its transmissivity and hydraulic conductivity AWE (2007). The Glenforslan Formation aquifer is karstic at Site 1, Site 14 and possibly Site 15. There is no evidence to suggest that these karst patches are connected to each other or to the floodplain. The range of transmissivity values is presented in Figure 2.12: the histogram is skewed to the left, with high values in very localised small karst areas but the majority of estimates are below 8 m^2/d. Disregarding the known karst areas, the transmissivity ranges from 0.49 to 15.7 m^2/d and the hydraulic conductivity ranges from 0.04 to 1.21 m/d, with a log-mean hydraulic conductivity value of 0.23 m/d (AWE 2011a).

Observations from drilling investigations suggest that the transmissivity of the Glenforslan Formation aquifer is higher in the Waikerie area than the Qualco-Sunlands area due to the development of karst at the water table (Telfer & Watkins 1991 & AWE 2011a) but no aquifer tests have been conducted to verify this supposition.

There are no known data regarding storage in the Glenforslan Formation aquifer within the study area.

In the Qualco-Sunlands area, the Glenforslan Formation and the Monoman Formation aquifers are hydraulically connected and act as a single aquifer. Figure 2.13 shows the 2008 potentiometric head contours for the aquifers in the Waikerie and Qualco areas. Groundwater mounds exist beneath three sources of surface recharge: the Qualco-Sunlands irrigation area, the Ramco Heights and Golden Heights irrigation area and the Stockyard Plain Disposal Basin.

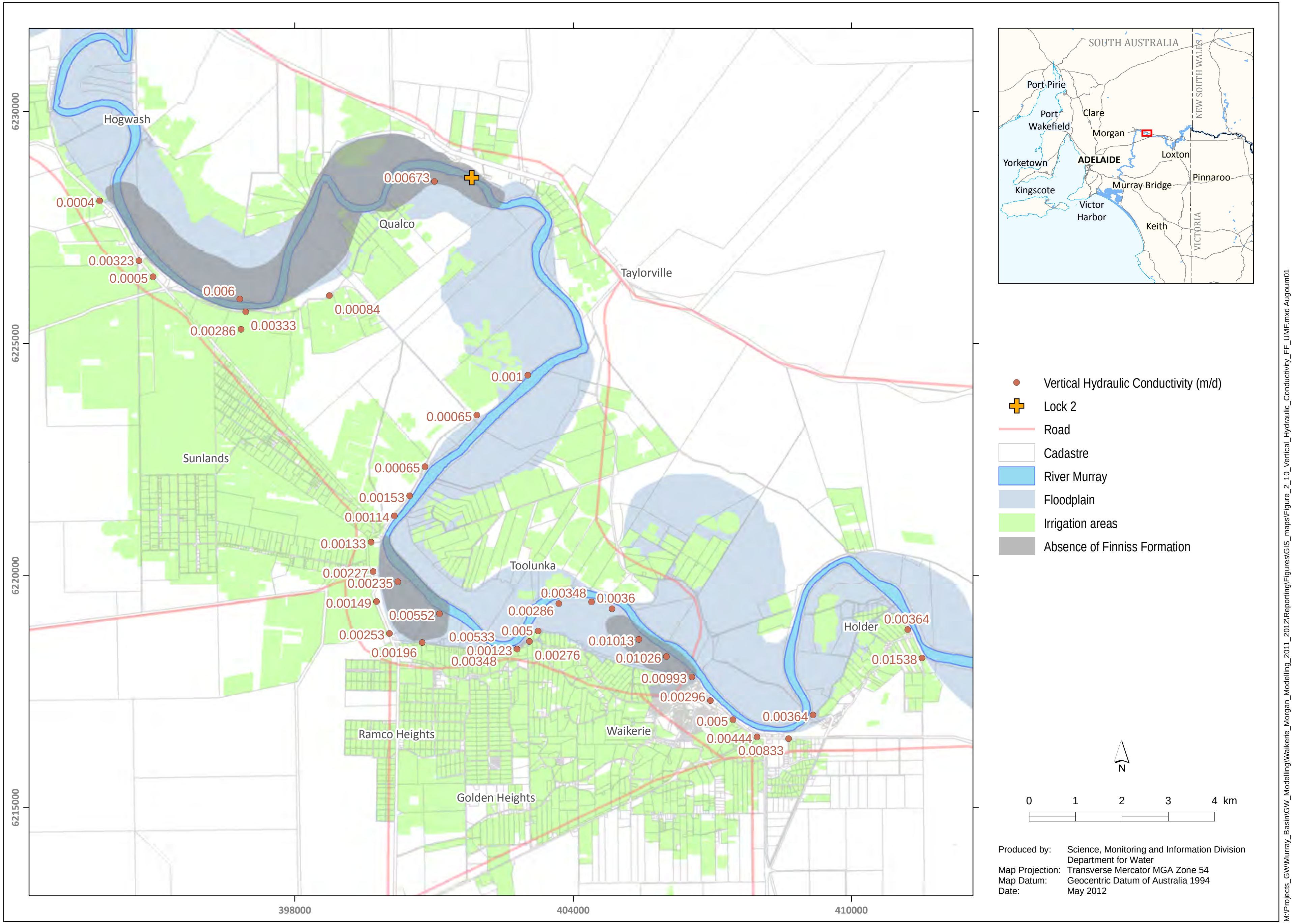


Figure 2.10 Vertical Hydraulic Conductivity Estimates for the Finniss and Upper Mannum Formation Aquitards

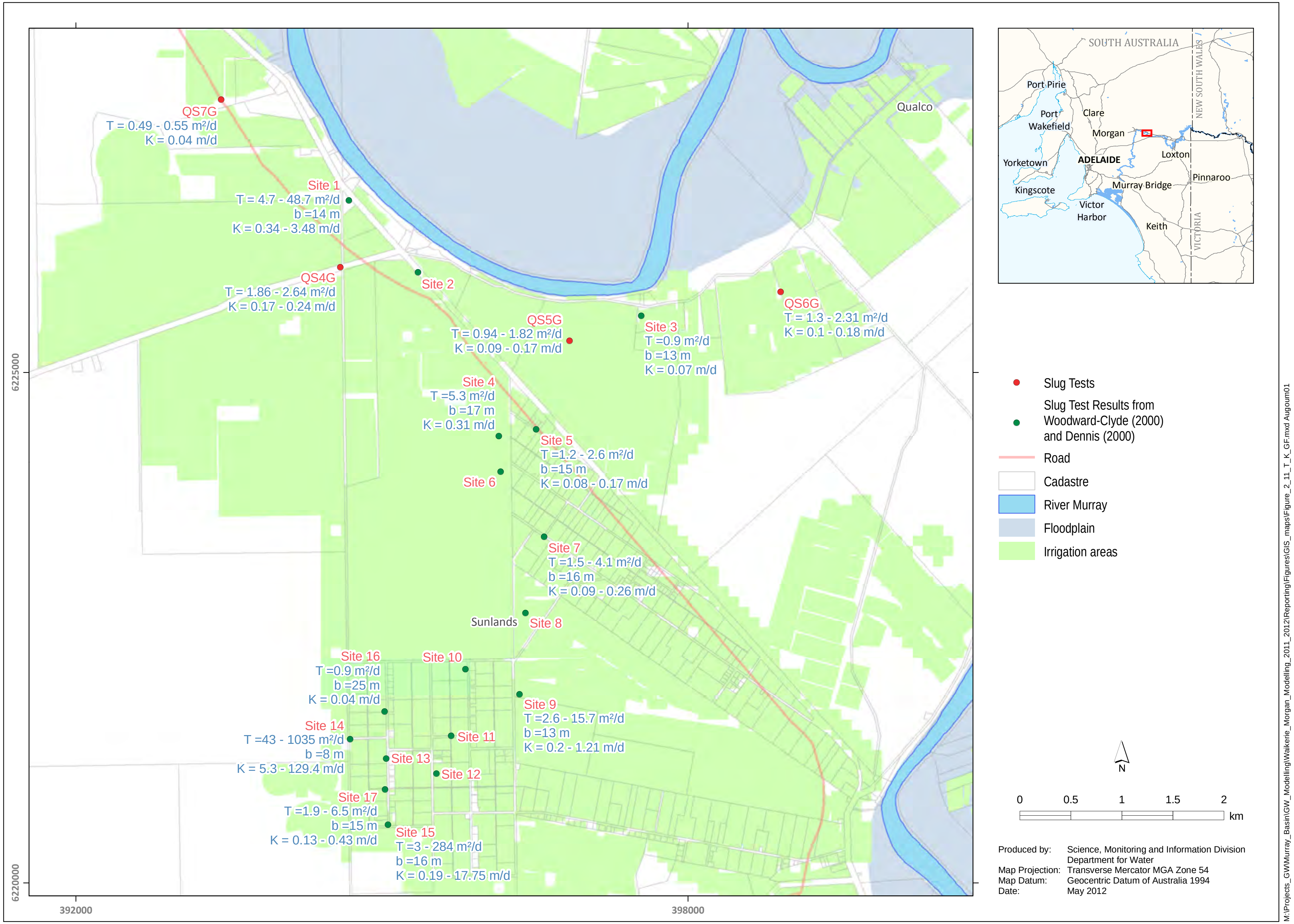


Figure 2.11 Transmissivity and Hydraulic Conductivity Estimates for the Glenforslan Formation Aquifer

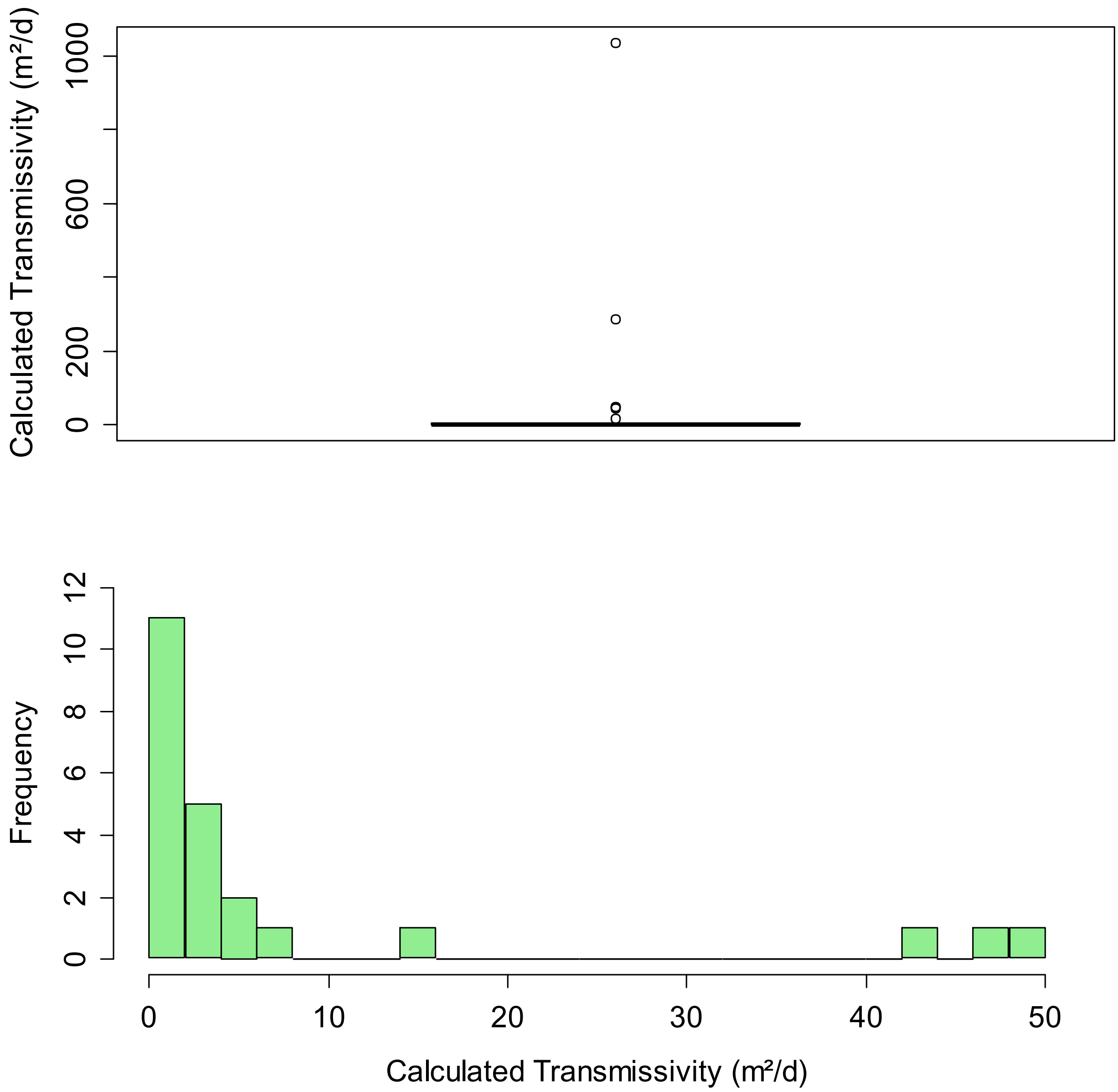


Figure 2.12 Box Plot Showing All the Transmissivity Values for the Glenforslan Formation (Above); Histogram Showing All the Non-Karstic Transmissivity Values for the Glenforslan Formation (Below)

A comparison of the potentiometric head values in the Glenforslan/Monoman and Lower Mannum Formation aquifers (Figures 2.8 and 2.13) shows that the direction of vertical leakage depends on location. At the centre of the Qualco-Sunlands groundwater mound, leakage is downwards, as the Glenforslan aquifer head is up to 5 m greater than the Lower Mannum aquifer head. Within the floodplain, the LMF head is greater than the head in the Monoman Formation, so the vertical leakage is upwards (AWE 2007a). At Waikerie, Golden Heights and Toolunka, the head in the Glenforslan Formation aquifer is lower than that in the Lower Mannum Formation aquifer by approximately 1 m. AWE (2011a) interprets this as reflecting high transmissivity of the Glenforslan Formation in these areas, which facilitates rapid lateral movement, lowering head.

Figure 2.14 displays the salinity values for the Glenforslan Formation on the highland. This figure also includes additional salinity data for the Murray Group for locations where the sub-unit of the Murray

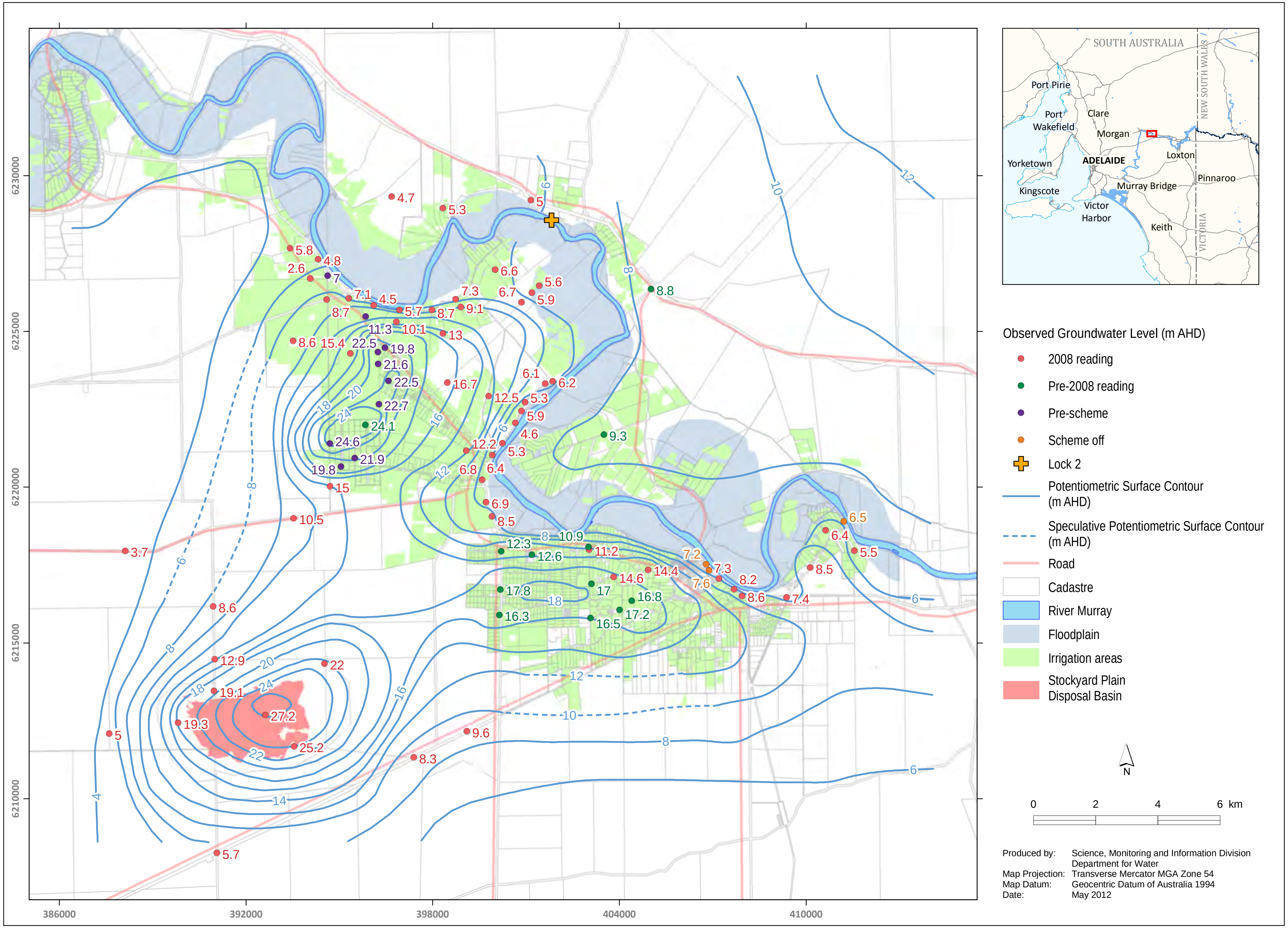


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Figure 2.13 Potentiometric Surface for the Glenforslan Formation Aquifer 2008

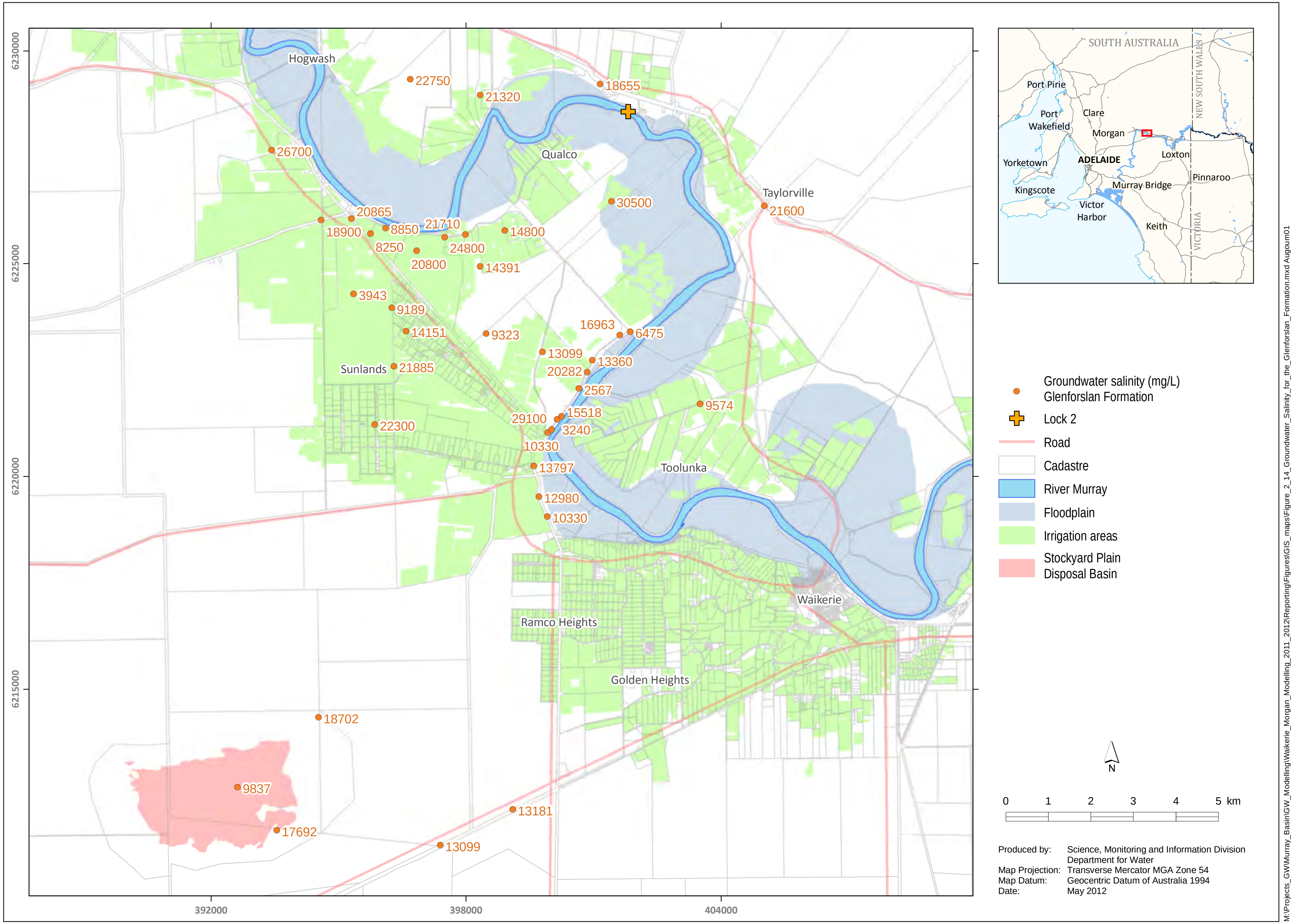

Figure 2.14 Groundwater Salinities for the Glenforslan Formation Aquifer

Group is not known. Groundwater salinity in the Glenforslan Formation aquifer within the study area ranges between 3900 to 30 500 mg/L, with a median value of 18 900 mg/L.

2.3.3.4. Bryant Creek and Cadell Formations

The Bryant Creek and Cadell Formations underlie the Loxton Sands and are the top of the Murray Group Limestone in the study area. The Bryant Creek Formation is a well-cemented silty limestone with stiff clay and skeletal calcarenite portions (Lukasik and James 1998). The Cadell Formations are fossiliferous clay-marls and clays (Lukasik and James 1998). The Bryant Creek Formation is a low permeability layer whereas the Cadell Formation is a marly aquitard: together they behave as an aquitard separating the Loxton Sands from the underlying Glenforslan Formation aquifer (AWE 2011a). Downwards leakage from the Loxton Sands through the Bryant Creek and Cadell Formation to the Glenforslan Formation clearly occurs, given the development of groundwater mounds in the Glenforslan aquifer under irrigation areas. In some areas the downwards leakage has been increased by the installation of drainage bores.

2.3.4. LOXTON SANDS

The Loxton Sands is an Early Pliocene formation of marine and fluvial origin, consisting of quartz sand and sandstone, with minor clay, silt and pebble conglomerate (Brown 1989). It is unconsolidated to weakly cemented (Barnett 1992). In the study area, it is absent in the river trench but overlies the Murray Group elsewhere.

The Loxton Sands are generally unsaturated in the study area, but are partially saturated in some locations (Watkins and Teoh 1995; Woodward Clyde 1998) due to irrigation and the Stockyard Plain Disposal Basin. Figure 2.15 displays the potentiometric head in the Loxton Sands Formation for 2008 (AWE 2011a). The partially saturated areas have developed below four sources of surface recharge: the Qualco-Sunlands irrigation area, the Ramco Heights and Golden Heights irrigation area, the Toolunka irrigation area and the Stockyard Plain Disposal Basin. The saturated areas will initially have been perched aquifers, but in some places the saturated zone may now extend fully from the Loxton Sands through the Bryant Creek/Cadell aquitard into the Glenforslan to form a continuous watertable. The extents of the irrigation-induced Loxton Sands saturated areas are not clearly known due to the lack of Loxton Sands piezometers outside the irrigation areas (AWE 2011a). Figure 2.15 shows that the extent of the saturated area in the Loxton Sands below Stockyard Plain Disposal Basin is wider than the basin itself.

The past and present existence of perched aquifers within the Loxton Sands Formation impacts local recharge processes, complicating the estimation of lag times and volumes of recharge to the water table. A proportion of the root zone drainage volume goes into the building up of the saturated areas within the Loxton Sands, which reduces the volume of water recharging the regional water table.

The potentiometric head in the Glenforslan Formation is generally lower than the head in the Loxton Sands Formation, indicating downward leakage: it is 2 m less at Qualco-Sunlands and Stockyard Plain Disposal Basin, approximately 14 m less at Waikerie and Golden Heights and 20 m less at Toolunka. AWE (2011a) interprets this as due to the karstic and hence relatively transmissive nature of the Glenforslan Formation at Waikerie and Golden Heights/Toolunka compared to a largely non-karstic sequence at Qualco-Sunlands. The high karstic transmissivities facilitate lateral discharge from the Glenforslan Formation and hence sharply reduce heads in that formation.

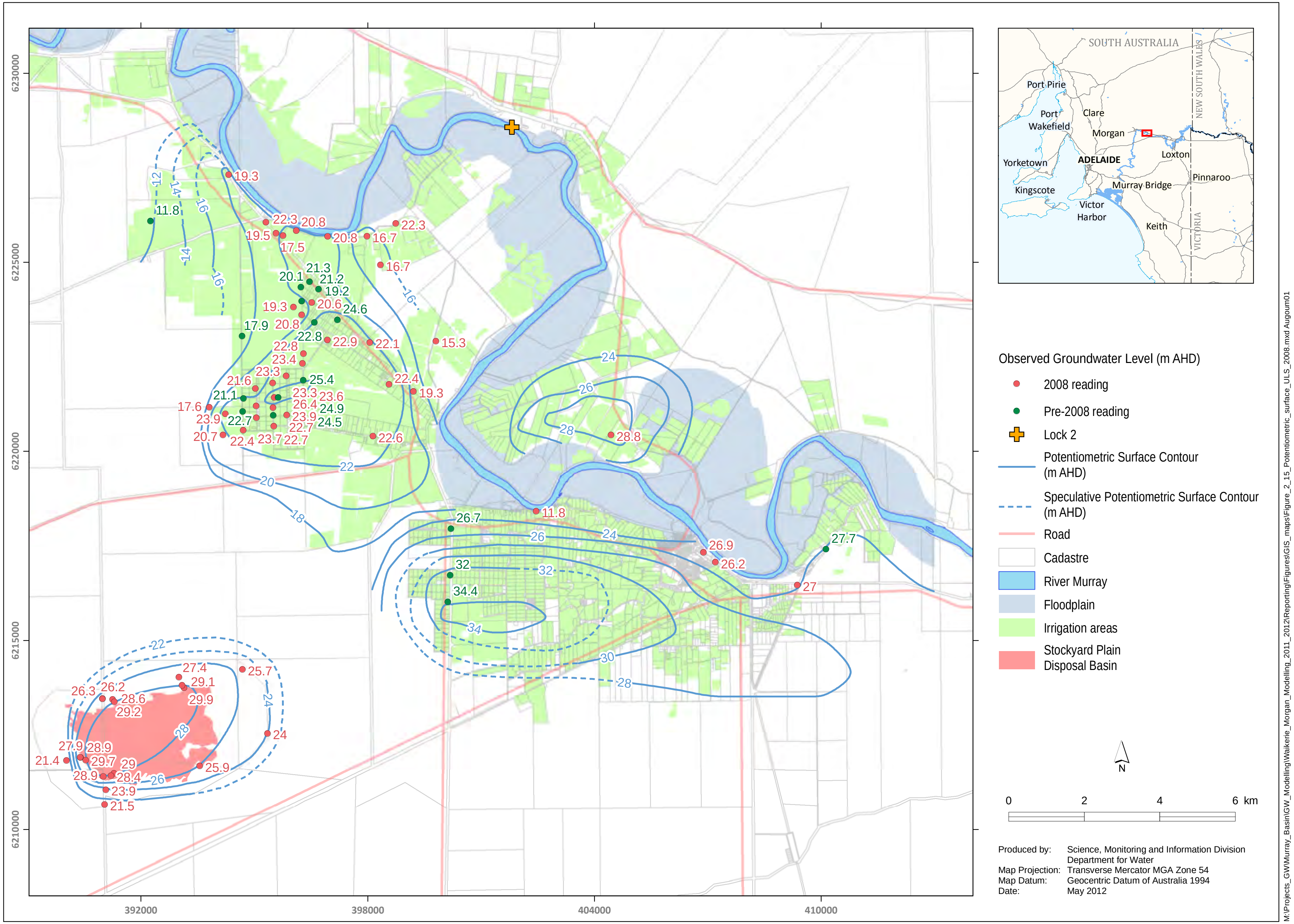

Figure 2.15 Potentiometric Surface for the Upper Loxton Sands 2008

2.3.5. MONOMAN FORMATION

The Monoman Formation consists of relatively clean, fine to coarse-grained, fluvial sands deposited as point bar sands within a wide floodplain. This unit occasionally includes minor clay and silt layers and occasional lignite bands towards the base of section (Yan *et al*. 2005). The Monoman Formation aquifer is the watertable aquifer in the floodplain. It is semi-confined by the overlying Coonambidgal Formation. Where the Coonambidgal Formation is absent, the River Murray is in direct connection with the Monoman Formation aquifer and hydraulic resistance between the two is controlled by the river bed hydraulic conductivity. An AWE (2011a) analysis of elevation of the Coonambidgal Clay/Monoman Formation boundary compared with river bottom elevation from NanoTEM surveys (Telfer *et al*. 2005) suggests that the River Murray is in direct connection with the Coonambidgal Clay in some reaches and in connection with the Monoman Formation aquifer in others.

In some reaches of the floodplain, in particular downstream of Cadell, the Monoman Formation is laterally connected to the Finniss and Upper Mannum Formation. Upstream of Cadell the Monoman Formation is laterally connected to the Glenforslan Formation (AWE 2005).

Figure 2.16 shows all available data on the hydraulic conductivity of the Monoman Formation aquifer (AWE 2011a). These sites are immediately downstream of Lock 2 within the floodplain. The hydraulic conductivity estimates are 6.5 m/d and 11.0 m/d.

Salinity data are presented in Figure 2.17; it is sourced from the data review conducted by AWE for the Morgan to Lock 3 accredited groundwater model (AWE 2007a), the groundwater sampling program conducted by AWE during observation and production well drilling in late 2008 (AWE 2008b), data collated during the review of the hydrogeology of the Morgan to Wellington area (AWE 2008a) and additional data obtained from the Obswell database. Groundwater salinity ranges from 583 to 32 300 mg/L. The Monoman Formation aquifer is more saline in areas where the River Murray is adjacent to the highland, for example a salinity of 26 650 mg/L has been measured on the floodplain opposite Qualco. Salinity within the Monoman Formation aquifer near Lock 2 is higher than observed elsewhere and this may reflect the impact of filling Schiller’s Lagoon (AWE 2011a). Relatively fresh groundwater is encountered on the floodplain at Cadell, presumably because of the freshening effects of recharge to the water table beneath irrigation areas, although regional groundwater is not as saline as other areas. Salinographs for the Monoman Formation in the study area are presented in Appendix C-2.

2.3.6. COONAMBIDGAL FORMATION

Within the floodplain, the uppermost sediments are the late Quaternary Coonambidgal Formation. It comprises clay and silt deposited during periods of episodic flooding (Yan *et al*. 2005). This unit is the confining bed overlying the Monoman Formation aquifer. Its thickness varies, with the greater thicknesses observed at the break in slope between the floodplain and highland (Yan *et al*. 2005). This unit has been reworked in part by the meanders of the River Murray and the reworked sediments may be more permeable (AWE 2011b). The hydraulic conductivity of the formation is not known but is likely to vary spatially.

The Coonambidgal Clay is not present everywhere in the floodplain but there is not enough data to confidently map its extent. It is known to be absent in some areas of Markaranka floodplain, Toolunka Floodplain and immediately upstream of Lock 2 (AWE 2011b).

2.3.7. BLANCHETOWN CLAY

The discontinuous Blanchetown Clay underlies the surface deposits of the Woorinen Formation and overlies the Loxton Sands. It is a Quaternary lacustrine unit, consisting of poorly consolidated greenish

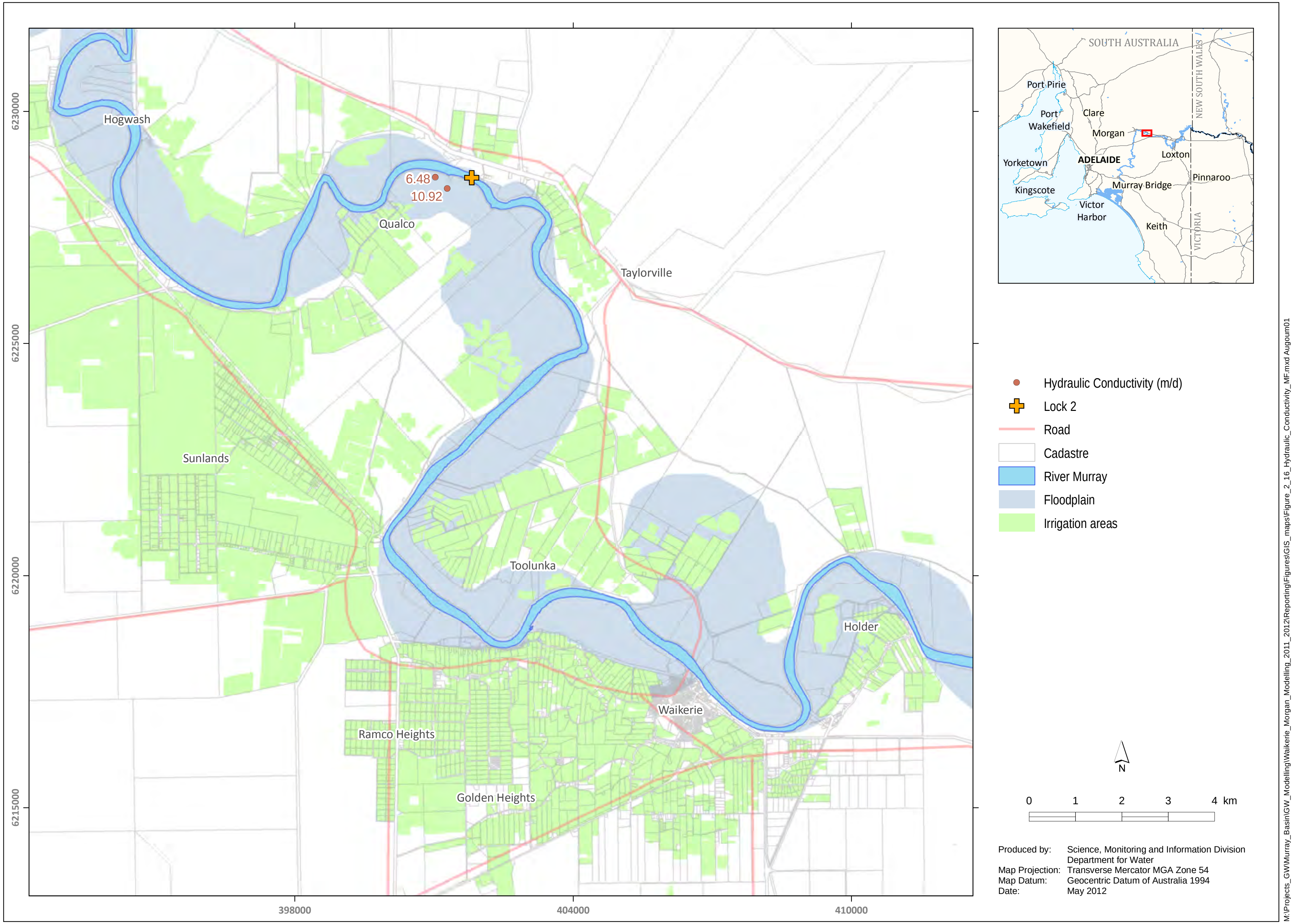

Figure 2.16 Hydraulic Conductivity Estimates for the Monoman Formation Aquifer

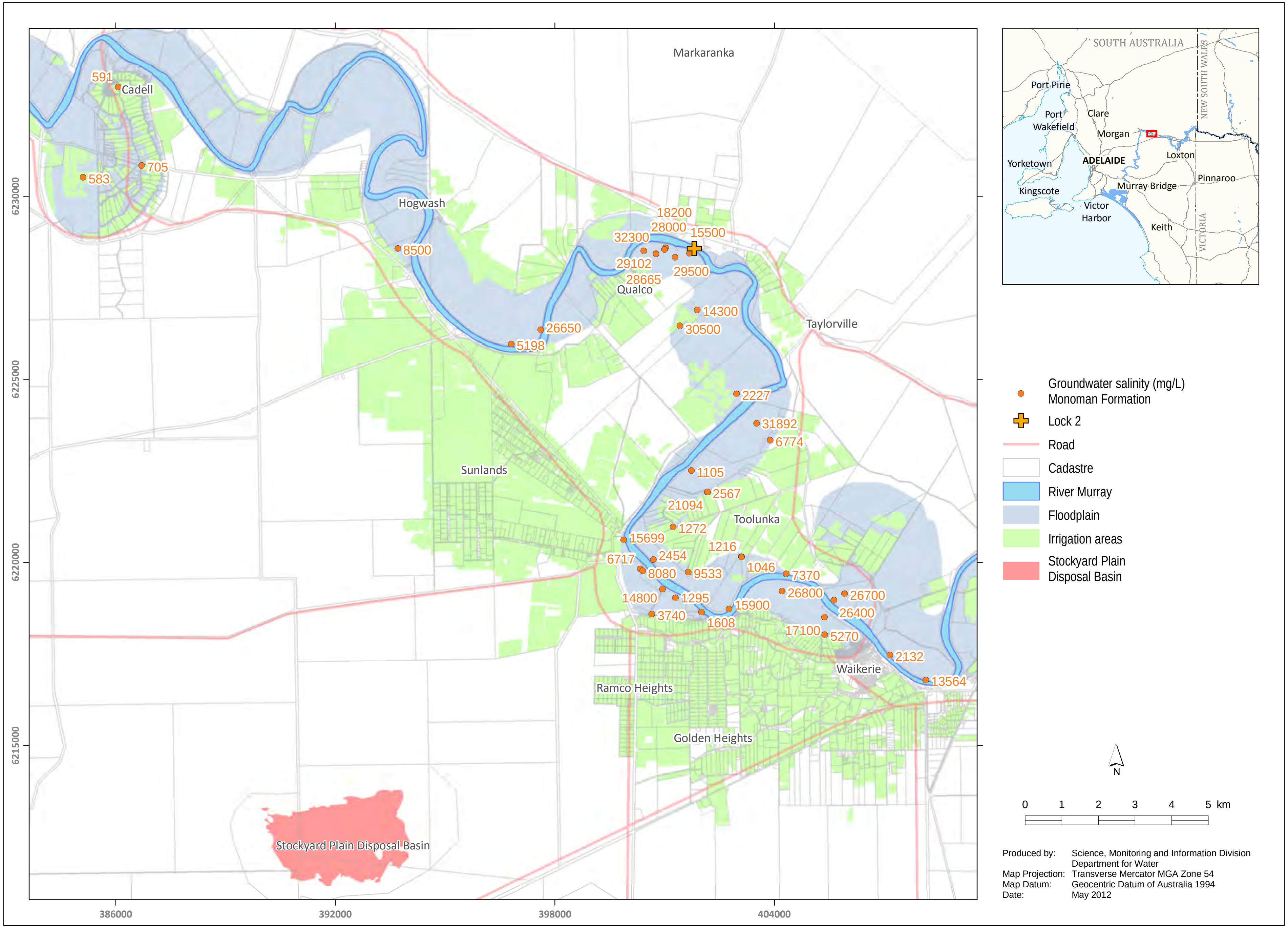

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Figure 2.17 Groundwater Salinities for the Monoman Formation Aquifer grey and red-brown laminated clay which may be locally silty and sandy (Barnett 1991). Regionally, it is within the unsaturated zone. AEM data suggests that the Blanchetown Clay is absent in some isolated areas of Qualco, Markaranka and Ramco (Munday *et al*. 2007).

2.3.8. WOORINEN FORMATION

The Woorinen Formation consists of Quaternary unconsolidated red-brown silty sand and clay (Barnett 1991). This is an aeolian dune formation. It is generally unsaturated, but perched aquifers up to 5 m of saturated thickness have been observed within the Formation in the Qualco-Sunlands area (Woodward Clyde 1998) and are likely to exist under other irrigation areas. Historically, the perching at Qualco was dealt with by drilling drainage bores into lower sediments, leading to the development of a groundwater mound in the Loxton Sands (Watkins, Teoh & Way, 1995).

2.3.9. GROUNDWATER FLOW AND INTERACTION BETWEEN AQUIFERS

The study reach is characterised by a layered leaky confined-aquifer system. Regional groundwater flow is generally from east to west. Prior to irrigation, it is presumed that the Loxton Sands was unsaturated while the water table upstream of Cadell lay in, or just above, the Glenforslan Formation. This has been altered by irrigation: in the Qualco and Waikerie irrigation areas perched aquifers have formed in the Loxton Sands and the Woorinen Formation and there may now be areas where the watertable lies within the Loxton Sands. The predominant flow is downwards from the upper layers into the Glenforslan Formation and then the Lower Mannum Formation. Downstream of Cadell and in the northwest of the study area the water table is presumed to lie within the Mannum Formation.

The major contributors of flux to sediments of the river valley are lateral flux from the Glenforslan Formation and upward leakage from the Lower Mannum Formation aquifer. It is presumed that more flux enters the Monoman Formation aquifer from below than from the floodplain edge when relative areas are considered.

Flux to the floodplain from below is driven by the hydraulic gradient between the Monoman and Lower Mannum aquifers, the hydraulic conductivity of the aquifers and the vertical hydraulic conductivity and thickness of the separating aquitard.

Lateral flux to the floodplain is dependent on head gradient, the thickness of the Glenforslan Formation/Monoman Formation interface at the highland/floodplain boundary and also the hydraulic conductivity of the Formations. In the Waikerie Lock 2 reach, the Glenforslan Formation aquifer may have too low a hydraulic conductivity to transfer large volumes laterally from the mound to the river under the existing driving heads (AWE 2007a).

2.3.10. GROUNDWATER LEVEL MONITORING

More than 200 observation bores are monitored within the project area. 93 bores were selected for presentation in this report and for comparison with model results. The selected bores are well distributed within the project area and have recorded reliable long-term historical observation data. If there are several nearby bores of similar trends and levels, then as a single bore is chosen to represent them. Obvious outlier observations such as physically impossible head levels are omitted. Water level data are sourced from the Obswell database. Hydrograph data are presented along with calibrated model results in Section 4. Observation bore locations are presented in Figures 2.18 to 2.20.

Observation bores within the Qualco-Sunlands irrigation area were constructed from 1999 in the Glenforslan and Lower Mannum Formations, to monitor pumping from the QSTGCS. As the groundwater mound developed prior to 1990, the observations do not record its growth but do record its decline and response to QSTGCS pumping.

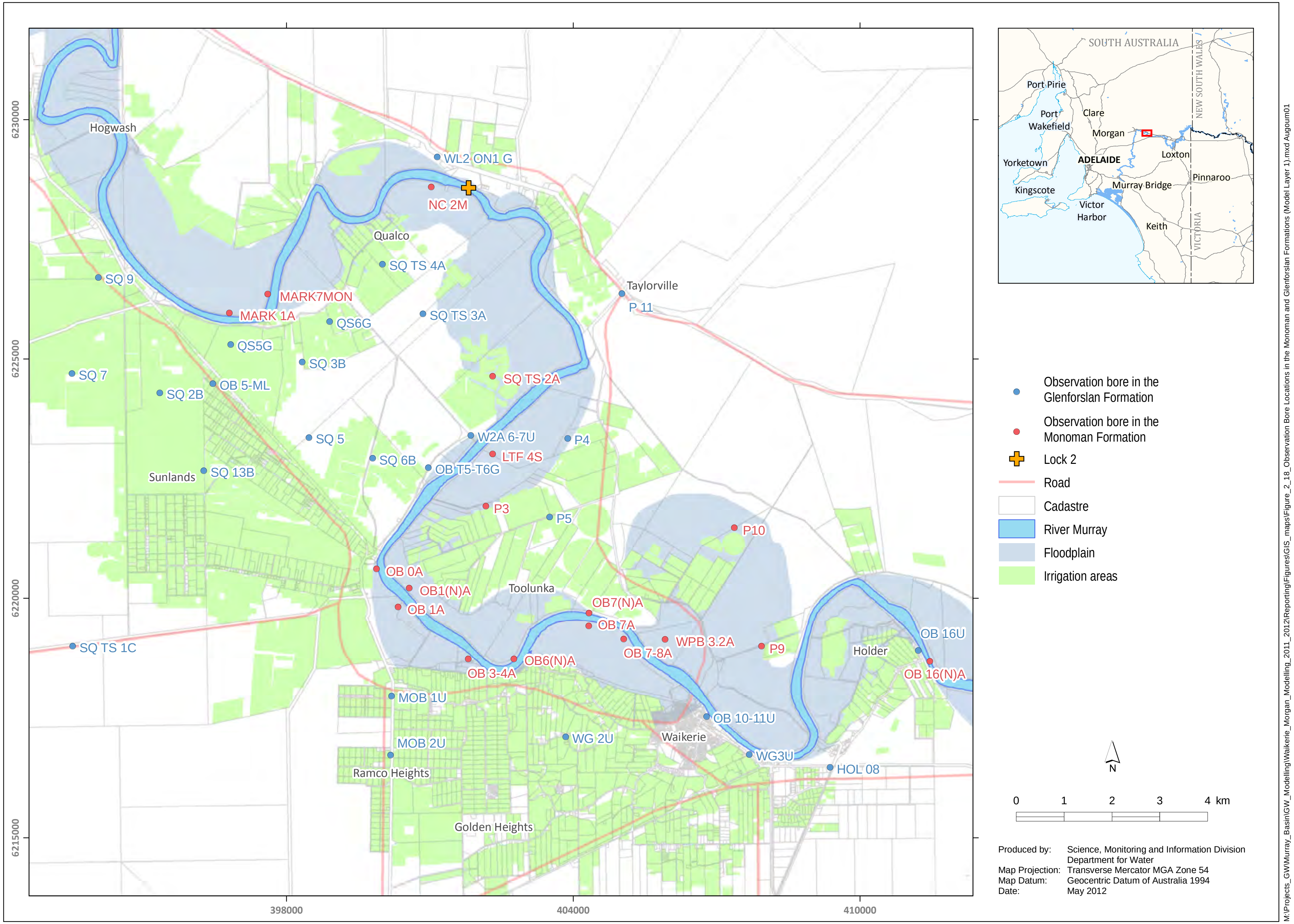

Figure 2.18 Observation Bore Locations in the Monoman and Glenforslan Formation Aquifers (Model Layer 1)

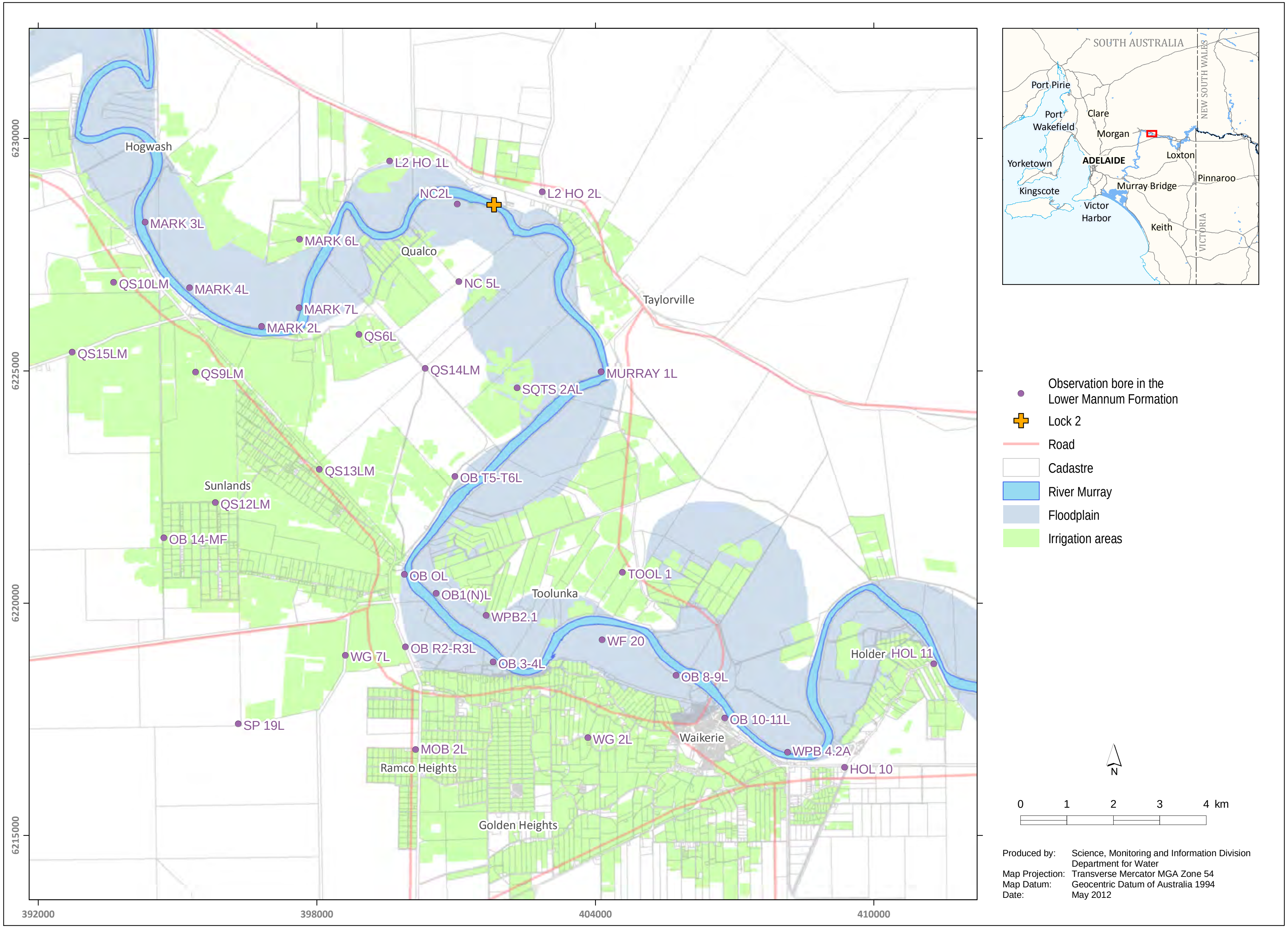

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Figure 2.19 Observation Bore Locations in the Lower Mannum Formation Aquifer (Model Layer 3)

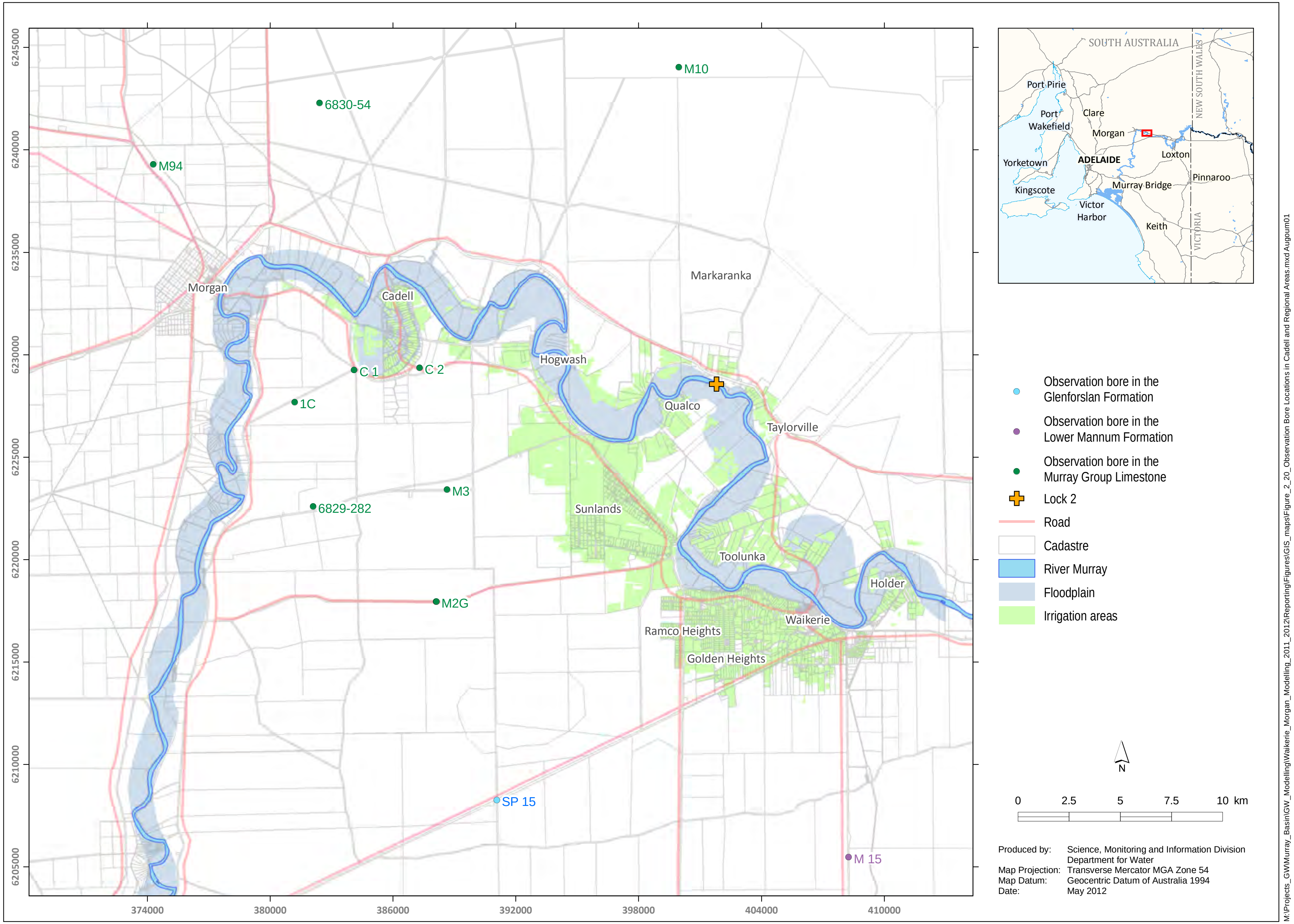


Figure 2.20 Observation Bore Locations in Cadell and Regional Areas

Observation bores at the edges of the Qualco-Sunlands groundwater mound have been monitored since the early 1990s. Water level data collected from these bores is valuable in demonstrating the spread of the groundwater mound over time. The water level in many bores appeared to rise until 2001 and then remained steady or declined after 2001, presumably in response to QSTGCS pumping (e.g. SQ3B, SQ5 and SQ6B).

Observation bores closer to the floodplain, both upstream and downstream of Lock 2, have been monitored since the mid-1990s and show variation in groundwater levels that can be attributed to changes in river-level influencing aquifer head. Responses are observed in bores screened in the Monoman Formation aquifer (e.g. SQTS2A and SQTS4B) and the Glenforslan Formation aquifer (e.g. SQTS3A, STQS3B, SQTS3C and SQTS4A). Variation in groundwater levels due to changes in river level can also be observed in the long term monitoring data of Toolunka floodplain bores (e.g. P3 and P4).

Groundwater levels in the Waikerie region have been monitored since the early 1990s. Groundwater levels in bores located inland from the SIS reveal the approximate height of mounds that have developed in the Glenforslan Formation aquifer and the Lower Mannum Formation aquifer at Waikerie. Water levels decline after 2000, which could be attributed to a combination of the SIS, improved irrigation and drought conditions (e.g. MOB2L, MOB3L, WG2U and WG2L).

Midpoint observation bores of the Waikerie SIS, close to the river (‘OB’ and ‘WF’ bores) capture the water level pre-pumping and the fluctuation in water level caused by pumping. Some bores completed in the Monoman Formation aquifer show a response to variations in river level in the early 1990s as a result of flood conditions.

Midpoint observation bores of the Waikerie II SIS close to the river do not capture groundwater levels pre-pumping, but monitoring data does exhibit a variation in head caused by pumping from the SIS.

2.4. SURFACE WATER FEATURES IMPACTING GROUNDWATER

This section describes the data and information available on features within the Waikerie to Morgan area which interact with groundwater flow. These include the River Murray, Stockyard Plain Disposal Basin, area recharge, groundwater evapotranspiration and SIS pumping. Much of this section is derived from the AWE (2011a) report commissioned by DFW and is quoted verbatim.

2.4.1. THE RIVER MURRAY

The Waikerie to Morgan reach lies between Lock 3 and Lock 1, where the river pool level is:

- 6.1 m AHD between Lock 3 and 2
- 3.2 m AHD between Lock 2 and 1
- 0.75 m AHD below Lock 1.

The locks were constructed in the late 1920s and early 1930s.

River levels have changed over time in periods of flood and drought, which alter the gradient between the River Murray and the groundwater and hence the flux. However, changes in gradient due to changes in river level will be minimal when compared to the very steep gradient from the irrigation-induced groundwater mounds, which may be up to 20 m of head difference from highland to floodplain: the average head difference between river level and pool level since 2000 ranges from 0.1 m to 0.5 m at different sites. The general pool levels given above are relatively stable during normal and low flow conditions. In the simulated reach from Holder to Morgan (river kilometres 395 to 320), backwater curves show that river levels vary by less than a metre for flows of 15 000 ML/d or less.

Flux to the River Murray from groundwater also depends on the hydraulic gradient and 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. For example, the Coonambidgal Formation provides more hydraulic resistance to flow than the Monoman Formation. Where the River Murray is incised into the Monoman Formation the dominant hydraulic resistance to flow will be provided by the hydraulic conductivity of the river bed. The variability in river sediment hydraulic conductivity and the presence or absence of the Coonambidgal Clay can influence the total hydraulic resistance between river and aquifer.

Backwaters may also influence groundwater and 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 the Run of River surveys, as described below.

2.4.1.1. NanoTEM

NanoTEM surveys estimate the electrical resistivity of sediments below the river bed. Low electrical resistivity corresponds to potential high salinities or proportion of clay and suggests a gaining stream reach, where high-salinity groundwater flows into the Murray. High electrical resistivity corresponds to low salinities or clay proportion, suggesting a losing stream reach where low-salinity river water flows into the aquifer.

Figure 2.21 shows NanoTEM data collected in 2004 for sediments immediately below the river bed (Telfer *et al*. 2005). AWE (2011a) discusses the key features as follows: The river is gaining in the reach from downstream of Lock 2 to adjacent Qualco (i.e. river km 362 to 354). The river is also gaining adjacent to Taylorville irrigation area where the river abuts cliffs and there is little or no floodplain to lower the head gradient between the highland and the river (river km 369 to 365). The river also appears to be gaining stream in the Cadell reach from river km 328 to 326. This is likely due to the impact of irrigation developments on the floodplain.

There are minor reaches of the river between km 393 and 370 that appear to be gaining stream, however most of the reach appears to be losing. This is believed to be due to the effectiveness of the Waikerie and Waikerie IIA SIS in reducing groundwater flux to the river. Prior to implementation of salt interception schemes along these reaches, it is likely that most of this reach would have been a gaining stream. Pumping from the SIS reduces the flux entering the floodplain and therefore reduces the salt load contribution to the river.

2.4.1.2. Run of River

Run of River (RoR) analysis results are presented in Figure 2.22. Three reaches are considered: Holder to Lock 2 (Waikerie) reach spanning river kilometres 393.5 to 362.5, Lock 2 to Hogwash (Qualco) reach spanning river kilometres 362.5 to 351 and the Hogwash to Morgan (Cadell) reach spanning river kilometres 351 to 320. These reaches are consistent with those used later during model calibration (Table 4.1). There is a great deal of variation from survey to survey. There is a clear declining trend for the Holder to Lock 2 (Waikerie) reach.

RoR results can exhibit significant variation due to factors such as river and backwater levels. For example, a RoR survey conducted immediately after a flood event (high river level) would be expected to show high salt load to river, due to the impacts of flood-induced groundwater recession. The 2006 survey may provide an example of the influence of backwaters, as the high salt load between kilometres 362 and 358 (Lock 2 to Hogwash reach) has been attributed to the filling of Schiller’s Lagoon, adjacent to

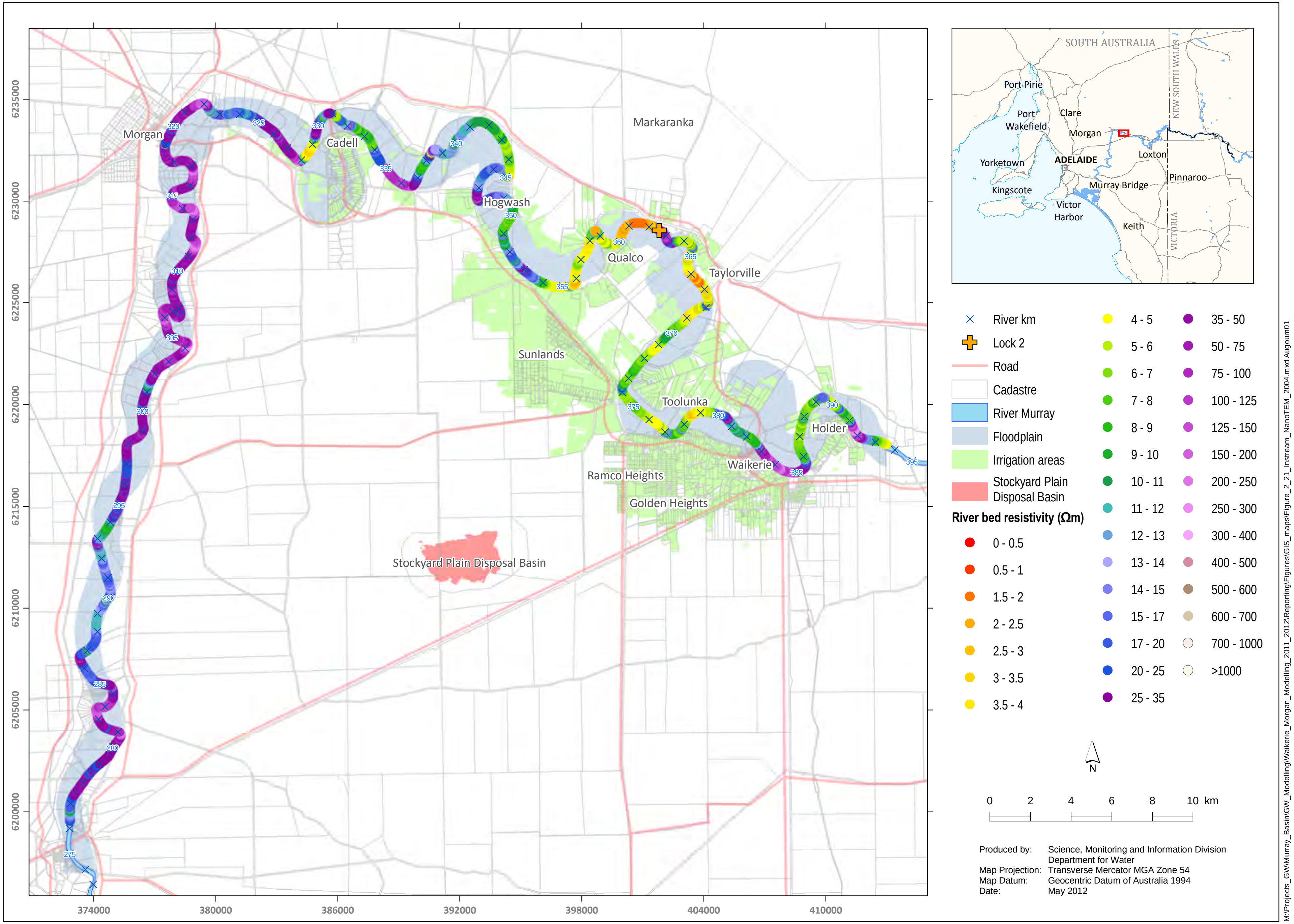


Figure 2.21 Instream NanoTEM 2004

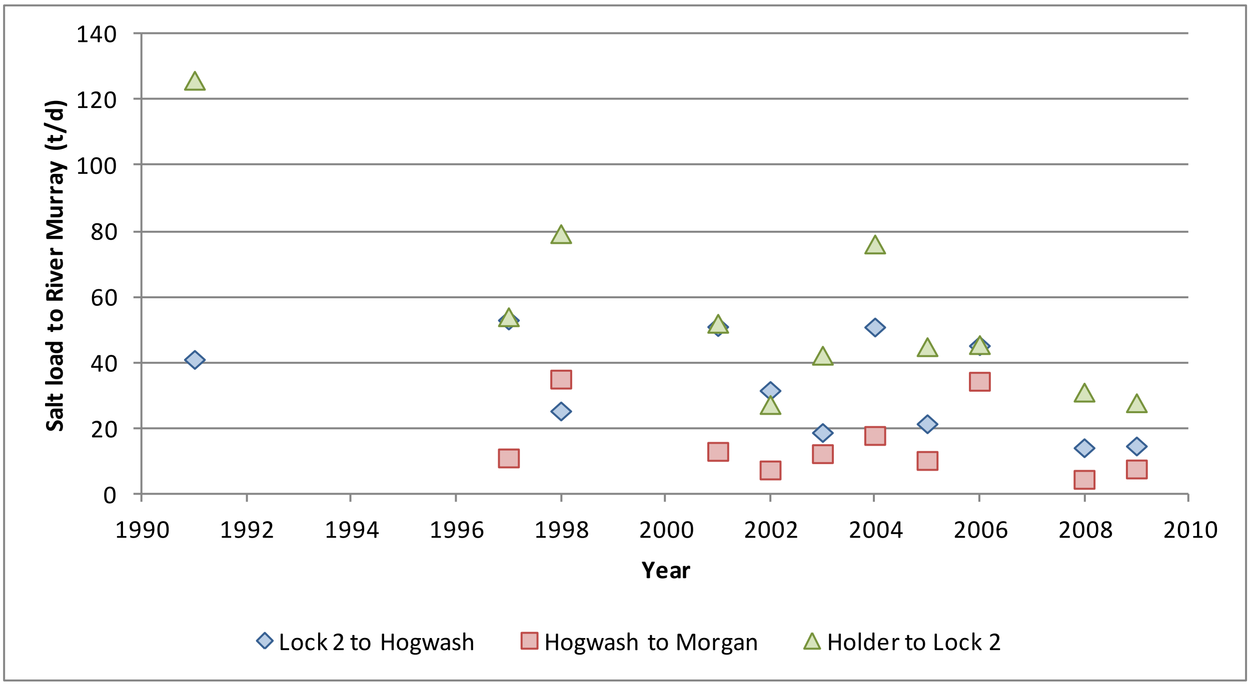


Figure 2.22 Salt Load Entering the River Murray from RoR Analysis

Lock 2, which can have head levels 3 m above river level (AWE 2011a). A model which does not simulate changes in river and backwater level will not match all RoR observations.

2.4.2. SURFACE WATER BODIES

There are a number of ephemeral wetlands and lagoons within the study area. Some of these may have a significant but only temporary impact on salt loads to the River Murray. When their water level is high, they add additional salt load to the River for a short period of time. Some of the lagoons have regulators and their water levels are generally kept at pool level, but may differ from river level fluctuations. These surface water features are not simulated in the model.

Only the Nigra Creek is simulated in the model as it is a permanent surface water feature. It is an irrigation offtake channel directly connected to the river upstream of Lock 2, with a head at river level (AWE 2011a). It includes three culverts which allow water to be held back or released into a nearby ephemeral lagoon (AWE 2011a).

2.4.3. RECHARGE

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

2.4.3.1. Dryland recharge

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

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

2.4.3.2. Irrigation development

Irrigation is mostly confined to highland areas both north and south of the river, with grapes and citrus the major crops cultivated. Irrigation of the floodplain occurs in Cadell and in portions of Qualco and eastern Toolunka. DFW collated, summarised and verified irrigation data for the Waikerie to Morgan area, including changes in irrigation area over time (Figure 2.23) and volume of water applied to crops (Fordham *et al*. 2012). The details are included as Appendix C-1. A brief summary is provided below.

Irrigation began in the study area in the mid-1890s at Holder, Waikerie and Ramco. Cadell was first irrigated in 1920. The next period of major expansion occurred in the late 1950s and early 1960s, with irrigation commencing at Taylorville and Markaranka, Golden Heights (1958), Sunlands (1961-2) and Ramco Heights (1962). Problems with waterlogging meant that drains and drainage bores were often constructed within a few years of the start of irrigation (see Section 2.4.3.3). Irrigation practices in the South Australian Riverland have changed over time. Generally speaking, older irrigation sites used flood irrigation, on a four or two-week schedule. As irrigators could not know what the rainfall would be like over the weeks until the next watering, large volumes were used to ensure that crops had sufficient water. Later there was a shift from flood irrigation to sprinklers, then drip systems. Many irrigators now use soil moisture monitors to target water application. These changes in irrigation practices have reduced irrigation application volumes and hence the volume of root zone drainage and irrigation-derived aquifer recharge. Figure 2.24 shows a typical irrigation practice history for the Riverland (Vears 2010, adapted from Adams & Meissner 2009).

Root zone drainage volumes can be estimated based on a water balance calculation which includes rainfall and irrigation application volumes. The latest estimates of root zone drainage for the Waikerie to Morgan irrigation areas are given in Appendix C-1.

The root zone drainage percolates into the unsaturated sediments and a proportion will remain in the unsaturated zone within the pore spaces. If there is a low-hydraulic conductivity layer in the unsaturated zone, such as the Cadell/Bryant Creek Formation aquitard or Blanchetown Clay, a perched aquifer may form. Some of the root zone drainage will then remain in the perched aquifer, or will flow laterally across the surface of the aquitard before seeping down towards saturated sediments. Due to these unsaturated zone processes, the root zone drainage rates and footprint may differ from the recharge rates and footprint.

In the Waikerie to Morgan area, saturated areas within the Loxton Sands occur beneath older irrigation developments and the Stockyard Plain Basin. These would have initially been perched aquifers but in some locations the saturated zone may now extend through to the Glenforslan Formation. They may also occur in localised depressions, or where the Cadell/Bryant Creek aquitard is particularly thick and/or of low vertical hydraulic conductivity, but these perched aquifers have not been mapped. Where perched aquifers occur, root zone drainage spreads laterally over the Cadell/Bryant Creek aquitard until the drainage volume can percolate through the aquitard and recharge the Glenforslan Formation aquifer.

The root zone drainage takes time to percolate through the unsaturated zone to reach the watertable. Initially, the lag time (initial lag time) under a new irrigation area is several years or more, as the unsaturated sediments become wetter and perched aquifers form (Fuller *et al*. 2005; AWE 2011c). Once an irrigation area is established, the unsaturated sediments below are wetter and the lag time (late lag time) is reduced or even becomes negligible. This is due in part to the relationship between hydraulic conductivity and saturation. The lag-time mechanism has been demonstrated in saturated/unsaturated models of Murtho (Nakai *et al*. 2010) and Loxton-Bookpurnong (Lisdon Associates 2010).

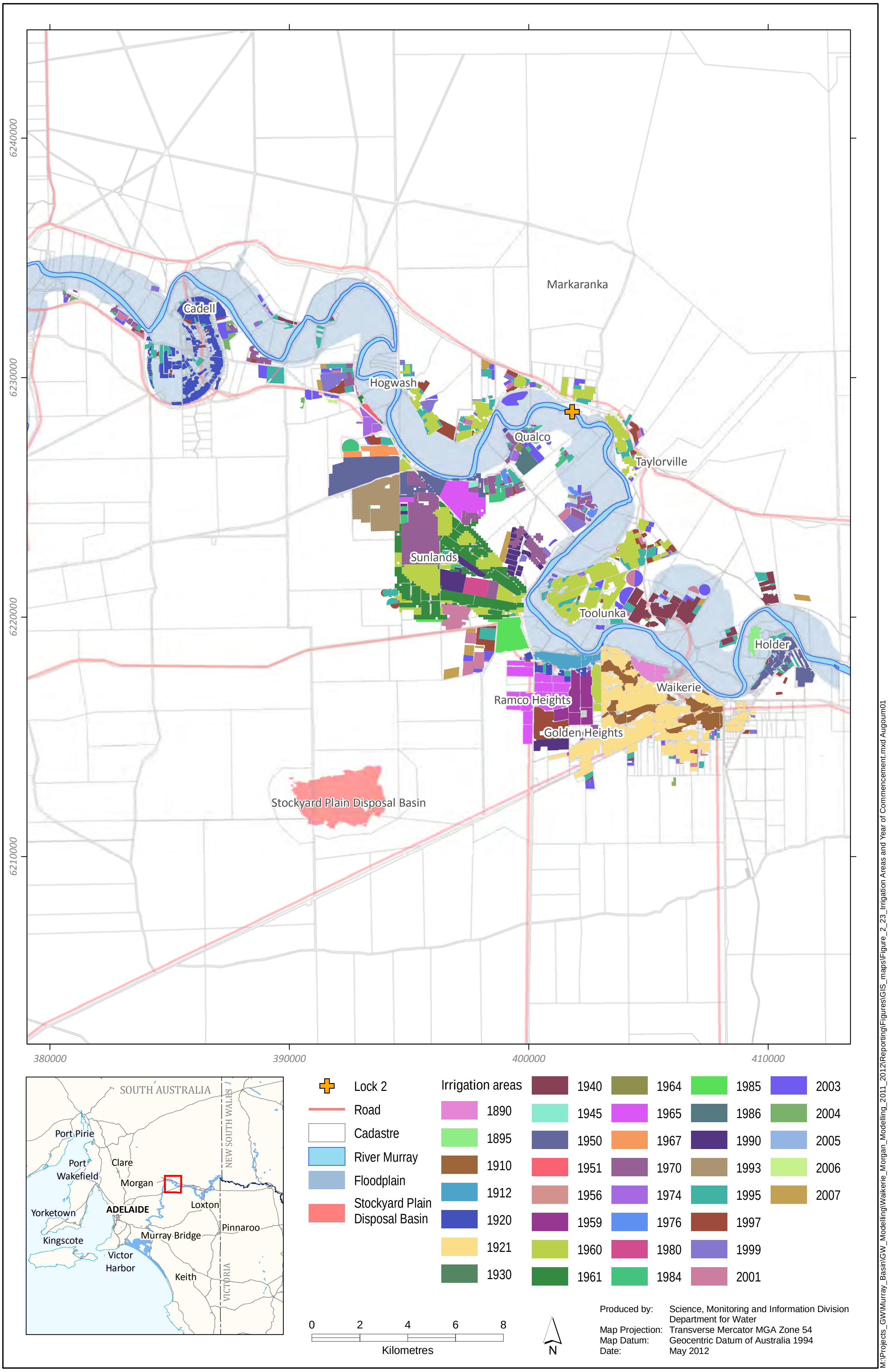


Figure 2.23 Irrigation Areas and Year of Commencement

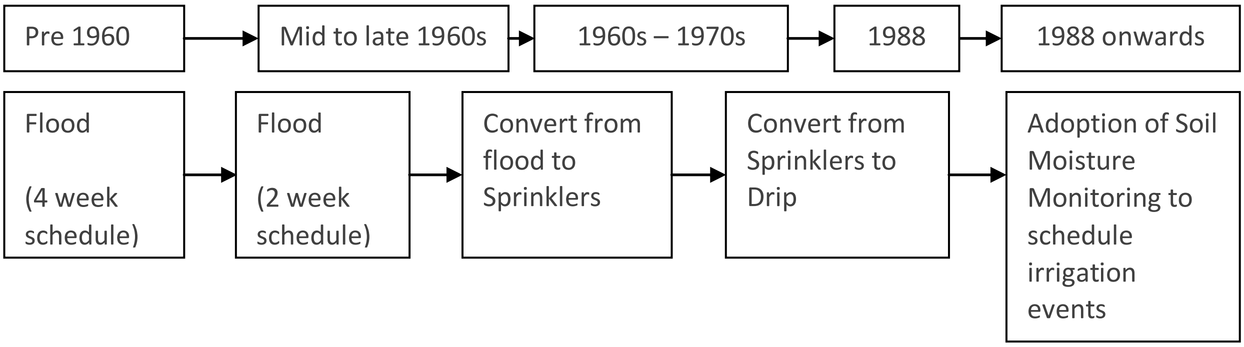


Figure 2.24 Irrigation history (Vears 2010)

2.4.3.3. Drains and drainage bores

The construction and use of drains and drainage bores in the study area has been summarised by AWE (2011a) and Fordham *et al*. (2012, included as Appendix C-1). The discussion below is based on these two main sources.

Tile drains and drainage bores are constructed to divert root zone drainage to deeper formations or to different locations, usually to prevent waterlogging of the root zone. Waterlogging has been a major problem within the study area and most irrigation areas constructed tile drains and/or drainage bores soon after irrigation commenced (Fordham *et al*. 2012, Appendix C-1).

Tile drains operate to capture irrigation water that infiltrates past the root zone and transport it away from the area to evaporation basins such as Stockyard Plain Disposal Basin. These tile drains reduce the volume of root zone drainage that recharges the water table. A comprehensive drainage system was constructed at Cadell in 1922 and was refurbished in 1976 (Fordham *et al*. 2012). The generation of a groundwater mound in the Loxton Sands at Qualco has meant that some low lying areas require dewatering from caissons installed in the Loxton Sands to prevent water logging (AWE 2011a). The root zone drainage captured is diverted to a lucerne reuse area on the southwest margin of Qualco-Sunlands irrigation area (Watkins, Teoh & Way, 1995). Tile drains are also present in the Taylorville and Markaranka areas (Fordham *et al*. 2012).

Drainage bores are designed to dispose of excess root zone drainage to deeper units via discharge down a well. Drainage bores often result in increased local recharge with negligible lag time and will contribute directly to the development of groundwater mounds in the formation they are completed within.

Drainage bores in the Qualco-Sunlands and Waikerie and Golden Heights areas were drilled into the Murray Group Limestone. Historically there were a total of 377 drainage bores operating in the Qualco-Sunlands and Waikerie and Golden Heights irrigation areas (AWE 2011a). Approximately 59 of these bores were completed in the Lower Mannum Formation aquifer (AWE 2011a).

Drainage bores completed in the Glenforslan Formation in the Qualco-Sunlands area commonly did not work as well as those in the Waikerie area (Telfer & Watkins 1991), which is further evidence of the higher transmissivity of the Glenforslan Formation aquifer in the Waikerie region. The locations of drainage bores in the Qualco region are documented in Watkins, Teoh & Way (1995) but drainage bore fluxes are not known.

2.4.4. GROUNDWATER EVAPOTRANSPIRATION

Groundwater evapotranspiration (ET) combines two processes: evaporation of water from groundwater lying close to the ground surface and transpiration from plants that use groundwater. Groundwater ET varies with rainfall, humidity, temperature, soil type, vegetation type and groundwater salinity (as plants preferentially use low-salinity sources of water). In the study area, groundwater ET occurs only on the floodplain or adjacent to the Stockyard Plain Basin, as elsewhere the groundwater is too far below the ground surface.

The Climatic Atlas of Australia (Bureau of Meteorology 2001) distinguishes between areal actual ET, areal potential ET and point potential ET. For the Waikerie to Morgan region annual average areal potential ET is between 1000 and 1100 mm/y.

There are no known field estimates of actual groundwater ET within the study area. Doody *et al*. (2009) conducted a study at a Bookpurnong floodplain. 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 confidence interval is large when compared to the values.

An unpublished study measured an actual groundwater ET of 196 mm/y for the fringing river woodland of River Red Gum, Black Box and River Cooba. In the Loxton–Bookpurnong floodplain areas, the woodland generally covers 30–40% of the total floodplain, suggesting an overall floodplain average groundwater ET of ~60 to 80 mm/y (K Holland, CSIRO, pers. comm., 2011).

2.4.5. CLIFF SEEPAGE

Cliff seepage has been observed in part of the Waikerie Lock 2 reach, between river km 351 and 356 (AWE 2011a), where it can be seen on the side of the river. It is caused by irrigation.

One source is perched aquifers, such as the Loxton Sands located in the top half of the cliff. This seepage makes little contribution to the salt load to the River Murray due to evaporation and relative freshness of the water which is from irrigation drainage.

A second seepage is from the Glenforslan Formation, which is located at the foot of the cliff or along side the River Murray. This is where the river is immediately adjacent to the highland, with little to no floodplain and the exposed saturated sediments are therefore in direct connection with the river. This seepage contributes salt load to the River Murray due to the high salinity of the groundwater in the Glenforslan Formation.

2.4.6. SALT INTERCEPTION SCHEMES

Salt interception schemes (SIS) are designed to control groundwater salt accessions to the River Murray. There are three SIS that operate from Waikerie to Hogwash that locally influence the hydraulic head of the aquifers: the Waikerie, Waikerie IIA and Waikerie Lock 2 schemes. The Qualco-Sunlands Trust Groundwater Control Scheme (QSTGCS) was developed to lower a groundwater mound under the Qualco-Sunlands irrigation area to reduce water logging problems. It was not built as an SIS, but in part the scheme lowers groundwater gradients towards to the river and hence also reduces groundwater flux to the river. The location of the scheme's bores are shown in Figure 2.25.

The first SIS scheme to be commissioned in the region was the Waikerie SIS in 1993. It has 20 pumping wells. The Waikerie IIA SIS consists of nine pumping wells and commenced pumping in 2003. The Waikerie Lock 2 SIS began pumping in 2009 and contains seven pumping wells. The QSTGCS, the groundwater control scheme in the study area, comprises 15 pumping wells and commenced in 2001.

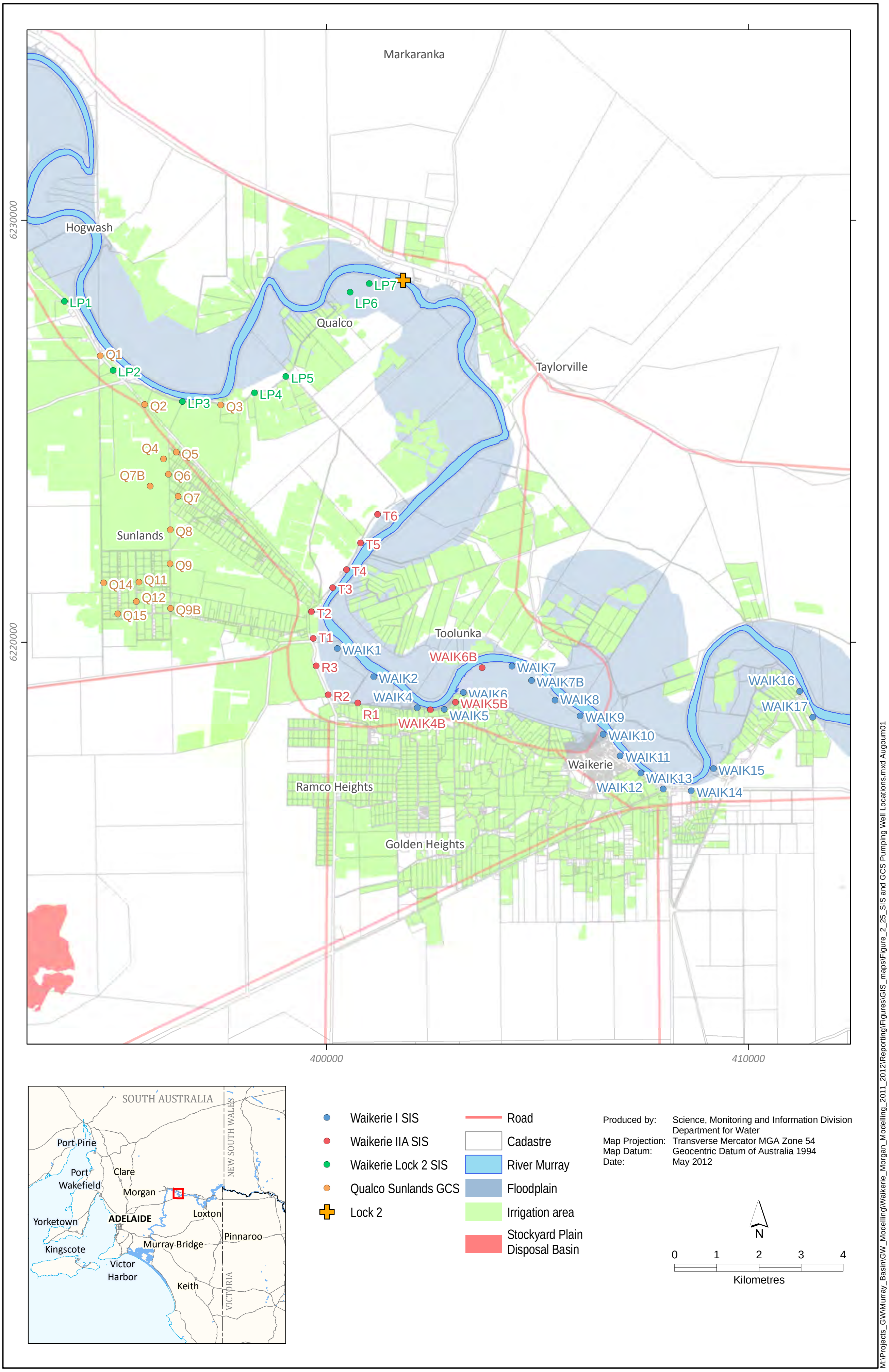


Figure 2.25 SIS and GCS Pumping Well Locations

The aim of most of the SIS production bores on the floodplain in the project area is to achieve a potentiometric head of around river pool level at the midpoint observation bores. Groundwater is mainly pumped from the Lower Mannum Formation aquifer but is also pumped from the Glenforslan and Upper Mannum Formations at some bores.

2.4.7. DISPOSAL BASIN

Groundwater intercepted by the SIS is transported into Stockyard Plain Disposal Basin (SPDB), which is located approximately south of the Qualco groundwater mound and approximately southwest of the Waikerie groundwater mound. There are multiple basins within Stockyard Plain Disposal Basin which may have different pond levels (AWE 2011a). The primary basin has a relatively stable pond level of 30 m AHD while the secondary basins exhibit more variation over time (AWE 2011a). Changes in water level over time are attributed to changes in disposal volume and evapotranspiration (AWE 2009b).

Figure 2.26 displays water level over time in the Glenforslan Formation observation bore SP 12. Due to its proximity to the basin and frequency of measurements, it is presumed to be an adequate representation of the groundwater level in the Glenforslan Formation aquifer beneath SPDB (AWE 2011a). The SPDB commenced in 1990 as the Woolpunda SIS commenced pumping in 1990. Figure 2.26 shows a rapid increase in groundwater level from 1992 to 1996 due to leakage from the SPDB basin.

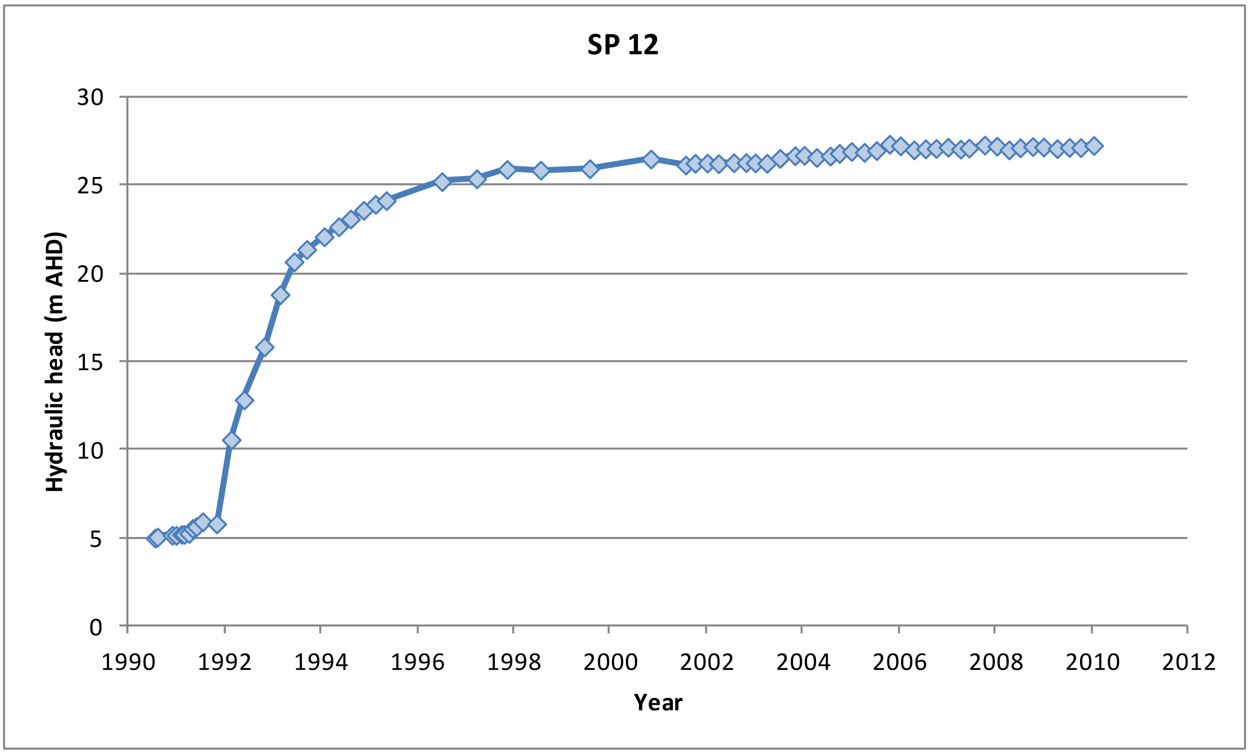


Figure 2.26 Hydrograph for Observation Bore SP 12 in the Glenforslan Formation Aquifer at the Stockyard Plain Disposal Basin

2.5. CONCEPTUAL MODEL

2.5.1. OVERVIEW

The principle hydrostratigraphic sequence in the Waikerie to Qualco region consists of the following, increasing with depth:

- Quaternary sands of the Woorinen Formation
- Blanchetown Clay
- Upper Loxton Sands
- Bryant Creek and Cadell Formations
- Glenforslan Formation
- Finniss and Upper Mannum Formations
- Lower Mannum Formation
- Ettrick Formation
- Renmark Group
- Basement rock.

In the region west of Qualco, there is insufficient interpreted stratigraphic data to distinguish the sub-units within the saturated Murray Group. The River Murray has carved a valley through the landscape, into which the Coonambidgal and Monoman Formations have been deposited. The Monoman Formation is laterally juxtaposed with the Glenforslan Formation upstream of Cadell and the Finniss and Upper Mannum Formations and/or undifferentiated Murray Group at Cadell and downstream of Cadell.

The regional aquifers in the study area are within the Glenforslan Formation, Lower Mannum Formation and Renmark Group. The regional aquitards are the Finniss and Upper Mannum Formations and Ettrick Formation. The regional groundwater lateral flow is from east to west, ultimately driven by distant recharge sources. The regional groundwater is highly saline.

In addition to the regional aquifers, there is a further aquifer in the Murray Trench, within the Monoman Sands Formation. 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, which may lower heads to below river level in some areas. The river and other surface water bodies (such as Hart Lagoon, Schiller's Lagoon and Markaranka Lagoon) interact with the groundwater system.

Under natural conditions, prior to land clearance and irrigation, the watertable lay in the Glenforslan and Monoman Formations upstream of Cadell and in the Mannum and Monoman Formations downstream of Cadell. Heads in the watertable aquifers reflected long-term river levels. There may have been some upwards vertical flux driven by greater heads in the deeper aquifers. Rainfall recharge was low due to low rainfall, the dry climate and the presence of water-efficient mallee vegetation. Groundwater flux to the River Murray was minimal due to the low gradient between the groundwater head and river level.

Land clearance and irrigation substantially increased recharge to groundwater. Recharge rates under cleared dryland are one or two orders of magnitude greater than uncleared mallee and recharge under irrigation areas is much greater. Recharge rates have changed over time due to unsaturated zone processes (e.g. ‘wetting up’ of sediments, lateral movement within perched aquifers), changes in irrigation area, construction and later decommissioning of drainage bores, improvements in irrigation practice and rehabilitation of irrigation infrastructure.

The increased recharge rates have significantly altered the hydrogeology of the region. In the main irrigation areas of Waikerie and Qualco-Sunlands, substantial groundwater mounds have formed in the Glenforslan and Lower Mannum aquifers and perched (or partially perched) aquifers have developed in the Loxton Sands and Woorinen Formations. Smaller groundwater mounds have formed in other irrigation areas. In irrigated highland areas, the vertical flux became downwards, but in the floodplain the vertical flux was upwards as groundwater moved from the Lower Mannum Formation into the Monoman Formation. The steeper gradient between the watertable and the river valley drove additional groundwater flux into the valley and the River Murray, increasing groundwater salt loads to the river. Cliff seepage occurred where the Glenforslan Formation abuts the River Murray valley. The higher heads also caused waterlogging in the Qualco and Waikerie areas.

To mitigate the salt load impacts of the additional recharge, a series of Salt Interception Schemes have been built in the last decade between Waikerie and Hogwash. The Qualco-Sunlands Groundwater Control Scheme was built to reduce waterlogging. The SIS and QSTGCS divert saline groundwater to the Stockyard Plain Disposal Basin, which is located approximately south of the Qualco irrigation area. The SIS and GCS have sharply reduced the potentiometric head in the pumped aquifers. There are no other groundwater extractions in the area, as the groundwater is too saline for crop, stock or human 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 change some gaining reaches of river to become losing reaches, inducing freshwater flow into floodplain groundwater. Groundwater salinity may also decrease in aquifers where significant volumes of irrigation-derived recharge have begun to mix with groundwater. Where the watertable lies close to the ground surface, groundwater salinity may increase due to groundwater ET.

2.5.2. SITE SPECIFIC

The conceptual hydrogeological model is illustrated in Figures 2.27 to 2.29 for the Waikerie, Qualco and Cadell areas. The figures detail the conceptual model of groundwater flow between the aquifers, the broader regional groundwater flow system, inter-aquifer flow and local recharge mechanisms.

Figure 2.27 is a schematic diagram of Waikerie and Toolunka. The regional watertable originally lay within the Glenforslan Formation and Monoman Sands. The gradient between the Glenforslan potentiometric heads at the edge of the floodplain and the river level was relatively low, leading to little groundwater flux and salt load entering the River Murray. Irrigation increased recharge by several orders of magnitude, leading to the development of a perched aquifer within the Loxton Sands and groundwater mounds in the Glenforslan aquifer. Recharge to the Glenforslan was also facilitated by drainage bores. Cliff seepage now occurs where saturated sediments abut the floodplain. The gradient between the Glenforslan aquifer potentiometric heads and the river level is now steeper, leading to increased groundwater flux and salt load to the River Murray. The smaller irrigation area of Toolunka has experienced a similar history. The Waikerie I and Waikerie II SIS have since been constructed to reduce groundwater salt load to the River Murray.

The main processes seen at Waikerie can also be observed at Qualco-Sunlands, Taylorville and Markaranka (Figure 2.28). The topography of Qualco also leads to waterlogging of low-lying locations within and adjacent to the irrigation areas. The Qualco-Sunlands Groundwater Control Scheme was constructed to reduce waterlogging and the Waikerie Lock 2 SIS was constructed to reduce groundwater salt load.

Figure 2.29 is a schematic diagram of Cadell. Irrigation began in 1920 and a comprehensive drainage system was constructed in 1922 (Fordham *et al*. 2012). At Cadell the irrigation occurs on the floodplain and the Monoman Sands aquifer is recharged directly. Drainage schemes help to control the potentiometric head, so groundwater salt load to the River Murray has been low compared with Waikerie and Qualco.

2.5.3. PATHWAYS FOR SALT TO THE RIVER MURRAY

The purpose of the numerical model is to estimate salt loads to the River Murray for Salinity Register entry.

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 areas where the head in the floodplain was below river level due to groundwater ET, there would have been a small flux from the River Murray into the Monoman Formation.

Locks and weirs were constructed on the River Murray in the 1920s and 1930s to regulate the flow. These would have changed the river level and hence local groundwater gradients and fluxes to and from the river.

Large-scale irrigation began in the Waikerie to Morgan area by the 1920s and increased significantly from the 1960s, altering the local interaction between groundwater and the River Murray as groundwater mounds developed in the underlying aquifers.

Saline groundwater now enters the River Murray by the following mechanisms in the Waikerie to Morgan area:

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

Section 3 describes the numerical groundwater model which is a simplified representation of this conceptual model, as constrained by data availability and computational efficiency.

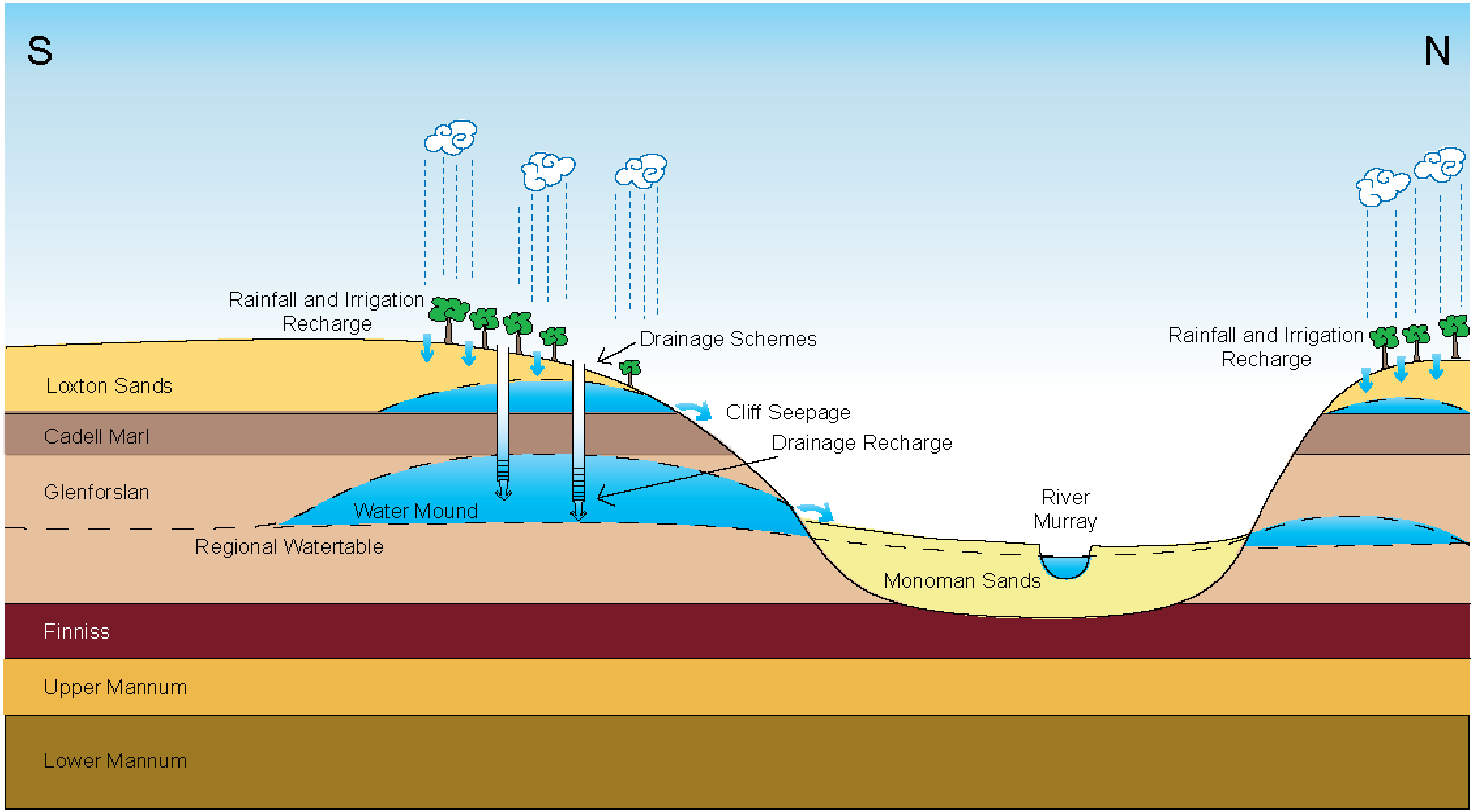


Figure 2.27 **Conceptual Diagram for Waikerie and Toolunka**

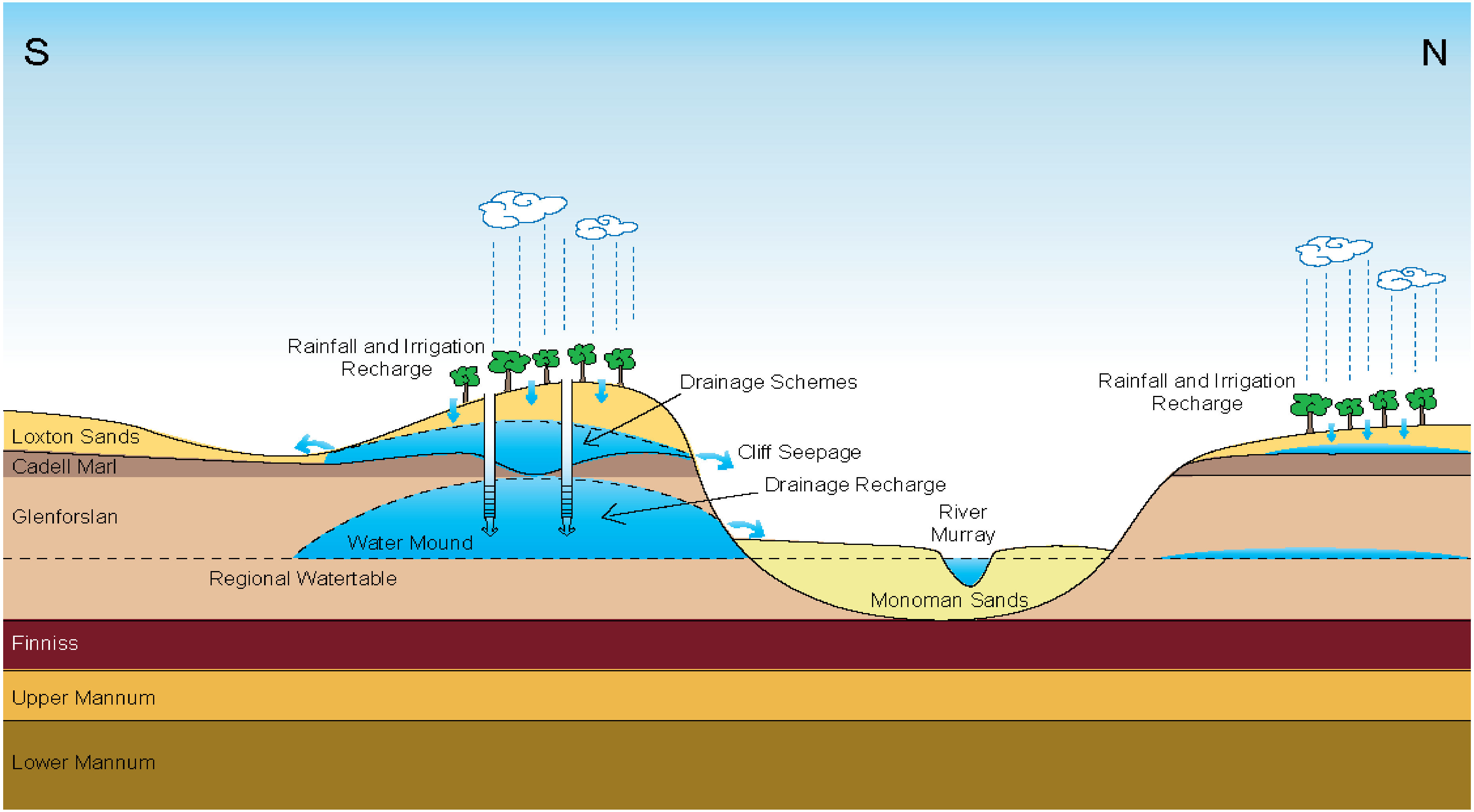


Figure 2.28 **Conceptual Diagram for Qualco Sunlands, Taylorville and Markaranka**

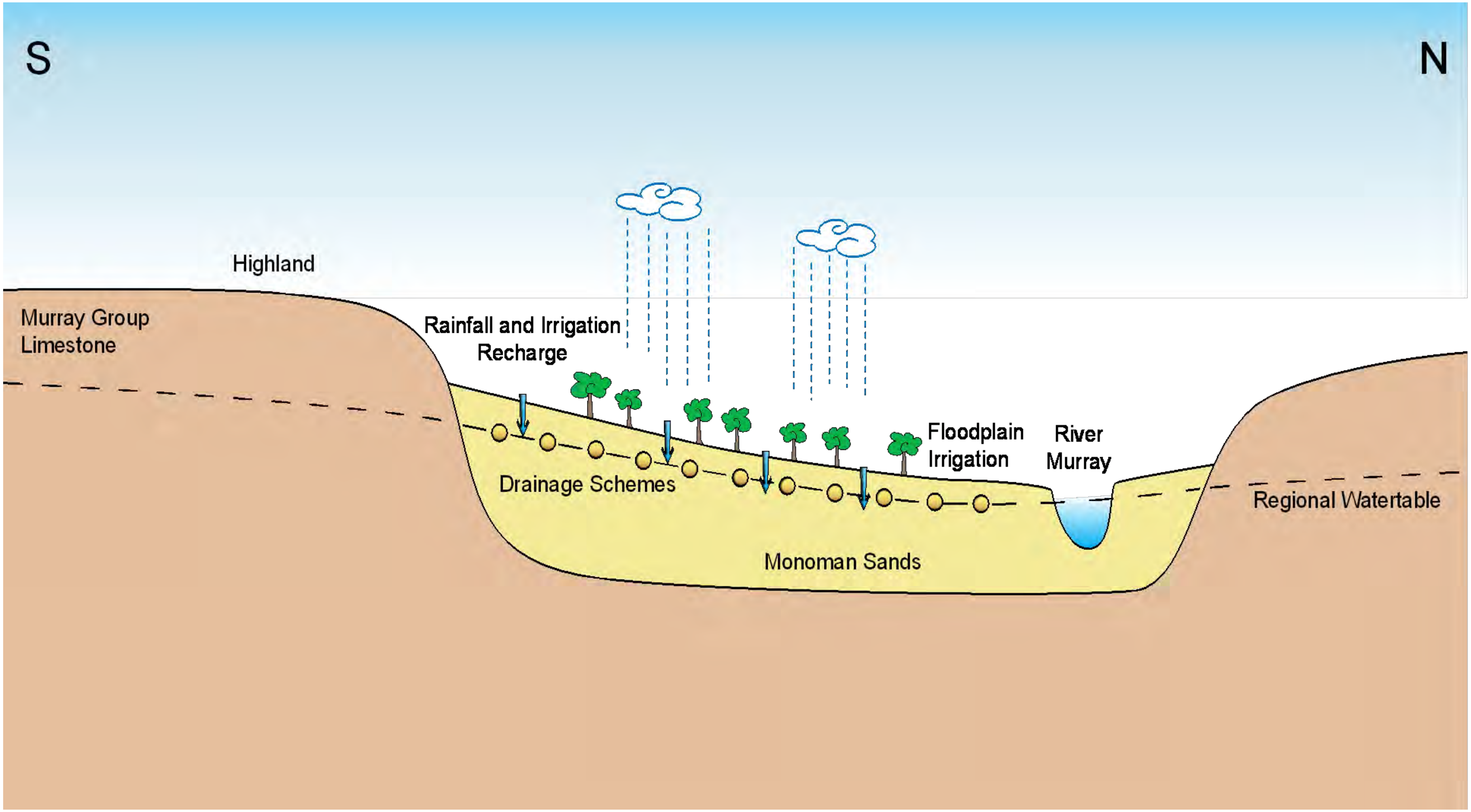


Figure 2.29 **Conceptual Diagram for Cadell**

3. MODEL CONSTRUCTION

The purpose of this model is to provide a predictive management tool for determining salt loads entering the River Murray from the Waikerie to Morgan area for the Salinity Registers (see Section 1.1 for the policy background). The model provides quantitative estimates of salt loads entering the River Murray under a range of past and future land and water use conditions.

The future impact of accountable actions, such as irrigation and SIS, need to be distinguished. The estimation of future impacts due to climate sequence, such as changes in river level due to flood events, are not required for the Salinity Register.

3.1. MODFLOW AND VISUAL MODFLOW

MODFLOW-2000 was selected as the numerical code for the Waikerie to Morgan model. It was chosen for reasons of reliability and consistency, as it is the industry standard groundwater flow code and the other South Australian models for the Salinity Register are also MODFLOW-2000 models. It is a three-dimensional finite difference code that was developed by the US Geological Survey (McDonald & Harbaugh 1988).

The choice of code constrains the types of flow processes that can be simulated. The standard version of MODFLOW-2000 simulates flow exclusively within the saturated zone and cannot simulate saturated/unsaturated zone processes, such as the development of perched aquifers. Hence the model omits the direct simulation of perched aquifers in the Loxton Sands and Woorinen Sands.

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

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

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

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

3.2. MODEL DOMAIN AND GRID

The model domain simulates an area 41 km east–west by 53 km north–south. The bounding GDA 1994 coordinates of the model domain are E372000 N6197000 in the south-west and E413000 N6250000 in the north-east (Figures 3.1 and 3.2). The grid is orientated north–south. The model domain is larger than

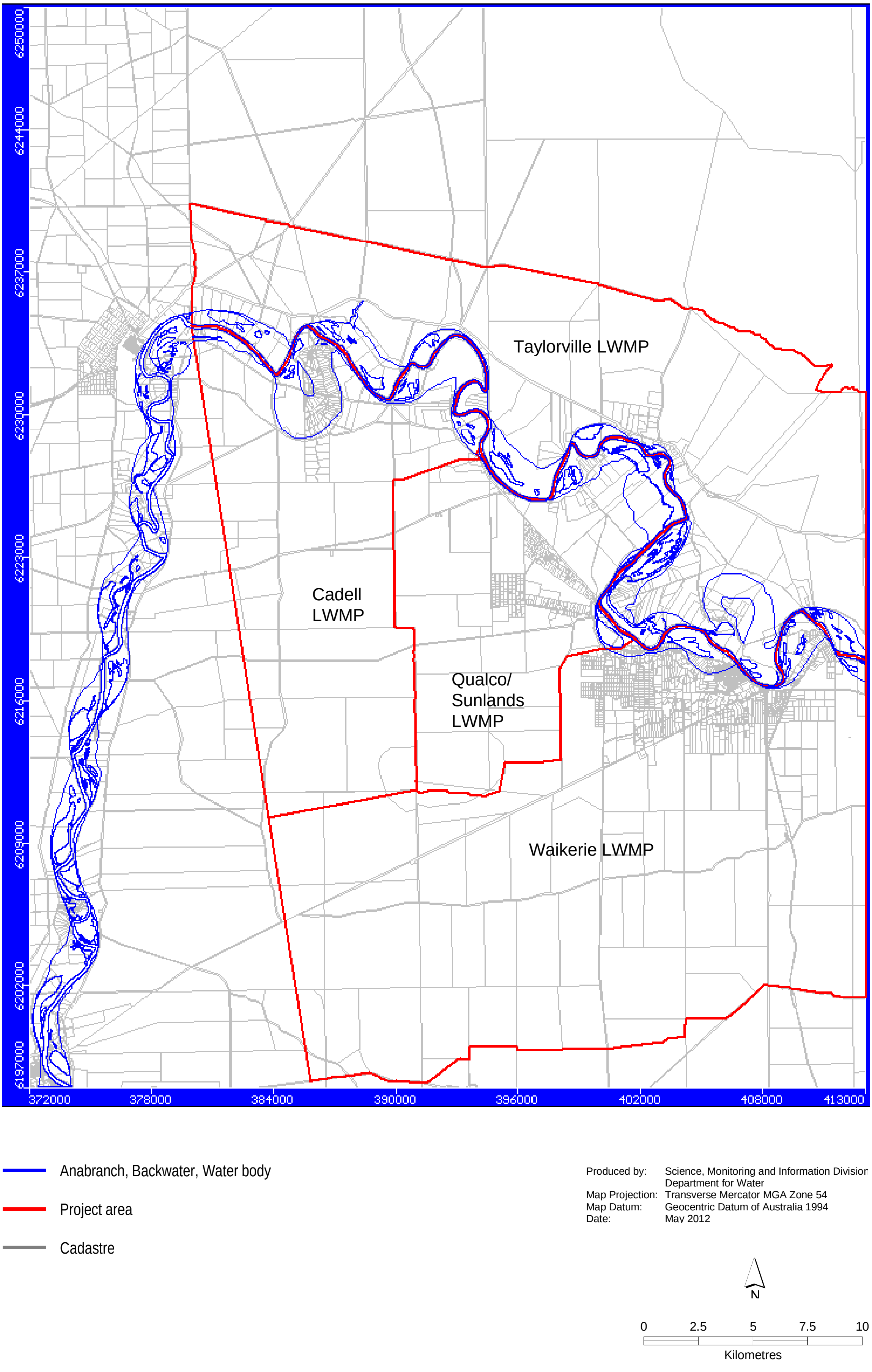


Figure 3.1 Regional Model Domain and Project area

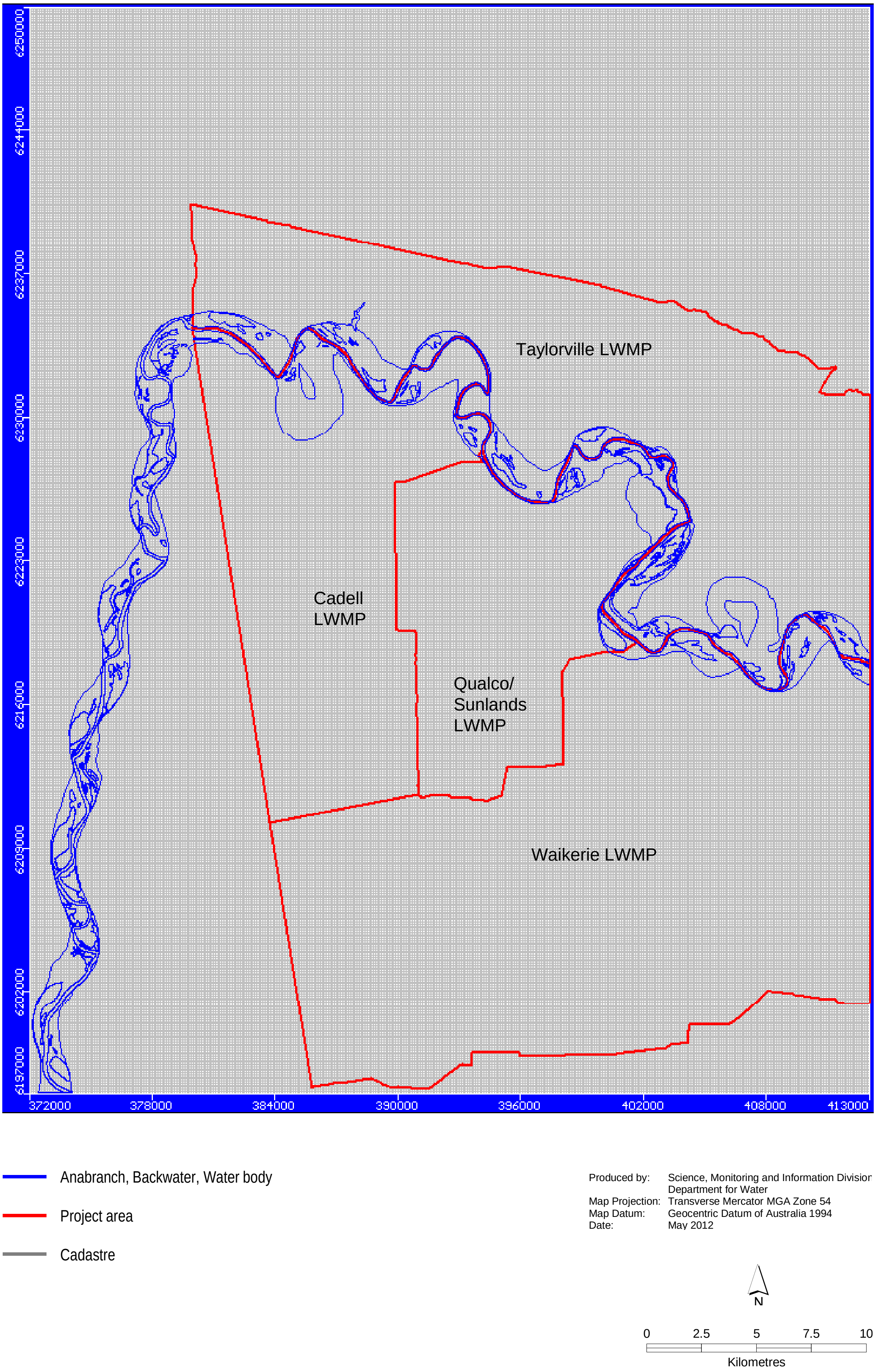


Figure 3.2 Model Grid

the study area, which 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. The northern, southern and western model domain boundaries are set at a sufficient distance such that they should not be influenced by the behaviour of the aquifer system in the study. The eastern boundary is set at a location between Waikerie and Woolpunda where the dominating hydrogeological conditions and drivers change: at Waikerie the watertable lies within or above the Glenforslan aquifer and head gradients are dominated by groundwater mounds induced by downwards drainage from irrigation, while to the east at Woolpunda, the watertable lies within the Upper Mannum Formation (AWE 2007b) and head gradients are driven by a groundwater mound caused by upward leakage from the Renmark Group. It is reasonable to adopt a model boundary close to the area of interest only if stresses from outside the domain are unlikely to affect potentiometric head within the model domain. The Woolpunda reach has little irrigation and its potentiometric head has changed over time mainly in response to the construction of the Woolpunda SIS. A simulation conducted with the 2005/7 accredited model (Rural Solutions 2005; Aquaterra 2007) showed that the Woolpunda SIS had negligible impact on salt loads at Waikerie. The hydrograph of the Waikerie reach LMF bore lying closest to the model boundary (HOLL 11, Section 4.3.2) shows no obvious response to the commencement of the Woolpunda SIS in 1990, but clearly responds to the commencement of the Waikerie SIS in 1992. Based on this evidence, the position of the eastern boundary is considered reasonable.

The River Murray is represented west of Woolpunda to Lock 1 (river km 393 to 274). The model domain includes Stockyard Plain Disposal Basin in the south.

The rectangular model grid is divided into 410 columns, 530 rows and three layers, resulting in 651 900 finite difference cells. All of the cells have a uniform size of 100 × 100 m. The objective of using a 100 x 100 m grid is to provide a sufficient resolution for evaluating fluxes to the River Murray while minimizing computational times. A cross-section of the model grid is shown in Figure 3.3.

3.3. MODEL 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 (with one exception discussed further in Section 3.6.1).

Two transient models are used to simulate the historical period and future predictions:

- Calibrated model — The historical transient model simulates 1920 to 2011. A total of 111 stress periods are included in the model (see Appendix B)
- Prediction model — The calibrated transient model is used to develop the scenario modelling for predictions. All prediction models included historical and prediction run from 1920 to 2111. A total of 153 stress periods are included in the model (see Appendix B).

In general, the calibrated model has annual stress periods, except for the period between 1993 and 2010, in which the calibrated model has finer half-a-year stress periods to simulate SIS pumping more accurately.

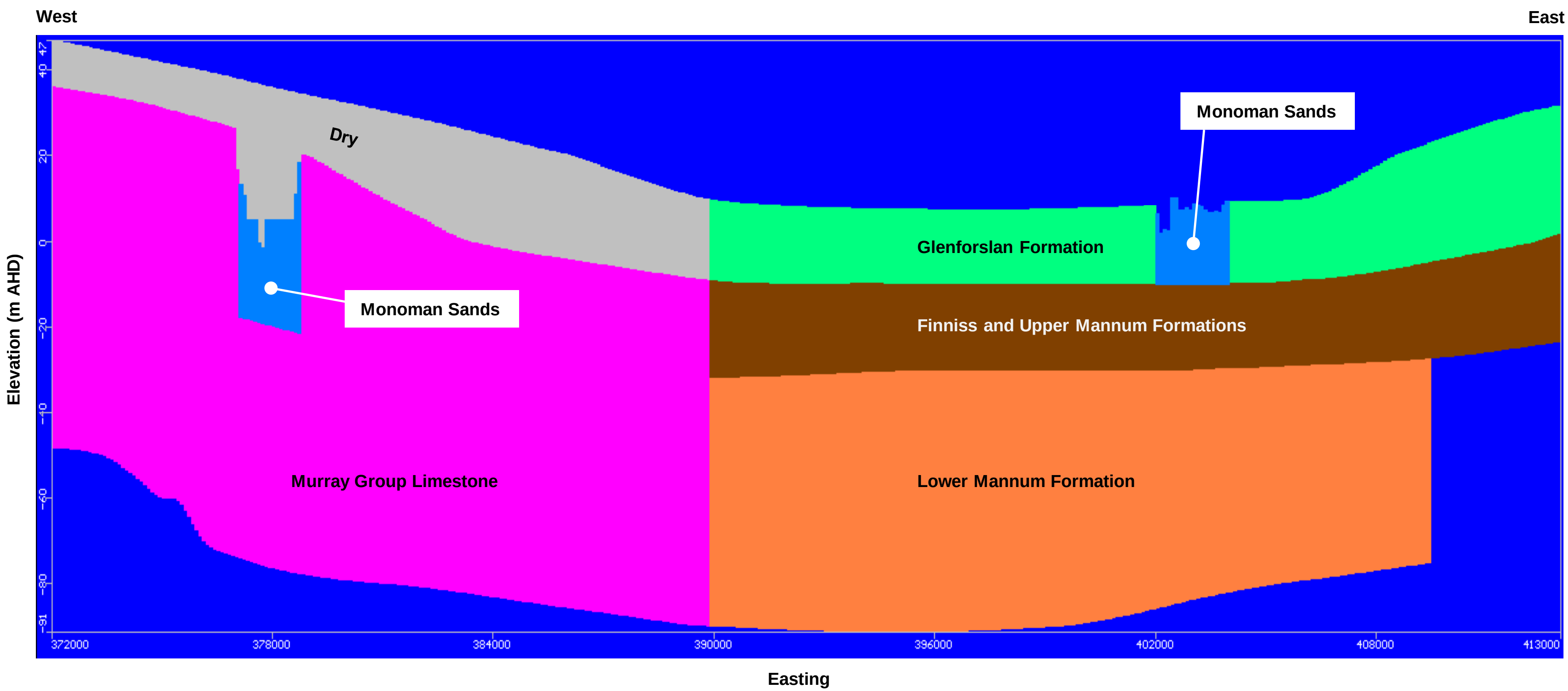


Figure 3.3 Model Layers (Cross-Section through Model Row 266, N6223450)

To reduce computation effort, the stress periods of the prediction models are up to 10 years in length at the beginning of the simulation, based on the frequency of available irrigation information. From 1988 onwards, the stress periods are one year or less in length, as annual salt loads from 1988 to 2111 are required by the MDBA for the Salinity Register but simulation of seasonal changes is not desired. Between 1993 and 2010, the model has finer half-a-year stress periods to simulate SIS pumping more accurately.

All transient models have a time step multiplier of 1.2 and 10 time steps per stress period. The stress period length and the actual date that each stress period represents are shown in Appendix B, which report detailed flux and salt load to the river.

3.4. MODEL LAYERS IN THE WAIKERIE TO MORGAN AREA

The Waikerie-Morgan numerical model simulates groundwater flow within the hydrogeological units which interact directly with the river and/or are separated from the River Murray by a single aquitard or aquifer. These are the Monoman Formation aquifer, Glenforslan Formation aquifer, Finniss Formation and Upper Mannum Formation aquitard and the Lower Mannum Formation aquifer. In regions where the Murray Group sub-units are not easily distinguishable (or where the sub-units may not exist), the model simulates an undifferentiated Murray Group aquifer.

The Waikerie to Morgan model represents key hydrogeological units within three layers, including two aquifer layers and one aquitard (Figure 3.3, Table 3.1). The layering chosen reflects the regional hydrogeology to the best of current knowledge based on interpreted data. The model grid, applied to three layers, results in a total of 651 900 finite difference cells. In the majority of the model domain, layer 1 represents the Glenforslan Formation aquifer, layer 2 represents the combined aquitard of the Finniss Formation (where it is present) plus the Upper Mannum Formation and layer 3 represents the Lower Mannum Formation aquifer. In the western portion of the model domain, there is very little information on the Murray Group sub-units, so the numerical model simulates this area as undifferentiated Murray Group. This is consistent with prior hydrogeological studies and the Morgan to Wellington numerical model (Yan *et al*. 2009). MODFLOW layer options are given in Table 3.2.

The river valley has eroded through the Murray Group sediments. The alluvial sediments of the Monoman Formation, within the river valley, are laterally connected to the Glenforslan Formation aquifer except downstream of Hogwash, where borelog interpretations coupled with water level data suggests that the Monoman Formation aquifer is laterally connected to the Finniss and Upper Mannum Formations and/or the undifferentiated Murray Group. The Glenforslan Formation aquifer is unsaturated in this region. As a result, the Monoman Formation is simulated in model layer 1 upstream of Hogwash and in model layer 2 downstream of Hogwash.

There are some small areas within the Woorinen and Loxton Sands which are saturated due to irrigation-derived recharge. These areas would have begun as perched aquifers and may still be perched or partially perched. These areas are not directly simulated in the model as this would require significantly more computational effort but yield little improvement in model accuracy. The simulation of perched aquifers requires the numerical solution of the highly nonlinear equations governing unsaturated/saturated zone flow. Accurate simulation typically requires much finer grids than saturated zone flow models, so unsaturated/saturated flow is computationally intensive and slow to simulate. Such models are also more likely to be numerically unstable, so no accurate solution may be found. They further require input parameters such as saturation factors for which there are no local field data. Some unsaturated/saturated flow models have been developed for Riverland regions (e.g. Woodward-Clyde 2000, AWE 2011d, Lisdon Associates 2011) but these simulate vertical cross-sections representing simplified cases for illustrative purposes rather than detailed regional-scale flow. From a practical standpoint, the saturated areas within the Woorinen and Loxton Sands contribute to river salt load mainly via downward leakage/recharge to the regional aquifers that flow into the River Murray, as demonstrated by the development of groundwater mounds in the Murray Group aquifers. Hence these saturated areas are represented within the model as recharge to the Monoman Formation, Glenforslan Formation and the undifferentiated Murray Group. The recharge footprint is modelled as wider than the irrigation footprint to represent the lateral flow within the Woorinen and Loxton Sands Formations. One limitation of this representation is that cliff seepage from the Woorinen and Loxton Sands Formations is not simulated, but the volume of salt reaching the River Murray from cliff seepage is very likely to be negligible when compared to other sources.

The Coonambidgal Formation is not simulated as drilling investigations at various sites within the study area have confirmed that its presence is intermittent but its extent has not been fully mapped. This means that the Monoman aquifer is modelled as unconfined, whereas it is actually semi-confined.

The Renmark Group aquifer is not simulated, due to a lack of data and its separation from the River Murray. The sole reliable Renmark Group bore in the study area shows negligible change in potentiometric head over the past two decades, despite significant changes within the Murray Group above, suggesting slow or minimal leakage between the aquifers. Also, the Renmark Group is separated from the River Murray by the Ettrick Formation aquitard, Lower Mannum Formation aquifer, the Finniss Formation/Upper Mannum Formation aquitard, the Glenforslan Formation aquifer and the Monoman Formation aquifer, so any impact it may have is moderated by these units. As there is no evidence of significant upward leakage from the Renmark Group (such as the upwelling groundwater mound seen at Woolpunda), it is anticipated that its local impact on the River Murray is insignificant and that changes in the interaction between the Renmark Group and the upper aquifers occur over longer timescales than those simulated in the current study.

The top and bottom of each model layer are based on ground elevation data, borehole data and estimated structural contours. Most of the borehole data is concentrated in the Qualco and Waikerie areas, where the stratigraphy of the Murray Group has been subdivided into the Glenforslan, Finniss, Upper Mannum and Lower Mannum sub-units. Outside those areas, boreholes are fewer and the available stratigraphical interpretations are less detailed, identifying the Murray Group but not its sub-units. The accuracy of the structural contours at a location will depend strongly on the proximity of interpreted borehole data. The north and western portions of the model domain, including Cadell, are based on very limited data. A few locations with borehole data outside the model domain were used to constrain the structural contour interpolations.

Table 3.1 Model layer aquifers and aquitards

Layer number	Hydrogeological unit	Aquifer/ aquitard	MODFLOW layer
1	Glenforslan Formation regionally, Monoman Formation in the river valley	Aquifers	Type-3
2	Upper Mannum and Finniss Formations, Monoman Formation, undifferentiated Murray Group to the west	Aquitard/ Aquifer	Type-3
3	Lower Mannum Formation, undifferentiated Murray Group to the west	Aquifer	Type-0

Table 3.2 MODFLOW layer types

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

3.4.1. LAYER 1: GLENFORSLAN FORMATION AND MONOMAN FORMATION AQUIFERS

Layer 1 represents the Glenforslan Formation aquifer in the majority of the highland, the undifferentiated Murray Group in the west and the Monoman Formation aquifer in the floodplain. Layer 1 is modelled as MODFLOW layer type 3, which means that it can switch between confined and unconfined depending on the height of the water table in relation to the top of the aquifer, as the Glenforslan aquifer is confined in areas such as Waikerie and Qualco, unconfined in other areas and unsaturated in the north-east of the model domain.

The top of model layer 1 in the highland is the top of the Glenforslan Formation as interpolated from contour and spot height data. It was processed using GIS into a raster dataset of 100 m cell size and was imported into Visual MODFLOW.

The top of model layer 1 in the floodplain upstream of Hogwash (i.e. the top of the Monoman Formation) is derived from surface elevation data, which is LIDAR data provided by MDBA. The 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, particularly where the clay happens to be quite thick. This is unlikely to have considerable impact on flux predictions along the Waikerie to Morgan reach as the Coonambidgal is very patchy in this region.

The top of model layer 1 in the floodplain downstream of Hogwash is the interpolated top of the Glenforslan Formation. The top of layer 1 in this area is not relevant as these cells are "dry" (unsaturated) in the initial steady state period and remain inactive for the remainder of the simulation.

The top of Layer 1 elevation contours are shown in Figure 3.4. The elevation ranges from -12 to 54 m AHD.

3.4.2. LAYER 2: FINNISS AND UPPER MANNUM FORMATIONS AQUITARD, MONOMAN FORMATION AQUIFER

Layer 2 represents the Finniss and Upper Mannum Formation aquitards in the majority of the model domain, the undifferentiated Murray Group in the west and the Monoman Formation aquifer downstream of Hogwash. This assumes that the Finniss Formation and Upper Mannum Formation aquitard either does not extend to the west or ceases to act as an effective aquitard in that region. This is consistent with the very limited available interpreted data: this assumption may require review in future. Layer 2 is modelled as MODFLOW layer type 3, which means that it can switch between confined and unconfined depending on the height of the water table in relation to the top of the aquifer.

Downstream of Hogwash in the floodplain, the top of model layer 2 represents the top of the Monoman Formation aquifer, which is derived from surface elevation data sourced from LIDAR data and provided by the MDBA.

The top of the layer 2 occurs between -14 and 49 m AHD (see Figure 3.5) and is interpolated from contour and spot height data. Where field investigations have confirmed the absence of the Finniss Formation beneath the floodplain, spot heights and contours for the top of the UMF were used in the interpolation. Two raster datasets, one for the Monoman and one for the aquitard, were processed and merged before being imported into Visual MODFLOW. This methodology was adopted so that the thinning of the aquitard is adequately represented within the model.

3.4.3. LAYER 3: LOWER MANNUM FORMATION AQUIFER

Layer 3 represents the Lower Mannum Formation aquifer and is modelled as layer type 0, which is confined. The top of model layer 3 represents the top of the Lower Mannum Formation aquifer everywhere in the model domain. The top of the Lower Mannum Formation is interpolated from contour and spot height data, which was then processed into a raster dataset of 100 m cell size and imported into Visual MODFLOW. The top elevation occurs between -32 and 11 m AHD.

The base of model layer 3 represents the base of the Lower Mannum Formation aquifer in the majority of the model domain and the undifferentiated Murray Group in the west. These units have similar properties. Data is informed by the Morgan to Wellington model review (AWE 2008a) including the location of faults. The base of layer 3 is interpolated from contour and spot height data which was then processed into a raster dataset of 100 m cell size and imported into Visual MODFLOW. The bottom elevation occurs between -92 and -38 m AHD.

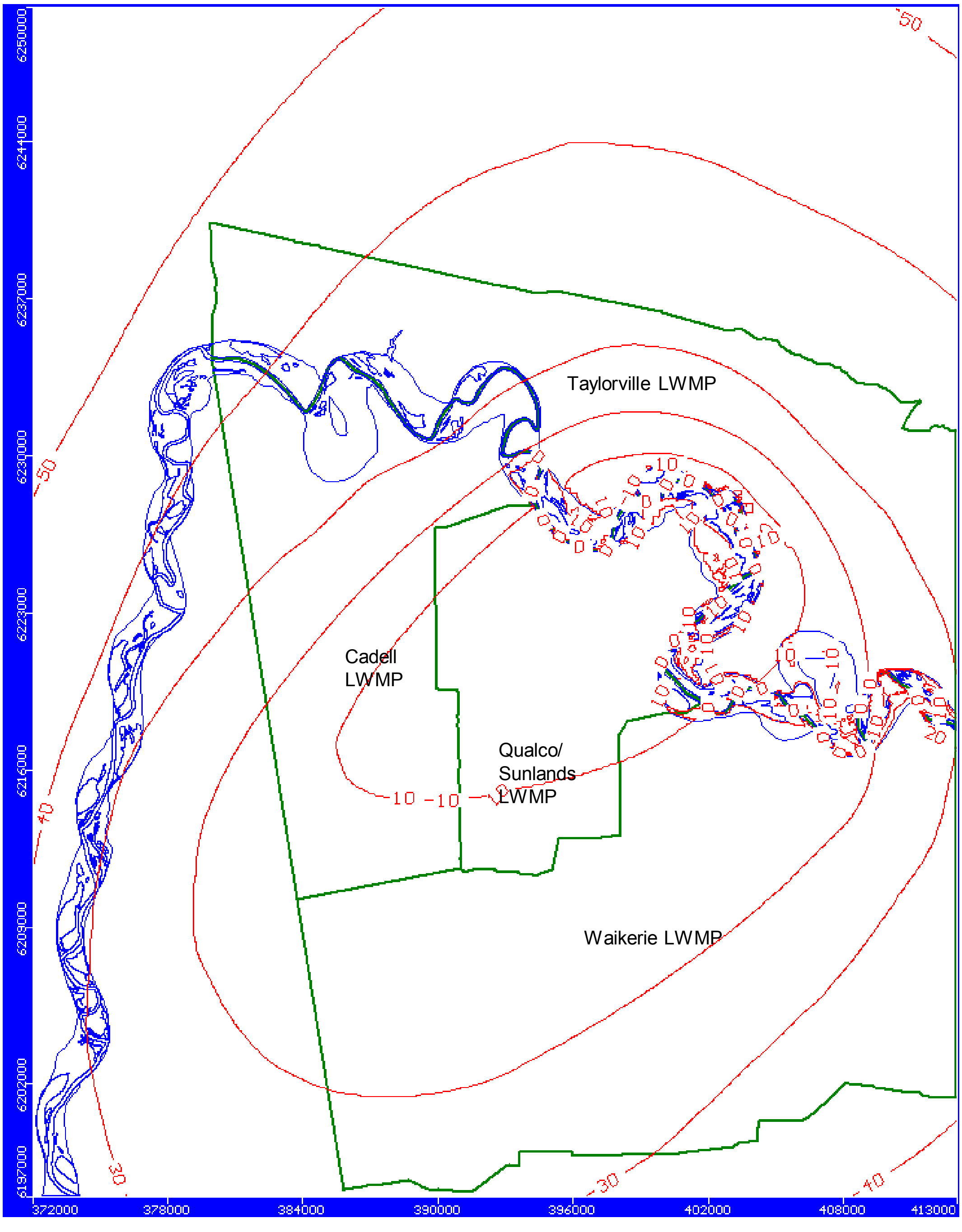
The top and base of layer 3 elevation contours are shown in Figures 3.6 and 3.7, respectively.

3.5. MODEL HYDRAULIC PARAMETERS

In order to constrain the model calibration, a physically realistic range of aquifer and aquitard hydraulic parameters were derived from previous reports and new data (Table 2.2). Hydraulic parameter zones and values from AWE (2011a) were adopted for initial runs of the model except in the west, where the Murray Group is represented as an undifferentiated aquifer rather than as separate aquifer and aquitard sub-units. The initial parameters were then varied during calibration (see Section 4 for further details).

The adopted aquifer and aquitard hydraulic parameters are given in Table 3.3, with their spatial distribution within each layer shown in Figures 3.8 to 3.13.

The horizontal hydraulic conductivities of the aquifers and the vertical hydraulic conductivities of the aquitards are based on the logarithmic mean of aquifer test observations and are generally within the observed ranges given in Table 2.2. The Monoman horizontal hydraulic conductivity is 10 m/d, close to the logarithmic mean of observations, 8.4 m/d. Aquifer test estimates of horizontal hydraulic conductivity of the Glenforslan aquifer are available for the Qualco region only, where the adopted model value of 0.2 is the same as the logarithmic mean of field estimates. A small 1 m/d zone is located at a site where aquifer tests estimate a hydraulic conductivity of 0.34 to 3.48 m/d. The 20 and 80 m/d



Anabranch, Backwater, Water body

Project area

Elevation contour (m AHD)

Produced by: Science, Monitoring and Information Division, Department for Water
Map Projection: Transverse Mercator MGA Zone 54
Map Datum: Geocentric Datum of Australia 1994
Date: May 2012

N

0 2.5 5 7.5 10
Kilometres

Figure 3.4 Elevation Contours for the Top of Glenforslan and Monoman Formations (Model Layer 1)

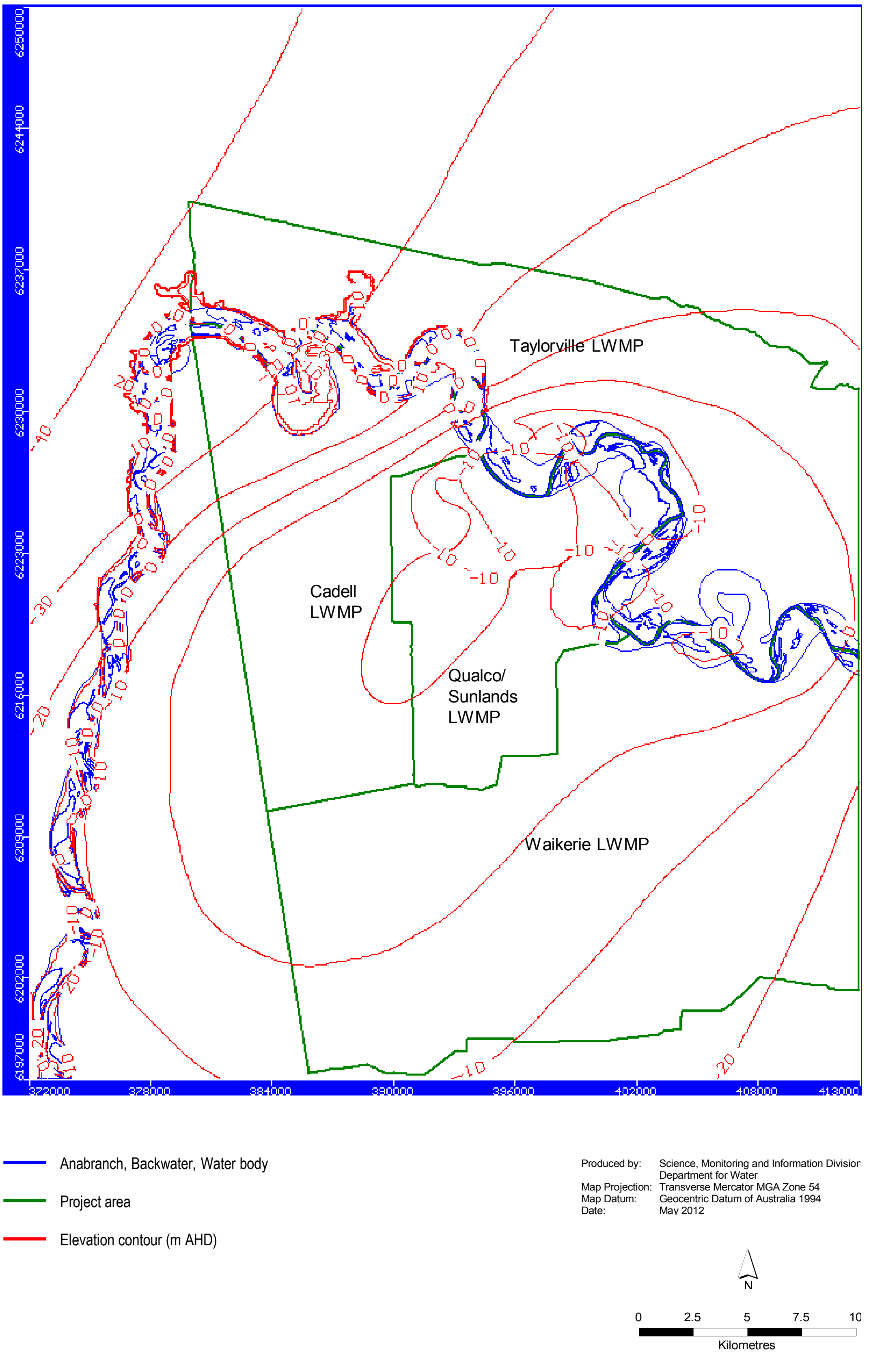


Figure 3.5 Elevation Contours for the Top of Finniss and Upper Mannum Formations and Murray Group Limestone (Model Layer 2)

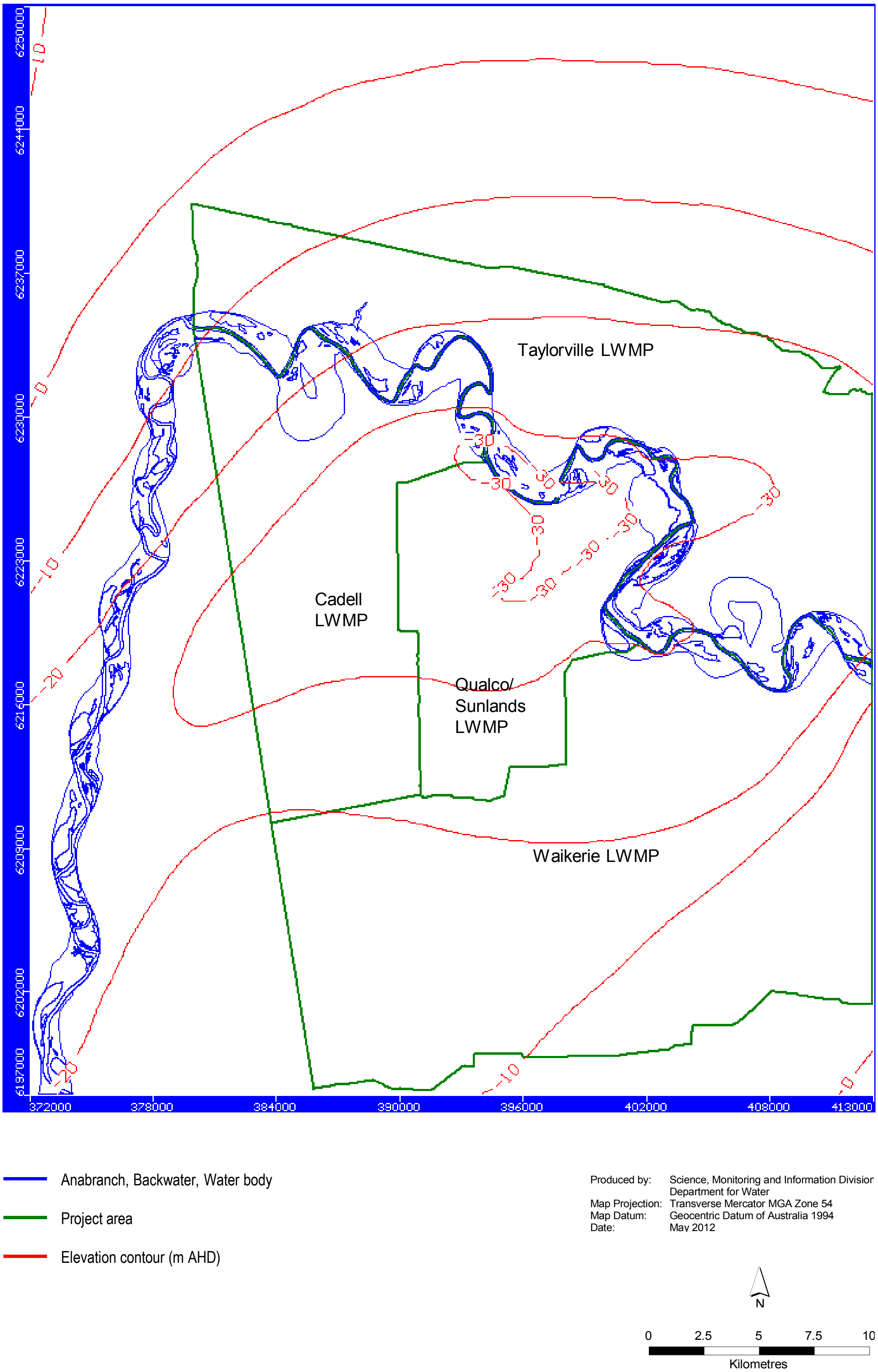


Figure 3.6 Elevation Contours for the Top of Lower Mannum Formation (Model Layer 3)

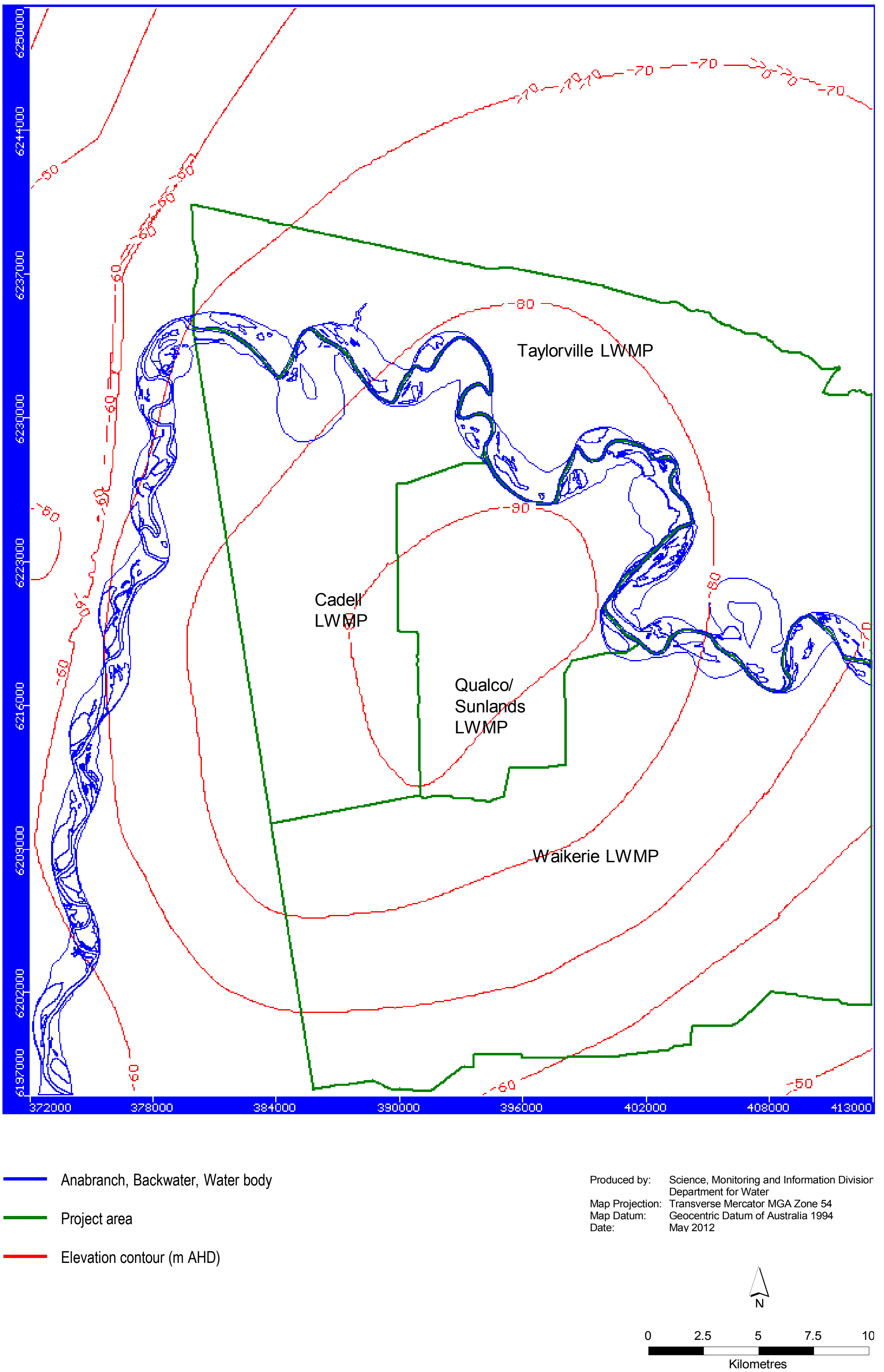
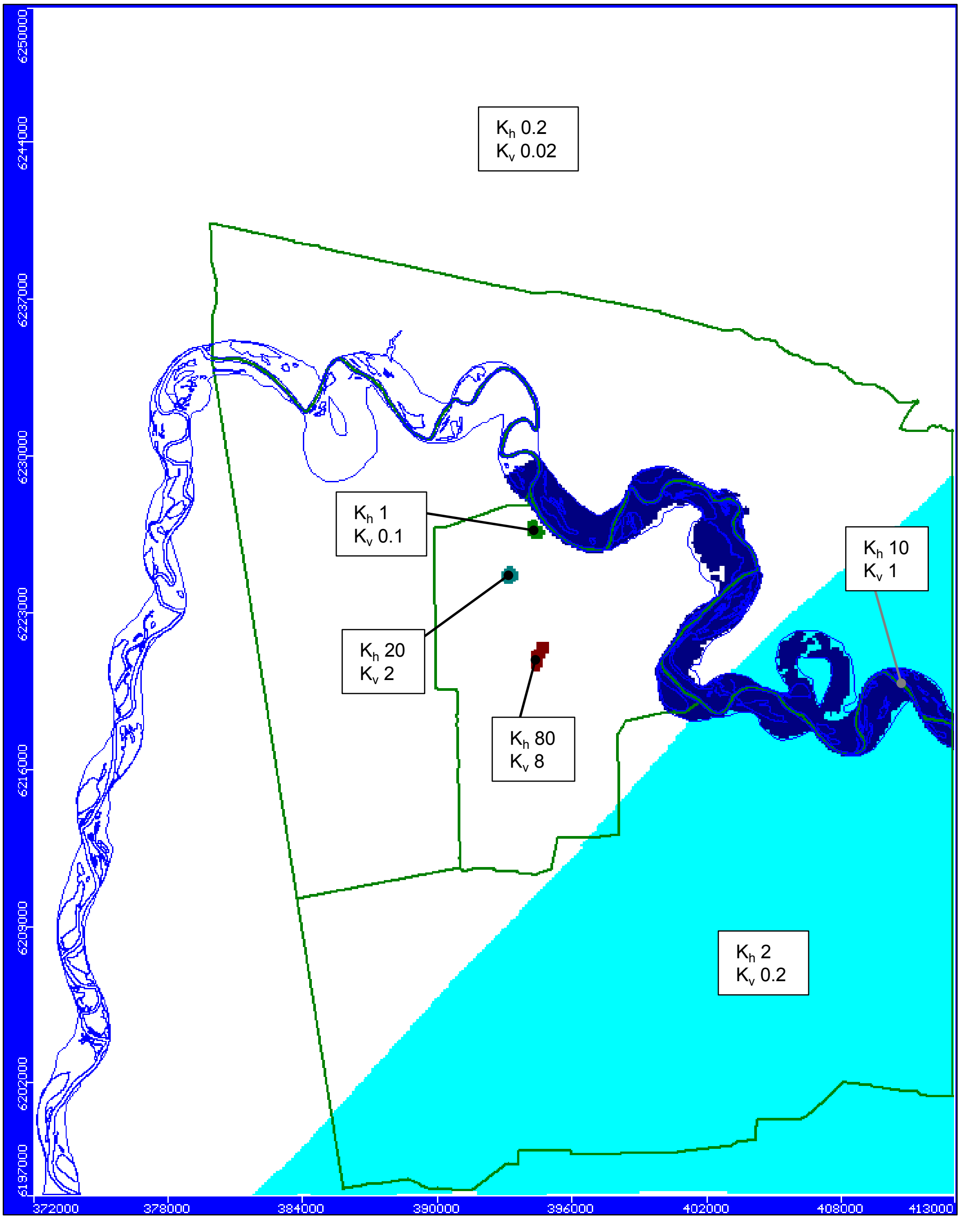


Figure 3.7 Elevation Contours for the Base of Lower Mannum Formation and Murray Group Limestone (Model Layer 3)



K_h Horizontal hydraulic conductivity (m/d)

K_z Vertical hydraulic conductivity (m/d)

Anabranch, Backwater, Water body

Project area

Produced by: Science, Monitoring and Information Division
Department for Water
Map Projection: Transverse Mercator MGA Zone 54
Map Datum: Geocentric Datum of Australia 1994
Date: May 2012

N

0 2.5 5 7.5 10
Kilometres

Figure 3.8 Model Hydraulic Conductivity for the Monoman and Glenforslan Formations (Model Layer 1)

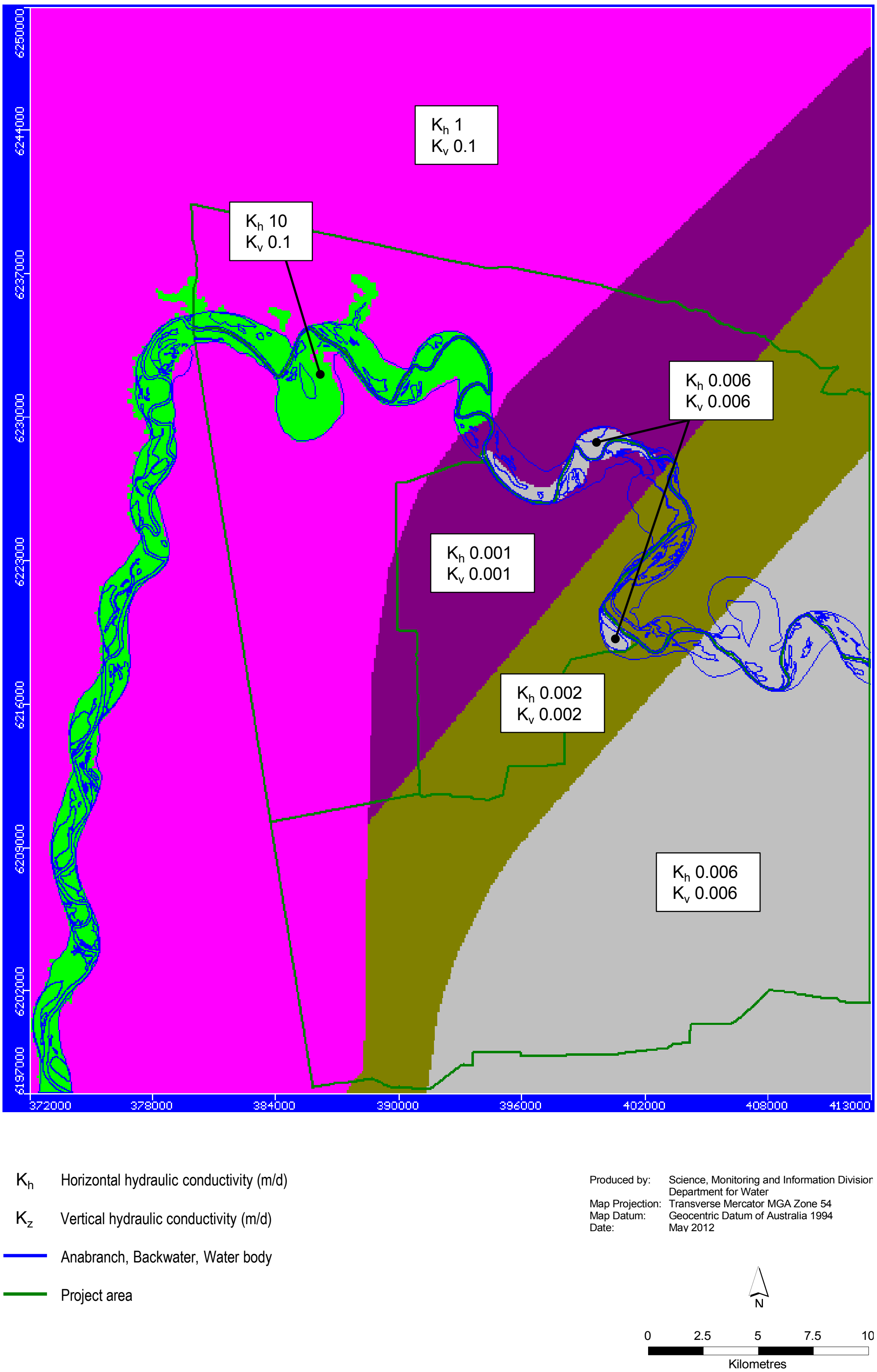


Figure 3.9 Model Hydraulic Conductivity for the Finniss and Upper Mannum Formations and Murray Group Limestone (Model Layer 2)

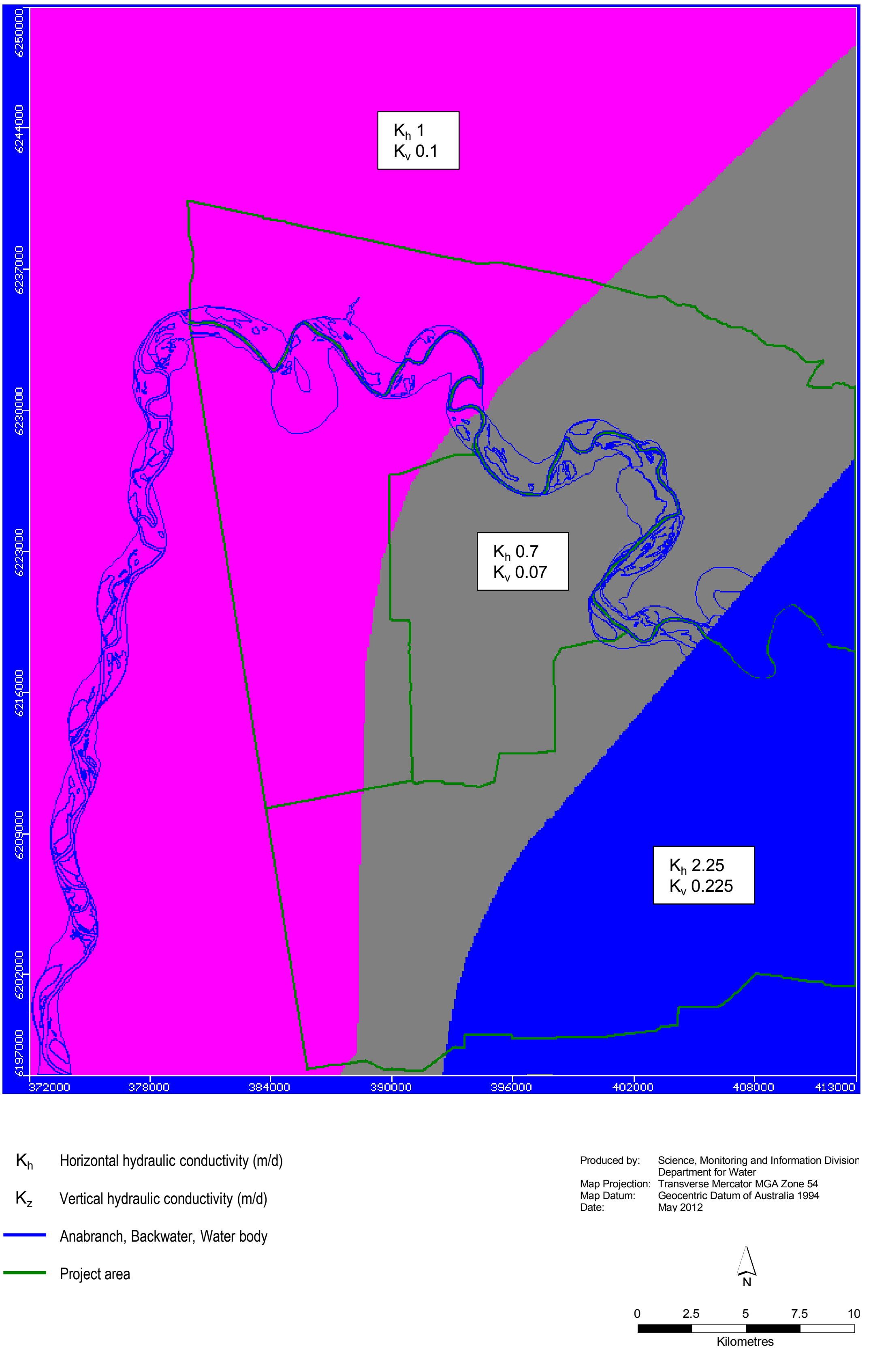
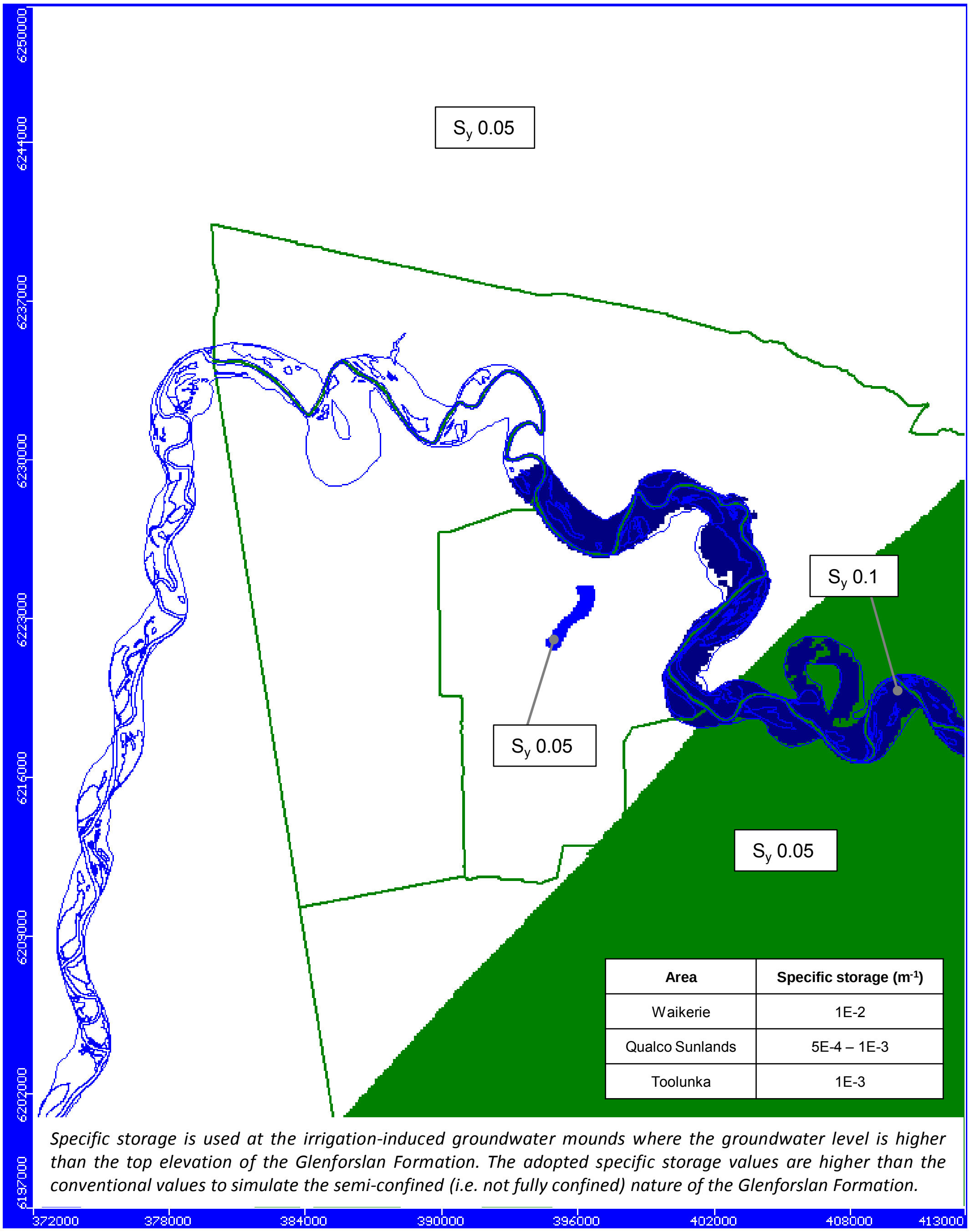


Figure 3.10 Model Hydraulic Conductivity for the Lower Mannum Formation and Murray Group Limestone (Model Layer 3)



Area	Specific storage (m^{-1})
Waikerie	1E-2
Qualco Sunlands	5E-4 – 1E-3
Toolunka	1E-3

Specific storage is used at the irrigation-induced groundwater mounds where the groundwater level is higher than the top elevation of the Glenforslan Formation. The adopted specific storage values are higher than the conventional values to simulate the semi-confined (i.e. not fully confined) nature of the Glenforslan Formation.

S_y Specific yield (dimensionless)

Anabranch, Backwater, Water body

Project area

Produced by: Science, Monitoring and Information Division, Department for Water
Map Projection: Transverse Mercator MGA Zone 54
Map Datum: Geocentric Datum of Australia 1994
Date: May 2012

N

0 2.5 5 7.5 10
Kilometres

Figure 3.11 Model Specific Yield and Specific Storage for the Monoman and Glenforslan Formations (Model Layer 1)

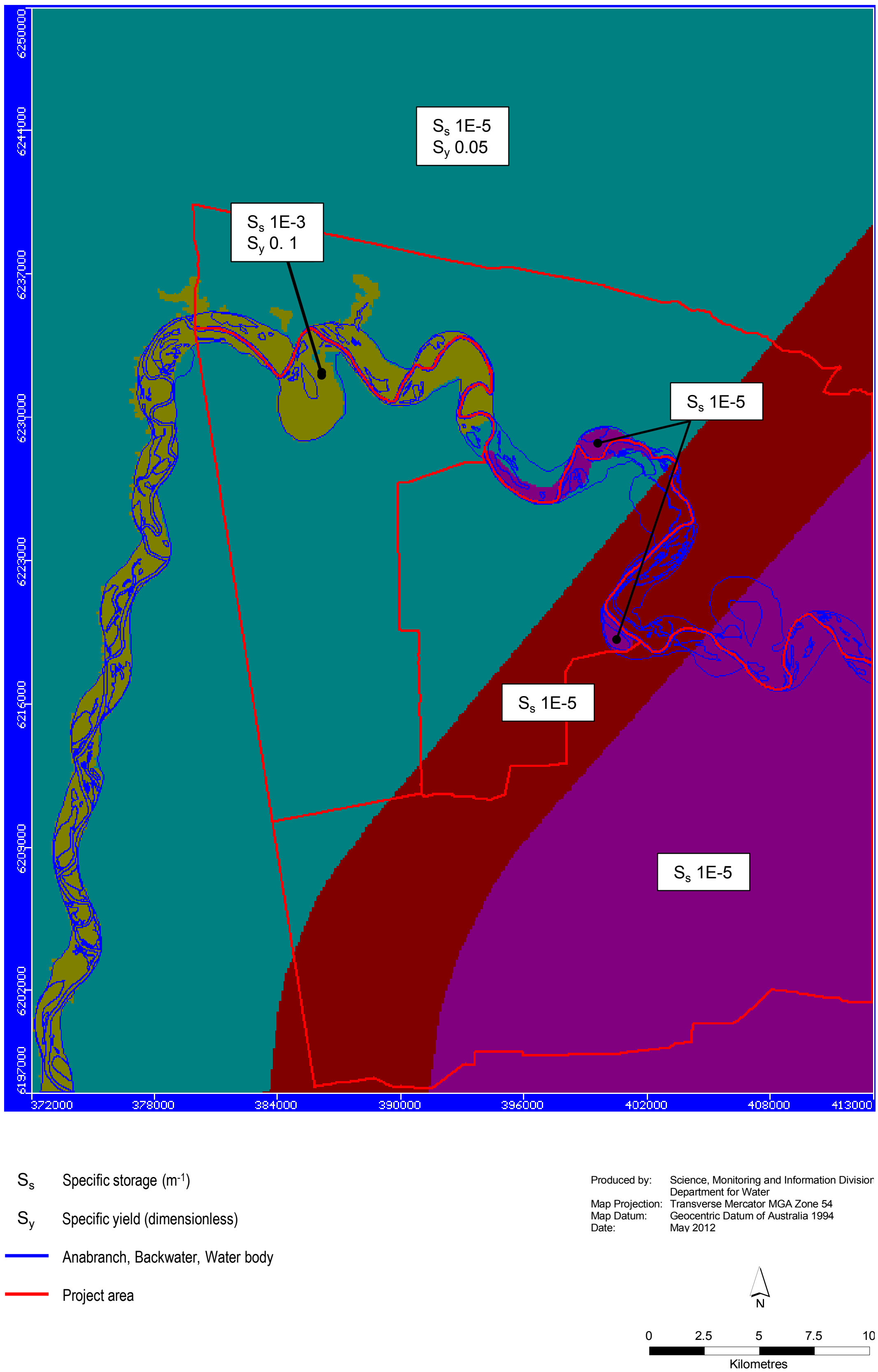


Figure 3.12 Model Specific Storage and Specific Yield for the Finniss and Upper Mannum Formations and Murray Group Limestone (Model Layer 2)

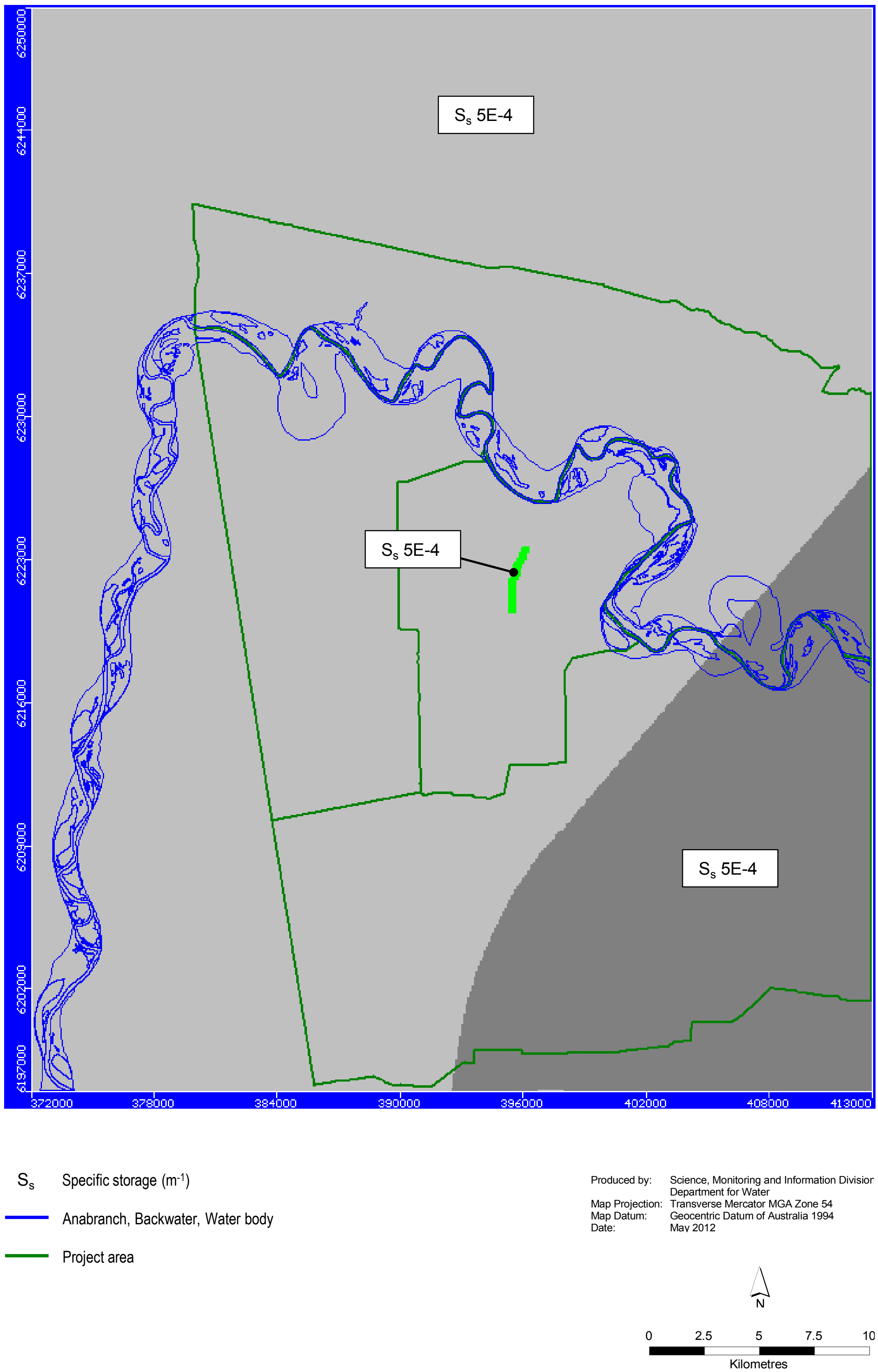


Figure 3.13 Model Specific Storage for the Lower Mannum Formations and Murray Group Limestone (Model Layer 3)

values are more speculative and are applied to some very small areas where karst has been inferred. No aquifer tests have been conducted in the Glenforslan Formation at Waikerie, so the model's hydraulic conductivity for the Glenforslan Formation is based on previous studies and primarily on calibration results. A value of 2 m/d for horizontal hydraulic conductivity was found to provide a good match to local hydrographs (including response to SIS pumping) and is an order of magnitude greater than the value adopted for Qualco, consistent with evidence that the hydraulic conductivity is higher at Waikerie than at Qualco (Section 2.3.3.3). The vertical hydraulic conductivity of the Finniss Formation/Upper Mannum Formation aquitard has been zoned to match the logarithmic mean of observations. 0.001 m/d is adopted at Qualco, except where the Finniss Formation is absent, where a higher value of 0.006 m/d is adopted for the Upper Mannum Formation aquitard. Upstream regions are also assigned vertical hydraulic conductivities to match the logarithmic mean of estimates, 0.002 or 0.006, although the lateral extent of these zones away from the river is not known due to a lack of aquifer tests. A small zone of 0.006 m/d vertical hydraulic conductivity is included at Waikerie to match estimated aquifer test values and to improve the calibration.

The storativity and specific yield values are based on aquifer test data, where available. As the Monoman Formation is treated as an unconfined aquifer in the model, the confined storage coefficient values determined from pumping tests are not applicable. No storativity data are available for the Glenforslan, Finniss or Upper Mannum Formations in this region. The storativity assigned to the Lower Mannum Formation is the logarithmic mean of observations, 5×10^{-4}.

Table 3.3 Adopted aquifer and aquitard hydraulic parameters in the Waikerie to Morgan model

Aquifer/aquitard	Model layer	Hydraulic conductivity		Storage	
		K_h (m/d)	K_v (m/d)	S_s (-/m)	S_y (-)
Monoman Formation	1, 2	10	0.1 – 1	1×10^{-3}	0.1
Glenforslan Formation	1	0.2, 2, 1, 20 or 80	0.02, 0.2, 0.1, 2 or 8	1×10^{-2}* - 5×10^{-4}	0.05
Finniss Formation / Upper Mannum Formation	2	0.001, 0.002 or 0.006	0.001, 0.002 or 0.006	1×10^{-5}	-
Lower Mannum Formation	3	0.7 or 2.25	0.07 or 0.225	5×10^{-4}	-

** Specific storage is used at the irrigation-induced groundwater mounds where the groundwater level is higher than the top elevation of the Glenforslan Formation. The adopted specific storage values are higher than the normally adopted values to simulate the semi-confined (i.e. not fully confined) nature of the Glenforslan Formation.*

3.6. MODEL BOUNDARIES

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

(i) regional flow in and out of the model domain

(ii) surface water features including the River Murray

(iii) the localised natural processes of groundwater evapotranspiration and cliff seepage

(iv) the salt interception and groundwater control schemes.

The model boundary conditions are summarised for each layer in Figures 3.14 to 3.16.

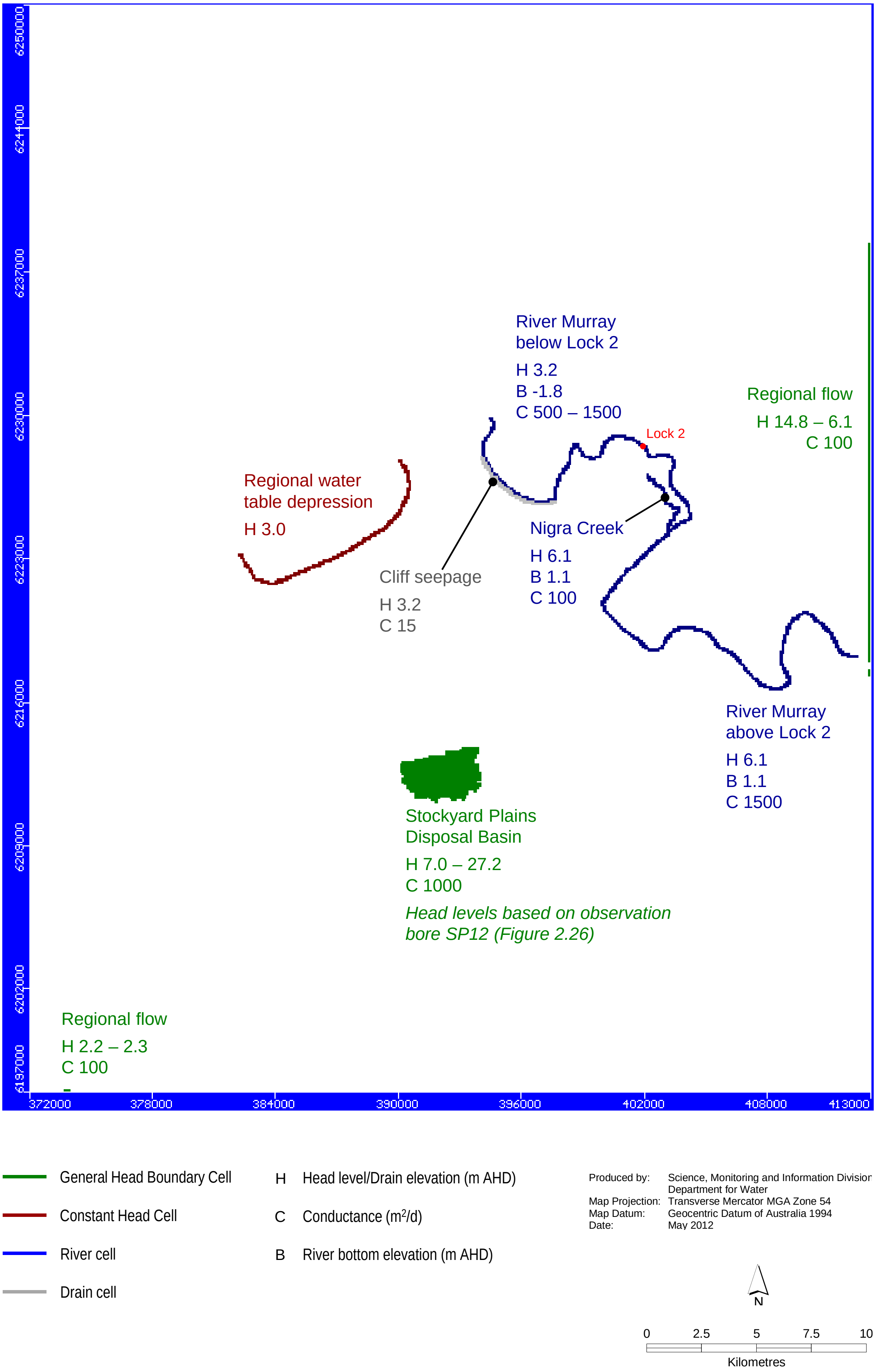


Figure 3.14 Model Boundary Conditions for the Monoman and Glenforslan Formations (Model Layer 1)

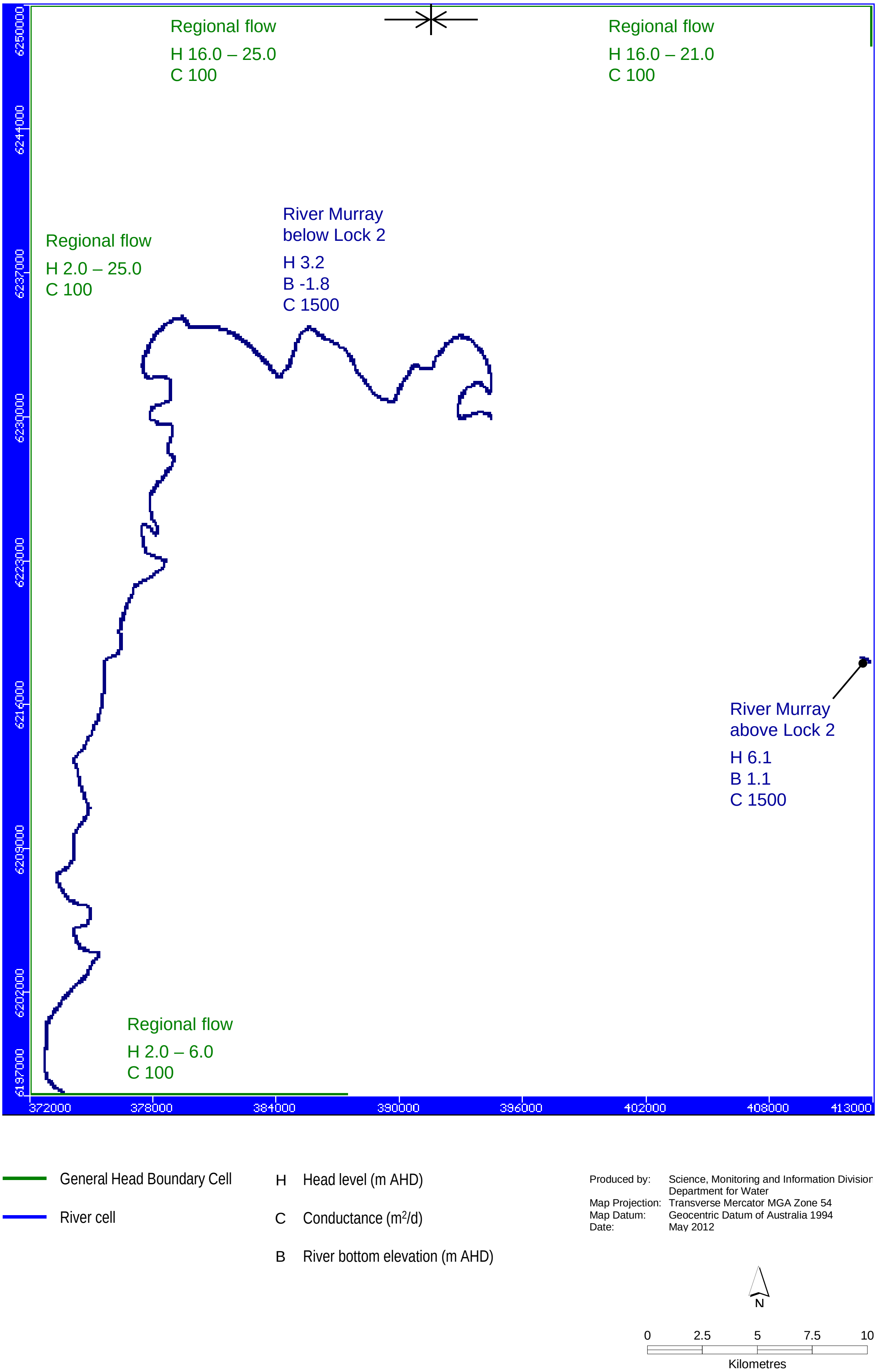


Figure 3.15 Model Boundary Conditions for the Finniss and Upper Mannum Formations and Murray Group Limestone (Model Layer 2)

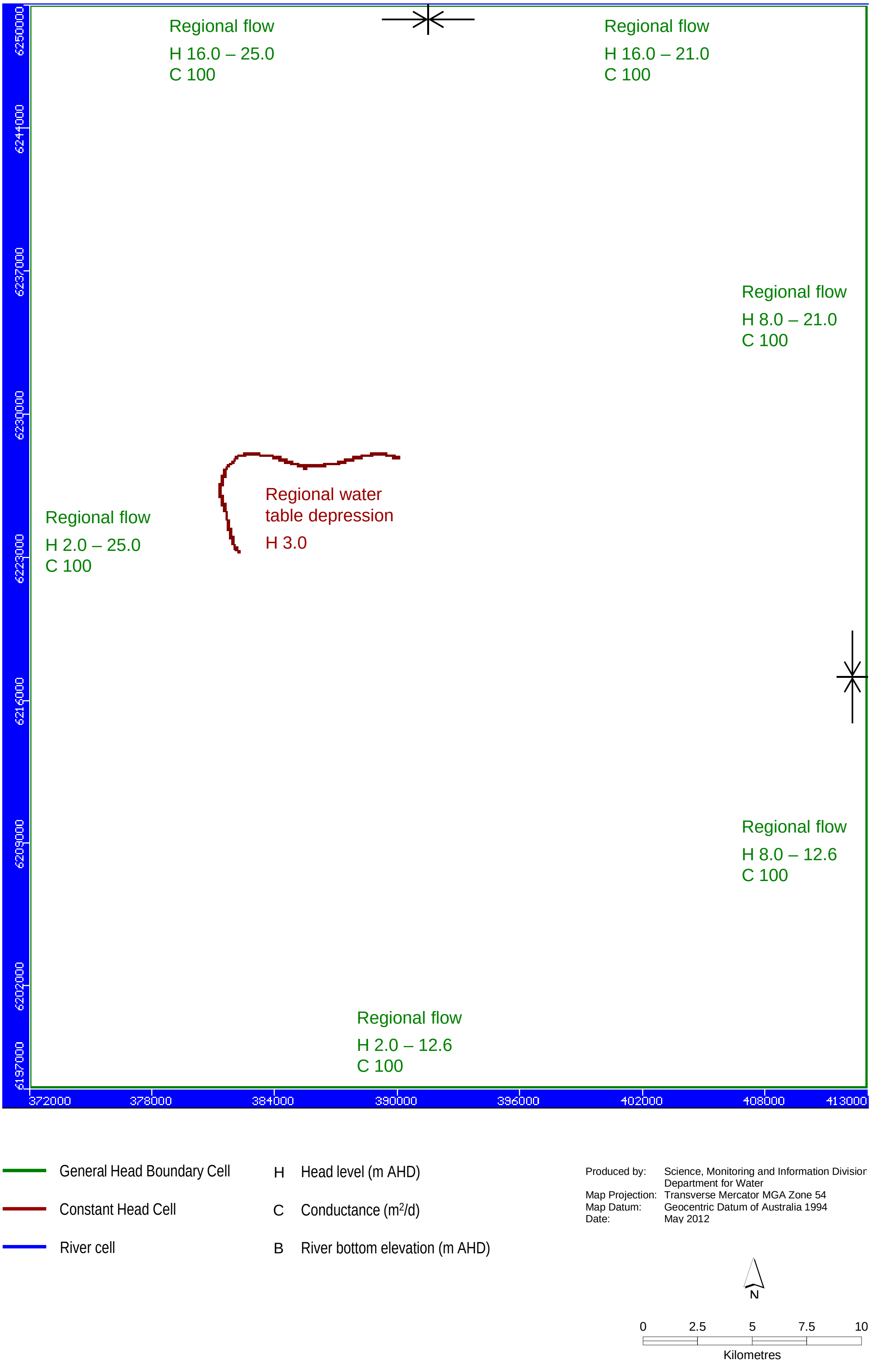


Figure 3.16 Model Boundary Conditions for the Lower Mannum Formations and Murray Group Limestone (Model Layer 3)

3.6.1. REGIONAL FLOW

The regional groundwater flow in the Waikerie to Morgan 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 where the aquifers are saturated. The assigned head values for the general head boundary (Figures 3.14 to 3.16) are based on observations from Barnett (1991, 1994). The assigned head values do not change with time. There are no hydraulic processes to the north, west and south which would substantially change potentiometric head along the boundaries over the period simulated by the model. To the east lies the Woolpunda SIS, but bore hydrographs and previous simulation work suggest that the Woolpunda SIS does not significantly change potentiometric heads within the Waikerie to Morgan region (see Section 3.2).

In model layer 1, general head cells are only present along boundaries where the watertable is higher than the base of the Glenforslan aquifer. In layer 2, general head cells are employed where the layer represents the undifferentiated Murray Group but not where it represents the aquitard of the Finniss Formation and Upper Mannum Formation. Layer 3, representing the Lower Mannum Formation aquifer and the undifferentiated Murray Group, has general head cells along all boundaries. Where general head cells are applied to more than one layer, the same head value is assigned to both, except where the Glenforslan is hydraulically connected to the River Murray at the eastern boundary.

The conductance is 100 m^2/d and provides a reasonable match between the steady-state model outputs and potentiometric head from Barnett (1991, 1994).

The conductance was varied during the calibration until a good match to observed heads was achieved regionally.

A depression in the regional water table to the south of Cadell is represented in the model as a group of constant head cells with an assigned value of 3 m AHD. It is believed that this depression reflects the lower groundwater heads prior to the construction of the river locks and that this area has not yet reached the new equilibrium head. In model layer 1, some of the cells have a bottom elevation higher than 3 m AHD and therefore the constant head cells are moved to model layer 3.

3.6.2. SURFACE WATER FEATURES

3.6.2.1. River Murray

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

The reach of river west of Woolpunda to Lock 1 (river kilometres 393 to 274) is included in the model. Based on the river bed elevations as inferred from the 2004 NanoTEM survey (Telfer *et al*. 2005), the River Murray is present in model layer 1 upstream of Hogwash (river km 349). Downstream of Hogwash, the River Murray is present in model layer 2.

A constant river depth of 5 m is used for the whole river reach in the model. This is a simplified representation of the river depths recorded in the 2004 NanoTEM survey (Telfer *et al*. 2005). The river bed elevation is calculated as the difference between the river pool level and the river depth. This assumption should not affect model results as the river bed elevation value is only used in MODFLOW calculations when the groundwater level is lower than the river bed elevation, which does not occur in the Waikerie to Morgan area based on observed data.

The river stages for the River Murray are as follows:

- 6.1 m AHD between Lock 3 and Lock 2
- 3.2 m AHD between Lock 2 and Lock 1.

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[1].

The conductance of MODFLOW river cells controls flux to and from the river. The conductance was obtained during calibration to obtain a good match between observed and modelled hydrographs for bores near the river; values were confirmed through comparison of modelled and Run of River salt loads. The conductance values adopted are similar to those of previous studies. The main river channel has a conductance of 500-1500 m^2/d, which is consistent with the conductance values adopted in the other numerical groundwater models simulating the River Murray region.

3.6.2.2. Nigra Creek

Ephemeral surface water features are not simulated in the model. Nigra Creek is simulated in the model because it is a permanent feature. Nigra Creek is represented as a series of river cells within the model, with a head at river level (6.1 m AHD) and a conductance of 100 m^2/d, which is consistent with the conductance values used to simulate streams and wetlands in other Riverland models.

3.6.2.3. Stockyard Plain Disposal Basin

Stockyard Plain Disposal Basin (SPDB) is represented as a collection of time-varying general head cells in layer 1 of the model. It is assumed that a mound has built gradually below the SPDB since water began to be pumped there from the Woolpunda SIS, which became operational in 1991. The development of the mound below the SPDB is based on trends in the hydrograph for bore SP 12 (Figure 2.26). Figure 3.14 shows the specified head for the general head cells.

3.6.3. GROUNDWATER EVAPOTRANSPIRATION

Groundwater ET is simulated using the ground surface as the ET surface. The maximum groundwater ET rate is set at the annual average areal potential ET of 1100 mm/y given in *The Climatic Atlas of Australia (Bureau of Meteorology 2001).* The extinction depth is set at 2 m, as this value is consistent with previous studies and produces a good match between modelled and observed hydrographs in the floodplain. The actual ET from groundwater is within the same order of magnitude with other SA Salinity Register models such as Loxton-Bookpurnong (Yan, Li & Woods 2011).

Groundwater ET occurs where the watertable is shallow, on the floodplains and in some other lowland areas. Upstream of Hogwash (river km 349), ET is applied to model layer 1. Downstream of Hogwash, where the watertable lies in layer 2, groundwater ET is applied to model layer 2.

3.6.4. CLIFF SEEPAGE

Where the river directly abuts the southern highland (i.e. between river kms 351 and 356) there is potential for cliff seepage to occur through the Glenforslan Formation. Cliff seepage has been observed

[1] 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. Following instruction from MDBA, constant pool level at normal condition was adopted in the calculation especially for Salinity Register purpose.

at numerous sites in the area (AWE 2011a). MODFLOW's drain cells are inserted at the cliff edge within model layer 1. These drain cells are given an elevation of river level (3.2 m AHD) and a conductance of 10 m^2/d. Flux into the drain cells, which simulate the flux from the seepage, were included in the calculation of salt load entering the River Murray.

3.6.5. DRAINAGE SCHEMES AND BORES

There are a large number (hundreds) of drainage bores in the Waikerie area and part of the Qualco area. Most of these drainage bores drain the irrigation drainage water into the Glenforslan Formation with very low rates in the Waikerie area and relatively large rates in some Qualco bores. The drainage bores in Qualco area were terminated around 1995. The drainage bore water is simulated as part of recharge in the model. Flux that directly enters the Glenforslan Formation aquifer through drainage bore discharge is represented by increasing recharge and shortening lag times in the locations of known drainage bores. For the purposes of the model and given the lack of available data on drainage bore fluxes, this inverse modelling approach is considered adequate.

3.6.6. SALT INTERCEPTION AND GROUNDWATER CONTROL SCHEMES

The model simulates pumping from the Waikerie, Waikerie IIA and Waikerie Lock 2 SIS and the Qualco-Sunlands Groundwater Control Scheme using MODFLOW's Well Package. Figure 2.25 shows the location of the production bores of the schemes.

Production bores of the Waikerie and Waikerie IIA SIS are screened within the Mannum Formation: primarily Lower Mannum Formation, with some bores also screened in the Upper Mannum Formation. The production zone for these bores is therefore within model layers 2 and/or 3. Production bores of the Waikerie Lock 2 SIS are screened within the Lower Mannum Formation. QSTCGS production bores are screened within the Glenforslan, Upper Mannum and/or Lower Mannum, (i.e. model layers 1, 2 and/or 3). QSTCGS replacement bores are only screened within the Lower Mannum Formation.

The total metered flow data for all the schemes was provided by SA Water. These data were used to calculate an average flow every six months for each pumping well, assuming that the bores are always operating. These calculated rates are then imported into the model. For pumping wells that screen multiple layers, pumping rates are allocated between model layers based upon the screen lengths and hydraulic conductivity of the layers.

Bore Q9 of the QSTGCS is the only pumping well that is partially screened in a layer not represented in the model, that being the Loxton Sands Formation. The pump rate of this Loxton Sands/Glenforslan Formation bore had to be adjusted so that it was not over-pumping from the Glenforslan Formation aquifer. The pump rate for bore Q9 was therefore reduced to a quarter of its original flow. This reduction is based on the comparative estimated transmissivities of the Loxton Sands Formation and Glenforslan Formation at the bore.

For most pumping wells, the screen elevations, or production zones, were imported directly into the model. The exceptions are bores Q3, Q5, Q6 and Q9B of the QSTGCS, where the elevation of the base of the screen was deepened to increase the pumped transmissivity of the Lower Mannum Formation. This was performed because of a mismatch between modelled and real top of Lower Mannum Formation at the bore, due to averaging over a 100 m cell size.

Modelled pump rates for each bore and active stress period are provided in Appendixes A-6 to A-9.

3.6.7. GROUNDWATER ALLOCATION AND USE

There is no allocation of groundwater or known groundwater use in the Waikerie to Morgan area.

3.7. MODEL RECHARGE

Modelled recharge rates and areas simulate recharge due to rainfall, irrigation and drainage bores.

3.7.1. RECHARGE UNDER NATIVE VEGETATION

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

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 expert panel from MDBA.

3.7.2. RECHARGE DUE TO MALLEE CLEARANCE

In prediction modelling, Scenario 2 (see Section 5) simulates the impact of mallee clearance on River Murray salt loads. The multiple recharge zones and rates are specified by DENR and are estimated 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 aquitard. The mallee clearance is assumed to have started in 1920. There are 41 recharge zones and rates vary from 0.1 to 15 mm/y. The details of recharge zones shown in Figure 3.17 and rates are given in Appendix A-1.

3.7.3. OUTLINE OF APPROACH OF RECHARGE DUE TO IRRIGATION

It is not currently possible to accurately measure or calculate recharge over time based on irrigation and hydrogeological information alone, owing to a lack of historical irrigation data, a lack of data of 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 estimated from measured groundwater levels via inverse groundwater numerical modelling, as described below.

The total spatial extent of recharge for a given year is based on irrigation footprint and commencement year data from DENR. For Qualco, where there are multiple perched aquifers, the recharge footprint is widened beyond the irrigation footprint to reflect the lateral movement of drainage water within the perched aquifers. 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.

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.

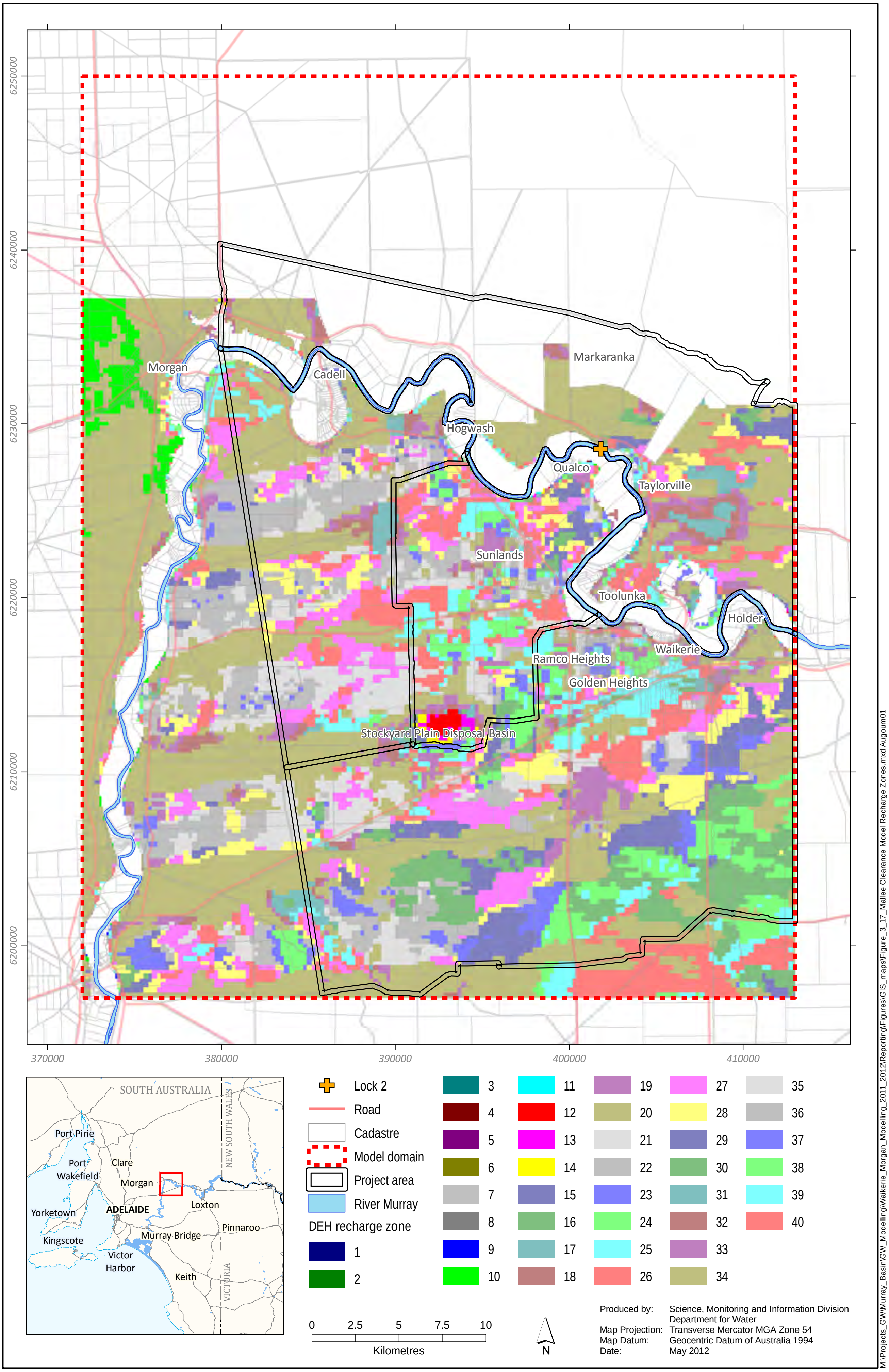


Figure 3.17 Mallee Clearance Model Recharge Zones

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 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 that time period's irrigation practices. 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 are compared to available data sources, including:
    - a comparison of lag time estimates with results from a cross-sectional variable-saturation model by Lisdon Associates (2010)
    - a comparison of recharge estimates with known historical practices and an independent assessment of accession water, as included in Appendix C-1
    - a comparison of estimated salt loads with historical monitoring sites and RoR data.
- Sensitivity and uncertainty analyses are performed to estimate model uncertainty.

3.7.4. MODEL IRRIGATION RECHARGE SETTINGS AND ASSUMPTIONS

The process in developing modelled recharge is described below.

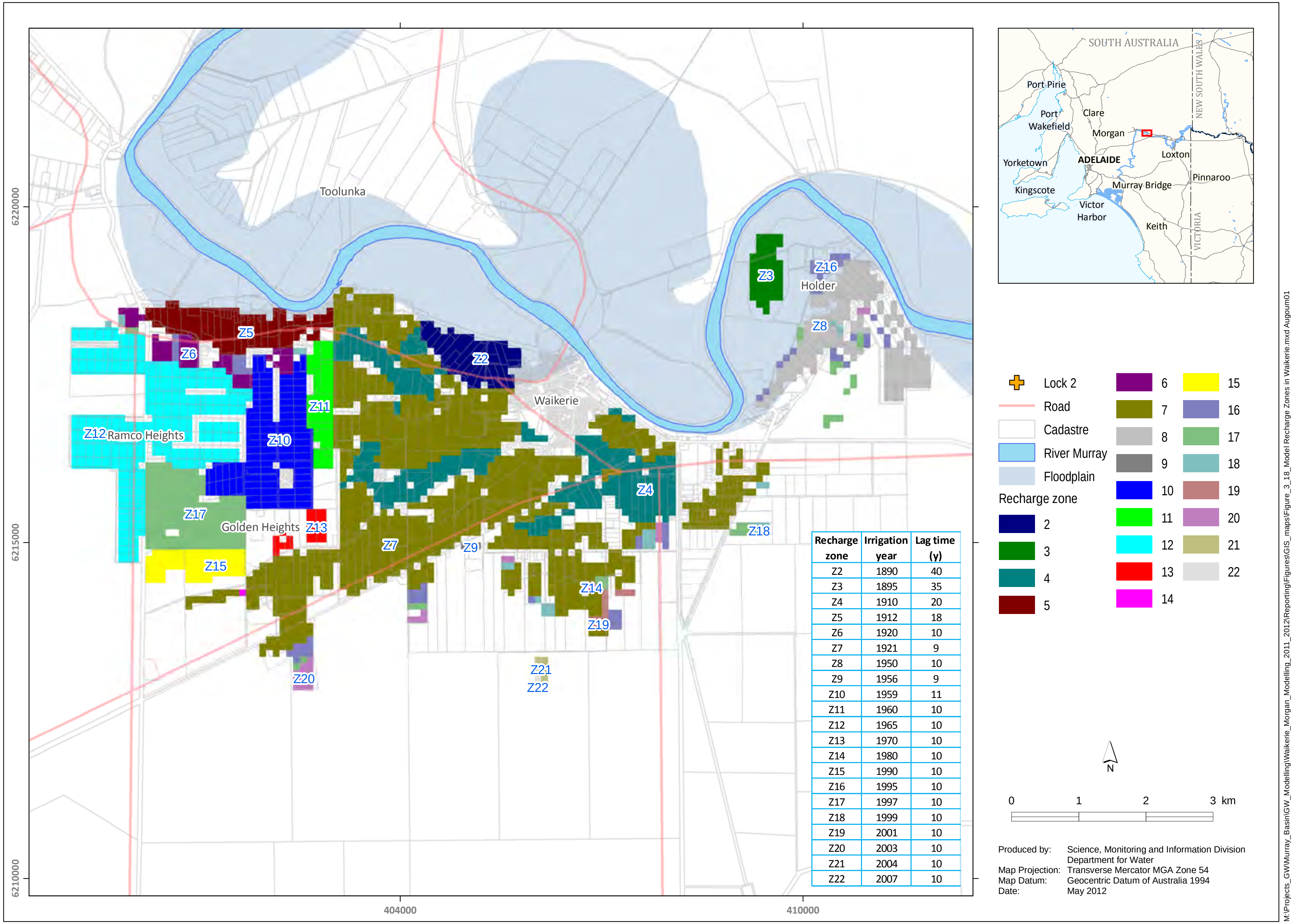
3.7.4.1. Recharge area

The areas of recharge in the model are assumed to be the same as the irrigation areas in the Waikerie to Morgan area, except the Qualco area where the edge of the recharge area is estimated to be approximately 300 m wider than the irrigation application area, due to the presumed spread of perched aquifers (see Section 3.7.7.1).

The model recharge areas are based on the irrigation footprint GIS data collected as part of the irrigation data review of Fordham *et al*. (2012). The spatial extent of irrigation development at specific milestones (1920, 1940, 1956, 1960, 1970, 1976, 1980, 1984, 1995, 1997, 1999, 2001 and 2003 to 2008 yearly data) was used to generate recharge areas over time. The location of irrigation areas and starting years are indicated in Figure 2.23.

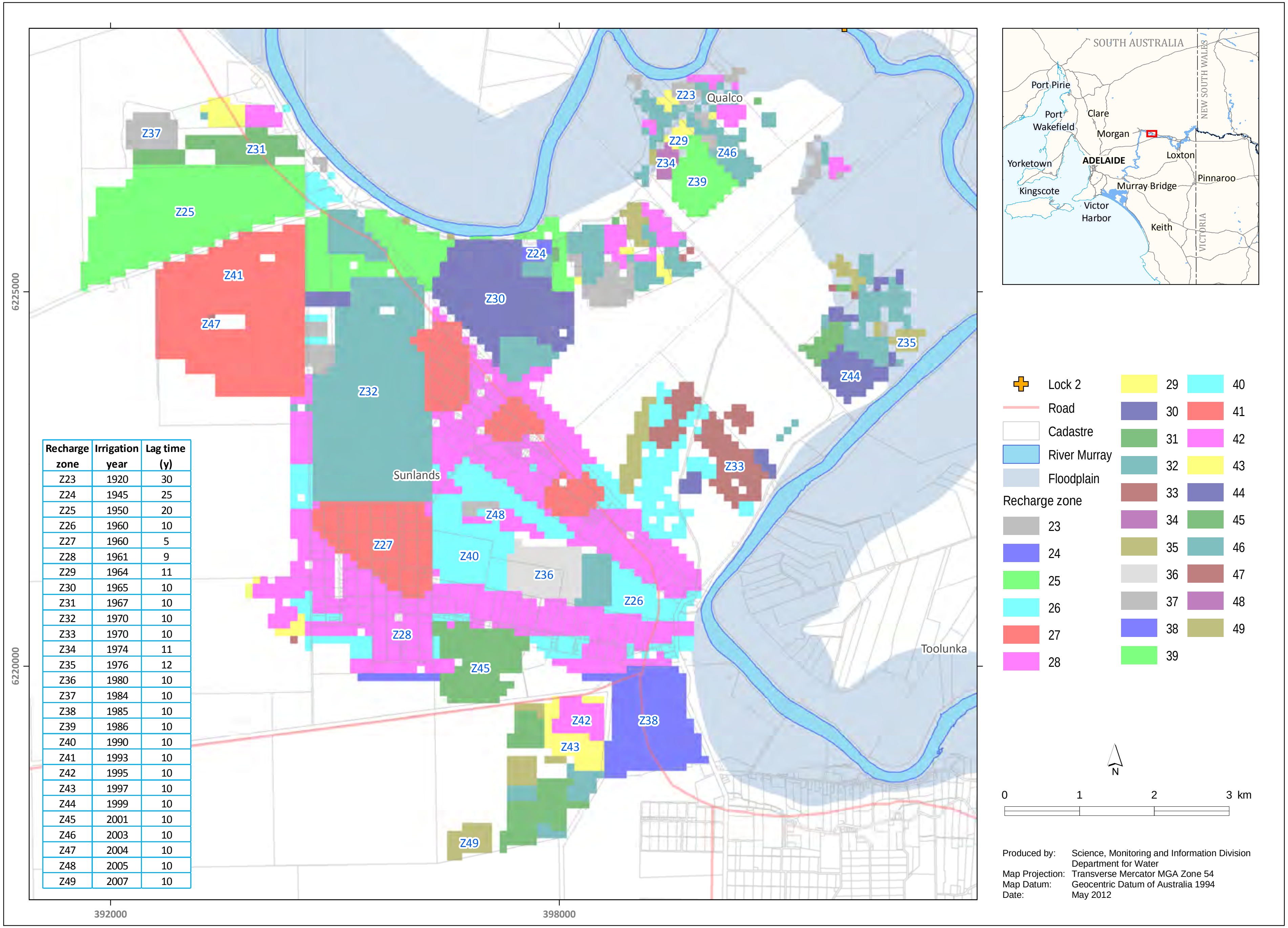
As the irrigation footprint data indicate that irrigation areas expand with time (Figure 2.23), the GIS files were used to assign model recharge areas with different starting years. As irrigation continues to develop, more model irrigation recharge areas become active to simulate the irrigation area 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 Waikerie to Morgan areas are given in Figures 3.18 to 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. Potential localised lateral movement of accession water in the unsaturated zone and in perched aquifers is addressed indirectly by varying recharge during calibration.



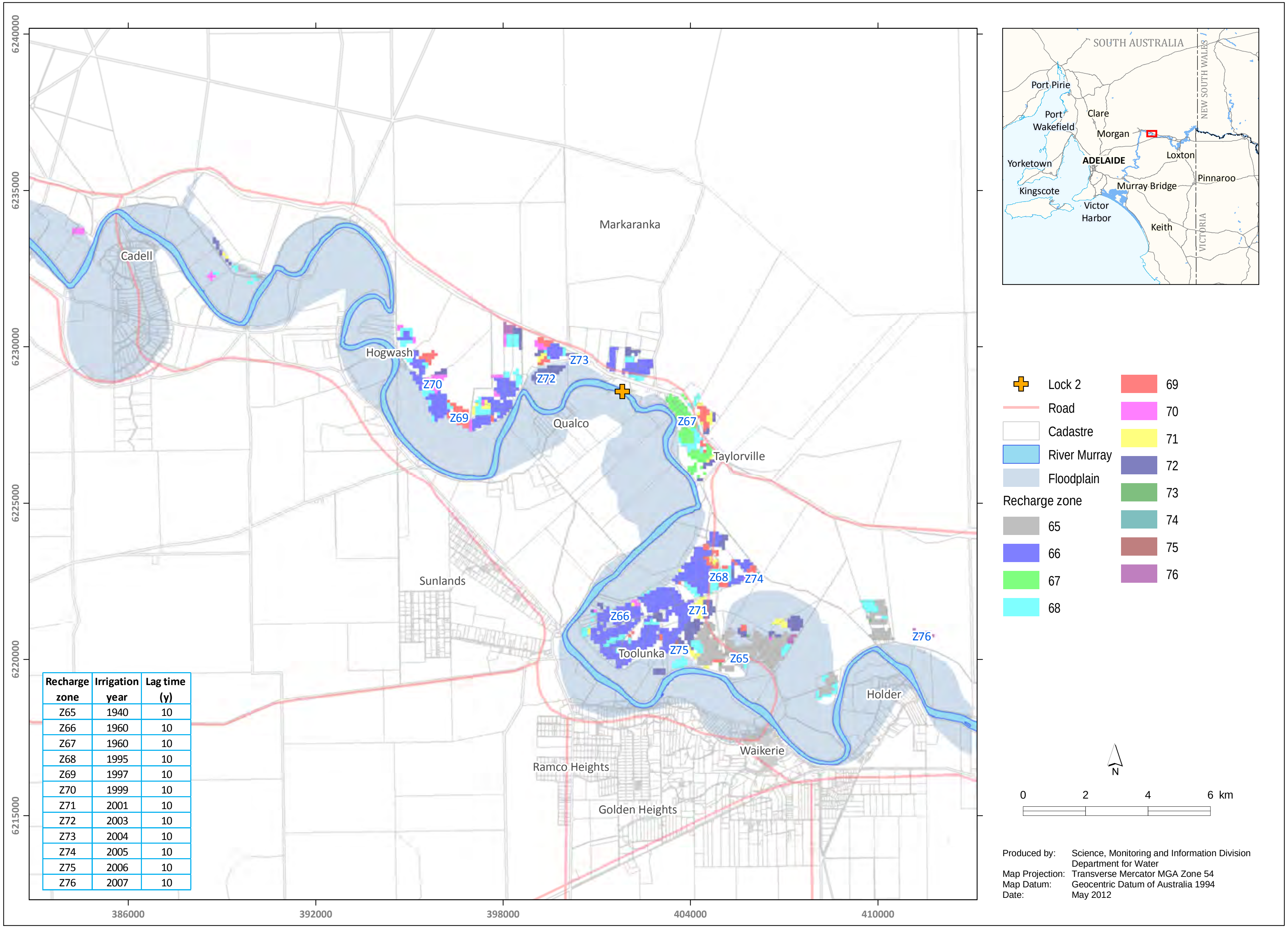
Recharge zone	Irrigation year	Lag time (y)
Z2	1890	40
Z3	1895	35
Z4	1910	20
Z5	1912	18
Z6	1920	10
Z7	1921	9
Z8	1950	10
Z9	1956	9
Z10	1959	11
Z11	1960	10
Z12	1965	10
Z13	1970	10
Z14	1980	10
Z15	1990	10
Z16	1995	10
Z17	1997	10
Z18	1999	10
Z19	2001	10
Z20	2003	10
Z21	2004	10
Z22	2007	10

Figure 3.18 Model Recharge Zones in Waikerie



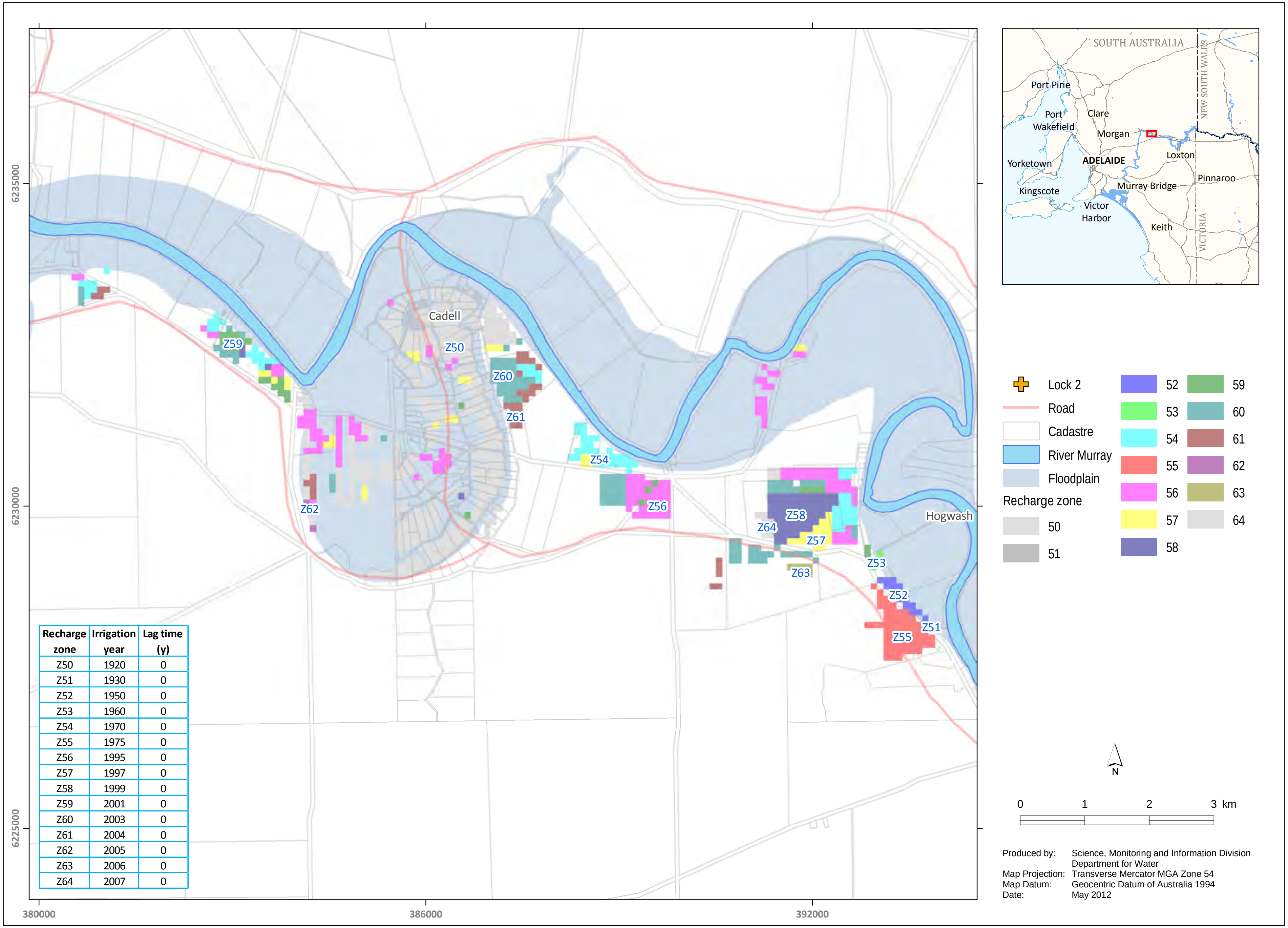
Recharge zone	Irrigation year	Lag time (y)
Z23	1920	30
Z24	1945	25
Z25	1950	20
Z26	1960	10
Z27	1960	5
Z28	1961	9
Z29	1964	11
Z30	1965	10
Z31	1967	10
Z32	1970	10
Z33	1970	10
Z34	1974	11
Z35	1976	12
Z36	1980	10
Z37	1984	10
Z38	1985	10
Z39	1986	10
Z40	1990	10
Z41	1993	10
Z42	1995	10
Z43	1997	10
Z44	1999	10
Z45	2001	10
Z46	2003	10
Z47	2004	10
Z48	2005	10
Z49	2007	10

Figure 3.19 Model Recharge Zones in Qualco Sunlands



Recharge zone	Irrigation year	Lag time (y)
Z65	1940	10
Z66	1960	10
Z67	1960	10
Z68	1995	10
Z69	1997	10
Z70	1999	10
Z71	2001	10
Z72	2003	10
Z73	2004	10
Z74	2005	10
Z75	2006	10
Z76	2007	10

Figure 3.20 Model Recharge Zones in the Taylorville North LWMP Area



Recharge zone	Irrigation year	Lag time (y)
Z50	1920	0
Z51	1930	0
Z52	1950	0
Z53	1960	0
Z54	1970	0
Z55	1975	0
Z56	1995	0
Z57	1997	0
Z58	1999	0
Z59	2001	0
Z60	2003	0
Z61	2004	0
Z62	2005	0
Z63	2006	0
Z64	2007	0

Figure 3.21 Model Recharge Zones in Cadell

3.7.4.2. Initial lag time

Initial lag time is the time taken for the irrigation-water wetting front to pass from the root zone through the unsaturated zone to reach the groundwater table — this can be several years to many decades, depending on key variables. It depends on 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. SIMRAT makes a number of simplifying assumptions that do not apply to the Waikerie to Morgan region — for example, that the water moves vertically and not laterally and that the irrigation accession rate is 120 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.

An independent study by Lisdon Associates (2010) involved a variably-saturated cross-sectional model of Loxton that estimated both initial lag time and late lag time — the time taken for changes to root zone drainage volumes to alter recharge to the watertable. The simulations show that the initial lag time for accession water (220 mm/y) from a new irrigation area to reach the watertable is approximately 12 years in the Loxton area. This study supports the initial lag times used in the final calibrated groundwater numerical model which were around 10 to 15 years in the Waikerie to Morgan area.

The Lisdon Associates (2010) estimated lag times are shorter than SIMRAT's estimate of 20 to 30 years, but were found to be acceptable as the early (1950s) irrigation accession water in Loxton could be up to 420 mm/y, implying that the actual initial lag time was in fact significantly shorter than SIMRAT's run which assumed 120 mm/y. 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 the best available evidence — observed hydrographs and other data.

3.7.4.3. Recharge zoning

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

Irrigation commencement year
Model recharge areas were divided into a number of model recharge zones based on the commencement year of the irrigation. For instance, irrigation areas starting in 1920 and 1940 were simulated by two different model recharge zones.

Initial lag time
Model recharge zones that may have different lag times were separated into different model recharge zones. For example, if the model recharge zone simulating the irrigation area starting in 1940 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 bore, it was possible that the observation bores showed different groundwater level trends, hence the recharge rates needed to achieve calibration for those bores 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.

3.7.4.4. 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 study by Lisdon Associates (2010) also estimated the late lag time using a variably-saturated cross-section model. 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 model calibration and scenario modelling to distinguish impacts from irrigation activities.

3.7.5. REFINEMENT OF RECHARGE DURING THE CALIBRATION PROCESS

For the simulation of groundwater mound development due to irrigation, the calibration was conducted based on available long-term observation data (hydrographs) in highland areas where irrigation-induced groundwater mounds have developed.

The initial model run adopted the inputs as described in the previous section. The hydraulic parameters were first altered to achieve steady-state model calibration that provides the initial head for transient model calibration. The transient model calibration was then conducted, as described below, to achieve a good match between modelled outputs and available observations, particularly modelled heads and trends from hydrographs.

For a given recharge zone, or group of zones near observation bores, recharge rates and lag times were iteratively altered to better match observed head and especially trends. In some cases, zones were further subdivided to reflect varying rates to improve the match. The recharge rates were adjusted within predefined ranges based on knowledge of irrigation practices over time (Adams & Meissner 2009), as given in Table 3.4 and further verified through the independent assessment of irrigation accession, as included in Appendix C-1.

If there was a poor match to the observed trend of heads in an area that could not be addressed by varying the recharge in the appropriate range, then the hydraulic conductivity zones were reconsidered. Where supported by the available hydrogeological knowledge and other potential evidence, the hydraulic conductivity of a zone was altered.

To achieve best calibration results with available information, more than 100 model runs were conducted. The result is a calibrated model that:

- is consistent with available regional-scale hydrogeological data
- has recharge rates within reasonable bounds
- matches observed hydrographs well
- compares well with other datasets, as described in the next section.

It is important to note that irrigation recharge is the major factor that drives groundwater level change (trend) in the Waikerie to Morgan highland area. Hydraulic conductivities control the head level rather than the trend. Specific yield has little impact on the trend-matching process due to the relatively slow pace of irrigation-induced groundwater level change (month/years) in the highland area. Note that this is distinctly different to the rapid aquifer response from pumping activities such as SIS.

Table 3.4 Modelled recharge and irrigation legacy

Irrigation Time Period	Interpreted Irrigation Activities	Model Recharge Time Period	Model recharge rates (mm/y)			
			Waikerie	Qualco-Sunlands	Taylorville LWMP	Cadell
1920–65	Flood irrigation (4 week schedule) Drainage bores at Waikerie	1930–65	150 – 420	100	150	500
Mid- to late-1960s	Flood irrigation (2 week schedule) Drainage bores at Qualco	1965–70	150 – 320	100 – 350	130	450
1970s	Convert from flood to sprinklers	1970–80	100 – 280	60 – 350	100 – 220	400
1980s to early 1990s	Convert from sprinklers to drip	1980–95	70 – 260	50 – 250	70 – 220	250 – 400
1995–2005	Adoption of Soil Moisture Monitoring to schedule irrigation events start from middle of 1990s	1995–2005	50 – 150	40 – 250	50 – 150	150 – 250
2006–09	Water restrictions from 2006 to 2010	2006–10	50 – 120	40 – 220	50 – 100	100 – 150

3.7.6. CONFIRMATION FOR IRRIGATION RECHARGE

The good match to groundwater trends indicates that the recharge rates estimated via inverse modelling (calibration) are consistent with available potentiometric head information. Model results are also compared against other datasets to confirm the recharge estimates.

To seek confirmation of recharge estimates, an independent estimate of accession water volumes was undertaken by Fordham *et al*. (2012) and is included in Appendix C-1. The accession estimates are based on a review of irrigation and infrastructure information for the Waikerie to Morgan area sourced from DFW and historical irrigation trust records. A water balance method was employed in the calculation similar to that used by Laroona Environmentrics (2011) for the Loxton-Bookpurnong model (Yan, Li & Woods 2011).

The outputs of this work are compared in Section 4.4.3 to the total recharge applied in the calibrated model to confirm that the modelled recharge is within an appropriate range. The comparison provides confidence that the total recharge applied in the model is within the appropriate range and is consistent with accession estimates. It can be clearly seen that, once the initial lag time is considered, there is close alignment in the increase in calculated and modelled accession volumes. The early gap may indicate the initial losses through wetting front and lateral movement. After the wetting front reaches the watertable, the trends become similar for both the accession water and the total recharge. As expected, the total recharge volume is lower than the accession water. It is noted that accession water is not the same as the total recharge, as in reality they 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. Additionally, the accession water rates differ from the recharge due to losses in the unsaturated zone due to 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 Section 4.4, model outputs are also carefully checked against other key data, including:

- observation bore hydrographs

- RoR salt loads
- NanoTEM patterns of gaining and losing streams.

The confirmations provide confidence that the recharge rates 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.

3.7.7. RECHARGE IN THE WAIKERIE TO MORGAN AREA

3.7.7.1. Recharge in the Qualco-Sunlands area

The edge of recharge to the Glenforslan Formation aquifer under older irrigation developments at Qualco is approximately 300 m wider than the application area, due to the presumed spread of perched aquifers. The existence of two or more clay layers between the root zone and the water table impede the vertical flow of the drainage volume and encourage lateral movement, perching of water and pressure build-up in the Loxton Sands formation.

A study of unsaturated zone modelling at Murtho suggests that after 50 years of irrigation recharge, the lateral spread of water over a 5 m thick aquitard of vertical hydraulic conductivity 10^{-4} m/d is 300 metres wider than the application area (AWE 2011d). Sensitivity analysis suggests that recharge to the water table is highly sensitive to variations in the conditions of the clay layer, such as vertical hydraulic conductivity, thickness and/or weaknesses in the clay (such as higher hydraulic conductivity zones and preferential flow paths, which will increase localized recharge). These variations affect recharge rate, area and lag time.

Lag times of between 5 and 30 years are assumed beneath irrigation areas and perched aquifers. It is assumed that drainage bores began operating approximately five years after irrigation commenced in the area. A lag time of zero is assumed at these “drain bore zones”.

Recharge at the “drain bore zones” commences in 1965 at a rate of 350 mm/y. Recharge within older irrigation developments and beneath perched aquifers commences in 1970 at a rate of 60 to 100 mm/y. Recharge rates in most zones show a decline in 2000 to reflect the assumed improvements in irrigation efficiency in the early 1990s.

3.7.7.2. Recharge in the Waikerie, Golden Heights and Ramco Heights areas

Observation data suggests that the Loxton Sands is partially saturated in the Waikerie area. It is possible that this and other perched aquifers have developed and that their behaviour dominates the volume, area and timing of recharge to the water table. However it is also recognised that many drainage bores were drilled in the Waikerie, Golden Heights and Ramco Heights regions and that these are also partly responsible for the development of the groundwater mounds in the Glenforslan Formation and Mannum Formations.

For simplicity, it is assumed that the footprint of recharge to the water table is equal to the irrigation footprint in the Waikerie, Golden Heights and Ramco Heights areas. Lag times of between 10 and 40 years are assumed. Recharge commences in 1930 at a rate of up to 420 mm/y, declining to approximately 120 mm/y by 2000. Recharge in newer irrigation areas (i.e. established in 1990 or later) commences at a rate of 75 mm/y or less.

3.7.7.3. Recharge in the Markaranka, Taylorville and Toolunka regions

There is no evidence to suggest that perched aquifers have developed in the areas of Markaranka, Taylorville or Toolunka. For this reason, the footprint of recharge is the same as the irrigation footprint in these areas. Recharge rates in most zones show a decline in 2000 to reflect the assumed improvements in irrigation efficiency in the early 1990s.

In the irrigation area of Markaranka, lag times of 10 years are assumed. Recharge commences in 1970 at a rate of 100 mm/y, declining to 50 mm/y by 2000. Recharge in newer irrigation areas (i.e. established in 1990 or later) commences at a rate of 75 mm/y or less.

In the irrigation area of Taylorville, lag times of 10 years are assumed. Recharge commences in 1970 at a rate of 220 mm/y, declining to 100 mm/y by 2000. Recharge in newer irrigation areas (i.e. established in 1990 or later) commences at a rate of 75 mm/y or less.

In the irrigation area of Toolunka, lag times of 10 years are assumed. Recharge commences in 1950 at a rate of 150 mm/y, declining to 75 mm/y by 1995. Recharge in newer irrigation areas (i.e. established in 1990 or later) commences at a rate of 75 mm/y or less.

3.7.7.4. Recharge in the Cadell area

The irrigation areas at Cadell are located on the floodplain. As the watertable is shallow, the waterlogging problem occurred soon after irrigation started. A comprehensive drainage system was constructed in 1923 (Fordham *et al*. 2012) to keep the watertable at a certain depth. There is limited study and insufficient data to inform the timing of groundwater recharge. However, given the shallowness of the watertable in the area, modelled recharge is very similar to the irrigation accession estimated by Fordham *et al*. 2012 and a lag time of zero is assumed.

3.8. MODEL SALINITY ZONES

Salt loads from groundwater to the River Murray are calculated by multiplying the modelled flux through each river kilometre reach by a salinity value assigned to that river kilometre.

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 assigned salinity for a river kilometre is usually the highest local groundwater salinity observed within the Monoman Sands Formation or Glenforslan Formation. If a river kilometre reach has groundwater flux entering it much more strongly from one side than the other, then the adopted salinity value is based on salinity observations from the dominant direction.

The location of the model budget zones and the associated groundwater salinity values are shown in Figures 3.22 to 3.24.

3.9. MODEL SIMPLIFICATION

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

Simulated processes:

- The model does not estimate future impacts due to climate sequence, such as changes in river level, as these are not required for the Salinity Register. One consequence is that the modelled floodplain heads will not mimic fluctuations in observed head due to changes in river level.

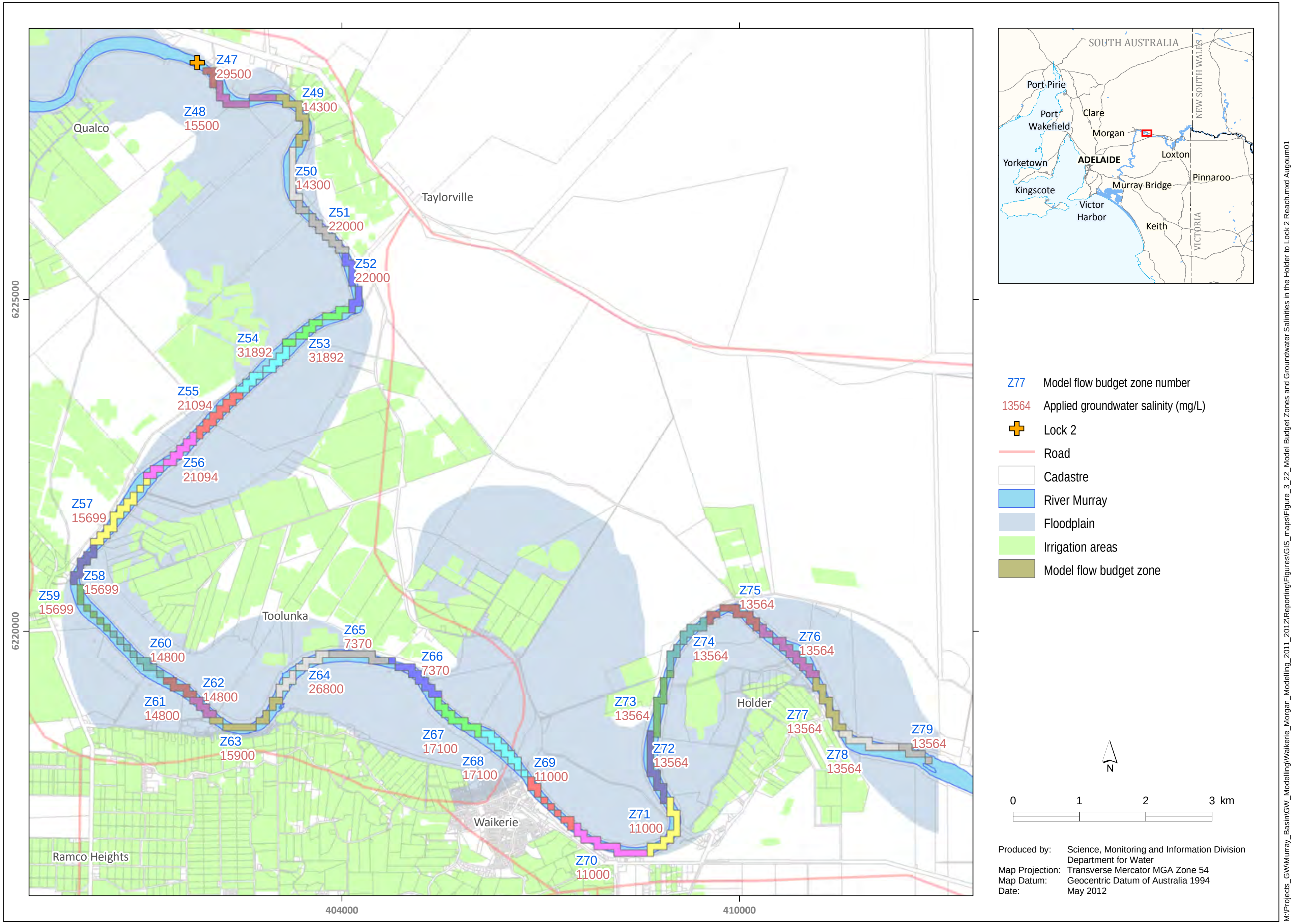


Figure 3.22 Model Budget Zones and Groundwater Salinities in the Holder to Lock 2 Reach

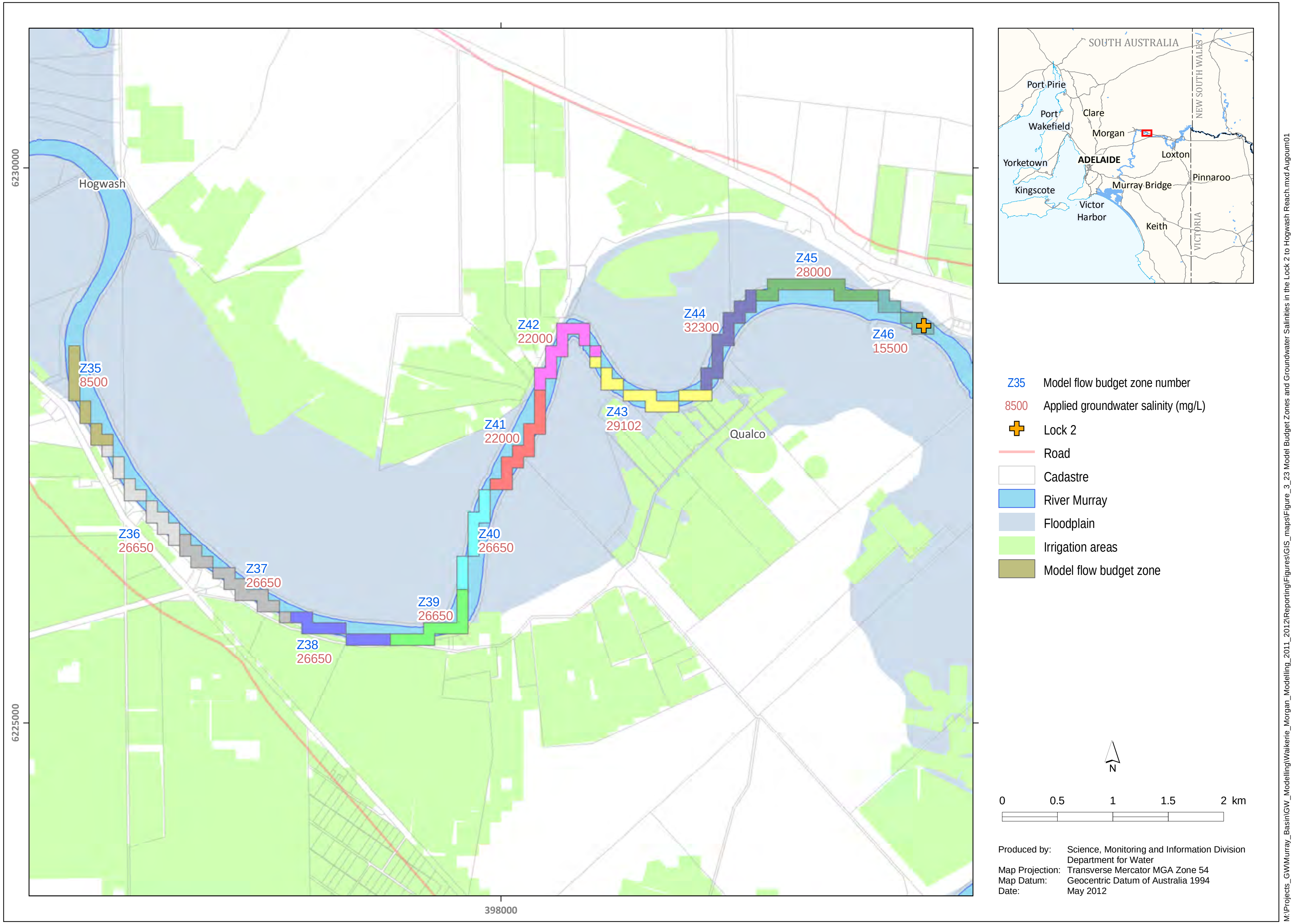


Figure 3.23 Model Budget Zones and Groundwater Salinities in the Lock 2 to Hogwash Reach

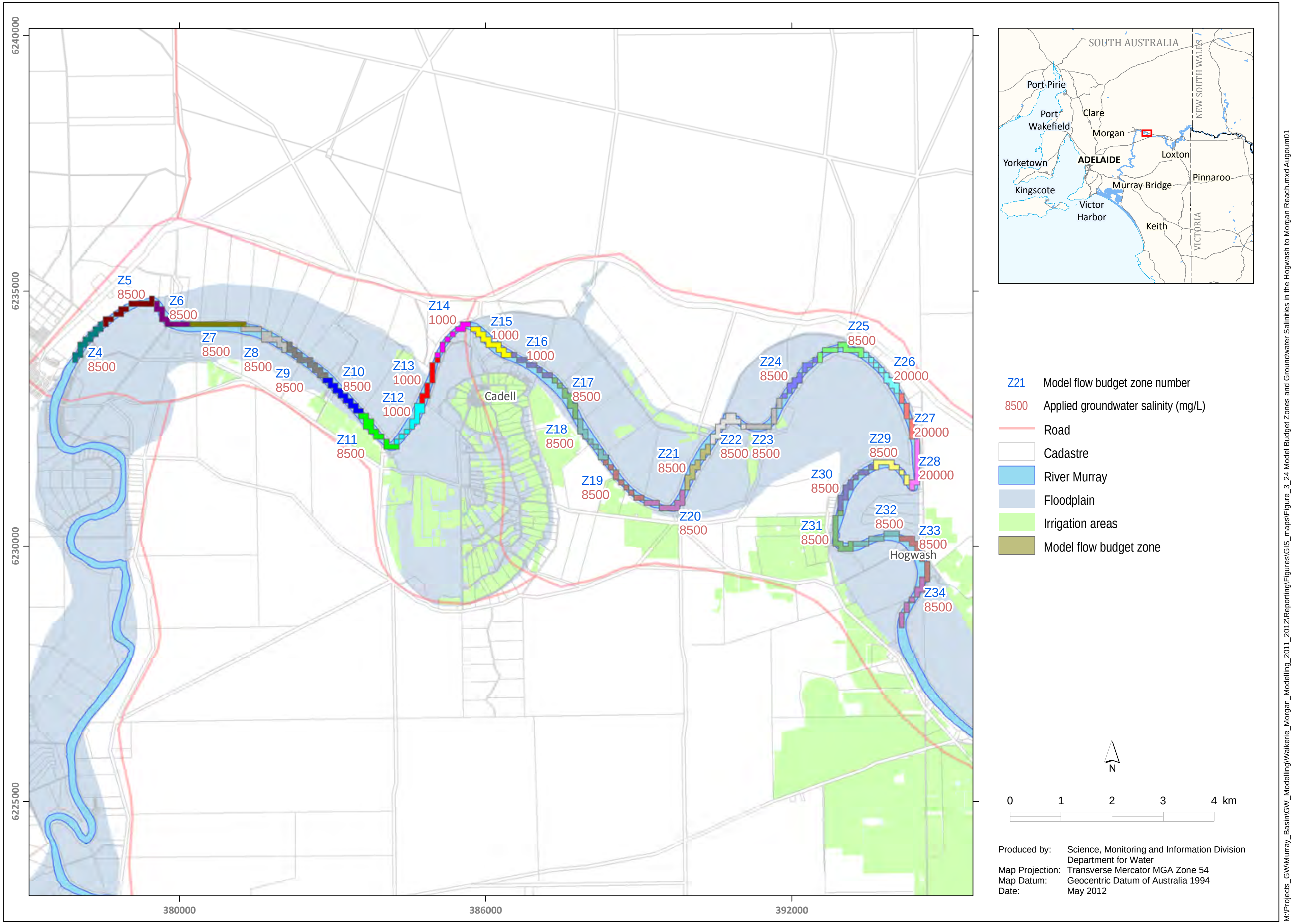


Figure 3.24 Model Budget Zones and Groundwater Salinities in the Hogwash to Morgan Reach

- Perched aquifers and the unsaturated zone are not simulated directly; the impact on recharge rates is instead estimated during the calibration process.
- 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.

Model layers:

- Due to the limited data available, the model layer elevations are necessarily approximate and will not reflect the full heterogeneity of the system (this limitation is true of all numerical models).
- Limited information is available on the top and bottom elevations of the sub-units of the Murray Group outside of the Waikerie and Qualco areas. However, the impact on salt load is considered to be minimal as the majority of salt load comes from the Waikerie and Qualco areas.
- 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.
- The Renmark Group aquifer is not simulated as it is anticipated that the impact to the River Murray is minimal and changes in the interaction between the Renmark Group and the upper aquifers occur over longer timescales than those simulated in the current study.

Stress periods:

- Each stress period is half-a-year long from the commencement of SIS in 1993 and the end of the calibration period in 2011 so short-term changes in SIS pump rates are not included.
- The model does not simulate seasonal changes such as groundwater ET rates that vary over the year.

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.
- Qualitative data suggests that the Glenforslan Formation aquifer may be karstic at the water table in the Waikerie region. It is unknown how far the karst extends.
- No quantitative data exists to inform the storage of the Glenforslan Formation aquifer in the region.
- Cadell is a region of limited field study and there are no aquifer test data available to inform appropriate ranges in aquifer parameters.
- Little data are available for the western portion of the model domain 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.

Boundary conditions:

- Riverbed hydraulic conductivity has not been estimated in the field, so the conductance of the river boundary was estimated during calibration.
- The model assumes a constant groundwater ET rate and extinction depth. This may suit average conditions, but neglects local variations in vegetation, soil type and groundwater salinity.
- 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.
- Except for Qualco, the model assumes that the recharge footprint is the same as the irrigation footprint. This is a reasonable assumption where there are no aquitards in the unsaturated zone, or where irrigation drainage bores extend through such aquitards. There are places within the Waikerie to Morgan area where this assumption is not valid, but there is not enough data on the perched aquifers to precisely identify the extent of the local structures.
- Recharge due to irrigation is complex to define because there is a considerable amount of uncertainty relating to the commencement time of irrigation flux to the surface and the time for the flux to reach the watertable (lag time). It is accepted that the values reported by DFW, AWE and DENR involve professional judgement in the derivation.
- The model simulates Stockyard Plain Disposal Basin in limited detail.
- Some lagoons are not simulated. They may have significant impact on salt loads over brief periods but are less important for the average conditions required for this model.
- Drains and drainage bores are not simulated as distinct, individual features. Their impact is simulated via the recharge rates.

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. An uncertainty analysis should be performed to gauge the robustness of the calibrated model results (Section 6).

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

4.2. STEADY-STATE MODEL CALIBRATION

Steady-state calibration was undertaken to develop a broad-scale hydraulic conductivity distribution and regional boundary conditions. Dynamic stresses and storage effects are excluded from steady-state calibration by definition. Here the steady-state model simulates conditions after river regulation (i.e. after the locks were constructed) but before irrigation.

Hydraulic conductivities and regional flow boundary conditions were varied within reasonable limits. Modelled heads were compared to head observations in areas where there have been no known major changes to the hydrologic processes since the river locks were built, i.e. areas distant from irrigation areas, pumps and the disposal basin.

Barnett (1992) provides estimated potentiometric contours for the regional watertable based on the limited data available. Figure 4.1 shows these potentiometric contours once the irrigation-induced groundwater mounds are removed, providing a provisional description of the pre-irrigation heads. Figure 4.1 also presents the modelled steady-state potentiometric head contours of layer 3 for comparison. Layer 3, representing the undifferentiated Murray Group and Lower Mannum Formations, is the appropriate choice for the comparison, as the watertable lies within the undifferentiated Murray Group along most of the model boundaries and it is expected that there was little head difference between the Lower Mannum and Glenforslan Formations prior to irrigation.

The estimated and modelled contours match well along the model boundaries, indicating that the general head boundary cells provide a good representation of the regional groundwater flow. The estimated and modelled contours also match well in the interior, except that the 4 m AHD contour crosses the River Murray near Hogwash in the estimated contours rather than the modelled location near Lock 2. This is a region where there is no pre-irrigation data on which to base the contour, so the transient calibration is a much better test of the model's accuracy in this area.

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

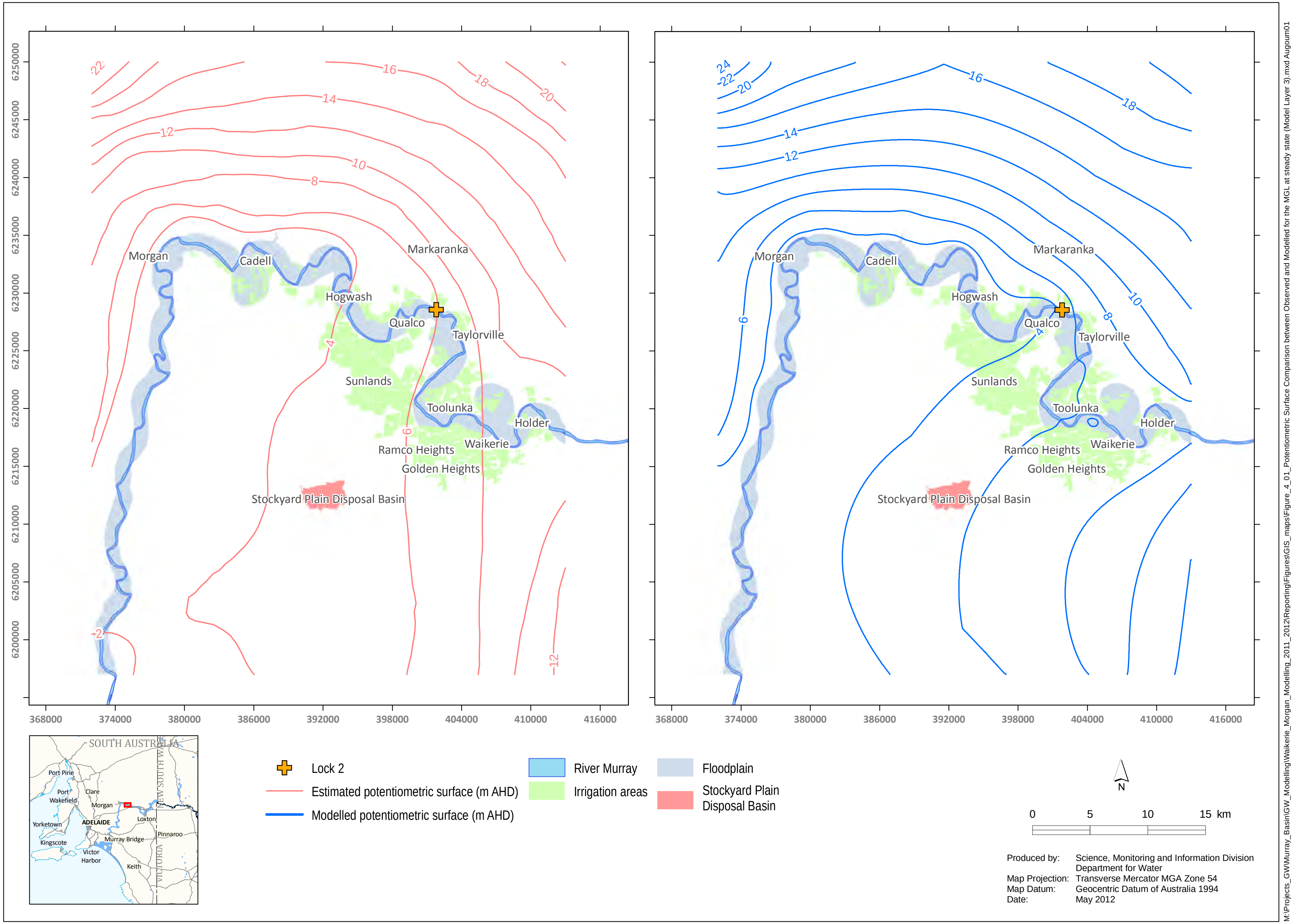


Figure 4.1 Comparison of Estimated and Modelled Potentiometric Surface in Model Layer 3 Lower Mannum Formation and Murray Group Limestone Aquifers in Steady-State conditions

4.3. TRANSIENT MODEL CALIBRATION

The output from the steady-state model with matching parameters and boundary conditions provides the initial conditions for transient model runs. The historical period from 1920 to 2011 was simulated.

Transient calibration was undertaken on an iterative trial-and-error basis. The parameters varied during the transient calibration were hydraulic conductivity, boundary conditions and irrigation recharge. Hydraulic conductivities and boundary conditions were altered within known ranges and reasonable limits, to achieve a good match to observed heads at early times.

The irrigation recharge was the main parameter used in the transient calibration to achieve a good match between modelled and observed groundwater trends, as the trends were mainly driven by irrigation recharge in the study 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 available data, but can be checked whether it is within the estimated ranges of irrigation accessions, as the latter can be estimated with some confidence.

Model calibration was guided by the following actions, in accordance with the *Groundwater Flow Modelling Guideline* (MDBC 2001):

- qualitative comparison between modelled and observed potentiometric heads, both contours and hydrographs
- quantitative assessments of the Scaled Root Mean Square (SRMS) error
- quantitative confirmation that the water balance error is <1% for all times
- confirmation, as a water balance cross-check, by comparing model outcomes with:
    - total RoR salt load entering the River Murray
    - in-river NanoTEM
    - estimated accession volumes
    - actual groundwater evapotranspiration.

The purpose of the model is to estimate salt loads in the Waikerie to Morgan project area. The majority of the salt loads entering the River Murray are from the following sources:

- lateral groundwater flux from the Glenforslan Formation to the river through the Monoman Formation as a natural process and with increased flux as a resulting from irrigation water mounding
- vertical groundwater flux from the Mannum Formation to the river valley through the Monoman Formation as a natural process with increased flux as a result of irrigation water mounding.

Matching observed groundwater level trends in the irrigation areas near the River Murray was therefore considered imperative during calibration.

Section 3.7.5 provides further information on the calibration process, particularly in regard to irrigation recharge estimation.

4.3.1. CALIBRATION RESULTS — POTENTIOMETRIC HEAD CONTOURS

Modelled regional potentiometric head contours were compared with potentiometric head values observed at the end of 2008 (AWE 2011a). The model contour shapes were also compared with contours developed from 2008 observations supplemented by older observations in regions with little 2008 data (AWE 2008b). Both the head elevations and the flow directions should be evaluated.

4.3.1.1. Layer 1: Glenforslan Formation and Monoman Formation

The key model output, groundwater salt load to the River Murray, depends on potentiometric head gradients near the river. Figure 4.2 and the model hydrographs (Section 4.3.2) show a good match between observations and model results near the river and within the floodplain.

The peak 2008 observed potentiometric heads within the irrigation-induced groundwater mounds were 20.0 m AHD at bore SQ13B in Qualco and 14.4 m AHD at bore WG2U in Waikerie and Golden Heights. At these bore locations, the modelled head is 17.6 m AHD and 14.5 m AHD respectively. The model estimates that the maximum groundwater mound head occurs some distance from the observation bores, peaking at 20.5 m AHD and 19.6 m AHD respectively.

Head may be overestimated to the west and south of Stockyard Plain disposal basin, suggesting that it may be possible to improve the model’s representation of the basin. The higher head is unlikely to affect salt loads to the River Murray, which depend on groundwater gradients closer to the river than these areas.

Figure 2.13 shows the 2008 Glenforslan potentiometric head contours estimated in AWE (2008b) which can be compared with the model contours of Figure 4.2. The flow directions, perpendicular to the contours, match well in most areas. The main discrepancy is at Qualco, where the AWE (2008) groundwater mound has higher head and extends closer to the river, however, this is due to the contours incorporating pre-scheme head values (marked in red) which will have dropped since the construction of the QSTGCS. Similarly, the wider spread of the 16 m AHD contour at Waikerie and Golden Heights in the AWE (2008) contours may be due to the incorporation of pre-2008 observations between Golden Heights and Stockyard Plain.

4.3.1.2. Layer 3: Lower Mannum Formation

Figure 4.3 displays the modelled potentiometric contours and observed values for the Lower Mannum Formation (model layer 3) in 2008.

There is a good match between observed values and model results, including near the river (see also Section 4.3.2 for hydrographs). The maximum observed head within the Qualco-Sunlands groundwater mound is 19.4 m AHD at bore QS12LM, while the modelled maximum for the mound is 16.7 m AHD. This suggests that the model may underestimate the peak value, but the model has a better match at other locations within the mound and matches the hydrographs reasonably well (Section 4.3.2). The maximum observed potentiometric head for the Waikerie and Golden Heights groundwater mound in 2008 was 14.4 m AHD at bore WG2L, while the modelled head at this location was 14.5 m AHD.

No observation data from 2008 are available within the central part of Waikerie and Golden Heights groundwater mound for comparison with model results.

Figure 2.8 shows the 2008 Lower Mannum Formation potentiometric head contours estimated in AWE (2008b) which can be compared with the model contours of Figure 4.3. The contours have similar shapes, indicating that the AWE (2008) estimates and model results have very similar flow directions.

4.3.2. CALIBRATION RESULTS — HYDROGRAPHS

As mentioned in Section 3.7.5, irrigation recharge is the major factor that drove groundwater level change (trends) in the irrigation areas prior to the construction of the GCS and SIS. Hydraulic conductivities control the head level rather than the trend. Specific yield has little impact on the trend-matching process due to the relatively slow pace of irrigation-induced groundwater level change

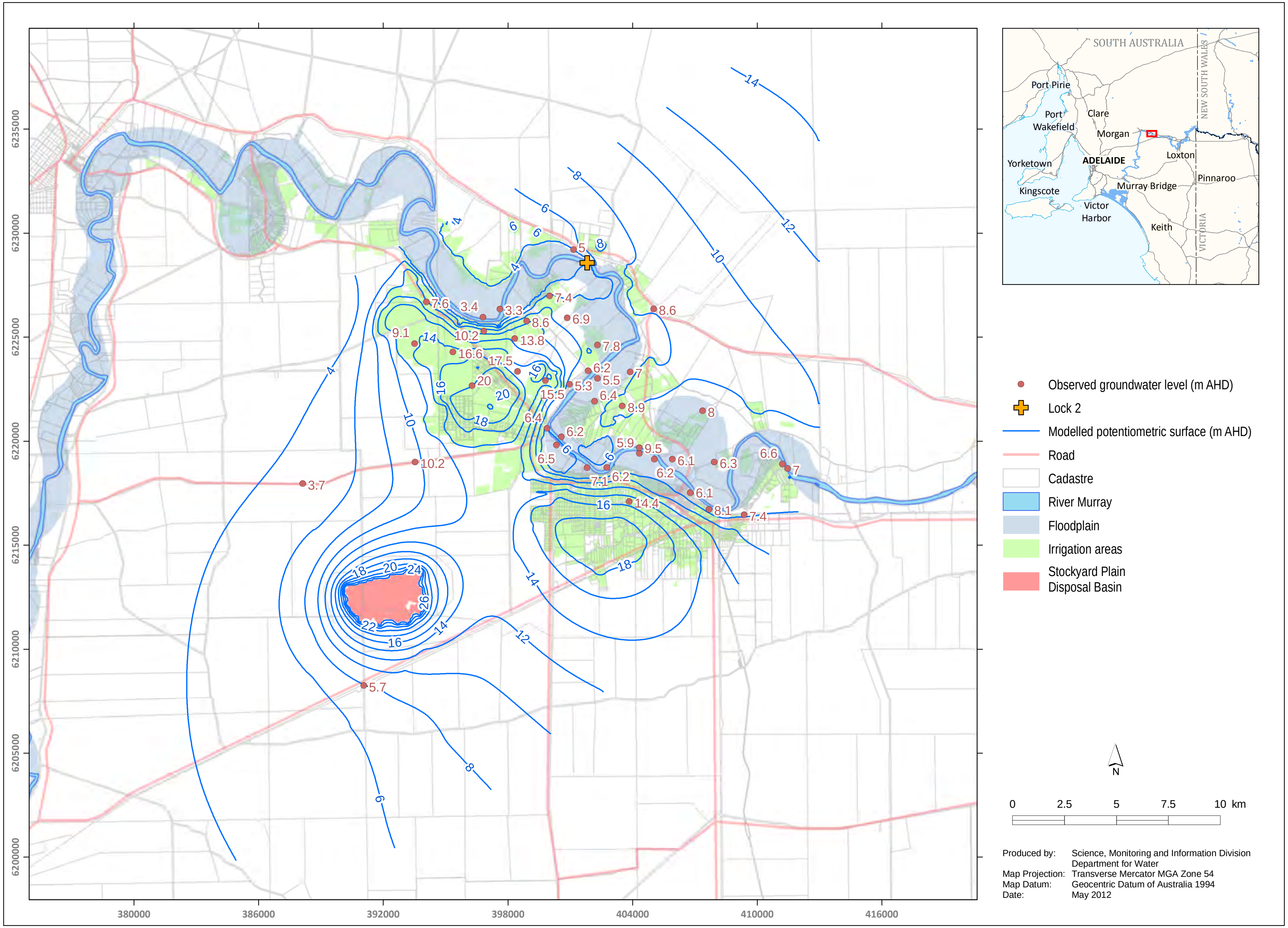
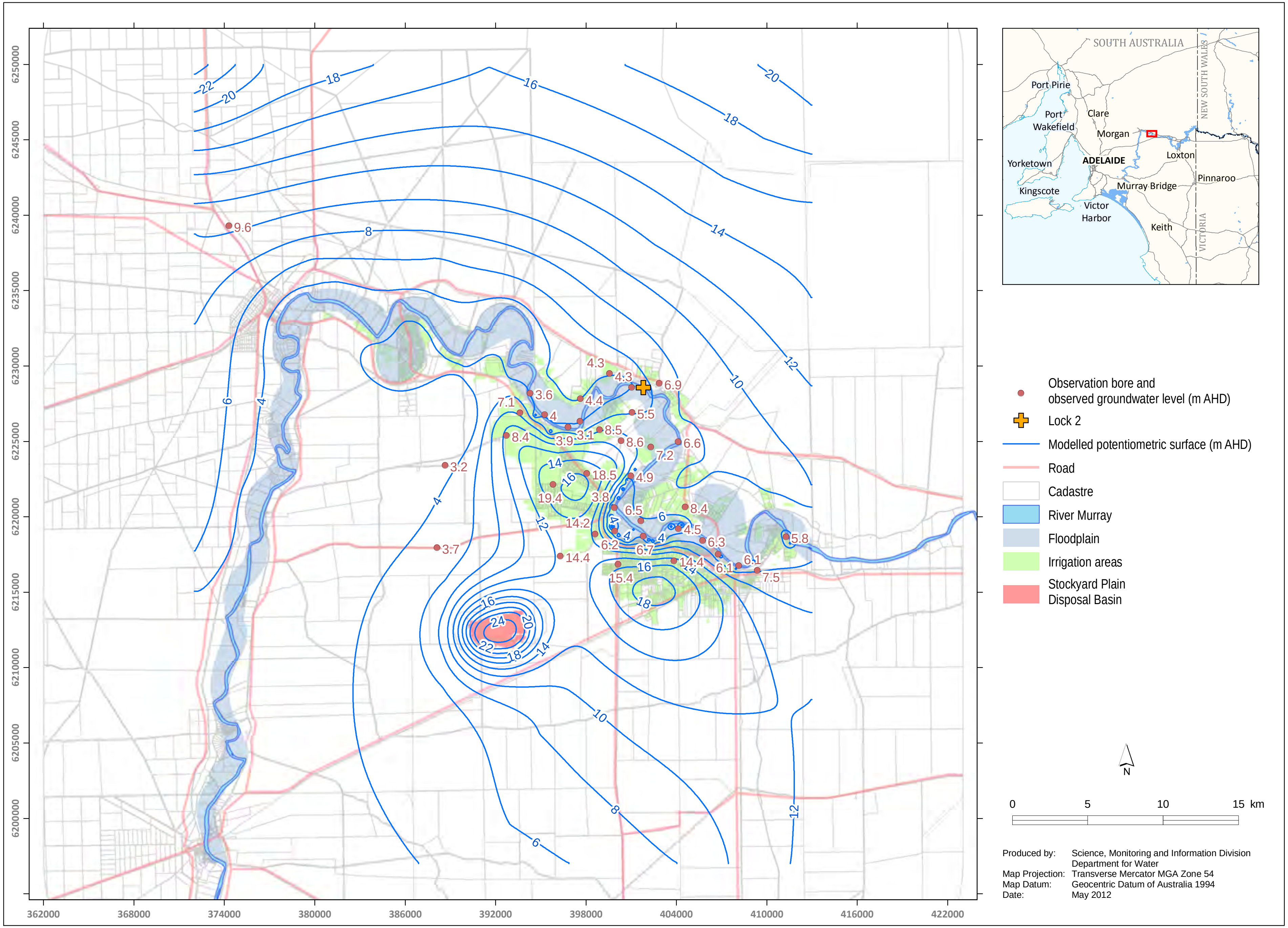


Figure 4.2 Comparison of Observed Groundwater Level and Modelled Potentiometric Surface in Model Layer 1 Glenforslan and Monoman Formation Aquifers at 2008

M:\Projects_GW\Murray_Basin\GW_Modelling\Waikerie_Morgan_Modelling_2011_2012\Reporting\Figures\GIS_maps\Figure_4_02_Potentiometric Surface Comparison between Observed and Modelled for the GF and MF at 2008 (Model Layer 1).mxd Auguoum01



M:\Projects_GW\Murray_Basin\GW_Modelling\Waikerie_Morgan_Modelling_2011_2012\Reporting\Figures\GIS_maps\Figure_4_03 Potentiometric Surface Comparison between Observed and Modelled for the LMF and MGL at 2008 (Model Layer 3).mxd Augoum01

Figure 4.3 Potentiometric Surface Comparison between Observed and Modelled for the Lower Mannum Formation and Murray Group Limestone Aquifers at 2008 (Model Layer 3) (month/years) in the highland area. Note that this is distinctly different to the rapid changes in head in response to pumping activities such as salt interception schemes.

There are many observation bores in the model area, so a subset was chosen (see Section 2.3.10). The selected bores either contain reliable long-term historical observation data or are SIS observation bores. Some of the SIS bores are of recent construction and provide little historical data, but are included as they provide information on aquifer response to pumping. Most of the selected observation bores are located in areas where irrigation mounds occur, or are close to the river, so that a good match to observations would suggest that the model adequately simulates groundwater flux to the river.

Most of the selected observation bores are in the Glenforslan and Monoman Formations (layer 1) and the Lower Mannum Formation (Layer 3), as these are the major aquifers that contribute salt load to the River Murray in the Waikerie to Qualco reach. A few bores lie within the model layer 2 in the Cadell area, where layer 2 represents the undifferentiated Murray Group Limestone aquifer. The location of the selected observations bores is given in Figures 2.18 to 2.20.

Most irrigation-area hydrographs in the Glenforslan and Lower Mannum Formations show a rising trend as groundwater mounds develop due to irrigation recharge. The hydrographs generally decline as changes in irrigation practice lower recharge rates and as the GCS and SIS become operational. For the Monoman Formation floodplain hydrographs, water level fluctuations are due to river level change and SIS pumping.

A comparison of modelled and observed (historical) potentiometric heads indicates a close match in most bores (Figures 4.4 to 4.10) in terms of actual levels and trends.

4.3.2.1. Waikerie

Figure 4.4 compares the observed and modelled hydrographs for Waikerie, including the Holder and Ramco Heights areas.

At Holder, adjacent to the River Murray and the model's eastern boundary, the match between observed and modelled hydrographs is extremely good. All bores have a good match to head levels. Bores HOL 08, HOL 10 and HOL 11 demonstrate that the modelled head and response to pumping from the Waikerie SIS is accurate in both the Glenforslan and the Lower Mannum Formations. The observation bores close to the river, HOL 11 and OB 16U, show elevated heads when the river level is high in the early 1990s and late 2010, which the model is not designed to match, but the match is good during times of lower river level.

Near the town of Waikerie, the comparison is again extremely good. LMF bores OB 8-9, OB 10-11, WF 20, close to the Waikerie SIS production bores, show a good match to both heads and response to pumping. The Glenforslan and Monoman bores near the SIS and the river, OB 7–8a, OB 10-11 and WG3U, match trends except those due to high river levels, which are not modelled. OB 7–8a and OB 10-11 match well to observed potentiometric heads while head at WG3U is underestimated by the model. A bore further away from the river and within the Waikerie groundwater mound, WG 2U, shows a good match to the head and to its decline in the past twenty years, although the observed heads may have been slightly higher than modelled in the early 1990s.

Results are similar for the Ramco Heights region. Bores OB 3-4L shows a good modelled head and response to pumping, Monoman Sands bore OB 3-4A has a good match between observed and modelled head, except during times of high river level and the bores within the groundwater mound, MOB 1U, MOB 2L and MOB2U, show a fair to very good match to levels and trends.

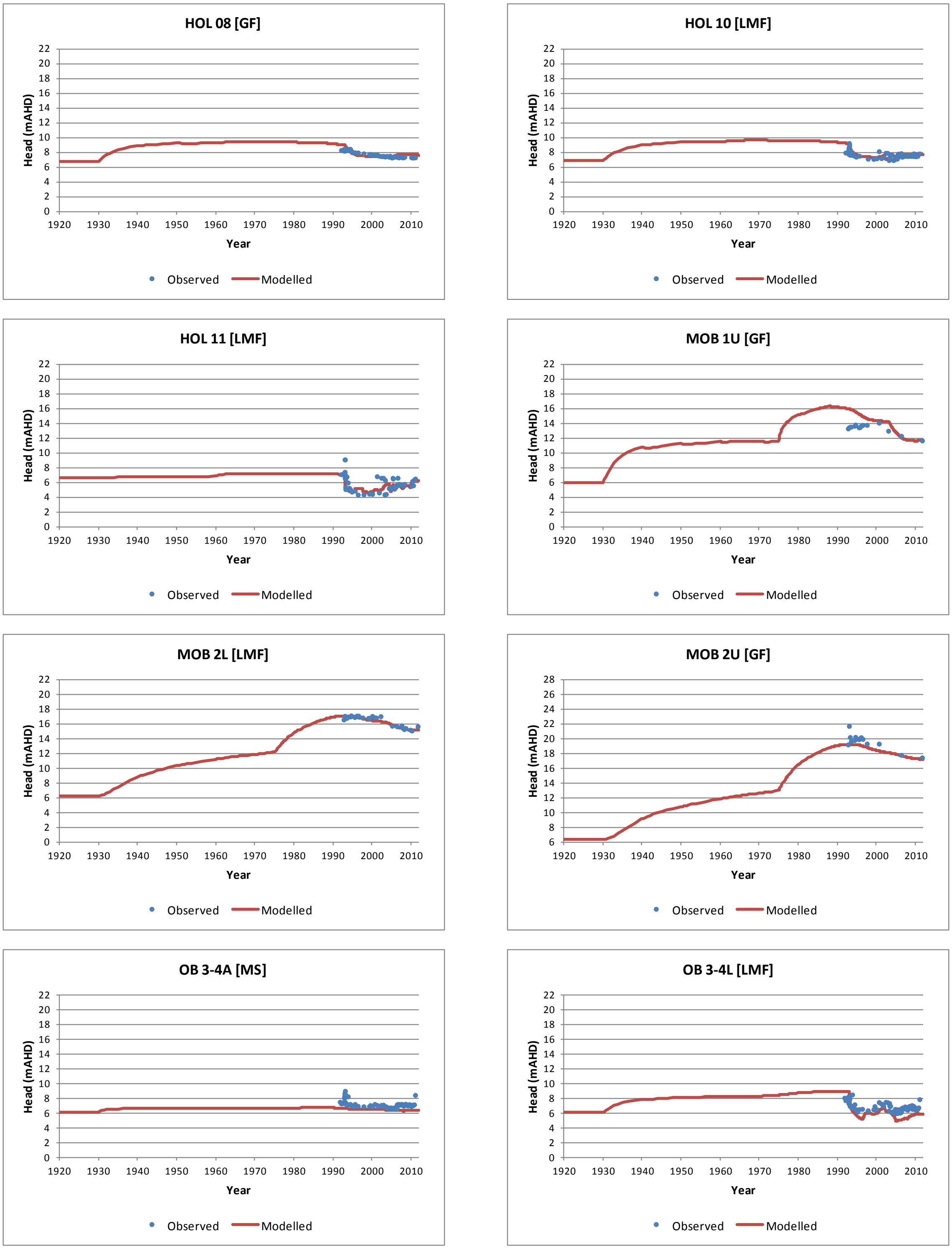


Figure 4.4a **Hydrographs Comparison between Observed and Modelled for Waikerie**

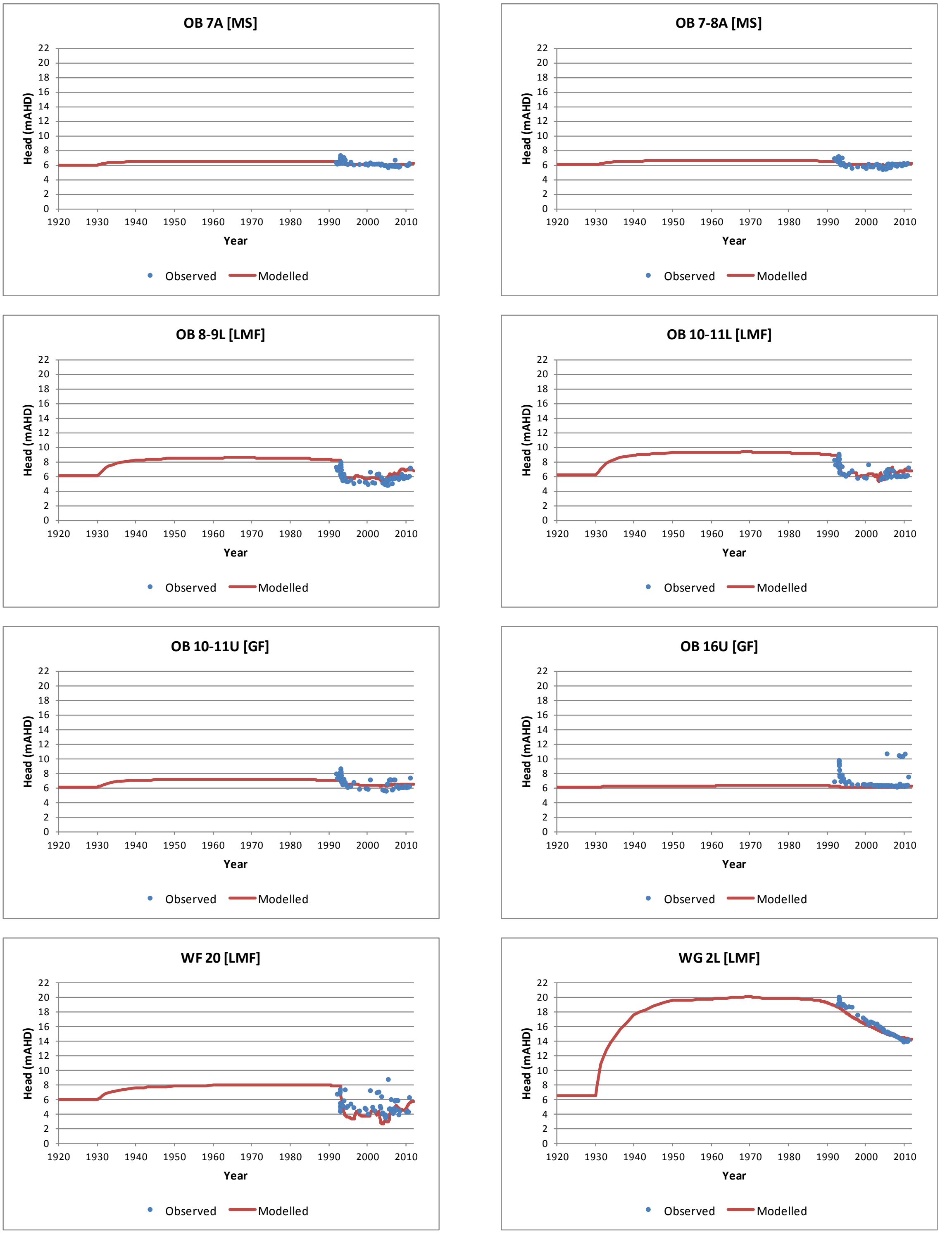
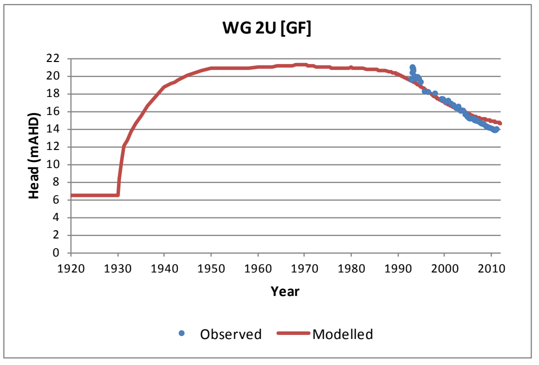


Figure 4.4b Hydrographs Comparison between Observed and Modelled for Waikerie



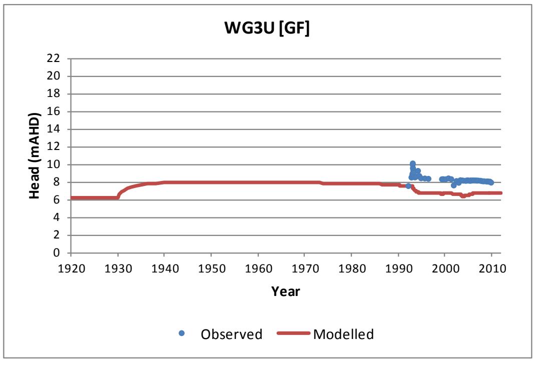


Figure 4.4c Hydrographs Comparison between Observed and Modelled for Waikerie

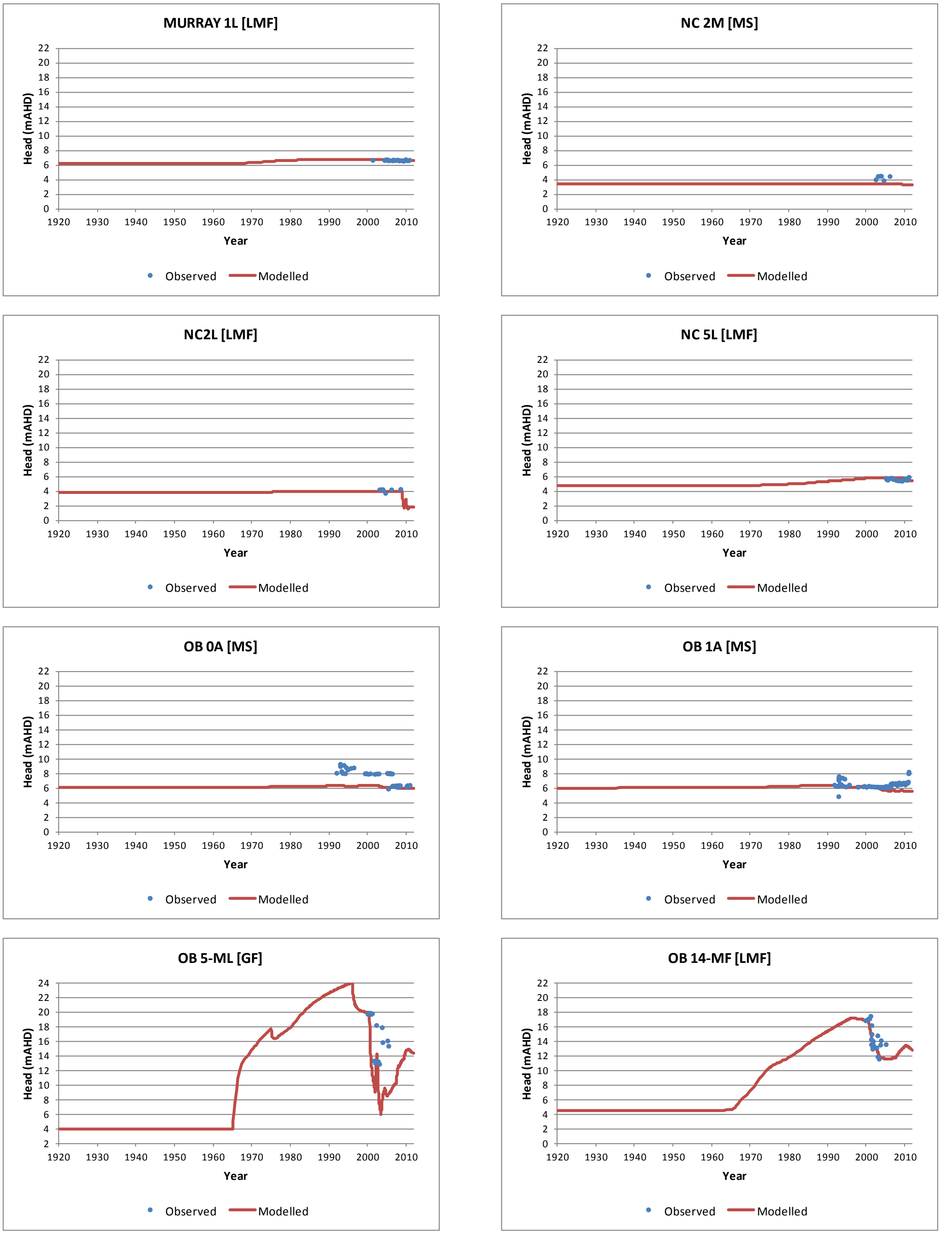


Figure 4.5a **Hydrographs Comparison between Observed and Modelled for Qualco-Sunlands**

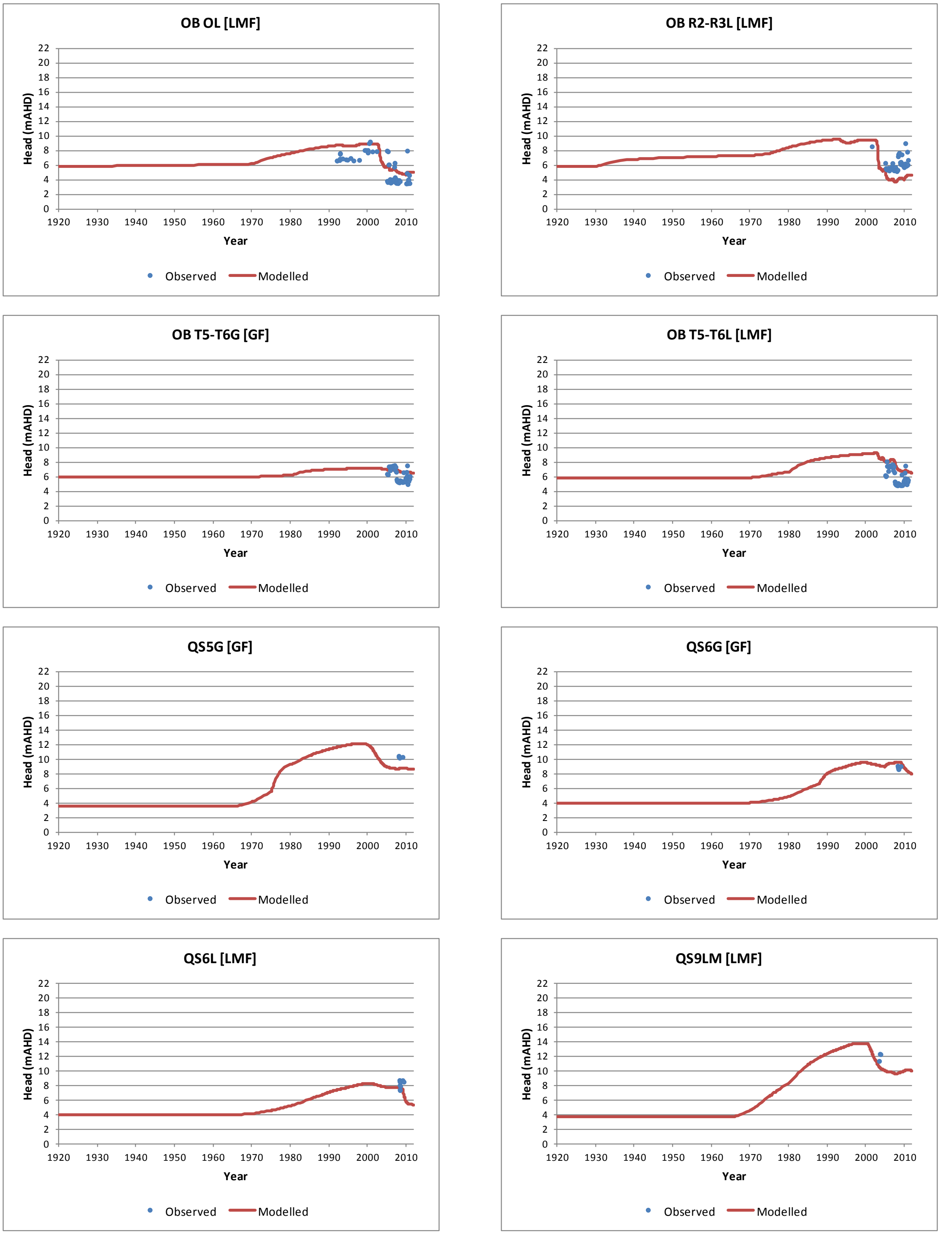


Figure 4.5b Hydrographs Comparison between Observed and Modelled for Qualco-Sunlands

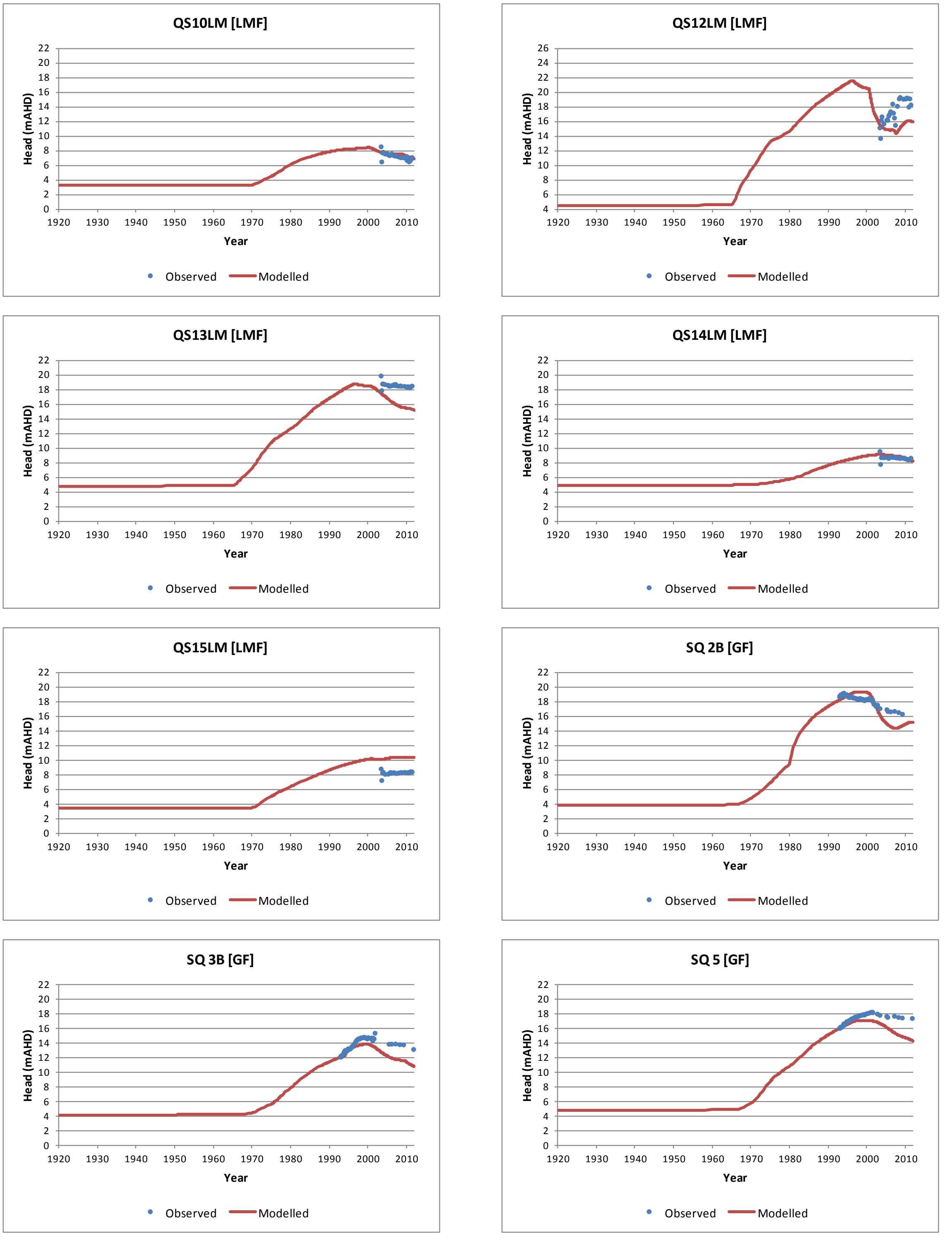


Figure 4.5c Hydrographs Comparison between Observed and Modelled for Qualco-Sunlands

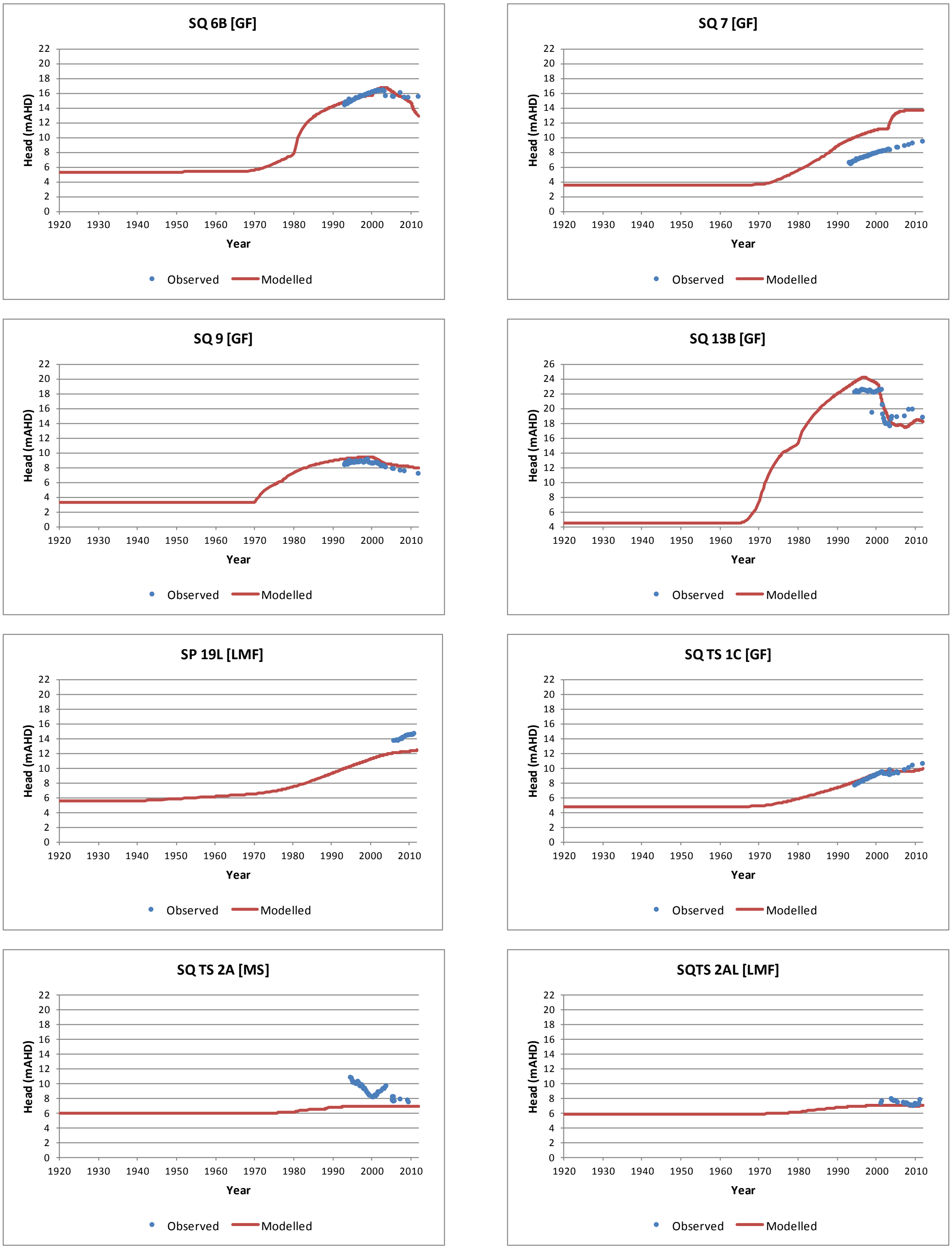


Figure 4.5d Hydrographs Comparison between Observed and Modelled for Qualco-Sunlands

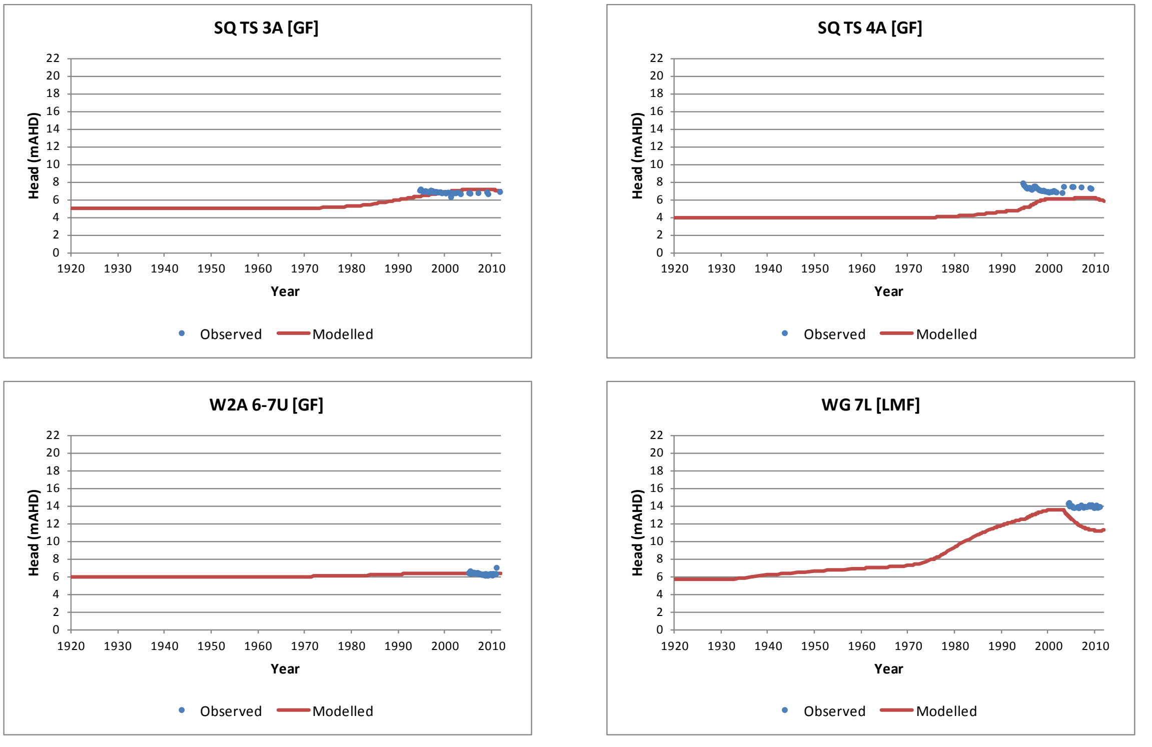


Figure 4.5e Hydrographs Comparison between Observed and Modelled for Qualco-Sunlands

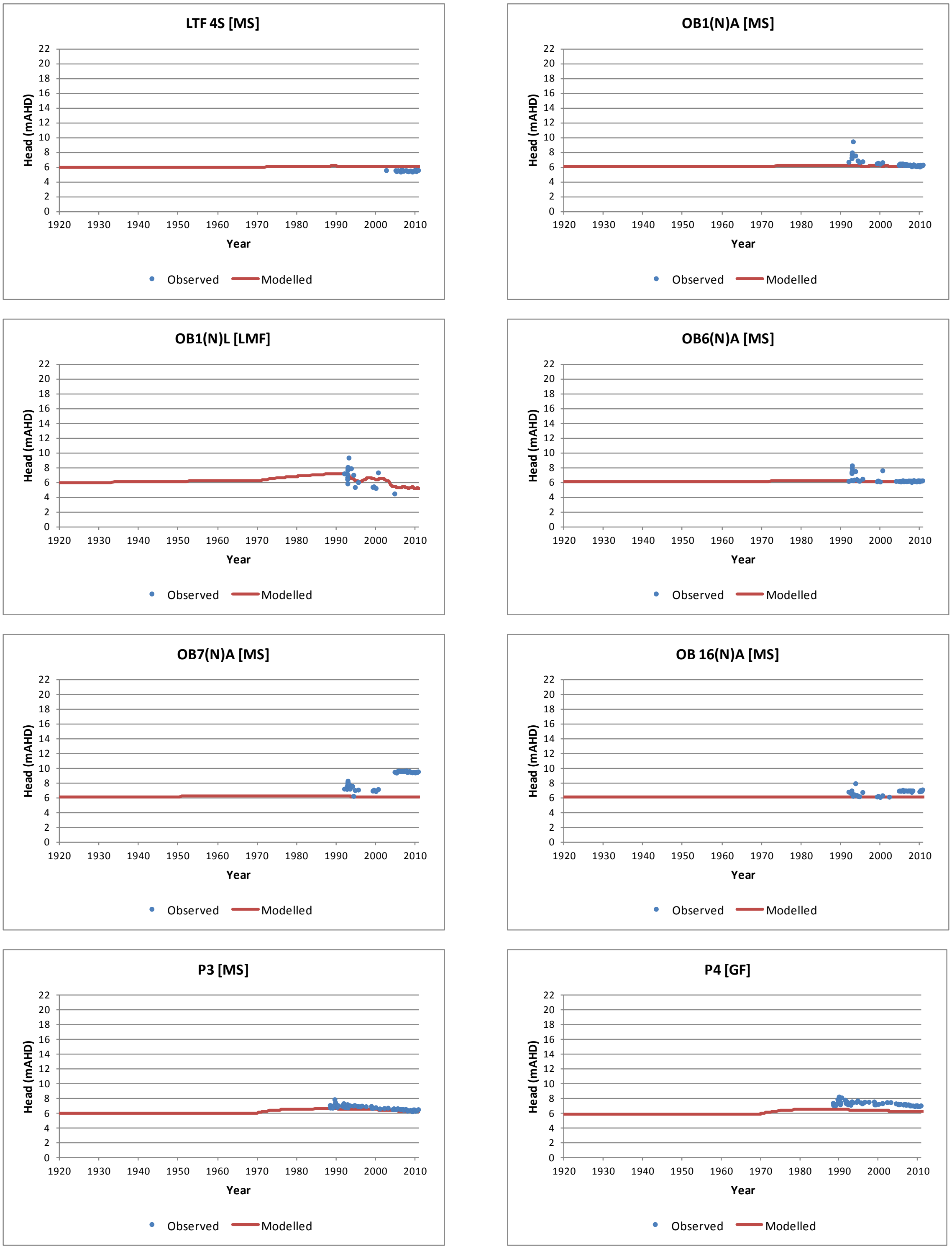


Figure 4.6a Hydrographs Comparison between Observed and Modelled for Toolunka

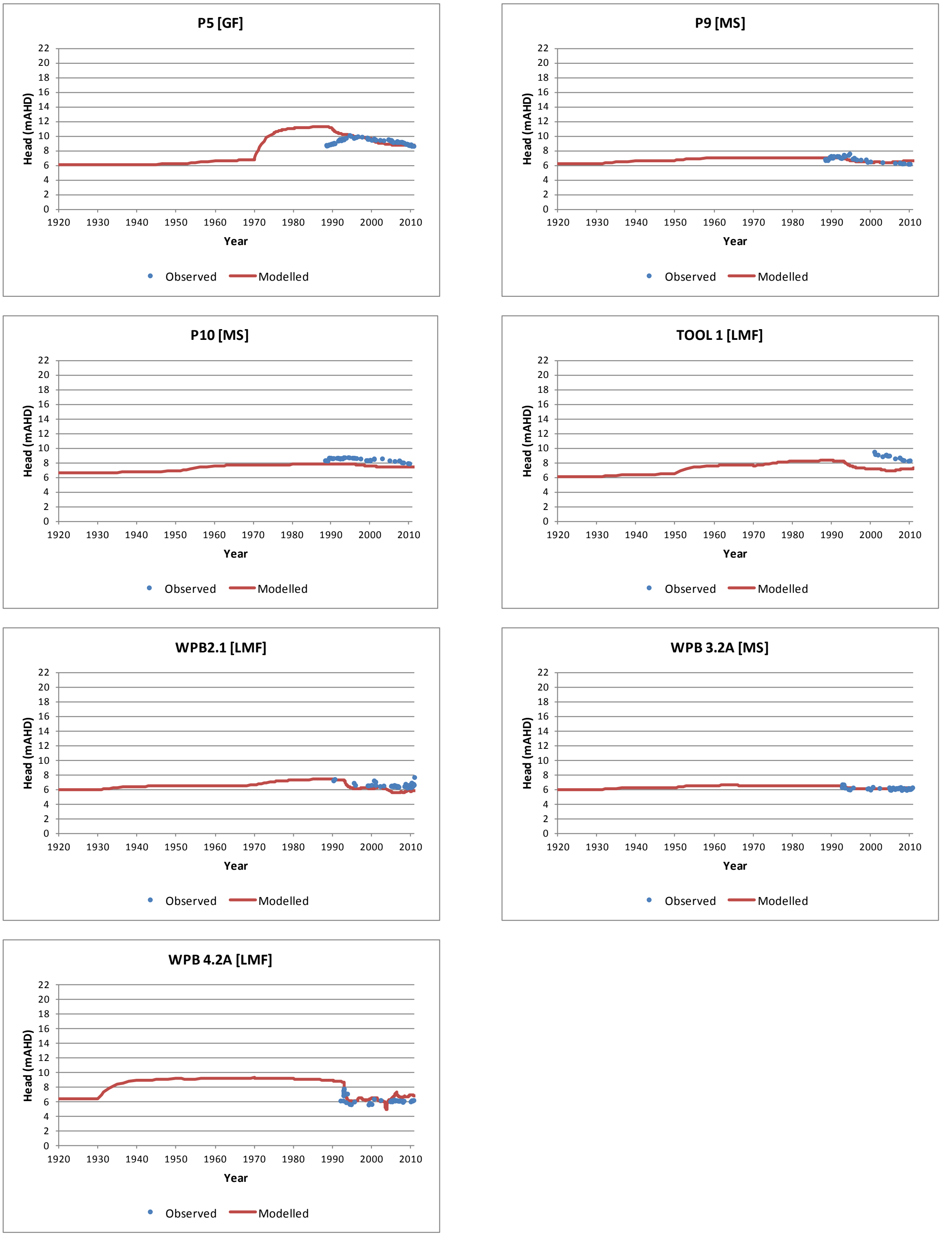


Figure 4.6b Hydrographs Comparison between Observed and Modelled for Toolunka

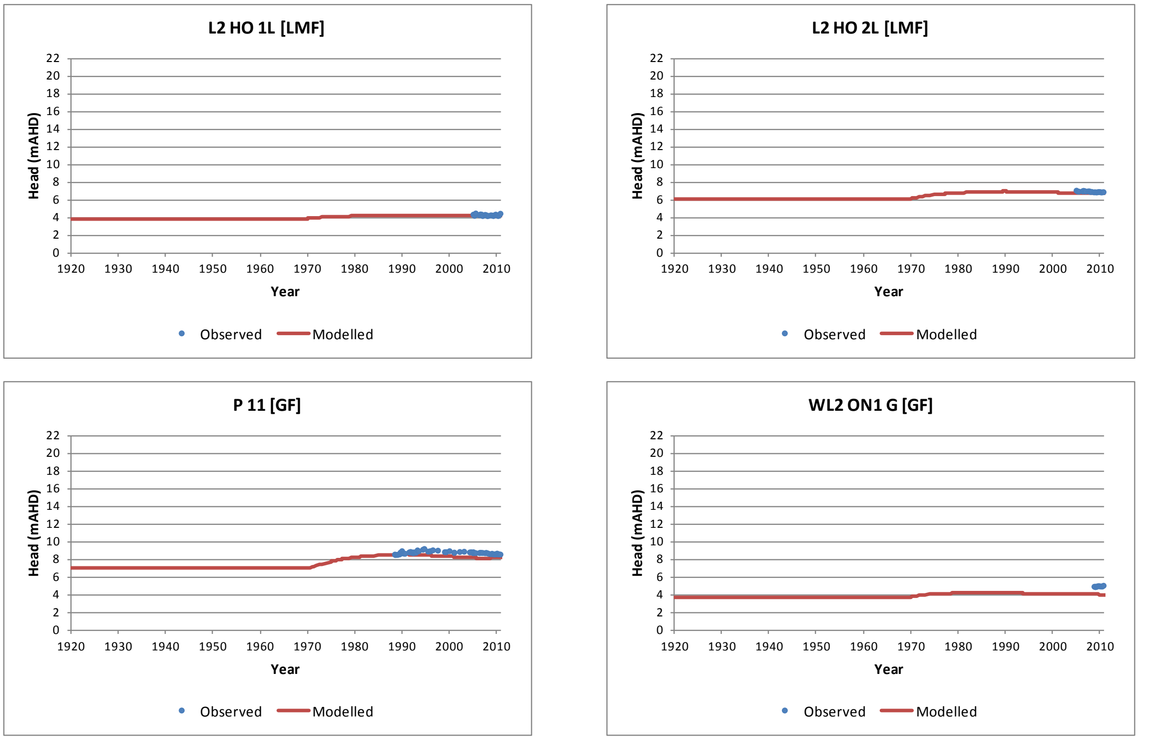


Figure 4.7 Hydrographs Comparison between Observed and Modelled for Taylorville

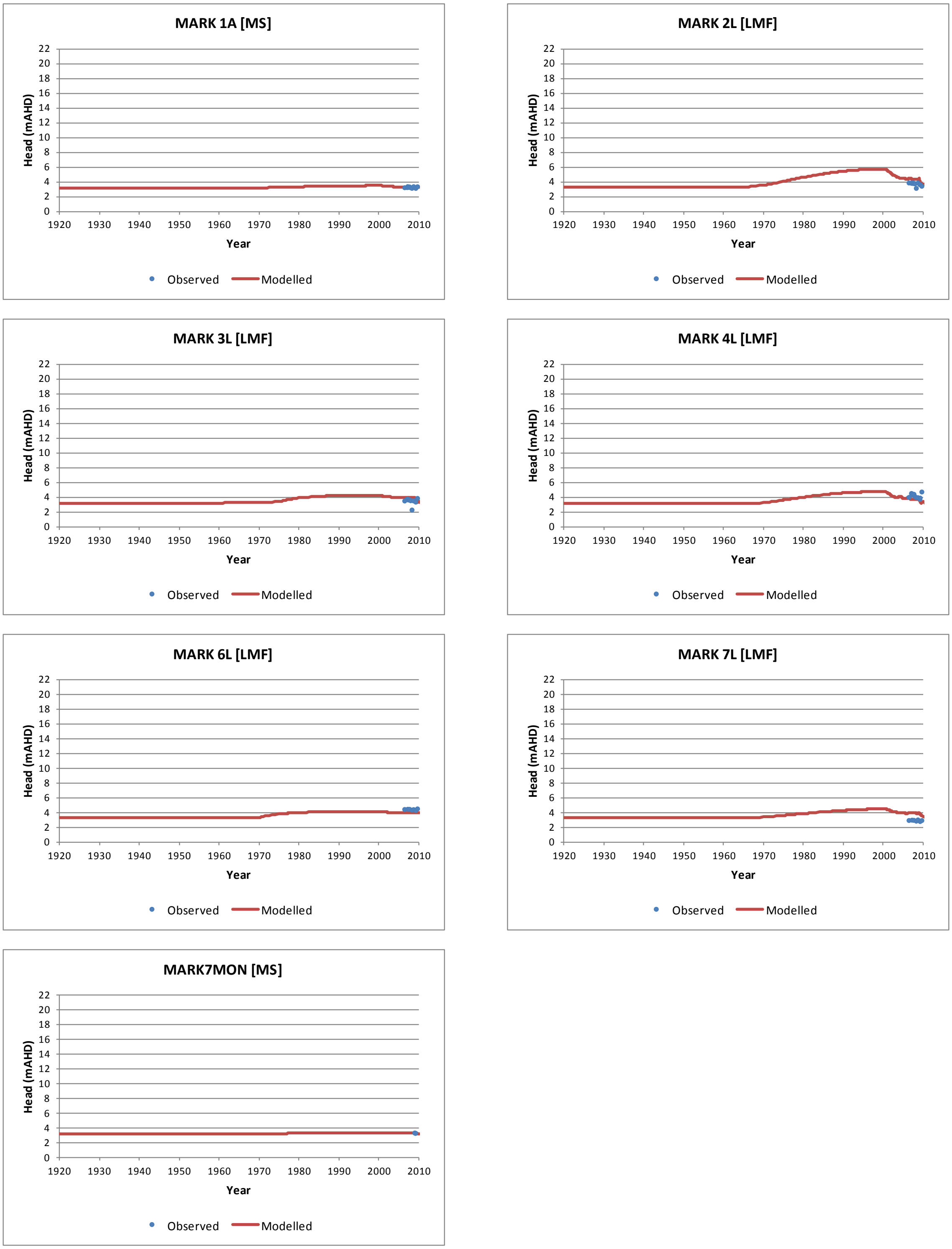
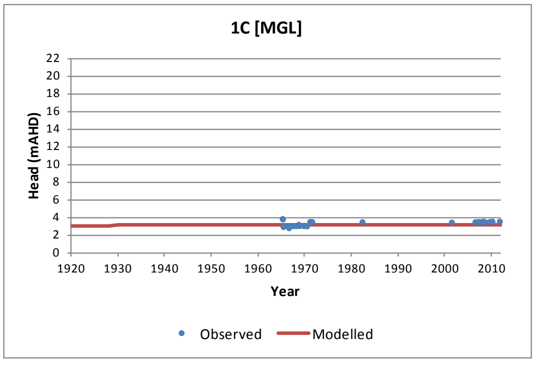
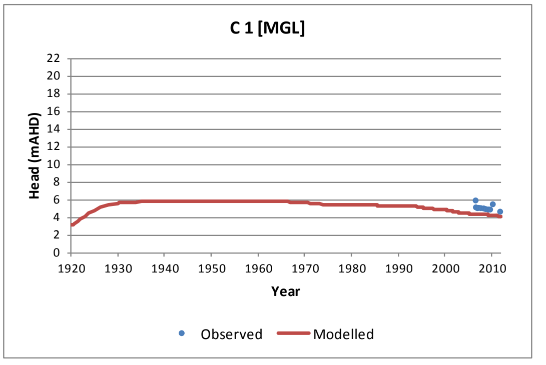


Figure 4.8 Hydrographs Comparison between Observed and Modelled for Markaranka





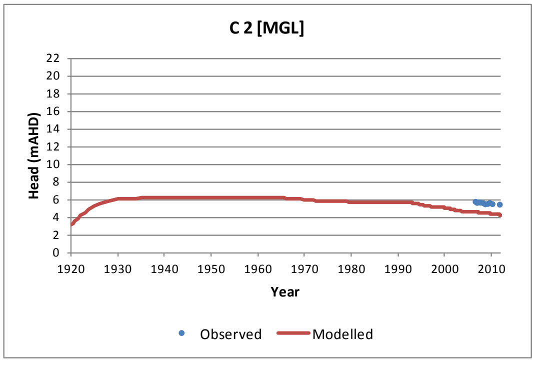


Figure 4.9 Hydrographs Comparison between Observed and Modelled for Cadell

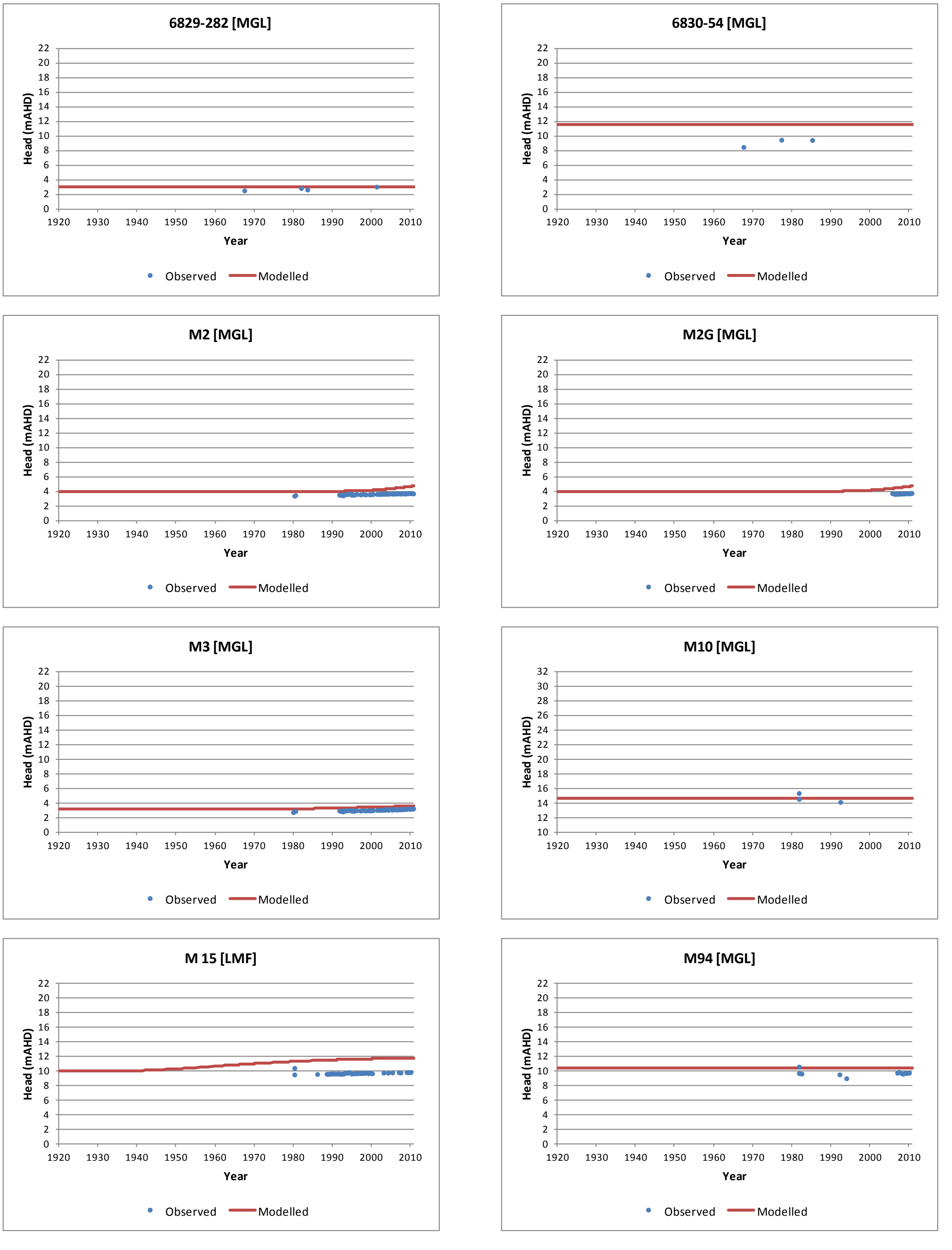


Figure 4.10a Hydrographs Comparison between Observed and Modelled for Regional Areas

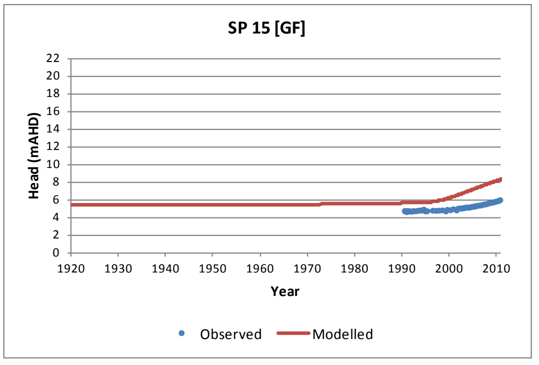


Figure 4.10b Hydrographs Comparison between Observed and Modelled for Regional Areas

4.3.2.2. Qualco-Sunlands

Figure 4.5 compares the observed and modelled hydrographs for Qualco-Sunlands.

For the region north of Ramco Heights along the western stretch of the Waikerie II scheme, there is a good to excellent match between observations and model results with the Glenforslan aquifer (bores SQ 6B, W2A 6-7U, OB T5-T6G). Monoman Sands bore OB 1A has good results, given that the model does not simulate changes in river level, but OB 0A has a good match only for 2005 onwards. Most of the LMF bores have a good modelled trend, including response to SIS pumping, but the head is 1 to 2 m higher or lower than observed (OB 0L, OB T5-T6L, OB R2-R3L, SP 19L). LMF bore WG 7L shows a poor match between observed and modelled trends for reasons which are unclear.

Another group of bores lies south of Lock 2, within or close to the floodplain. The Monoman and LMF bores have an excellent match between observed and modelled heads (Murray 1L, NC 5L, NC2L, NC2M, QS14LM, QS6L and SQTS 2AL). The Glenforslan bores have a good match at QS6G, but the trends are imperfect at bore SQ TS 3a and poor at SQ TA 4A. Nearby Monoman bore SQ TS 2A also has a poor match. These three bores lie within or near the floodplain and are close to irrigation. It is possible that some localised process may have occurred here which is not simulated in the model.

The calibration of Glenforslan bores in the Sunlands and QSTGCS area is not as successful as elsewhere, perhaps reflecting the complexity of the processes occurring to irrigation drainage as it passes through multiple strata before recharging the Glenforslan Formation aquifer. Some bores, SQ 2B, SQ 3B, SQ 5 and perhaps OB-5-ML, match potentiometric head fairly well, but the rate of decline since 1990 is more rapid in the model results than in observations. SQ 7 demonstrates a poor match between modelled and observed heads, but this has been true of previous models, indicating that some unknown feature affects potentiometric head at that site. Three bores which lie further away from the centre of the groundwater mound, SQ 13B, SQ 9, SQ TS 1C, do show a good match between observed and modelled heads and trends. The model underestimates potentiometric head for bore QS 5G.

The LMF bores at Qualco also vary in their quality of calibration. Bores showing a good match to potentiometric head and trends include: OB 14-MF, QS10LM and arguably QS9LM. QS15LM shows a good trend but modelled heads are higher than those observed. Bores with a poor match between observed and modelled trends are QS12LM and QS13LM. There is no obvious correlation between location and quality of calibration.

4.3.2.3. Toolunka, Taylorville and Markaranka

Figure 4.6 compares observations to modelled hydrographs for bores near Toolunka. There are numerous observation bores within the Monoman Sands. The modelled hydrographs are an excellent match with observation potentiometric head, given that the model does not simulate changing river levels (bores LTF 4S, OB 16(N)A, OB1(N)A, OB6(N)A, WPB 3.2A, P3, P9 and P10). The one exception is OB7(N)A, where observed heads rose by more than 3 m from 2001 to 2005 for reasons which are unclear.

Two of the selected calibration bores at Toolunka monitor the Glenforslan Formation. The modelled head for bore P4 shows a good match to trends but can be 1 m lower than observed. The modelled head for bore P5 is a poor match to observations until the mid-1990s, after which point the match is very good.

Four of the Toolunka calibration bores monitor the Lower Mannum Formation. WPB 4.2A and WPB2.1 show an excellent match between observed and modelled heads and OB1(N)L shows a reasonable match. TOOL-1 shows a poor match, as the observed heads are higher and are declining more rapidly than the modelled heads. In summary, the Toolunka bores generally show a good calibration, except in the area near the adjacent bores OB7(N)A, P5 and TOOL-1.

Based on the chosen hydrographs, the model simulates trends in potentiometric head accurately at Taylorville (Figure 4.7). The modelled head levels are generally very close to observed levels (bores L2 HO2L, P11). WL2 ON1 G has modelled heads which are approximately 1 m too high.

All but one of the bores in Markaranka show a good match between observed and modelled potentiometric heads (Figure 4.8). The exception is MARK 7L, which has a modelled head approximately 1 m higher than observed.

4.3.2.4. Cadell and Regional

The selected observation bores at Cadell (Figure 4.9) show a generally good match between observed and modelled hydrograph trends in the Murray Group Limestone. The match to potentiometric head is particularly good for bore 1C. Heads are underestimated at bore C2 by 1.5 m.

Most of the regional bores show a good match between observed and modelled potentiometric head (Figure 4.10), including 6829-282, M10, M3 and M94. Bores 6830-54 and M 15 have reasonable modelled trends but have potentiometric heads approximately 2 m higher than observed. The two bores closest to Stockyard Plain Disposal Basin, M2, M2G and SP 15, have a reasonable starting potentiometric head but then the modelled heads rise faster than observed, which may be due to the assumption that the aquifer is homogeneous.

4.3.3. CALIBRATION RESULTS — ITERATION RESIDUAL ERROR

The SRMS error between observed and modelled heads was calculated for the years 1980, 1992 and 2008. These years span the period during which data are available and represent three different hydrogeological conditions. 1980 had substantial irrigation and 1992 was the year just before the commencement of the QSTGCS and SIS. 2008 was a time of lowered irrigation recharge, due to improved efficiency and drought restrictions and includes the Waikerie I SIS, the QSTGCS and the Waikerie II SIS. The number of observation bores increased greatly between 1980 and 1992 and between 1992 and 2008.

Figures 4.11 to 4.13 plot observed head against modelled head for the years 1980, 1992 and 2008 respectively. The SRMS for 1980 is 4.3% and there is no obvious systematic bias in the errors. The SRMS for 1992 is 6.2%. Figure 4.12 suggests that potentiometric heads in layer 1 tend to be underestimated by the model while layer 3 heads are overestimated. The SRMS for 2008 is 7.8 % and there is no obvious pattern of systematic bias for this year.

4.3.4. CALIBRATION RESULTS — WATER BALANCE ERROR

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

4.4. MODEL CONFIRMATION

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

Model results are compared with observed salt loads, instream electrical resistivity (NanoTEM), estimates of accession water volumes and observed actual groundwater ET rates.

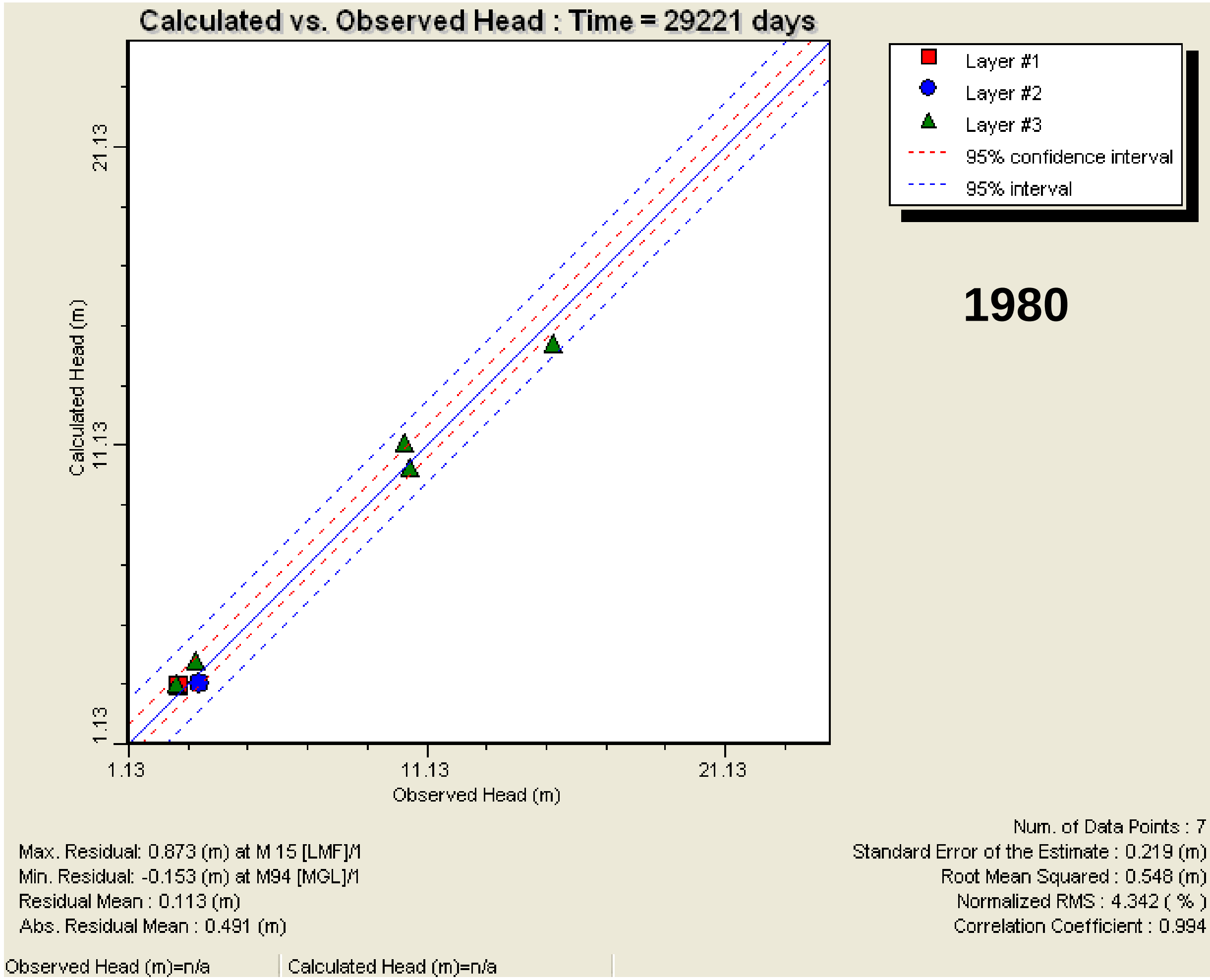


Figure 4.11 Scaled Root Mean Square (SRMS) at 1980

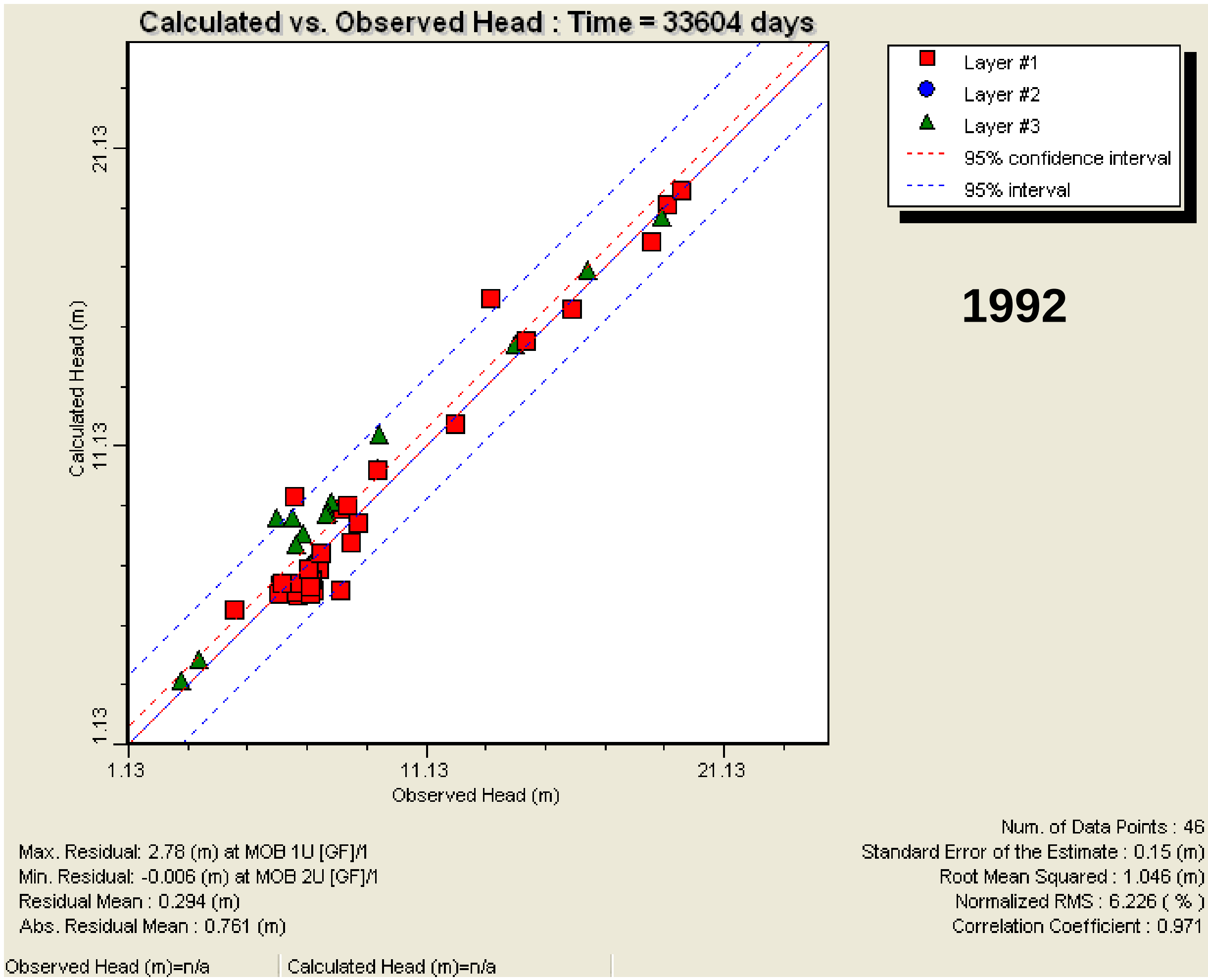


Figure 4.12 Scaled Root Mean Square (SRMS) at 1992

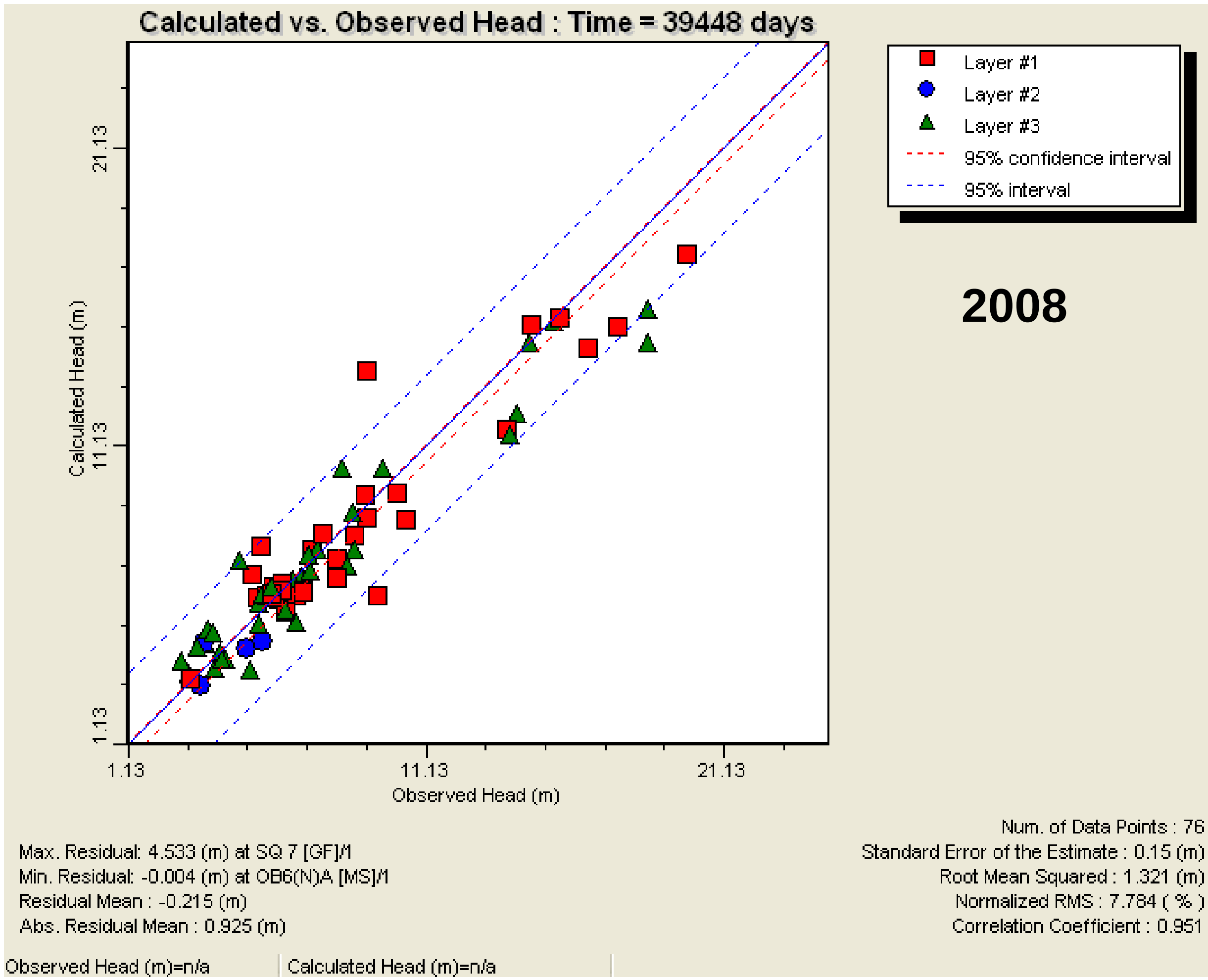


Figure 4.13 Scaled Root Mean Square (SRMS) at 2008

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). Most flow budget zones correspond to a single river kilometre reach; a few end or start at a fraction of a river kilometre due to a model boundary or the location of a river lock. The resulting calculations of the salt load for the calibrated model are given in detail in Appendixes B-3 to B-5.

Groundwater flux to river and salt load estimates are summarised over three reaches defined in Table 4.1. Model results for sample years are given in Table 4.2. The spatial distribution of modelled salt load are shown in Figures 4.14 to 4.16.

Table 4.1 Definition of river reaches used for salt load comparison

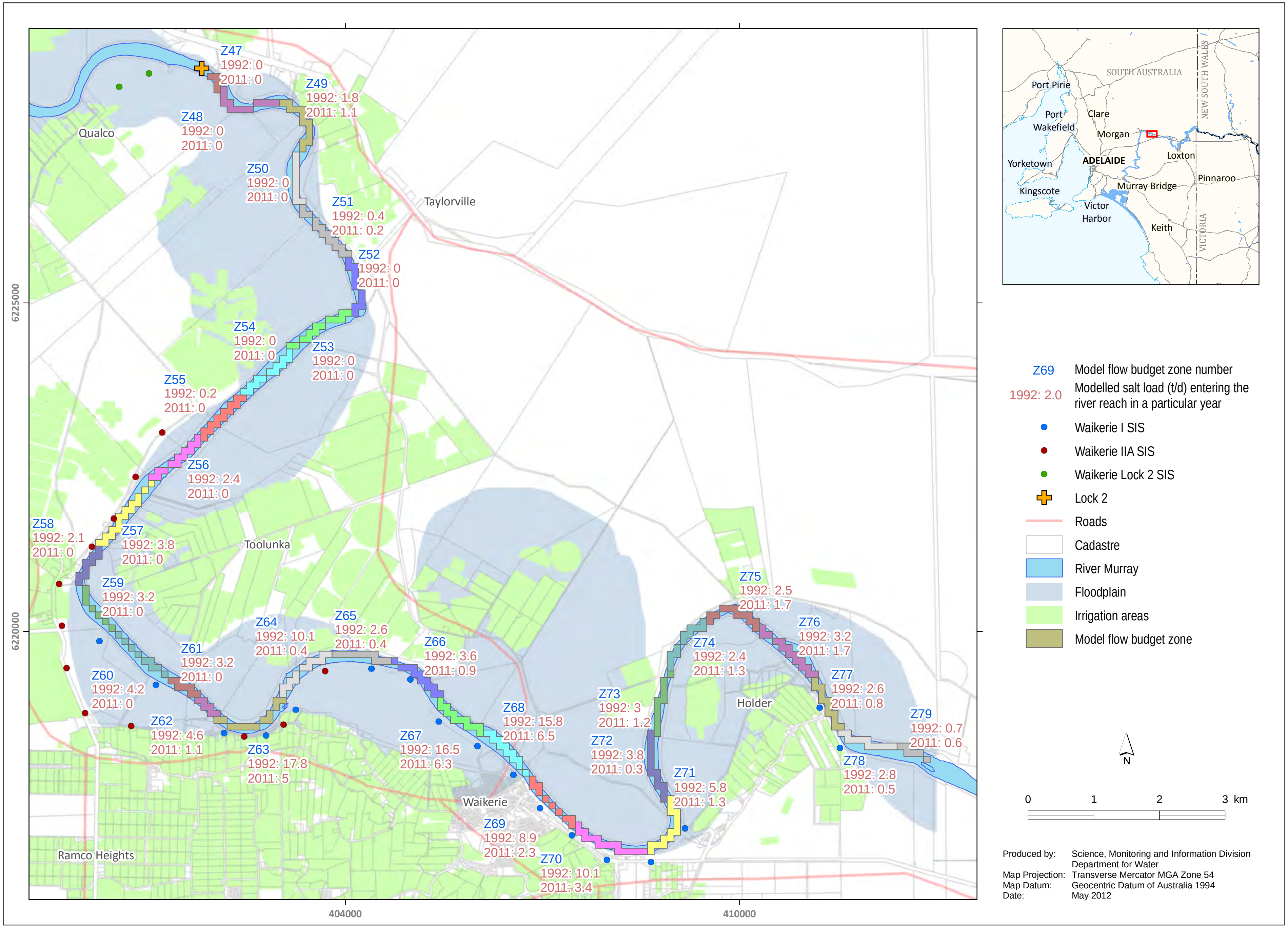
River reach	River km
Holder to Lock 2	393.5 – 362.5
Lock 2 to Hogwash	362.5 – 351
Hogwash to Morgan	351 – 320

Table 4.2 Modelled groundwater flux and salt load in the Waikerie to Morgan calibrated model

	Year		
	Steady-state	**1992**	**2011**
Holder to Lock 2			
Flux to river (m^3/d)	431	9688	2648
Salt load to river (t/d)	5.6	138.1	37.0
Lock 2 to Hogwash			
Flux to river (m^3/d)	717	2697	1049
Salt load to river (t/d)	13.5	61.2	21.6
Hogwash to Morgan			
Flux to river (m^3/d)	405	3893	2034
Salt load to river (t/d)	4.6	21.4	14.0

Figure 4.14 shows the spatial distribution of modelled salt load for the Holder to Lock 2 reach for the years 1992 and 2011. In 1992, the detailed model budget zone with the highest salt load to the River Murray was near Waikerie (zone 63), which shows 17.8 t/d/km, presumably due to the steep potentiometric head gradients of the Waikerie groundwater mound. The Waikerie I SIS was constructed in 1993 and the Waikerie IIA scheme in 2003. By 2011, salt loads have reduced sharply near the Waikerie I bores and have reduced to zero near the Waikerie IIA bores.

Figure 4.15 shows the modelled salt load for the Lock 2 to Hogwash reach. 1992 salt loads in this reach are relatively lower than those in the Holder to Lock 2 reach, with a maximum of 8.8 t/d/km at zone 46, downstream of Lock 2. The QSTGCS was operational by 2001 and the modelled 2011 salt loads near the QSTCGS bores have declined since the scheme commenced. The only high salt-load zone which does not decline significantly from 1992 to 2011 is zone 46, which includes Lock 2. Lock 2 causes the significant



M:\Projects_GW\Murray_Basin\GW_Modelling\Waikerie_Morgan_Modelling_2011_2012\Reporting\Figures\GIS_maps\Figure_4_14 Modelled Salt Load Spatial Distribution at 1992 and 2011 for the Holder to Lock 2 Reach.mxd Augoum01

Figure 4.14 Modelled Salt Load Spatial Distributions at 1992 and 2011 for the Holder to Lock 2 Reach

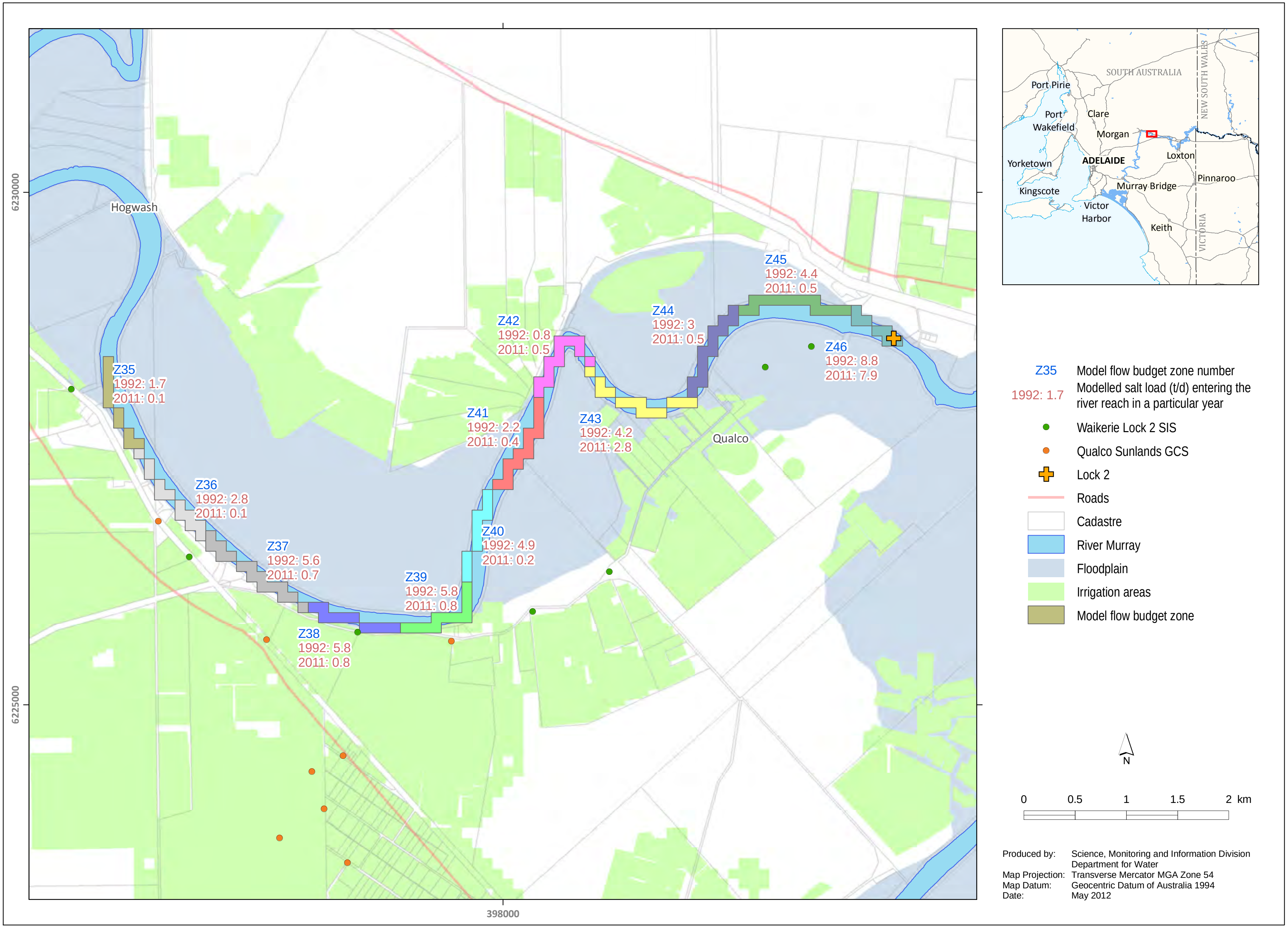
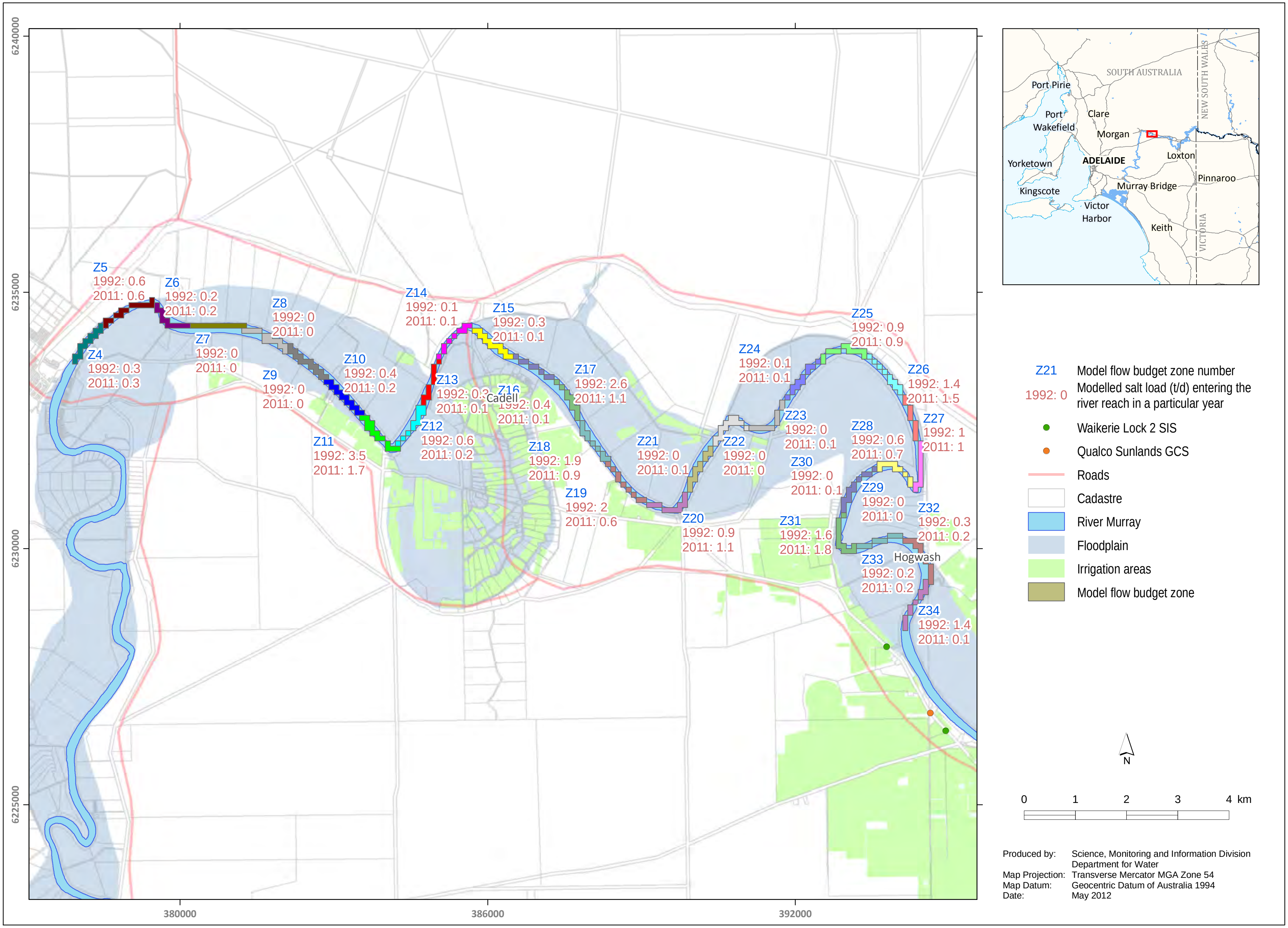


Figure 4.15 Modelled Salt Load Spatial Distributions at 1992 and 2011 for the Lock 2 to Hogwash Reach



M:\Projects_GW\Murray_Basin\GW_Modelling\Waikerie_Morgan_Modelling_2011_2012\Reporting\Figures\GIS_maps\Figure_4_16 Modelled Salt Load Spatial Distribution at 1992 and 2011 for the Hogwash to Morgan Reach.mxd Augoum01

Figure 4.16 Modelled Salt Load Spatial Distribution at 1992 and 2011 for the Hogwash to Morgan Reach salt load, as groundwater levels in equilibrium with the river upstream of Lock 2 will be higher than river levels downstream of Lock 2 and the gradient induces groundwater flow to the river downstream.

Figure 4.16 shows the spatial distribution of groundwater salt load to the River Murray for the Hogwash to Morgan reach. In zones not adjacent to irrigation, salt loads are typically low and do not change over time. In zones adjacent to irrigation, salt loads are generally higher; up to 3.5 t/d/km for zone 11 in 1992. Salt loads decline over time near the Cadell irrigation area, presumably due to improvements in irrigation efficiency. Some zones lying near newer irrigation areas, near Hogwash (e.g. zones 20 and 31), show small increases in salt load from 1992 to 2011.

Figures 4.17 to 4.19 compare Run of River estimates of salt loads with modelled salt loads for the three main reaches. While the RoR results exhibit a great deal of variation, as discussed in Section 2.4.1.2, the modelled results show a reasonable match to values and trends. There has been a steep decline in the Holder to Lock 2 reach since the mid-1990s, a less steep decline for the Lock 2 to Hogwash reach and little change over the Hogwash to Morgan reach.

4.4.2. GAINING AND LOSING REACHES

The 2004 NanoTEM data (Figure 2.21) show that the majority of salt load entering the River Murray comes from the river reach near Cadell (river km 327 to 328), between Qualco and Lock 2 (river km 355 to Lock 2) and most sections between Lock 2 and Holder. Figures 4.14 to 4.16 show the 2011 modelled salt load along the river reaches for Holder to Lock 2, Lock 2 to Hogwash and Hogwash to Morgan, respectively. The location of the river reaches with high modelled salt load values coincides with the NanoTEM data, hence increasing the confidence in the model results. Upstream of Lock 2, the correlation is poorer for reasons that are unclear.

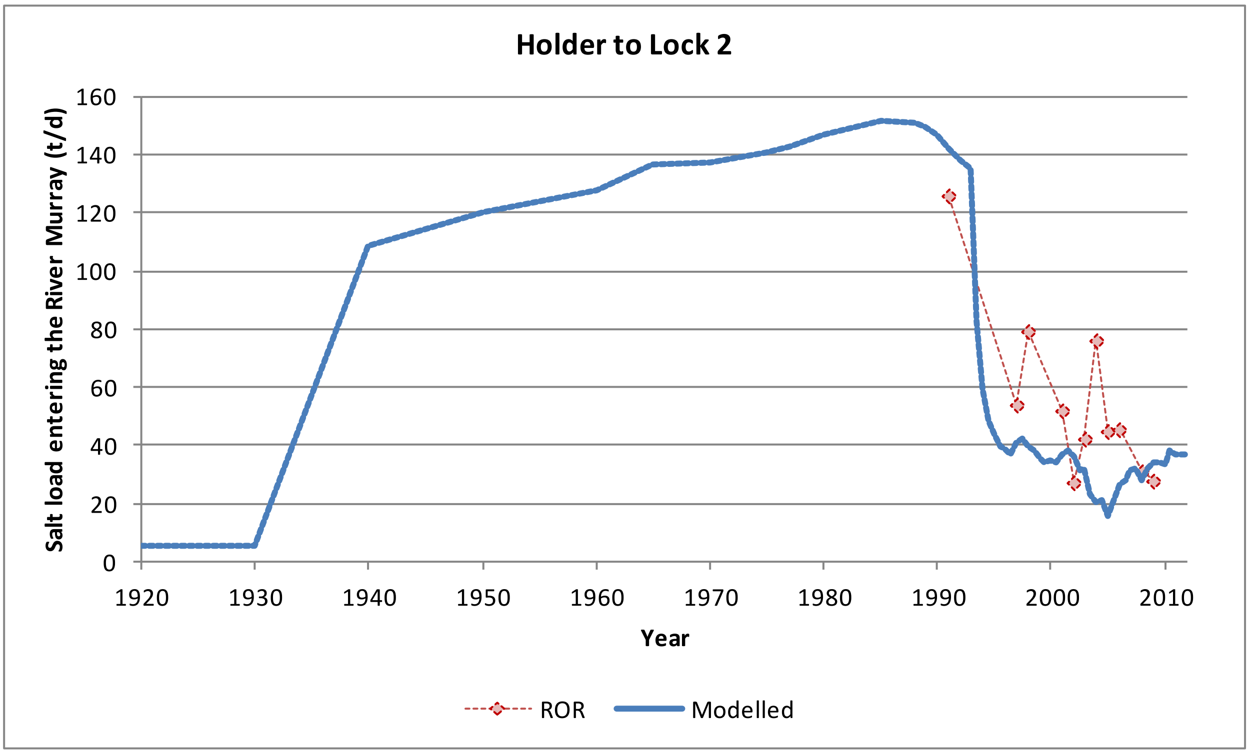


Figure 4.17 Salt Load Comparison between Run-of-River Measurements and the Calibrated Model Outputs for the Holder to Lock 2 Reach

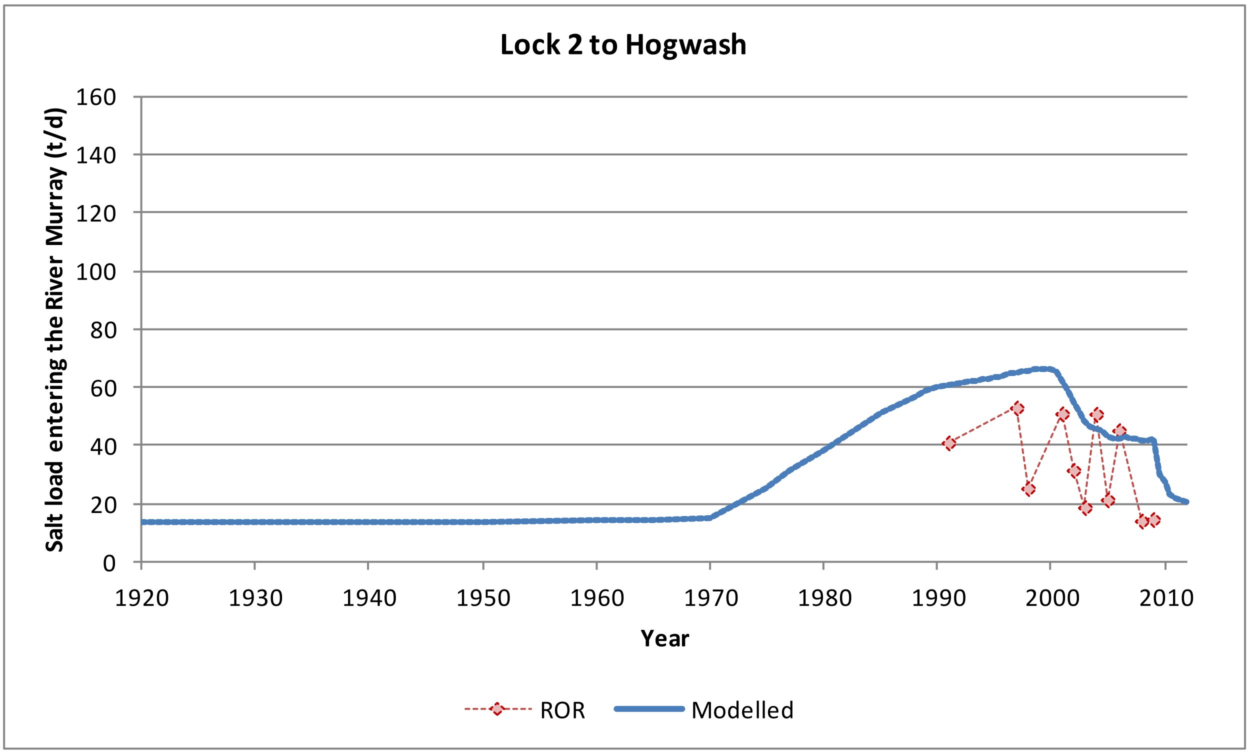


Figure 4.18 **Salt Load Comparison between Run-of-River Measurements and the Calibrated Model Outputs for the Lock 2 to Hogwash Reach**

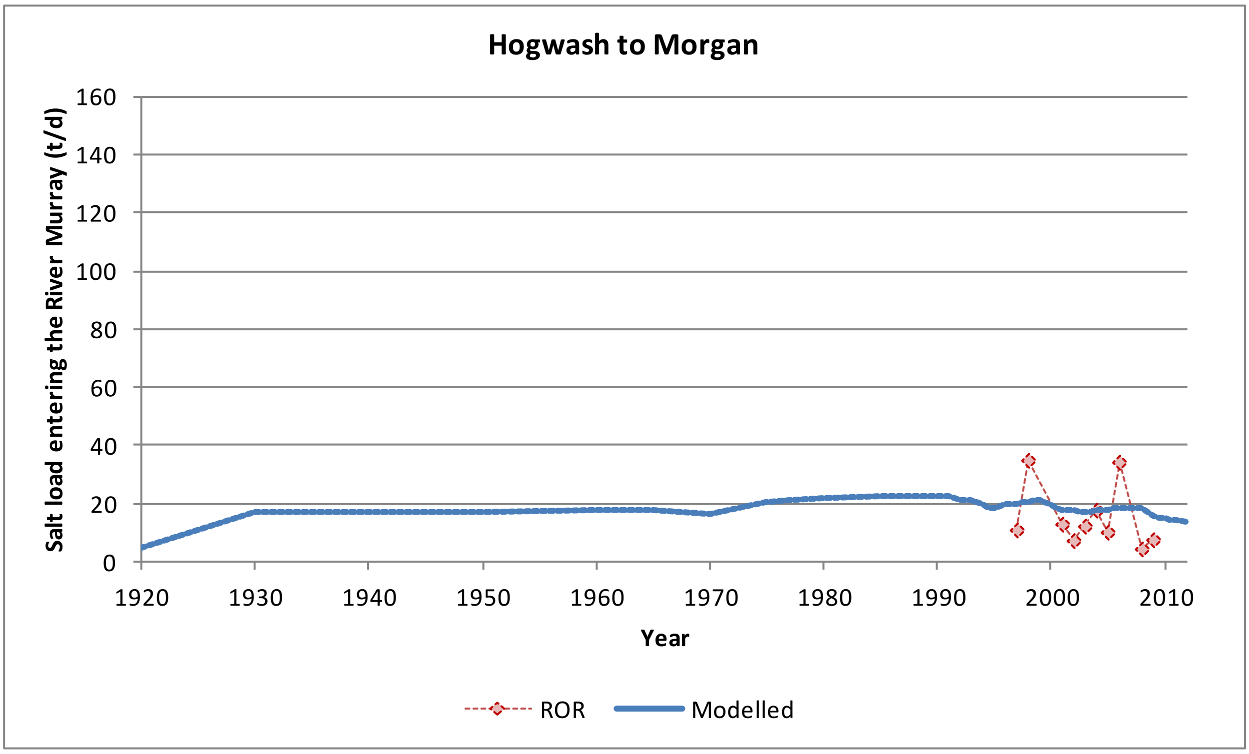


Figure 4.19 **Salt Load Comparison between Run-of-River Measurements and the Calibrated Model Outputs for the Hogwash to Morgan Reach**

4.4.3. RECHARGE VOLUMES

To seek confirmation of recharge estimates, an independent estimate of accession water volumes was undertaken (Fordham *et al*. 2012, in App. C-1). The accession estimates are based on a review of irrigation and infrastructure information for irrigation areas, sourced from DFW and historical irrigation trust records. A water balance method was employed in the calculation and the details are shown in Appendix C-1. The outputs of this work were compared with the total recharge applied in the calibrated model to confirm that the modelled recharge was within the appropriate range.

Figures 4.20 to 4.23 compare the accession water estimates of Fordham *et al*. (2011) for LWMP areas (see Figure 2.1 for LWMP areas) with the total recharge volume to the Glenforslan, Monoman and undifferentiated Murray Group Formations from the calibrated model. The accession volume and model recharge volumes are expected to match well in areas where the watertable is close to the root zone, such as Cadell where irrigation occurs on the floodplain (Figure 2.29).

The relationship between accession volume and recharge volume is expected to be different in areas where the accession water needs to pass through a much thicker unsaturated zone and multiple hydrogeological units before it recharges the regional watertable aquifer (model layer 1). For example, at Qualco, accession water may pass through the Woorinen Formation, Blanchetown Clay, Loxton Sands and Cadell Formation to reach the Glenforslan Formation aquifer (Figure 2.28). Waikerie is similar (Figure 2.27). There will be an initial lag time as accession water passes through the unsaturated zone to reach the original watertable. The lag time will reduce after the initial arrival of irrigation recharge as hydraulic conductivity increases with saturation. Some of the accession water will remain in the pore spaces of the unsaturated zone and within perched aquifers, some is lost as cliff seepage and as water logging in local depressions, so the recharge volume will be lower than the accession water. Additionally, the accession water rates differ from the recharge due to lateral movement, especially when there is an intervening clay layer.

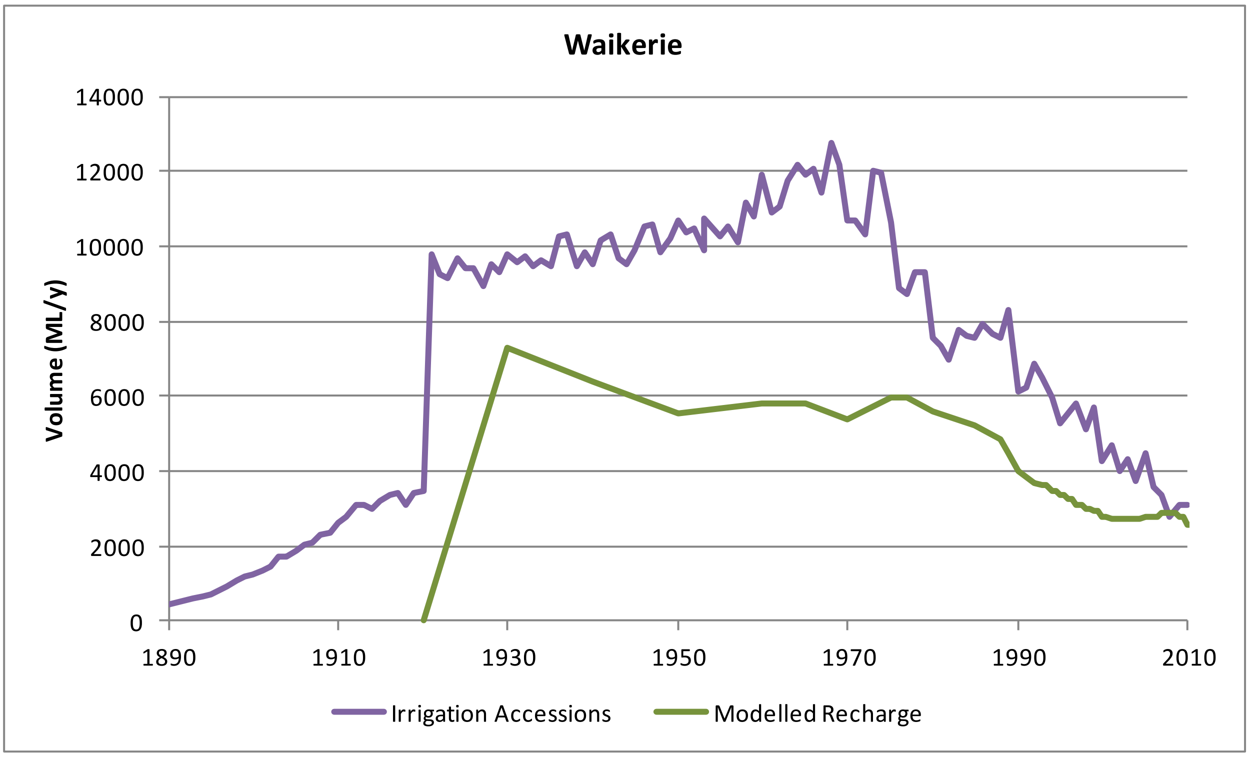


Figure 4.20 Total Recharge Volume Comparison between the Calculated Accession Estimates and the Calibrated Model Inputs for Waikerie

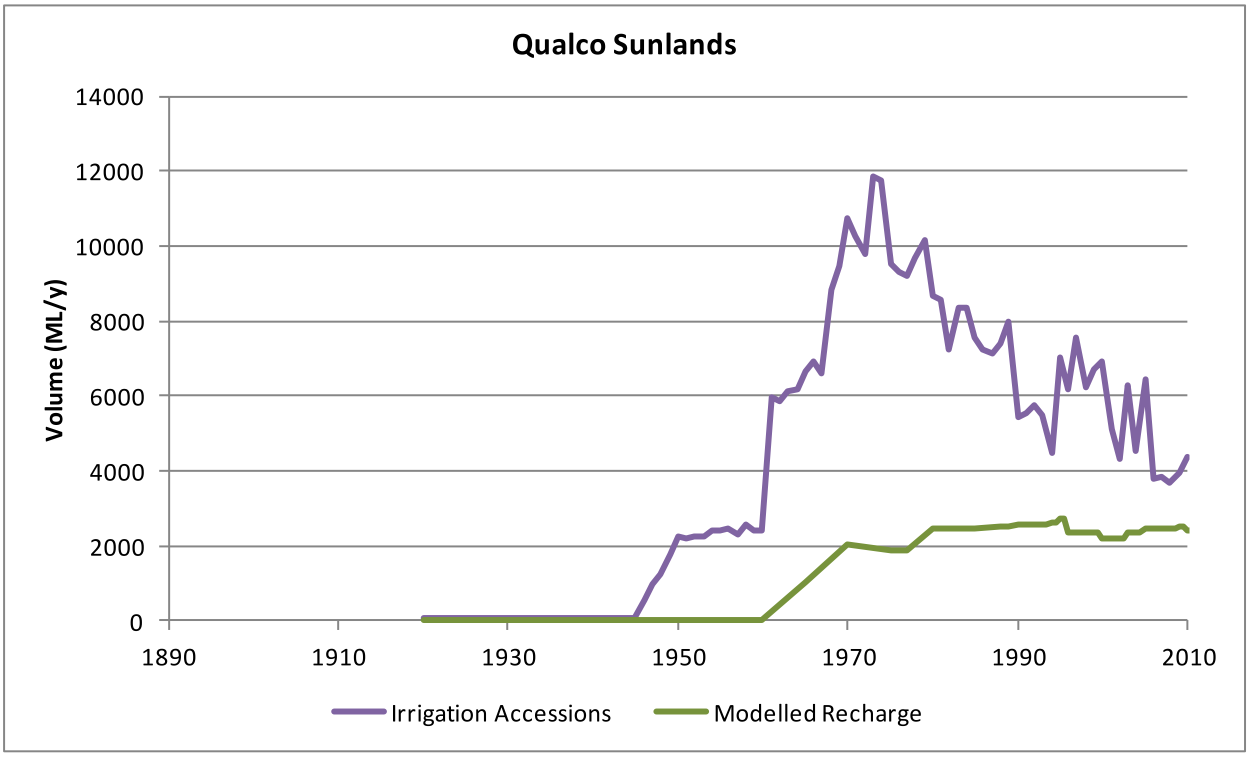


Figure 4.21 **Total Recharge Volume Comparison between the Calculated Accession Estimates and the Calibrated Model Inputs for Qualco-Sunlands**

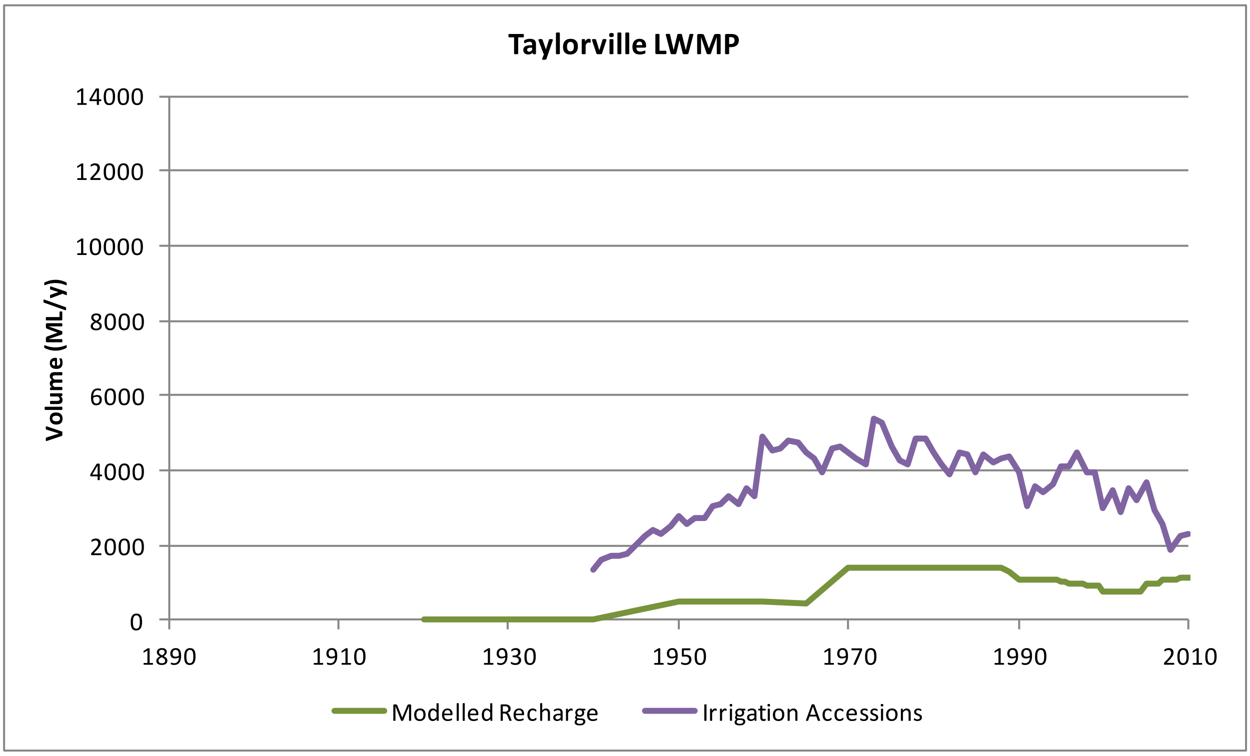


Figure 4.22 **Total Recharge Volume Comparison between the Calculated Accession Estimates and the Calibrated Model Inputs for Taylorville LWMP Area**

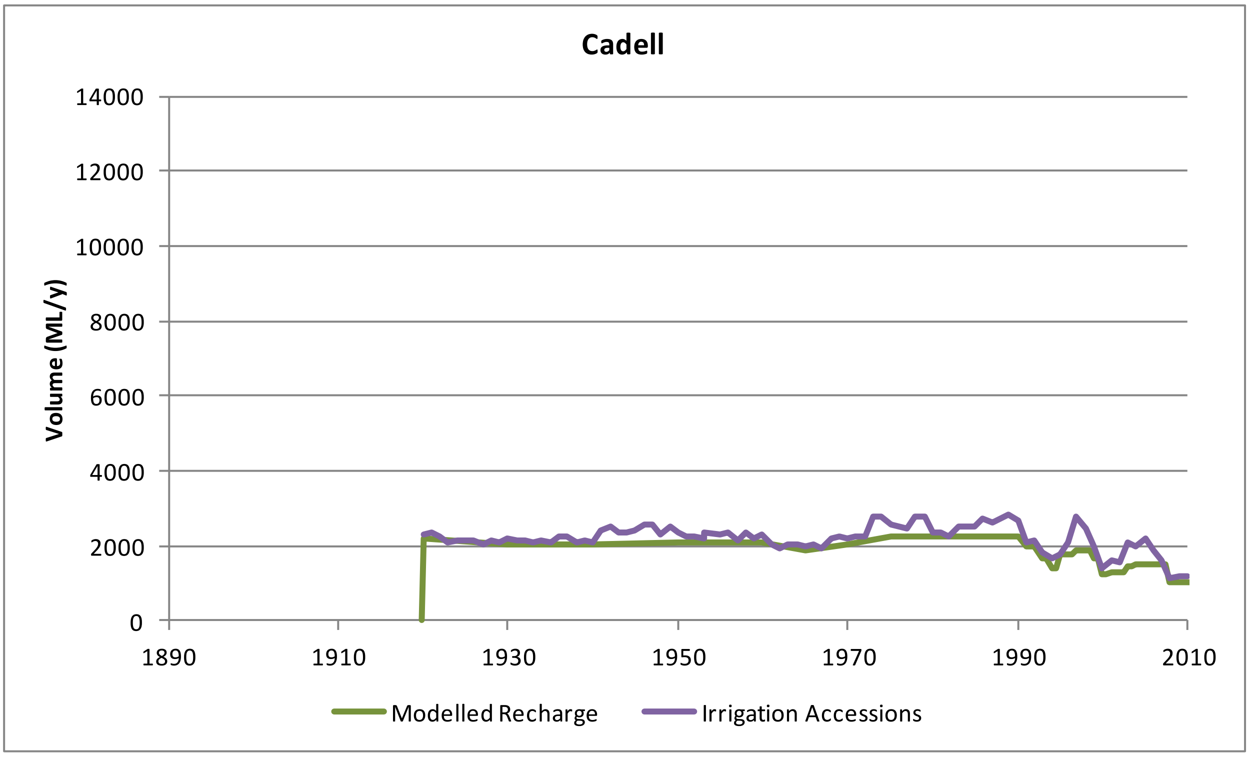


Figure 4.23 Total Recharge Volume Comparison between the Calculated Accession Estimates and the Calibrated Model Inputs for Cadell

Figure 4.20 compares estimates of irrigation accession for the Waikerie LWMP with the recharge volume from the calibrated model. Accessions begin in 1890 and recharge in 1920, an initial lag time of 30 years, which is reasonable. Accessions rise sharply in 1920, with a corresponding rise in modelled recharge by 1930, i.e. the lag time for the drainage has decreased to 10 years. The recharge is also likely to be influenced in this decade by the construction of the drainage bores (Fordham *et al*. 2012, in App. C-1).

Figure 4.21 compares the estimated accessions with modelled recharge for the Qualco-Sunlands LWMP. Irrigation begins in the 1940s and recharge begins in 1960 with an initial lag time of 20 years. The volume of accessions from water balance calculation is much greater than the recharge volume, which is appropriate for this region as large volumes of drainage are stored within previously-unsaturated sediments of the Woorinen Sands and Loxton Sands or lost though seepages and ET in lowland areas.

The difference between the accession and recharge volumes at Waikerie and Qualco-Sunlands is attributed to processes in the initially-unsaturated sediments above the regional watertable. The water balance for these sediments was estimated to check whether the modelled recharge volume is reasonable. Flow into the initially unsaturated sediments is from accession. Flow out of these sediments is via recharge to the saturated zone and cliff and surface seepage. Water is stored in perched aquifers within both the Woorinen Sands and the Loxton Sands.

Calculations are presented in Appendix C-3. Accession volume is from the independent study of Fordham *et al*. 2012 (App. C-1). Recharge is from the calibrated historical model. Seepage is estimated from seepage front areas and Darcy's Law. The volume of perched water is based on potentiometric head contours for the Loxton Sands, assuming some assumed lateral spread outside the monitored area. As there are no data for the perched water in the Woorinen Sands, the estimated volume is assumed to be 1/3 of the volume in the Loxton Sands, as the Woorinen is approximately 1/3 of the thickness of the

Loxton Sands. All volumes are summed over the years from the start of irrigation in 1890 to 2010. A summary is shown in Table 4.3:

Table 4.3 Estimated water budget for sediments above the initial regional watertable

Irrigation Area	INFLOW WB* Estimated Accession [ML]	OUTFLOW Modelled Recharge (ML)	OUTFLOW Estimated Seepages [ML]	OUTFLOW Estimated Perched [ML]	TOTAL OUTFLOW [ML]	INFLOW-OUTFLOW [%]
Waikerie	846 230	425 291	46 027	380 677	851 995	-0.7%
Qualco-Sunlands	390 081	100 899	104 303	196 621	401 823	-3.0%

**WB means Water Balance calculation which was conducted by Fordham* et al. *2012*

In the Waikerie area, the total accession volume is 846 230 ML. Outflows are 425 291 ML of recharge to the regional aquifer (Glenforslan Formation), 46 027 ML of cliff seepage and 380 677 ML stored within the Loxton Sands perched aquifer (319 690 ML as lateral expansion of the water mound and 64 456 ML for forming the existing water mounds). The total inflow of 846 230 ML is approximately equal to the estimated outflows of 851 995 ML.

In the Qualco area, the total accession volume is 390 081 ML. Outflows are 100 899 ML of recharge to the regional aquifer (Glenforslan Formation), 104 303 ML of seepages (two cliff seepages and one loss to lower land area), 196 621 ML stored within the perched aquifers (121 645 ML as potential lateral expansion of the water mound and 77 546 ML in the main mounds). The total inflow of 390 081 ML is approximately equal to the estimated outflows of 401 823 ML.

While the details of the calculations given in Appendix C-3 depend on several unknowns (such as the extent of the lateral movement of perched water), the calculations demonstrate that a reasonable water balance can be developed which is consistent with the estimated accession volume and the modelled recharge.

A comparison between estimated accession and modelled recharge for the Taylorville LWMP area is given in Figure 4.22. The Taylorville LWMP includes the irrigation areas of Toolunka, Taylorville and Markaranka. Some of the irrigation in these areas occurs on the floodplain but most of the irrigation occurs in highland areas, so the relationship between the estimated accessions and the modelled recharge is expected to resemble Waikerie and Qualco-Sunlands LWMPs more than the Cadell LWMP. Irrigation began in 1940 and irrigation-derived recharge began in the calibrated model in 1950, a lag time of 10 years. The accession volume is much greater than the modelled recharge, which is expected.

Figure 4.23 compares the estimated accessions with modelled recharge for the Cadell LWMP. Irrigation at Cadell occurs on the floodplain, where the root zone is at a similar level as the watertable, so there should be a very short initial lag time (less than two years) between irrigation application and recharge of the watertable. The figure shows that the estimated accessions and modelled recharge are almost identical.

This comparison provides confidence that the total recharge applied in the model is within the reasonable range and is consistent with accession estimates.

4.4.4. GROUNDWATER EVAPOTRANSPIRATION

There has been no recent research undertaken in the project area about groundwater ET on the floodplain area. CSIRO has investigated groundwater ET rates in the Rilli's Floodplain at Loxton and the

Bookpurnong floodplain (Holland *et al*. 2001; Doody *et al*. 2009). An unpublished recent study indicates that average actual groundwater ET rates on floodplains may be in the range of 60–80 mm/y, assuming that woodland covers 30 to 40% of the floodplain (K Holland, CSIRO, pers. comm., 2011).

The calibrated model has a specified maximum (i.e. potential) groundwater ET rate of 1100 mm/y based on Bureau of Meteorology (2001) and an extinction depth of 2 m. The model result (Figure 4.24) shows that 30 to 35 mm/y of groundwater is lost as ET (i.e. actual groundwater ET) in the floodplain within the project area. This is less than the floodplain ET in CSIRO's Loxton-Bookpurnong study but is of the correct order of magnitude. Groundwater ET depends on soil type, plant cover, groundwater salinity, depth to the watertable and other factors which may differ from site to site. The sensitivity of the model to groundwater ET parameters is explored in Section 6.1.

4.5. MODEL WATER BALANCE

Table 4.3 reports the water balance for the Waikerie to Morgan project area in all layers. The details of flow are given for the steady-state period (prior to irrigation), the beginning of 1992 (typical irrigation conditions prior to SIS and GCS) and 2011 (most recent year including SIS and GCS).

Under the natural conditions of the steady-state model, most of the flows into the aquifers were from losing-stream reaches of the river (6.3 ML/d) and lateral regional flow into the study area (4.5 ML/d), with recharge, from rainfall, adding a relatively minor 0.3 ML/d. Outflow from the aquifers was dominated by groundwater evapotranspiration (8.8 ML/d). Other outflows from the aquifers were into gaining reaches of the River Murray (1.4 ML/d) and lateral regional flow (0.9 ML/d).

At the beginning of 1992, the conditions and water balance were different. Inflows to the aquifers had more than tripled, mostly due to increasing recharge from irrigation (26.3 ML/d). Flow from losing reaches of the Murray was still significant (1.8 ML/d) but had decreased by 4.5 ML/d due to the growing irrigation-water mound (higher watertable) which increases the gradient towards the river. There was also some inflow from the Stockyard Plain Disposal Basin (0.5 ML/d). The increase in inflows lead to an increase in flow to the River Murray's gaining reaches (15.7 ML/d, an increase of 14.3 ML/d from steady-state), regional lateral flow out of the study area (3.1 ML/d, an increase of 2.2 ML/d) and into storage where groundwater mounds were still growing (6.0 ML/d). There was an increase of 1.5 ML/d in groundwater evapotranspiration to 10.3 ML/d. Cliff seepage, which did not occur at steady-state, was 0.5 ML/d.

By 2011, total recharge had declined due to SIS, GCS, irrigation efficiency improvement and water restrictions during drought. The recharge had declined by 6.3 ML/d to 20.0 ML/d. The SIS and GCS bores extracted 11.5 ML/d in 2011. The main impact was on the River Murray. Groundwater flow from the river (losing) increased by 1.3 ML/d (to 3.1 ML/d) and groundwater flow entering the river (gaining) declined to 5.4 ML/d, a reduction of 10.3 ML/d. There were small reductions in groundwater evapotranspiration and in cliff seepage. Leakage from the Stockyard Plain Disposal Basin increased to 4.4 ML/d. The net change in storage in 2011 was lower at 1.9 ML/d compared with 2.4 ML/d in 1992, as the groundwater mounds reduce in size, owing to the decline in recharge and the pumping of the GCS and SIS bores.

In summary, the natural water balance was dominated by inflows from river leakage and regional flow that left the aquifers mostly via groundwater evapotranspiration. Irrigation vastly increased recharge to the aquifers and outflow from the aquifers to the river. Since the SIS and GCS had commenced and irrigation efficiency had improved, groundwater flux entering the River Murray had declined substantially, as designed. These model results are consistent with the hydrogeological understanding of the region.

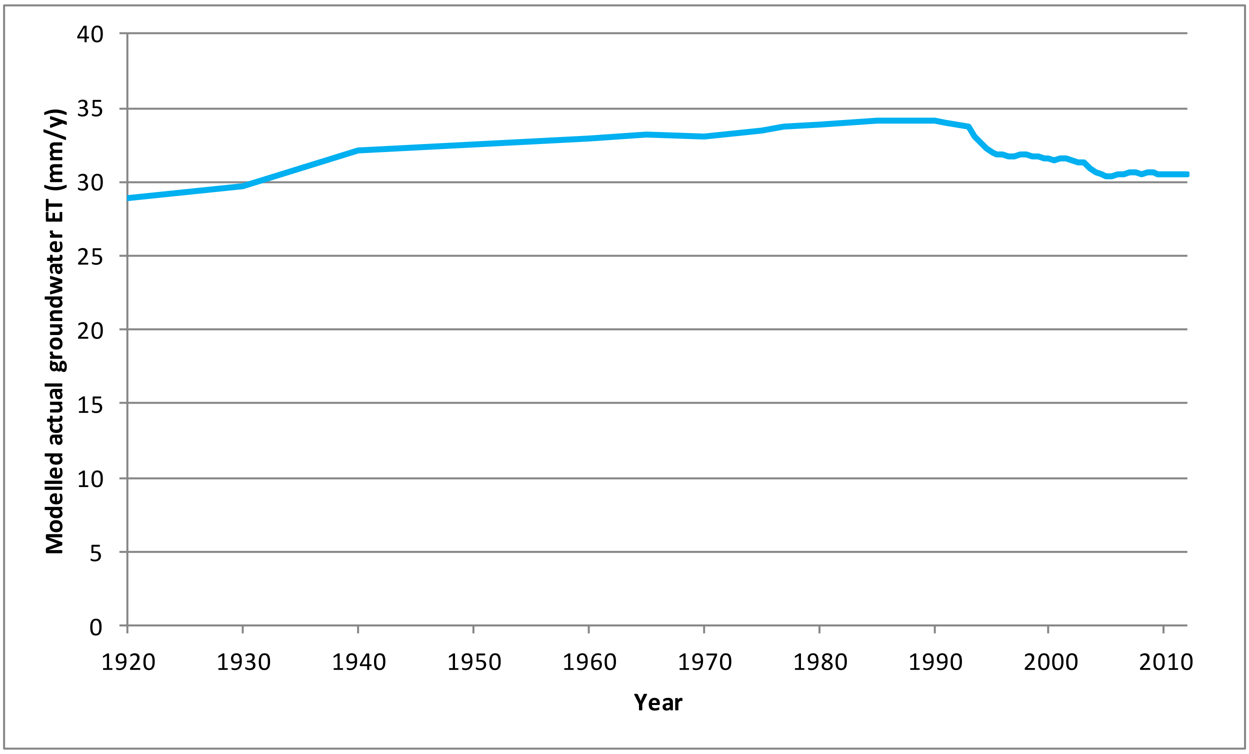


Figure 4.24 Modelled Actual Groundwater Evapotranspiration

Table 4.4 Water balance for the Waikerie to Morgan area

Water Balance Component INFLOW to the aquifer	Water volume (ML/d)		
	Steady-state	1992	2011
Withdrawal from storage	0.0	3.6	4.5
Recharge from irrigation and rainfall	0.3	26.3	20.0
River leakage (river losses to the aquifer)	6.3	1.8	3.1
Stockyard Plain Disposal Basin leakage (GHB)	0.0	0.5	4.4
Lateral flow (into the project area)	4.5	3.4	3.6
Total IN	**11.1**	**35.6**	**35.6**
Water Balance Component OUTFLOW from the aquifer	**Water volume (ML/d)**		
	Steady-state	**1992**	**2011**
Flow to storage	0.0	6.0	6.4
SIS wells	0.0	0.0	11.5
Cliff seepage (model drain cells)	0.0	0.5	0.3
ET	8.8	10.3	9.3
River leakage (discharge to the river)	1.4	15.7	5.4
Lateral flow (outward from the project area)	0.9	3.1	2.8
Total OUT	**11.1**	**35.6**	**35.6**

5. MODEL SCENARIOS AND PREDICTIONS

The calibrated historical model is used as a basis for estimating past and future salt loads to the River Murray under a number of scenarios. A standard suite of scenarios has been developed for the Salinity Register SA models. The scenarios used for the Waikerie to Morgan study area are consistent with the standard suite but some scenarios are omitted and others are broken into sub-cases, owing to the specific conditions in the study area.

The standard suite of SA scenarios has been developed progressively in consultation with State (DFW) 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, GCS and the SIS. Some standard scenarios assist State decisions on salinity management, such as Scenarios 5 and 8C, which simulate the impacts of new irrigation developments. The aims are to:

1. evaluate the impact of various accountable actions, to be recorded on the MDBA Salinity Registers A and B, including:
    a. the in-stream salinity impact of the various pre- and post-1988 actions on the groundwater flux and salt load entering the River Murray
    b. the in-stream salinity impact of improved irrigation practices (IIP) and the rehabilitation (RH) of distribution systems
    c. the potential in-stream salinity benefits from SIS and GCS.
2. determine the State and Federal responsibility for cost sharing
3. satisfy the reporting requirements of:
    a. Schedule C of the Murray-Darling Basin Agreement 1992
    b. the Basin Salinity Management Strategy Operational Protocols 2003.

The standard suite of Salinity Register SA modelling scenarios are summarised in Table 5.1.

The scenarios presented in this report are consistent in approach with scenarios of the same name used in other SA Salinity Register models. However, two standard scenarios are omitted and two are broken into sub-cases, as described below.

Table 5.2 describes the scenarios simulated for the Waikerie to Morgan study area.

Two scenarios from the standard suite, Scenarios 5 and 8C simulating additional new irrigation areas, have been omitted, as no substantial new irrigation is currently anticipated in the study area (Section 5.8). This decision was made by the 5 Year Review Team.

Standard Scenarios 8a and 8b, which estimate the in-stream salinity benefit of SIS and GCS, have been separated into different sub-cases which represent the history of GCS and SIS in the study area. The Waikerie I SIS was constructed first, followed by the QSTGCS, the Waikerie IIA SIS and the Waikerie Lock 2 SIS. In order to estimate the additive impact of each scheme as constructed, Scenarios 8a(i) and 8b(i) include only the first of the schemes, while Scenarios 8a(ii) and 8b(ii) include the first two schemes, Scenarios 8a(iii) and 8b(iii) include the first three schemes and Scenarios 8a(iv) and 8b(iv) include all four of the constructed SIS and GCS.

All scenarios are discussed in detail in the following sections. The model names, e.g. WM2012_S3A, refer to the MODFLOW files preserved in the SA Groundwater Model Warehouse, following the protocol given in Appendix C-4.

To prevent the over-estimation of salinity credits, future scenarios presume that recharge due to irrigation will be similar to the 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, unless the calibration model indicates a lower recharge rate prior to 2006. This means that the impacts of improved irrigation practices and rehabilitation are also not over-estimated. 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 will be input into MSM-BIGMOD by the MDBA to calculate the in-river EC impact at Morgan.

Table 5.3 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 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 5.11 below.

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

Scenario	Description	Report period*	Irrigation development area	IIP and RH	SIS
Calibrated model	Historical	1920 –CY	Footprint of irrigation history	Yes	Yes
Scenario–1	Natural system	Steady-state	None	–	–
Scenario–2	Mallee clearance	1988–CY100	None (but includes mallee clearance area)	–	–
Scenario–3a	Pre-1988, no IIP, no RH	1988–CY100	Pre-1988	No	–
Scenario–3c	Pre-1988, with IIP and with RH	1988–CY100	Pre-1988	Yes	No
Scenario–4	Current irrigation	1988–CY100	Pre-1988 + post-1988	Yes	No
Scenario–5	Current plus future irrigation	1988–CY100	Pre-1988 + post-1988 + future development	Yes	No
Scenario–8a	Current irrigation plus constructed SIS	1988–CY100	Pre-1988 + post-1988	Yes	Yes
Scenario–8b	Pre-1988, with IIP and with RH plus constructed SIS	1988–CY100	Pre-1988	Yes	Yes
Scenario–8C	Current plus future irrigation plus constructed SIS	1988–CY100	Pre-1988 + post-1988 + future development	Yes	Yes

IIP: Improved Irrigation Practices *RH: Rehabilitation of irrigation distribution networks* *SIS: Salt Interception Scheme*

CY: Current Year *CY100: 100 years from the current year*

** Report period represents the period for model outputs which is required for the MDBA Salinity Register entries. Conditions and input details are documented in a later section.*

Table 5.2 Summary of modelled scenarios and conditions adopted for Waikerie to Morgan

Scenario	Description	Report period*	Irrigation development	IIP and RH	SIS
Calibrated model	Historical	1920 – CY	Footprint of irrigation history	Yes	Waikerie I + QSTGCS + Waikerie IIA + Waikerie Lock 2
S-1	Natural System (Steady State since 1920)	Steady State	None	No	No
S-2	Mallee Clearance	1988 – CY100	None	No	No
S–3a	Irrigation Pre-1988, no IIP, no RH	1988 – CY100	Pre-1988	No	No
S–3c	Irrigation Pre-1988, with IIP & RH	1988 – CY100	Pre-1988	Yes	No
S-4	Current irrigation	1988 – CY100	Pre-1988 + Post-1988	Yes	No
S–8a(i)	Current irrigation plus constructed SIS	1988 – CY100	Pre-1988 + Post-1988	Yes	Waikerie I only
S–8a(ii)	Current irrigation plus constructed SIS	1988 – CY100	Pre-1988 + Post-1988	Yes	Waikerie I + QSTGCS
S–8a(iii)	Current irrigation plus constructed SIS	1988 – CY100	Pre-1988 + Post-1988	Yes	Waikerie I + QSTGCS + Waikerie IIA
S–8a(iv)	Current irrigation plus constructed SIS	1988 – CY100	Pre-1988 + Post-1988	Yes	Waikerie I + QSTGCS + Waikerie IIA + Waikerie Lock 2
S–8b(i)	Pre-1988, with IIP & RH plus constructed SIS	1988 – CY100	Pre-1988	Yes	Waikerie I only
S–8b(ii)	Pre-1988, with IIP & RH plus constructed SIS	1988 – CY100	Pre-1988	Yes	Waikerie I + QSTGCS
S–8b(iii)	Pre-1988, with IIP & RH plus constructed SIS	1988 – CY100	Pre-1988	Yes	Waikerie I + QSTGCS + Waikerie IIA
S–8b(iv)	Pre-1988, with IIP & RH plus constructed SIS	1988 – CY100	Pre-1988	Yes	Waikerie I + QSTGCS + Waikerie IIA + Waikerie Lock 2

IIP: Improved Irrigation Practices *RH: Rehabilitation of irrigation distribution networks* *SIS: Salt Interception Scheme*

CY: Current Year *CY100: 100 years from the current year*

** Report period represents the period for model outputs which is required for the MDBA Salinity Register entries. Conditions and input details are documented in a later section.*

Table 5.3 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. 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. 2010
Current year + 100 (CY100)	100 years from the current year (e.g. if current year is 2010, then CY100 = 2110)
Pre-1988 irrigation	Irrigation development area and recharge rates that occurred prior to 01/01/1988
Post-1988 irrigation	Irrigation development area and recharge that occurred between 01/01/1988 and the current year
Future development	Future irrigation development area and recharge (assuming recharge of 100 mm/y) resulting from activation of already allocated water that is assumed to occur after the current year (i.e. 2015).
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 (e.g. in the Loxton area rehabilitation commenced in 2002) resulted in reduced water transportation losses which are reflected by reduced recharge to the groundwater table. Rehabilitation in pre-1988 irrigation areas is explicitly omitted from Salinity Register scenarios.
Concept Design SIS	The Concept Design SIS designed to intercept the maximum groundwater flux and salt load resulting from all past, present and future irrigation development, or the naturally occurring groundwater flux where this is large and must be intercepted and

	used in the MDBA Approval Submission process to determine the: • cost-benefit ratio • sharing of costs between the State and the MDBA total SIS wellfield flux for pipeline design. The Concept Design SIS may not be able to control 100% of the salt load due to technical or economic constraints. The modelled Concept Design SIS may not represent the actual numbers of production wells that are eventually constructed.
Revised Design SIS	During the investigation and construction phase of an SIS, expectations regarding the effectiveness of the SIS, or its extent, may be revised due to technical issues that arise, resulting in the Revised Design SIS. The Revised Design SIS represents the current view of what the final constructed and operating SIS is most likely to be. The Revised Design SIS may change, as issues that have arisen are resolved. The Revised Design SIS may not be able to control 100% of the salt load due to technical or economic constraints. The modelled Revised Design SIS may not represent the actual number of production wells that are eventually constructed.
As Constructed SIS	Model representation of the on-ground As-Constructed SIS infrastructure using historical pumping rates and forward projections that may or may not be constrained by production well pumping capacity or pipeline capacity or disposal basin capacity. Significant differences to the Concept or Revised SIS may result in the need to recalibrate the model at the time of the 5-year review. The As-Constructed SIS may not be able to control 100% of the salt load due to technical or economic constraints. The modelled As-Constructed SIS may result in the need for model recalibration and re-accreditation, if the actual numbers of on-ground wells are different to those that have been applied in the Concept and Revised Design SIS.
Modelled result	Output from the calibrated model (e.g. potentiometric head distribution) that can be compared to observed data.
Predicted result	Output from the prediction model has been used to determine the future result of a particular scenario.

5.1. RECHARGE APPLIED IN IRRIGATION SCENARIOS

As a result of the model calibration described in the previous section, the following areas and rates are utilised 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).

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

5.2. SCENARIO 1: NATURAL CONDITION

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

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.

There are no irrigation recharge and SIS in this scenario. This scenario is identical to the steady-state model used during calibration to provide initial conditions for the transient historical model.

Table 5.4 gives the modelled flux and salt load entering the River Murray in the Waikerie to Morgan area for Scenario 1 (see Section 4.4.1 for the definition of the reaches).

Table 5.4 Predicted groundwater flux and salt load – Scenario 1: Natural Condition

	Holder to Lock 2	Lock 2 to Hogwash	Hogwash to Morgan
Flux to river (m^3/d)	431	717	405
Salt load to river (t/d)	5.6	13.5	4.6

5.3. SCENARIO 2: MALLEE CLEARANCE

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

The following conditions are applied to the transient model (WM2012_S2):

- the simulated time period is 1920 to CY100
- land clearance prior to 1920 is assumed to have occurred in 1920

- recharge due to mallee clearance is represented by zones and rates estimated by CSIRO and provided by DENR, except where inconsistent with aerial photography. These recharge rates are greater than or equal to 0.1 mm/y, increasing in some areas to ~10 mm/y, with changes occurring every 10 years. The rates and zones are given in Appendix A-1.
- the vegetation outside the cleared zones is mallee, so a recharge rate of 0.1 mm/y is applied
- there is no irrigation development
- the annual salt load 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 Waikerie to Morgan area. Further results are given Appendixes B-1 to B-2. The starting values in 1920 are those given for Scenario 1 in Table 5.4.

Overall salt loads are low when compared to other scenarios.

Table 5.5 Predicted groundwater flux and salt load – Scenario 2: Mallee clearance

	Year					
	1988	**2000**	**2011**	**2015**	**2050**	**2111**
Holder to Lock 2						
Flux to river (m^3/d)	464	480	512	532	790	1335
Salt load to river (t/d)	6.0	6.2	6.7	6.9	10.5	18.1
Lock 2 to Hogwash						
Flux to river (m^3/d)	729	739	754	761	852	1097
Salt load to river (t/d)	13.8	14.0	14.4	14.6	16.9	23.2
Hogwash to Morgan						
Flux to river (m^3/d)	409	410	412	413	424	455
Salt load to river (t/d)	4.6	4.6	4.7	4.7	4.7	5.0

5.4. SCENARIO 3A: PRE-1988 IRRIGATION WITHOUT IMPROVED IRRIGATION PRACTICES AND 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 (WM2012_S3A):

- the simulated time period is from 1920 to CY100
- the model is identical to the calibrated historical model until 1 January 1988
- the recharge zones for 1988 to CY100 are based on the 1988 irrigation development area, extended slightly around Qualco to represent the lateral spread of accession water within sediments overlying the Glenforslan Formation,
- recharge rates for 1988 to CY100 are assigned as follows and are given in Appendixes A-2 and A-5:

  - in established irrigation groundwater mound 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 means that root zone drainage has not yet reached the watertable by 1988. In those areas, recharge rates may still increase after 1988 to reflect the delay. Recharge becomes constant no more than lag time years after 1988.
  - in areas where irrigation did not exist in 1988, the mallee recharge rate of 0.1 mm/y is adopted
- the annual salt loads for 1988 to CY100 are reported as required by the MDBA for the Salinity Register.

Table 5.6 summarises the predicted flux and salt load entering the River Murray in the Waikerie to Morgan area. Further results are given in Appendixes B-1 to B-2. The starting values in 1920 are those given for Scenario 1 in Table 5.4.

Table 5.6 Predicted groundwater flux and salt load – Scenario 3a: Pre-1988, no IIP, no RH

	Year					
	1988	**2000**	**2011**	**2015**	**2050**	**2111**
Holder to Lock 2						
Flux to river (m^3/d)	10 606	10 560	10 746	10 807	11 260	11 710
Salt load to river (t/d)	151.1	151.8	155.1	156.1	163.3	170.1
Lock 2 to Hogwash						
Flux to river (m^3/d)	2528	3120	3385	3441	3679	3799
Salt load to river (t/d)	56.6	71.6	78.2	79.6	85.6	88.6
Hogwash to Morgan						
Flux to river (m^3/d)	4099	4164	4197	4204	4236	4255
Salt load to river (t/d)	22.4	23.1	23.4	23.5	23.8	24.0

5.5. SCENARIO 3B: PRE-1988 IRRIGATION WITH IMPROVED IRRIGATION PRACTICES BUT NO REHABILITATION

Scenario 3b is used in conjunction with Scenario 3c to estimate the salinity benefits due to the rehabilitation of irrigation infrastructure after 1988. It simulates what would have happened if irrigation development and infrastructure had remained unchanged from 1988 but improvements had been made in irrigation practices.

This scenario has been simulated in earlier reports so that the impact of improved irrigation practices could be estimated separately from the impact of rehabilitation. However, this scenario is not required for the Salinity Registers. Note also that there is no clear and established methodology to estimate the decline in recharge due to improved irrigation practices separately from rehabilitation. For these reasons, this scenario is not simulated in this study.

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 (WM2012_S3C):

- the simulated time period is from 1920 to CY100
- the model is identical to the calibrated historical model until 1 January 1988
- the recharge zones for 1988 to CY100 are based on the 1988 irrigation development area, extended slightly around Qualco to represent the lateral spread of accession water within sediments overlying the Glenforslan Formation,
- recharge rates for 1988 to CY100 are assigned as follows and are given in Appendixes A-2 and A-5:
  - the rates from the calibrated model are used until 2006, to reflect best estimates of the impact of rehabilitation and improved irrigation practice.
  - from 2006 until 2011 (CY), the calibrated rates from the historical model are adopted, except where these fall below 100 mm/y, due to the drought restrictions of those years. This is because the Salinity Register scenarios should not include climate sequence impacts. In those zones, the recharge rates are instead held constant at 100 mm/y from 2006 to CY100.
  - zones with a calibrated recharge rate less than 100 mm/y prior to the drought restriction period of 2006 to 2010 are fixed at the lower rate unless the lower rate is likely to be due to lag times in newer irrigation developments, in which case the recharge rate will rise to a similar level to the surrounding recharge zones
  - in areas where irrigation did not exist in 1988, the mallee recharge rate of 0.1 mm/y is adopted
- the annual salt loads for 1988 to CY100 are reported as required by the MDBA for the Salinity Register.

In other Salinity Register SA models, zones with a recharge rate above 100 mm/y at CY are assumed to benefit from presumed future improvements in irrigation practices and their recharge rates are reduced to 100 mm/y from CY. This is not necessary for the Waikerie to Morgan model, as the maximum calibrated recharge rate for all zones at CY is 100 mm/y.

Table 5.7 summarises the predicted flux and salt load entering the River Murray in the Waikerie to Morgan area. Further results are given in Appendixes B-1 to B-2. The starting values in 1920 are those given for Scenario 1 in Table 5.4.

Table 5.7 Predicted groundwater flux and salt load – Scenario 3c: Pre-1988, with IIP and with RH

	Year					
	1988	**2000**	**2011**	**2015**	**2050**	**2111**
Holder to Lock 2						
Flux to river (m^3/d)	10 606	8343	6770	6336	5500	5499
Salt load to river (t/d)	151.1	119.5	96.5	90.1	78.1	78.2
Lock 2 to Hogwash						
Flux to river (m^3/d)	2528	2861	2563	2532	2497	2555
Salt load to river (t/d)	56.6	66.5	60.0	59.3	58.4	59.9
Hogwash to Morgan						
Flux to river (m^3/d)	4099	2541	1281	1153	1075	1081
Salt load to river (t/d)	22.4	14.8	8.7	8.1	7.7	7.8

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 8a, it can be used to estimate SIS benefits. It estimates the resulting hydrological changes, groundwater flux and salt load entering the River Murray. As the Salinity Register entries should not include the impact of climate sequence, the model does not simulate the contraction of irrigation area and reduction in recharge rates due to drought restrictions from 2006 to 2010. The irrigation rates for future years are based on those of 2005 rather than 2010, as 2010 is presumed to be anomalous.

The following conditions are applied to the transient model (WM2012_S4):

- the simulated time period is from 1920 to CY100
- the model recharge rates are identical to the calibrated historical model until 1 January 2006
- the recharge zones for 2006 to CY100 include all areas irrigated in 2005 and all newer irrigation areas which began after 2005 (i.e. the scenario does not simulate any reductions in irrigation area which occurred in the drought-restricted years 2006 to 2010), extended slightly around Qualco to represent the lateral spread of accession water within sediments overlying the Glenforslan Formation
- recharge rates for 2006 to CY100 are assigned as follows and are given in Appendixes A-2 and A-5:
  - from 2006 until 2010 (CY), the calibrated rates from the historical model are adopted, except where these fall below 100 mm/y due to the drought restrictions of those years. In those zones, the recharge rates are instead held constant at 100 mm/y from 2006 to CY100.
  - zones with a calibrated recharge rate less than 100 mm/y prior to the drought restriction period of 2006 to 2010 are fixed at the lower rate, unless the lower rate is likely to be due to lag times in newer irrigation developments, in which case the recharge rate will rise to a similar level to the surrounding recharge zones
  - an initial lag time of 10 years were applied in irrigation areas developed after 2001 as the new developed areas are not in the established groundwater mound area

  - in areas where irrigation did not exist in 2005 or 2011, the mallee recharge rate of 0.1 mm/y is adopted
- the annual salt load for 1988 to CY100 are reported as required by the MDBA for the Salinity Register.

In other Salinity Register SA models, zones with a recharge rate above 100 mm/y at CY are assumed to benefit from presumed future improvements in irrigation practices and their recharge rates are reduced to 100 mm/y from CY. This is not necessary for the Waikerie to Morgan model, as the maximum calibrated recharge rate for all zones at CY is 100 mm/y.

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

Table 5.8 Predicted groundwater flux and salt load – Scenario 4: Current irrigation

	Year					
	1988	**2000**	**2011**	**2015**	**2050**	**2111**
Holder to Lock 2						
Flux to river (m^3/d)	10 606	8343	7198	6970	6762	6944
Salt load to river (t/d)	151.1	119.5	103.2	100.1	97.7	100.6
Lock 2 to Hogwash						
Flux to river (m^3/d)	2528	2864	2880	3027	3332	3449
Salt load to river (t/d)	56.6	66.5	67.7	71.6	79.3	82.2
Hogwash to Morgan						
Flux to river (m^3/d)	4099	3254	2130	1982	1945	1971
Salt load to river (t/d)	22.4	20.0	14.8	14.2	14.4	14.7

5.8. SCENARIO 5: CURRENT, PLUS FUTURE EXPANSION OF IRRIGATION

Scenario 5 simulates the impact of current and new irrigation developments within the study area.

No new irrigation developments are anticipated within the Waikerie-Morgan study area, as irrigation has contracted during the recent drought and it is expected that it will take some years before the region resumes irrigation levels similar to 2005. Without new irrigation areas, Scenario 5 is identical to Scenario 4. For this reason, Scenario 5 is omitted from this study. This decision should be reviewed at the time of the next 5 Year Review.

5.9. SCENARIO 8A: CURRENT IRRIGATION WITH AS-CONSTRUCTED SIS

Scenarios 8a(i) to 8a(iv) simulate what will happen if the current irrigation development and practices continue indefinitely and one or more of the SIS and the QSTGCS continue to operate as currently constructed. The scenarios are identical to Scenario 4 except that they include one or more of the SIS and QSTGCS, so the scenarios can be compared to estimate each SIS and the QSTGCS benefits. The scenarios estimate the resulting hydrological changes, groundwater flux and salt load entering the River Murray. As with Scenario 4, Scenarios 8a(i) to 8a(iv) do not simulate the impact of the 2006 to 2010 drought restrictions and the irrigation rates for future years are based on those of 2005 rather than 2010, as 2010 is presumed to be anomalous.

The following conditions are applied to all Scenario 8a transient models (WM2012_S8A(i), WM2012_S8A(ii), WM2012_S8A(iii), WM2012_S8A(iv))

- the simulated time period is from 1920 to CY100
- the model is identical to the Scenario 4 model except that SIS and/or QSTGCS are included in chronological order as follows:
  - 8a(i) includes the Waikerie I SIS,
  - 8a(ii) includes the Waikerie I SIS and the QSTGCS,
  - 8a(iii) includes the Waikerie I SIS, the QSTGCS and the Waikerie IIA SIS,
  - 8a(iv) includes the Waikerie I SIS, the QSTGCS, the Waikerie IIA SIS and the Waikerie Lock 2 SIS
- The Waikerie I SIS is represented in Scenarios 8a(i) to 8a(iv) as follows:
  - The SIS production wells are simulated using the 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 midpoint observation bores.
  - 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 elevations in the model are 5.6 m AHD and the conductance is 1000 m^2/d
  - The simulated Waikerie I SIS starts in 1993, the same as the actual operational year
- The QSTGCS is represented in Scenarios 8a(ii) to 8a(iv) as follows:
  - Unlike the other schemes which are simulated by the Drain Package, most of the QSTGCS pumping wells are simulated by the Well Package, because the nominal target level for most of the pumping wells is 3 m below ground level (P Forward, SA Water, pers. comm., 2012). Note that this target level lies in the Loxton Sands, which is not simulated in the model (see Section 3.4).
  - The pumping rates adopted in the scenarios are the medians of the recorded pumping rates (Appendix A-11), to reflect the pumping rates under average conditions
  - Three QSTGCS pumping wells (Q1, Q2 and Q3) are located near the river and function like other SIS bores. Therefore these three pumping wells are simulated using the Drain Package. Different drain elevation and conductance values were trialled until the model achieve 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 midpoint level equal to or slightly lower than the river level and pumping rates within the actual recorded pumping rates, the adopted drain elevations in the model are 2.7 m AHD and the conductance is between 10 and 200 m^2/d
  - The simulated QSTGCS, represented by both Well and Drain Packages, starts in 2001, the same as the actual operational year

- The Waikerie IIA SIS is represented in Scenarios 8a(iii) and 8a(iv) as follows:
    - The SIS production wells are simulated using the 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 midpoint observation bores.
    - 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 elevations in the model are 5.6 m AHD and the conductance is between 10 and 1000 m^2/d
    - The simulated Waikerie IIA SIS starts in 2003, the same as the actual operational year
- The Waikerie Lock 2 SIS is represented in Scenario 8a(iv) as follows:
    - The SIS production wells are simulated using the 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 midpoint observation bores.
    - 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 elevations in the model are 2.7 m AHD and the conductance is between 20 and 1000 m^2/d
    - The simulated Waikerie Lock 2 SIS starts in 2009, the same as the actual operational year
- The annual salt loads for 1988 to CY100 are reported for each Scenarios 8a(i) to 8a(iv) as required by the MDBA for the Salinity Register.

Figure 5.1 shows how the SIS and GCS are simulated Scenarios 8a and 8b and the adopted conductance values for the drain cells.

The benefits of the SIS and the QSTGCS are assessed by comparing scenarios in SIS/QSTGCS construction sequence, so that each new scheme is compared to the situation prior to its construction. That is, the Waikerie I SIS is assessed by comparing Scenario 8a(i) with Scenario 4 (no SIS or QSTGCS). The QSTGCS is assessed by comparing Scenarios 8a(ii) with 8a(i). The Waikerie IIA SIS is assessed by comparing Scenarios 8a(iii) with 8a(ii). The Waikerie Lock 2 SIS is assessed by comparing Scenarios 8a(iv) with 8a(iii).

Table 5.9 to Table 5.12 summarise the predicted flux and salt load entering the River Murray in the Waikerie to Morgan area for Scenarios 8a(i) to 8a(iv) respectively. Further results of the predicted flux of saline groundwater and salt load are given in Appendixes B-1 to B-2. The salt loads are significantly lower than those of Scenario 4.

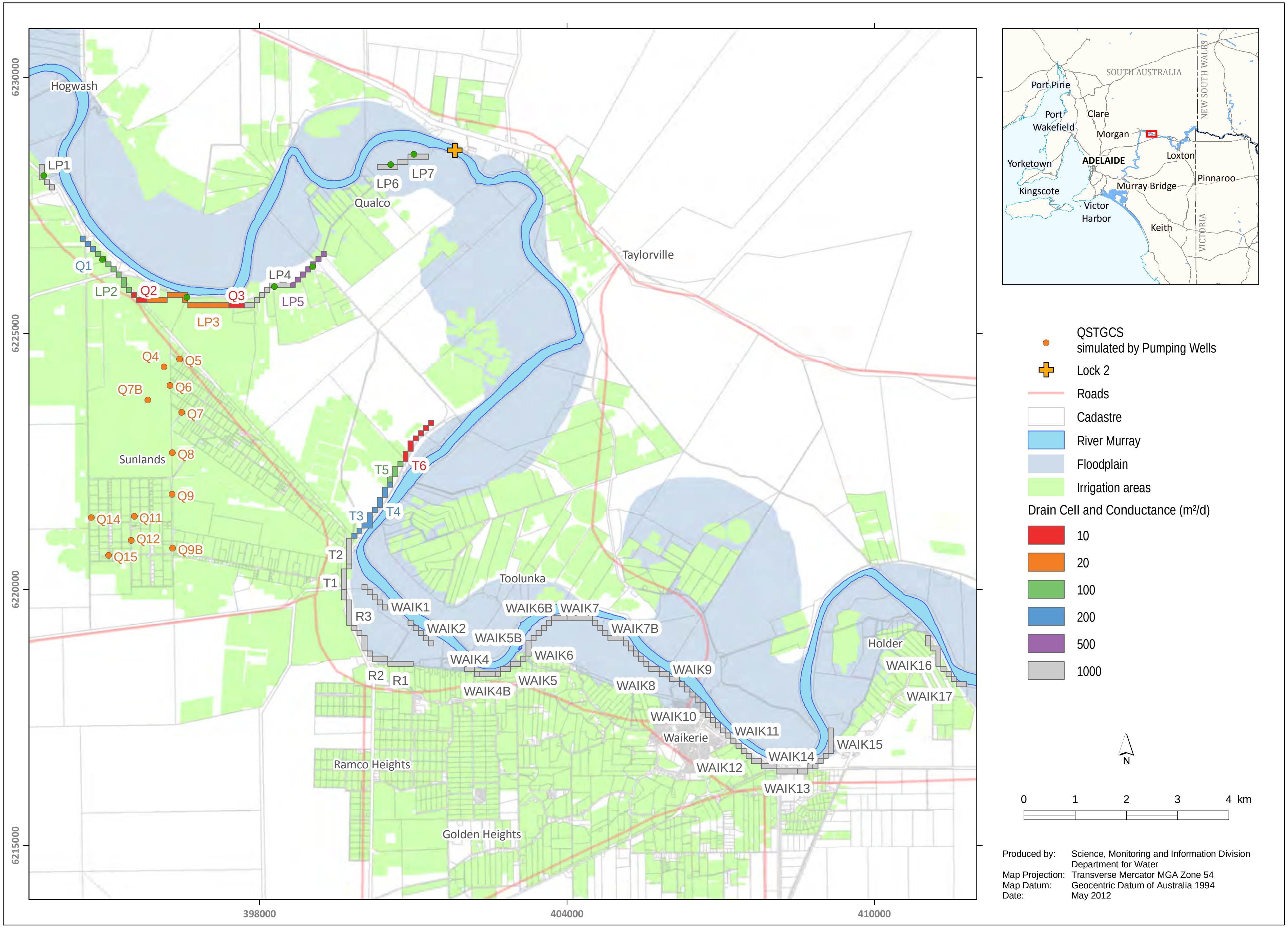


Figure 5.1 Modelled SIS and GCS in the Prediction Models

Table 5.9 Predicted groundwater flux and salt load – Scenario 8a(i): Current irrigation plus Waikerie I SIS

	Year					
	1988	**2000**	**2011**	**2015**	**2050**	**2111**
Holder to Lock 2						
Flux to river (m^3/d)	10 606	3322	2665	2578	2618	2730
Salt load to river (t/d)	151.1	50.4	40.6	39.3	40.1	41.9
Lock 2 to Hogwash						
Flux to river (m^3/d)	2528	2864	2877	3024	3325	3438
Salt load to river (t/d)	56.6	66.5	67.7	71.5	79.1	81.9
Hogwash to Morgan						
Flux to river (m^3/d)	4099	3254	2130	1982	1945	1970
Salt load to river (t/d)	22.4	20.0	14.8	14.2	14.4	14.7

Table 5.10 Predicted groundwater flux and salt load – Scenario 8a(ii): Current irrigation plus Waikerie I SIS and the QSTGCS

	Year					
	1988	**2000**	**2011**	**2015**	**2050**	**2111**
Holder to Lock 2						
Flux to river (m^3/d)	10 606	3322	2600	2466	2309	2355
Salt load to river (t/d)	151.1	50.4	39.6	37.4	34.9	35.6
Lock 2 to Hogwash						
Flux to river (m^3/d)	2528	2864	2220	2282	2309	2349
Salt load to river (t/d)	56.6	66.5	51.2	52.9	53.7	54.7
Hogwash to Morgan						
Flux to river (m^3/d)	4099	3254	2101	1946	1878	1893
Salt load to river (t/d)	22.4	20.0	14.6	13.9	13.8	14.1

Table 5.11 Predicted groundwater flux and salt load – Scenario 8a(iii): Current irrigation plus Waikerie I SIS, the QSTGCS and Waikerie IIA SIS

	Year					
	1988	**2000**	**2011**	**2015**	**2050**	**2111**
Holder to Lock 2						
Flux to river (m^3/d)	10 606	3322	1778	1697	1542	1540
Salt load to river (t/d)	151.1	50.4	25.9	24.7	22.2	22.2
Lock 2 to Hogwash						
Flux to river (m^3/d)	2528	2864	2205	2252	2246	2278
Salt load to river (t/d)	56.6	66.5	50.8	52.2	52.0	52.9
Hogwash to Morgan						
Flux to river (m^3/d)	4099	3254	2101	1946	1876	1891
Salt load to river (t/d)	22.4	20.0	14.6	13.9	13.8	14.0

Table 5.12 Predicted groundwater flux and salt load – Scenario 8a(iv): Current irrigation plus Waikerie I SIS, the QSTGCS, Waikerie IIA SIS and Waikerie Lock 2 SIS

	Year					
	1988	**2000**	**2011**	**2015**	**2050**	**2111**
Holder to Lock 2						
Flux to river (m^3/d)	10 606	3322	1777	1695	1536	1534
Salt load to river (t/d)	151.1	50.4	25.9	24.7	22.1	22.1
Lock 2 to Hogwash						
Flux to river (m^3/d)	2528	2864	1276	1218	1226	1239
Salt load to river (t/d)	56.6	66.5	27.3	26.0	26.3	26.6
Hogwash to Morgan						
Flux to river (m^3/d)	4099	3254	2047	1870	1785	1797
Salt load to river (t/d)	22.4	20.0	14.1	13.2	13.0	13.2

5.10. SCENARIO 8B: PRE-1988 IRRIGATION WITH AS-CONSTRUCTED SIS

Scenarios 8b(i) to 8b(iv) simulate 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 and the SIS and QSTGCS had been constructed. The scenarios are identical to Scenario 3c except that they include one or more of the SIS and the QSTGCS, so the scenarios can be compared to estimate the SIS and the QSTGCS benefits for cost-sharing calculations. They estimate the resulting hydrological changes, groundwater flux and salt load entering the River Murray.

The following conditions are applied to the transient model (WM2012_S8B(i), WM2012_S8B(ii), WM2012_S8B(iii), WM2012_S8B(iv)):

- the simulated time period is from 1920 to CY100
- the model is identical to the Scenario 3c model except that GCS and/or SIS are included in chronological order as follows:
  - 8b(i) includes the Waikerie I SIS,
  - 8b(ii) includes the Waikerie I SIS and the QSTGCS,
  - 8b(iii) includes the Waikerie I SIS, the QSTGCS and the Waikerie IIA SIS,
  - 8b(iv) includes the Waikerie I SIS, the QSTGCS, the Waikerie IIA SIS and the Waikerie Lock 2 SIS
- the SIS and QSTGCS are simulated using the same methodology as Scenario 8a. Appendices A-10 to A-13 provide further detail.
- the annual salt load for 1988 to CY100 are reported as required by the MDBA for the Salinity Register.

Figure 5.1 shows how the SIS and GCS are simulated in Scenarios 8a and 8b and the adopted conductance values for the drain cells.

Tables 5.1 to 5.2 summarise the predicted flux and salt load entering the River Murray in the Waikerie to Morgan area. Further results of the predicted flux of saline groundwater and salt load are given in Appendixes B-1 to B-2.

Table 5.13 Predicted groundwater flux and salt load (Scenario 8b(i): Current irrigation plus Waikerie I SIS)

	Year					
	1988	**2000**	**2011**	**2015**	**2050**	**2111**
Holder to Lock 2						
Flux to river (m^3/d)	10 606	3322	2343	2114	1768	1784
Salt load to river (t/d)	151.1	50.4	35.5	31.8	26.5	26.8
Lock 2 to Hogwash						
Flux to river (m^3/d)	2528	2861	2561	2529	2491	2547
Salt load to river (t/d)	56.6	66.5	60.0	59.2	58.3	59.7
Hogwash to Morgan						
Flux to river (m^3/d)	4099	2541	1281	1153	1075	1081
Salt load to river (t/d)	22.4	14.8	8.7	8.1	7.7	7.8

Table 5.14 Predicted groundwater flux and salt load (Scenario 8b(ii): Current irrigation plus Waikerie I SIS and the QSTGCS)

	Year					
	1988	**2000**	**2011**	**2015**	**2050**	**2111**
Holder to Lock 2						
Flux to river (m^3/d)	10 606	3322	2280	2009	1518	1477
Salt load to river (t/d)	151.1	50.4	34.4	30.1	22.5	21.8
Lock 2 to Hogwash						
Flux to river (m^3/d)	2528	2861	1953	1860	1616	1609
Salt load to river (t/d)	56.6	66.5	44.7	42.3	36.1	36.0
Hogwash to Morgan						
Flux to river (m^3/d)	4099	2541	1260	1129	1035	1035
Salt load to river (t/d)	22.4	14.8	8.5	7.9	7.4	7.4

Table 5.15 Predicted groundwater flux and salt load (Scenario 8b(iii): Current irrigation plus Waikerie I SIS, the QSTGCS and Waikerie IIA SIS)

	Year					
	1988	**2000**	**2011**	**2015**	**2050**	**2111**
Holder to Lock 2						
Flux to river (m^3/d)	10 606	3322	1629	1478	1159	1122
Salt load to river (t/d)	151.1	50.4	23.7	21.5	16.8	16.2
Lock 2 to Hogwash						
Flux to river (m^3/d)	2528	2861	1940	1834	1575	1573
Salt load to river (t/d)	56.6	66.5	44.3	41.7	35.1	35.0
Hogwash to Morgan						
Flux to river (m^3/d)	4099	2541	1260	1129	1034	1035
Salt load to river (t/d)	22.4	14.8	8.5	7.9	7.4	7.4

Table 5.16 Predicted groundwater flux and salt load (Scenario 8b(iv): Current irrigation plus Waikerie I SIS, the QSTGCS, Waikerie IIA SIS and Waikerie Lock 2 SIS)

	Year					
	1988	**2000**	**2011**	**2015**	**2050**	**2111**
Holder to Lock 2						
Flux to river (m^3/d)	10 606	3322	1628	1477	1157	1119
Salt load to river (t/d)	151.1	50.4	23.7	21.5	16.8	16.2
Lock 2 to Hogwash						
Flux to river (m^3/d)	2528	2861	1127	1002	912	910
Salt load to river (t/d)	56.6	66.5	23.6	20.5	18.2	18.2
Hogwash to Morgan						
Flux to river (m^3/d)	4099	2541	1226	1088	994	994
Salt load to river (t/d)	22.4	14.8	8.2	7.5	7.0	7.0

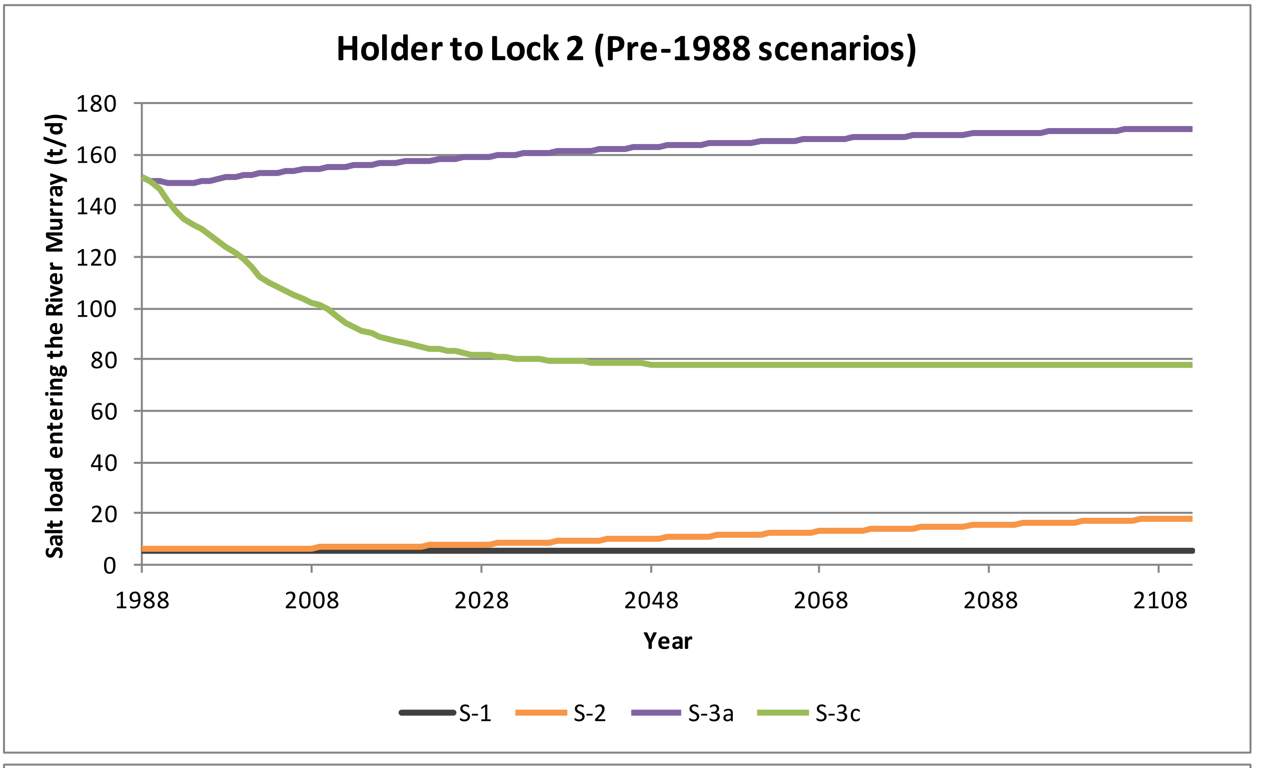
5.11. SCENARIO 8C: FUTURE IRRIGATION WITH AS-CONSTRUCTED SIS

Scenario 8C simulates the impact of current and new irrigation developments within the study area when the as-constructed SIS and QSTGCS are included.

As discussed for Scenario 5, no new irrigation developments are anticipated within the Waikerie-Morgan study area. Without new irrigation areas, Scenario 8c is identical to Scenario 8a. For this reason, Scenario 8c is omitted from this study. This decision should be reviewed at the time of the next 5 Year Review.

5.12. COMPARISON OF SCENARIO SALT LOADS

Figures 5.2 to 5.7 display the annual salt loads from 1988 to 2111 for all scenarios for each of the three river reaches, Holder to Lock 2, Lock 2 to Hogwash, and Hogwash to Morgan. Details of the model results (both flux and salt load) for all scenarios are given in Appendix B.



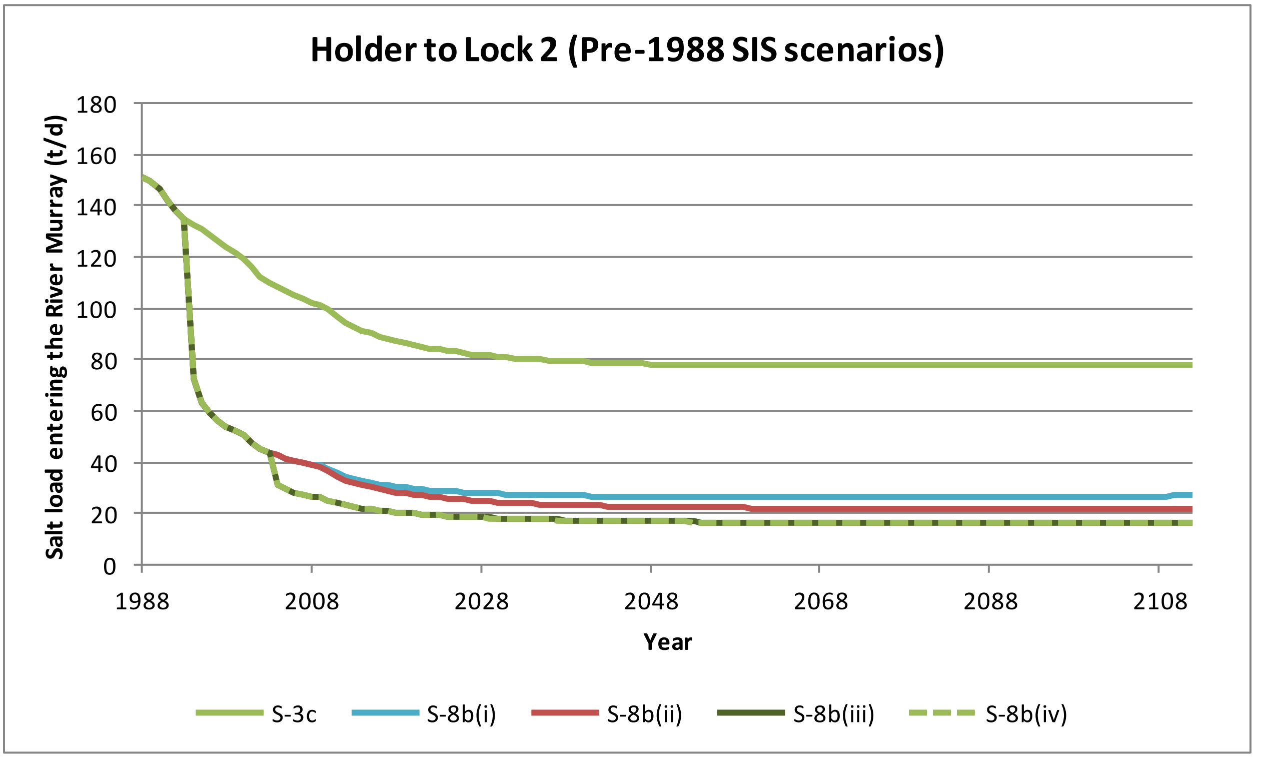
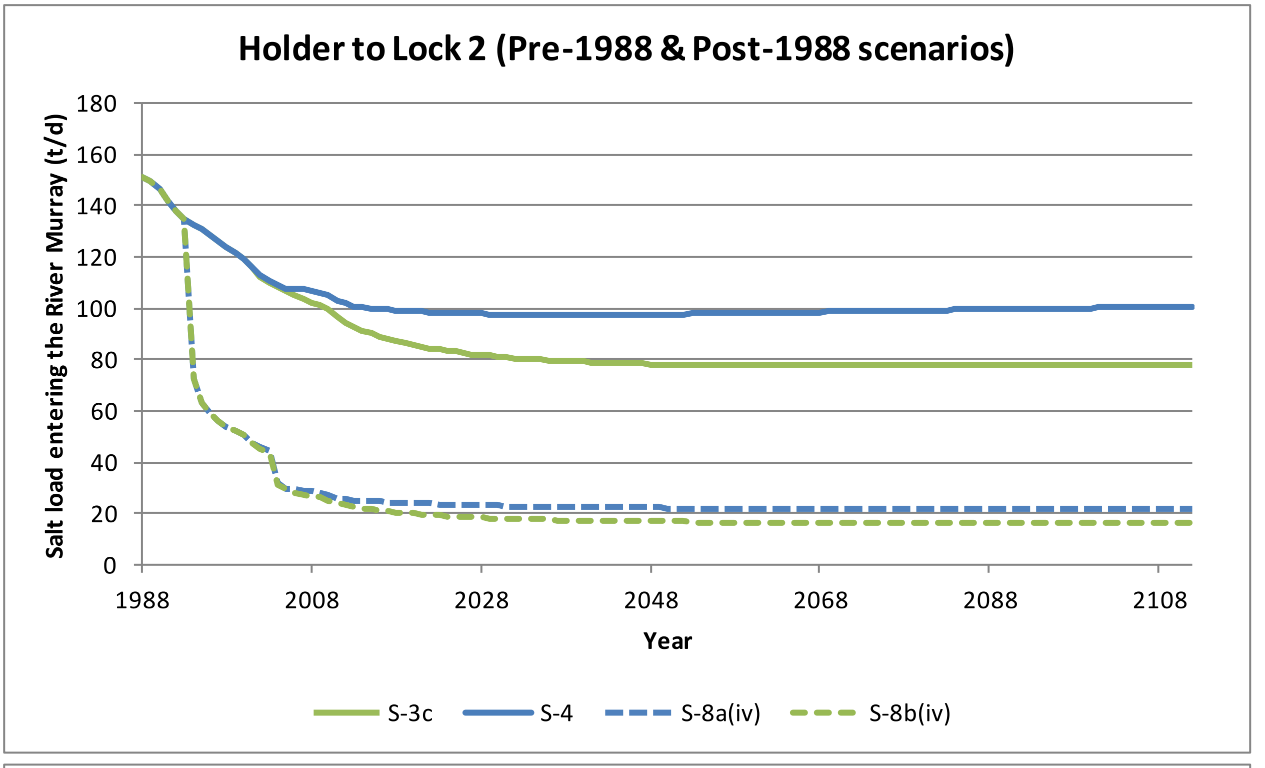


Figure 5.2 Predicted Total Salt Loads Entering the River Murray from the Holder–Lock 2 Reach for Pre-1988 Scenarios



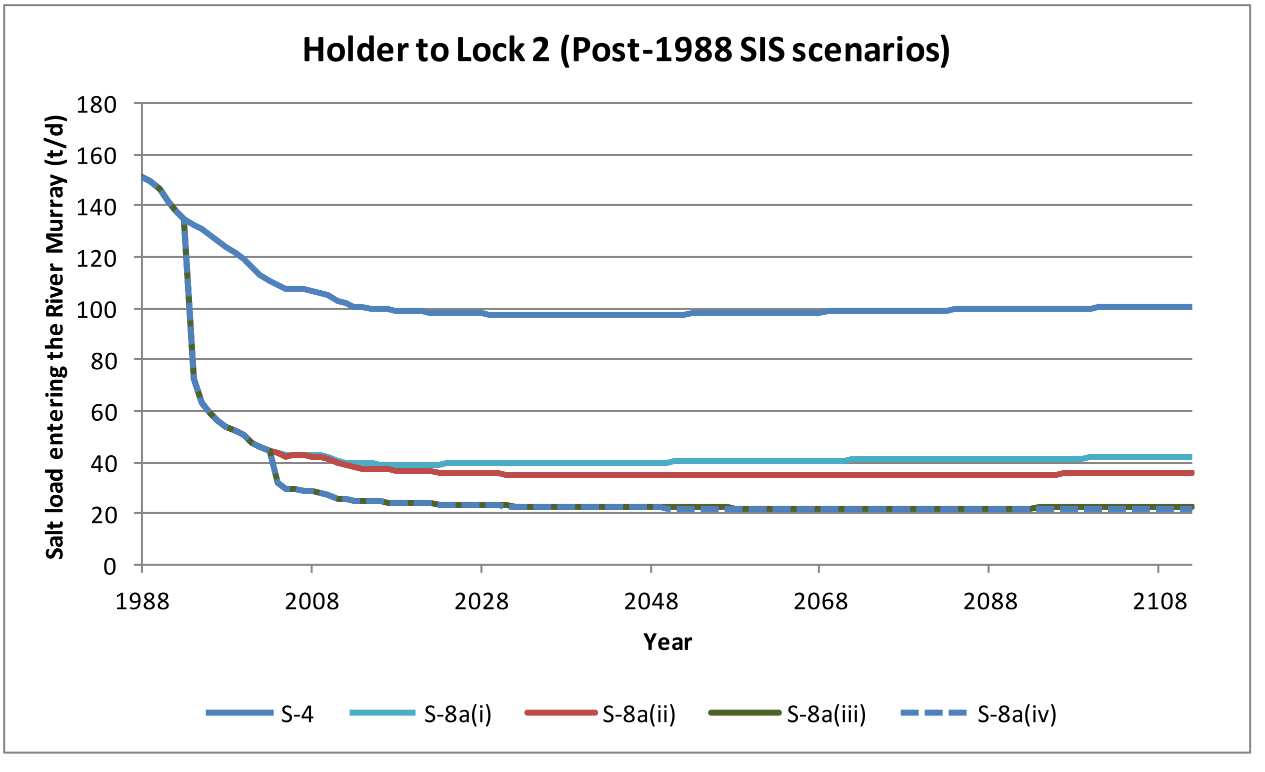


Figure 5.3 Predicted Total Salt Loads Entering the River Murray from the Holder–Lock 2 Reach for Pre-1988 and Post-1988 Scenarios

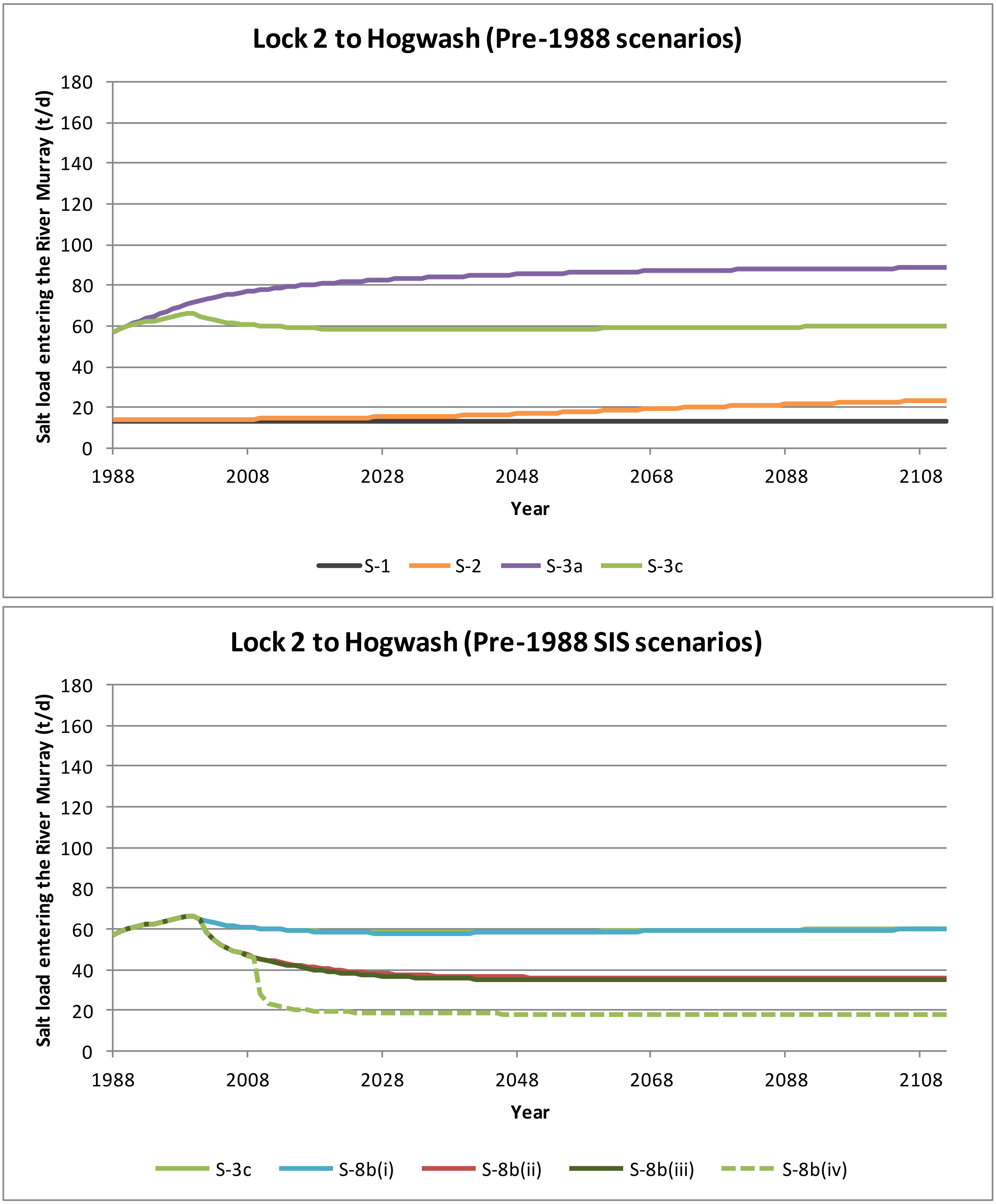
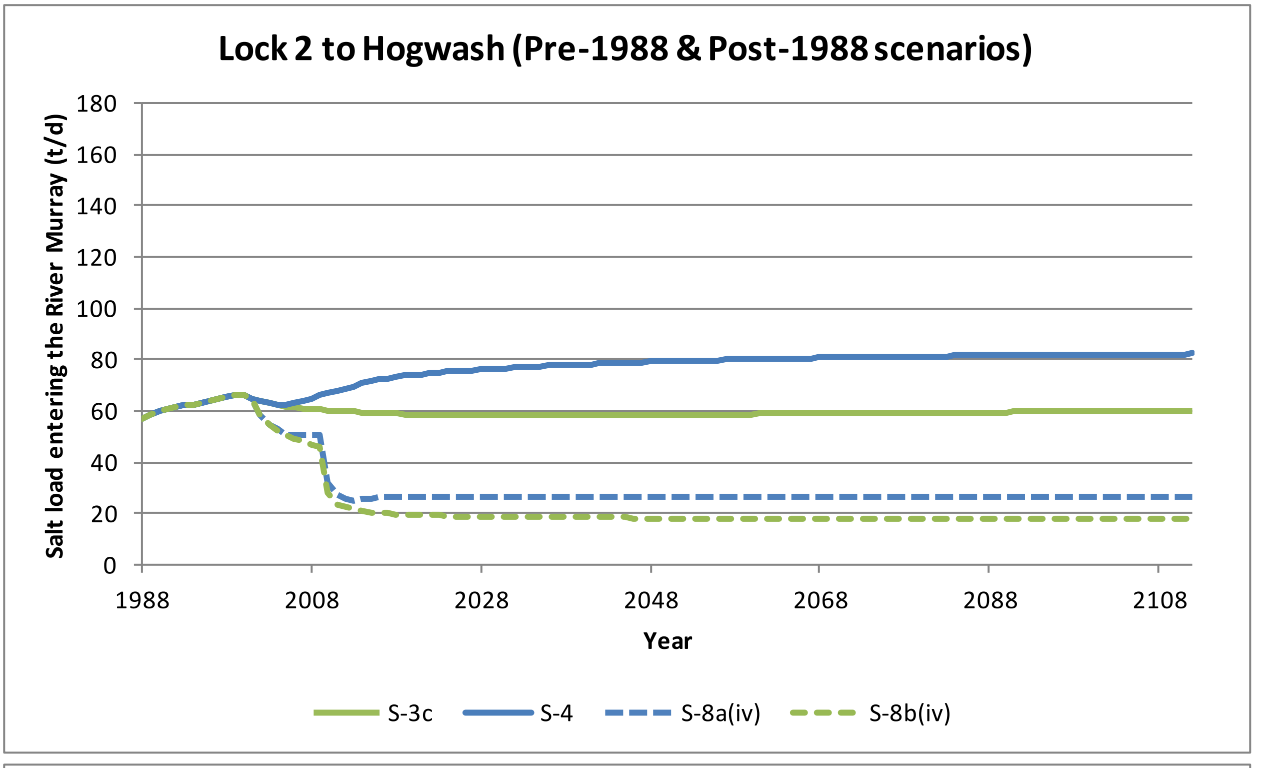


Figure 5.4 Predicted Total Salt Loads Entering the River Murray from the Lock 2–Hogwash Reach for Pre-1988 Scenarios



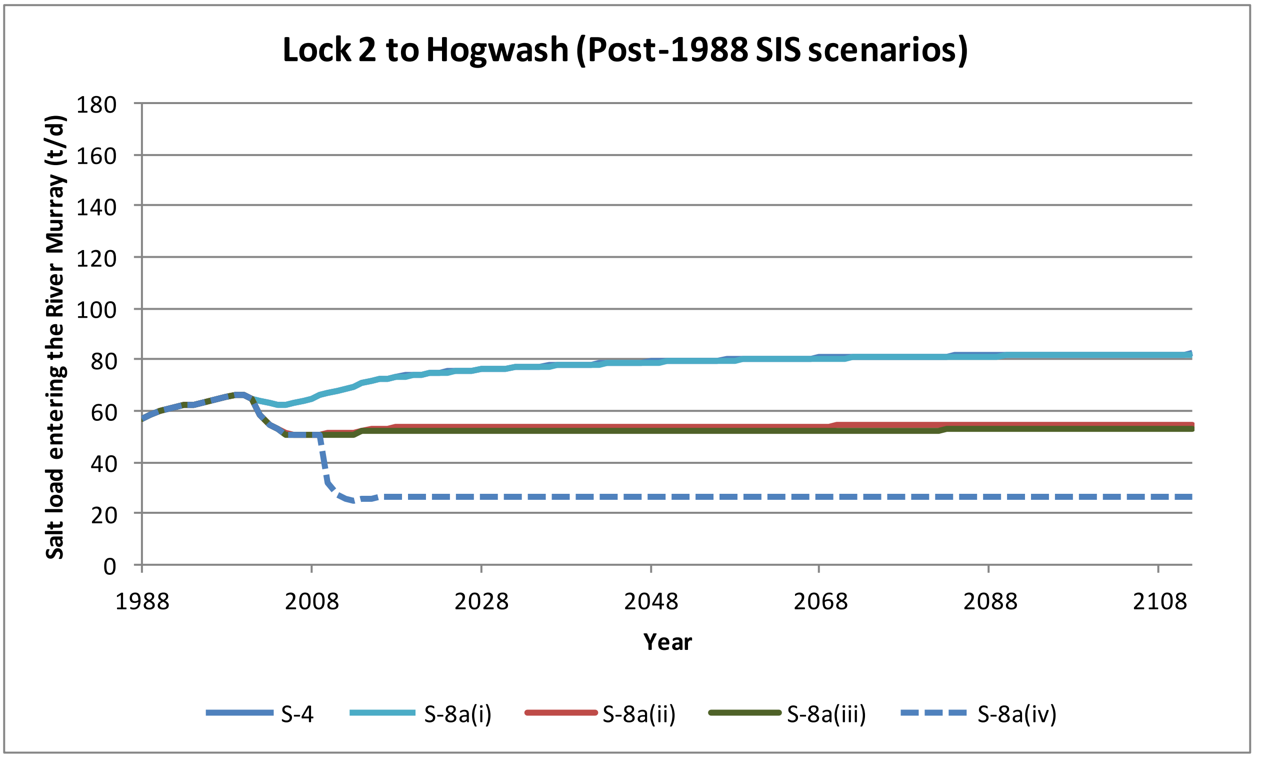
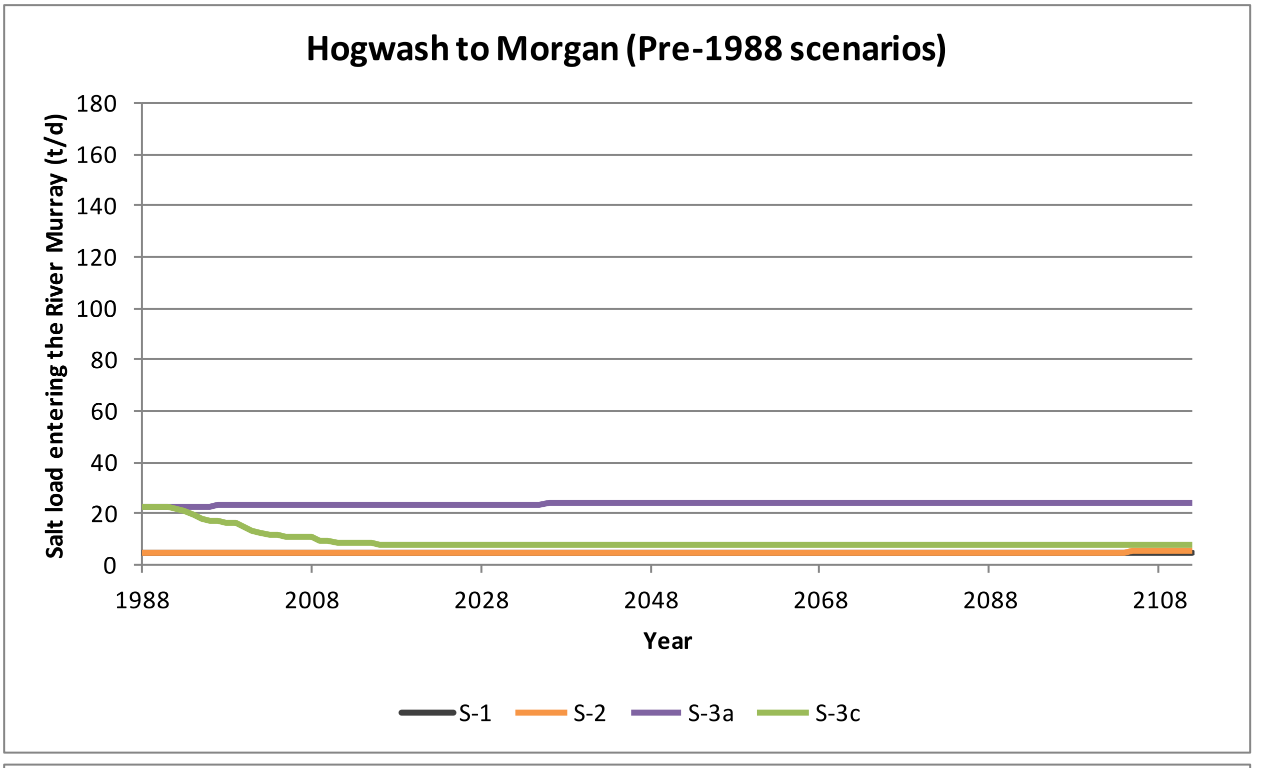


Figure 5.5 Predicted Total Salt Loads Entering the River Murray from the Lock 2–Hogwash Reach for Pre-1988 and Post-1988 Scenarios



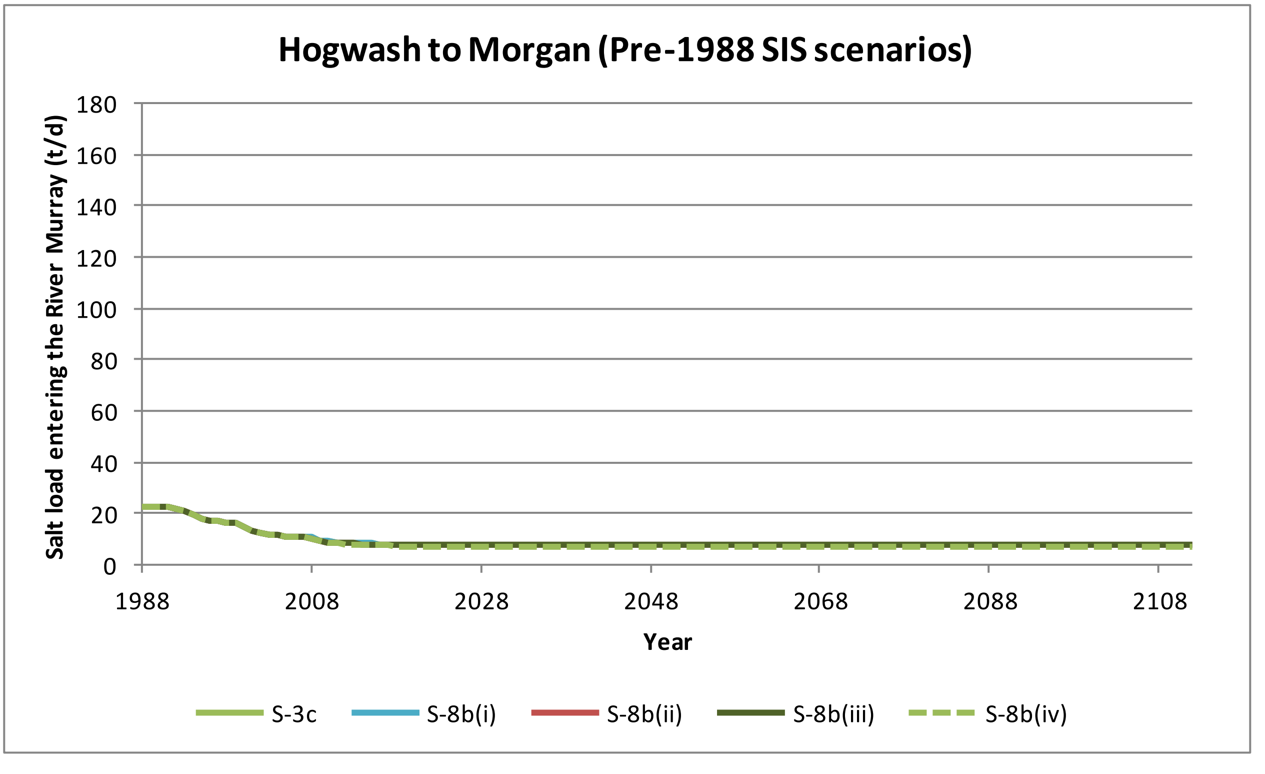
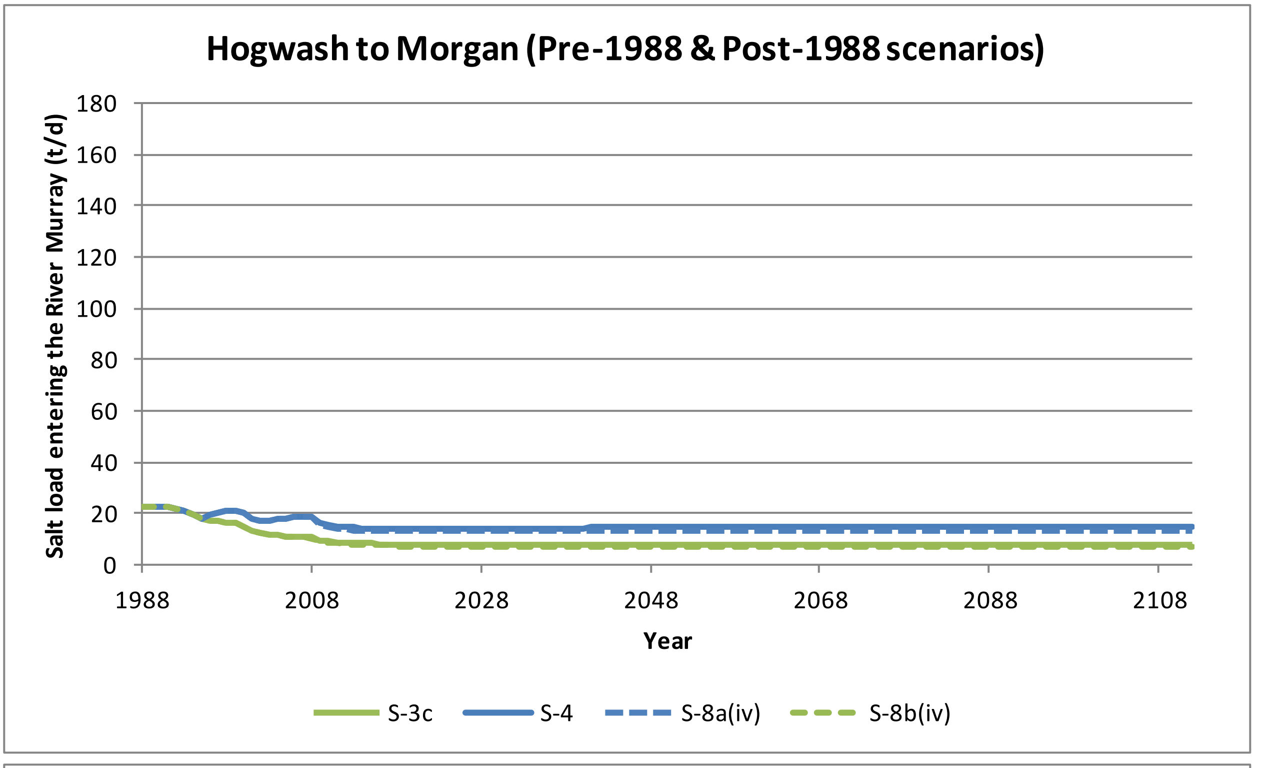


Figure 5.6 Predicted Total Salt Loads Entering the River Murray from the Hogwash–Morgan Reach for Pre-1988 Scenarios



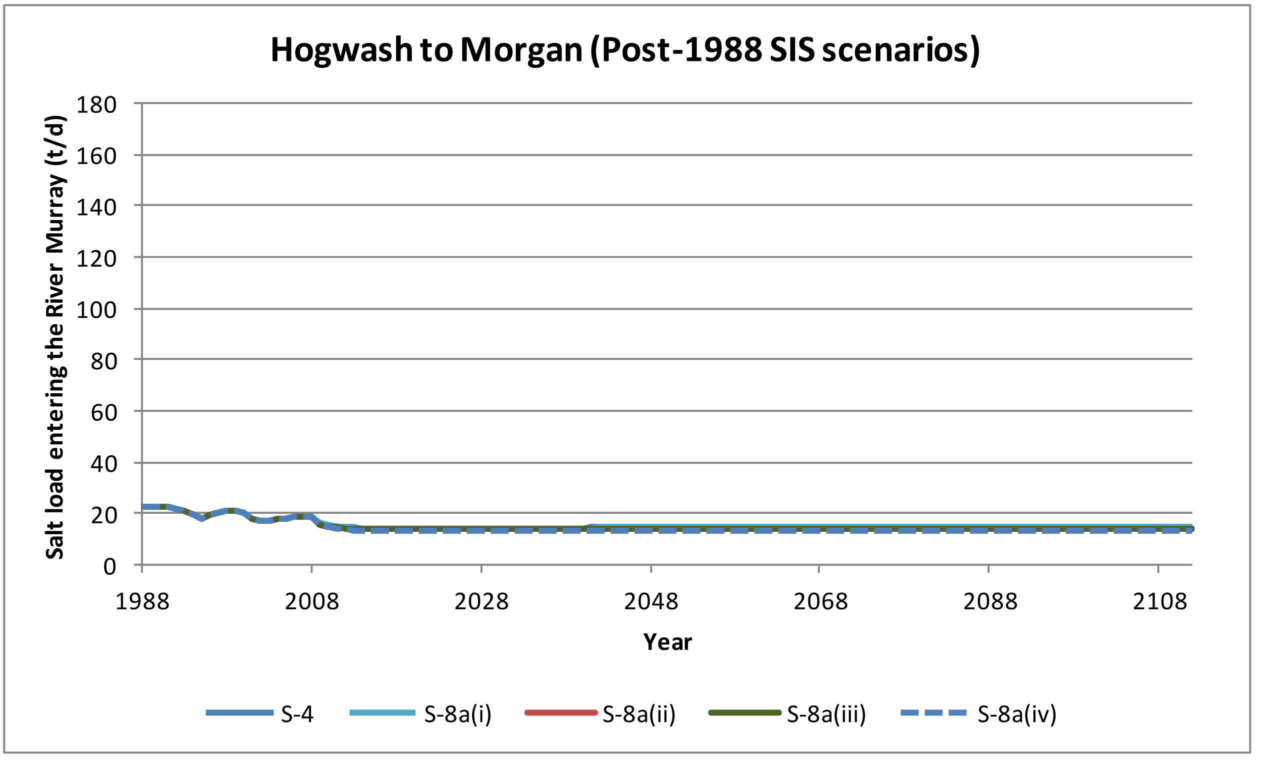


Figure 5.7 Predicted Total Salt Loads Entering the River Murray from the Hogwash–Morgan Reach for Pre-1988 and Post-1988 Scenarios

6. SENSITIVITY AND UNCERTAINTY ANALYSIS

Sensitivity analysis is a procedure for quantifying the impact of an incremental variation in aquifer hydraulic parameters or stresses on modelled responses (MDBC 2001). For a given calibrated model, it identifies whether changes in model inputs lead to large changes in modelled outputs. The *Groundwater Flow Modelling Guideline* (MDBC 2001) recommends for high complexity models, such as the Waikerie to Morgan 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 Waikerie to Morgan 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 (i) the SRMS to head observations and (ii) salt load.

Four key model inputs are varied for the sensitivity analysis:

- groundwater evapotranspiration extinction depth
- Glenforslan hydraulic conductivity
- riverbed conductance
- river level.

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

The aim of the uncertainty analysis for the Waikerie to Morgan model is to gauge the confidence of the salt load predictions and the impact on predictions of different assumptions and inputs. The scenarios demonstrating the greatest magnitude of salt load are Scenarios 4 and 8a(iv) so these are simulated for the analysis.

Two model inputs are varied for the uncertainty analysis:

- groundwater salinity
- recharge.

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.

6.1. SENSITIVITY ANALYSIS

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

6.1.1. PARAMETERS AND VALUES

The parameters investigated for the sensitivity analysis are those where there is a degree of uncertainty of their value and where their importance to model results is not immediately clear. The standard practice is to vary the values within 15% or less of their calibrated values. That approach is not adopted here. Instead, the four parameters are varied within reasonable bounds to more robustly check their impact on key model outputs, as described below. Table 6.1 gives the values of the four parameters in the calibrated model and other values considered in the sensitivity simulations.

Groundwater evapotranspiration extinction depth is included in the sensitivity analysis as it is difficult to establish a regionally representative value based on fieldwork: it can be measured in the field but may be highly variable within small areas. The groundwater ET extinction depth is varied by 0.5 m from the value of 2 m used in the calibrated model.

The hydraulic conductivity of the Glenforslan Formation has been estimated from aquifer tests at Qualco but not elsewhere. For the sensitivity analysis, the horizontal hydraulic conductivity of the Glenforslan Formation is varied through the range 0.04 to 1.21 m/d observed in aquifer tests at Qualco, not including values from highly karstic samples as these are unlikely to be regionally representative. The vertical hydraulic conductivity is scaled to be one tenth of the horizontal conductivity.

Riverbed conductance depends on riverbed sediment thickness and hydraulic conductivity, neither of which has been sampled within the study area. The two riverbed conductance values considered are lower than the value used in the calibrated model. The conductance is the product of the riverbed vertical conductivity and the grid cell area divided by the thickness of the riverbed. The thickness of the riverbed is not known. The calibrated model's riverbed conductance of 1500 m^2/d is equivalent to a vertical conductivity of 0.15 m/d for a riverbed thickness of 1 m, which is considered to be towards the upper end of the reasonable range. For this reason, the sensitivity analysis considers two conductance values lower than 1500 m^2/d but no value higher. The two lower conductance values, 10 and 500 m^2/d, are equivalent to vertical conductivities of 0.001 and 0.050 m/d respectively, for a riverbed thickness of 1 m.

River levels are extensively monitored, but as the model does not simulate changes in river level over time, the question is how the river level impacts the model outputs. In the calibrated model, the river level can be considered "average" or representative of constant-climate conditions. An analysis of river levels upstream and downstream of Lock 2 recorded from 1975 to 2010 was conducted. It was found that upstream of Lock 2, where the pool level is 6.10 m AHD, the median level is 6.15 m AHD and the 75th percentile is 6.19 m AHD. Levels are more variable downstream of Lock 2, where the pool level is 3.20 m AHD, the median is 3.48 m AHD and the 75th percentile is 4.55 m AHD. The median and 75th percentile values are adopted for the river level sensitivity analysis. Only values higher than those adopted for the calibrated model are considered, as the model assumes river pool level, below which river levels are unlikely to drop in the Waikerie to Morgan reach.

6.1.2. RESULTS

Figure 6.1 shows the sensitivity of the calibration fit (SRMS of the difference between modelled and observed potentiometric head) to the sensitivity parameters for 1980, 1992 and 2008. Positive values indicate a better fit to observation data than the calibrated model, negative values indicate a worse fit.

Two of the selected parameters make negligible difference to the calibration fit, indicating that they do not substantially alter modelled potentiometric heads. Model results are not sensitive to groundwater extinction depth or river level.

Table 6.1 Sensitivity test parameter values

	Lower value	Low value	Calibrated model	High value	Higher value
Groundwater ET ext depth (m)		1.5	2.0	2.5	
Glenforslan K (m/d)					
K_h		0.040	0.200	1.210	
K_v		0.004	0.020	0.121	
Riverbed conductance (m^2/d)	10	500	1500		
River level (m AHD)			*Pool level*	*Median*	*75th percentile*
Upstream Lock 2			6.10	6.15	6.19
Downstream Lock 2			3.20	3.48	4.55

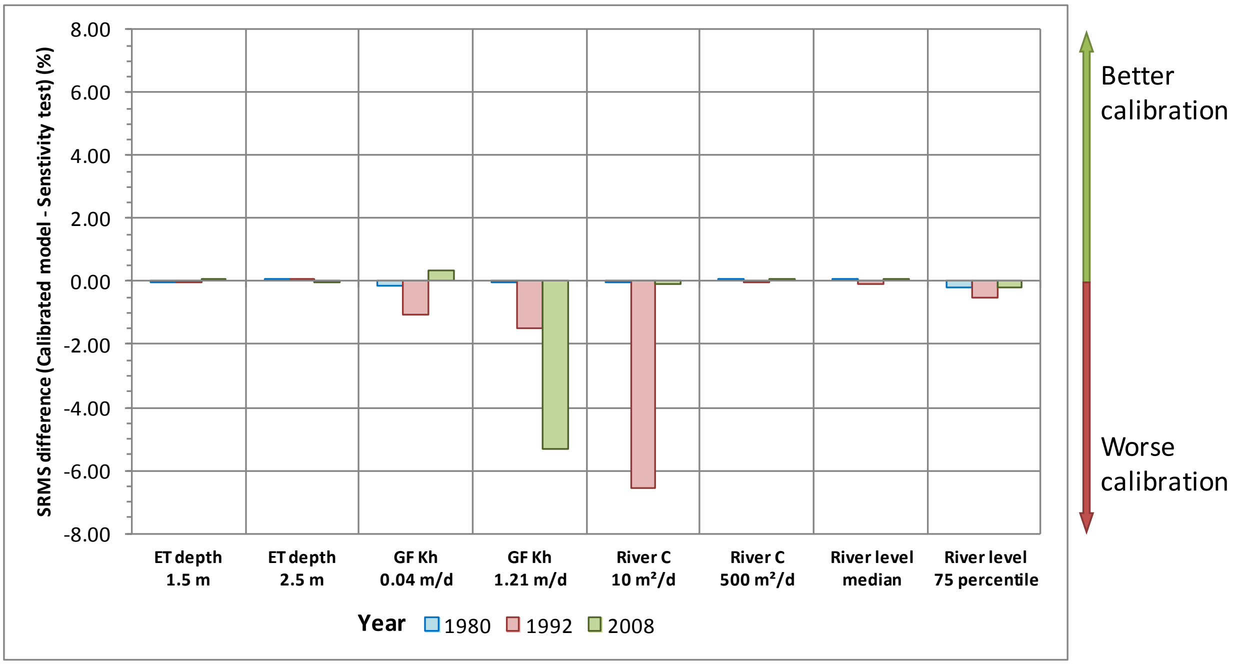


Figure 6.1 Sensitivity of Calibration Fit to Observed Heads (SRMS)

The calibration fit is noticeably affected by the Glenforslan hydraulic conductivity. A low value slightly improves calibration for 2008, but in general the fit is significantly worse for altered values of Glenforslan hydraulic conductivity than for the calibrated model. The calibration fit is also poor for the low riverbed conductance of 10 m^2/d for the year 1992 (i.e. when the groundwater mounds are high and prior to SIS and GCS operation).

Figures 6.2 to 6.4 show the salt load over time for the Holder to Lock 2, Lock 2 to Hogwash and Hogwash to Morgan reaches respectively (see Table 4.1 for definitions). The figures show the sensitivity of the groundwater salt load to the River Murray to the sensitivity parameters.

Figure 6.2 gives the salt load for the Holder to Lock 2 reach. Salt loads are not sensitive to river level, the lower Glenforslan hydraulic conductivity or a threefold reduction in riverbed conductance. Salt loads are slightly sensitive to groundwater ET extinction depth and to increased Glenforslan hydraulic conductivity. Salt loads are strongly reduced when a much lower riverbed conductance of 10 m^2/d is adopted. Note that the salt loads may respond more strongly under some hydrogeological conditions than others. For example, salt loads are more sensitive to groundwater ET extinction depth during the decades of groundwater mound growth (1940 to mid-1990s) than in more recent years when the SIS are operational.

Figure 6.3 gives the salt load for the Lock 2 to Hogwash reach. The results differ somewhat from those seen for the Holder to Lock 2 reach. Salt loads are again minimally influenced by groundwater ET extinction depth. Salt loads are more sensitive to increased Glenforslan hydraulic conductivity but less sensitive to the riverbed conductance of 10 m^2/d in this reach than in the Holder to Lock 2 reach. Also, salt loads in this reach are sensitive to river levels, lowering as river levels rise, as higher river levels will reduce the gradient between groundwater potentiometric head and the river.

Figure 6.4 gives the salt load for the Hogwash to Morgan reach. Salt loads are not sensitive to groundwater ET extinction depth or Glenforslan hydraulic conductivity. Salt loads are reduced when a riverbed conductance of 10 m^2/d or a 75^{th} percentile river level is adopted.

In summary, the calibrated model results are not sensitive to reasonable changes in groundwater ET extinction depth. A higher Glenforslan hydraulic conductivity shows a poorer match to observations and increases salt load principally in the Lock 2 to Hogwash reach. A low riverbed conductance of 10 m^2/d also shows a poorer match to observations and almost halves the salt load in the Holder to Lock 2 reach in some years. Salt loads are sensitive to higher river levels mainly in the Lock 2 to Hogwash reach, presumably because there is less variance in river levels upstream of Lock 2 than downstream.

6.2. UNCERTAINTY ANALYSIS

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

Two model inputs are varied for the uncertainty analysis:

- Groundwater salinity
- Irrigation area recharge.

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. There is uncertainty as to what salinity value may be selected due to different approaches to assessment and analyses. Section 3.8 explains how ‘representative’ salinity values were estimated for each salinity zone in this study.

The model calculates groundwater flow but does not simulate groundwater salinity changes either using observed values or solute transport modelling. The salt loads for each reach are estimated externally to the MODFLOW model, by multiplying the modelled flux value by the selected salinity zone value. For the purposes of the Salinity Register, it assumed that regional groundwater salinity is constant over time.

Owing to the variability in measured groundwater salinity, it is possible to develop more than one valid methodology and different expert opinion on salinity value selection. For the uncertainty analysis of the Waikerie to Morgan model, three approaches are compared:

1. the adopted salinities of the current calibrated model, generally adopting nearest to the river and higher values which are considered to be representative of the regional groundwater salinity values

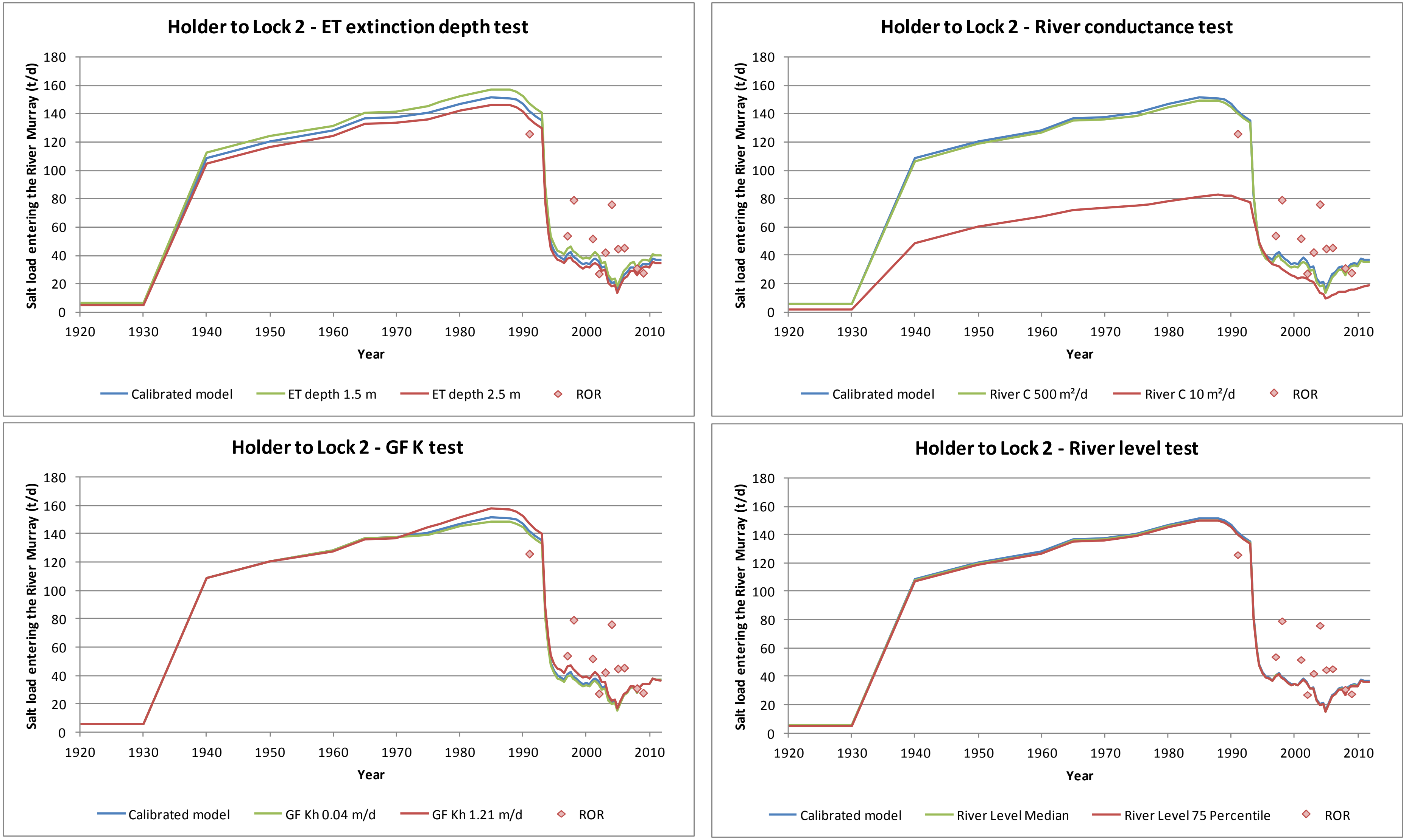


Figure 6.2 **Sensitivity of Salt Loads for the Holder to Lock 2 Reach**

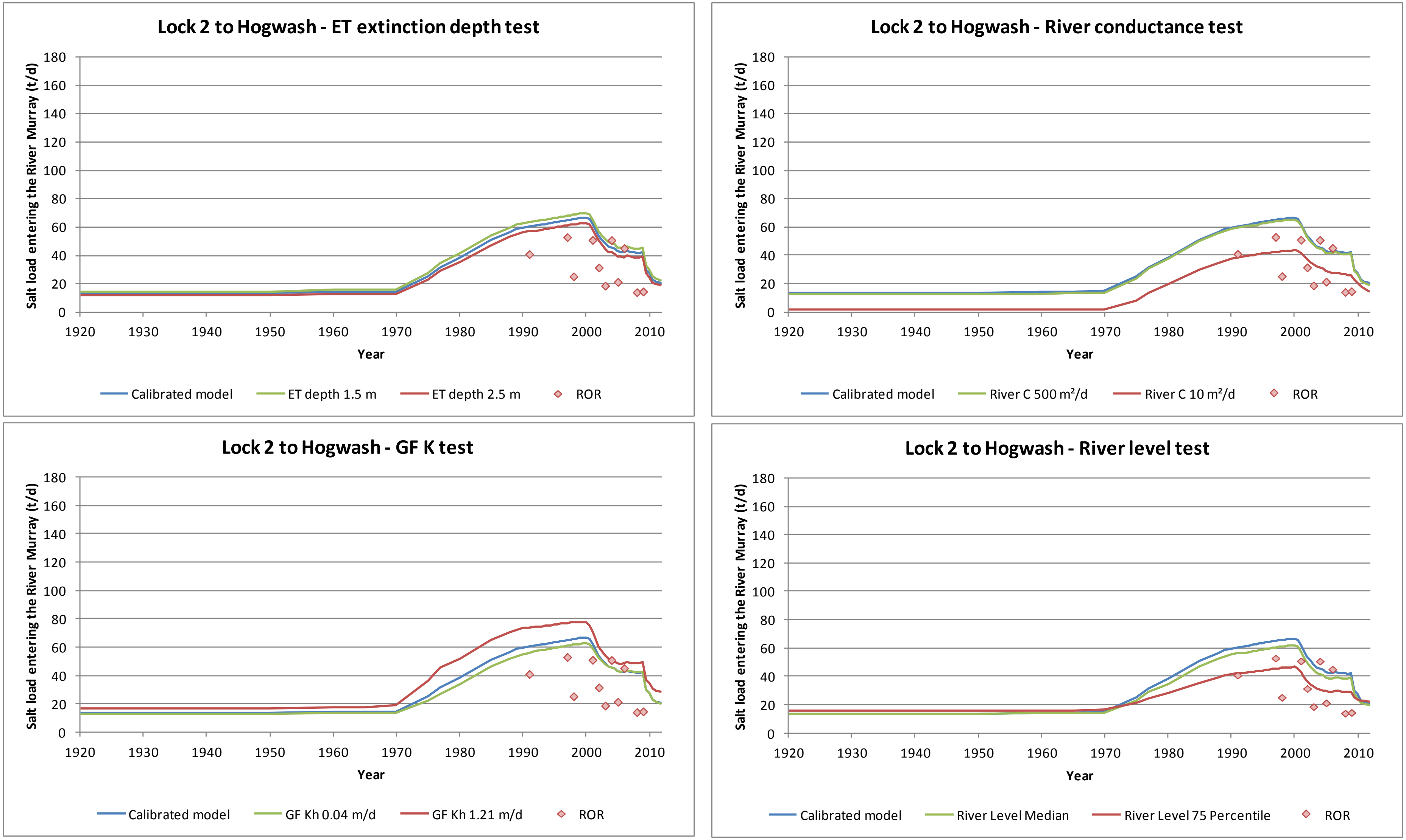


Figure 6.3 Sensitivity of Salt Loads for the Lock 2 to Hogwash Reach

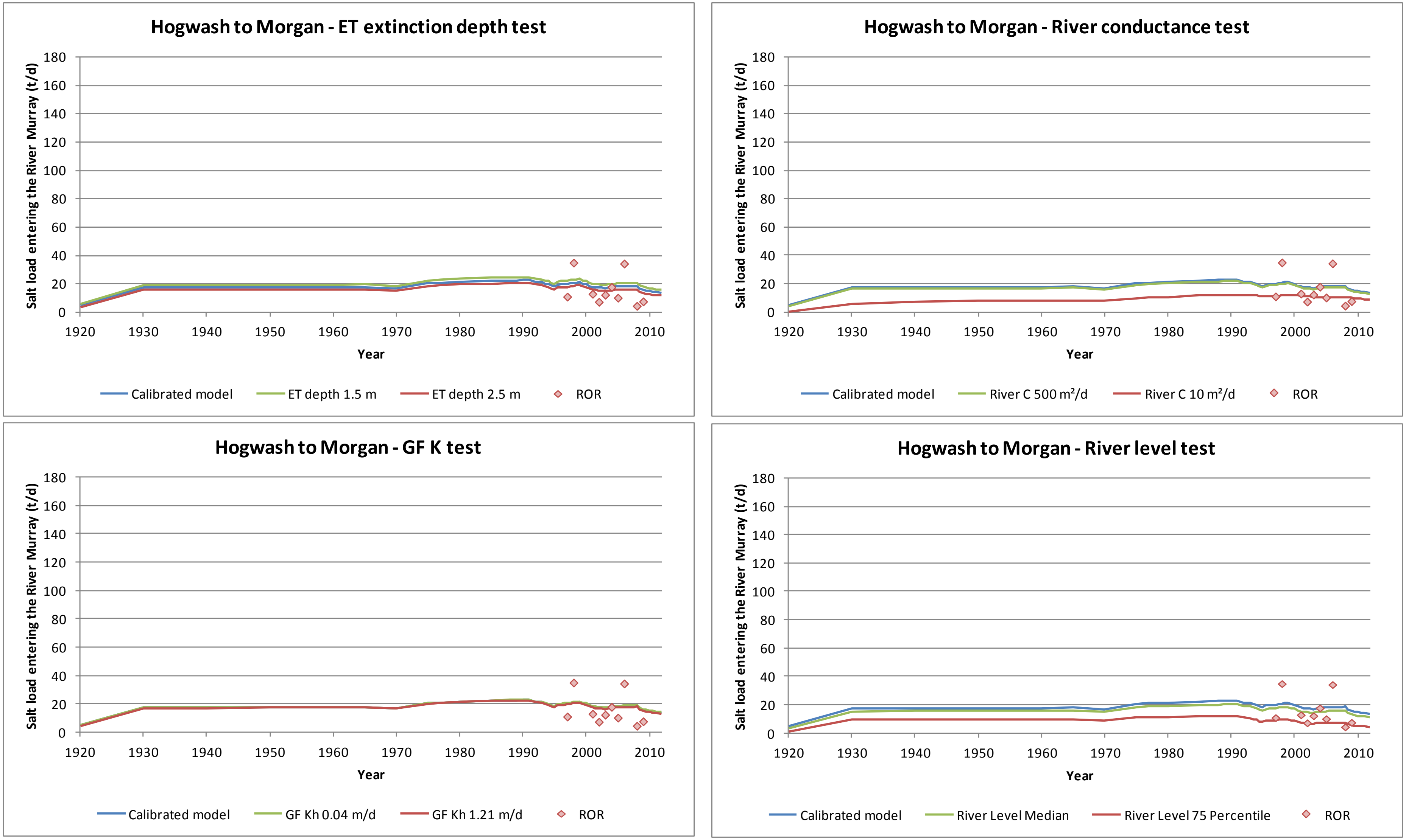


Figure 6.4 Sensitivity of Salt Loads for the Hogwash to Morgan Reach

2. salinities used in the previous version of this model from AWE (2011a), based on average values within the selected zone area near the river
3. salinities used in the previous Salinity Register model, the Morgan to Lock 3 model of Aquaterra (Rural Solutions, 2005) which are based on personal judgment.

The baseline simulations are Scenarios 4 and 8a(iv)—the maximum salt load impact scenarios (current irrigation).

The various salt loads derived through applying the three sets of salinity values are presented in Table 6.2 and are compared with RoR data in Figures 6.5 to 6.6.

Table 6.2 Modelled salt load (t/d) for groundwater salinity uncertainty test

			Year/Salt load (t/d)					
			1988	**2000**	**2011**	**2015**	**2050**	**2111**
Holder to Lock 2	**S4**	*Adopted salinities*	151.1	119.5	103.2	100.1	97.7	100.6
		AWE (2011a) salinities	114.0	88.0	76.0	73.9	71.8	73.5
		Rural Solutions (2005) salinities	107.4	85.1	73.7	71.4	69.7	71.7
	S8a(iv)	*Adopted salinities*	151.1	50.4	25.9	24.7	22.1	22.1
		AWE (2011a) salinities	114.0	35.6	19.1	18.5	17.3	17.3
		Rural Solutions (2005) salinities	107.4	34.5	17.8	17.0	15.4	15.4
Lock 2 to Hogwash	**S4**	*Adopted salinities*	56.6	66.5	67.7	71.6	79.3	82.2
		AWE (2011a) salinities	57.8	66.1	66.9	70.1	76.7	79.3
		Rural Solutions (2005) salinities	27.2	30.9	31.2	32.9	36.3	37.6
	S8a(iv)	*Adopted salinities*	56.6	66.5	27.3	26.0	26.3	26.6
		AWE (2011a) salinities	57.8	66.1	32.3	31.0	31.1	31.4
		Rural Solutions (2005) salinities	27.2	30.9	13.0	12.4	12.5	12.7

Figure 6.5 shows the modelled salt loads for the Holder to Lock 2 reach. Salt loads from the AWE and Aquaterra salinities for Scenario 4 are typically 75 t/d, lower than the salt load from the currently adopted salinities by around 25 t/d or more. However, salt loads for Scenario 8a(iv) after the SIS became operational differ little regardless of the adopted salinity methodology, presumably because fluxes are low in locations where the methodologies adopt significantly different salinities. Hence the reduction in salt load due to the SIS and GCS is greater for the salinities used in the current calibrated model.

All three approaches to estimating the salinity lead to salt loads that match reasonably well with Run of River estimates, so the AWE and Aquaterra results are plausible. If an AWE or Aquaterra approach is adopted, the irrigation impact will be around 30 t/d less and also the SIS benefit could be 25 t/d less than the prediction results of this study.

Figure 6.6 shows the modelled salt loads for the Lock 2 to Hogwash reach. For this reach, the AWE salinities produce similar salt loads to the current model while Aquaterra salinities greatly reduce salt loads for both Scenario 4 and Scenario 8a(iv).

The salt loads based on Aquaterra's approach to salinity give a poor match to Run of River estimates in this reach. That means that confidence of the current result is relatively high.

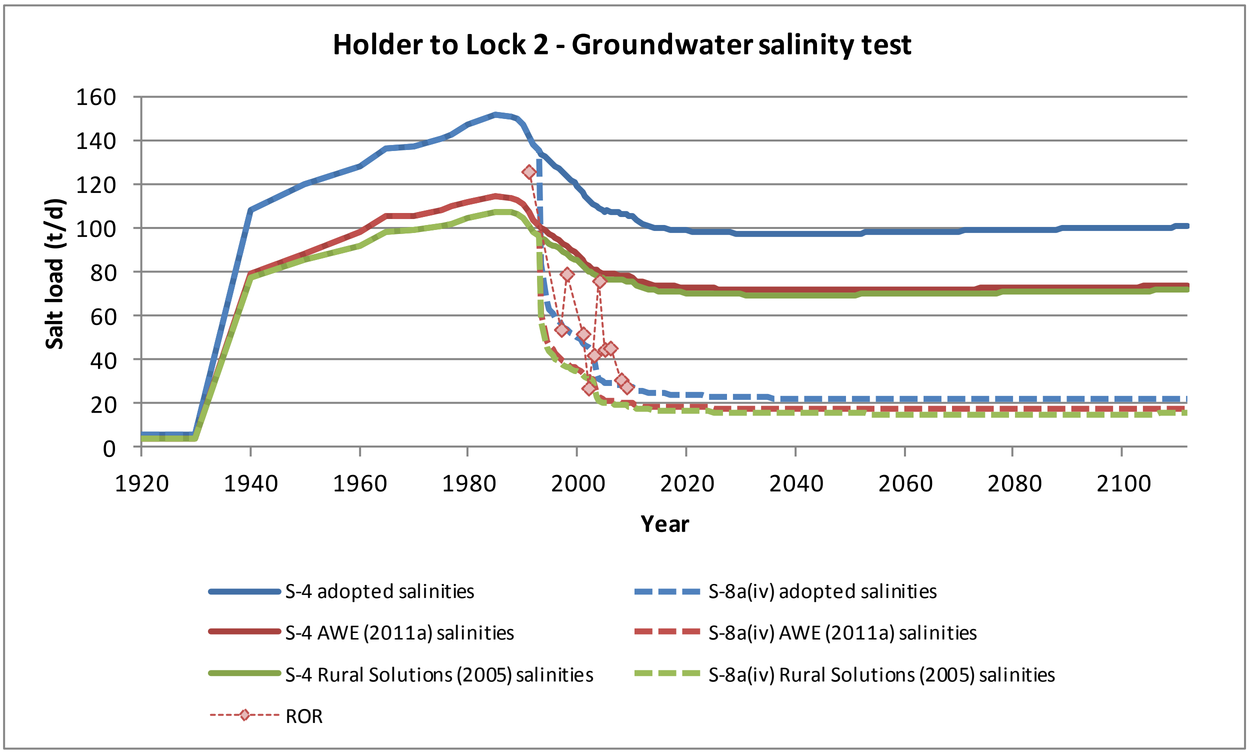


Figure 6.5 Uncertainty of Groundwater Salinity in Predicted Salt loads for the Holder to Lock 2 Reach

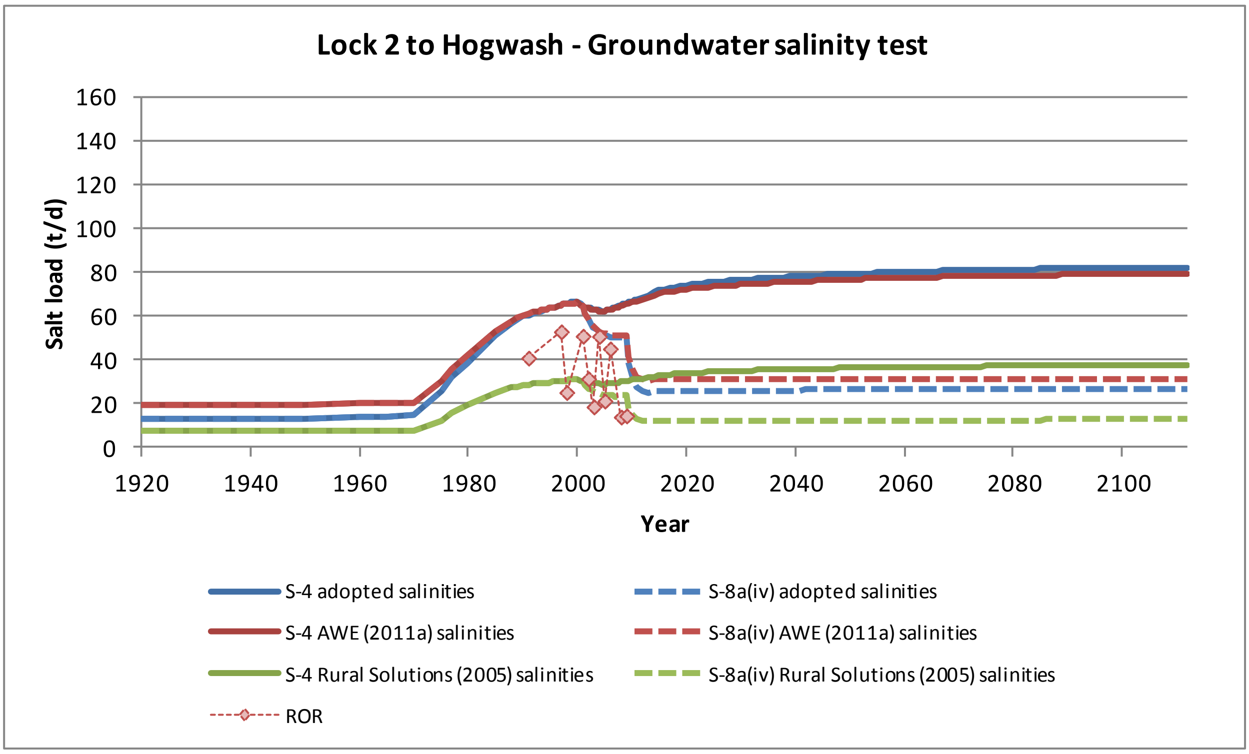


Figure 6.6 Uncertainty of Groundwater Salinity in Predicted Salt Loads for the Lock 2 to Hogwash Reach

The Hogwash to Morgan reach is not shown as the Aquaterra model did not report its salt load calculations as far as Morgan.

6.2.2. IRRIGATION RECHARGE

Recharge over time forms a critical suite of input parameters to the model. Groundwater flux to the river is driven by the groundwater mounds formed by irrigation-derived recharge.

Recharge is difficult to measure in the field. Section 2.4.3 summarises known relevant data, but there remains a great deal of uncertainty about recharge rates over time.

The model scenarios of Section 5 explore the impact of different recharge areas and rates over time, with and without SIS. These pairs of scenarios can be treated as uncertainty tests for recharge:

- Scenarios 3a and 3c have identical recharge areas but differ by recharge rate after 1988. By 2009, Scenario 3a recharge rates generally range between 130 and 400 mm/y while Scenario 3c recharge rates have mostly decreased to 100 mm/y.
- Scenarios 3c and 4 have identical irrigation recharge rates but differ by irrigation recharge area.

Tables 6.3 to 6.5 show how the salt loads differ between base case and scenarios.

Table 6.3 Salt load difference (t/d) at 2011 for groundwater recharge uncertainty test for the Waikerie LWMP area (from river km 393.5 to 376.5)

	Base case	Different Recharge Rate Case	Different Recharge Area Case
	S3c	S3a	S4
Total recharge volume (ML)	2334	4871 (+109%)	2602 (+11%)
Total recharge area (ha)	2613	2613 (+0%)	3002 (+15%)
Salt load (t/d)	77.9	121.4	80.9
Salt load difference (t/d)	-	43.5	3.0

Table 6.4 Salt load difference (t/d) at 2011 for groundwater recharge uncertainty test for the Qualco-Sunlands and Taylorville LWMP areas (from river km 376.5 to 351)

	Base case	Different Recharge Rate Case	Different Recharge Area Case
	S3c	S3a	S4
Total recharge volume (ML)	2664	4153 (+56%)	3714 (+39%)
Total recharge area (ha)	4477	4477 (+0%)	6610 (+48%)
Salt load (t/d)	78.7	111.9	90.0
Salt load difference (t/d)	-	33.2	11.3

Table 6.5 Salt load difference (t/d) at 2011 for groundwater recharge uncertainty test for the Cadell LWMP area (from river km 351 to 320)

	Base case	Different Recharge Rate Case	Different Recharge Area Case
	S3c	S3a	S4
Total recharge volume (ML)	563	2249 (+299%)	1019 (+81%)
Total recharge area (ha)	562	562 (+0%)	1019 (+81%)
Salt load (t/d)	8.7	23.4	14.8
Salt load difference (t/d)	-	14.7	6.1

Note that a given percentage change in recharge does not lead to the same percentage change in salt load entering the River Murray in each area. This is because the salt load impact depends on the location of the recharge (distance to the river), the recharge rates and hydrogeological conditions (Yan, Li and Woods 2011).

These three cases represent significantly different irrigation conditions in history. In future, it is currently considered more likely that increase in irrigation area and rate will be minimal. The uncertainty of the future modelled salt loads is likely to depend on small changes in recharge conditions. Based on assumption of 10% change in recharge rate or change in irrigation area and a simplified linear relationship approach calculation (from the tables above):

- a 10% increase in total recharge volume without any changes to the recharge area may lead to an increase in salt load of 4.0 t/d for the Waikerie area (river km from 393.5 to 376.5), 5.9 t/d for the Qualco area (river km from 376.5 to 351) and 0.5 t/d for the Cadell area (river km from 351 to 320)
- a 10% increase in total recharge area may result in a 7% increase in total recharge volume for the Waikerie area, 8% increase for the Qualco area and 7% increase for the Cadell area. This will lead to a 2.0 t/d increase in salt load for the Waikerie area, 2.4 t/d increase for the Qualco section and 0.8 t/d increase for the Cadell area.

The results above only indicate uncertainty of estimated impact due to change irrigation conditions. Again the actual salt load impact depends on the location of the irrigation area, irrigation practice and hydrogeological conditions.

6.3. CONCLUSIONS

The inputs used in the calibrated historical model are based on currently available data. Four properties which are difficult to measure in the field have been used in sensitivity tests and varied within reasonable ranges in the model to determine the impact on model calibration. The modelled salt loads are most sensitive to river conductance, especially in the Holder to Lock 2 reach. However, the low riverbed conductance of 10 m^2/d leads to poorer calibration to observed heads, indicating that this is not a good choice for the model. The modelled salt loads in the Lock 2 to Hogwash reach are sensitive to a higher Glenforslan hydraulic conductivity, but this also leads to a poorer calibration to observed heads. Salt loads are sensitive to higher river levels downstream of Lock 2, with higher river levels leading to slightly worse calibration to observed heads. The model is not sensitive to groundwater ET extinction depth.

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

The uncertainty analysis considers the range of salt load predictions when assumptions concerning groundwater salinity and recharge are changed. Different assumptions about groundwater salinity lead to significant differences in irrigation load impacts in the Holder to Lock 2 reach and to pre-SIS and post-SIS salt loads for the Lock 2 to Hogwash reach. Different potential irrigation recharge rates and change areas may also lead to changes in salt load. This indicates that there is considerable uncertainty about predicted future salt loads entering the River Murray, depending on model assumptions, selection of groundwater salinity and irrigation development.

7. MODEL CAPABILITIES AND LIMITATIONS

The *MDBC Groundwater Modelling Guideline* (2001) states that: *It is important to recognise that there is no such thing as a perfect model and all models should be regarded as works in progress of continuous improvement as hydrogeological understanding and data availability improve. By definition, model limitations comprise relatively negative statements and they should not necessarily be viewed as serious flaws that affect the fitness for purpose of the model, but rather as a guide to where improvements should be made during work.*

The 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 6.3 describes the model uncertainties due to uncertainties in key input parameters, which may serve as a guide for where improvements could be made in the future with the availability of additional data or with the improvement of hydrogeological understanding.

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

1. Fine detail of hydrogeological units is not included, as this level of detail is not required for the Salinity Register and cannot be included in a regional numerical model.

2. As the Salinity Register salt loads are about average long term impact from accountable (human activity) actions, it does not include climate sequence impacts or river level fluctuations, so salt loads in effect assume average conditions in future predictions. Short-term changes in groundwater level and salt load are not simulated.

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

4. Model recharge zones and rates are based on the best available information, but are likely to be different in reality. Future recharge zones and rates are likely to differ from those used in the predictive modelling.

8. CONCLUSIONS AND RECOMMENDATIONS

8.1. MODEL IMPROVEMENTS

The Waikerie to Morgan numerical groundwater flow model has been upgraded as part of the review of the SIS and Salinity Register entries. The model was upgraded based on new information from hydrogeological investigations, particularly irrigation data and SIS construction and SIS operations. Following the MDBC Guideline (2001), the modified model was recalibrated using long-term observed (historical) potentiometric heads and newer data from SIS observation bores. Its results have been confirmed using RoR data, irrigation accession estimates and other information. The model was used to estimate salt loads to the River Murray for different scenarios required for the Salinity Register and cost-sharing. As specified by the Guideline (MDBC 2001), sensitivity and uncertainty tests were undertaken to aid risk assessment in management and policy decisions.

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

8.2. MODELLING RESULTS

The model is an 'impact assessment model of high complexity' in the terminology of the MDBC Guideline (MDBC 2001). The modelling work has resulted in an improved understanding of the hydrogeology of the aquifer system in the Waikerie to Morgan area. The upgraded model was used to predict the flux of saline groundwater (salt load) entering the River Murray under different irrigation practices and development scenarios. Comparison of scenario modelling results (salt loads) can be seen in Figures 5.2 to 5.7 and in Tables 8.1 to 8.3. The annual salt loads for each scenario are given in Figures 8.1 to 8.6.

8.3. RECOMMENDATIONS FOR FUTURE WORK

The numerical model is required by Schedule B to be reviewed at intervals of not more than seven years. 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. The following recommendations are made so that 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:

- collection of irrigation data should ideally continue. Application volumes, irrigation area, crop type and drainage volumes should be recorded and collated to provide estimates of root zone drainage over time. This information provides higher confidence on model recharge.
- the current monitoring of potentiometric head and salinity at Obswell and SIS bores should continue for model validation in the next Five Year Review
- RoR surveys should continue as they are used for model confirmation which increases model output confidence
- monitoring groundwater salinity over time may improve salt load calculations.

Table 8.1 Summary of Predicted Salt Load (t/d) Entering the River Murray – Holder to Lock 2

Holder to Lock 2	Years simulated	Salt Load required by Salinity Register						
		1988	2000	2011	2015	2050	2100	2111
Calibrated historical model	1920 - 2011	151.1	34.8	37.0	-	-	-	-
Scenario 1	Steady-state	5.6	5.6	5.6	5.6	5.6	5.6	5.6
Scenario 2	1920 - 2111	6.0	6.2	6.7	6.9	10.5	16.8	18.1
Scenario 3a	1988 - 2111	151.1	151.8	155.1	156.1	163.3	169.3	170.1
Scenario 3c	1988 - 2111	151.1	119.5	96.5	90.1	78.1	78.0	78.2
Scenario 4	1988 - 2111	151.1	119.5	103.2	100.1	97.7	100.1	100.6
Scenario 8a(i)	1988 - 2111	151.1	50.4	40.6	39.3	40.1	41.7	41.9
Scenario 8a(ii)	1988 - 2111	151.1	50.4	39.6	37.4	34.9	35.4	35.6
Scenario 8a(iii)	1988 - 2111	151.1	50.4	25.9	24.7	22.2	22.2	22.2
Scenario 8a(iv)	1988 - 2111	151.1	50.4	25.9	24.7	22.1	22.1	22.1
Scenario 8b(i)	1988 - 2111	151.1	50.4	35.5	31.8	26.5	26.7	26.8
Scenario 8b(ii)	1988 - 2111	151.1	50.4	34.4	30.1	22.5	21.8	21.8
Scenario 8b(iii)	1988 - 2111	151.1	50.4	23.7	21.5	16.8	16.2	16.2
Scenario 8b(iv)	1988 - 2111	151.1	50.4	23.7	21.5	16.8	16.2	16.2

Table 8.2 Summary of Predicted Salt Load (t/d) Entering the River Murray – Lock 2 to Hogwash

Lock 2 to Hogwash	Years simulated	Salt Load required by Salinity Register						
		1988	2000	2011	2015	2050	2100	2111
Calibrated historical model	1920 - 2011	56.6	66.5	21.6	-	-	-	-
Scenario 1	Steady-state	13.5	13.5	13.5	13.5	13.5	13.5	13.5
Scenario 2	1920 - 2111	13.8	14.0	14.4	14.6	16.9	22.5	23.2
Scenario 3a	1988 - 2111	56.6	71.6	78.2	79.6	85.6	88.3	88.6
Scenario 3c	1988 - 2111	56.6	66.5	60.0	59.3	58.4	59.7	59.9
Scenario 4	1988 - 2111	56.6	66.5	67.7	71.6	79.3	81.9	82.2
Scenario 8a(i)	1988 - 2111	56.6	66.5	67.7	71.5	79.1	81.7	81.9
Scenario 8a(ii)	1988 - 2111	56.6	66.5	51.2	52.9	53.7	54.6	54.7
Scenario 8a(iii)	1988 - 2111	56.6	66.5	50.8	52.2	52.0	52.8	52.9
Scenario 8a(iv)	1988 - 2111	56.6	66.5	27.3	26.0	26.3	26.6	26.6
Scenario 8b(i)	1988 - 2111	56.6	66.5	60.0	59.2	58.3	59.5	59.7
Scenario 8b(ii)	1988 - 2111	56.6	66.5	44.7	42.3	36.1	35.9	36.0
Scenario 8b(iii)	1988 - 2111	56.6	66.5	44.3	41.7	35.1	35.0	35.0
Scenario 8b(iv)	1988 - 2111	56.6	66.5	23.6	20.5	18.2	18.2	18.2

Table 8.3 Summary of Predicted Salt Load (t/d) Entering the River Murray – Hogwash to Morgan

Hogwash to Morgan	Years simulated	Salt Load required by Salinity Register						
		1988	2000	2011	2015	2050	2100	2111
Calibrated historical model	**1920 - 2011**	22.4	20.0	14.0	-	-	-	-
Scenario 1	**Steady-state**	4.6	4.6	4.6	4.6	4.6	4.6	4.6
Scenario 2	**1920 - 2111**	4.6	4.6	4.7	4.7	4.7	5.0	5.0
Scenario 3a	**1988 - 2111**	22.4	23.1	23.4	23.5	23.8	24.0	24.0
Scenario 3c	**1988 - 2111**	22.4	14.8	8.7	8.1	7.7	7.8	7.8
Scenario 4	**1988 - 2111**	22.4	20.0	14.8	14.2	14.4	14.7	14.7
Scenario 8a(i)	**1988 - 2111**	22.4	20.0	14.8	14.2	14.4	14.7	14.7
Scenario 8a(ii)	**1988 - 2111**	22.4	20.0	14.6	13.9	13.8	14.0	14.1
Scenario 8a(iii)	**1988 - 2111**	22.4	20.0	14.6	13.9	13.8	14.0	14.0
Scenario 8a(iv)	**1988 - 2111**	22.4	20.0	14.1	13.2	13.0	13.2	13.2
Scenario 8b(i)	**1988 - 2111**	22.4	14.8	8.7	8.1	7.7	7.8	7.8
Scenario 8b(ii)	**1988 - 2111**	22.4	14.8	8.5	7.9	7.4	7.4	7.4
Scenario 8b(iii)	**1988 - 2111**	22.4	14.8	8.5	7.9	7.4	7.4	7.4
Scenario 8b(iv)	**1988 - 2111**	22.4	14.8	8.2	7.5	7.0	7.0	7.0

8.3.2. ADDITIONAL MODEL FEATURES AND PROCESSES

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

Features requiring additional model development:

- improving simulation of evapotranspiration from groundwater, if more information becomes available
- possibly improving calibration in the floodplain area against flood events, such as fluctuations in river level over time, when data becomes available (e.g. detailed pool level and inundation area).

8.3.3. POTENTIAL WORK FOR FUTURE

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

- investigation of riverbed hydraulic conductivity
- AEM data will improve salt load calculations. These data will be useful if solute transport modelling is included in future models
- improved understanding of flow in the unsaturated zone, including perched aquifers, to inform recharge rates and areas

- consideration of groundwater salinity changes over time in salt load calculations when valid information becomes available. This will affect salt loads and calculation of salt loads by either:
    - multiplying groundwater flux to the river by salinity that varies with time for each reach, or
    - full solute transport simulation.

Time (y)	S-1 (t/d)	S-2 (t/d)	S-3a (t/d)	S-3c (t/d)	S-4 (t/d)	S-8a(i) (t/d)	S-8a(ii) (t/d)	S-8a(iii) (t/d)	S-8a(iv) (t/d)	S-8b(i) (t/d)	S-8b(ii) (t/d)	S-8b(iii) (t/d)	S-8b(iv) (t/d)
1988	5.6	6.0	151.1	151.1	151.1	151.1	151.1	151.1	151.1	151.1	151.1	151.1	151.1
1989	5.6	6.0	149.8	149.8	149.8	149.8	149.8	149.8	149.8	149.8	149.8	149.8	149.8
1990	5.6	6.0	149.3	146.8	146.8	146.8	146.8	146.8	146.8	146.8	146.8	146.8	146.8
1991	5.6	6.1	149.1	142.0	142.0	142.0	142.0	142.0	142.0	142.0	142.0	142.0	142.0
1992	5.6	6.1	149.1	138.1	138.1	138.1	138.1	138.1	138.1	138.1	138.1	138.1	138.1
1993	5.6	6.1	149.1	135.2	135.2	135.2	135.2	135.2	135.2	135.2	135.2	135.2	135.2
1994	5.6	6.1	149.2	132.8	132.8	72.1	72.1	72.1	72.1	72.1	72.1	72.1	72.1
1995	5.6	6.2	149.4	130.6	130.6	63.3	63.3	63.3	63.3	63.3	63.3	63.3	63.3
1996	5.6	6.2	149.9	128.5	128.5	59.2	59.2	59.2	59.2	59.2	59.2	59.2	59.2
1997	5.6	6.2	150.5	126.2	126.2	56.3	56.3	56.3	56.3	56.3	56.3	56.3	56.3
1998	5.6	6.2	151.0	124.0	124.0	54.1	54.1	54.1	54.1	54.1	54.1	54.1	54.1
1999	5.6	6.2	151.4	121.8	121.8	52.2	52.2	52.2	52.2	52.2	52.2	52.2	52.2
2000	5.6	6.2	151.8	119.5	119.5	50.4	50.4	50.4	50.4	50.4	50.4	50.4	50.4
2001	5.6	6.3	152.1	115.8	115.9	47.7	47.7	47.7	47.7	47.6	47.6	47.6	47.6
2002	5.6	6.3	152.5	112.5	112.9	45.7	45.7	45.7	45.7	45.3	45.3	45.3	45.3
2003	5.6	6.4	152.8	110.1	110.7	44.3	44.3	44.3	44.3	43.8	43.8	43.8	43.8
2004	5.6	6.4	153.1	108.1	108.9	43.3	43.3	31.6	31.6	42.6	42.5	31.4	31.4
2005	5.6	6.4	153.4	106.4	107.4	42.4	42.3	29.5	29.5	41.5	41.4	29.4	29.4
2006	5.6	6.5	153.7	104.9	107.7	43.1	42.9	29.4	29.4	40.7	40.5	28.3	28.3
2007	5.6	6.5	154.0	103.6	107.2	43.0	42.6	28.9	28.9	39.9	39.6	27.5	27.5
2008	5.6	6.5	154.3	102.4	106.8	42.8	42.3	28.5	28.5	39.2	38.7	26.8	26.8
2009	5.6	6.6	154.6	101.3	106.3	42.6	41.9	28.1	28.1	38.6	38.0	26.2	26.2
2010	5.6	6.6	154.8	99.4	105.3	42.1	41.2	27.3	27.3	37.4	36.6	25.1	25.1
2011	5.6	6.7	155.1	96.5	103.2	40.6	39.6	25.9	25.9	35.5	34.4	23.7	23.7
2012	5.6	6.7	155.4	94.5	101.9	40.0	38.7	25.4	25.4	34.2	33.0	23.0	23.0
2013	5.6	6.8	155.6	92.8	100.8	39.4	37.9	25.0	24.9	33.3	31.9	22.4	22.4
2014	5.6	6.9	155.9	91.3	100.5	39.4	37.7	24.9	24.8	32.5	30.9	21.9	21.9
2015	5.6	6.9	156.1	90.1	100.1	39.3	37.4	24.7	24.7	31.8	30.1	21.5	21.5
2016	5.6	7.0	156.4	89.0	99.7	39.2	37.2	24.5	24.5	31.3	29.4	21.1	21.1
2017	5.6	7.0	156.6	88.1	99.5	39.2	37.0	24.4	24.4	30.8	28.8	20.8	20.7
2018	5.6	7.1	156.9	87.2	99.2	39.2	36.8	24.3	24.2	30.4	28.2	20.4	20.4
2019	5.6	7.2	157.1	86.4	99.0	39.2	36.6	24.2	24.1	30.0	27.7	20.1	20.1
2020	5.6	7.2	157.3	85.7	98.8	39.2	36.5	24.1	24.0	29.7	27.3	19.9	19.9
2021	5.6	7.3	157.6	85.1	98.7	39.3	36.4	23.9	23.9	29.4	26.9	19.6	19.6
2022	5.6	7.4	157.8	84.5	98.5	39.3	36.2	23.8	23.7	29.1	26.5	19.4	19.4
2023	5.6	7.5	158.0	83.9	98.4	39.3	36.1	23.7	23.6	28.9	26.2	19.2	19.2
2024	5.6	7.6	158.3	83.4	98.3	39.3	36.0	23.6	23.5	28.6	25.9	19.0	19.0
2025	5.6	7.7	158.5	83.0	98.1	39.3	35.9	23.5	23.4	28.4	25.6	18.8	18.8
2026	5.6	7.8	158.7	82.6	98.0	39.3	35.8	23.4	23.3	28.2	25.3	18.7	18.6
2027	5.6	7.9	158.9	82.2	97.9	39.3	35.7	23.3	23.2	28.1	25.1	18.5	18.5
2028	5.6	8.0	159.1	81.8	97.9	39.4	35.6	23.2	23.1	27.9	24.8	18.4	18.3
2029	5.6	8.0	159.4	81.5	97.8	39.4	35.5	23.1	23.0	27.8	24.6	18.2	18.2
2030	5.6	8.1	159.6	81.2	97.7	39.4	35.4	23.0	22.9	27.7	24.4	18.1	18.1
2031	5.6	8.2	159.8	80.9	97.7	39.4	35.4	23.0	22.9	27.5	24.3	18.0	18.0
2032	5.6	8.4	160.0	80.6	97.6	39.5	35.3	22.9	22.8	27.4	24.1	17.9	17.9
2033	5.6	8.5	160.2	80.4	97.6	39.5	35.3	22.8	22.7	27.3	23.9	17.8	17.8
2034	5.6	8.6	160.4	80.1	97.5	39.5	35.2	22.8	22.7	27.2	23.8	17.7	17.7
2035	5.6	8.7	160.6	79.9	97.5	39.5	35.2	22.7	22.6	27.2	23.7	17.6	17.6
2036	5.6	8.8	160.8	79.7	97.5	39.6	35.1	22.7	22.6	27.1	23.5	17.5	17.5
2037	5.6	8.9	161.0	79.5	97.5	39.6	35.1	22.6	22.5	27.0	23.4	17.5	17.4
2038	5.6	9.0	161.2	79.4	97.5	39.6	35.0	22.6	22.5	27.0	23.3	17.4	17.4
2039	5.6	9.2	161.4	79.2	97.5	39.7	35.0	22.5	22.4	26.9	23.2	17.3	17.3
2040	5.6	9.3	161.6	79.1	97.5	39.7	35.0	22.5	22.4	26.9	23.1	17.3	17.2
2041	5.6	9.4	161.7	78.9	97.5	39.7	35.0	22.5	22.4	26.8	23.0	17.2	17.2
2042	5.6	9.5	161.9	78.8	97.5	39.8	34.9	22.4	22.3	26.8	23.0	17.1	17.1
2043	5.6	9.7	162.1	78.7	97.5	39.8	34.9	22.4	22.3	26.7	22.9	17.1	17.1
2044	5.6	9.8	162.3	78.6	97.5	39.8	34.9	22.4	22.3	26.7	22.8	17.0	17.0
2045	5.6	9.9	162.5	78.5	97.5	39.9	34.9	22.3	22.2	26.7	22.7	17.0	17.0
2046	5.6	10.0	162.6	78.4	97.6	39.9	34.9	22.3	22.2	26.6	22.7	16.9	16.9
2047	5.6	10.2	162.8	78.3	97.6	40.0	34.9	22.3	22.2	26.6	22.6	16.9	16.9
2048	5.6	10.3	163.0	78.3	97.6	40.0	34.9	22.3	22.2	26.6	22.6	16.9	16.8
2049	5.6	10.4	163.1	78.2	97.7	40.0	34.9	22.3	22.1	26.6	22.5	16.8	16.8
2050	5.6	10.5	163.3	78.1	97.7	40.1	34.9	22.2	22.1	26.5	22.5	16.8	16.8
2051	5.6	10.6	163.5	78.1	97.7	40.1	34.9	22.2	22.1	26.5	22.4	16.8	16.7
2052	5.6	10.8	163.6	78.0	97.8	40.2	34.9	22.2	22.1	26.5	22.4	16.7	16.7
2053	5.6	10.9	163.8	78.0	97.8	40.2	34.9	22.2	22.1	26.5	22.3	16.7	16.7
2054	5.6	11.0	164.0	77.9	97.9	40.2	34.9	22.2	22.1	26.5	22.3	16.7	16.6
2055	5.6	11.2	164.1	77.9	97.9	40.3	34.9	22.2	22.1	26.5	22.3	16.6	16.6
2056	5.6	11.3	164.3	77.9	97.9	40.3	34.9	22.2	22.1	26.5	22.2	16.6	16.6
2057	5.6	11.4	164.4	77.8	98.0	40.3	34.9	22.1	22.0	26.5	22.2	16.6	16.6
2058	5.6	11.5	164.6	77.8	98.0	40.4	34.9	22.1	22.0	26.5	22.2	16.6	16.5
2059	5.6	11.7	164.7	77.8	98.1	40.4	34.9	22.1	22.0	26.5	22.1	16.5	16.5
2060	5.6	11.8	164.9	77.7	98.1	40.5	34.9	22.1	22.0	26.5	22.1	16.5	16.5
2061	5.6	11.9	165.0	77.7	98.2	40.5	34.9	22.1	22.0	26.5	22.1	16.5	16.5
2062	5.6	12.1	165.1	77.7	98.2	40.5	34.9	22.1	22.0	26.5	22.1	16.5	16.5
2063	5.6	12.2	165.3	77.7	98.3	40.6	34.9	22.1	22.0	26.5	22.1	16.5	16.4
2064	5.6	12.3	165.4	77.7	98.3	40.6	34.9	22.1	22.0	26.5	22.0	16.5	16.4
2065	5.6	12.5	165.6	77.7	98.4	40.6	35.0	22.1	22.0	26.5	22.0	16.4	16.4
2066	5.6	12.6	165.7	77.7	98.4	40.7	35.0	22.1	22.0	26.5	22.0	16.4	16.4
2067	5.6	12.7	165.8	77.7	98.5	40.7	35.0	22.1	22.0	26.5	22.0	16.4	16.4
2068	5.6	12.9	165.9	77.7	98.5	40.7	35.0	22.1	22.0	26.5	22.0	16.4	16.4
2069	5.6	13.0	166.1	77.7	98.6	40.8	35.0	22.1	22.0	26.5	22.0	16.4	16.4
2070	5.6	13.1	166.2	77.7	98.6	40.8	35.0	22.1	22.0	26.5	21.9	16.4	16.3
2071	5.6	13.2	166.3	77.7	98.7	40.8	35.0	22.1	22.0	26.5	21.9	16.4	16.3
2072	5.6	13.4	166.4	77.7	98.8	40.9	35.0	22.1	22.0	26.5	21.9	16.4	16.3
2073	5.6	13.5	166.6	77.7	98.8	40.9	35.1	22.1	22.0	26.5	21.9	16.4	16.3
2074	5.6	13.6	166.7	77.7	98.9	40.9	35.1	22.1	22.0	26.5	21.9	16.3	16.3
2075	5.6	13.8	166.8	77.7	98.9	41.0	35.1	22.1	22.0	26.5	21.9	16.3	16.3
2076	5.6	13.9	166.9	77.7	99.0	41.0	35.1	22.1	22.0	26.5	21.9	16.3	16.3
2077	5.6	14.0	167.0	77.7	99.0	41.0	35.1	22.1	22.0	26.5	21.9	16.3	16.3
2078	5.6	14.1	167.1	77.7	99.1	41.1	35.1	22.1	22.0	26.5	21.9	16.3	16.3
2079	5.6	14.3	167.3	77.7	99.1	41.1	35.1	22.1	22.0	26.5	21.9	16.3	16.3
2080	5.6	14.4	167.4	77.7	99.2	41.1	35.2	22.1	22.0	26.6	21.9	16.3	16.3
2081	5.6	14.5	167.5	77.7	99.2	41.2	35.2	22.1	22.0	26.6	21.9	16.3	16.3
2082	5.6	14.7	167.6	77.7	99.3	41.2	35.2	22.1	22.0	26.6	21.9	16.3	16.3
2083	5.6	14.8	167.7	77.8	99.3	41.2	35.2	22.1	22.0	26.6	21.9	16.3	16.2
2084	5.6	14.9	167.8	77.8	99.4	41.2	35.2	22.1	22.0	26.6	21.8	16.3	16.2
2085	5.6	15.0	167.9	77.8	99.4	41.3	35.2	22.1	22.0	26.6	21.8	16.3	16.2
2086	5.6	15.2	168.0	77.8	99.5	41.3	35.2	22.1	22.0	26.6	21.8	16.3	16.2
2087	5.6	15.3	168.1	77.8	99.5	41.3	35.3	22.1	22.0	26.6	21.8	16.3	16.2
2088	5.6	15.4	168.2	77.8	99.6	41.4	35.3	22.1	22.0	26.6	21.8	16.3	16.2
2089	5.6	15.5	168.3	77.8	99.6	41.4	35.3	22.1	22.0	26.6	21.8	16.3	16.2
2090	5.6	15.6	168.4	77.9	99.7	41.4	35.3	22.1	22.0	26.6	21.8	16.3	16.2
2091	5.6	15.8	168.5	77.9	99.7	41.4	35.3	22.1	22.0	26.7	21.8	16.3	16.2
2092	5.6	15.9	168.6	77.9	99.8	41.5	35.3	22.1	22.0	26.7	21.8	16.3	16.2
2093	5.6	16.0	168.7	77.9	99.8	41.5	35.3	22.1	22.0	26.7	21.8	16.3	16.2
2094	5.6	16.1	168.7	77.9	99.9	41.5	35.4	22.1	22.0	26.7	21.8	16.3	16.2
2095	5.6	16.3	168.8	77.9	99.9	41.5	35.4	22.1	22.0	26.7	21.8	16.3	16.2
2096	5.6	16.4	168.9	78.0	99.9	41.6	35.4	22.1	22.0	26.7	21.8	16.3	16.2
2097	5.6	16.5	169.0	78.0	100.0	41.6	35.4	22.2	22.0	26.7	21.8	16.2	16.2
2098	5.6	16.6	169.1	78.0	100.0	41.6	35.4	22.2	22.0	26.7	21.8	16.2	16.2
2099	5.6	16.7	169.2	78.0	100.1	41.6	35.4	22.2	22.0	26.7	21.8	16.2	16.2
2100	5.6	16.8	169.3	78.0	100.1	41.7	35.4	22.2	22.1	26.7	21.8	16.2	16.2
2101	5.6	16.9	169.3	78.0	100.2	41.7	35.5	22.2	22.1	26.7	21.8	16.2	16.2
2102	5.6	17.1	169.4	78.1	100.2	41.7	35.5	22.2	22.1	26.8	21.8	16.2	16.2
2103	5.6	17.2	169.5	78.1	100.2	41.7	35.5	22.2	22.1	26.8	21.8	16.2	16.2
2104	5.6	17.3	169.6	78.1	100.3	41.7	35.5	22.2	22.1	26.8	21.8	16.2	16.2
2105	5.6	17.4	169.6	78.1	100.3	41.8	35.5	22.2	22.1	26.8	21.8	16.2	16.2
2106	5.6	17.5	169.7	78.1	100.4	41.8	35.5	22.2	22.1	26.8	21.8	16.2	16.2
2107	5.6	17.6	169.8	78.1	100.4	41.8	35.5	22.2	22.1	26.8	21.8	16.2	16.2
2108	5.6	17.7	169.9	78.2	100.4	41.8	35.6	22.2	22.1	26.8	21.8	16.2	16.2
2109	5.6	17.8	169.9	78.2	100.5	41.8	35.6	22.2	22.1	26.8	21.8	16.2	16.2
2110	5.6	18.0	170.0	78.2	100.5	41.9	35.6	22.2	22.1	26.8	21.8	16.2	16.2
2111	5.6	18.1	170.1	78.2	100.6	41.9	35.6	22.2	22.1	26.8	21.8	16.2	16.2

Figure 8.1 Modelled Salt Load Entering the River Murray for All Scenarios for the Holder to Lock 2 Reach

Time	S-1	S-2	S-3a	S-3c	S-4	S-8a(i)	S-8a(ii)	S-8a(iii)	S-8a(iv)	S-8b(i)	S-8b(ii)	S-8b(iii)	S-8b(iv)
(y)	(t/d)	(t/d)	(t/d)	(t/d)	(t/d)	(t/d)	(t/d)	(t/d)	(t/d)	(t/d)	(t/d)	(t/d)	(t/d)
1988	13.5	13.8	56.6	56.6	56.6	56.6	56.6	56.6	56.6	56.6	56.6	56.6	56.6
1989	13.5	13.8	58.4	58.4	58.4	58.4	58.4	58.4	58.4	58.4	58.4	58.4	58.4
1990	13.5	13.8	60.0	59.7	59.7	59.7	59.7	59.7	59.7	59.7	59.7	59.7	59.7
1991	13.5	13.9	61.4	60.5	60.5	60.5	60.5	60.5	60.5	60.5	60.5	60.5	60.5
1992	13.5	13.9	62.7	61.2	61.2	61.2	61.2	61.2	61.2	61.2	61.2	61.2	61.2
1993	13.5	13.9	63.9	61.9	61.9	61.9	61.9	61.9	61.9	61.9	61.9	61.9	61.9
1994	13.5	13.9	65.0	62.6	62.6	62.6	62.6	62.6	62.6	62.6	62.6	62.6	62.6
1995	13.5	14.0	66.3	63.4	63.4	63.4	63.4	63.4	63.4	63.4	63.4	63.4	63.4
1996	13.5	14.0	67.3	64.2	64.2	64.2	64.2	64.2	64.2	64.2	64.2	64.2	64.2
1997	13.5	14.0	68.4	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0
1998	13.5	14.0	69.5	65.7	65.7	65.7	65.7	65.7	65.7	65.7	65.7	65.7	65.7
1999	13.5	14.0	70.6	66.2	66.2	66.2	66.2	66.2	66.2	66.2	66.2	66.2	66.2
2000	13.5	14.0	71.6	66.5	66.5	66.5	66.5	66.5	66.5	66.5	66.5	66.5	66.5
2001	13.5	14.1	72.5	64.8	64.8	64.8	64.8	64.8	64.8	64.8	64.8	64.8	64.8
2002	13.5	14.1	73.3	63.7	63.8	63.8	58.3	58.3	58.3	63.7	58.2	58.2	58.2
2003	13.5	14.2	74.0	62.9	63.0	63.0	54.9	54.9	54.9	62.9	54.8	54.8	54.8
2004	13.5	14.2	74.7	62.3	62.5	62.5	52.6	52.6	52.6	62.2	52.4	52.4	52.4
2005	13.5	14.2	75.3	61.8	62.3	62.2	51.0	51.0	51.0	61.8	50.6	50.6	50.6
2006	13.5	14.3	75.9	61.4	63.0	63.0	50.6	50.6	50.6	61.4	49.2	49.2	49.2
2007	13.5	14.3	76.4	61.1	63.8	63.8	50.4	50.3	50.3	61.0	48.1	48.0	48.0
2008	13.5	14.3	76.9	60.8	64.9	64.9	50.6	50.5	50.5	60.8	47.1	47.0	47.0
2009	13.5	14.3	77.4	60.5	66.0	65.9	50.9	50.7	50.7	60.4	46.2	46.0	46.0
2010	13.5	14.3	77.8	60.2	66.9	66.8	51.1	50.8	32.0	60.2	45.4	45.1	27.9
2011	13.5	14.4	78.2	60.0	67.7	67.7	51.2	50.8	27.3	60.0	44.7	44.3	23.6
2012	13.5	14.5	78.6	59.8	68.5	68.4	51.4	50.9	25.8	59.8	44.0	43.6	22.2
2013	13.5	14.5	79.0	59.7	69.1	69.1	51.5	50.9	25.2	59.6	43.4	42.9	21.4
2014	13.5	14.6	79.3	59.5	70.7	70.6	52.5	51.8	25.8	59.4	42.9	42.3	20.9
2015	13.5	14.6	79.6	59.3	71.6	71.5	52.9	52.2	26.0	59.2	42.3	41.7	20.5
2016	13.5	14.6	79.9	59.1	72.3	72.2	53.2	52.3	26.1	59.1	41.8	41.1	20.2
2017	13.5	14.7	80.2	59.0	72.8	72.7	53.3	52.4	26.1	58.9	41.4	40.6	19.9
2018	13.5	14.7	80.5	58.8	73.3	73.2	53.4	52.4	26.1	58.8	40.9	40.1	19.7
2019	13.5	14.7	80.8	58.7	73.7	73.6	53.4	52.4	26.1	58.6	40.5	39.6	19.5
2020	13.5	14.8	81.0	58.6	74.0	73.9	53.4	52.3	26.1	58.5	40.1	39.2	19.4
2021	13.5	14.9	81.2	58.5	74.4	74.3	53.4	52.3	26.1	58.4	39.8	38.8	19.3
2022	13.5	14.9	81.5	58.4	74.7	74.6	53.4	52.3	26.1	58.3	39.5	38.5	19.2
2023	13.5	15.0	81.7	58.3	75.0	74.8	53.4	52.2	26.1	58.2	39.2	38.2	19.1
2024	13.5	15.0	81.9	58.2	75.2	75.1	53.4	52.2	26.1	58.1	38.9	37.9	19.0
2025	13.5	15.1	82.1	58.2	75.5	75.4	53.4	52.1	26.1	58.1	38.6	37.6	18.9
2026	13.5	15.1	82.3	58.1	75.7	75.6	53.4	52.1	26.1	58.0	38.4	37.3	18.8
2027	13.5	15.1	82.5	58.1	75.9	75.8	53.4	52.1	26.1	58.0	38.2	37.1	18.7
2028	13.5	15.2	82.7	58.1	76.1	76.0	53.4	52.1	26.1	58.0	38.0	36.9	18.7
2029	13.5	15.2	82.9	58.1	76.3	76.2	53.4	52.0	26.1	57.9	37.8	36.7	18.6
2030	13.5	15.3	83.0	58.0	76.5	76.4	53.4	52.0	26.1	57.9	37.7	36.6	18.6
2031	13.5	15.4	83.2	58.0	76.7	76.6	53.4	52.0	26.1	57.9	37.5	36.4	18.5
2032	13.5	15.4	83.3	58.0	76.9	76.8	53.4	52.0	26.1	57.9	37.4	36.3	18.5
2033	13.5	15.5	83.5	58.0	77.1	76.9	53.4	52.0	26.2	57.9	37.2	36.1	18.5
2034	13.5	15.6	83.7	58.0	77.2	77.1	53.4	51.9	26.2	57.9	37.1	36.0	18.4
2035	13.5	15.6	83.8	58.0	77.4	77.3	53.4	51.9	26.2	57.9	37.0	35.9	18.4
2036	13.5	15.7	83.9	58.1	77.6	77.4	53.4	51.9	26.2	57.9	36.9	35.8	18.4
2037	13.5	15.8	84.1	58.1	77.7	77.6	53.4	51.9	26.2	57.9	36.8	35.7	18.4
2038	13.5	15.8	84.2	58.1	77.9	77.7	53.5	51.9	26.2	57.9	36.7	35.6	18.3
2039	13.5	15.9	84.4	58.1	78.0	77.8	53.5	51.9	26.2	58.0	36.7	35.5	18.3
2040	13.5	15.9	84.5	58.1	78.1	78.0	53.5	51.9	26.2	58.0	36.6	35.5	18.3
2041	13.5	16.1	84.6	58.2	78.3	78.1	53.5	51.9	26.2	58.0	36.5	35.4	18.3
2042	13.5	16.2	84.7	58.2	78.4	78.2	53.5	52.0	26.2	58.0	36.5	35.3	18.3
2043	13.5	16.3	84.8	58.2	78.5	78.3	53.5	52.0	26.2	58.1	36.4	35.3	18.3
2044	13.5	16.3	85.0	58.2	78.6	78.5	53.6	52.0	26.2	58.1	36.4	35.2	18.3
2045	13.5	16.4	85.1	58.3	78.8	78.6	53.6	52.0	26.2	58.1	36.3	35.2	18.2
2046	13.5	16.5	85.2	58.3	78.9	78.7	53.6	52.0	26.3	58.1	36.3	35.2	18.2
2047	13.5	16.6	85.3	58.3	79.0	78.8	53.6	52.0	26.3	58.2	36.2	35.1	18.2
2048	13.5	16.7	85.4	58.4	79.1	78.9	53.6	52.0	26.3	58.2	36.2	35.1	18.2
2049	13.5	16.8	85.5	58.4	79.2	79.0	53.7	52.0	26.3	58.2	36.2	35.1	18.2
2050	13.5	16.9	85.6	58.4	79.3	79.1	53.7	52.0	26.3	58.3	36.1	35.1	18.2
2051	13.5	17.0	85.7	58.5	79.4	79.2	53.7	52.1	26.3	58.3	36.1	35.0	18.2
2052	13.5	17.2	85.8	58.5	79.5	79.3	53.7	52.1	26.3	58.3	36.1	35.0	18.2
2053	13.5	17.3	85.9	58.5	79.6	79.4	53.8	52.1	26.3	58.4	36.1	35.0	18.2
2054	13.5	17.4	86.0	58.6	79.7	79.5	53.8	52.1	26.3	58.4	36.1	35.0	18.2
2055	13.5	17.5	86.0	58.6	79.7	79.6	53.8	52.1	26.3	58.4	36.0	35.0	18.2
2056	13.5	17.7	86.1	58.6	79.8	79.6	53.8	52.1	26.3	58.5	36.0	35.0	18.2
2057	13.5	17.8	86.2	58.7	79.9	79.7	53.8	52.2	26.3	58.5	36.0	35.0	18.2
2058	13.5	17.9	86.3	58.7	80.0	79.8	53.9	52.2	26.4	58.5	36.0	35.0	18.2
2059	13.5	18.0	86.4	58.7	80.1	79.9	53.9	52.2	26.4	58.6	36.0	35.0	18.2
2060	13.5	18.1	86.4	58.8	80.1	79.9	53.9	52.2	26.4	58.6	36.0	34.9	18.2
2061	13.5	18.2	86.5	58.8	80.2	80.0	53.9	52.2	26.4	58.6	36.0	34.9	18.2
2062	13.5	18.4	86.6	58.8	80.3	80.1	54.0	52.2	26.4	58.7	35.9	34.9	18.2
2063	13.5	18.5	86.7	58.9	80.4	80.2	54.0	52.3	26.4	58.7	35.9	34.9	18.2
2064	13.5	18.7	86.7	58.9	80.4	80.2	54.0	52.3	26.4	58.7	35.9	34.9	18.2
2065	13.5	18.8	86.8	58.9	80.5	80.3	54.0	52.3	26.4	58.8	35.9	34.9	18.2
2066	13.5	18.9	86.9	59.0	80.6	80.3	54.0	52.3	26.4	58.8	35.9	34.9	18.2
2067	13.5	19.1	86.9	59.0	80.6	80.4	54.1	52.3	26.4	58.8	35.9	34.9	18.2
2068	13.5	19.2	87.0	59.0	80.7	80.5	54.1	52.3	26.4	58.8	35.9	34.9	18.2
2069	13.5	19.3	87.0	59.1	80.7	80.5	54.1	52.4	26.4	58.9	35.9	34.9	18.2
2070	13.5	19.4	87.1	59.1	80.8	80.6	54.1	52.4	26.4	58.9	35.9	34.9	18.2
2071	13.5	19.5	87.2	59.1	80.8	80.6	54.1	52.4	26.4	58.9	35.9	34.9	18.2
2072	13.5	19.7	87.2	59.1	80.9	80.7	54.2	52.4	26.5	59.0	35.9	34.9	18.2
2073	13.5	19.8	87.3	59.2	81.0	80.7	54.2	52.4	26.5	59.0	35.9	34.9	18.2
2074	13.5	19.9	87.3	59.2	81.0	80.8	54.2	52.4	26.5	59.0	35.9	34.9	18.2
2075	13.5	20.1	87.4	59.2	81.1	80.8	54.2	52.5	26.5	59.0	35.9	34.9	18.2
2076	13.5	20.2	87.4	59.3	81.1	80.9	54.2	52.5	26.5	59.1	35.9	34.9	18.2
2077	13.5	20.3	87.5	59.3	81.2	80.9	54.3	52.5	26.5	59.1	35.9	34.9	18.2
2078	13.5	20.4	87.5	59.3	81.2	81.0	54.3	52.5	26.5	59.1	35.9	34.9	18.2
2079	13.5	20.5	87.6	59.3	81.2	81.0	54.3	52.5	26.5	59.1	35.9	34.9	18.2
2080	13.5	20.6	87.6	59.3	81.3	81.1	54.3	52.5	26.5	59.1	35.9	34.9	18.2
2081	13.5	20.7	87.7	59.4	81.3	81.1	54.3	52.5	26.5	59.2	35.9	34.9	18.2
2082	13.5	20.8	87.7	59.4	81.4	81.1	54.3	52.6	26.5	59.2	35.9	34.9	18.2
2083	13.5	20.9	87.7	59.4	81.4	81.2	54.4	52.6	26.5	59.2	35.9	34.9	18.2
2084	13.5	21.0	87.8	59.4	81.4	81.2	54.4	52.6	26.5	59.2	35.9	34.9	18.2
2085	13.5	21.2	87.8	59.5	81.5	81.2	54.4	52.6	26.5	59.3	35.9	34.9	18.2
2086	13.5	21.3	87.9	59.5	81.5	81.3	54.4	52.6	26.5	59.3	35.9	34.9	18.2
2087	13.5	21.4	87.9	59.5	81.6	81.3	54.4	52.6	26.5	59.3	35.9	34.9	18.2
2088	13.5	21.4	87.9	59.5	81.6	81.4	54.4	52.6	26.5	59.3	35.9	34.9	18.2
2089	13.5	21.5	88.0	59.5	81.6	81.4	54.4	52.6	26.5	59.3	35.9	34.9	18.2
2090	13.5	21.6	88.0	59.6	81.7	81.4	54.5	52.7	26.6	59.4	35.9	35.0	18.2
2091	13.5	21.7	88.0	59.6	81.7	81.5	54.5	52.7	26.6	59.4	35.9	35.0	18.2
2092	13.5	21.8	88.1	59.6	81.7	81.5	54.5	52.7	26.6	59.4	35.9	35.0	18.2
2093	13.5	21.9	88.1	59.6	81.8	81.5	54.5	52.7	26.6	59.4	35.9	35.0	18.2
2094	13.5	22.0	88.1	59.6	81.8	81.5	54.5	52.7	26.6	59.4	35.9	35.0	18.2
2095	13.5	22.1	88.2	59.7	81.8	81.6	54.5	52.7	26.6	59.4	35.9	35.0	18.2
2096	13.5	22.2	88.2	59.7	81.8	81.6	54.5	52.7	26.6	59.5	35.9	35.0	18.2
2097	13.5	22.3	88.2	59.7	81.9	81.6	54.6	52.7	26.6	59.5	35.9	35.0	18.2
2098	13.5	22.3	88.3	59.7	81.9	81.6	54.6	52.7	26.6	59.5	35.9	35.0	18.2
2099	13.5	22.4	88.3	59.7	81.9	81.7	54.6	52.7	26.6	59.5	35.9	35.0	18.2
2100	13.5	22.5	88.3	59.7	81.9	81.7	54.6	52.8	26.6	59.5	35.9	35.0	18.2
2101	13.5	22.6	88.3	59.7	82.0	81.7	54.6	52.8	26.6	59.5	35.9	35.0	18.2
2102	13.5	22.6	88.4	59.8	82.0	81.7	54.6	52.8	26.6	59.5	35.9	35.0	18.2
2103	13.5	22.7	88.4	59.8	82.0	81.8	54.6	52.8	26.6	59.6	35.9	35.0	18.2
2104	13.5	22.8	88.4	59.8	82.0	81.8	54.6	52.8	26.6	59.6	35.9	35.0	18.2
2105	13.5	22.9	88.5	59.8	82.1	81.8	54.6	52.8	26.6	59.6	35.9	35.0	18.2
2106	13.5	22.9	88.5	59.8	82.1	81.8	54.7	52.8	26.6	59.6	35.9	35.0	18.2
2107	13.5	23.0	88.5	59.8	82.1	81.9	54.7	52.8	26.6	59.6	35.9	35.0	18.2
2108	13.5	23.1	88.5	59.8	82.1	81.9	54.7	52.8	26.6	59.6	35.9	35.0	18.2
2109	13.5	23.1	88.5	59.9	82.2	81.9	54.7	52.8	26.6	59.6	35.9	35.0	18.2
2110	13.5	23.2	88.6	59.9	82.2	81.9	54.7	52.8	26.6	59.6	35.9	35.0	18.2
2111	13.5	23.2	88.6	59.9	82.2	81.9	54.7	52.9	26.6	59.7	36.0	35.0	18.2

Figure 8.2 Modelled Salt Load Entering the River Murray for All Scenarios for the Lock 2 to Hogwash Reach

Time	S-1	S-2	S-3a	S-3c	S-4	S-8a(i)	S-8a(ii)	S-8a(iii)	S-8a(iv)	S-8b(i)	S-8b(ii)	S-8b(iii)	S-8b(iv)
(y)	(t/d)	(t/d)	(t/d)	(t/d)	(t/d)	(t/d)	(t/d)	(t/d)	(t/d)	(t/d)	(t/d)	(t/d)	(t/d)
1988	4.6	4.6	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.4
1989	4.6	4.6	22.5	22.5	22.5	22.5	22.5	22.5	22.5	22.5	22.5	22.5	22.5
1990	4.6	4.6	22.6	22.6	22.6	22.6	22.6	22.6	22.6	22.6	22.6	22.6	22.6
1991	4.6	4.6	22.7	22.5	22.5	22.5	22.5	22.5	22.5	22.5	22.5	22.5	22.5
1992	4.6	4.6	22.7	21.4	21.4	21.4	21.4	21.4	21.4	21.4	21.4	21.4	21.4
1993	4.6	4.6	22.8	21.1	21.1	21.1	21.1	21.1	21.1	21.1	21.1	21.1	21.1
1994	4.6	4.6	22.8	19.7	19.7	19.7	19.7	19.7	19.7	19.7	19.7	19.7	19.7
1995	4.6	4.6	22.9	18.1	18.1	18.1	18.1	18.1	18.1	18.1	18.1	18.1	18.1
1996	4.6	4.6	22.9	17.3	19.7	19.7	19.7	19.7	19.7	17.3	17.3	17.3	17.3
1997	4.6	4.6	22.9	16.8	20.0	20.0	20.0	20.0	20.0	16.8	16.8	16.8	16.8
1998	4.6	4.6	23.0	16.4	20.8	20.8	20.8	20.8	20.8	16.4	16.4	16.4	16.4
1999	4.6	4.6	23.0	16.1	21.0	21.0	21.0	21.0	21.0	16.1	16.1	16.1	16.1
2000	4.6	4.6	23.1	14.8	20.0	20.0	20.0	20.0	20.0	14.8	14.8	14.8	14.8
2001	4.6	4.6	23.1	13.1	17.8	17.8	17.8	17.8	17.8	13.1	13.1	13.1	13.1
2002	4.6	4.6	23.2	12.4	17.4	17.4	17.4	17.4	17.4	12.4	12.3	12.3	12.3
2003	4.6	4.6	23.2	11.8	16.9	16.9	16.9	16.9	16.9	11.8	11.8	11.8	11.8
2004	4.6	4.6	23.2	11.4	17.6	17.6	17.5	17.5	17.5	11.4	11.3	11.3	11.3
2005	4.6	4.7	23.2	11.1	18.1	18.1	18.0	18.0	18.0	11.1	11.0	11.0	11.0
2006	4.6	4.7	23.3	10.9	18.4	18.4	18.3	18.3	18.3	10.9	10.7	10.7	10.7
2007	4.6	4.7	23.3	10.7	18.5	18.5	18.4	18.4	18.4	10.7	10.5	10.5	10.5
2008	4.6	4.7	23.3	10.5	18.7	18.7	18.5	18.5	18.5	10.5	10.4	10.4	10.4
2009	4.6	4.7	23.4	9.4	16.1	16.1	15.9	15.9	15.9	9.4	9.3	9.3	9.3
2010	4.6	4.7	23.4	9.0	15.3	15.3	15.1	15.1	14.8	9.0	8.8	8.8	8.6
2011	4.6	4.7	23.4	8.7	14.8	14.8	14.6	14.6	14.1	8.7	8.5	8.5	8.2
2012	4.6	4.7	23.4	8.5	14.6	14.6	14.3	14.3	13.7	8.5	8.3	8.3	8.0
2013	4.6	4.7	23.4	8.3	14.4	14.4	14.1	14.1	13.5	8.3	8.1	8.1	7.8
2014	4.6	4.7	23.4	8.2	14.3	14.3	14.0	14.0	13.3	8.2	8.0	8.0	7.6
2015	4.6	4.7	23.5	8.1	14.2	14.2	13.9	13.9	13.2	8.1	7.9	7.9	7.5
2016	4.6	4.7	23.5	8.0	14.1	14.1	13.8	13.8	13.1	8.0	7.8	7.8	7.4
2017	4.6	4.7	23.5	8.0	14.1	14.1	13.7	13.7	13.0	8.0	7.7	7.7	7.4
2018	4.6	4.7	23.5	7.9	14.0	14.0	13.7	13.7	13.0	7.9	7.7	7.7	7.3
2019	4.6	4.7	23.5	7.9	14.0	14.0	13.7	13.7	12.9	7.9	7.6	7.6	7.3
2020	4.6	4.7	23.5	7.8	14.0	14.0	13.6	13.6	12.9	7.8	7.6	7.6	7.2
2021	4.6	4.7	23.6	7.8	14.0	14.0	13.6	13.6	12.9	7.8	7.6	7.6	7.2
2022	4.6	4.7	23.6	7.8	14.0	14.0	13.6	13.6	12.9	7.8	7.5	7.5	7.2
2023	4.6	4.7	23.6	7.8	14.0	14.0	13.6	13.6	12.9	7.8	7.5	7.5	7.2
2024	4.6	4.7	23.6	7.8	14.1	14.1	13.6	13.6	12.9	7.8	7.5	7.5	7.1
2025	4.6	4.7	23.6	7.8	14.1	14.1	13.6	13.6	12.9	7.8	7.5	7.5	7.1
2026	4.6	4.7	23.6	7.8	14.1	14.1	13.6	13.6	12.9	7.8	7.5	7.5	7.1
2027	4.6	4.7	23.6	7.8	14.1	14.1	13.6	13.6	12.9	7.8	7.5	7.5	7.1
2028	4.6	4.7	23.6	7.7	14.1	14.1	13.7	13.6	12.9	7.7	7.5	7.5	7.1
2029	4.6	4.7	23.6	7.7	14.1	14.1	13.7	13.7	12.9	7.7	7.4	7.4	7.1
2030	4.6	4.7	23.7	7.7	14.2	14.2	13.7	13.7	12.9	7.7	7.4	7.4	7.1
2031	4.6	4.7	23.7	7.7	14.2	14.2	13.7	13.7	12.9	7.7	7.4	7.4	7.1
2032	4.6	4.7	23.7	7.7	14.2	14.2	13.7	13.7	12.9	7.7	7.4	7.4	7.1
2033	4.6	4.7	23.7	7.7	14.2	14.2	13.7	13.7	12.9	7.7	7.4	7.4	7.1
2034	4.6	4.7	23.7	7.7	14.2	14.2	13.7	13.7	12.9	7.7	7.4	7.4	7.1
2035	4.6	4.7	23.7	7.7	14.2	14.2	13.7	13.7	12.9	7.7	7.4	7.4	7.0
2036	4.6	4.7	23.7	7.7	14.3	14.3	13.7	13.7	12.9	7.7	7.4	7.4	7.0
2037	4.6	4.7	23.7	7.7	14.3	14.3	13.7	13.7	12.9	7.7	7.4	7.4	7.0
2038	4.6	4.7	23.7	7.7	14.3	14.3	13.8	13.7	12.9	7.7	7.4	7.4	7.0
2039	4.6	4.7	23.7	7.7	14.3	14.3	13.8	13.8	13.0	7.7	7.4	7.4	7.0
2040	4.6	4.7	23.7	7.7	14.3	14.3	13.8	13.8	13.0	7.7	7.4	7.4	7.0
2041	4.6	4.7	23.7	7.7	14.3	14.3	13.8	13.8	13.0	7.7	7.4	7.4	7.0
2042	4.6	4.7	23.7	7.7	14.4	14.4	13.8	13.8	13.0	7.7	7.4	7.4	7.0
2043	4.6	4.7	23.8	7.7	14.4	14.4	13.8	13.8	13.0	7.7	7.4	7.4	7.0
2044	4.6	4.7	23.8	7.7	14.4	14.4	13.8	13.8	13.0	7.7	7.4	7.4	7.0
2045	4.6	4.7	23.8	7.7	14.4	14.4	13.8	13.8	13.0	7.7	7.4	7.4	7.0
2046	4.6	4.7	23.8	7.7	14.4	14.4	13.8	13.8	13.0	7.7	7.4	7.4	7.0
2047	4.6	4.7	23.8	7.7	14.4	14.4	13.8	13.8	13.0	7.7	7.4	7.4	7.0
2048	4.6	4.7	23.8	7.7	14.4	14.4	13.8	13.8	13.0	7.7	7.4	7.4	7.0
2049	4.6	4.7	23.8	7.7	14.4	14.4	13.8	13.8	13.0	7.7	7.4	7.4	7.0

Time	S-1	S-2	S-3a	S-3c	S-4	S-8a(i)	S-8a(ii)	S-8a(iii)	S-8a(iv)	S-8b(i)	S-8b(ii)	S-8b(iii)	S-8b(iv)
(y)	(t/d)	(t/d)	(t/d)	(t/d)	(t/d)	(t/d)	(t/d)	(t/d)	(t/d)	(t/d)	(t/d)	(t/d)	(t/d)
2050	4.6	4.7	23.8	7.7	14.4	14.4	13.8	13.8	13.0	7.7	7.4	7.4	7.0
2051	4.6	4.8	23.8	7.7	14.5	14.5	13.9	13.8	13.0	7.7	7.4	7.4	7.0
2052	4.6	4.8	23.8	7.7	14.5	14.5	13.9	13.8	13.0	7.7	7.4	7.4	7.0
2053	4.6	4.8	23.8	7.7	14.5	14.5	13.9	13.9	13.0	7.7	7.4	7.4	7.0
2054	4.6	4.8	23.8	7.8	14.5	14.5	13.9	13.9	13.0	7.7	7.4	7.4	7.0
2055	4.6	4.8	23.8	7.8	14.5	14.5	13.9	13.9	13.0	7.7	7.4	7.4	7.0
2056	4.6	4.8	23.8	7.8	14.5	14.5	13.9	13.9	13.1	7.8	7.4	7.4	7.0
2057	4.6	4.8	23.8	7.8	14.5	14.5	13.9	13.9	13.1	7.8	7.4	7.4	7.0
2058	4.6	4.8	23.8	7.8	14.5	14.5	13.9	13.9	13.1	7.8	7.4	7.4	7.0
2059	4.6	4.8	23.8	7.8	14.5	14.5	13.9	13.9	13.1	7.8	7.4	7.4	7.0
2060	4.6	4.8	23.9	7.8	14.5	14.5	13.9	13.9	13.1	7.8	7.4	7.4	7.0
2061	4.6	4.8	23.9	7.8	14.5	14.5	13.9	13.9	13.1	7.8	7.4	7.4	7.0
2062	4.6	4.8	23.9	7.8	14.5	14.5	13.9	13.9	13.1	7.8	7.4	7.4	7.0
2063	4.6	4.8	23.9	7.8	14.6	14.6	13.9	13.9	13.1	7.8	7.4	7.4	7.0
2064	4.6	4.8	23.9	7.8	14.6	14.6	13.9	13.9	13.1	7.8	7.4	7.4	7.0
2065	4.6	4.8	23.9	7.8	14.6	14.6	13.9	13.9	13.1	7.8	7.4	7.4	7.0
2066	4.6	4.8	23.9	7.8	14.6	14.6	13.9	13.9	13.1	7.8	7.4	7.4	7.0
2067	4.6	4.8	23.9	7.8	14.6	14.6	13.9	13.9	13.1	7.8	7.4	7.4	7.0
2068	4.6	4.8	23.9	7.8	14.6	14.6	13.9	13.9	13.1	7.8	7.4	7.4	7.0
2069	4.6	4.8	23.9	7.8	14.6	14.6	13.9	13.9	13.1	7.8	7.4	7.4	7.0
2070	4.6	4.8	23.9	7.8	14.6	14.6	14.0	13.9	13.1	7.8	7.4	7.4	7.0
2071	4.6	4.8	23.9	7.8	14.6	14.6	14.0	13.9	13.1	7.8	7.4	7.4	7.0
2072	4.6	4.8	23.9	7.8	14.6	14.6	14.0	13.9	13.1	7.8	7.4	7.4	7.0
2073	4.6	4.8	23.9	7.8	14.6	14.6	14.0	13.9	13.1	7.8	7.4	7.4	7.0
2074	4.6	4.8	23.9	7.8	14.6	14.6	14.0	13.9	13.1	7.8	7.4	7.4	7.0
2075	4.6	4.9	23.9	7.8	14.6	14.6	14.0	13.9	13.1	7.8	7.4	7.4	7.0
2076	4.6	4.9	23.9	7.8	14.6	14.6	14.0	14.0	13.1	7.8	7.4	7.4	7.0
2077	4.6	4.9	23.9	7.8	14.6	14.6	14.0	14.0	13.1	7.8	7.4	7.4	7.0
2078	4.6	4.9	23.9	7.8	14.6	14.6	14.0	14.0	13.1	7.8	7.4	7.4	7.0
2079	4.6	4.9	23.9	7.8	14.6	14.6	14.0	14.0	13.1	7.8	7.4	7.4	7.0
2080	4.6	4.9	23.9	7.8	14.6	14.6	14.0	14.0	13.1	7.8	7.4	7.4	7.0
2081	4.6	4.9	23.9	7.8	14.7	14.6	14.0	14.0	13.1	7.8	7.4	7.4	7.0
2082	4.6	4.9	23.9	7.8	14.7	14.7	14.0	14.0	13.1	7.8	7.4	7.4	7.0
2083	4.6	4.9	23.9	7.8	14.7	14.7	14.0	14.0	13.1	7.8	7.4	7.4	7.0
2084	4.6	4.9	23.9	7.8	14.7	14.7	14.0	14.0	13.1	7.8	7.4	7.4	7.0
2085	4.6	4.9	23.9	7.8	14.7	14.7	14.0	14.0	13.1	7.8	7.4	7.4	7.0
2086	4.6	4.9	23.9	7.8	14.7	14.7	14.0	14.0	13.2	7.8	7.4	7.4	7.0
2087	4.6	4.9	23.9	7.8	14.7	14.7	14.0	14.0	13.2	7.8	7.4	7.4	7.0
2088	4.6	4.9	23.9	7.8	14.7	14.7	14.0	14.0	13.2	7.8	7.4	7.4	7.0
2089	4.6	4.9	24.0	7.8	14.7	14.7	14.0	14.0	13.2	7.8	7.4	7.4	7.0
2090	4.6	4.9	24.0	7.8	14.7	14.7	14.0	14.0	13.2	7.8	7.4	7.4	7.0
2091	4.6	4.9	24.0	7.8	14.7	14.7	14.0	14.0	13.2	7.8	7.4	7.4	7.0
2092	4.6	4.9	24.0	7.8	14.7	14.7	14.0	14.0	13.2	7.8	7.4	7.4	7.0
2093	4.6	4.9	24.0	7.8	14.7	14.7	14.0	14.0	13.2	7.8	7.4	7.4	7.0
2094	4.6	4.9	24.0	7.8	14.7	14.7	14.0	14.0	13.2	7.8	7.4	7.4	7.0
2095	4.6	4.9	24.0	7.8	14.7	14.7	14.0	14.0	13.2	7.8	7.4	7.4	7.0
2096	4.6	4.9	24.0	7.8	14.7	14.7	14.0	14.0	13.2	7.8	7.4	7.4	7.0
2097	4.6	4.9	24.0	7.8	14.7	14.7	14.0	14.0	13.2	7.8	7.4	7.4	7.0
2098	4.6	5.0	24.0	7.8	14.7	14.7	14.0	14.0	13.2	7.8	7.4	7.4	7.0
2099	4.6	5.0	24.0	7.8	14.7	14.7	14.0	14.0	13.2	7.8	7.4	7.4	7.0
2100	4.6	5.0	24.0	7.8	14.7	14.7	14.0	14.0	13.2	7.8	7.4	7.4	7.0
2101	4.6	5.0	24.0	7.8	14.7	14.7	14.0	14.0	13.2	7.8	7.4	7.4	7.0
2102	4.6	5.0	24.0	7.8	14.7	14.7	14.0	14.0	13.2	7.8	7.4	7.4	7.0
2103	4.6	5.0	24.0	7.8	14.7	14.7	14.0	14.0	13.2	7.8	7.4	7.4	7.0
2104	4.6	5.0	24.0	7.8	14.7	14.7	14.0	14.0	13.2	7.8	7.4	7.4	7.0
2105	4.6	5.0	24.0	7.8	14.7	14.7	14.1	14.0	13.2	7.8	7.4	7.4	7.0
2106	4.6	5.0	24.0	7.8	14.7	14.7	14.1	14.0	13.2	7.8	7.4	7.4	7.0
2107	4.6	5.0	24.0	7.8	14.7	14.7	14.1	14.0	13.2	7.8	7.4	7.4	7.0
2108	4.6	5.0	24.0	7.8	14.7	14.7	14.1	14.0	13.2	7.8	7.4	7.4	7.0
2109	4.6	5.0	24.0	7.8	14.7	14.7	14.1	14.0	13.2	7.8	7.4	7.4	7.0
2110	4.6	5.0	24.0	7.8	14.7	14.7	14.1	14.0	13.2	7.8	7.4	7.4	7.0
2111	4.6	5.0	24.0	7.8	14.7	14.7	14.1	14.0	13.2	7.8	7.4	7.4	7.0

Figure 8.3 Modelled Salt Load Entering the River Murray for All Scenarios for the Hogwash to Morgan Reach

Time	S-1	S-2	S-3a	S-3c	S-4	S-8a(i)	S-8a(ii)	S-8a(iii)	S-8a(iv)	S-8b(i)	S-8b(ii)	S-8b(iii)	S-8b(iv)
(y)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)
1988	431	464	10606	10606	10606	10606	10606	10606	10606	10606	10606	10606	10606
1989	431	464	10506	10506	10506	10506	10506	10506	10506	10506	10506	10506	10506
1990	431	465	10462	10289	10289	10289	10289	10289	10289	10289	10289	10289	10289
1991	431	467	10439	9959	9959	9959	9959	9959	9959	9959	9959	9959	9959
1992	431	469	10427	9688	9688	9688	9688	9688	9688	9688	9688	9688	9688
1993	431	471	10424	9482	9482	9482	9482	9482	9482	9482	9482	9482	9482
1994	431	473	10426	9311	9311	4837	4837	4837	4837	4837	4837	4837	4837
1995	431	474	10431	9155	9155	4226	4226	4226	4226	4226	4226	4226	4226
1996	431	476	10455	9002	9002	3943	3943	3943	3943	3943	3943	3943	3943
1997	431	477	10489	8829	8829	3735	3735	3735	3735	3735	3735	3735	3735
1998	431	478	10516	8666	8666	3577	3577	3577	3577	3577	3577	3577	3577
1999	431	479	10540	8504	8504	3443	3443	3443	3443	3443	3443	3443	3443
2000	431	480	10560	8343	8343	3322	3322	3322	3322	3322	3322	3322	3322
2001	431	484	10580	8089	8098	3143	3143	3143	3143	3135	3135	3135	3135
2002	431	487	10598	7869	7890	3009	3009	3009	3009	2988	2988	2988	2988
2003	431	490	10616	7702	7737	2920	2919	2919	2919	2887	2887	2887	2887
2004	431	493	10633	7565	7612	2851	2848	2140	2140	2807	2805	2129	2129
2005	431	496	10650	7447	7505	2793	2787	2009	2009	2739	2733	2001	2001
2006	431	498	10666	7344	7517	2832	2819	2004	2004	2682	2669	1931	1931
2007	431	500	10683	7251	7483	2823	2802	1973	1973	2632	2611	1878	1878
2008	431	503	10699	7168	7452	2813	2782	1949	1949	2587	2557	1833	1833
2009	431	505	10715	7093	7421	2801	2760	1925	1925	2548	2507	1794	1794
2010	431	507	10730	6961	7344	2759	2707	1867	1867	2468	2417	1719	1718
2011	431	512	10746	6770	7198	2665	2600	1778	1777	2343	2280	1629	1628
2012	431	518	10761	6630	7108	2622	2545	1744	1743	2265	2190	1579	1578
2013	431	523	10776	6515	7034	2588	2499	1715	1714	2204	2119	1540	1539
2014	431	528	10792	6419	7000	2583	2482	1707	1705	2155	2060	1507	1506
2015	431	532	10807	6336	6970	2578	2466	1697	1695	2114	2009	1478	1477
2016	431	537	10822	6262	6944	2573	2450	1687	1685	2079	1964	1452	1450
2017	431	541	10836	6196	6923	2573	2438	1679	1677	2048	1924	1428	1426
2018	431	545	10851	6137	6906	2572	2428	1672	1669	2021	1889	1406	1405
2019	431	549	10866	6083	6890	2573	2419	1665	1662	1996	1858	1387	1385
2020	431	553	10880	6035	6876	2574	2410	1658	1654	1975	1829	1369	1367
2021	431	560	10895	5990	6863	2574	2402	1650	1646	1955	1803	1352	1351
2022	431	568	10909	5949	6850	2575	2394	1642	1638	1937	1779	1337	1335
2023	431	575	10923	5911	6839	2575	2386	1635	1631	1921	1758	1323	1321
2024	431	582	10937	5877	6828	2576	2379	1628	1624	1907	1738	1310	1309
2025	431	588	10951	5844	6819	2576	2373	1621	1617	1893	1719	1298	1296
2026	431	595	10965	5815	6810	2577	2366	1615	1611	1881	1702	1287	1285
2027	431	601	10979	5787	6802	2578	2361	1609	1604	1870	1687	1277	1275
2028	431	606	10992	5762	6794	2579	2355	1603	1599	1860	1672	1268	1265
2029	431	612	11006	5738	6788	2580	2350	1598	1593	1851	1659	1259	1256
2030	431	618	11019	5717	6782	2581	2346	1593	1588	1843	1646	1250	1248
2031	431	627	11032	5697	6777	2582	2341	1588	1584	1835	1635	1243	1240
2032	431	636	11046	5678	6772	2583	2337	1584	1579	1828	1624	1235	1233
2033	431	645	11059	5660	6768	2585	2334	1580	1575	1821	1614	1228	1226
2034	431	653	11071	5644	6765	2586	2331	1576	1571	1815	1605	1222	1220
2035	431	662	11084	5629	6762	2588	2328	1573	1568	1810	1596	1216	1214
2036	431	670	11097	5615	6759	2589	2325	1569	1564	1805	1588	1210	1208
2037	431	678	11109	5602	6757	2591	2323	1566	1561	1800	1581	1205	1203
2038	431	686	11122	5591	6756	2593	2320	1564	1558	1796	1574	1200	1198
2039	431	693	11134	5579	6755	2595	2319	1561	1556	1792	1567	1196	1193
2040	431	700	11146	5569	6754	2597	2317	1558	1553	1789	1561	1191	1189
2041	431	711	11158	5560	6754	2599	2315	1556	1551	1786	1555	1187	1185
2042	431	721	11170	5551	6754	2601	2314	1554	1549	1783	1550	1183	1181
2043	431	731	11182	5543	6754	2603	2313	1552	1547	1780	1545	1179	1177
2044	431	740	11193	5535	6754	2605	2312	1550	1545	1778	1540	1176	1174
2045	431	749	11204	5528	6755	2607	2311	1548	1543	1776	1536	1173	1170
2046	431	758	11216	5522	6756	2609	2311	1547	1542	1774	1532	1170	1167
2047	431	766	11227	5516	6757	2611	2310	1545	1540	1772	1528	1167	1164
2048	431	774	11238	5510	6759	2614	2310	1544	1539	1770	1524	1164	1162
2049	431	782	11249	5505	6760	2616	2309	1543	1537	1769	1521	1162	1159

Time	S-1	S-2	S-3a	S-3c	S-4	S-8a(i)	S-8a(ii)	S-8a(iii)	S-8a(iv)	S-8b(i)	S-8b(ii)	S-8b(iii)	S-8b(iv)
(y)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)
2050	431	790	11260	5500	6762	2618	2309	1542	1536	1768	1518	1159	1157
2051	431	800	11271	5496	6764	2620	2309	1541	1535	1767	1515	1157	1154
2052	431	810	11281	5492	6766	2623	2309	1540	1534	1766	1512	1155	1152
2053	431	820	11292	5489	6768	2625	2309	1539	1533	1765	1509	1153	1150
2054	431	830	11302	5485	6771	2627	2309	1538	1532	1764	1507	1151	1148
2055	431	839	11312	5483	6773	2630	2310	1537	1532	1763	1505	1149	1146
2056	431	848	11322	5480	6776	2632	2310	1537	1531	1763	1503	1147	1145
2057	431	857	11332	5477	6779	2634	2310	1536	1530	1762	1501	1146	1143
2058	431	866	11342	5475	6781	2637	2311	1535	1530	1762	1499	1144	1142
2059	431	874	11351	5473	6784	2639	2311	1535	1529	1762	1497	1143	1140
2060	431	883	11361	5472	6787	2641	2312	1534	1529	1761	1495	1141	1139
2061	431	894	11370	5470	6790	2643	2312	1534	1528	1761	1494	1140	1137
2062	431	905	11380	5469	6793	2646	2313	1534	1528	1761	1492	1139	1136
2063	431	914	11389	5468	6796	2648	2313	1533	1528	1761	1491	1138	1135
2064	431	924	11398	5467	6799	2650	2314	1533	1527	1761	1490	1137	1134
2065	431	933	11407	5466	6802	2652	2315	1533	1527	1761	1489	1136	1133
2066	431	943	11416	5465	6806	2654	2315	1533	1527	1761	1488	1135	1132
2067	431	952	11424	5465	6809	2657	2316	1533	1527	1762	1487	1134	1131
2068	431	961	11433	5464	6812	2659	2317	1532	1527	1762	1486	1133	1130
2069	431	970	11441	5464	6815	2661	2318	1532	1527	1762	1485	1132	1130
2070	431	978	11450	5464	6819	2663	2319	1532	1526	1762	1484	1132	1129
2071	431	989	11458	5464	6822	2665	2319	1532	1526	1763	1483	1131	1128
2072	431	999	11466	5464	6825	2667	2320	1532	1526	1763	1482	1130	1127
2073	431	1009	11474	5464	6829	2669	2321	1532	1526	1763	1482	1130	1127
2074	431	1018	11482	5464	6832	2671	2322	1532	1526	1764	1481	1129	1126
2075	431	1027	11490	5464	6835	2673	2323	1532	1526	1764	1481	1128	1126
2076	431	1036	11498	5465	6839	2675	2324	1532	1526	1765	1480	1128	1125
2077	431	1045	11505	5465	6842	2677	2325	1532	1527	1765	1480	1127	1125
2078	431	1054	11513	5465	6845	2679	2326	1533	1527	1766	1479	1127	1124
2079	431	1063	11520	5466	6849	2681	2327	1533	1527	1766	1479	1127	1124
2080	431	1071	11528	5467	6852	2683	2327	1533	1527	1767	1478	1126	1123
2081	431	1081	11535	5467	6855	2685	2328	1533	1527	1767	1478	1126	1123
2082	431	1091	11542	5468	6858	2686	2329	1533	1527	1768	1478	1125	1122
2083	431	1100	11549	5469	6862	2688	2330	1533	1527	1768	1477	1125	1122
2084	431	1110	11556	5470	6865	2690	2331	1533	1527	1769	1477	1125	1122
2085	431	1119	11562	5470	6868	2692	2332	1534	1528	1769	1477	1124	1122
2086	431	1127	11569	5471	6871	2694	2333	1534	1528	1770	1477	1124	1121
2087	431	1136	11576	5472	6875	2695	2334	1534	1528	1770	1477	1124	1121
2088	431	1144	11582	5473	6878	2697	2335	1534	1528	1771	1476	1124	1121
2089	431	1153	11589	5474	6881	2699	2336	1534	1528	1771	1476	1124	1121
2090	431	1161	11595	5475	6884	2700	2337	1535	1529	1772	1476	1123	1120
2091	431	1170	11601	5476	6887	2702	2338	1535	1529	1773	1476	1123	1120
2092	431	1180	11608	5477	6890	2703	2339	1535	1529	1773	1476	1123	1120
2093	431	1189	11614	5478	6893	2705	2339	1535	1529	1774	1476	1123	1120
2094	431	1197	11620	5479	6896	2707	2340	1536	1530	1774	1476	1123	1120
2095	431	1206	11626	5480	6899	2708	2341	1536	1530	1775	1476	1123	1120
2096	431	1214	11632	5482	6902	2710	2342	1536	1530	1776	1476	1122	1119
2097	431	1223	11637	5483	6905	2711	2343	1536	1530	1776	1476	1122	1119
2098	431	1231	11643	5484	6908	2713	2344	1537	1531	1777	1476	1122	1119
2099	431	1238	11649	5485	6911	2714	2345	1537	1531	1777	1476	1122	1119
2100	431	1246	11654	5486	6914	2716	2346	1537	1531	1778	1476	1122	1119
2101	431	1255	11660	5487	6917	2717	2346	1538	1531	1779	1476	1122	1119
2102	431	1263	11665	5488	6920	2718	2347	1538	1532	1779	1476	1122	1119
2103	431	1272	11670	5490	6922	2720	2348	1538	1532	1780	1476	1122	1119
2104	431	1280	11675	5491	6925	2721	2349	1538	1532	1780	1476	1122	1119
2105	431	1288	11681	5492	6928	2722	2350	1539	1532	1781	1476	1122	1119
2106	431	1296	11686	5493	6931	2724	2351	1539	1533	1781	1476	1122	1119
2107	431	1304	11691	5494	6933	2725	2351	1539	1533	1782	1476	1122	1119
2108	431	1311	11696	5496	6936	2726	2352	1540	1533	1783	1476	1122	1119
2109	431	1319	11701	5497	6938	2728	2353	1540	1534	1783	1477	1122	1119
2110	431	1326	11705	5498	6941	2729	2354	1540	1534	1784	1477	1122	1119
2111	431	1335	11710	5499	6944	2730	2355	1540	1534	1784	1477	1122	1119

Figure 8.4 Modelled Groundwater Flux Entering the River Murray for All Scenarios for the Holder to Lock 2 Reach

Time	S-1	S-2	S-3a	S-3c	S-4	S-8a(i)	S-8a(ii)	S-8a(iii)	S-8a(iv)	S-8b(i)	S-8b(ii)	S-8b(iii)	S-8b(iv)
(y)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)
1988	717	729	2528	2528	2528	2528	2528	2528	2528	2528	2528	2528	2528
1989	717	729	2599	2599	2599	2599	2599	2599	2599	2599	2599	2599	2599
1990	717	730	2660	2651	2651	2651	2651	2651	2651	2651	2651	2651	2651
1991	717	732	2717	2680	2680	2680	2680	2680	2680	2680	2680	2680	2680
1992	717	733	2769	2697	2697	2697	2697	2697	2697	2697	2697	2697	2697
1993	717	734	2816	2722	2722	2722	2722	2722	2722	2722	2722	2722	2722
1994	717	735	2860	2738	2738	2738	2738	2738	2738	2738	2738	2738	2738
1995	717	735	2910	2759	2759	2759	2759	2759	2759	2759	2759	2759	2759
1996	717	736	2953	2784	2784	2784	2784	2784	2784	2784	2784	2784	2784
1997	717	737	2996	2813	2813	2813	2813	2813	2813	2813	2813	2813	2813
1998	717	737	3040	2838	2838	2838	2838	2838	2838	2837	2837	2837	2837
1999	717	738	3082	2857	2859	2858	2858	2858	2858	2857	2857	2857	2857
2000	717	739	3120	2861	2864	2864	2864	2864	2864	2861	2861	2861	2861
2001	717	741	3155	2782	2785	2785	2785	2785	2785	2781	2781	2781	2781
2002	717	743	3187	2733	2738	2737	2519	2519	2519	2732	2514	2514	2514
2003	717	744	3217	2697	2704	2703	2377	2377	2377	2696	2371	2371	2371
2004	717	745	3244	2669	2681	2680	2283	2283	2283	2669	2274	2274	2274
2005	717	746	3269	2649	2671	2670	2220	2220	2220	2648	2202	2202	2202
2006	717	747	3292	2632	2700	2699	2203	2202	2202	2631	2146	2145	2145
2007	717	748	3313	2619	2732	2730	2196	2193	2193	2617	2100	2098	2098
2008	717	749	3333	2608	2777	2775	2205	2201	2201	2606	2062	2058	2058
2009	717	750	3351	2587	2813	2811	2208	2201	2201	2585	2018	2011	2011
2010	717	751	3369	2573	2847	2845	2214	2203	1461	2571	1983	1973	1297
2011	717	754	3385	2563	2880	2877	2220	2205	1276	2561	1953	1940	1127
2012	717	756	3400	2554	2909	2907	2225	2206	1217	2552	1927	1910	1070
2013	717	758	3414	2546	2936	2933	2230	2207	1192	2544	1903	1883	1039
2014	717	759	3428	2539	2992	2989	2265	2239	1212	2536	1881	1858	1018
2015	717	761	3441	2532	3027	3024	2282	2252	1218	2529	1860	1834	1002
2016	717	762	3453	2525	3053	3050	2290	2258	1220	2522	1840	1811	990
2017	717	764	3464	2518	3075	3071	2295	2260	1220	2515	1821	1790	980
2018	717	765	3475	2513	3093	3089	2297	2260	1220	2509	1804	1771	972
2019	717	766	3486	2507	3109	3105	2299	2259	1220	2504	1788	1754	965
2020	717	767	3496	2503	3123	3119	2299	2258	1220	2499	1773	1737	959
2021	717	771	3505	2498	3136	3132	2299	2256	1220	2495	1759	1722	954
2022	717	774	3514	2495	3148	3144	2299	2254	1220	2491	1746	1709	949
2023	717	776	3523	2492	3160	3155	2299	2253	1220	2488	1735	1696	945
2024	717	778	3532	2489	3170	3166	2299	2251	1220	2485	1724	1684	942
2025	717	779	3540	2487	3180	3176	2299	2250	1220	2482	1714	1674	939
2026	717	781	3547	2485	3189	3185	2298	2248	1220	2480	1705	1664	936
2027	717	783	3555	2483	3198	3194	2298	2247	1220	2479	1697	1656	933
2028	717	784	3562	2482	3207	3202	2298	2246	1220	2478	1689	1648	931
2029	717	786	3569	2481	3215	3210	2298	2245	1220	2477	1682	1640	929
2030	717	787	3576	2481	3223	3218	2298	2244	1220	2476	1675	1634	927
2031	717	792	3583	2481	3230	3225	2298	2243	1220	2475	1670	1627	925
2032	717	795	3589	2480	3237	3232	2298	2243	1220	2475	1664	1622	924
2033	717	797	3596	2480	3244	3239	2298	2242	1221	2475	1659	1617	922
2034	717	800	3602	2481	3251	3245	2298	2242	1221	2475	1655	1612	921
2035	717	802	3607	2481	3257	3252	2299	2242	1221	2476	1651	1608	920
2036	717	805	3613	2482	3263	3258	2299	2241	1221	2476	1647	1604	919
2037	717	807	3619	2482	3269	3263	2300	2241	1222	2477	1643	1600	918
2038	717	810	3624	2483	3275	3269	2300	2241	1222	2477	1640	1597	917
2039	717	812	3629	2484	3281	3275	2301	2241	1222	2478	1637	1593	916
2040	717	814	3634	2485	3286	3280	2301	2242	1222	2479	1634	1591	916
2041	717	819	3639	2486	3291	3285	2302	2242	1223	2480	1632	1588	915
2042	717	823	3644	2487	3297	3290	2303	2242	1223	2481	1629	1586	915
2043	717	827	3649	2488	3301	3295	2303	2242	1223	2482	1627	1584	914
2044	717	830	3654	2489	3306	3300	2304	2243	1224	2483	1625	1582	914
2045	717	834	3658	2491	3311	3304	2305	2243	1224	2484	1623	1580	913
2046	717	837	3663	2492	3315	3309	2306	2244	1224	2486	1622	1579	913
2047	717	841	3667	2493	3320	3313	2306	2244	1225	2487	1620	1578	913
2048	717	845	3671	2495	3324	3317	2307	2245	1225	2488	1619	1577	912
2049	717	848	3675	2496	3328	3321	2308	2245	1225	2489	1618	1576	912
2050	717	852	3679	2497	3332	3325	2309	2246	1226	2491	1616	1575	912
2051	717	858	3683	2499	3336	3329	2310	2246	1226	2492	1615	1574	912
2052	717	863	3686	2500	3340	3333	2311	2247	1226	2493	1614	1573	912
2053	717	868	3690	2501	3343	3336	2312	2247	1227	2495	1613	1573	911
2054	717	872	3694	2503	3347	3340	2312	2248	1227	2496	1613	1572	911
2055	717	877	3697	2504	3351	3343	2313	2249	1227	2497	1612	1572	911
2056	717	881	3701	2506	3354	3346	2314	2249	1228	2499	1611	1571	911
2057	717	886	3704	2507	3357	3350	2315	2250	1228	2500	1611	1571	911
2058	717	890	3707	2508	3360	3353	2316	2251	1228	2501	1610	1570	911
2059	717	894	3710	2510	3363	3356	2317	2251	1229	2503	1610	1570	911
2060	717	899	3713	2511	3367	3359	2318	2252	1229	2504	1609	1570	910
2061	717	904	3716	2512	3369	3361	2319	2253	1229	2505	1609	1570	910
2062	717	910	3719	2514	3372	3364	2320	2253	1229	2507	1608	1570	910
2063	717	915	3722	2515	3375	3367	2320	2254	1230	2508	1608	1569	910
2064	717	920	3725	2516	3378	3370	2321	2255	1230	2509	1608	1569	910
2065	717	925	3727	2517	3380	3372	2322	2255	1230	2510	1607	1569	910
2066	717	931	3730	2519	3383	3375	2323	2256	1231	2511	1607	1569	910
2067	717	935	3732	2520	3385	3377	2324	2257	1231	2513	1607	1569	910
2068	717	940	3735	2521	3388	3379	2325	2257	1231	2514	1607	1569	910
2069	717	945	3737	2522	3390	3382	2325	2258	1231	2515	1607	1569	910
2070	717	949	3740	2523	3392	3384	2326	2259	1232	2516	1606	1569	910
2071	717	954	3742	2525	3395	3386	2327	2259	1232	2517	1606	1569	910
2072	717	959	3744	2526	3397	3388	2328	2260	1232	2518	1606	1569	910
2073	717	964	3746	2527	3399	3390	2329	2260	1232	2519	1606	1569	910
2074	717	969	3749	2528	3401	3392	2329	2261	1233	2520	1606	1569	910
2075	717	974	3751	2529	3403	3394	2330	2262	1233	2521	1606	1569	910
2076	717	978	3753	2530	3405	3396	2331	2262	1233	2522	1606	1569	910
2077	717	983	3755	2531	3407	3398	2332	2263	1233	2523	1606	1569	910
2078	717	987	3757	2532	3409	3400	2332	2263	1234	2524	1606	1569	910
2079	717	991	3758	2533	3410	3401	2333	2264	1234	2525	1606	1569	910
2080	717	995	3760	2534	3412	3403	2334	2264	1234	2526	1606	1569	910
2081	717	999	3762	2535	3414	3405	2334	2265	1234	2527	1606	1569	910
2082	717	1004	3764	2536	3416	3406	2335	2266	1234	2528	1606	1569	910
2083	717	1008	3765	2537	3417	3408	2336	2266	1235	2529	1606	1569	910
2084	717	1012	3767	2538	3419	3409	2336	2267	1235	2530	1606	1570	910
2085	717	1016	3769	2538	3420	3411	2337	2267	1235	2530	1606	1570	910
2086	717	1020	3770	2539	3422	3412	2337	2268	1235	2531	1606	1570	910
2087	717	1024	3772	2540	3423	3414	2338	2268	1235	2532	1606	1570	910
2088	717	1027	3773	2541	3425	3415	2339	2269	1236	2533	1606	1570	910
2089	717	1031	3775	2542	3426	3416	2339	2269	1236	2534	1606	1570	910
2090	717	1034	3776	2543	3427	3418	2340	2270	1236	2534	1606	1570	910
2091	717	1038	3778	2543	3429	3419	2340	2270	1236	2535	1607	1570	910
2092	717	1042	3779	2544	3430	3420	2341	2270	1236	2536	1607	1570	910
2093	717	1045	3780	2545	3431	3421	2341	2271	1236	2536	1607	1571	910
2094	717	1049	3781	2545	3432	3423	2342	2271	1237	2537	1607	1571	910
2095	717	1052	3783	2546	3433	3424	2342	2272	1237	2538	1607	1571	910
2096	717	1056	3784	2547	3435	3425	2343	2272	1237	2539	1607	1571	910
2097	717	1059	3785	2547	3436	3426	2343	2273	1237	2539	1607	1571	910
2098	717	1062	3786	2548	3437	3427	2344	2273	1237	2540	1607	1571	910
2099	717	1065	3787	2549	3438	3428	2344	2273	1237	2540	1607	1571	910
2100	717	1068	3789	2549	3439	3429	2345	2274	1238	2541	1607	1571	910
2101	717	1070	3790	2550	3440	3430	2345	2274	1238	2542	1608	1571	910
2102	717	1073	3791	2551	3441	3431	2346	2275	1238	2542	1608	1572	910
2103	717	1076	3792	2551	3442	3432	2346	2275	1238	2543	1608	1572	910
2104	717	1079	3793	2552	3443	3433	2347	2275	1238	2543	1608	1572	910
2105	717	1082	3794	2552	3444	3434	2347	2276	1238	2544	1608	1572	910
2106	717	1085	3795	2553	3444	3434	2348	2276	1238	2544	1608	1572	910
2107	717	1087	3796	2553	3445	3435	2348	2276	1238	2545	1608	1572	910
2108	717	1090	3797	2554	3446	3436	2348	2277	1239	2545	1608	1572	910
2109	717	1092	3797	2554	3447	3437	2349	2277	1239	2546	1608	1572	910
2110	717	1094	3798	2555	3448	3438	2349	2277	1239	2546	1608	1573	910
2111	717	1097	3799	2555	3449	3438	2349	2278	1239	2547	1609	1573	910

Figure 8.5 Modelled Groundwater Flux Entering the River Murray for All Scenarios for the Lock 2 to Hogwash Reach

Time	S-1	S-2	S-3a	S-3c	S-4	S-8a(i)	S-8a(ii)	S-8a(iii)	S-8a(iv)	S-8b(i)	S-8b(ii)	S-8b(iii)	S-8b(iv)
(y)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)
1988	405	409	4099	4099	4099	4099	4099	4099	4099	4099	4099	4099	4099
1989	405	409	4106	4106	4106	4106	4106	4106	4106	4106	4106	4106	4106
1990	405	409	4113	4110	4110	4110	4110	4110	4110	4110	4110	4110	4110
1991	405	409	4120	4108	4108	4108	4108	4108	4108	4108	4108	4108	4108
1992	405	409	4126	3893	3893	3893	3893	3893	3893	3893	3893	3893	3893
1993	405	409	4131	3808	3808	3808	3808	3808	3808	3808	3808	3808	3808
1994	405	410	4136	3541	3541	3541	3541	3541	3541	3541	3541	3541	3541
1995	405	410	4141	3205	3205	3205	3205	3205	3205	3205	3205	3205	3205
1996	405	410	4146	3041	3360	3360	3360	3360	3360	3041	3041	3041	3041
1997	405	410	4150	2933	3365	3365	3365	3365	3365	2933	2933	2933	2933
1998	405	410	4155	2856	3455	3455	3455	3455	3455	2856	2856	2856	2856
1999	405	410	4160	2799	3481	3481	3481	3481	3481	2799	2799	2799	2799
2000	405	410	4164	2541	3254	3254	3254	3254	3254	2541	2541	2541	2541
2001	405	410	4168	2205	2851	2851	2851	2851	2851	2205	2205	2205	2205
2002	405	411	4172	2039	2732	2732	2729	2729	2729	2039	2037	2037	2037
2003	405	411	4175	1926	2628	2628	2621	2621	2621	1926	1920	1920	1920
2004	405	411	4179	1844	2682	2682	2671	2671	2671	1844	1834	1834	1834
2005	405	411	4182	1781	2728	2728	2714	2714	2714	1781	1769	1769	1769
2006	405	411	4185	1733	2754	2754	2737	2737	2737	1733	1719	1719	1719
2007	405	412	4187	1696	2761	2761	2742	2742	2742	1696	1679	1679	1679
2008	405	412	4190	1666	2772	2772	2750	2750	2750	1666	1648	1648	1648
2009	405	412	4192	1445	2362	2362	2338	2338	2338	1445	1426	1426	1426
2010	405	412	4195	1346	2219	2219	2193	2193	2159	1346	1325	1325	1301
2011	405	412	4197	1281	2130	2130	2101	2101	2047	1281	1260	1260	1226
2012	405	412	4199	1235	2071	2071	2041	2041	1977	1235	1213	1213	1175
2013	405	413	4200	1200	2029	2029	1997	1996	1928	1200	1178	1178	1138
2014	405	413	4202	1174	2003	2003	1969	1968	1896	1174	1150	1150	1110
2015	405	413	4204	1153	1982	1982	1946	1946	1870	1153	1129	1129	1088
2016	405	413	4206	1137	1965	1965	1928	1927	1850	1137	1112	1112	1071
2017	405	413	4207	1124	1953	1952	1913	1913	1833	1124	1098	1098	1057
2018	405	414	4209	1114	1943	1943	1902	1902	1821	1114	1087	1087	1046
2019	405	414	4210	1106	1936	1936	1894	1894	1811	1106	1078	1078	1037
2020	405	414	4211	1099	1931	1931	1887	1887	1803	1099	1071	1071	1029
2021	405	414	4213	1094	1927	1927	1882	1882	1797	1094	1065	1065	1024
2022	405	414	4214	1090	1925	1925	1878	1878	1792	1090	1061	1061	1019
2023	405	415	4215	1086	1923	1923	1875	1875	1789	1086	1057	1057	1015
2024	405	415	4216	1084	1922	1922	1873	1873	1786	1084	1054	1053	1012
2025	405	416	4217	1082	1922	1922	1872	1871	1784	1082	1051	1051	1009
2026	405	416	4218	1080	1922	1922	1871	1870	1782	1080	1049	1048	1007
2027	405	416	4219	1079	1922	1922	1870	1869	1781	1079	1047	1046	1005
2028	405	416	4220	1078	1923	1923	1870	1869	1781	1077	1045	1045	1004
2029	405	416	4221	1077	1924	1924	1869	1869	1780	1077	1044	1043	1003
2030	405	417	4222	1076	1925	1925	1869	1869	1780	1076	1043	1042	1001
2031	405	417	4223	1075	1926	1926	1870	1869	1780	1075	1042	1041	1000
2032	405	418	4224	1075	1927	1927	1870	1869	1779	1075	1041	1040	1000
2033	405	418	4225	1075	1928	1928	1870	1869	1780	1075	1040	1040	999
2034	405	419	4226	1074	1929	1929	1870	1869	1780	1074	1039	1039	998
2035	405	419	4226	1074	1930	1930	1871	1870	1780	1074	1039	1038	998
2036	405	419	4227	1074	1931	1931	1871	1870	1780	1074	1038	1038	997
2037	405	420	4228	1074	1932	1932	1872	1871	1780	1074	1038	1037	997
2038	405	420	4229	1074	1934	1933	1872	1871	1781	1074	1037	1037	997
2039	405	420	4229	1074	1935	1935	1873	1871	1781	1074	1037	1036	996
2040	405	420	4230	1074	1936	1936	1873	1872	1781	1074	1037	1036	996
2041	405	421	4231	1074	1937	1937	1874	1872	1782	1074	1036	1036	996
2042	405	421	4232	1074	1938	1938	1874	1873	1782	1074	1036	1036	996
2043	405	422	4232	1074	1939	1939	1875	1873	1782	1074	1036	1035	995
2044	405	422	4233	1074	1940	1940	1875	1874	1783	1074	1036	1035	995
2045	405	422	4233	1074	1941	1941	1876	1874	1783	1074	1036	1035	995
2046	405	423	4234	1074	1942	1942	1876	1874	1783	1074	1035	1035	995
2047	405	423	4235	1074	1943	1942	1876	1875	1784	1074	1035	1035	995
2048	405	423	4235	1075	1944	1943	1877	1875	1784	1074	1035	1034	995
2049	405	423	4236	1075	1944	1944	1877	1876	1784	1075	1035	1034	995
2050	405	424	4236	1075	1945	1945	1878	1876	1785	1075	1035	1034	994
2051	405	424	4237	1075	1946	1946	1878	1877	1785	1075	1035	1034	994
2052	405	425	4237	1075	1947	1947	1879	1877	1785	1075	1035	1034	994
2053	405	425	4238	1075	1948	1947	1879	1877	1786	1075	1035	1034	994
2054	405	426	4238	1075	1948	1948	1879	1878	1786	1075	1035	1034	994
2055	405	426	4239	1075	1949	1949	1880	1878	1786	1075	1035	1034	994
2056	405	427	4239	1076	1950	1949	1880	1878	1787	1075	1034	1034	994
2057	405	427	4240	1076	1950	1950	1881	1879	1787	1076	1034	1034	994
2058	405	427	4240	1076	1951	1951	1881	1879	1787	1076	1034	1034	994
2059	405	428	4241	1076	1952	1951	1881	1879	1787	1076	1034	1034	994
2060	405	428	4241	1076	1952	1952	1882	1880	1788	1076	1034	1034	994
2061	405	429	4242	1076	1953	1953	1882	1880	1788	1076	1034	1033	994
2062	405	430	4242	1076	1954	1953	1882	1880	1788	1076	1034	1033	994
2063	405	430	4243	1077	1954	1954	1883	1881	1788	1076	1034	1033	994
2064	405	431	4243	1077	1955	1954	1883	1881	1789	1076	1034	1033	994
2065	405	431	4243	1077	1955	1955	1883	1881	1789	1077	1034	1033	994
2066	405	432	4244	1077	1956	1955	1884	1882	1789	1077	1034	1033	994
2067	405	432	4244	1077	1956	1956	1884	1882	1789	1077	1034	1033	994
2068	405	433	4245	1077	1957	1957	1884	1882	1790	1077	1034	1033	994
2069	405	433	4245	1077	1957	1957	1885	1882	1790	1077	1034	1033	994
2070	405	433	4245	1077	1958	1957	1885	1883	1790	1077	1034	1033	994
2071	405	435	4246	1078	1958	1958	1885	1883	1790	1077	1034	1033	994
2072	405	435	4246	1078	1959	1958	1885	1883	1791	1077	1034	1033	994
2073	405	436	4246	1078	1959	1959	1886	1884	1791	1078	1034	1034	994
2074	405	437	4247	1078	1960	1959	1886	1884	1791	1078	1034	1034	994
2075	405	437	4247	1078	1960	1960	1886	1884	1791	1078	1034	1034	994
2076	405	438	4247	1078	1961	1960	1887	1884	1791	1078	1034	1034	994
2077	405	438	4248	1078	1961	1961	1887	1885	1792	1078	1034	1034	994
2078	405	438	4248	1078	1961	1961	1887	1885	1792	1078	1034	1034	994
2079	405	439	4248	1079	1962	1961	1887	1885	1792	1078	1034	1034	994
2080	405	439	4249	1079	1962	1962	1888	1885	1792	1078	1034	1034	994
2081	405	440	4249	1079	1962	1962	1888	1885	1792	1078	1034	1034	994
2082	405	441	4249	1079	1963	1962	1888	1886	1793	1079	1034	1034	994
2083	405	442	4249	1079	1963	1963	1888	1886	1793	1079	1034	1034	994
2084	405	442	4250	1079	1964	1963	1889	1886	1793	1079	1034	1034	994
2085	405	442	4250	1079	1964	1963	1889	1886	1793	1079	1034	1034	994
2086	405	443	4250	1079	1964	1964	1889	1887	1793	1079	1034	1034	994
2087	405	443	4250	1079	1965	1964	1889	1887	1793	1079	1035	1034	994
2088	405	444	4251	1079	1965	1964	1889	1887	1794	1079	1035	1034	994
2089	405	444	4251	1080	1965	1965	1890	1887	1794	1079	1035	1034	994
2090	405	444	4251	1080	1965	1965	1890	1887	1794	1079	1035	1034	994
2091	405	445	4251	1080	1966	1965	1890	1888	1794	1079	1035	1034	994
2092	405	446	4252	1080	1966	1966	1890	1888	1794	1079	1035	1034	994
2093	405	447	4252	1080	1966	1966	1890	1888	1794	1080	1035	1034	994
2094	405	447	4252	1080	1967	1966	1891	1888	1794	1080	1035	1034	994
2095	405	448	4252	1080	1967	1966	1891	1888	1795	1080	1035	1034	994
2096	405	448	4252	1080	1967	1967	1891	1888	1795	1080	1035	1034	994
2097	405	448	4253	1080	1967	1967	1891	1889	1795	1080	1035	1034	994
2098	405	449	4253	1080	1968	1967	1891	1889	1795	1080	1035	1034	994
2099	405	449	4253	1080	1968	1967	1892	1889	1795	1080	1035	1034	994
2100	405	449	4253	1080	1968	1968	1892	1889	1795	1080	1035	1034	994
2101	405	450	4253	1081	1968	1968	1892	1889	1795	1080	1035	1034	994
2102	405	451	4254	1081	1969	1968	1892	1889	1796	1080	1035	1034	994
2103	405	452	4254	1081	1969	1968	1892	1890	1796	1080	1035	1034	994
2104	405	452	4254	1081	1969	1969	1892	1890	1796	1080	1035	1034	994
2105	405	452	4254	1081	1969	1969	1892	1890	1796	1080	1035	1034	994
2106	405	453	4254	1081	1970	1969	1893	1890	1796	1081	1035	1034	994
2107	405	453	4255	1081	1970	1969	1893	1890	1796	1081	1035	1034	994
2108	405	454	4255	1081	1970	1969	1893	1890	1796	1081	1035	1034	994
2109	405	454	4255	1081	1970	1970	1893	1890	1796	1081	1035	1034	994
2110	405	454	4255	1081	1970	1970	1893	1891	1797	1081	1035	1035	994
2111	405	455	4255	1081	1971	1970	1893	1891	1797	1081	1035	1035	994

Figure 8.6 Modelled Groundwater Flux Entering the River Murray for All Scenarios for the Hogwash to Morgan Reach

UNITS OF MEASUREMENT

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

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

Shortened forms

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

GLOSSARY

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

AWE — Australian Water Environments Pty Ltd

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

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

BIGMOD — MSM and BIGMOD are two computer based models that work together. Output from MSM (Monthly Simulation Model) feeds into BIGMOD (daily simulation model). The models route flow and salinity in the River Murray and associated storages. Models are used for water accounting, planning and flow and salinity forecasting. MSM-BIGMOD can simulate the operation of the River Murray system to investigate what would happen under a given set of conditions.

BoM — Bureau of Meteorology, Australia

Bore — See 'well'

BSMS — Basin Salinity Management Strategy developed by Murray-Darling Basin Authority

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

Decision support system — A system of logic or a set of rules derived from experts, to assist decision making. Typically they are constructed as computer programs

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

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

DES — Drillhole Enquiry System; a database of groundwater wells in South Australia, compiled by the South Australian Department of Water, Land and Biodiversity Conservation (DWLBC)

DFW — 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.

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

EC — Electrical hydraulic 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

Electrical resistivity — a measure of how strongly a material opposes the flow of an electric current.

Groundwater 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

Future irrigation development — Future irrigation development area and recharge (assuming recharge of 100 mm/y) resulting from activation of already allocated water that is assumed to occur after current year

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 hydraulic resistance, or high flow conditions; measured in metres per day

Hydraulic resistance — measure of how strongly a material opposes fluid flow. Lower hydraulic resistance indicates a greater ease of flow. It is saturated thickness divided by vertical conductivity of a sediment.

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

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

IAG-Salinity — Independent Audit Group for Salinity

Improved Irrigation Practices (IIP) — Commencing in the mid 1990s when flood irrigation via earth channels was replaced by sprinkler and drip irrigation systems, thus increasing irrigation efficiency (70% - 85%) and reducing recharge to the groundwater table

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

Irrigation mound — Elevated hydraulic heads under irrigation areas due to excessive irrigation drainage, increasing saline groundwater flux and salt load entering the River Murray

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

Lag time — Time (in years) taken for recharge to reach the water table. Lag time is affected by depth to water table and the presence and properties of aquitards.

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

MDBA — Murray–Darling Basin Authority

MDBC — Murray–Darling Basin Commission

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

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

NanoTEM — A geophysical method that measures the electrical resistivity of subsurface materials. Electrical resistivity is affected by the properties, porosity and saturation of the subsurface materials and water salinity.

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

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

Obswell — Observation Well Network

Penetrating well — See 'fully-penetrating well'

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.

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

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

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

PIRSA — Primary Industries and Resources 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

River kilometre — It is a measure of distance in kilometres along the River Murray from its mouth

Run of River (RoR) — Instream salinity surveys (when river flow conditions allow) that produce a kilometre-by-kilometre "snapshot" of salinity accessions along the length of the river

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, petroleum and groundwater is vested in PIRSA and DWLBC, respectively. DWLBC should be contacted for database extracts related to groundwater

Salt interception scheme (SIS) — a series of production wells that are designed to lower the hydraulic head gradient towards the River Murray, hence reducing saline groundwater flux and salt load entering the river

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

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

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

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

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

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

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

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

USGS — United States Geological Survey

Water table — The surface in an unconfined aquifer or confining bed at which the pore water pressure is atmospheric.

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

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