# Stage 1 Review of SIMRAT V2.0.1

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# Summary

**Background and scope of review**

The Salinity Impact Rapid Assessment Tool (SIMRAT) is one of a suite of tools developed for estimating salinity impacts of accountable actions to support Basin Salinity Management Strategy (BSMS) objectives. SIMRAT was developed for the Murray–Darling Basin Commission (MDBC) and accredited in 2005 to assess the salinity impacts of new irrigation. The model domain includes regions within 15 km of the discharge edge (within SA, the discharge edge is the edge of the floodplain based on the 1956 flood level; elsewhere it is considered to be the closest edge of the River Murray) stretching from Nyah in Victoria to the Goolwa barrages in SA (Figure 1.1). SIMRAT is used to fulfill requirements of BSMS Schedule B but its implementation differs across the three states.

In accordance with Schedule B of the Murray–Darling Basin Agreement, all models which support salinity impact assessments are required to undergo a review at intervals of no more than seven years. The Murray–Darling Basin Authority (MDBA) have contracted the South Australian Department of Environment, Water and Natural Resources to undertake this work on their behalf, which was overseen by an inter-jurisdictional steering committee with representatives from Victoria, New South Wales and South Australia. The review described in this report is considered Stage 1 of the project which was to:

- review the accredited SIMRAT documentation, including peer review reports to inform reviewers of the current status of the model
- review capabilities and limitations as pertaining to current use of the model
- conduct a literature review to determine the best practice to inform review recommendations
- investigate alternatives for the upgrade of the SIMRAT model platform through consultation with GIS experts within NSW and SA to inform the most appropriate model platform in which to rewrite the model (there is a need to consider updating the SIMRAT code as the language it is implemented in ESRI ArcGIS is no longer supported).

If the MDBA decides to proceed with Stage 2, it will implement key recommendations, including the update of the model code and associated Data Atlas.

**SIMRAT implementation**

SIMRAT was designed as a rapid assessment tool, aiming to "explain the maximum amount of change in river salinity impacts with the smallest set of variables" (Fuller *et al.,* 2005). It provides a consistent and deliberately simple approach across the lower River Murray which can be used in areas where there is a high uncertainty in the hydrogeological factors which influence groundwater salt flux to the river.

The SIMRAT process is divided into five stages, from application at the irrigation area to an estimate of its salinity impact at Morgan. Stage 1 determines (or specifies) the increased root zone drainage due to irrigation. Stage 2 estimates the resulting additional recharge to the watertable aquifer over time. Stage 3 estimates the groundwater flux and salt load to the discharge edge (i.e. to the floodplain or river). Stage 4 applies factors to account for varying levels of river connectivity and floodplain attenuation. Stage 5 converts the additional groundwater salt load to an EC impact at Morgan.

SIMRAT is implemented in two platforms, Microsoft Excel and ESRI ArcGIS, for different purposes. The Excel version of SIMRAT, SIMRAT-XL, is a point-based assessment tool which can be used for a quick assessment of a locale. The ArcGIS version of SIMRAT is a spatially-based model which utilises a concurrently-developed Data Atlas for spatially-varying parameters.

**SIMRAT uses**

SIMRAT model was originally designed to:

1. Assess the salinity impact of new irrigation developments within the Mallee region. Salinity impacts are recorded on Register A and are superseded by estimates from accredited groundwater models (within five years in SA and irregularly in NSW). This is the purpose for which the model has been accredited and the primary use of the model.

2. Assist in estimating the timelag between increased root zone drainage and recharge to the watertable in numerical groundwater models for both cleared land (SA, NSW and Vic) and irrigation areas (SA).
3. Guide the definition of the High Salinity Impact Zone Line for the South Australian River Murray Salinity Zoning Policy and is used to guide decision making for new irrigation developments, using a triage approach in NSW.
4. Assess revegetation options to reduce salt loads to the River Murray in SA (but it is no longer used for this).

While this review focusses on the accredited use of SIMRAT, i.e. the salinity impact assessment of new irrigation areas: (1), some comments are made regarding (2), the timelag for numerical models, due to its importance for Salinity Register entries.

**Review findings and recommendations**

SIMRAT continues to be fundamentally suitable for its primary purpose as a rapid assessment tool for salinity impacts of greenfield irrigation sites in the Mallee region. The equations and assumptions for Stages 1 to 3 are essentially sound *where the hydrogeology is relatively simple*. The assumptions are not met in some areas, which will reduce the accuracy. There are also some uncertainties to be addressed.

Many minor improvements to SIMRAT's methodology and datasets could be made to improve its accuracy and ensure appropriate use and interpretation of results. Fuller *et al.* (2005) made recommendations about the use and review of SIMRAT, principally that there is a 'need for strong hydrogeological input and review as part of model operation. *SIMRAT should not be treated as a "black box" model and run by users unfamiliar with the hydrogeological setting and information associated with trade sites'*. In practice, this has not proved feasible for a rapid assessment tool. Several of the recommendations below aim to reduce the need for day-to-day detailed hydrogeological oversight by incorporating more hydrogeological knowledge upfront, improving the methodology where possible and mapping where SIMRAT is likely to be less accurate and why.

Table ES-1 summarizes the review findings and provides recommendations in order of importance.

### Table ES-1 Key findings and recommendations (in order of importance)

| | Key findings | Recommendations / Considerations |
|---|---|---|
| 1 | The GIS version of SIMRAT currently operates on an ESRI ArcGIS platform that is no longer supported. Based on initial investigations it is considered that standard ArcGIS for Desktop v10.2.x is the most appropriate alternative platform, with Python considered the most efficient and appropriate programming language. | Rewrite SIMRAT in Python, for ArcGIS for Desktop v10.2.x, to ensure that SIMRAT can continue to be used. |
| 2 | SIMRAT equations and assumptions for Stage 2 are critical to the Salinity Register entries as they strongly influence the timing of salt impacts. There are considerable uncertainties about their calculation and parameters.<br>SIMRAT soil parameters are based on field studies of cleared but not irrigated land. Timelag estimates can be extremely sensitive to the parameters. | Test and review the timelag/recharge algorithm in further detail. A more extensive review should involve:<br>a) Compare SIMRAT timelag estimates against hydrographs of observation wells. For mallee clearance, compile hydrographs of wells at cleared sites, distant from irrigation areas, then compare with timelag estimates from SIMRAT. For irrigated areas, compile hydrographs within more recently-developed areas (i.e. greenfield sites). This would be useful in benchmarking SIMRAT outputs against actual conditions seen in the Mallee region.<br>b) Consult with soil science experts to confirm the need for a review of algorithms and parameters, particularly in the context of SIMRAT as a rapid assessment tool. Conduct further research, including field studies and numerical modelling, to compare SIMRAT estimates for a number of sites and conditions<br>c) Consider whether there is a need for a drying algorithm and investigate whether there is a method that would be useful, given the lack of data available on irrigation history for most sites. |

| | Key findings | Recommendations / Considerations |
|---|---|---|
| | | In the interim, SIMRAT's timelag algorithm remains the best available for a rapid assessment tool and should be retained. |
| 3 | The Data Atlases could be improved and updated, substantially improving SIMRAT's accuracy. They contain minimal detail on how the layers were developed.<br>If a state is not using a particular data layer, there is no need to update it in that area. | Update the Data Atlases. A draft has been completed for SA however an update of the clay thickness layer, as recommended in Section 4 would also be useful. Where available, the data layers could be based on information already incorporated into numerical models.<br>If a state is not using a particular data layer, there is no need to update it in that area.<br>The updated data layers should be reviewed by expert hydrogeologists, and the accompanying documentation revised to include greater detail about the sources and values of the data used to compile the data layers. |
| 4 | Currently, the SIMRAT model contains no indication of the accuracy or reliability of the result at a given location. | Develop new data layers which indicate:<br>overall confidence in the use of the model at that location<br>a) whether the SIMRAT assumptions are reasonable for that location<br>b) whether a different form of the Unit Response Equation (URE) would be more accurate<br>c) whether SIMRAT assumptions are not appropriate and the results are liable to have a large error.<br>d) Some areas may need to be masked. |
| 5 | SIMRAT is currently used in SA to assist in estimating the timelag between increased root zone drainage and recharge in numerical groundwater models for irrigation areas. This timelag estimation is based on 125 mm/y root zone drainage, regardless of whether this is the root zone drainage rate applied. | Run SIMRAT with a variety of historical root zone drainage rates to inform historical timelags. These would provide a better starting point for the initial timelags used in numerical models. |
| 6 | SIMRAT equations and assumptions for Stage 3 are essentially sound where the hydrogeology is relatively simple. The assumptions are not met in some areas which would reduce the accuracy. | Consider including alternate forms of the URE in SIMRAT when the code is rewritten. While this is likely to make only modest improvements in accuracy compared to an updated Data Atlas, initial investigations suggest that this would not require much additional work, however this should be confirmed during Stage 2. The following should be considered:<br>• The URE variations provided in Rassam *et al.* (2004)<br>• A leaky aquifer solution, if possible, based on Strack (2014)<br>• A spatial distribution curve for discharge along the discharge edge, replacing the current 1D assumption of discharge to a point, which does not account for changes in groundwater salinity along the discharge edge. Rassam *et al.* (2004). |
| 7 | A full hydraulic connection between the aquifer and river is assumed for all current uses of SIMRAT in SA and NSW. Therefore the Data Atlas river connectivity layer is not currently used. | The jurisdictions should confer on the aim and definition of the River Connectivity data layer. A consistent methodology should be developed and implemented, or, if the layer is agreed to have no purpose, it should be omitted. |
| 8 | For all current uses of SIMRAT, it is assumed that the additional salt, mobilised by human actions from the regional aquifers into the floodplain, is transported immediately to the River Murray. Therefore the Data Atlas floodplain attenuation layer is not currently used. | The jurisdictions should confer on the aim and definition of the Floodplain Attenuation data layer. A consistent methodology should be developed and implemented, or, if the layer is agreed to have no purpose, it should be omitted. |

| | Key findings | Recommendations / Considerations |
|---|---|---|
| 9 | SIMRAT estimates of salt load impacts at the river are converted to EC impacts at Morgan and costs to downstream users, using Ready Reckoner values that differ from those in the BSMS Operational Protocols. | Although SIMRAT Stage 5 has relatively limited applications, primarily to provide an indication within the jurisdictions of likely EC implications for State Salinity Register balances, the relevant data layers and lookup tables should be updated to reflect the values given in the BSMS Operational Protocols for consistency. |
| 10 | Jurisdictions expressed interest in sensitivity analyses of the results. | It would be possible to undertake a sensitivity analysis for each assessment. This would require the development of additional data layers to give the minimum and maximum value for each parameter to be tested, such as root zone drainage or diffusivity. This should only be implemented if the usefulness of this output is judged commensurate with the effort required to develop it. |

Table ES-2 summarizes items which are not recommendations for SIMRAT, but are considerations for the MDBA and jurisdictions raised by this review of SIMRAT. They concern the lack of consistency across jurisdictions in applying rapid assessment tools for irrigation Salinity Register entries.

**Table ES-2 Other considerations for MDBA**

| | Key findings | Recommendations / Considerations |
|---|---|---|
| 1 | The states adopt different approaches to timelag for irrigation areas. SA applies a timelag to mallee clearance and irrigation, while NSW and Vic apply timelag to mallee clearance impacts but not irrigation impacts. | It may be entirely appropriate to assume zero timelag where irrigation occurs in areas of shallow watertables or complicated land use history. A literature review and compilation of hydrograph and irrigation site histories would assist in confirming whether zero timelag is appropriate for all irrigation areas. |
| 2 | The states adopt different approaches to calculating discharge. | As there is a lack of consistency between jurisdictions, it is recommended that the MDBA consider a study comparing the different methods for estimation of salinity impacts for Register entries based on rapid assessment approaches. |
| 3 | There is no agreed and accurate methodology for assigning the root zone drainage rate for new irrigation areas. Assumption of 100 mm/y root zone drainage (RZD) for new irrigation areas is consistent between SA and NSW, and is consistent with SA Salinity Register models. Vic calculates the RZD based on crop type. | Consistency regarding RZD assumptions across states should be reviewed by the MDBA. Reasonable ranges of RZD could be determined through field studies at greenfield sites and numerical modeling. In the interim, the assumption of 100 mm/y RZD should be retained for SIMRAT's Salinity Register calculations for SA and NSW. |

# 1 Introduction

## 1.1 Background of project

Salinity levels are a significant issue in the lower River Murray due to inflows of naturally saline groundwater (Brown, 1989, Evans & Kellet, 1989, Herczeg *et al.*, 2001). Due to the geological structure of the Murray–Darling Basin (MDB), the River Murray acts as a drain for salt out of the landscape. Agricultural practices can mobilise additional salt from groundwater to the River Murray. This affects the water quality of the River Murray for all users.

Due to its ecological and economic impacts, federal and state initiatives have been developed to manage River Murray salinity. The Basin Salinity Management Strategy (BSMS) is implemented under Schedule B of the Murray–Darling Basin Agreement to monitor and manage salt loads in all tributary rivers of the Murray–Darling Basin (MDBA, 2001). Salinity Registers record and report on all salinity debits (actions that potentially increase salinity impacts such as irrigation practices) and salinity credits (actions that mitigate salinity impacts, such as Salt Interception Schemes (SIS)). State governments (SA, Vic and NSW) have an obligation under Schedule B of the Murray–Darling Basin Agreement to maintain a positive balance on the Salinity Registers (Clause 17, Schedule B, *Water Act, 2007* (Cth)).

The Salinity Impact Rapid Assessment Tool (SIMRAT) is one of a suite of tools developed for estimating salinity impacts of accountable actions to support BSMS objectives. SIMRAT was developed for the Murray–Darling Basin Commission (MDBC) and accredited in 2005. The model domain includes regions within 15 km of the discharge edge (which can represent edge of floodplain or edge of river) stretching from Nyah in Vic to the Goolwa barrages in SA (Figure 1.1). SIMRAT is used to fulfill requirements of Schedule B but its implementation differs across the three states. The current uses of the SIMRAT model are to:

1. Assess the salinity impact of new irrigation developments within the Mallee region. Salinity impacts are recorded on Register A and are superseded by estimates from accredited groundwater models (within five years in SA and irregularly in NSW)
2. Assist in estimating the timelag between increased root zone drainage and recharge in numerical groundwater models for both cleared land (SA, NSW and Vic) and irrigation areas (SA)
3. Guide the definition of the High Salinity Impact Zone Line for the South Australian River Murray Salinity Zoning Policy and is used to guide decision making for new irrigation developments, using a triage approach in NSW
4. Assessment of revegetation options to reduce salt loads to the River Murray (SA).

Details on these uses are provided in Chapter 6. While the focus of this review is upon the accredited use of the model (Item 1 in list above) commentary will also be provided on the use of SIMRAT for timelag estimations and to delineate a high impact zone line.

In accordance with Schedule B of the Murray–Darling Basin Agreement, all models which support salinity impact assessments are required to undergo a review at intervals of no more than seven years. The need for this project was raised at the Basin Salinity Management Advisory Panel Meeting #14 (2 October 2012) as the model was due for review in 2012. The Murray–Darling Basin Authority (MDBA) contracted the South Australian Department of Environment, Water and Natural Resources (DEWNR) to undertake this work on their behalf.

Traditionally the review and update of a model accredited for the purpose of Schedule B would be undertaken as one project. However, due to budget constraints, the review and update of the SIMRAT model has been conducted in two stages:

1. Review the model (this project)
2. Update and reaccredit the model (timing and funding to be confirmed pending MDBA budget).

This project will coordinate the first stage review of SIMRAT which will result in recommendations to the MDBA regarding the updates required in SIMRAT for accreditation. These updates will be undertaken in the second stage of the model review to be completed by the MDBA. The project is overseen by a steering committee and technical exports have been engaged where appropriate.

## 1.2 Scope of review

The review described in this report is considered Stage 1 of the project. The scope of Stage 1 is to:

- review the accredited SIMRAT documentation, including peer review reports to inform reviewers of the current status of the model
- review capabilities and limitations as pertaining to current use of the model
- conduct a literature review to determine the best practice to inform review recommendations
- investigate alternatives for the upgrade of the SIMRAT model platform through consultation with GIS experts within NSW and SA to inform the most appropriate model platform in which to rewrite the model.

There is a need to consider updating the SIMRAT code as the language it is implemented in ArcGIS is no longer supported.

**Exclusions**

Stage 1 of the project does not:

- update the model code
- update the data layers
- include the MDBA independent review of the SIMRAT model review report, as required by Schedule B. This will occur during Stage 2 of the project, when the updated model is developed.

**Dependencies**

- This project has built on the previous work by South Australia in 2013–14 to review the South Australian SIMRAT data sets.

Stage 2 is currently proposed, and will focus on updating the SIMRAT model code and updating the GIS model platform.

## 1.3 Documents reviewed

The key resources for this review include those reports written on the development and review of SIMRAT. For the purposes of this review, the following documents were included:

**Documentation for the SIMRAT model version 2.0.1, as included on the SIMRAT CD-ROM in the following order**

Fuller, D, Watkins, N, Woods, J, Hoxley, G, Miles, M (2005) *SIMRAT V2.0.1 Summary Report*, report prepared for the Murray–Darling Basin Commission, May 2005

Fuller, D, Fargher, J, Watkins, N, Miles, M & Collett, K (2005) *SIMRAT V2.0.1 Administrative Arrangements*, report prepared for the Murray–Darling Basin Commission, May 2005

Fuller, D, Watkins, N, Woods, J, Miles, M, Hoxley, G (2005) *SIMRAT V2.0.1 Model Conceptualisation*, report prepared for the Murray–Darling Basin Commission, May 2005

Watkins, N, Woods, J, Miles, M, Hoxley, G & Fuller, D (2005) *SIMRAT V2.0.1 Model Case Studies and the Bookpurnong Test*, report prepared for the Murray–Darling Basin Commission, May 2005

Rassam, D, Walker, G & Knight, J (2004) *Applicability of the Unit Response Equation to assess salinity impacts of irrigation development in the Mallee region,* CSIRO Land and Water Technical Report No. 35/04, October 2004

Miles, M & Vears, L (2005) *SIMRAT V2.0.1 Software User Manual*, report prepared for the Murray–Darling Basin Commission, May 2005

Fuller, D, Watkins, N, Miles, M & Hoxley, G (2005) *SIMRAT V2.0.1 Data Report and Atlas*, report prepared for the Murray–Darling Basin Commission, May 2005

**Other reports reviewed**

Aquaterra Simulations (2005) *SIMRAT model review final report (version C)*, report prepared for the Water Trade Salinity Impact Evaluation Panel, Murray–Darling Basin Commission, May 2005

Department for Water (2011), *South Australia's 2010-2011 Report to the Basin Salinity Management Strategy*, Government of South Australia

Fargher, J, Fuller, D, Watkins, N, Miles, M & Collet, K (2003) *Tools for assessing salinity impacts of interstate water trade in the Southern Murray–Darling Basin*, stage 1B final report, October 2003

Kirk, JA, Cole, PJ, Miles, MW & Burrows, DM (2004) *South Australian Salinity Accountability 1988 – 2003*, Department of Water, Land, Biodiversity Conservation Report, DWLBC 2004/30, Adelaide, August 2004

Middlemis, H (2013) *Mallee Salinity Workshop May 30 2012: Chapter 7 – key tools (strengths and weaknesses)*, report prepared for Mallee Catchment Management Authority, April 2013

Miles, M (2005) *GIS Methodology Report: How SIMPACT 2 was used to create the River Murray Salinity Impact Zone line*, report prepared for the Department of Environment and Heritage, June 2005

Miles, M & Kirk, J (2005) *Applications of the SIMRAT Model for Salinity Management in the Lower Murray–Darling*, extended abstract from MODSIM 2005 conference, 2005

Murray–Darling Basin Commission (2005) *Basin Salinity Management Strategy Operation Protocols*, version 2.0, March 2005

Sinclair Knight Merz (2004*) SIMRAT irrigation impact model – reality check case study descriptions for Victoria and New South Wales*, final report, February 2004

Watkins, N, Miles, M & Fuller, D (2004) *SIMRAT model development – results from salinity check for South Australia,* final report, January 2004

## 1.4 Structure of this report

This report is structured to provide clarity on the processes involved in SIMRAT, as well as outlining the assumptions and limitations at each stage of the SIMRAT process. Section 2 discusses the purpose, history and basic structure of SIMRAT. Sections 3 to 4 provide a detailed discussion of the respective stages of SIMRAT, describing the equations, parameters and assumptions at each stage, providing sensitivity analyses where applicable. Section 6 discusses how SIMRAT is presently used by the three states (SA, Vic and NSW).

Section 5 discusses options for the GIS update. Section 7 summarises the capabilities and limitations of SIMRAT. Section 8 provides recommendations regarding model design, parameters and use.

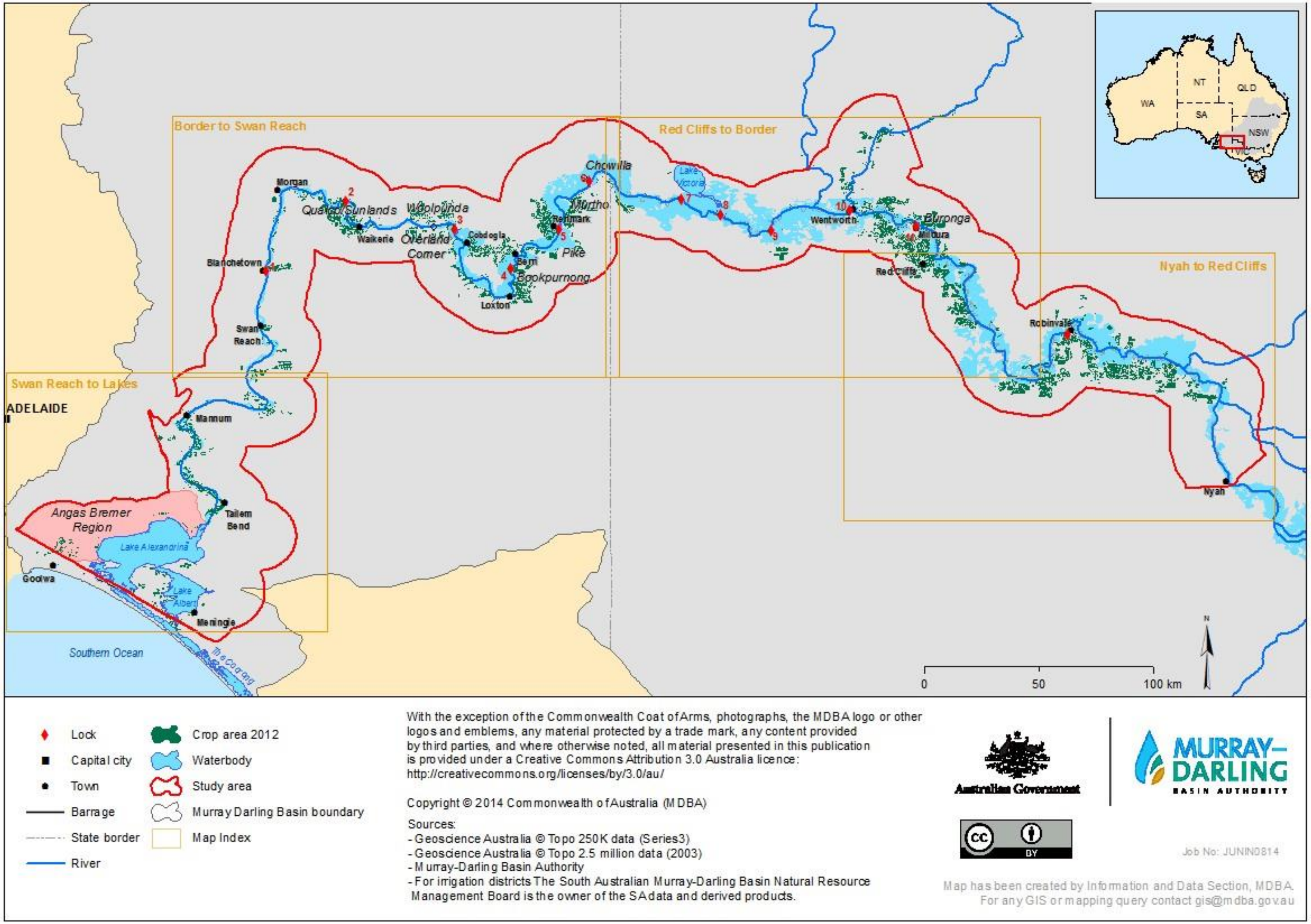


**Figure 1.1 SIMRAT model domain**

# 2 SIMRAT overview

## 2.1 Purpose and scope of SIMRAT

The primary purpose of SIMRAT is to provide initial estimates of increases in salt load from groundwater to the River Murray arising from the development of new irrigation as a result of the trading of irrigation water. Both South Australia and New South Wales have provided estimates of impacts to allow the MDBA to adjust the Salinity Registers established under Schedule B of the Murray–Darling Basin Agreement. The salt load impact is calculated over a period of the next 100 years. These estimates have been recorded on Salinity Register A and are superseded by estimates from accredited numerical groundwater models (within five years for South Australian entries and irregularly for New South Wales entries).

SIMRAT is one of a variety of tools which have been developed to provide salt load estimates for the Salinity Registers. Different approaches require different levels of investment and provide different levels of accuracy. SIMRAT is designed as a rapid assessment tool, aiming to “explain the maximum amount of change in River salinity impacts with the smallest set of variables" (Fuller *et al.,* 2005). It provides a consistent and deliberately simple approach across the lower River Murray which that can be used in areas where there is a high uncertainty in the hydrogeological factors which influence groundwater salt flux to the river. As the uncertainty in model inputs and outputs is usually high, a rapid assessment approach is not recommended where precision is required.

SIMRAT is accredited by the MDBA for assessing salinity debits due to water trades to greenfield irrigation sites within the Pilot Interstate Water Trading area (i.e. Mallee region of Vic, NSW, SA). SIMRAT’s hydrogeological assumptions are treated as valid over an area following the River Murray from Nyah in Victoria to the Goolwa barrages in SA, within 15 km of the discharge edge. The discharge edge is considered the sink for groundwater, i.e. the location at which groundwater accessions driven by irrigation activity arrive. Within South Australia, the discharge edge is considered to be the outer edge of the floodplain based on the 1956 flood level. East of Chowilla, the discharge edge is considered to be the closest bank of the River Murray. SIMRAT includes a masking layer that outlines areas where the model is not recommended for use. This includes the Angas Bremer region, areas within 100 m of the floodplain in South Australia, and areas within 1000 m of the river in New South Wales and Victoria.

Early in its development, it was planned that SIMRAT would also be used for assessing salinity credits for cases where cessation of irrigation led to reduced recharge. However, this use would have required detailed information on irrigation history, which is rarely available, so the model is not used for this purpose and is not accredited for assessing salinity credits.

SIMRAT is also used for other, related purposes, described in Section 6. In SA and NSW, it is used to guide mapping of areas of high salinity impact for irrigation. Its Stage 2 algorithm (for estimating the timelag between increased drainage and aquifer recharge; see Section 4) is used as an input to derive the Mallee clearance scenarios used in numerical models for the Salinity Register in all three states, and in irrigation scenarios in SA.

## 2.2 History of SIMRAT development

Figure 2.1 illustrates the evolution of rapid assessment tools for assessing salinity impacts on the River Murray and provides a brief summary of models that were developed between 1999 and 2005. In 1995 the Murray–Darling Basin Ministerial Council agreed to a Cap (upper limit) on surface water diversions in response to a decline in river health. The Cap is managed under Schedule E of the Murray–Darling Basin Agreement and directs that new irrigation developments can only occur through trade of water entitlements unless owners have access to existing unused allocations.

In November 1997 the Ministerial Council approved a Pilot Interstate Water Trading Project in the Mallee region, incorporating areas of NSW, Vic and SA from Nyah in Vic to the barrages at the mouth of the River Murray in SA. The project aimed to facilitate improved effectiveness and productivity of consumptive water use by encouraging the transfer of water allocations from current irrigation activities to higher value irrigation developments (Fuller *et al*., 2005a).

In 1999 Planning SA (PSA) led a pilot study in South Australia’s Riverland region, using GIS to develop a spatial tool to assess salt load impacts from new irrigation developments focusing on the reach of river between Renmark and Overland Corner (Miles and Kirk, 1999). This GIS-based model quantified salinity impacts of potential irrigation developments by using pre-determined type curves representing salt load to the river under specific sets of conditions (Watkins and Waclawik, 1996). The type curves were based on MODFLOW model simulations, with results scaled for 25 ha of irrigation at 125 mm/y root zone drainage for 500 m distances from the floodplain up to 5 km away. The model proved a successful first attempt at utilizing GIS to determine potential salt loads in a spatial manner.

In 2001, the former South Australian Department for Environment and Heritage (DEH) in conjunction with the former South Australian Department of Water, Land and Biodiversity Conservation (DWLBC) expanded on pilot study concepts to develop an improved GIS-based salinity impact tool known as SIMPACT I (Miles *et al.*, 2001). SIMPACT I supported the development of salinity zoning policy in SA, with the purpose of providing a river-wide perspective on where irrigation development will have higher and lower impacts. The SIMPACT I model domain included highland areas within 15 km of the floodplain from the SA border to the Goolwa barrages. Like the pilot study, SIMPACT I adopted the Watkins and Waclawik (1999) method of calculating timelag and salt loads, assuming root zone drainage rates of 125 mm/y.

In 2002 DEH in conjunction with DWLBC sought to improve the mathematical foundation of zoning salinity impact in SA, developing the SIMPACT II model. The SIMPACT II model built upon SIMPACT I to improve flexibility in input data, refine the resolution of the model and incorporate more robust mathematical equations. A more detailed algorithm for movement of water through the unsaturated zone was adopted to improve timelag estimation based on Cook (1992), and an analytical approach known as Unit Response Equation (URE) of Knight *et al.* (2002) was implemented for calculation of horizontal groundwater discharge (Miles & Kirk, 2005).

Around the same time as SIMPACT was being developed, an interim Rapid Assessment Tool (iRAT) was under development for the MDBC. The iRAT model was developed in Microsoft Excel and was capable of point-based assessment of river salinity impacts from trade in water entitlements (URS & AWE, 2002). This analytical tool was developed to meet the need for a rapid, consistent but interim tool to support policy makers and water resource regulators as they assess applications for water trade within the Pilot Interstate Water Trading area. Hydrogeological data was implemented in the form of lookup tables referenced by river reach (river km) and distance from river. The Watkins and Waclawik (1999) type curves for estimation of timelag were adopted. Groundwater discharge to the river/floodplain was calculated using the Unit Response Equation (Knight *et al.*, 2002).

In late 2002, the MDBC investigated opportunities to consolidate and improve rapid assessment tools to include assessment capabilities across SA, NSW and Vic. An inter-jurisdictional project steering committee oversaw the development of the Salinity Impact Rapid Assessment Tool (SIMRAT). SIMRAT is the integration of a GIS-based model and an Excel-based model. The GIS-based model is essentially an expansion of the SIMPACT II model domain into NSW and Vic and includes more sophisticated calculations developed by Cook *et al.* (2004) for timelag, based on two soil types and a wetting function to describe a distribution of recharge to the watertable. A Data Atlas provides spatially-variable parameters. The Excel version (SIMRAT-XL) allows the user to enter hydrogeological parameters explicitly. SIMRAT contains conversion values from the MSM-BIGMOD (the MDBA river flow model for the entire Murray–Darling system) through a Ready Reckoner to convert groundwater salt loads to EC impacts at Morgan.

The SIMRAT model was reviewed by Aquaterra (Aquaterra, 2003) and was regarded as largely fit for purpose with respect to Schedule B of Murray–Darling Basin Agreement. The SIMRAT model underwent significant testing in case study areas to give further confidence in model results (SKM, 2004; URS *et al.*, 2005). In June 2004 the MDBC approved the model as fit for purpose, and SIMRAT was accredited under Schedule C Clause 38(5) of the Murray–Darling Basin Agreement (Fuller *et al.*, 2005b). A final review report included comments on the additional testing (Aquaterra, 2005).

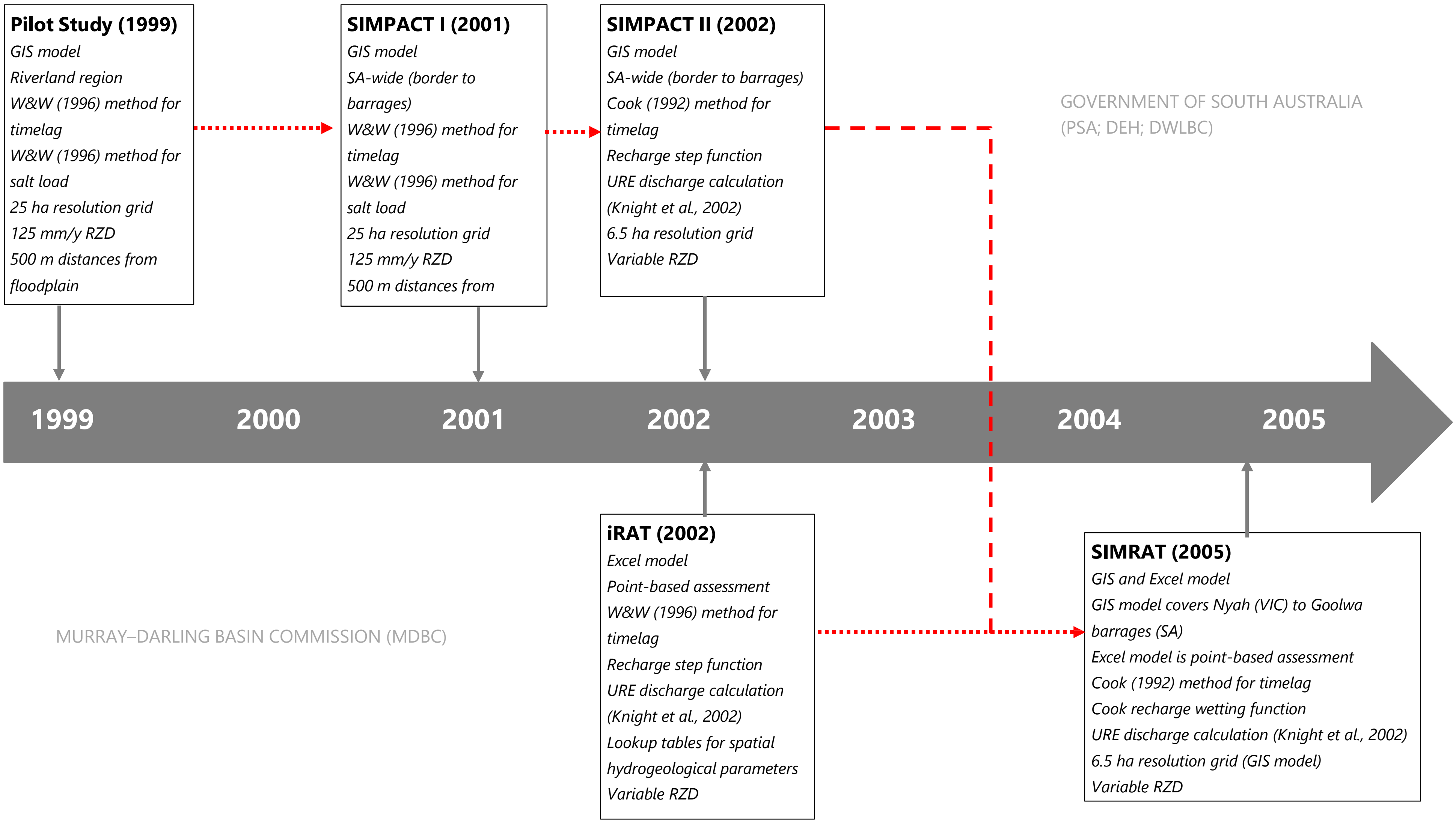


**Figure 2.1 SIMRAT model development**

## 2.3 The five stages

The SIMRAT process is divided into five stages, from application of water at the irrigation area to an estimate of its salinity impact at Morgan. Stage 1 determines (or specifies) the increased root zone drainage due to irrigation. Stage 2 estimates the resulting additional recharge to the watertable aquifer over time. Stage 3 estimates the groundwater flux and salt load to the discharge edge (i.e. to the floodplain or river). Stage 4 applies factors to account for varying levels of river connectivity and floodplain attenuation. Stage 5 converts the additional groundwater salt load to an EC impact at Morgan.

Figure 2.2 superimposes the simpler SIMRAT conceptualization over a more complex conceptual model of a typical site in South Australia. Irrigation occurs at the land surface, leading to root zone drainage (Stage 1). Drainage passes through the unsaturated zone of the Woorinen Sands (Stage 2), perching above the Blanchetown Clay in some areas, passing through drainage bores where they exist, or passing as unimpeded vertical flow to the watertable. Increased recharge to the watertable increases discharge of groundwater and salt from the Loxton Parilla Sands aquifer to the floodplain (Stage 3). Not all of the discharge to the floodplain is received by the river (Stage 4).

**Stage 1: Application to root zone drainage**

SIMRAT can calculate the proportion of the application volume that drains past the root zone, however in all current uses of SIMRAT the root zone drainage rate is specified by the user instead. Section 3 provides a detailed discussion of the assumptions and parameters.

**Stage 2: Root zone drainage to recharge**

Analytical equations for 1D vertical flow are used to calculate the mean timelag for drainage water passing the root zone through unsaturated layers of sandy loam and clay to recharge the watertable (the recharge step function). It is assumed that the site is initially Mallee vegetation which is cleared and/or irrigated, increasing the root zone drainage and wetting the unsaturated zone below the site. The time delay, or timelag, between drainage passing the root zone and recharge to the watertable is dependent on the properties of the soil types, depth to the watertable, and the root zone drainage rate.

However, recharge rates have been observed to be highly variable over small areas due to small-scale spatial heterogeneity in soil properties (Fuller *et al.,* 2005; Cook *et al.,* 1989). Recharge at some point locations will arrive earlier than recharge from others. The total recharge under an irrigation area is therefore unlikely to follow a sharp step function, and instead will follow a curve. SIMRAT applies a log-normal distribution based on Cook *et al.,* (1989). The plot of the resulting recharge wetting function has an S-like (sigmoidal) curve.

SIMRAT also includes an option for drying conditions, where an irrigation area ceases operation so root zone drainage drops. The equations are based on Sisson *et al.* (1980). Use of this option requires knowledge of the root zone drainage rates before and after the cessation of irrigation. As this information is rarely available for specific sites, SIMRAT is explicitly not accredited for this use for the Salinity Registers, nor is this algorithm currently used by SA, NSW or Vic for any other purpose. As it is not being used, this option is not discussed further in this review.

Section 4 discusses the unsaturated zone model including the analytical equations, parameters, implementation and sensitivity analysis.

**Stage 3: Recharge to impact at the discharge edge**

Stage 3 estimates the additional groundwater fluxes and salt reaching the River Murray or its floodplain due to the increased drainage. A 1D horizontal flow equation for the saturated zone, the Unit Response Equation (URE), provides a groundwater discharge response for a unit recharge based on the distance from the location of recharge to the discharge edge and the properties of the aquifer. All of the estimated groundwater flux is assumed to discharge at the closest point on the discharge edge. The URE flux is multiplied by the recharge rate to obtain the discharge over time. The discharge over time is multiplied by a groundwater salinity value to estimate the salt load impact.

Section 2 describes the saturated zone model including the analytical equations, parameters, implementation and sensitivity analysis.

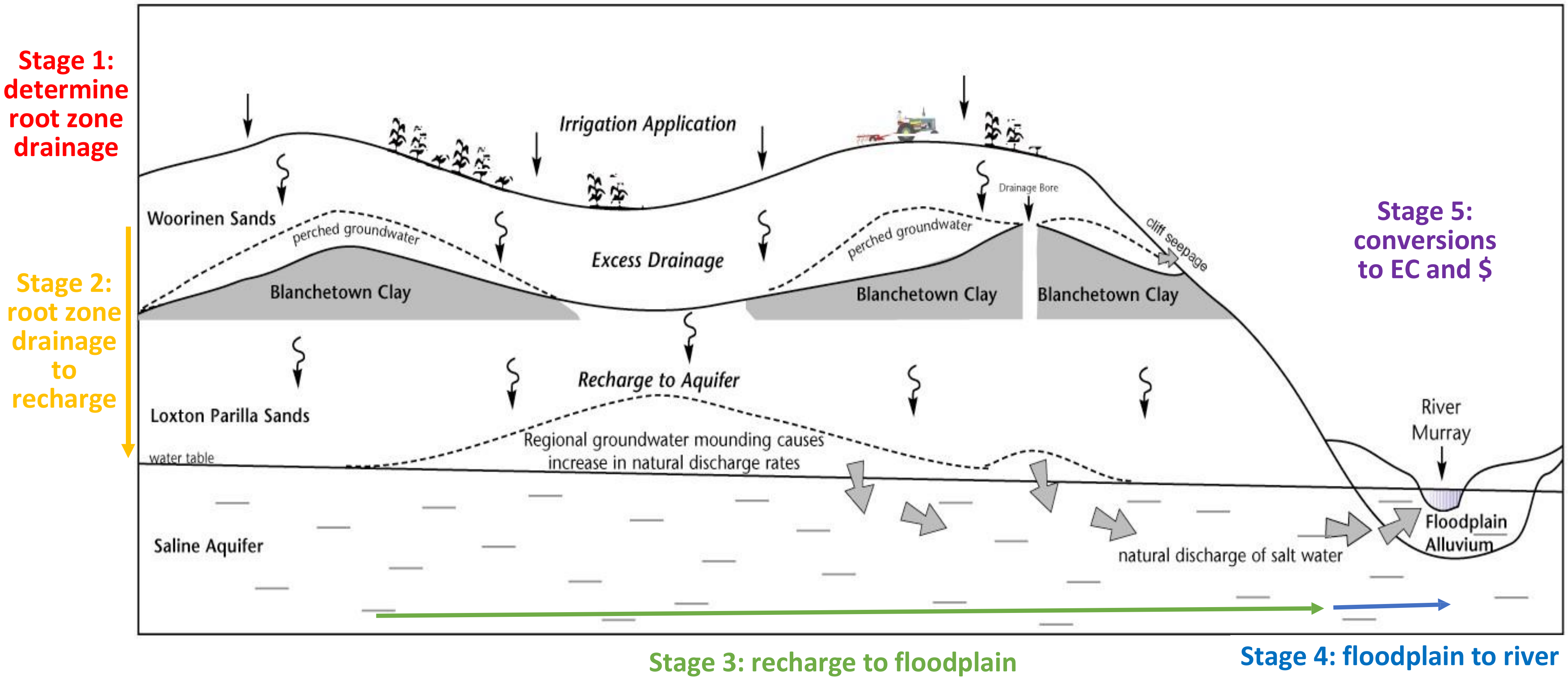


**Figure 2.2** **Conceptualisation with SIMRAT stages superimposed (modified from Fuller *et al.* 2005 & AWE 1999)**

**Stage 4: River connectivity and floodplain attenuation**

Stage 4 accounts for the possibility that not all the additional groundwater flux to the discharge edge becomes groundwater flow into the River Murray. A river connectivity factor can be applied if the regional aquifer is partially hydraulically separated from the river, e.g. by a clay layer, which occurs at locations in NSW and Victoria. Similarly, a floodplain attenuation factor can be applied to account for the amount of salt that remains in the floodplain and is not mobilized to the river.

Chapter 3 provides a more detailed description of the river connectivity and floodplain attenuation factors and their applicability.

**Stage 5: Conversion to assessment units**

A Ready Reckoner based on outputs from the MDBA's MSM-BIGMOD model can be used to convert salt load impacts from Stage 4 to EC impacts and economic costs ($) to downstream users.

Section 4 provides only a limited discussion of Stage 5 as this stage is considered out of the scope of this review.

## 2.4 Implementation

SIMRAT is implemented in two platforms, Microsoft Excel and ESRI ArcGIS, for different purposes:

1. The Excel version of SIMAT, SIMRAT-XL, is a point-based assessment tool. The user can manually specify all input parameters except the soil parameters. It can be used for a quick assessment of a locale, for example in cases where site-specific data are available which are not incorporated into the Data Atlas of the GIS version of SIMRAT. Also, it includes some variant equations for Stage 3 which are not included in the GIS version of SIMRAT. The variant equations cover special cases, for example where an irrigation area is close to a major bend in the River Murray. These variants can be used to test the applicability of SIMRAT algorithms at problematic locations.

2. The GIS version of SIMRAT is a spatially-based model. It utilizes a Data Atlas for spatially-varying parameters, except soil parameters (Fuller *et al*., 2005d). The Data Atlas was developed concurrently with SIMRAT, based on available data and expert knowledge. It was recommended that the Data Atlas "shall be updated as new data became available, and should be substantially reviewed at least every five years" (Fuller *et al*., 2005b). DEWNR recently undertook an internal review and update of SIMRAT data layers such as depth to groundwater, aquifer diffusivity and groundwater salinity (Peat & Yan, 2013).

# 3 Stage 1: Application to root zone drainage

This stage calculates the proportion of the rainfall and irrigation application volume that drains past the root zone.

## 3.1 SIMRAT assumptions and parameters

Root zone drainage (RZD) describes the rate at which drainage water moves past the root zone. SIMRAT estimates the salinity impact of an increase in RZD at a specified site. The site RZD is assumed to be constant over the next 100 years. SIMRAT allows for two possibilities: (i) the RZD is calculated from the irrigation volume, irrigation area, rainfall, and an irrigation efficiency constant, or (ii) the RZD is specified by the user.

If the RZD is not specified by the user, SIMRAT calculates it as follows:

$$RZD = \left(\frac{V_{irr}}{A_{irr}} + R\right) * \left(\frac{Perc}{100}\right)$$

where *RZD* is root zone drainage [L/T], $V_{irr}$ is the application volume (also referred to as the trade volume) [$L^3/T$], $A_{irr}$ is the area irrigated [$L^2$], *R* is effective rainfall [L/T] and *Perc* is the percentage of drainage which percolates past the root zone (i.e. it is the irrigation efficiency constant) [-]. Hence *RZD* is a set percentage of the sum of irrigation application and effective rainfall (Fuller *et al.,* 2005c). In SIMRAT-XL, the volume, area of application and rainfall are supplied by the user. In the GIS version of SIMRAT, the volume and area of application are supplied by the user and a spatial rainfall data layer can be obtained from the Data Atlas. The Data Atlas rainfall layer is based on annual average rainfall data sourced from rainfall station records between 1961 and 1991, supplied by the Bureau of Meteorology (Fuller *et al*., 2005d).

In all current applications of SIMRAT, the RZD is estimated outside the SIMRAT program and is specified by the user. Where SIMRAT is used to assess the salinity impact of new irrigation development (greenfield sites), the trade volume is known and the irrigation area is adjusted to meet application, including rainfall, of 10 ML/ha. Water use efficiency of 85% is assumed, and allowing for 5% losses this leaves 10% root zone drainage. The RZD is therefore assumed to be 100 mm/y for all future trade. This method is documented in the BSMS Operational Protocols (MDBC, 2005).

Root zone drainage of 120 mm/y is assumed for the calculation of the high salinity impact zone line for the South Australia River Murray Zoning Policy, based on a theoretical application, including rainfall, of 8 ML/ha and 15% root zone drainage (Miles, 2005). Maps of the timelags for a RZD of 120 mm/y are used as initial estimates for numerical groundwater models such as the SA Salinity Register models (e.g. Yan, Li & Woods, 2012; Woods *et al.* 2013).

The mallee clearance scenarios are based on SIMRAT calculations for which RZD is estimated outside SIMRAT using rainfall data and soil mapping (Wang *et al.,* 2005). SIMRAT calculations of recharge under cleared mallee are used as input to numerical groundwater models in SA, Vic and NSW.

## 3.2 Discussion

### 3.2.1 Impacts of new irrigation areas

Constant root zone drainage rates have been adopted for new irrigation applications of SIMRAT. This is necessarily a simplification. In actuality, RZD will vary spatially and temporally, depending on crop type, crop health, climate, soil type, depth to water and irrigation method. Where the watertable is close to the ground surface, net RZD may be lowered by evapotranspiration. Commonly, irrigators apply more water than is used by the plant to flush salts out of the root zone. Detailed models, such as LEACHM (Hutson & Wagenet, 1992) have been developed to estimate RZD for different conditions and times.

A comprehensive review of irrigation root zone drainage was conducted for the Mallee region in 2011 using agronomic methods

(CMC, 2011). This concluded that in 2005 the root zone drainage beneath irrigation areas within the Mallee ranged between

90 mm/y and 280 mm/y, with considerable variation between irrigation districts. RZD was estimated at between 15% and 30% of the applied water, which is based on irrigation plus effective rainfall (CMC, 2011).

Four possible approaches to specify RZD for new irrigation sites are:

1. Use a single, constant, specified value for all (current SIMRAT assumption)
2. Use RZD rates from CMC (2011) from the nearest irrigation area
3. Use a constant specified value that depends on the crop type (as used in Victoria)
4. Use a numerical model to estimate RZD over time.

Each of these methods has limitations. Using a constant value is simplistic. CMC (2011) RZD rates will depend on complicated site histories, including past and present irrigation practices, and are unlikely to be representative of a newly cleared site that has just commenced irrigation. Intended crop types for a new site may not be known. Numerical models require many inputs, few of which will be known for a site, and are not suitable as part of a rapid assessment tool; however, they could be used to determine the likely range of RZD, given current irrigation practices.

The adopted 10% RZD rate was the outcome of considerable discussion between the jurisdictional and technical stakeholders, and is an acknowledged assumption. The assumption of 100 mm/y provides a consistent value across the states for new irrigation areas. In the absence of a more rigorous methodology that can be consistently applied, we recommend that this assumption be retained for Salinity Register calculations.

### *Timelags for numerical models*

In the absence of other information, maps of timelags for 120 mm/y RZD have been used as initial inputs for numerical models. The numerical models use information on when an irrigation area commenced and add the timelag to estimate when recharge began below the irrigation site. This is applied both to simulations of historical conditions and to future scenarios. The assumption of 120 mm/y root zone drainage will underestimate root zone drainage beneath irrigation areas in earlier times, when less efficient irrigation methods were used. For example, in the 1960s root zone drainage beneath irrigation areas such as Buronga and Qualco–Sunlands may have been as high as 500 mm/y (CMC, 2011). The 120 mm/y RZD maps will over-estimate the initial timelag under the higher RZD conditions of past decades (see Sect. 4). It is stressed that in practice, the timelags for older irrigation areas are adjusted during numerical model calibration to match observations to hydrographs, so the use of the 120 mm/y timelag maps is unlikely to have led to inaccuracies in the models where observations are available. Rather, we recommend that timelag maps be developed for a range of RZD rates, so that the correct one can be used to match conditions for a specific decade’s irrigation practices.

# 4 Stage 2: Root zone drainage to recharge

Water that drains past the root zone passes through the unsaturated zone to reach the watertable and recharge the regional unconfined aquifer. In the Mallee region of the Murray–Darling Basin, it passes through a series of Quaternary and Tertiary hydrostratigraphic units of different properties to reach the watertable. Figure 4.1 shows typical stratigraphic columns from South Australia, showing both the regional sequence and the sequence within the River Murray floodplain. To the west of the Hamley Fault, the floodplain sediments are typically adjacent to the Glenforslan or Upper Mannum Formations. To the east of the Hamley Fault, the floodplain sediments are adjacent to the Loxton Sands.

Depending on location, the watertable may lie in the Mannum Formation within the Murray Group, the Loxton Sands Formation or the Monoman Formation. Hence the root zone drainage will pass through a series of sands, clays and limestones. This may take months, years or decades.

SIMRAT, as a rapid assessment tool, needs to efficiently estimate the time taken for a change in root zone drainage to reach the watertable: this is referred to as the timelag. SIMRAT adopts analytic equations based on simplified soil physics.

SIMRAT has options to estimate the timelag for either an increase in drainage (wetting) and or a reduction in drainage (drying). However, SIMRAT is explicitly not accredited to estimate the impacts of drying for the Salinity Registers, nor is this algorithm currently used by SA, NSW or Vic for any other purpose. Hence the option is not discussed further here.

## 4.1 SIMRAT assumptions and equations

The derivation of the SIMRAT Stage 2 equations is given in Appendix A. A summary is presented here.

For one-dimensional (1D) vertical flow of a wetting front under free drainage conditions in a homogeneous soil, the time taken for the additional root zone drainage to reach the watertable, timelag $t_L$, is the time taken to change $\theta$ in the whole soil column to a water content at which $K(\theta)$ is equal to the drainage rate $D_1$. This is the change in the volume of water in a 1D column of unit area in the unsaturated zone, divided by the drainage rate $D_1$. That is, the timelag is the depth to water $z_{wt}$ multiplied by the change in water content $\theta_1 - \theta_0$ divided by the drainage rate $D_1$:

1 $$t_L = \frac{z_{wt}(\theta_1 - \theta_0)}{D_1}.$$

This assumes that the initial drainage rate is negligible, which is true for mallee vegetation. If the unsaturated zone is not homogeneous but instead consists of two soil types of respective thickness $z_a$ and $z_b$ (such that $z_a + z_b = z_{wt}$) the total timelag is the sum of the timelags for each soil type, i.e.:

2 $$t_L = \frac{z_a(\theta_1^a - \theta_0^a)}{D_1} + \frac{z_b(\theta_1^b - \theta_0^b)}{D_1}.$$

The soil water contents $\theta_1^a$ and $\theta_1^b$, corresponding to drainage rate $D_1$ in soil types a and *b* respectively, can be estimated using a relationship between hydraulic conductivity *K(θ)* and water content. Many different formulae are used in the soil science literature. SIMRAT employs a modified Brooks-Corey equation (Brooks & Corey, 1964) and parameters given in Cook *et al.* (2004):

3 $$\frac{K(\theta)}{K_r} = \left(\frac{\theta - \theta_0}{\theta_r - \theta_0}\right)^2$$

where $\theta_0$ is the mean soil water content beneath native Mallee vegetation. $\theta_r$ is the reference soil water content and $K_r$ is the reference soil hydraulic conductivity such that $K(\theta_r) = K_r$. Note that $\theta_r$ is not necessarily the maximum water content and $K_r$ is therefore not necessarily the saturated hydraulic conductivity.

Under free drainage, $K(\theta_1)=D_1$. The Brooks-Corey relationship can be rearranged to show:

4 $$\theta_1 = \sqrt{\frac{D_1}{K_r}}(\theta_s - \theta_0) + \theta_0.$$

Hence the SIMRAT equation for the mean timelag $t_L$ of increased root zone drainage to the watertable is:

5 $$t_L = \frac{z_a(\theta_s - \theta_0) + z_b(\theta_s - \theta_0)}{\sqrt{D_1 K_r}}$$

This is sometimes referred to as the step wetting function. To summarize, the mean timelag depends on the total thickness of sandy loam in the unsaturated zone and the total thickness of clay in the unsaturated zone (summed together, these are the depth to water), the root zone drainage rate, and the soil properties of the sandy loam and clay. The equation is based on the following assumptions:

- Unsteady (transient flow) (i.e. system is not in equilibrium steady-state)
- The effective hydraulic conductivity is a quadratic function depending on soil water contents (modified Brooks-Corey equation), implying rigid soils (no swelling or shrinking of clays)
- Free drainage conditions
- One-dimensional vertical piston flow of the wetting front
- Soil conditions are initially in equilibrium with recharge under Mallee vegetation
- The depth to water does not change significantly between the onset of increased recharge and the arrival of the wetting front at the watertable
- Constant root drainage after the initial increase
- All root zone drainage becomes recharge to the watertable aquifer
- There are two soil types, *a* and *b,* in the unsaturated zone.
- The mean value and distribution of soil parameters are constant across the SIMRAT study area
- Root zone drainage is less than reference hydraulic conductivity $K_r$.

It is further assumed that small-scale variations in soil properties within the irrigation area lead to a log-normal distribution of timelags to the watertable (Cook *et al.,* 1989). This results in the wetting gradual recharge function *R(t),* the recharge reaching the watertable at time *t*:

6 $$R(t) = \frac{1}{2} e^{\mu+\frac{\sigma^2}{2}} \left(1 - \mathrm{erf}\frac{\ln\frac{t}{L} - \mu - \sigma^2}{\sigma\sqrt{2}}\right)$$

where *L* is:

7 $$L = \frac{\left[z_a(\theta_s - \theta_0) + z_b(\theta_s - \theta_0)\right]^2}{t_L \ldots}$$

Small-scale variations in soil properties certainly occur and available data is not inconsistent with a log-normal distribution (Cook *et al.*, 1989). Definitions of the parameters are given in Table 4-1 and Table 4-2. The derivation is provided in Appendix A.

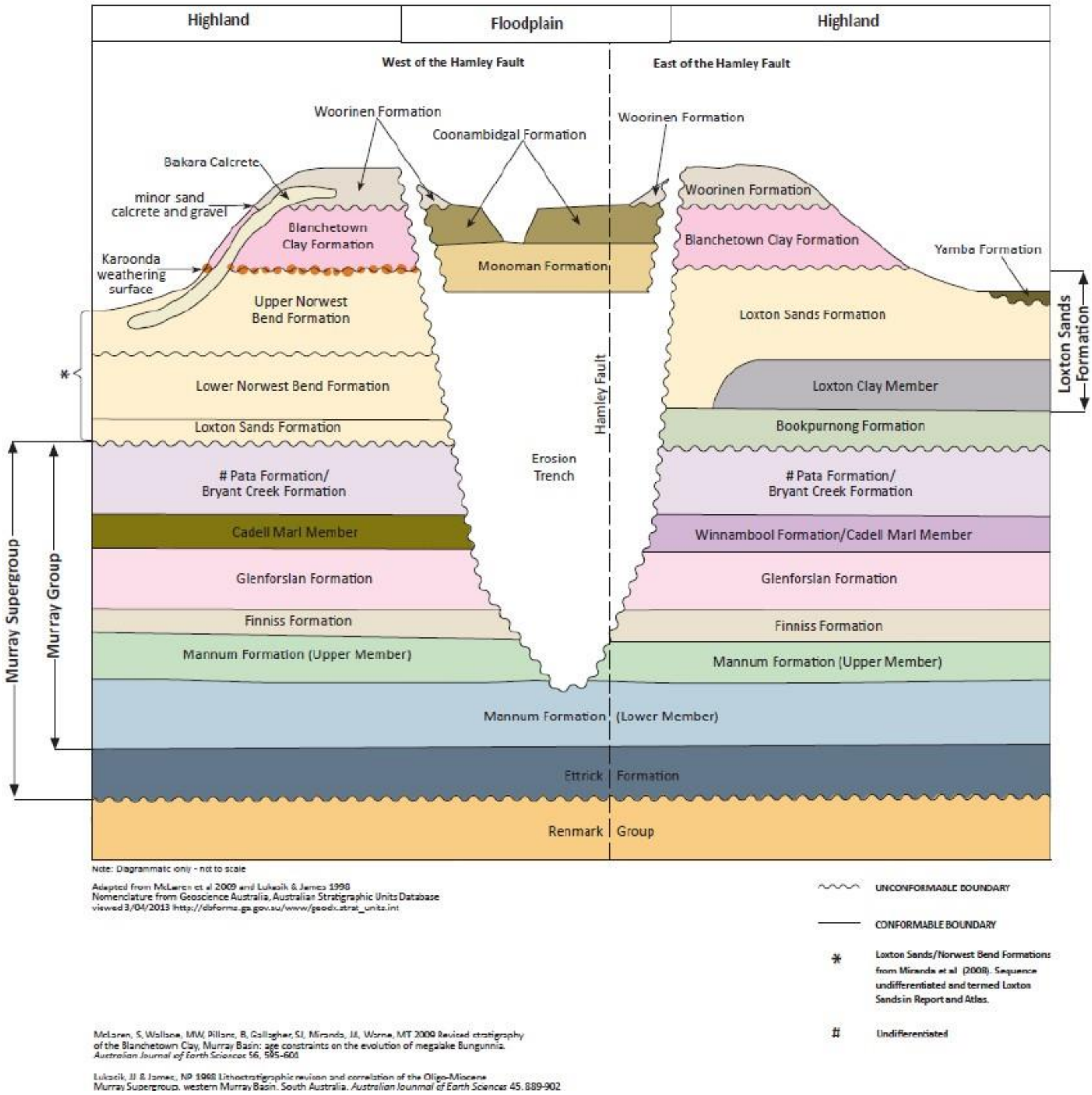


**Figure 4.1 Sample stratigraphic columns for Murray Basin in SA (from AWE, 2014)**

## 4.2 SIMRAT parameters

Parameters which are used in Stage 2 are described in two tables. Table 4-1 gives a list of SIMRAT variables that are entered by the user or obtained from the Data Atlas. Table 4-2 summarizes the SIMRAT parameters that are fixed in the model, or where uniform properties are assumed within the model extent.

In SIMRAT-XL, the RZD is an output of Stage 1 (Sect. 3). The user can specify the aquitard thickness and the depth to the regional watertable. The soil properties are not specified by the user but are fixed. Mean timelag and recharge over time (calculated from both step and wetting function) are calculated.

In the GIS version of SIMRAT, the RZD is again an output of Stage 1. The soil water reference hydraulic conductivity is hard coded, yet the minimum and maximum soil water content parameters are read from an input data table. The values in the input data table match those that are fixed in SIMRAT-XL. The soil water content and hydraulic conductivity properties are therefore assumed to be uniform within the model extent. During this review, the project team found no occurrences of use of SIMRAT where there soil water content parameters were varied from the values given in the input data table.

The two soil types are assumed to be sandy loam and clay. Model parameters including thickness of clay and depth to watertable are sourced from the Data Atlas. The difference between the depth to water and clay thickness is presumed to be the thickness of sandy loam, so all other soil types and hydrogeological units are treated as sandy loam. Mean timelag and recharge over time is calculated for each 6.4 ha cell within the irrigation area.

### Table 4-1 SIMRAT unsaturated zone model parameters which may not be fixed

| Parameter description | Source (Excel version) | Source (ArcGIS version) | Symbol | Unit |
|---|---|---|---|---|
| Root zone drainage | Stage 1 output | Stage 1 output | *RZD* | mm/y |
| Thickness of clay | User | Data Atlas | $z_b$ | m |
| Depth to regional watertable | User | Data Atlas | $z_{wt}$ | M |

### Table 4-2 SIMRAT unsaturated zone model uniform parameters

| Parameter description | Symbol | Value | Unit |
|---|---|---|---|
| Mean soil water content pre-irrigation (sandy loam) | $\theta_0$ | 0.06 | - |
| Mean soil water content pre-irrigation (clay) | $\theta_0$ | 0.15 | - |
| Reference soil water content (sandy loam) | $\theta_m$ | 0.27 | - |
| Reference soil water content (clay) | $\theta_m$ | 0.60 | - |
| Reference hydraulic conductivity (sandy loam and clay) | $K_0$ | 0.45 | m/y |
| Exponent of the modified Brooks-Corey equation | | 2 | - |
| Shape parameter of log-normal probability density function | σ | 0.28 | - |

The Data Atlas clay thickness layer assumes that the clay is the Blanchetown Clay only, therefore omitting deeper clay units such as the Lower Loxton Clay and Bookpurnong Beds, Bryant Creek/Cadell Marl or the Finniss Formation. Within the SA extent of the model, the thickness of the aquitard was developed using interpolation of bore log data and AEM data (Fuller *et al.*, 2005d). Areas where the clay is absent are accounted for. Within NSW, the dataset is developed using the SA thickness layer mapped as far as Wentworth. Upstream of Wentworth, where limited data were available, the NSW Government was consulted to determine the most likely thickness (Fuller *et al.*, 2005d). In the highland areas a clay thickness of 5 m is assumed, and in floodplain areas a clay thickness of 1 m is assumed. In Victoria the thickness is interpolated from contour data for thickness of Blanchetown Clay mapped by Thorne *et al.* (1990) that has contour intervals of 10 m.

The Data Atlas depth to groundwater is interpolated from available water level data. Within the SA extent of the model, the depth to groundwater is calculated by subtracting an interpolated watertable surface for year 2000 from a resampled Digital Elevation Model (DEM) (Fuller *et al.*, 2005d). Within the Victorian extent of the model, a watertable depth for 2001 was provided by the

Mallee CMA (Fuller *et al.,* 2005d). Within NSW, Murray Basin Hydrogeology GIS watertable contours were subtracted from 9 second DEM. In SA, a revised data layer based on watertable for year 2005, estimated from numerical groundwater models, was developed in 2013 but is yet to be formally adopted (Peat & Yan, 2013).

The soil properties are fixed and are based on parameters given in Cook *et al.* (2004). The soil water content values were based on synthesis of data obtained from dozens of deep profile measurements at several locations in the Mallee region (P Cook (CSIRO) 2014, pers. comm.). The study considered cleared land but not irrigated land.

## 4.3 Sensitivity analysis

Sensitivity analysis involves changing a model parameter by a small amount to establish how model predictions are affected by that change (Barnett *et al.,* 2012). This section considers the sensitivity of the timelag and recharge to SIMRAT parameters. Depth to groundwater, thickness of clay, root zone drainage and the shape parameters of the log-normal distribution are varied. The calculations are performed using a Python script that implements the governing equations given in Section 4.1.

### 4.3.1 An illustration of the pressure front

Figure 4.2 and Figure 4.3 provide a simple illustration of the movement of the pressure front through the soil profile until it reaches the watertable. A root zone drainage of 225 mm and depth to watertable of 25 m is assumed. Two model runs are presented: 1) no clay present (Figure 4.2) and 2) 8 m of clay present in the profile (Figure 4.3).

The pressure front moves through the homogenous sandy loam profile at a constant velocity of over 1.5 m/y, reaching the watertable in 16.5 years (Figure 4.2). The movement of the pressure front is noticeably slower with 8 m of clay present (Figure 4.3). For illustrative purposes, the clay layer exists at a depth of between 8 m and 16 m, but theoretically could occur anywhere in the soil profile as only the aggregate thicknesses of sandy loam and clay are important to calculation of mean timelag. Above the clay layer the pressure front moves through the soil profile at a constant velocity of 1.5 m/y and then slows through the clay, progressing at a rate of 0.7 m/y. The pressure front reaches the watertable in 22.5 years, six years longer than if it were moving through homogenous sandy loam. The pressure front always moves at approximately double the speed through sandy loam as it does though the clay, due to the choice of soil parameters.

### 1.1.1 Sensitivity of the mean timelag

The mean timelag is:

$$t_L = \frac{z_a(\theta_m - \theta_0) + z_b(\theta_m - \theta_0)}{\sqrt{D K_m}}.$$

SIMRAT has constant values for the water content parameters, so the timelag will vary with root zone drainage *D*, depth to water ($z_a$+$z_b$) and the thickness of the aquitard $z_b$. It is inversely proportional to the square root of *D*.

Figure 4.4 shows the sensitivity of mean timelag $t_L$ to root zone drainage, depth to water and the thickness of the aquitard. The root zone drainage is varied from <1 mm/y (native vegetation) to 350 mm/y (inefficient irrigation). The depth to water is 10 m, 30 m or 80 m, spanning the range seen outside the Murray trench (i.e. in highland areas; it can be lower in Sunraysia). Clay thickness is varied from 0 m to 20 m, which is the range of thicknesses given for the Blanchetown Clay in Miranda *et al.* (2009). Greater clay thicknesses are given for Victoria in the Data Atlas in the Mallee, which may be including other clay units.

The mean timelag is greater where the RZD is low, the watertable is deep and the clay is thick. For a RZD of 10 mm/y, corresponding to cleared dryland, the timelag ranges from 30 years (10 m depth to water, no clay) to greater than 350 years (depth to water 80 m), For a RZD of 100 mm/y, corresponding to efficient irrigation, the timelag ranges from 10 years to 100 years, depending on depth to water and clay thickness. For inefficient irrigation with an RZD of 350 mm/y, the timelag is <5 years to 50 years.

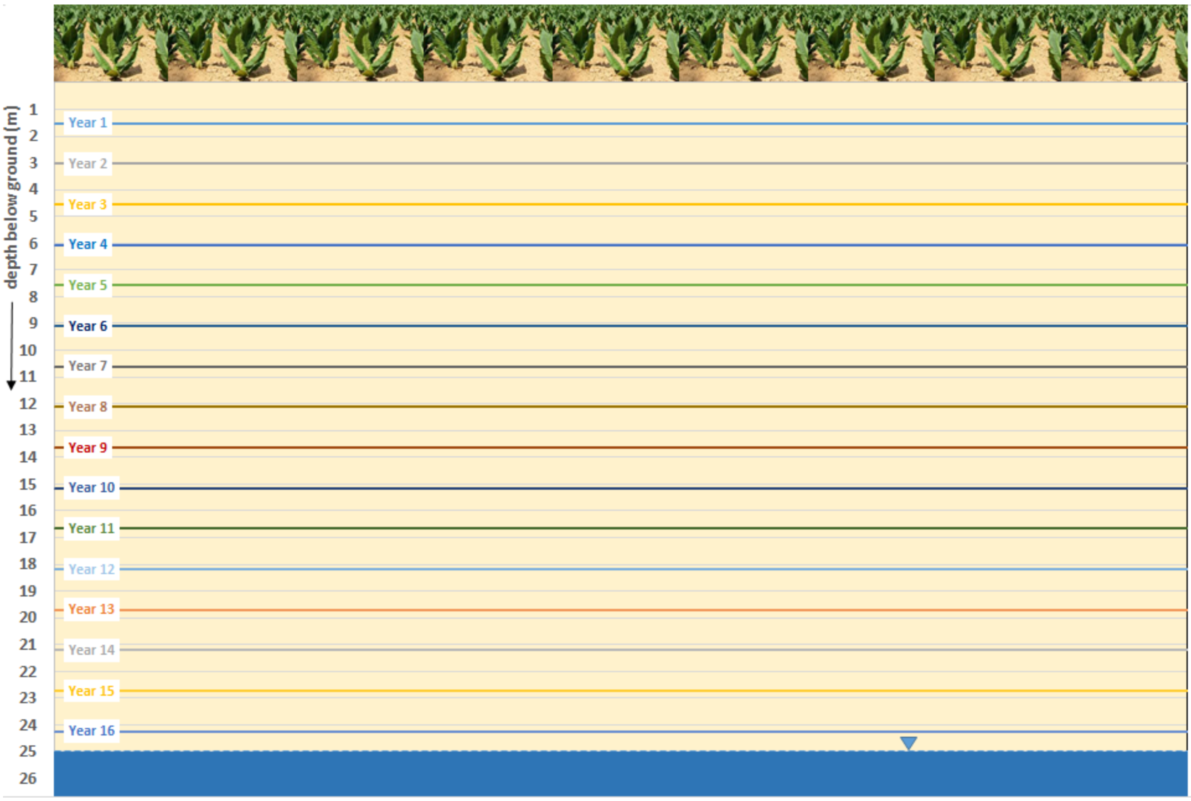


**Figure 4.2 Movement of pressure front – RZD 225 mm/y, 25 m sandy loam**

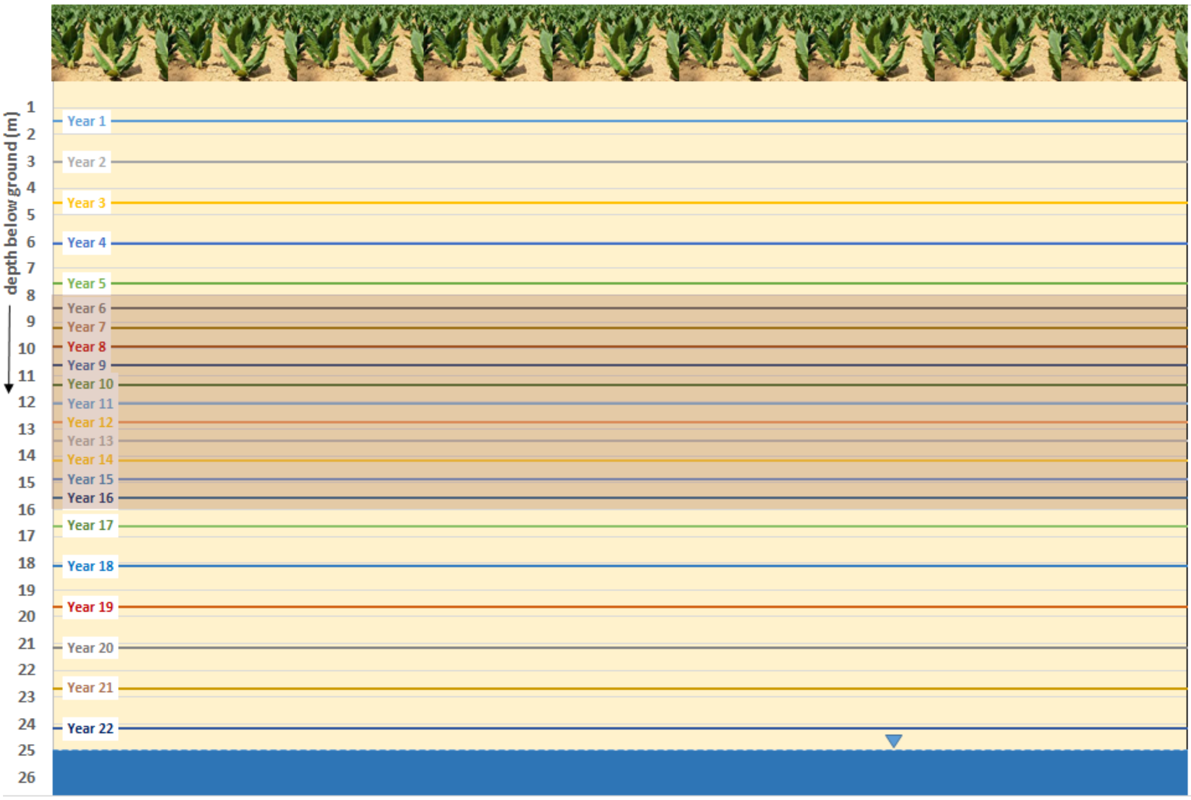


**Figure 4.3 Movement of pressure front – RZD 225 mm/y, 17 m sandy loam, 8 m clay**

The thickness of clay and the overall depth to water can add decades. For example, for a RZD of 100 mm/y and depth to water of 30 m, the timelag is 30 years if clays are absent and 50 years if there is 20 m of clay. For a RZD of 100 mm/y and a 10 m clay thickness, the timelag varies with depth to water from 30 years to 90 years.

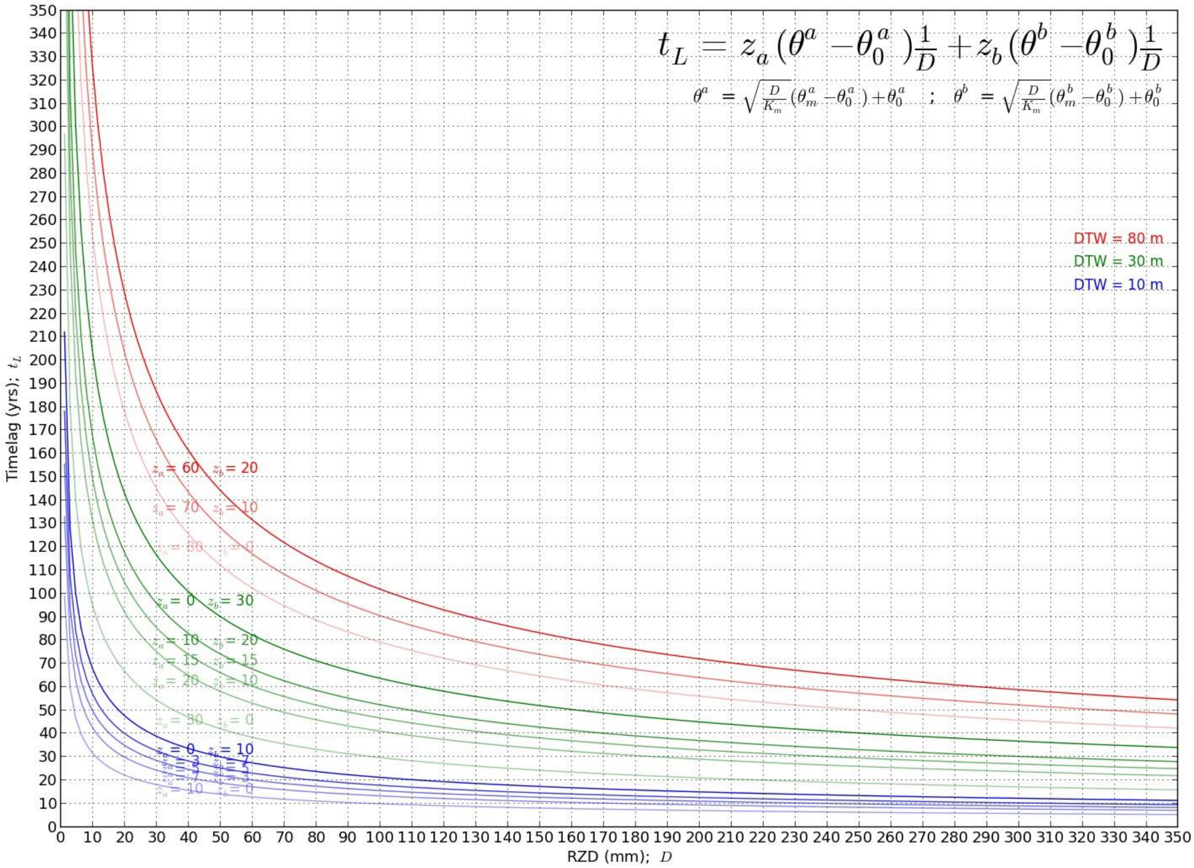


**Figure 4.4 Calculation of mean timelag – sensitivity to RZD, DTW and clay thickness ($z_b$)**

### 1.1.2 Sensitivity of recharge

The sensitivity of recharge over time to root zone drainage and clay thickness is shown in Figure 4.5. Root zone drainage rates are for highly efficient, efficient and inefficient irrigation (75 mm, 125 mm and 300 mm). The clay is either absent or is 10 m thick. The standard SIMRAT function for recharge over time is plotted as recharge gradual and compared with the mean timelag (recharge step).

The time taken for recharge to reach equilibrium and become equivalent to the root zone drainage increases with increasing aquitard thickness and decreasing root zone drainage (Figure 4.5). For a depth to water of 20 m, a thickness of 10 m of clay will increase the mean timelag by six years for 300 mm RZD, 10 years for 125 mm RZD and 13 years for 50 mm RZD.

Sensitivity to parameters such as root zone drainage, clay thickness and depth to water are presented in Fuller *et al.* (2005c). Results are expressed in terms of EC impact and therefore require careful interpretation. Sensitivity of recharge under cleared mallee to soil parameters and depth to water are given in Cook *et al.* (2001).

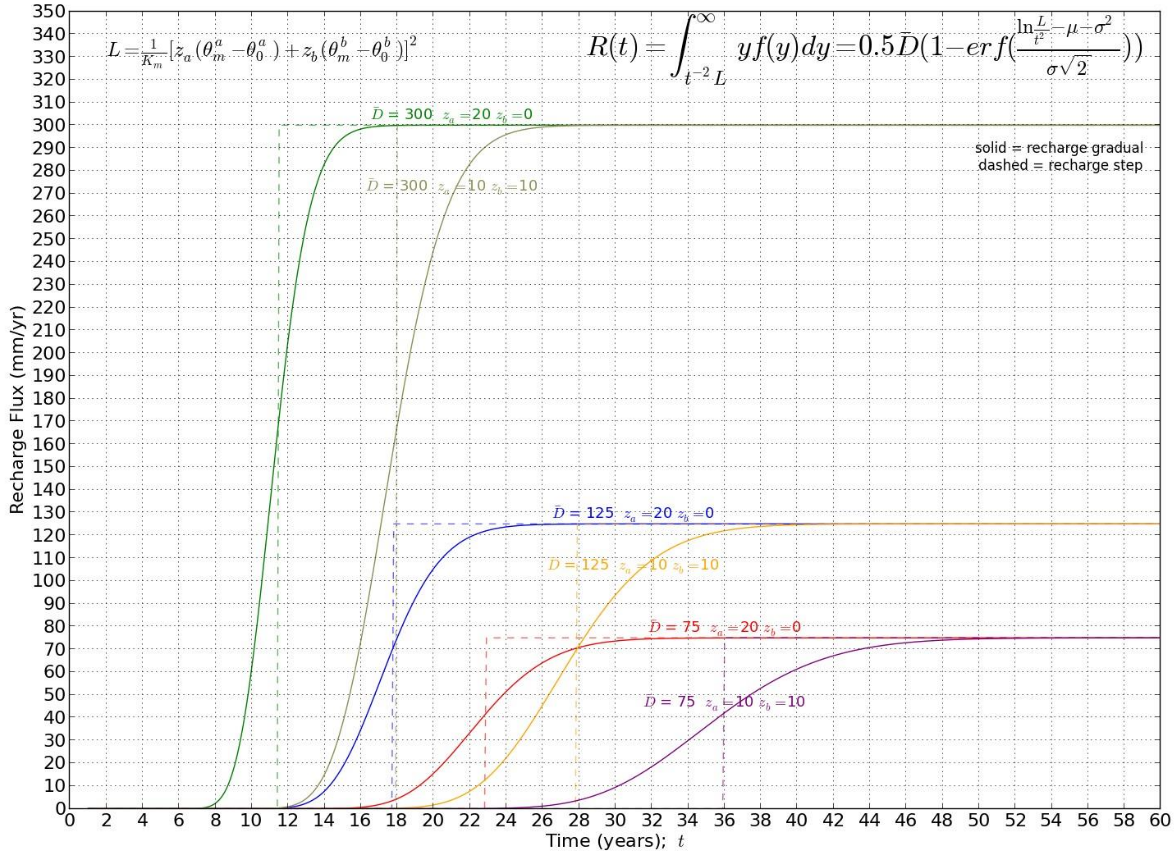


**Figure 4.5 Recharge – sensitivity to RZD and clay thickness**

### 1.1.3 Sensitivity of recharge to log-normal probability density function parameters

An additional test was conducted to analyze how the shape parameters of the log-normal distribution ($\sigma$ and $\mu$) influence the recharge trend over time. The standard deviation *($\sigma$)* is varied and the $\mu$ is calculated based on the equation:

$$\mu = \ln(\bar{t}) - \frac{1}{2}\sigma^2$$

A fixed $\sigma$ of 0.28 is used in SIMRAT. A field study of recharge at Borrika in the Mallee region of SA (Cook, Walker & Jolly, 1989) demonstrated that recharge rates estimated using electromagnetic techniques fit a log-normal distribution with fitting parameters $\mu$ = 2.23 and $\sigma^2$ = 0.848 (Cook *et al.*, 2004).

Figure 4.6 shows how the sigma value affects the shape of the recharge function for different root zone drainage and thicknesses of sandy loam and clay. Two sigma values are tested; the value applied in the SIMRAT model ($\sigma$ = 0.28) and the value from the Borrika study ($\sigma$ = 0.92). The choice of sigma does not affect the mean timelag calculation or the long-term recharge (which is equivalent to the root zone drainage), but does change the shape of the recharge function (the sigmoidal curve) and the time taken to reach an equilibrium (Figure 4.6). Recharge to the watertable occurs more gradually for larger sigma values ($\sigma$ = 0.92).

Other values for $\sigma$ and $\mu$ are given in Prathapar *et al.* (1994). The sensitivity of recharge under cleared mallee to $\sigma$ and $\mu$ is discussed in Cook *et al.* (2001).

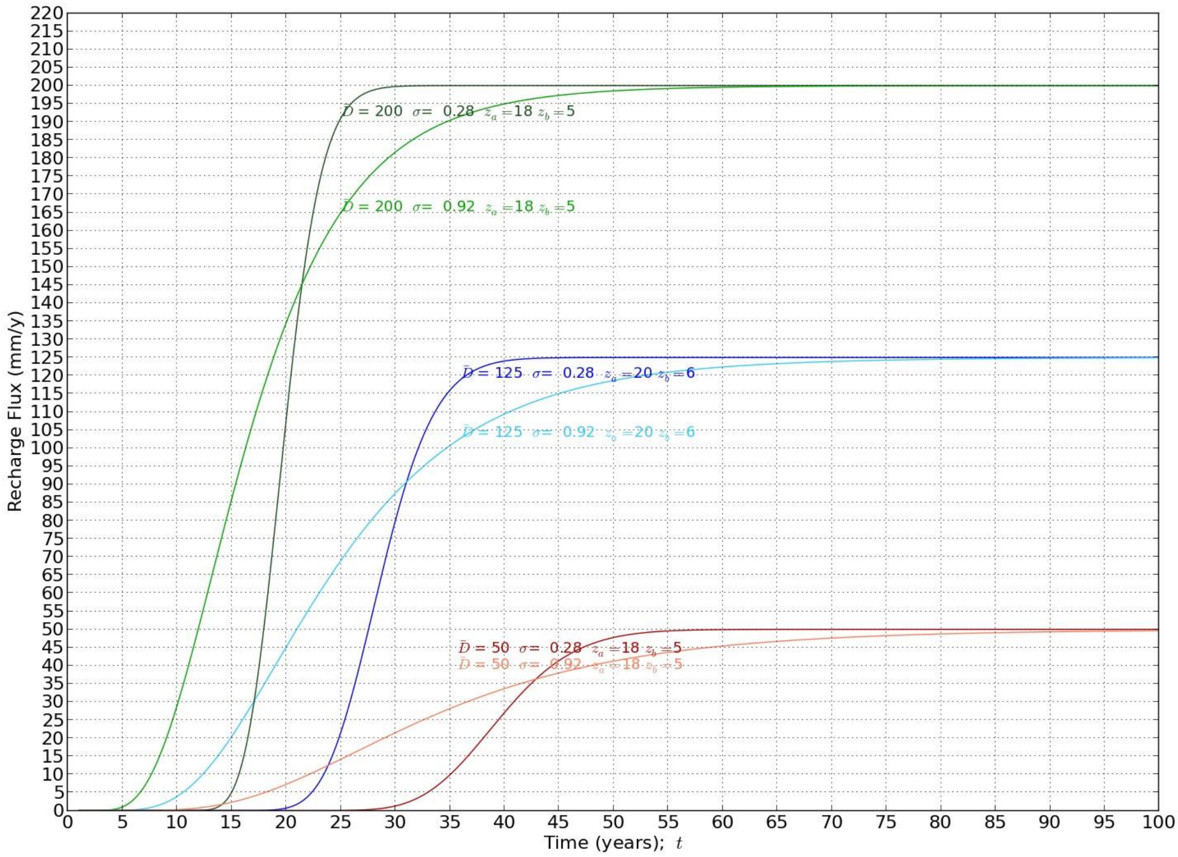


**Figure 4.6 Recharge for different sigma values – RZD 200 mm/y (green), 125 mm/y (blue) and 50 mm/y (red)**

## 4.4 Discussion

### 1.1.4 Uncertainty of timelag due to soil parameters

The timelag depends on a relationship between hydraulic conductivity and soil water content. The modified Brooks-Corey equation and parameters adopted by SIMRAT (Table 4-2) are from studies of cleared land in the SA Mallee (Cook *et al.,* 2004). Table 4-3 provides standard reference values from the Rosetta Lite database (Sejna *et al.,* 2013) which can be compared with the SIMRAT values. Note, however, that these values are based on studies of US soils. Late during this review the project team was alerted to Australian soil databases which would provide a better comparison for Mallee soils (e.g. Minasny *et al.*, 1999; Minasny & Mc Bratney, 2002).

To gauge the possible uncertainties in these assumptions, this section compares estimates based on the Cook *et al.* (2004) equation with estimates based on alternative data from the Mallee (Table 4-4). The alternative curves for hydraulic conductivity as a function of soil water content are derived from the following sources. Meissner (2004) examined 294 soil samples from irrigation districts in the Mallee in the SA Riverland and Vic Sunraysia, fitting moisture content data against Campbell and van Genuchten-Mualem curves. Meissner (2004) provides estimates of the residual and saturated water content for a variety of soil types, including the Blanchetown Clay, but does not provide saturated hydraulic conductivities. For the comparison presented here, the vertical hydraulic conductivity of a sandy soil is presumed to be 0.5 m/d, one-tenth of a typical value for the horizontal conductivity of the Loxton Sands used in the Salinity Register groundwater models (e.g. Woods *et al.*, 2014). The vertical hydraulic conductivity of the Blanchetown Clay is considered as either $10^{-3}$ m/d or $10^{-2}$ m/d. Laboratory estimates from Thorne *et al.* (1990) range from extremely low to 1.7 x $10^{-3}$ m/d while an aquifer test provided an estimate of 3.5 x $10^{-2}$ m/d. The range adopted here allows for free drainage to occur provided RZD is less than 365 mm/y, similar to the 1D assumptions of SIMRAT.

Table 4-4 provides the parameters used. The van Genuchten-Mualem equation is:

8 $$\frac{K(\theta)}{K_s} = \left[\frac{\theta - \theta_r}{\theta_s - \theta_r}\right]^a \left[1 - \left\{1 - \left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)^{\frac{1}{m}}\right\}^m\right]^b$$

where $K_s$ is the hydraulic conductivity at saturation, $\Theta_s$ is the soil water content at saturation, $\Theta_r$ is the residual soil water content, $a$ and $b$ are Mualem model parameters and $m$ is a Mualem shape parameter where:

9 $$m = \frac{\lambda}{1+\lambda}$$

Figure 4.7 shows SIMRAT's functions for hydraulic conductivity as a function of water content. Figure 4.8 to Figure 4.11 compare these functions with the alternative functions. Figure 4.8 and Figure 4.9 shows that the alternative function for sandy loam has much greater hydraulic conductivity than that assumed by SIMRAT: they are different enough that two figures on different scales are provided to make the comparison clearer. Figure 4.10 and Figure 4.11 compare the functions for clay. Figure 4.10 assumes the saturated hydraulic conductivity of the clay is $10^{-3}$ m/d: the curves differ in shape but have a similar range of hydraulic conductivities. Figure 4.11 assumes the saturated hydraulic conductivity of the clay is $10^{-2}$ m/d: the alternative function yields higher conductivities than those assumed by SIMRAT.

**Table 4-3 Soil hydraulic parameters from the Rosetta-Lite database (Sejna *et al.* 2013)**

| Textural class description | Residual water content (Θr) (-) | Saturated water content (Θs) (-) | Saturated hydraulic conductivity (Ks) (m/d) |
|---|---|---|---|
| sand | 0.053 | 0.375 | 6.43 |
| loamy sand | 0.049 | 0.390 | 1.05 |
| sandy loam | 0.039 | 0.387 | 0.38 |
| loam | 0.061 | 0.399 | 0.12 |
| silt | 0.050 | 0.489 | 0.44 |
| silty loam | 0.065 | 0.439 | 0.18 |
| sandy clay loam | 0.063 | 0.384 | 0.13 |
| clay loam | 0.079 | 0.442 | 0.08 |
| silty clay loam | 0.090 | 0.482 | 0.11 |
| sandy clay | 0.117 | 0.385 | 0.11 |
| silty clay | 0.111 | 0.481 | 0.09 |
| clay | 0.098 | 0.459 | 0.15 |

**Table 4-4 Parameters for alternative hydraulic conductivity functions**

| Parameter description | Symbol | Value | Unit |
|---|---|---|---|
| Residual soil water content pre-irrigation (sandy loam) | $\theta_r$ | 0.05 | - |
| Residual soil water content pre-irrigation (clay) | $\theta_r$ | 0.06 | - |
| Soil water content at saturation (sandy loam) | $\theta_s$ | 0.39 | - |
| Soil water content at saturation (clay) | $\theta_s$ | 0.41 | - |
| Hydraulic conductivity at saturation (sandy loam) | $K_s$ | 0.5 | m/d |
| Hydraulic conductivity at saturation (clay) | $K_s$ | 0.01 - 0.001 | m/d |
| Lambda (sandy loam) | $\lambda$ | 2.94 | |
| Lambda (clay) | $\lambda$ | 1.18 | |
| Mualem model parameter | a | 2 | - |

| | | | |
|---|---|---|---|
| Mualem model parameter | b | 0.5 | - |

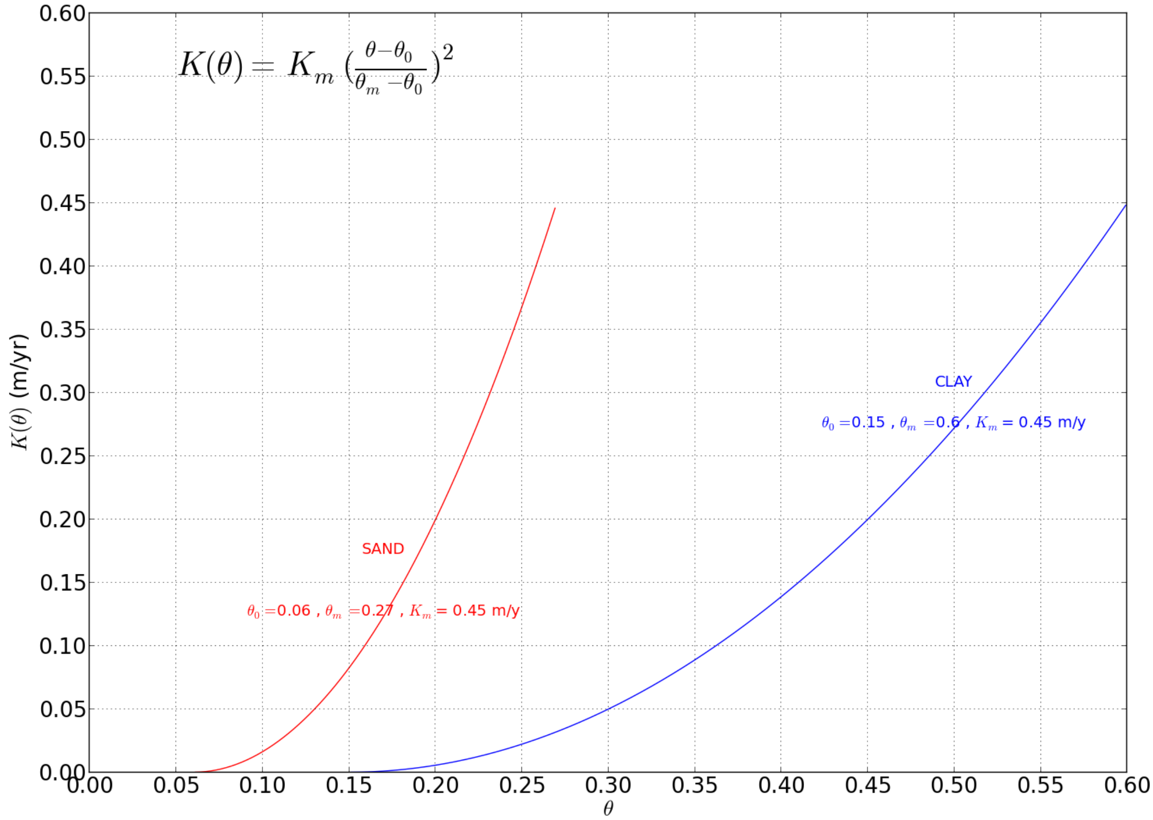


**Figure 4.7 SIMRAT's relationship for *K(θ)* for sandy loam (red) and clay (blue)**

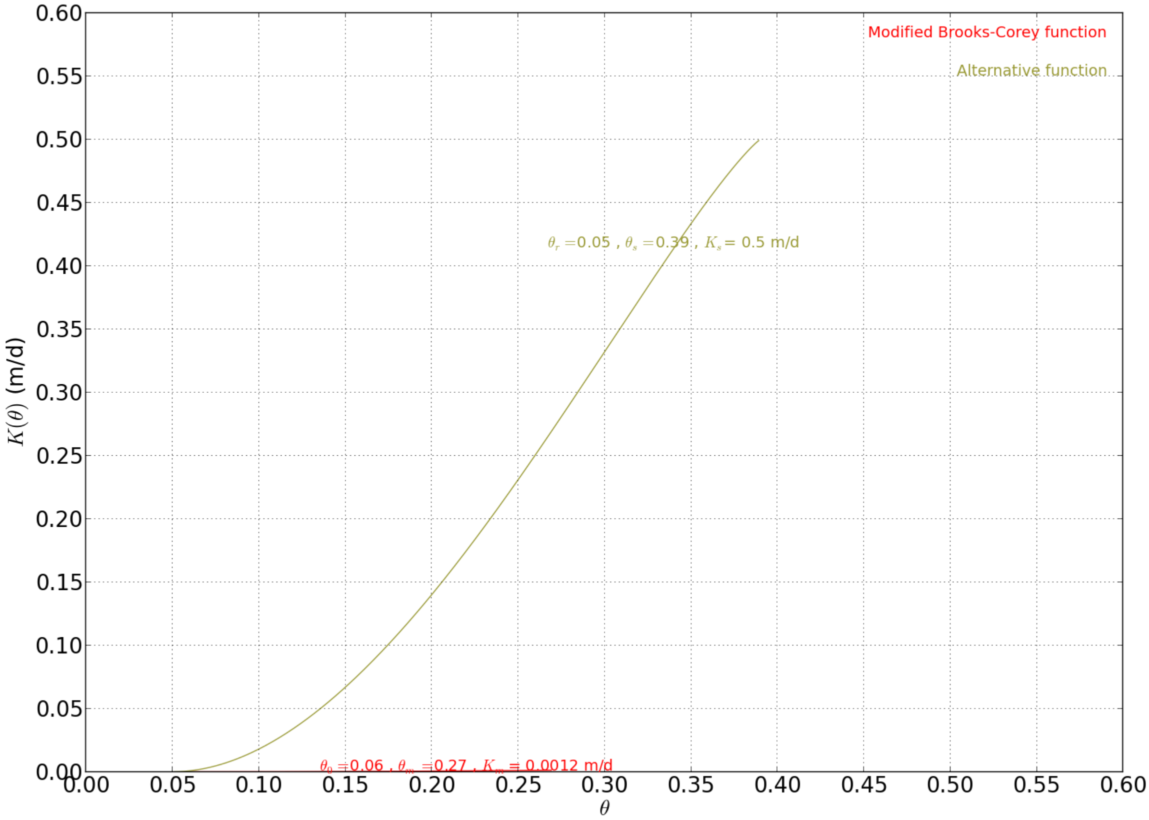


**Figure 4.8 SIMRAT's modified Brooks-Corey and alternative curve for *K(θ)* for sandy loam – full scale**

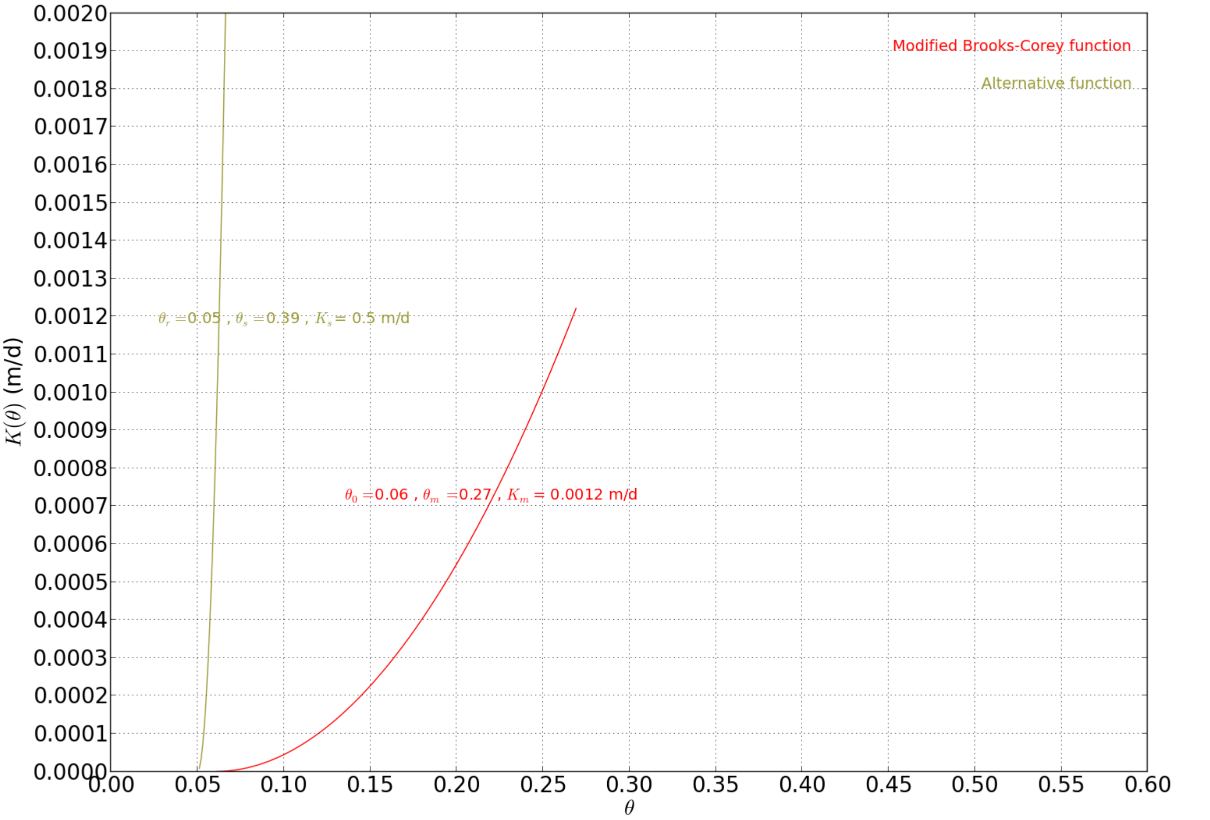


**Figure 4.9 SIMRAT's modified Brooks-Corey and alternative curve for *K(θ)* for sandy loam – closeup**

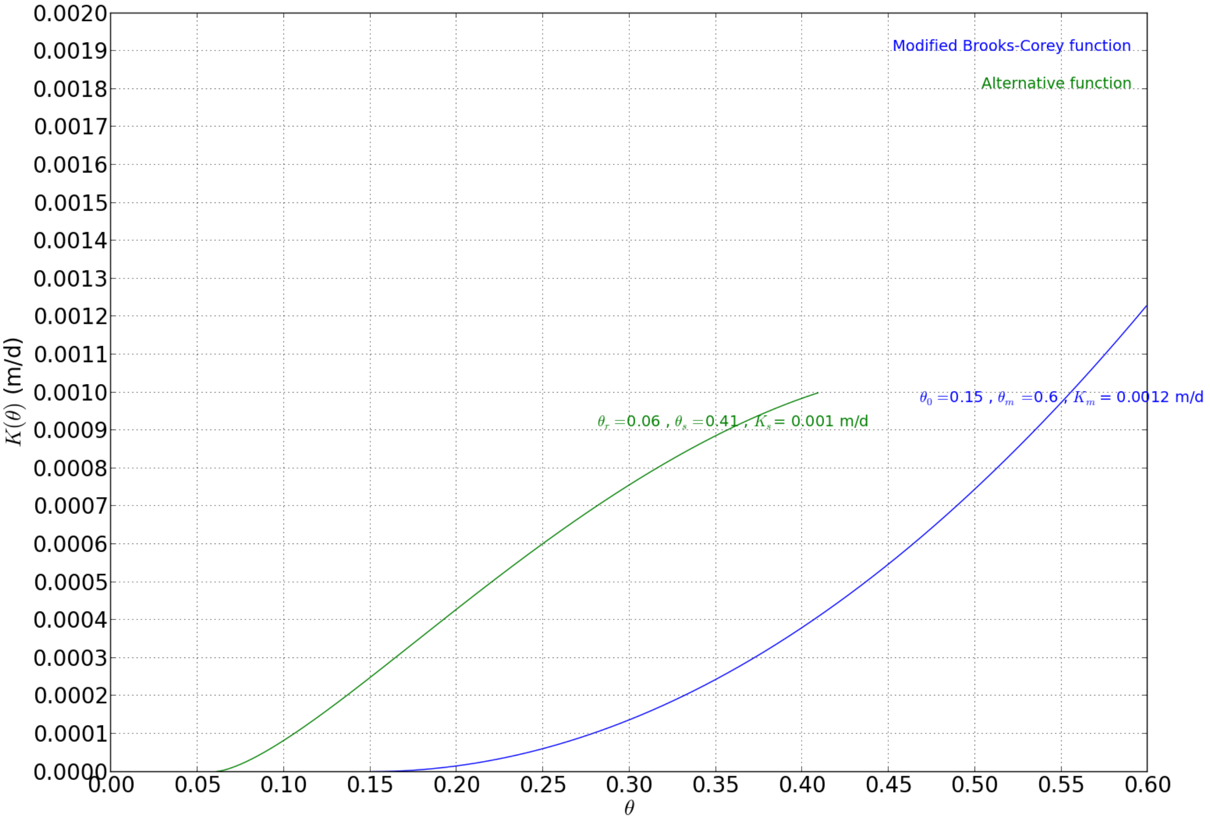


**Figure 4.10 SIMRAT's modified Brooks-Corey and alternative curve for *K(θ)* for clay ($K_s$ 0.001 m/d)**

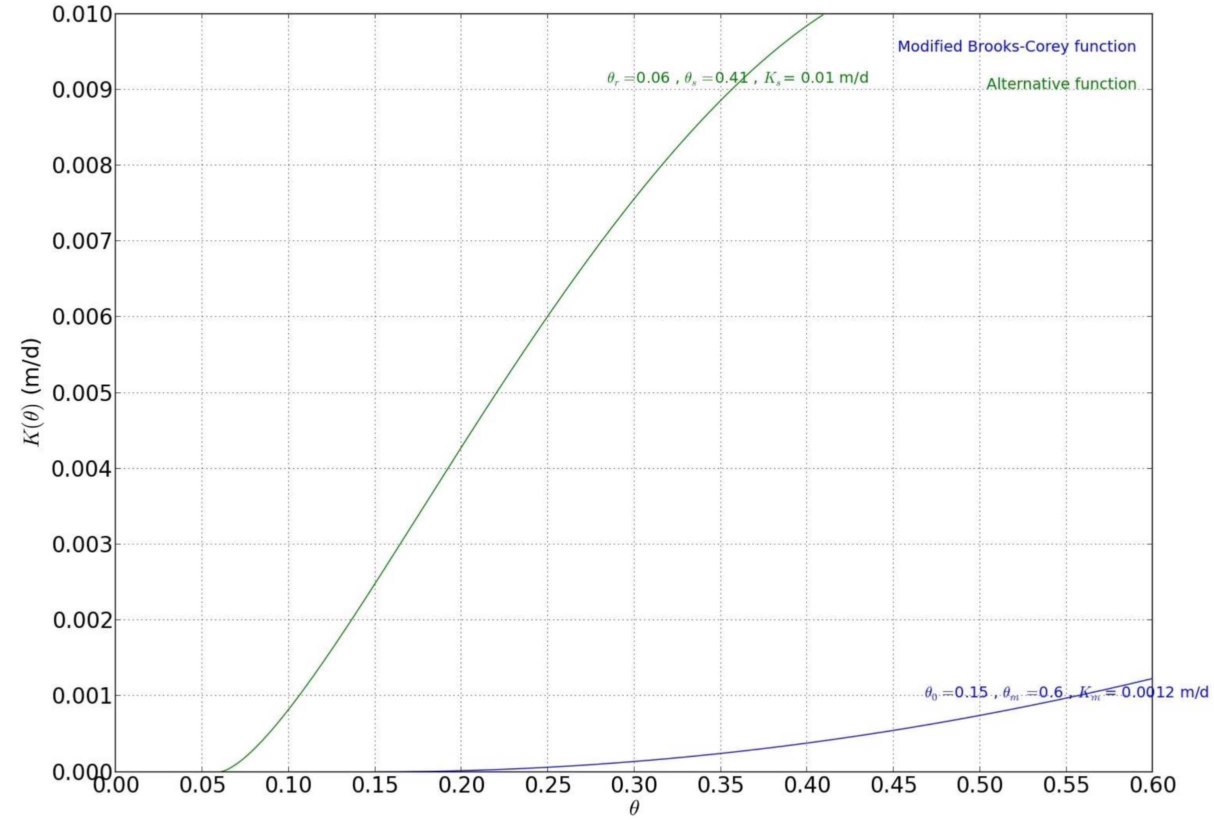


**Figure 4.11 SIMRAT's modified Brooks-Corey and alternative curve for *K(θ)* for clay ($K_s$ 0.01 m/d)**

An alternative relationship between soil water content and unsaturated hydraulic conductivity may impact upon the mean timelag. Consider root zone drainage rates of 100 mm/y and 300 mm/y, corresponding to efficient and inefficient irrigation respectively. Assume a depth to water of 30 m, including 20 m of sandy loam and 10 m of clay. SIMRAT calculates a timelag of 41 years for 100 mm/y. The alternative functions calculate a timelag of 3 years if the saturated hydraulic conductivity of the clay $K_v$ is $10^{-2}$ m/d and 11 years if $K_v$ is $10^{-3}$ m/d. For 300 mm/y, SIMRAT calculates a timelag of 23 years, compared with 6 to 28 years for the alternative functions. These are large uncertainties.

Now consider a root zone drainage of 10 mm/y, corresponding to cleared land. SIMRAT calculates a timelag of 130 years, while the alternative functions estimate 1 or 2 years only. Other methodologies have had other ranges for the timelag. For example, Prathapar *et al.* (1994) modelled timelags for cleared land using LANDMAN, estimating timelags of 26 to more than 200 years. This requires further investigation.

SIMRAT's Stage 2 assumptions are based on field studies of cleared land in the Mallee region and are likely to provide reasonable timelags under cleared conditions, given the data limitations and the need for a rapid assessment method. However, it is not known whether they are appropriate for irrigation areas.

### 1.1.5 Error in SIMRAT-XL recharge wetting function

There is an apparent error in the recharge wetting function of the Excel version of SIMRAT (SIMRAT-XL) which is not consistent with the reviewed literature and is not consistent with the GIS version of SIMRAT.

Two parameters $\mu$ and $v$ must be calculated for the recharge function, as follows:

10 $$\mu = \ln(\ldots) - \frac{\ln\left(\ldots + \frac{\ldots}{D^{\ldots}}\right)}{\ldots}$$

11 $$\ldots = D^{\ldots}(\ldots^{\ldots} - \ldots)$$

This is programmed correctly into the GIS version of SIMRAT. However, SIMRAT-XL does not calculate *v* and instead gives it a set value of 0.001.

Small errors in variance can lead to large errors in the shape of the recharge wetting function, the time taken for the recharge to reach equilibrium and the maximum recharge once equilibrium has been reached. Examples are provided in Figure 4.12 to Figure 4.14. For small root zone drainage of 10 mm/y (e.g. cleared land without irrigation), with a variance of 0.001, the error means that the model predicts a long term recharge that is less than the drainage and the time taken to reach equilibrium is delayed by several decades (Figure 4.12). For root zone drainage of 125 mm, the error in both timelag and long term recharge is minimal (Figure 4.13). For root zone drainage of 300 mm, there is minimal error in the timelag; however, long term recharge is greater than the drainage (Figure 4.14).

The sensitivity plots given in Fuller *et al.* (2005c) were developed using SIMRAT-XL. They will contain errors for low drainage cases.

### 1.1.1 Validity of one-dimensional piston flow under free drainage

Conceptually, the SIMRAT unsaturated zone model describes purely vertical piston flow under the force of gravity (free drainage). A simple soil moisture profile is assumed where a sharp wetting front moves at a constant velocity through a given homogenous soil layer. Under piston flow, the increase in root zone drainage drives out existing pore water with no mixing. Under assumptions of free drainage, the pressure head *h* in the soil profile is constant with depth and the water content is uniform with depth (Radcliffe & Šimůnek, 2010).

These assumptions neglect soil moisture redistribution effects due to changes in drainage, evaporation and transpiration. In actuality, the soil water content varies with time. For example, during periods of intense rainfall in cleared areas of the Mallee, drainage water can be pushed deep into the soil profile. When rainfall ceases, evapotranspiration (ET) may potentially occur at shallower depths within the profile. The soil water content will redistribute in response to drying of the upper soil profile. At times the net recharge to the watertable under cleared Mallee vegetation may be negative due to effects of evapotranspiration.

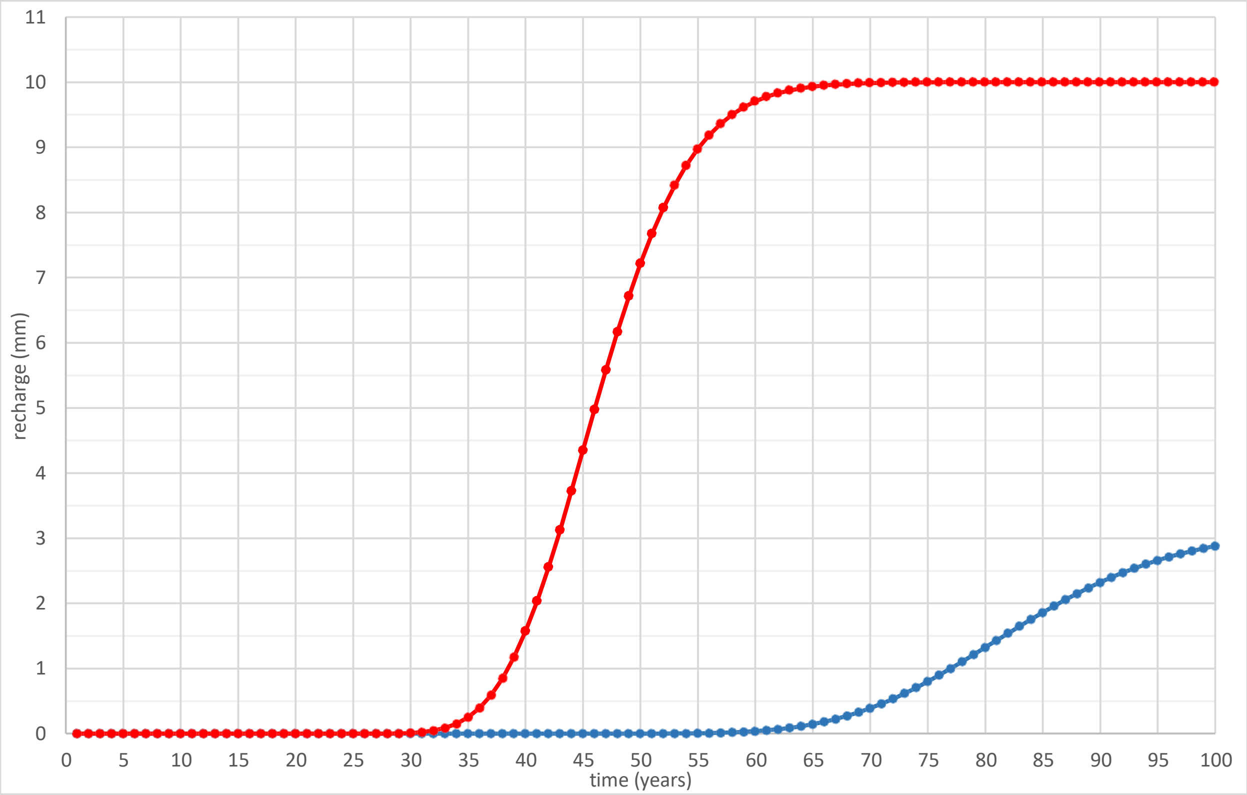


**Figure 4.12 Recharge function for 10 mm RZD – variance calculated (red) and hardcoded (blue)**

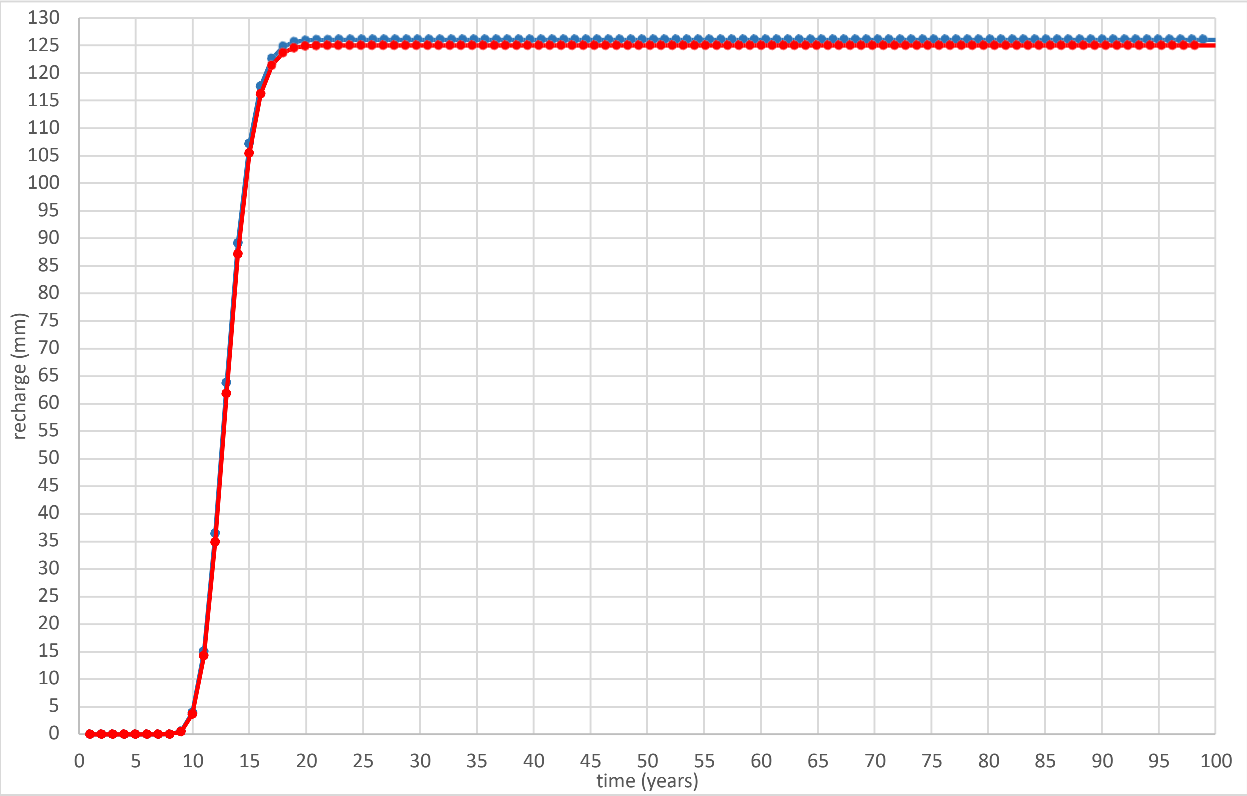


**Figure 4.13 Recharge function for 125 mm RZD – variance calculated (red) and hardcoded (blue)**

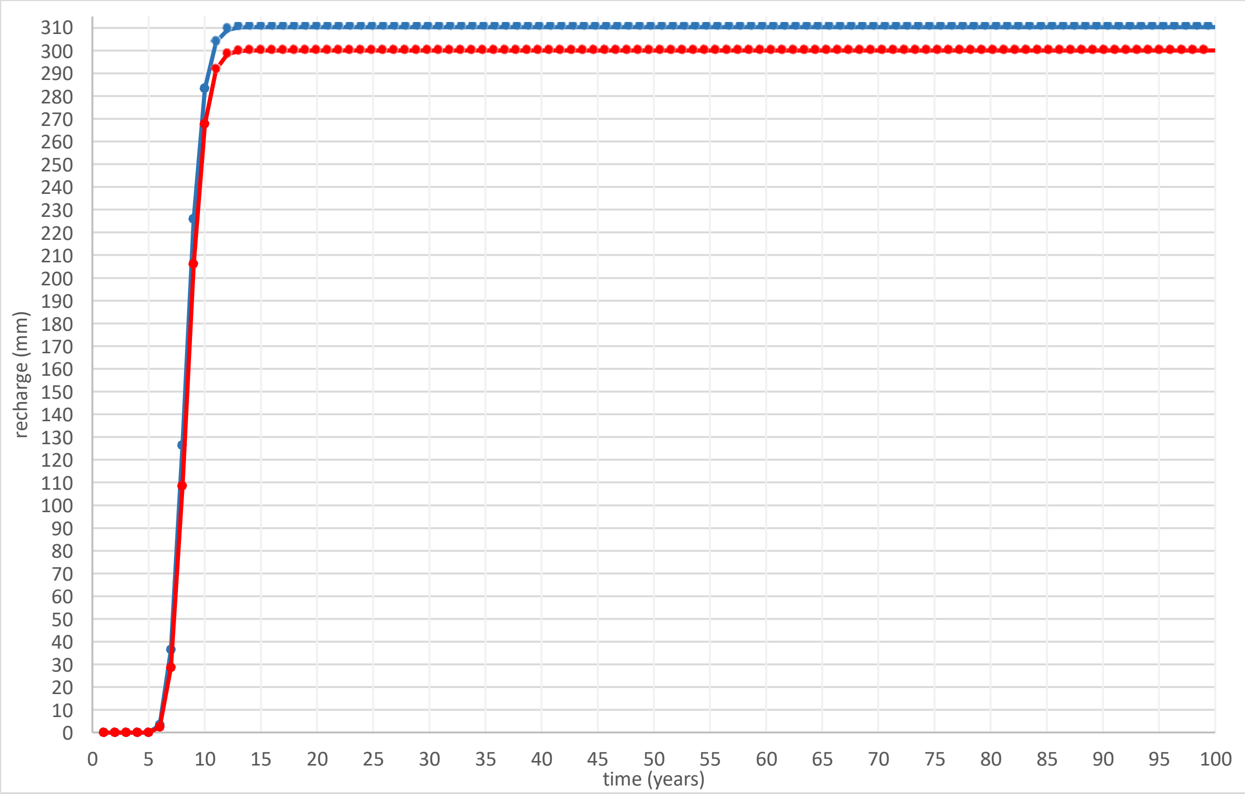


**Figure 4.14 Recharge function for 300 mm RZD – variance calculated (red) and hardcoded (blue)**

Free drainage cannot be used to describe conditions where perched aquifers have formed. The vertical flow will be limited by the vertical hydraulic conductivity of the clay. Lateral flow and perched aquifers have been observed at some locations, such as Qualco–Sunlands and Loxton, due to the presence of the low-permeability Blanchetown Clay or the Bryant Creek/Cadell Marl Formations. At other locations it can be inferred from infrastructure required by irrigators to reduce waterlogging, such as drainage bores and comprehensive drainage systems. Where perched aquifers have formed, the area of recharge will expand due to the lateral movement of water, becoming wider than the irrigation area. The mean timelag will increase and the recharge will take longer to be equivalent to the root zone drainage, as water is stored in the perched aquifers. Also, the recharge will probably reduce because evapotranspiration from the perched aquifer and the effects of drainage infrastructure will offset the irrigation RZD.

Perched aquifers will form where the saturated vertical conductivity $K_v$ of the clay is lower than the root zone drainage rate RZD. For example, if $K_v$=$10^{-3}$ m/d, perched aquifers may occur if RZD>365 mm/y. If $K_v$=$10^{-4}$ m/d, perched aquifers may occur for RZD>36.5 mm/y, i.e. for all irrigation.

It is likely that a clay layer may have areas of higher vertical conductivity which may become preferential flow paths for the root zone drainage. This may also lead to small-scale lateral flow. These higher $K_v$ areas may be due to natural features, from the depositional environment or later weathering, or may be artificial such as drainage bores.

SIMRAT is a rapid assessment tool for new irrigation areas at greenfield sites. It is assumed that the initial drainage at a site is negligible and the water content in the unsaturated zone is low. Hence existing irrigation areas should be masked from the SIMRAT domain. Where possible, a large irrigation area should be examined to see if lateral spread/perching has occurred. This area should also be masked, as it will have a higher initial water content. Areas which have been intermittently irrigated, e.g. pivot irrigation, may also have water contents in the unsaturated zone that do not match SIMRAT's assumptions.

Given all the limitations described above, it is difficult to estimate the practical impact of the assumption of one-dimensional piston flow with free drainage. Field studies and numerical models are recommended to estimate the resulting uncertainty.

### 1.1.2 Assumption regarding depth to water

SIMRAT assumes that the depth to water does not change significantly between the onset of increased recharge and the arrival of the wetting front at the watertable. In fact, depth to water changes over time, due to mallee clearance, new irrigation, changes in irrigation efficiency, pumping from salt interception schemes, and other factors.

As the depth to water changes, the unsaturated thickness of the sandy loam ($z_a$) and/or clay ($z_b$) changes. The timelags estimated in Equations 5 and 6 depend on $z_a$ and $z_b$, so the assumption of constant depth to water may introduce inaccuracies to the timelag. It is not clear whether the inaccuracies introduced would be significant, so we recommend that this be investigated. If the change in depth to water over time is known (from observations, or estimated from models), then it would be possible, if time-consuming, to modify SIMRAT's timelag calculations to take this into account.

### 1.1.3 Parameters

The Data Atlas provides thicknesses of clay. In SA, Victoria and NSW this thickness is based on estimates of Blanchetown Clay thickness only. This is not appropriate for areas where there are other low-permeability units in the unsaturated zone, e.g. Lower Loxton Clay, Bookpurnong Beds, Upper Mannum Limestone or others. The Data Atlas should be amended. Data availability for deeper clay sequences (such as Bryant Creek/Cadell, Finniss Formation) is more limited (S Barnett (DEWNR) 2014, pers. comm.).

The Data Atlas depth to water is based on depth to water in 2000 and 2001. As the depth to watertable has changed since then, it is recommended that this data layer be updated.

Soil parameters are based on studies of mallee clearance, not irrigation areas. The SIMRAT documentation does not mention what hydrostratigraphic units the soil parameters are based on, but they are most likely the top soils, Woorinen Formation and the Blanchetown Clay, It is not clear whether these parameters are appropriate for other hydrostratigraphic formations within the unsaturated zone. The properties of the deeper hydrogeological units may significantly differ from upper units (S Barnett (DEWNR) 2014, pers. comm.). This should be reviewed. Also, the curve of hydraulic conductivity to water content may be accurately fitted for low water contents, such as cleared dryland (P Cook (CSIRO) 2014, pers. comm.), but may not be accurate for high RZD of irrigated areas.

Soil parameters assume that the site is initially in equilibrium with mallee vegetation conditions, i.e. that the soil profile is close to the residual water content, a greenfield site. This will not be applicable where the site:

- Has been used for dryland farming (i.e. was cleared some years previously)
- Has been irrigated previously
- Is subject to flooding
- Is close to an irrigated area where there may have been lateral spread of drainage, e.g. where the irrigation area is underlain by a perched aquifer (as observed at Waikerie–Qualco).

# 2 Stage 3: Recharge to impact at discharge edge

In Stage 2, SIMRAT calculates how long it would take root zone drainage to pass through the unsaturated zone and recharge the watertable, producing a curve for recharge over time. The additional recharge increases the groundwater head gradient between the site and the discharge edge, inducing additional groundwater flux. Stage 3 calculates the additional groundwater flux and multiplies this by the salinity of the regional groundwater resulting in salt load to the discharge edge over time. The GIS version outputs groundwater flux and salt load annually from years 1 to 40 and then decadal from years 50 to 100. SIMRAT-XL outputs the flux and salt load for every year over the next 100 years.

The analytical solution that describes this groundwater discharge is the Unit Response Equation (URE) developed by Knight *et al.* (2002). It describes the instantaneous flux of water to the river over time as a result of a unit recharge step applied at a point. The URE groundwater discharge is a function of the distance between the irrigation area and the nearest discharge edge and is also a function of the aquifer properties such as transmissivity and specific yield. The URE discharge is multiplied by the recharge rate to calculate groundwater flux to the discharge edge over time, then multiplied by the salinity at a point on the discharge edge to obtain the salt load over time.

The discharge edge is considered the sink for groundwater, the location at which all groundwater accessions driven by irrigation activity arrive. Within South Australia, the discharge edge is considered to be the edge of the floodplain based on 1956 flood level. East of Chowilla, where the floodplain is wide and includes some substantial irrigation areas, the discharge edge is considered to be the closest edge of the River Murray.

## 2.1 SIMRAT assumptions and equations

The analytical equations described in this section are from review of Knight *et al.,* (2002) and Rassam *et al.,* (2004).

The Boussinesq equation is a non-linear partial differential equation describing two-dimensional, unsteady flow in a homogenous, isotropic unconfined aquifer (Fetter, 2001). The Boussinesq equation is:

12 $$\phi\frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left(H\frac{\partial h}{\partial x}\right) + K\frac{\partial}{\partial y}\left(H\frac{\partial h}{\partial y}\right) + N(x,y,t)$$

where Φ is the porosity, *K* is the hydraulic conductivity (a constant as the aquifer is isotropic and homogeneous), *H* is the height of the watertable or saturated thickness, *x* and *y* are the Cartesian coordinates of the horizontal plane and *t* is time. *N(x,y,t)* is a source or sink term, describing how groundwater is added or removed (e.g. via surface recharge or wells). If we consider the problem to be purely one dimensional and assume that fluctuations in the watertable, and therefore changes in saturated thickness, are minor compared to the initial saturated thickness of the aquifer, then the governing equation can be linearized and simplified:

13 $$\frac{\partial h}{\partial t} = \frac{K\bar{h}}{\phi}\left(\frac{\partial^2 h}{\partial x^2}\right) + \frac{N(x,t)}{\phi}$$

where $\bar{h}$ is the average height of the watertable or saturated thickness and $h = H - \bar{h}$. The exact solution depends on the initial conditions, boundary conditions, and forms of *N(x,t)*. Equation 13 is identical to the governing equation for confined flow if Φ represents storativity rather than porosity (Haitjema, 1995), hence the same equation can be applied to both unconfined and confined aquifers.

One important property of this equation is that the *principle of superposition* applies. This is the basis for such groundwater modeling approaches as the Analytical Element Method (Strack, 2014). In essence, this means that the head at a given location is the net sum of the individual impacts of various groundwater processes, such as regional flow, wells, and recharge.

To calculate the impact of recharge at a new greenfield site, the solution for a continuous source (step function) *N(a,t) = RZD* for *t>0* is used and *a* is the distance of the irrigation area to the discharge edge. There is a known analytic solution to Equation 13 for the case where *N(x,t)* involves an instantaneous point source at time *t=0*. A boundary condition representing the discharge edge is imposed and the method of images is applied as a means to obtain the solution (Strack, 2014).

The equation for the change in head caused by an instantaneous point source at *x=a* in a semi-infinite, homogenous, non-leaky aquifer where there is a discharge edge of fixed head *x=0* is:

14 $$h_3(x,t) = \frac{1}{2\phi\sqrt{\pi D t}}\left\{e^{\frac{-(x-a)^2}{4Dt}} - e^{\frac{-(x+a)^2}{4Dt}}\right\}$$

where *D* is the diffusivity of the aquifer, which is the transmissivity of the aquifer divided by the specific yield (for an unconfined aquifer) or storativity (for a confined aquifer). This is the *change* in head due to recharge of an instantaneous point source located at *x=a*.

Once the change in head over time is known, Darcy's Law is used to determine the additional discharge to the river/floodplain (at x=0) due to the instantaneous point source:

15 $$F(0,t) = \frac{-a}{2t\sqrt{\pi D t}}\, e^{\frac{-a^2}{4Dt}}$$

where the solution for flux is negative as it is describing groundwater flux to the discharge edge (gaining stream or floodplain). The discharge for a continuous source (such as an irrigation area) can be thought of as the sum of instantaneous sources provided the principle of superposition applies. Hence the change in discharge due to a continuous source is the integral over time of the change in discharge due to an instantaneous point source. The integral of an exponential function of the type described in Equation 15 returns the complimentary error function:

16 $$F_2(a,t) = \int_0^t F(0,\tau)\,d\tau = -\mathrm{erfc}\frac{a}{2\sqrt{Dt}}$$

This is the Unit Response Equation: the groundwater flux to the discharge edge due to a continuous unit source of recharge at *x=a*. That is, it is the discharge due to continuous recharge of 1 unit. Impacts are delayed horizontally as a result of the shape of the erfc function. The value of $F_2$ can be multiplied by the recharge flux (the recharge rate over an area) to calculate the total groundwater flux to the discharge edge. To obtain the salt load to the discharge edge due to the recharge, SIMRAT multiplies the flux by the groundwater salinity at nearest point on the discharge edge.

The Unit Response Equation describing groundwater discharge in response to recharge at an irrigation area is based on the following assumptions:

- Unsteady (transient) flow
- The potentiometric head at the discharge edge does not change over time
- Horizontal, one-dimensional groundwater flow
- No evapotranspiration or other processes which would reduce the volume of water reaching the discharge edge
- Single layer aquifer with no interaction with deeper aquifers (no vertical leakage)
- Aquifer is homogenous and isotropic with a horizontal base
- Vertical head gradients are negligible
- Uniform aquifer properties (such as transmissivity) between the irrigation area and the discharge edge
- Changes in saturated thickness are insignificant relative to the overall aquifer thickness
- The only bound on the aquifer is the discharge edge

- All flow is to the nearest point on the discharge edge
- A positive gradient between the irrigation area and discharge edge is upheld so that all groundwater flow is to the discharge edge and the river or floodplain is always gaining.

Definitions of the parameters are given in Table 2-1. The derivation is provided in Appendix B.

## 2.2 SIMRAT parameters

The following is a list of parameters required by the horizontal response model to calculate salt load impacts at the closest discharge edge. Aquifer properties including hydraulic conductivity, saturated thickness and specific yield are represented within the aquifer diffusivity parameter, given in Equation 16.

There are no fixed parameters in the horizontal response model; the only consideration is that the trend in recharge (according to the wetting function) is read automatically from the outputs of the unsaturated zone model within the SIMRAT code.

**Table 2-1 SIMRAT saturated zone model parameters which are not fixed**

| Parameter description | Source (Excel version) | Source (ArcGIS version) | Symbol | Unit |
|---|---|---|---|---|
| Aquifer diffusivity | User | Data Atlas | *D* | $m^2/y$ |
| Distance to discharge edge | User | Data Atlas | *a* | m |
| Direction to discharge | - | Data Atlas | | |
| Recharge rate over time | Stage 2 | Stage 2 | *R(t)* | mm/y |
| Area of application (irrigated area) | User | User | *A* | |
| Groundwater salinity | User | Data Atlas | - | mg/L |

In SIMRAT-XL, the user specifies the aquifer diffusivity, closest distance between the irrigation area and the discharge edge, area of application (this is the same parameter used in calculation of RZD in Stage 1) and the groundwater salinity.

In the GIS version, the aquifer diffusivity, distance to discharge edge, direction to discharge and groundwater salinity are sourced from GIS layers presented in the Data Atlas. The location of the irrigation site is provided as a polygon coverage. Model parameters from the Data Atlas are clipped within an approximate 500 m buffer of the polygon coverage. For each year, SIMRAT multiplies the discharge from the URE by the average recharge for that decade. This is calculated for each 6.4 ha cell that falls within the trade coverage, and is multiplied by the coincident cell in the groundwater salinity layer to produce salt load. The result for all 6.4 ha cells that fall within the trade coverage are summed to give the total salt load impact for the irrigation area.

The Data Atlas diffusivity layer was generated based on different sources of data for the three states. Within SA this layer was generated by defining broad areas of transmissivity (S. Barnett (DEWNR) 2014, pers. comm.) which were independently reviewed (Fuller *et al.,* 2005d). The transmissivity was then divided by a specific yield of 0.15 to create the aquifer diffusivity layer, therefore the layer assumes uniform aquifer storativity within SA. In Victoria only three zones for diffusivity were developed, which were adopted from mapping completed as part of the Nyah to SA Border Water Trade Model study (Thorne *et al.,* 1990). The diffusivity values are for the shallowest aquifer, which represents the Parilla Sands aquifer in some areas and the Monoman Sands (floodplain aquifer) in other areas. These same three diffusivity zones developed for Victoria were adopted for NSW. The diffusivity data layer was recently updated in the SA extent of the model based on recent hydrogeological investigations, particularly in Salt Interception Scheme reaches (Peat & Yan, 2013). This data layer is yet to be formally adopted.

The Data Atlas distance to discharge edge layer calculates the Euclidian distance between every cell node (centre) to the nearest location of the discharge edge. Within South Australia, the discharge edge is considered to be the edge of the floodplain based on 1956 flood level. East of Chowilla the discharge edge is considered to be the closest edge of the River Murray. The Data Atlas direction to discharge edge relates each cell to its nearest discharge edge based on direction.

The Data Atlas groundwater salinity layer specifies the groundwater salinity of the aquifer at every location along the discharge edge. Within the SA extent this layer was generated using groundwater salinities for year 2000 from the DWLBC database and values were verified against salinity classes in the Murray Basin Hydrogeological GIS Database (AGSO, 1995). In Vic this layer was based on data from the Murray Basin Hydrogeological GIS Database (AGSO, 1995). In NSW the layer was based on salinities from the DLWC database without verification, and where no data are available were based on the assigned values in Vic (Fuller *et al*., 2005d). The groundwater salinity data layer was recently updated in the SA extent so that it is more representative of the groundwater salinity of the regional aquifer (Peat & Yan, 2013). Generally, this resulted in an increase the groundwater salinity along most reaches.

## 2.3 Sensitivity analysis

The URE, Equation 16, shows that discharge to the discharge edge is a function of distance to the discharge edge *a*, aquifer diffusivity *D* and time *t*. Rassam *et al.* (2004) provide a detailed sensitivity analysis of the URE, including a discussion of the non-dimensional version. This is not repeated here.

This section considers the sensitivity of groundwater discharge as calculated by Stages 1 to 3 inclusive, rather than the URE alone. Sensitivity is examined for parameters including irrigation area, root zone drainage, distance between irrigation area and river, and diffusivity. The results are presented as discharge (ML) which is calculated by multiplying the URE by the recharge flux (the recharge rate over an area) and therefore takes the RZD and timelag into account.

The sensitivity results are presented in Figure 2.1 to Figure 2.4. The blue line is the base case in all figures (irrigation area 50 Ha, RZD 125 mm/y, 3000 m distance between irrigation are and discharge edge, diffusivity 100 000 $m^2$/d).

A sensitivity analysis is also presented in Fuller *et al.* (2005c), however results are expressed in terms of EC impact and therefore require careful interpretation.

### 2.3.1 Sensitivity to irrigation area

The sensitivity of the discharge to the irrigation area or trade area is presented for four cases (Figure 2.1). The irrigation area or trade area is multiplied by the recharge rate (the recharge rate over an area) due to a step point source to calculate groundwater flux to the discharge edge. That is, the discharge is linearly proportional to the area. The timelag does not depend on the irrigation area. This simple relationship is included for completeness.

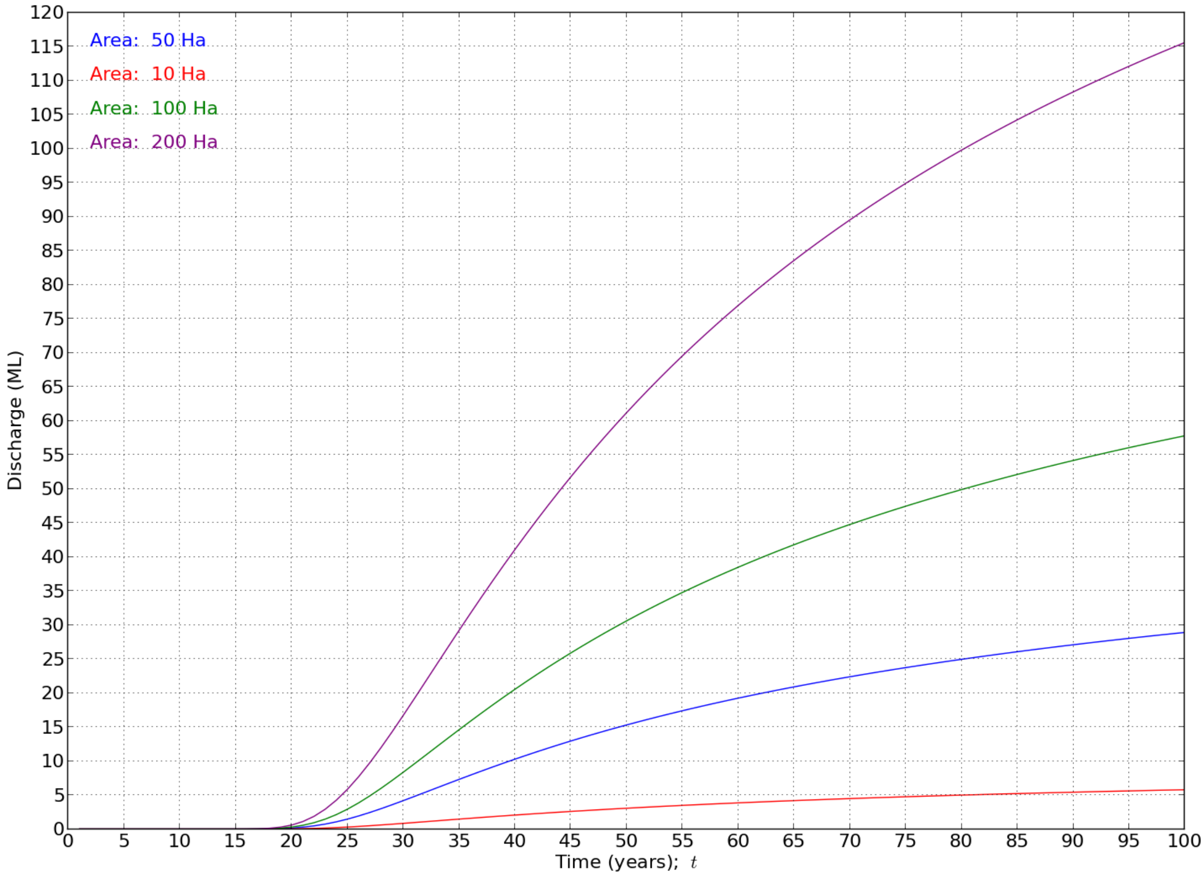


**Figure 2.1 Sensitivity to irrigation area – 125 RZD, 3000 m distance, 100 000 m²/d diffusivity**

### 2.3.2 Sensitivity to root zone drainage

The sensitivity of the model to the root zone drainage rate is presented for four cases ranging from efficient irrigation (75 mm/y) to more inefficient irrigation (300 mm/y). As already demonstrated in Section 4.3, the timelag is sensitive to root zone drainage with increasing root zone drainage, impacts occur sooner and are of greater magnitude. At long times, the groundwater discharge from the aquifer to the discharge edge is directly proportional to the root zone drainage (equilibrium value).

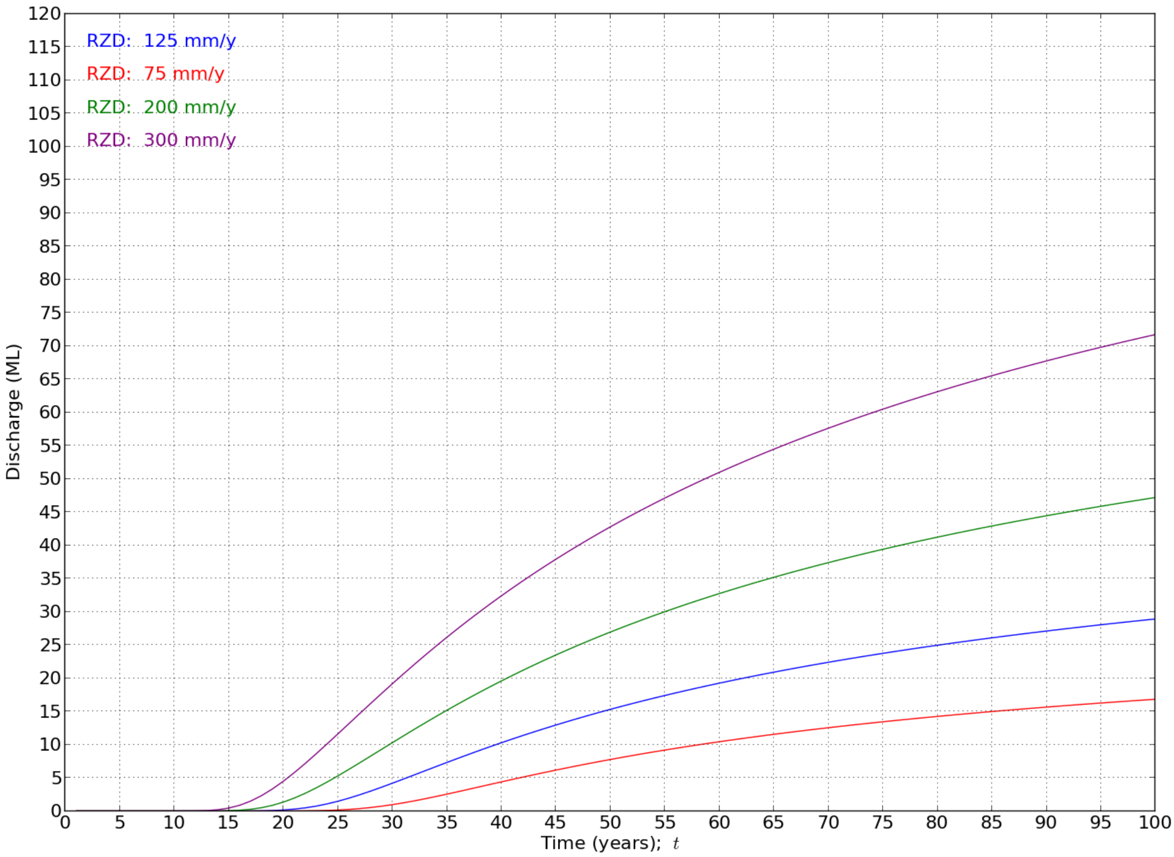


**Figure 2.2 Sensitivity to root zone drainage – 50 ha area, 3000 m distance, 100 000 m²/d diffusivity**

### 2.3.3 Sensitivity to distance between irrigation area and discharge edge

The horizontal response model is sensitive to distance between irrigation area and discharge edge as demonstrated in the trend and magnitude of groundwater discharge to the discharge edge in Figure 2.3. While the vertical timelag does not depend on the distance, the time for the discharge to commence at the discharge edge increases with greater distance from the irrigation area. This is reasonable and expected. Note that none of the scenarios have reached equilibrium after 100 years; in all scenarios the discharge would eventually reach the same equilibrium value.

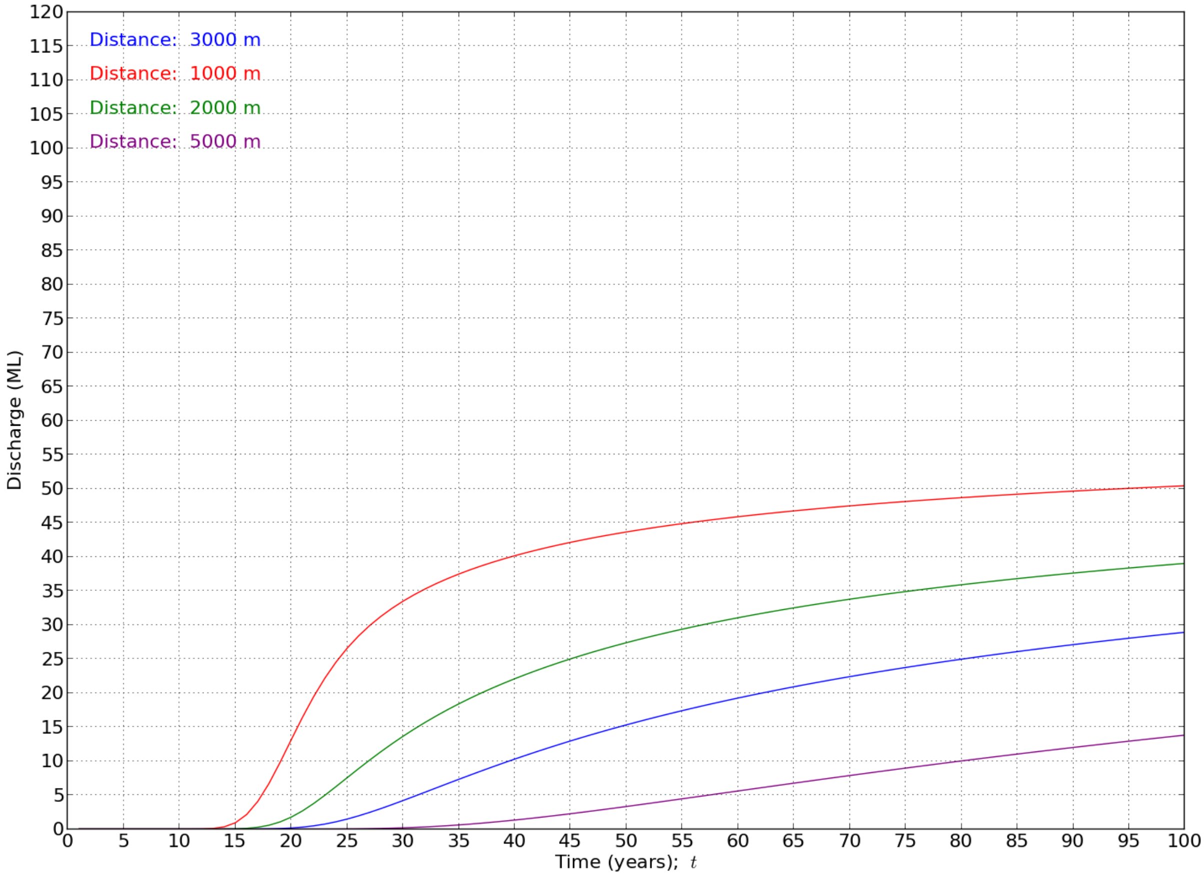


**Figure 2.3 Sensitivity to distance to discharge edge – 125 RZD, 50 ha area, 100 000 m²/d diffusivity**

### 2.3.4 Sensitivity to aquifer diffusivity

The horizontal response model is sensitive to aquifer diffusivity (the aquifer transmissivity divided by the specific yield) as demonstrated in Figure 2.4. The diffusivity is varied between 10 000 – 5 000 000 $m^2/y$, which is the range of most values of the Data Atlas diffusivity layer (Fuller *et al.,* 2005d). With greater aquifer diffusivity impacts occur sooner. The equilibrium discharge will be the same for all cases.

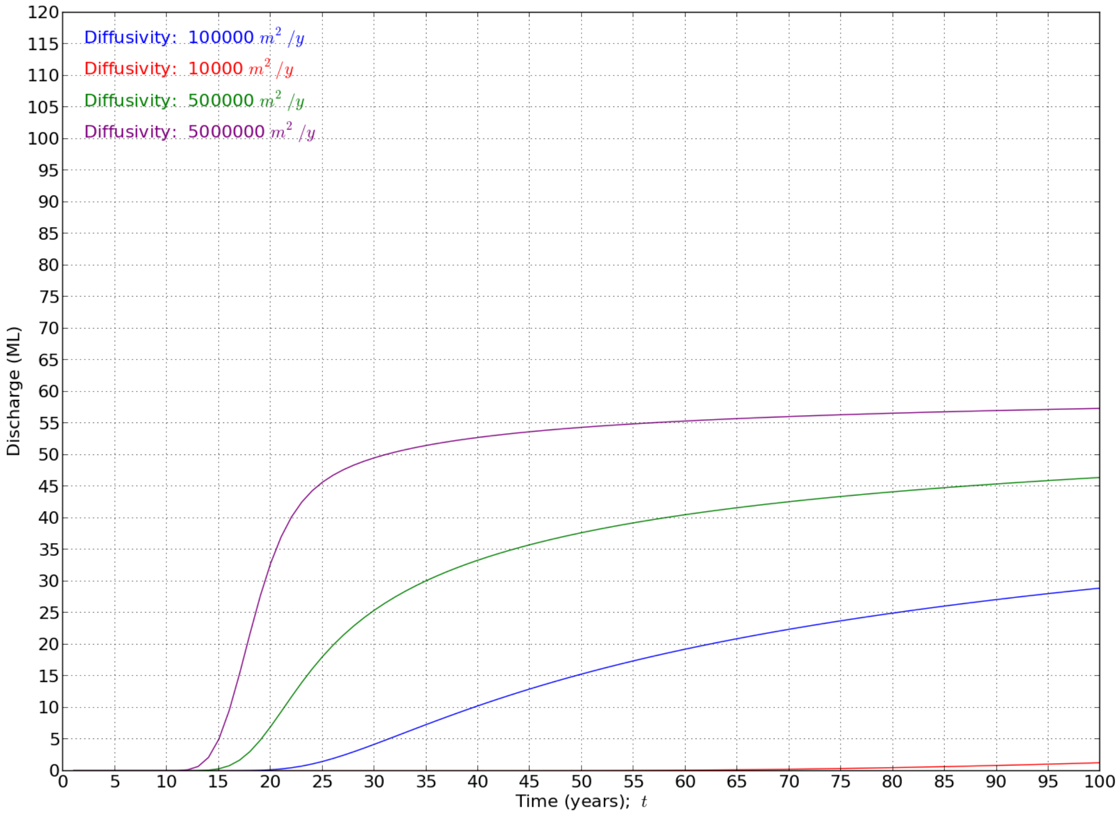


**Figure 2.4 Sensitivity to aquifer diffusivity – 125 RZD, 50 ha area, 3000 m distance**

## 2.4 Discussion

### 2.4.1 Assumption in calculation of groundwater flux

For each year, SIMRAT multiplies the discharge from the URE by the average recharge for that decade. The decadal time steps for the recharge was most likely chosen because it reduces computational overheads; however, this is not documented so the SIMRAT outputs are easily misinterpreted.

The use of decadal changes in recharge to calculate yearly groundwater discharge generates an alternative shape of the discharge curve in the first 30 years (Figure 2.5). The difference between the curves minimizes over time such that there is negligible difference after 30 years for most cases. The difference is also small if the overall groundwater response is small and fairly delayed. This is true for small aquifer diffusivity, greater distance between irrigation area and river.

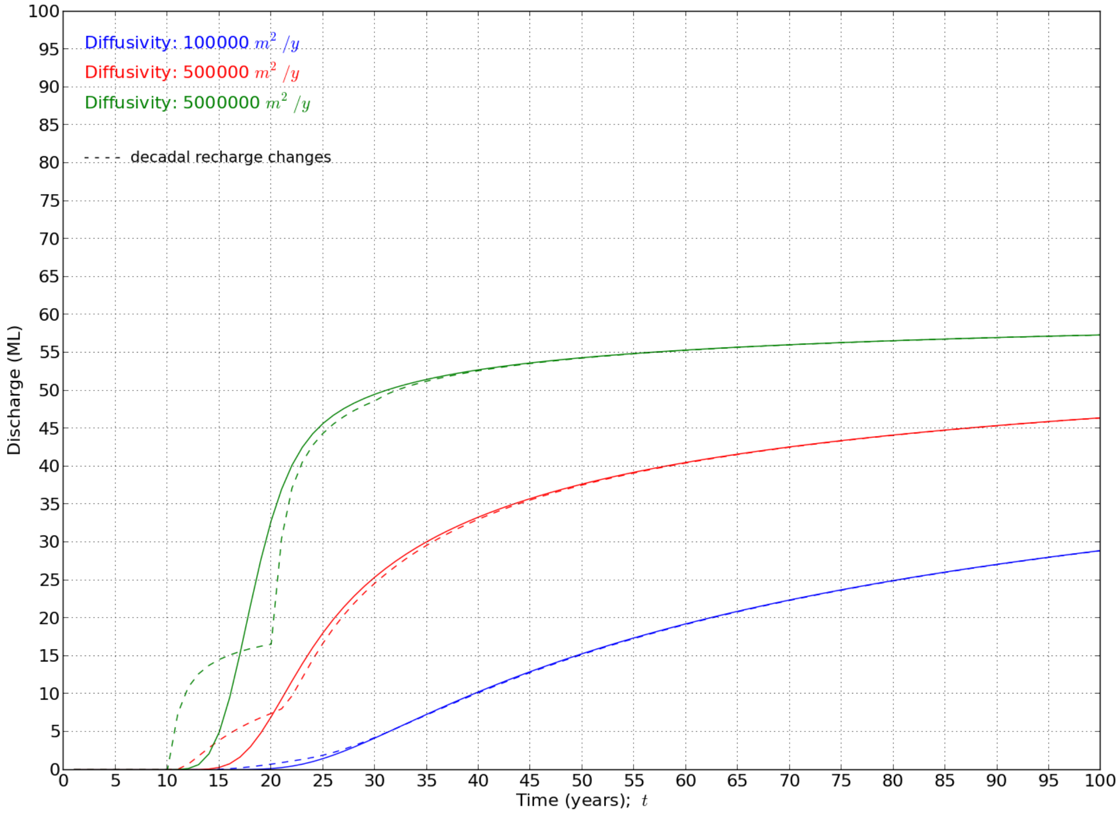


**Figure 2.5 Groundwater discharge calculated using continuous (solid) versus decadal (dashed) recharge changes**

### 2.4.2 Validity of URE assumptions

Conceptually, the horizontal response model describes purely 1D horizontal groundwater flow in a single layer, non-leaky, homogenous and isotropic aquifer, which can be either confined or unconfined. The only bound on the aquifer is the discharge edge, uniform properties are assumed between the irrigation area and the discharge edge and it is assumed that the saturated aquifer thickness does not change significantly.

There are several locations within Mallee region where URE assumptions are not met. These are areas where:

1. The saturated thickness of a shallow unconfined aquifer varies considerably due to the recharge volume, such as at Loxton-Bookpurnong where a groundwater mound has risen 17 m or more above a shallow watertable aquifer of 10 m saturated thickness (AWE, 2002).
2. There are significant bends in the river, particularly relevant for the Sunraysia region of Victoria.
3. The unconfined aquifer thins away from the river so that there is in effect a no-flow boundary parallel and 3 km from the river such as at Boeill Creek, NSW (G Hoxle (Jacobs)y, 2014, pers. comm.).
4. The base of the aquifer is not horizontal, such as west of Wemen, Vic (G Hoxley (Jacobs), 2014, pers. comm.) and at Murtho, SA.
5. there is complex hydrogeology involving multiple leaky aquifers, and the source of discharge to the floodplain may be from a different aquifer than the unconfined aquifer which receives the irrigation drainage. This occurs in Waikerie-Qualco, SA.
6. There is substantial cliff seepage such as at Trentham Cliffs, Victoria.
7. There is substantial surface evaporation and transpiration close to the discharge edge such as near Lake Alexandrina and Lake Albert SA, and areas in Victoria and New South Wales where irrigation occurs on the floodplain and depth to water is shallow.
8. There is significant heterogeneity or geological faulting which may impact flow to the discharge edge (Overland Corner)
9. The groundwater gradient is away from the discharge edge, i.e. where the discharge edge (river or floodplain) is losing, in which case the discharge is a reduction in flow from the discharge edge into the regional aquifer.

Rassam *et al.* (2004) explored the accuracy of the URE for situations (1) to (4) above. Significant errors are observed if:

1. A groundwater mound is greater than 10% above the saturated thickness of the aquifer
2. A meander is closer than four times the closest distance to the river
3. The width of the aquifer is twice the distance from irrigation area to river
4. The aquifer slope is greater than 1.5 degrees.

There are modified versions of the URE which can be used in these cases to give a more accurate result (Rassam *et al.* 2004). These could be incorporated into SIMRAT with minor effort when the code is rewritten in Python, as recommended in Section 5. One way to implement it would be to develop an additional spatial data layer which would specify which equation was most appropriate for each cell. Cases 1 to 3 could be determined using GIS tools, but Case 4 would require additional information, as aquifer stratigraphic surfaces are not part of the current SIMRAT datasets. Aquifer surfaces for the SIMRAT region have been developed for numerical models, which would inform the development of the data layer.

That said, when the errors for these situations are compared with an error range due to a twofold uncertainty in aquifer diffusivity, the error due to the conceptualization is less (Rassam *et al.,* 2004). In many cases, greater improvements are likely to come from improving the SIMRAT input data rather than improving the algorithms (Fuller *et al.,* 2005c).

Modified forms of the URE do not exist for Cases 5 to 9. It may be possible to develop one for a simple leaky aquifer situation (5), based on equations presented in Strack (2014), but not for complicated multilayered situations such as Waikerie–Qualco. Cases 5 to 8 should be identified and the SIMRAT masking layer should be updated to reflect areas in the Mallee where application of the URE is inappropriate. Currently the masking layer only includes areas within 100 m of the floodplain in SA, within 1000 m of the river in NSW and Vic and the Angas Bremer region in SA. Case 9 indicates only that the URE will overestimate the discharge and salt load.

Stage 3 assumes 1D horizontal flow and hence that all discharge occurs to a single point on the discharge edge. The discharge is multiplied by a salinity value typical for the point on the discharge edge. In practice, the discharge will spread radially from the irrigation area and pass into the discharge edge along a reach. Rassam *et al.* (2004) plot the distribution. 50% of the applied flux passes through a reach of the discharge edge that is *2a* wide. The assumption of discharge to a point is only of concern if there are significant changes in salinity along a discharge edge. Few such locations appear in the Data Atlas of salinity, the notable exception being the region in NSW east of Chowilla and west of the Darling River. SIMRAT could be modified to allow for the radial spread of discharge and subsequent range of groundwater salinities.

### 2.4.3 Parameters

The Data Atlas diffusivity layer is a measure of how the aquifer stores and transmits groundwater and will affect the timing and magnitude of groundwater discharge. Aquifer diffusivity is generally defined as the aquifer transmissivity (T) divided by the aquifer storativity (S) (Kruseman & de Ridder 1991). The storativity of a confined aquifer under pressure is considerably less than the storativity of an unconfined aquifer, which is otherwise known as the specific yield. In sandy unconfined aquifers, the specific yield (Sy) is typically similar to the porosity (Φ). In SA the diffusivity layer was developed by firstly defining broad zones of aquifer transmissivity and then dividing them by an aquifer storativity of 0.15, which is a typical value for the unconfined specific yield of a sandy aquifer. In Vic and NSW there are just two diffusivity values for the aquifer in the highland and a uniform diffusivity for the floodplain aquifer.

The diffusivity data layer should be updated to consider pathways for discharge to the floodplain in SA. Several hydrogeological investigations at key sites have been undertaken since the diffusivity data layer was developed. These hydrogeological investigations, typically associated with Salt Interception Scheme design and construction, have improved the conceptual hydrogeology in many areas of the Riverland. West of the Hamley Fault the regional watertable lies in the Murray Group Limestone and in areas such as Waikerie–Qualco there are multiple leaky aquifers that are sub units of the Murray Group. The uppermost aquifer receives the irrigation drainage however it is the deeper confined aquifer that contributes the majority of discharge to the floodplain. Hydrogeological investigations have demonstrated that discharge from the deeper confined aquifer to the floodplain aquifer is vertical (upward leakage). The consideration that recharge to the unconfined aquifer may incur a pressure response resulting in discharge from the confined aquifer will affect the timing and magnitude of groundwater discharge. This type of data and information should be considered when updating the diffusivity layer.

Recently, the diffusivity data layer in SA was updated with data from accredited groundwater models, assuming that these models incorporate the most up to date hydrogeological data and were calibrated to the best available data. The aquifer diffusivity ranges between 5000 $m^2$/d and 1 527 000 $m^2$/y (Peat & Yan, 2013). There is more reliable data and information that can be incorporated into the diffusivity layer in Vic and NSW. The diffusivity layer should be updated based on the current conceptual hydrogeology and drilling data reviewed during the development of the Eastern Mallee groundwater models.

The Data Atlas groundwater salinity layer is used to calculate the salt load impacts at the discharge edge. The groundwater salinity layer appears to adopt a level of detail and variation associated with extrapolation of borehole data in SA, Vic and NSW. In SA the discharge edge is the edge of the floodplain and therefore the groundwater salinity layer should reflect the native groundwater salinity in highland areas close to the floodplain (Peat & Yan, 2013). In some areas the groundwater salinity layer appears to be influenced by floodplain aquifer salinities and therefore should be revised. Recently, the groundwater salinity layer was updated in SA with salinity data extracted from the DEWNR database (Peat and Yan, 2013). The salinity data were processed to consider the aquifer that is the primary source of discharge, ignoring floodplain aquifer salinities, influence of SIS and freshening due to irrigation drainage. The groundwater salinity in SA ranges between 1 000 and 44 000 mg/L (Peat and Yan, 2013). The updated groundwater salinity layer from Peat and Yan (2013) is available for SA. In Vic and NSW the groundwater salinity layer should be updated based on the recent data and information considered in development of the Eastern Mallee groundwater models. It is expected that more salinity data should be available in Vic and NSW since the layer was developed, particularly along SIS reaches.

The Data Atlas masking layer considers where the SIMRAT model should not be used and includes areas within 100 m of the floodplain in South Australia, within 1000 m of the river in New South Wales and Victoria and the Angas Bremer region in South Australia. There are several situations where URE assumptions are not met or there are additional boundary conditions which are not included in the formulation of the standard URE, as outlined in section 2.4.2. It is recommended that a new data layer is developed in Stage 2 which can provide an indication of the reliability of the result. This reliability layer should consider areas where there are gaps in hydrogeological data as well as areas where the URE assumptions are not met. In these areas the reliability should be regarded as poor. This will give additional information for the states to interpret and use.

The data used to create the diffusivity and salinity data layers are not fully documented in the *Data Atlas*. It is recommended that when the Atlas is updated that further detail be included. For example, the salinity values used to create the layer could be plotted. The aquifer conductivity, aquifer saturated thickness and storativity values used to create the aquifer diffusivity layer should be documented.

# 3 Stage 4: River connectivity and floodplain attenuation

Stage 4 attempts to account for complicated processes occurring within the floodplain that may limit groundwater discharge to the discharge edge from reaching the river.

In NSW and Victoria, the Parilla Sands aquifer is occasionally separated from the river by a clay layer (Fuller *et al.*, 2005c). In other areas the river partially penetrates the aquifer, and groundwater flow gradients do not indicate a groundwater divide at the river (Fuller *et al.*, 2005d). The partial hydraulic connection of some aquifers with the river is addressed by the use of a river connectivity factor (RCF). The RCF represents the resistance to groundwater flow between the river bed and the aquifer. This resistance may be due to the properties of the river bed itself (silty or clayey sediments, sometimes called river skin) or the properties of the material that the river partially or fully penetrates.

The floodplain attenuation factor (FAF) accounts for storage of salt in the floodplain. This attenuation process describes the storage of groundwater and salt in the floodplain aquifers and backwaters at low flows that are mobilized to the river at high flows (Fuller *et al.*, 2005c).

## 3.1 SIMRAT assumptions and parameters

The river connectivity factor (RCF) and floodplain attenuation factor (FAF) are specified by the user in SIMRAT-XL and are read from the Data Atlas for the GIS version of SIMRAT (Table 3-1). The river connectivity factor varies between 0 % (fully disconnected) and 100 % (fully connected). The floodplain attenuation factor varies between 0 % (all salt is stored in floodplain and none reaches the river) and 100 % (no salt is stored in floodplain therefore all salt reaches the river).

**Table 3-1 SIMRAT Stage 4 parameters**

| Parameter description | Source (Excel version) | Source (ArcGIS version) | Symbol | Unit |
|---|---|---|---|---|
| Salt load to discharge edge | Stage 3 output | Stage 3 output | - | t/d |
| River connectivity | User | Data Atlas | *RCF* | % |
| Floodplain attenuation | User | Data Atlas | *FAF* | % |

The Data Atlas river connectivity layer was developed using professional judgment taking into account models and other studies in the region (Fuller *et al.*, 2005c). The river connectivity is assumed to be 100% along the reach of river in SA, except the Lower Lakes where a RCF of 0% is assumed. The river connectivity varies between 0% and 100% along river reaches in Vic and NSW. The river connectivity is equivalent on opposite sides of the river, in other words for any reach of river the same RCF is applied in Vic as NSW. Note that for all current uses of SIMRAT in NSW, the Data Atlas river connectivity layer is disregarded and complete hydraulic connection (100%) between the aquifer and river is assumed.

The Data Atlas floodplain attenuation layer has a value of 100% everywhere, therefore assuming no floodplain attenuation. Given the complex nature of processes occurring in the floodplain, it was considered that SIMAT should adopt an FAF of 100% until more data becomes available or more complicated algorithms can be included in the SIMRAT code (Fuller *et al.*, 2005c).

## 3.2 Discussion

The Data Atlas river connectivity layer was developed on the basis of expert knowledge and there is no documented approach to the development of this layer. It was acknowledged at the time that estimates could be refined with a more comprehensive approach in the future (Fuller *et al.,* 2005d). It was suggested that the river connectivity factor should be reviewed during future work programs (Aquaterra Simulations, 2003). Given that complete hydraulic connection between the aquifer and the river is assumed for SA and NSW, and SIMRAT is not used to assess salinity impacts on the river in Vic (see Sect. 6.2.3), the inclusion of river connectivity as a Data Atlas layer is not explicitly required.

At the time of Data Atlas development, floodplain attenuation processes were the subject of ongoing research and were therefore incorporated into SIMRAT in a very basic mode with a design for easy upgrade in the future (Aquaterra Simulations, 2003). It is expected that any salt stored in the floodplain will be mobilized during floods and that salt storage in the floodplain may affect the timing of salinity impacts but not the overall magnitude of the impact. It is not possible to predict in advance the timing of the salt impacts due to flooding as it depends on weather and climate.

Unless there is compelling evidence that salt is stored permanently in parts of the floodplain, it is suggested that the FAF remain fixed at 100% or be removed from SIMRAT entirely. The conservative assumption is to assume that all additional groundwater salt flowing through the discharge edge will eventually flow into the river.

It is still presumed that all of the additional salt is eventually mobilized to the River Murray, except where river connectivity is less than 100%. (In actuality, some of the salt may be intercepted by SIS, but the purpose of SIMRAT is to estimate the additional discharge of salt for the Salinity Registers. The impact of SIS is calculated using other tools.)

# 4 Stage 5: Conversion to assessment units

In Stage 5, salt load impacts at the river are translated into EC impacts at Morgan and economic costs to downstream users.

## 4.1 SIMRAT assumptions and parameters

EC impacts at Morgan and associated economic costs are calculated using relationships derived from MSM-BIGMOD modelling. MSM-BIGMOD is an MDBA flow model for the entire Murray–Darling system which converts Monthly Simulation Model (MSM) output to daily timesteps via BIGMOD. The BSMS Operational Protocols include a Ready Reckoner (Appendix 3.8, Table 1) to convert salinity impacts in tonnes per day to EC impact at Morgan and Cost to Downstream Users. The Ready Reckoner values documented in the SIMRAT User manual (Data Report and Atlas, 2005) are sourced as 'Oscar Mamalai, pers. comm., 9th Feb 2005' and differ from those in the BSMS Operational Protocols (MDBC, 2005). It is thought that the values presented in the SIMRAT user manual (dated May 2005) were documented prior to the adoption of the values listed in the BSMS Operational Protocols (dated March 2005). It is noted that the SIMRAT output provided to the MDBA for inclusion on Salinity Registers is the Stage 4 output (impact in tonnes per day) which is then converted to EC at Morgan by MDBA using MSM-BIGMOD. The SIMRAT conversions to EC and $-cost values are used as indicative estimates by the states, prior to receiving the MSM-BIGMOD converted estimate.

The parameters used in Stage 5 are summarized in Table 4-1 and explained below.

**Table 4-1 SIMRAT Stage 5 parameters**

| Parameter description | Source (Excel version) | Source (ArcGIS version) | Symbol | Unit |
|---|---|---|---|---|
| Salt load to river | Stage 4 output | Stage 4 output | - | t/d |
| Reach of river | Input menu option | location of input polygon | - | - |
| EC at Morgan per 100 t/d | Lookup Table | Data Atlas | *EC* | µS/cm |
| Cost to Downstream Users | Lookup Table | Data Atlas | *$* | $ |

In SIMRAT-XL, the EC impacts at Morgan (per 100 t/d) and the costs to downstream users ($) between river reaches are included as a lookup table. The data in this lookup table is sourced from Oscar Mamalai (pers. comm., cited in the SIMRAT Data Report and Atlas, 2005). The reach of river to be assessed is included in SIMRAT-XL as a drop down menu option. It is recommended that this lookup table is updated to reflect the values in the MDBC Ready Reckoner documented in the BSMS Operational Protocols, which relates MSM-BIGMOD calculations of EC increases for flows of less than 10 000 ML/d to an equivalent EC and economic costs to downstream users.

In the GIS version, the EC impacts at Morgan and economic costs to downstream users can be sourced from layers in the Data Atlas. These data layers are based on the same information used for SIMRAT-XL. To create the Data Atlas layer, the conversion values were specified at the start and end reach and then linearly interpolated along the river for each river kilometre. It is recommended that the conversion values are realigned with the Ready Reckoner documented in the BSMS Operational Protocols and the data layers recreated.

## 4.2 Discussion

The accuracy of data depends on other models and functions. A review of these models is considered to be out of the scope of this review.

Where SIMRAT is used to assess the salinity impacts of new irrigation in NSW and SA (its accredited purpose) the conversion to assessment units is not performed by SIMRAT. Instead, the Stage 4 outputs (salt load impacts in t/d) are provided to the MDBA to run MSM-BIGMOD to translate into EC impacts at Morgan and economic costs to downstream users. Currently, SIMRAT Stage 5 has relatively limited applications, primarily to provide an indication within the states of likely EC implications for State Salinity Register balances. It is recommended that the Data Atlas layers are updated to reflect the current Ready Reckoner conversion values, documented in the BSMS Operational Protocols, 2005.

# 5 GIS implementation

The GIS version of SIMRAT is a spatial modelling tool that is currently used within the three states (SA, NSW and Vic) for several purposes which are outlined in Section 9. Considering its validity as a rapid assessment tool, it is expected that SIMRAT will be used for those purposes until better tools or methods become available in the future.

## Configuration of the current GIS version of SIMRAT

The GIS version of SIMRAT currently operates on an ESRI ArcInfo Workstation 9.3 platform. It uses a set of scripts written in Arc Macro Language (AML) to perform data processing and prepare outputs such as maps and tables. An additional plug-in for ArcInfo called Ghostscript is required to print maps to pdf.

Most of the assessment part of SIMRAT is contained within a single AML script. Calculation of recharge to the watertable over time according to the recharge wetting function is coded in a separate script, with the intention that an alternative algorithm could be implemented easily in the future.

To enable flexibility, the SIMRAT code allows a number of variables to be read from input tables instead of being hard coded within the script(s). Soil parameters, percent root zone drainage, defined years of reporting and paths to spatial data layers are contained in input tables which are read by the code. The user can enter the root zone drainage directly or let SIMRAT perform the calculation based on trade volume, rainfall and percent root zone drainage. Before SIMRAT is run there is additional functionality to validate all data inputs, which is coded as a separate script (Miles & Vears, 2005).

To assess the impact of new irrigation developments arising from water trade, the program requires the user to create a polygon coverage representing the area(s) of application. The GIS version of SIMRAT allows for single trades (single polygon coverage) or multiple trades to be assessed (batch mode). Input grids are clipped to a 500 m buffer of the polygon coverage. SIMRAT creates a spatial output of salinity impacts. The salinity impact for all cells within the buffered polygon coverage are added together to give the overall salinity impact for the new irrigation area. After the assessment phase of SIMRAT is complete, maps and trade summary sheets can be automatically generated by calling various scripts from the menu (graphic user interface).

Archiving of SIMRAT inputs and outputs requires separate data management practices external to the function of SIMRAT (Miles & Vears, 2005).

## The need for an alternative GIS platform

As a commercial GIS software provider that licenses its products, ESRI have the entitlement to add and drop platforms and functionality at each release based on customer needs and technology trends (ESRI, 2012). ESRI have implemented depreciation plans for their GIS software which is outlined in its ArcGIS Product Lifecycle Support Policy (ESRI, 2014). As of 31 December 2012, ArcInfo Workstation 9.3 was retired. ArcInfo Workstation 10.0 is the final release of ArcInfo Workstation and is currently in the mature phase of the product lifecycle, with the likelihood that it will be retired sometime in the near future. Retirement of an ESRI product means that support for this product is withdrawn, with software patches no longer available and technical support no longer provided.

In recognition that ArcInfo Workstation will no longer be supported, there is a requirement for SIMRAT to be moved to a new platform. This is proposed for Stage 2 of this project and is required if SIMRAT is to be used in any capacity in the future.

## Discussion of alternative platforms

GIS experts within NSW and SA including Greg Smith (GIS Manager, NSW OW), Tim Noyce (Senior GIS Advisor, DEWNR) and Xen Markou (Spatial Data Administrator, DEWNR) provided specialist advice on the most appropriate model platform. Thomas

McAdams (Mallee CMA) and Louise Sullivan (DEPI) were consulted to determine the GIS software that is currently used in Victoria. When determining an appropriate alternative platform for SIMRAT, consideration is given to:

- The current uses of SIMRAT
- The GIS software currently used by the states
- The viability of alternative software (commercial and open source)
- Software linkages, dependencies and level of licencing required
- The resource needs and level of technical support required
- The level of training required for staff in use of the software
- The likelihood of available functionality with subsequent version upgrades.

There are several commercial and open source GIS software providers that may offer the functionality required to host SIMRAT. In consultation with GIS specialists in all three states (SA, Vic and NSW) it was determined that all have existing contracts with ESRI and work within the ESRI domain. The use of open source software as an alternative platform is only considered desirable if SIMRAT is to be distributed as a product. The GIS version of SIMRAT is run by the three states and outputs are distributed on a needs basis. As there is no current need for the GIS version of SIMRAT to be distributed as a product, open source software is not considered a viable alternative platform for SIMRAT.

All states are planning to upgrade to ArcGIS version 10.2.x within the next 12 months. Commonality between the states in use of GIS software exists and staff familiarity with this software reduces the need for additional training. States have yet to decide if ArcGIS version 10.2.1 or 10.2.2 will be adopted, so care would need to be taken to make the updated code work on all 10.2.x platforms.

There may potentially be some loss of functionality in subsequent versions of ArcGIS, and the risks this imposes must be considered. Software upgrades are unfortunately unavoidable and some loss of functionality is inevitable. ESRI have a detailed product lifecycle support policy (ESRI, 2014) that stipulates a staged approach to software depreciation, so that functionality is not abruptly withdrawn but is gradually phased out. ESRI have stipulated that ArcGIS version 10.2.x will be retired on 1 August 2019. If ArcGIS v10.2.x is considered the appropriate alternative platform for SIMRAT, the rewritten code may need to be updated and tested within the next five years to verify that it runs within newer versions of ArcGIS. The risks imposed by functionality losses may be minimized if SIMRAT is coded using Python, as ESRI has expressed that Python will be the scripting language of choice going forward.

Python is a popular open source programming language which includes a standard library of packages that provides a number of tools and methods. ArcPy is a package that was introduced by ESRI in ArcGIS version 10.0. The ArcPy package provides a useful and productive way to perform data analysis, data conversion, data management and map automation with Python. ArcPy provides access to geoprocessing tools as well as additional functions, classes and modules allowing the user to create simple or complex workflows quickly and easily.

The use of Python within the ArcGIS environment is extremely powerful. It is considered likely that, subsequent to ArcGIS v10.2, the functionality of ArcPy is likely to expand even further. Python and some other commonly used but non-standard modules (such as NumPy) are within the standard installation package for ArcGIS v10.0.x and newer versions. The substantial functionality of ArcPy means that additional plug-ins for SIMRAT are unlikely to be required, with the exception of some graphing and plotting packages, for which Python modules may need to be installed separately. The need for these additional packages will depend on the scope for Stage 2 and the future intended use of SIMRAT.

The level of complexity and flexibility required within the SIMRAT interface will depend on the scope of the Stage 2 project and ultimately on the intended use of SIMRAT. The graphical user interface (GUI) could be developed as:

- VB.net or C#.net plug-in that references the Python script(s)
- Python script tool(s) in a custom toolbox
- Python toolbox
- Python add-in developed using the ESRI Python add-in wizard.

Taking advantage of the available functionality of Python within ArcGIS would reduce the need for additional software (such as Visual Studio software for VB.net) and would reduce the need for additional coding skills. The advantage of creating script tools is, visually and in terms of their use, they are similar to any other tool available in the ArcGIS toolbox.

To determine the appropriate platform and coding for SIMRAT, the level of licensing and extensions required must be considered. The levels of licensing considered are the standard ArcGIS for Desktop (formerly ArcEditor) and advanced ArcGIS for Desktop (formerly ArcInfo). Currently SIMRAT operates on an ArcInfo Workstation which requires an advanced level of license to be able to run the AML scripts. Most GIS users within the states (SA, NSW and Vic) have access to the standard level of license and a restricted pool of users have access to the advanced level of license using a concurrent license manager. The functionality of Python with ArcGIS offered under the standard level of licensing is likely to be sufficient to code SIMRAT for the intended use. It is likely that the Spatial Analyst extension will be required for raster geoprocessing and statistical analysis.

## Recommendations for Stage 2

Based on initial investigations it is considered that standard ArcGIS for Desktop v10.2 is the most appropriate alternative platform for SIMRAT, given that the states (SA, Vic and NSW) are familiar with this software and are working toward upgrading to a common version (ArcGIS v10.2.x) within the next 12 months. Python is considered the most efficient and appropriate programming language to recode SIMRAT. ESRI have expressed that Python is the scripting language of choice going forward, and there is ample functionality currently offered within the ArcPy library that is likely to expand further with subsequent versions of ArcGIS. The most cost effective option is for SIMRAT to operate under a standard level of licensing. Initial investigations indicate that the current functionality of SIMRAT could be rewritten using Python and could run under a standard ArcGIS license with the spatial analyst extension required. It is recommended that further investigations are undertaken in Stage 2 to confirm this.

It is recommended that the Stage 2 scope is clearly defined during the initial phase of the project, as the scope will strongly influence how the new SIMRAT program is designed. The scope should be constrained to only consider the future intended uses of SIMRAT and how much user interaction is required. A clearly defined and limited scope would help to avoid overcomplicating the design of the SIMRAT program and to avoid including functionality that has limited use, knowing that some processes in the original SIMRAT program are now redundant. The graphic user interface could be built using an alternative programming language such as VB.net or C#.net but the most viable and efficient method would be to use existing functionality within ArcGIS and use Python to create an add-in or tool. This requires further investigation in Stage 2 of the project.

Within the scope and costing for Stage 2 it is recommended that consideration is given to testing the SIMRAT program and verifying its outputs. The outputs should be benchmarked against original outputs for a combination of input parameters. This would require the original AML code to be rerun several times on the original ArcInfo Workstation platform. It is recommended that the cost of updating and maintaining code with each subsequent update of ArcGIS is considered in Stage 2. It is likely that the states may upgrade to a newer version of ArcGIS before ArcGIS version 10.2 is schedule to retire, therefore there is a need to ensure the new SIMRAT tool works across newer releases. The management of SIMRAT input and output data should also be considered in Stage 2 of the project.

# 6 Current use of SIMRAT

As described below, the SIMRAT model has been applied by all three states for the purpose of Salinity Register entry calculations. Table 6-1 summarises the 2013 Salinity Register entries in which the SIMRAT model has been utilized in either its primary or secondary application, defined as:

- Primary – Stage 4 model output (salinity impact in tonnes per day) has directly informed a register entry or;
- Secondary – Stage 3 model output (timelag) has informed a groundwater model, which has directly informed a register entry.

**Table 6-1 Salinity Register entries which utilize SIMRAT**

| 2013 Register # | Entry description | Use of SIMRAT:<br>Primary, Secondary (timelag) or Not Used |
|---|---|---|
| | **AUTHORITY REGISTER A** | |
| | **JOINT WORKS & MEASURES** | |
| | **Former Salinity & Drainage Works** | |
| 1 | Woolpunda SIS | Not used in current entry.<br>When entry updated with the 5 Year Review this entry will have Secondary (timelag) use of SIMRAT |
| 4 | Waikerie SIS | Not used in current entry.<br>When entry updated with the 5 Year Review this entry will have Secondary (timelag) use of SIMRAT |
| 8 | Waikerie Phase 2A SIS | Not used in current entry.<br>When entry updated with the 5 Year Review this entry will have Secondary (timelag) use of SIMRAT |
| | **Basin Salinity Management Strategy** | |
| 12 | Bookpurnong SIS | Secondary (timelag) |
| 14 | Loxton SIS | Secondary (timelag) |
| 15 | Waikerie Lock 2 SIS | Not used in current entry.<br>When entry updated with the 5 Year Review this entry will have Secondary (timelag) use of SIMRAT |
| | Murtho SIS | Low confidence entry in 2014 based on 2006 model and 5 Year Review entry in 2015 based on 2014 model.<br>Both have Secondary (timelag) use of SIMRAT. |
| | **STATE WORKS & MEASURES** | |
| | **New South Wales** | |
| 24 | NSW Sunraysia Irrigation Development 1997 to 2006 | Primary (SIMRAT output) |
| | **South Australia** | |
| 43 | SA Irrigation Development Based on Footprint Data | Secondary (timelag) |
| 44 | SA Irrigation Development Due to Water Trade | Primary (SIMRAT output) |
| 45 | SA Irrigation Development Based on Site Use Approvals | Primary (SIMRAT output) |

| 2013 Register # | Entry description | Use of SIMRAT: Primary, Secondary (timelag) or Not Used |
|---|---|---|
| 46 | SA Component of Bookpurnong SIS | Secondary (timelag) |
| 47 | SA Component of Loxton SIS | Secondary (timelag) |
| 48 | SA component of Waikerie Lock 2 SIS | Secondary (timelag) |
| 49 | SA Improved Irrigation Efficiency and Scheme Rehabilitation Reg A | Secondary (timelag) |
| 50 | Qualco–Sunlands GWCS | Secondary (timelag) |
| 51 | Pike Stage 1 SIS | Secondary (timelag) |
| | SA Component of Murtho SIS | Low confidence entry in 2014 based on 2006 model and 5 Year Review entry in 2015 based on 2014 model.<br>Both have Secondary (timelag) use of SIMRAT. |
| | **AUTHORITY REGISTER B** | |
| | **New South Wales** | |
| 63 | NSW Mallee - dryland | Secondary (timelag) |
| | **Victoria** | |
| 70 | Victorian Mallee - dryland | Secondary (timelag) |
| | **South Australia** | |
| 72 | SA Mallee Legacy of History - Dryland | Secondary (timelag) |
| 73 | SA Mallee Legacy of History - Irrigation | Secondary (timelag) |
| 74 | SA Improved Irrigation Efficiency and Scheme Rehabilitation Reg B | Secondary (timelag) |

## 6.1 South Australia

As documented in Section 2.2, South Australia initially developed the pilot model and further refined into the SIMPACT I and SIMPACT II models.

SIMRAT was developed by the Murray–Darling Basin Commission and was accredited in 2005 to assess the salinity impacts of water trades in the Mallee Zone. Since then, South Australia has utilised SIMRAT for the provisional assessment of the salinity impacts of permanent water trade (up to 2009) and Site Use Approvals (since 2009). The SIMRAT assessments are used as annual/interim entries on the Salinity Registers until they are ultimately replaced by the output of the suite of numerical (MODFLOW) groundwater models, which are updated with the current irrigation footprint at intervals of approximately five years.

SIMRAT is also applied for other purposes in South Australia, notably:

- Time series of spatially variable dryland clearing recharge – for input to numerical models to evaluate the effects of dryland Mallee clearing (note that these numerical models undergo their own accreditation by MDBA).
- Timelag estimation – for input to (accredited) South Australian numerical models as an initial estimate of the time taken for irrigation recharge at the surface to arrive at the watertable (this initial estimate is usually adjusted during numerical model calibration to match measured groundwater levels; this approach is not applied in NSW or Victoria). Note that these numerical models undergo their own accreditation by MDBA.
- Assessment of revegetation options to reduce salt loads to the River Murray
- Salinity Impact Zoning – to guide identification of high and low salinity impact areas within 15 km of the floodplain to support the River Murray Salinity Zoning Policy (Miles, 2005). Noting that the SIMPACT II model was used for this purpose, which in SA, is the same as SIMRAT.

### 6.1.1 SIMRAT basis for interim SA Register entries

SIMRAT has been applied in SA to assess the salinity impacts of new irrigation development to comply with Schedule B accountability requirements and to administer licensing approvals: this is referred to as the primary use of SIMRAT in Table 9-1. The assumptions used in these assessments are documented in the BSMS Operational Protocols, e.g. application rates of 10 ML/ha and drainage rates of 10% of application (therefore Stage 1 of SIMRAT adopts a constant 100 mm/y drainage value). The SIMRAT results are compiled into *South Australia's Annual Report on Implementation of the BSMS* and are submitted to the MDBA annually for inclusion in the Salinity Registers.

This method has been applied to permanent water trades for the period 1988 to 2009 (Entry 44 on the Salinity Register) and to Site Use Approvals (SUA) (Entry 45 on the Salinity Register) following the unbundling of South Australian River Murray water licenses on 1 July 2009. The SUA represents the permission to use water at a particular site in a specified manner. Since 2009, the SUA has replaced traded water volumes as the basis for BSMS accounting using the SIMRAT model and to administer licensing approvals. The SUA represents the maximum amount of water that can be applied at a specific site, and thus a salinity impact assessment based on this volume will estimate the maximum potential impact, consistent with BSMS principles.

The SIMRAT-based entries are retained on the Salinity Registers for approximately five years, until they are replaced by numerical groundwater model assessments (Entry 43 on the Salinity Register).

In 2011, to facilitate an efficient salinity impact assessment process for an individual SUA, the SIMRAT model was used in a compilation model run of the entire South Australian Murray–Darling Basin (within the SIMRAT boundary). The compilation run assumed 100 mm of root zone drainage per annum (10% of 10 ML/ha) to all areas. The SIMRAT output was then compiled into a single spatial GIS layer, with individual grid layers representing salinity impact at annual increments to year 40 then at 10 year intervals to 100 years. Querying of the compiled SIMRAT output layer to inform salinity impact assessments has removed the need to run the SIMRAT model for each assessment and has reduced the time required to run each assessment from approximately 15-20 minutes to less than two minutes.

### 6.1.2 SIMRAT inputs to SA numerical models for irrigation and dryland clearing scenarios

South Australia has developed a suite of numerical groundwater models that span the SA River Murray from the border to Wellington. These numerical models provide Salinity Register entries of salinity impacts due to land clearance, irrigation development and salt interception schemes. SIMRAT provides inputs to these models for spatially variable recharge time series for Mallee dryland clearing scenarios, and for initial timelag estimates for irrigation recharge scenarios. This is referred to as 'secondary use' of the model in Table 9-1.

For irrigation scenarios, the numerical models use an initial estimate of irrigation recharge timelag calculated by SIMRAT and assuming 125 mm/y root zone drainage applied to spatial zones representing irrigation commencement/development. The timelags are adjusted during numerical model calibration (usually shortened substantially) so that the numerical model history match agrees with measured potentiometric heads. The assumption of 125 mm/y root zone drainage is likely to be an underestimate for typically inefficient historical irrigation (which often used flood irrigation methods), and possibly an over-estimate for more recent efficient irrigation methods. Overall, the assumption is considered reasonable to achieve an efficient tractable solution over a wide time scale and regional extent. While SIMRAT provides these initial estimates of irrigation recharge timelags, other water balance methods are used to estimate the rate of recharge (i.e. SIMRAT recharge rates are not applied to irrigation recharge in numerical models).

For future irrigation, the numerical models consider the geographical location of the land parcel and its proximity to established irrigation areas to estimate irrigation recharge timelag. For example, if the future irrigation area is located in close proximity or is surrounded by well-established irrigation areas, and monitoring data suggests the watertable is responding to irrigation recharge, then zero timelag is assumed. If the future irrigation area is distant from existing irrigation areas and unlikely to be impacted by existing irrigation recharge, the numerical models use an estimate of timelag calculated by SIMRAT assuming 125 mm/y root zone drainage.

For the dryland clearing scenarios of (accredited) numerical groundwater models, the SIMRAT-calculated values of both the timelags and the spatially variable recharge rates are used as inputs, assuming clearing starts in 1920. The SIMRAT outputs are then input to the numerical (MODFLOW) model scenarios for Mallee clearing, with uncleared areas assumed to receive 0.1 mm/y recharge and cleared areas between 0.1 mm/y and 10 mm/y recharge. This approach has also been applied to numerical modelling studies of Sunraysia Mallee clearing scenarios (Aquaterra, 2009a). The approach has successfully passed independent peer review for all SA numerical model areas and the Sunraysia EM1.2 model used for Schedule B assessments.

### 6.1.3 Assessment of revegetation options

The SIMPACT model (effectively SIMRAT in SA) was also used to evaluate options for revegetation (Wang *et al*, 2005). The aim was to reduce recharge and thus reduce salt loads to the River Murray within a 50-100 year timeframe. The study found that the priority areas were mostly constrained to a corridor of a few kilometres from the river, and appear mainly in two regions: area between Lock 3 to Lock 6 and in the Waikerie-Morgan-Blanchetown triangle. The impact of vegetation is shown to be relatively small compared to irrigation, which implies that revegetation to reduce salinity must be targeted to high impact zones to be effective, therefore this is no longer an active use of the tool.

### 6.1.4 River Murray Salinity Zoning Policy (RM SZP)

The River Murray Salinity Zoning Policy implements principles from the River Murray Water Allocation Plan (RM WAP) 2002 & 2015 and establishes three salinity impact zones: high impact, low impact and high impact (salt interception). Subject to the availability of salinity credits and compliance with other principles in the RM WAP, new Site Use Approvals (SUAs) and variations to existing SUAs may be granted in low impact zones and high impact (salt interception) zones. In the high impact zone, new SUAs or variations to existing SUAs will only be granted if the applicant can prove that they were financially or legally committed to the development prior to 30 June 2003 (referred to as Prior Commitment). Prior Commitment clauses were included in the SZP as a transitional measure to ensure that entities with commitments to developments within the high impact zone, prior to the implementation of the SZP in June 2003, were able to progress.

SIMRAT was used to delineate the high salinity impact zones. The method assumed a standardised (constant) irrigation drainage rate of 120 mm/y, assuming 15% drainage from an assumed irrigation application rate of 8 ML/ha/y (Miles, 2005).

The SA high impact zone (HIZ) line is located at the 0.02 t/ha/day contour calculated by SIMRAT after 100 years of irrigation. This roughly equates to 0.5 µS/cm per GL of water applied, which is a risk-based policy decision that is consistent with the maximum class of salinity impact established in the Victorian salinity zoning thresholds (Miles, 2005; SKM, 2001).

For comparison, the Victorian Salinity Impact Zones involve 12 classes (SKM, 2001):

- high impact zones, ranging from H1 at 0.3 EC per GL, to H5 at 0.5 EC per GL
  - low impact zones, ranging from L1 at 0.0 EC per GL, to L7 at 0.2 EC per GL.

## 6.2 Victoria

Victoria’s Nyah to the South Australian Border Salinity Management Plan (N2SAB SMP) accountable action currently utilizes an analytical method to calculate groundwater impacts of irrigation on the Murray River using the Theis solution to the well equation. The analytical method is not accredited as a BSMS model but has been peer reviewed and approved by the Murray-Darling Basin Commission in 2003/04 and reviewed by an MDBA appointed peer reviewer and found fit for purpose in 2013.

The 2013 N2SAB SMP review also applied two numerical groundwater models (using MODFLOW platforms) to assess salinity impacts for part of the area of the accountable action. The modelling indicated that the approved analytical method may over-estimated salinity impacts by around 50 % in some areas. Victoria has advised that they have commenced work to further investigate the use of numerical groundwater models to replace the analytical method.

### 6.2.1 Timelag estimates for Mallee dryland clearing

SIMRAT is currently applied for only one purpose in Victoria – to estimate timelags for cleared dryland recharge for input to numerical models that are used for the Victorian mallee clearance entry (Entry 70 on the Salinity Registers) (refer Sect. 6.1.2). SIMRAT is not used to estimate timelags for irrigation, as the numerical modelling studies (Aquaterra, 2009b) have identified that irrigation-related timelags are effectively zero (order of months). The SIMRAT timelag method applied to dryland clearing assessments by numerical models is consistent across all three states (Miles, 2005; Aquaterra, 2009a, 2009b, 2009c).

The EM1.2 study of dryland clearing salinity impacts within the Sunraysia region (Aquaterra, 2009) indicated that there are no bores within the study area that show increasing water levels. The study also found that a 50% change in dryland recharge rates resulted in a salt load variation of approximately +/- 25%, indicating lower sensitivity than that of irrigation impacts.

There is a suite of regional groundwater models developed for each CMA in Victoria under the ecoMarkets project for the purpose of land and water management, including the management of dryland salinity. However, the EnSym models do not use SIMRAT to estimate recharge, and they all assume a zero timelag for recharge to reach the watertable. The EnSym (Environmental Systems Modelling Platform) includes the BioSim model to estimate recharge under historical and potential climate, and that is then applied to the numerical EnSym groundwater model to evaluate hydrogeological effects.

The EM3 groundwater model was developed for the Mallee CMA in Victoria under the ecoMarkets project (Aquaterra, 2010). The stud noted that there are some dryland bores (in cleared and uncleared areas) that showed a rapid response to the drought onset in the 1990s, suggesting effectively zero timelag (i.e. not consistent with SIMRAT estimates). There were also bores that showed no response at all to the drought, indicating the importance of a monitoring review to assist in understanding the key processes (Aquaterra, 2010).

### 6.2.2 Issues for SIMRAT application to Victoria for Mallee irrigation

While SIMRAT is not applied in Victoria for its fundamental water trade purpose, it could be theoretically applied because the N2SAB SMP salinity impact zoning method (SKM, 2008; RMCG, 2008) is a similar method that was accredited for estimating irrigation salinity impacts prior to the development of SIMRAT.

Victoria has advised there is no benefit in applying an alternative analytical approach to the N2SAB SMP salinity impact zoning method. The 2013 review demonstrated that Victoria's analytical approach does not under-estimate salinity impact debits and fulfils BSMS accountability requirements. The 2013 review also indicated that a numerical modelling approach has the potential to significantly improve the estimation of the N2SAB SMP accountable action.

The relevance of N2SAB SMP salinity impact zoning method is broader than BSMS accountability purposes and is an integral component of wider land and water use planning arrangements in Victoria. These arrangements have been highly successful in managing the rapid expansion in irrigation development in the Victorian Mallee since the 1990's and incorporate:

- Victoria's salinity impact zoning policy which uses the current analytic methodology in applying salinity offset charges to approved irrigation developments, along with a market process for impact credits and debits
- Victoria approval processes for irrigation development which are set out in New Irrigation Development Guidelines and overseen by a steering committee and a departmental case manager to facilitate the irrigation development processes. These approval processes consider other local planning processes, as well as transactions provisions of the Victorian *Water Act 1989*, in a manner consistent with the provisions of COAG Water Reform (unbundling).

A change to the salinity impact zoning method may have significant implications for this important policy framework, thus Victoria's preference to pursue the more rigorous approach to salinity impact assessment achievable by a well-executed numerically modelling approach.

Further, there are some significant differences in the assumptions and the parameters that are applied to the analytical method in Victoria (compared to SIMRAT). This would mean that an attempt to benchmark a potential SIMRAT approach against the existing Victoria approach would likely not give comparable estimates of salinity impacts. The analytical method itself has been subject to several five year reviews (e.g. RMCG, 2008), which has involved analysis of groundwater level responses, area of irrigation and volume of water applied, and application of a MODFLOW model (from the N2SAB SMP suite; SKM, 2008) to benchmark the predictions of the accredited analytical model.

Having said that, it is noted that the most recent review of the N2SAB SMP Register entry recognized that irrigation induced impacts appear to be overestimated, as the model is applied at present in Victoria. The watertable has not risen as high or as rapidly as the N2SAB SMP analytical model predicts. The reasons most likely stem from the closeness of the watertable to the rootzone, and possibly more effective drainage. It was acknowledged that these matters can only be unpacked with a MODFLOW modelling approach, as SIMRAT as presently configured would not be suited for this task. There would appear to be some support for a review of the parameter data layers that are applied to the range of modelling approaches, with a view towards a converging on a common parameterisation if not a common modelling approach. Such a review would need to involve hydrogeologists with substantial experience in the Victorian Mallee. The MODFLOW suite of models would appear to be the most appropriate platform for this purpose, and could ultimately take over from SIMRAT and the N2SAB SMP analytical model in Victoria.

### 6.2.3 Established Victorian method to assess salt impacts of Water Trade

Since 2007, the salinity unit of account in the Mallee became the Annual Use Limit (AUL) conditions on each Water Use Licence (WUL). In BSMS terms, the AUL is effectively a measure of the potential salinity impact in the Mallee, and annual accountability reports are submitted accordingly (Water Act 1989).

In simple terms, the AUL is calculated based on:

- the volume AUL approved for each WUL which is set based on a specified Maximum Application Rate (MAR) for a specific crop (e.g. ranging from viticulture at 9 ML/ha/y, to walnuts at 15.5 ML/ha/y in Sunraysia; with other variations in other areas)
- application to a specific parcel of land (i.e. underlying hydrogeological parameters apply), and
- assuming a 10% deep recharge rate to the aquifer (this rate is consistent with SIMRAT).

A set of related salinity impact coefficients (Hoxley coefficients) have also been developed, based on the (SKM, 2001) analytical methodology outlined below, that convert the proposed irrigation development AUL parameters to salinity impact (EC) using BSMS Protocols. The method also utilised a suite of numerical models for the Nyah to the SA Border region (SKM, 2008) for related sensitivity testing and other analysis.

The analytical methodology has also been applied to develop the salinity impact zones, assuming a 100 ha area and other assumptions broadly consistent with the SIMRAT approach to zoning in SA. The basic analytical equations applied to devise the Hoxley coefficients and to map salinity impact zones in Victoria are similar to those applied to SIMRAT, as detailed in (SKM, 2001):

- The reverse application of the traditional Theis water well equation for the change in piezometric level due to a volume of extraction (i.e. in this case to estimate the increase (h) in water level due to irrigation recharge (Q): $h = \frac{Q}{4\pi T} W(u)$, where $u = \frac{r^2 S}{4Tt}$
- The Theis equation for steady state discharge (q) to a lateral boundary (within an angle of influence Ɵ) due to an increase in the hydraulic groundwater gradient (Δh/Δr):

$$q = \frac{h_1 - h_2}{\ln \frac{r_2}{r_1}} T\theta$$

- The product of the discharge with the near-river salinity provides the salt impact estimate, which is then applied to standard BSMS Protocols for Register purposes.

In principle, these equations and the approach are conceptually consistent with the SIMRAT methodology; indeed, it is understood that this approach was one of the key drivers behind the development of SIMRAT (Mallee CMA, 2013).

However, there are significant differences in the methods, parameters and assumptions. These differences include the following:

- The N2SAB SMP salinity impact zone method uses the volume of AUL issued for each WUL as a key parameter. The AUL provides an upper value for the volume of irrigation and is recorded in the Victorian Water Register. AUL volumes in the register are regularly updated as WULs are issued, varied or cancelled. A 10% recharge factor is applied (same as SIMRAT), and the location of the irrigation is assumed to be in the centre of the land parcel (compared to the front of the parcel for SIMRAT in SA).
- There is no timelag applied to the vertical recharge flux estimate and the increase in piezometric head due to irrigation recharge develops with time according to the Theis equation. This adopted approach reflects the generally shallower depth to water table in the N2AB SMP compared to the irrigation regions covered by SIMRAT in SA.
- The gradient to the river (which drives the Theis-calculated flux) is calculated at a point at 200 m from the river, based

on the increase in piezometric head under the irrigated land.

- A narrower range of parameter values are applied for transmissivity, unconfined specific yield and confined storativity (noting that the SIMRAT data layers in Victoria could be updated to reflect these values).
- Groundwater salinity values used are higher than that those currently observed immediately next to the river. This approach is used to represent the salinity of the groundwater that will reach the river after 30 to 50 years rather than an alternative assumption that the current freshwater lenses along the river will remain unchanged.

An example of the result of the salinity impact zone approach in Victoria, along with the numerical model suite for Nyah to the SA Border is presented in Figure 6.1.

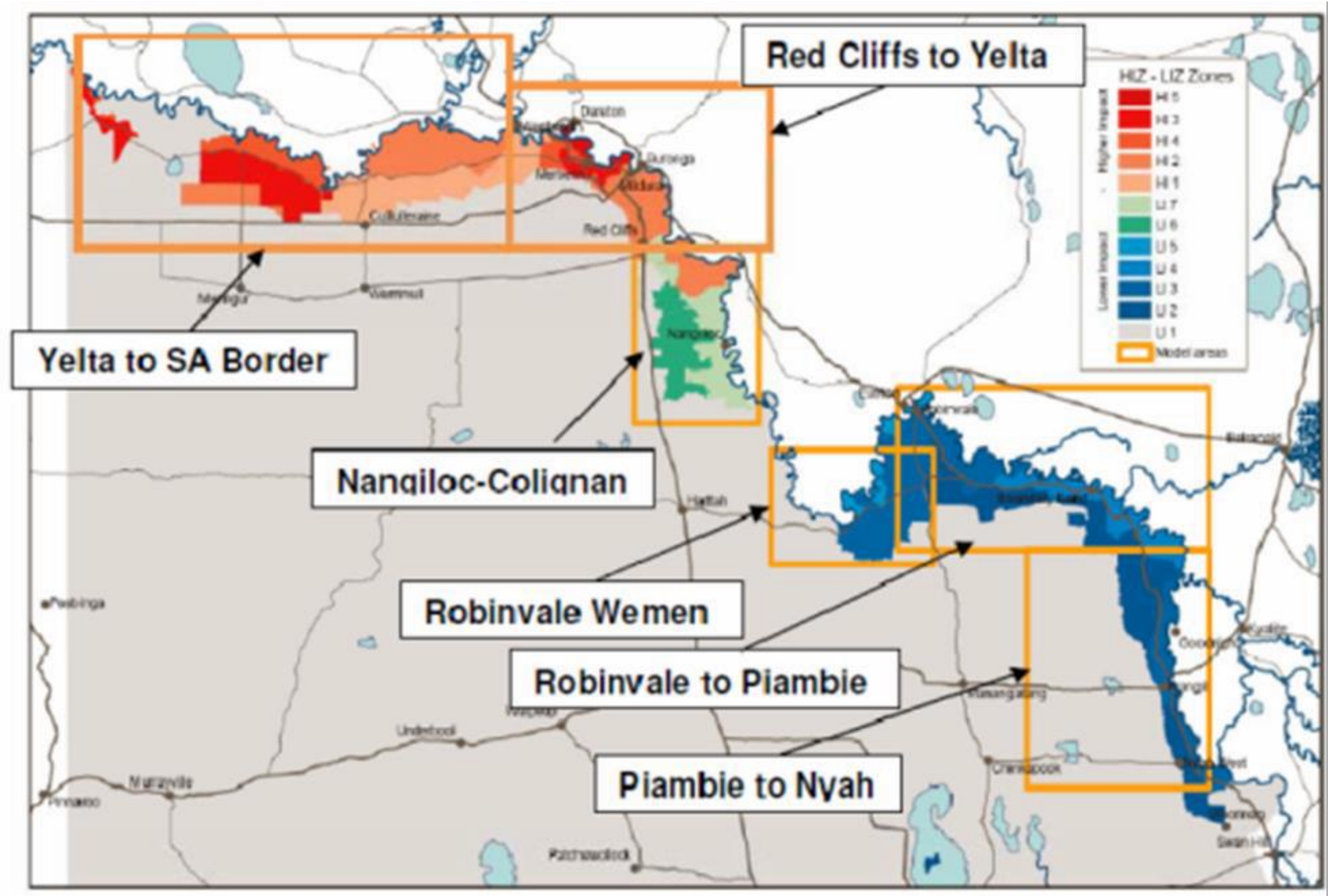


**Figure 6.1 Nyah to Border Salinity Impact Zone results and numerical model (after SKM, 2008)**

#### 6.2.4 Limitations to Victorian application of SIMRAT

Given the technical differences and the established AUL system, a substantial investigation and benchmarking program would be required to collate and review objective information on the potential effects of adopting SIMRAT for the purpose of assessing the salinity impacts of water trade in Victoria, which would seem neither appropriate nor warranted at this stage.

Although there are no current plans to apply SIMRAT in Victoria to assess the salinity impacts of water trade, for the purpose of this SIMRAT review, there is one key technical limitation in relation to the hydrogeological parameter data layers. The parameter values and distribution should be subject to review, to consider consistency with the parameterisation that has been mapped following hydrogeological investigations and applied to a number of numerical modelling studies in the region since 2005. The Mallee CMA Salinity Statement (2012) provides a good summary of the many investigations to 2012, and a list of relevant reports (notably these model reports: Aquaterra, 2009a; Aquaterra 2009b; Aquaterra 2009c; Aquaterra 2010; Passfield *et al*, 2009).

Other potential limitations also need to be considered, particularly the significant differences between SIMRAT and the accredited Victorian approach (refer Sect. 6.2.3). As indicated above, there would appear to be some support for a review of parameter data layers and possibly modelling approaches, with a view towards converging on a common approach. The MODFLOW suite of models would appear to be the most appropriate platform for the purpose of Register entries, and could ultimately take over from SIMRAT and the N2SAB SMP analytical model in Victoria.

## 6.3 New South Wales

The GIS version of SIMRAT is applied infrequently in NSW for the purpose of assessing new development water trade salinity impacts. When it is applied, the assumptions applied are consistent with those applied in SA, including the assumption of complete hydraulic connection between the aquifer and the river (Sect. 3). Originally SIMRAT was applied retrospectively to new developments in the NSW Sunraysia (Entry 24 on the Salinity Registers), where water was in some cases sourced from interstate water trade. In this mode, SIMRAT was applied using the default 10% RZD setting, assuming the full volume of traded water is used for irrigation, at an application rate of 10 ML/ha (P Pendlebury (NSW Office of Water), 2014 pers. comm.).

SIMRAT has been applied infrequently to undertake a high level semi-quantitative assessment of potential salinity impacts. Where the impacts were indicated to be in a high impact zone, the developer would be requested to undertake expert hydrogeological site-specific studies to evaluate the impacts. Potentially, additional conditions would be attached to any approval, to limit net impacts to those of a lower impact setting. To date, there have been few new development applications since 2006, and most of these have not proceeded to implementation stage. Where the impacts are assessed as low, the SIMRAT method would be used to update the Register. An accredited numerical modelling method would be required for situations of potential high impacts, or in areas where the SIMRAT methodology is inadequate for the local hydrogeological conditions. This approach is not inconsistent with the salinity impact zone approaches applied in SA and Vic.

SIMRAT was used in this way to establish NSW Register entries for conditions in 2003 and 2006 (P Pendlebury (NSW Office of Water), 2014 pers. comm.), but there has been very little development and thus little call for it since. SIMRAT is considered to be generally applicable to NSW conditions, and the parameters have been considered appropriate for that application.

Although SIMRAT is applied in NSW on a case-by-case basis as a high level (initial) assessment, it could potentially be applied in a zoning policy approach in NSW. However, it is recommended that the hydrogeological parameters applied to NSW be reviewed, tested for sensitivity, and validated for that purpose.

The other application of SIMRAT in NSW is to estimate vertical timelags for cleared dryland recharge for input to numerical models that are used for various BSMS purposes (refer to Sect. 6.1.2). The SIMRAT timelag method applied to dryland clearing assessments by numerical models is consistent across all three states (Miles, 2005; Aquaterra, 2009a, 2009b, 2009c). SIMRAT is not used to estimate vertical timelags for irrigation, as the numerical modelling studies (Aquaterra, 2009b) have identified that irrigation-related timelags are effectively zero (order of months).

# 7 Review findings

The uses of the SIMRAT model are to:

1. Assess the salinity impact of new irrigation developments within the Mallee region (primary purpose). Salinity impacts are recorded as a preliminary entry on Register A before being updated by accredited groundwater models (within five years in SA and irregularly in NSW).

2. Assist in estimating the timelag between increased root zone drainage and recharge in numerical groundwater models for both cleared land (SA, NSW and Vic) and irrigation areas (SA) (secondary purpose).

3. Delineate the High Salinity Impact Zone Line which underpins the South Australian River Murray Salinity Zoning Policy (SA) and is used to guide decision making for new irrigation developments, using a 'triage approach' (NSW).

4. Assess revegetation options to reduce salt loads to the River Murray (SA) (discontinued).

Usage (1) is the purpose for which SIMRAT was designed and remains SIMRAT's primary purpose. Usage (2) has timelag implications for Salinity Register entries derived from numerical models. Usage (3) assists state policy decisions. Usage (4) has been discontinued.

This aim of this review is to consider SIMRAT's use for (1), the salinity impact assessment of new irrigation areas. However, some comments are made regarding (2), the timelag for numerical models, due to its importance for Salinity Register entries.

**Methodology**

SIMRAT is designed as a rapid assessment tool, aiming to "explain the maximum amount of change in River salinity impacts with the smallest set of variables" (Fuller *et al.,* 2005c). It provides a consistent and deliberately simple approach across the lower River Murray which can be used in areas where there is a high uncertainty in the hydrogeological factors which influence groundwater salt flux to the river.

The SIMRAT process is divided into five stages, from application at the irrigation area to an estimate of its salinity impact at Morgan. Stage 1 determines (or specifies) the increased root zone drainage due to irrigation. Stage 2 estimates the resulting additional recharge to the watertable aquifer over time. Stage 3 estimates the groundwater flux and salt load to the discharge edge (i.e. to the floodplain or river). Stage 4 applies factors to account for varying levels of river connectivity and floodplain attenuation. Stage 5 converts the additional groundwater salt load to an EC impact at Morgan.

The equations and assumptions for Stages 1 to 3 are essentially sound when applied to locations *where the hydrogeology is relatively simple*. The assumptions are not met in some areas, which will reduce the accuracy. There are also numerous and significant uncertainties which need to be addressed.

***Root zone drainage rate***

SIMRAT is set up to calculate root zone drainage (RZD) from the irrigation volume, area and efficiency. In practice, the root zone drainage rate is specified by the user. The rates adopted depend on the use of the model. 100 mm/y is assumed for the salinity impact assessment of greenfield sites. 125 mm/y is assumed for the SA River Murray Zoning Policy. Mallee clearance scenarios are based on rainfall data and soil mapping, as calculated in Wang *et al.* (2005).

Four possible approaches to specify RZD for new irrigation sites are:

1. Use a single, constant, specified value for all (current SIMRAT assumption)

2. Use RZD rates from CMC (2011) from the nearest irrigation area

3. Use a constant specified value that depends on the crop type (as used in Victoria)

4. Use a numerical model to estimate RZD over time.

Each of these methods has limitations. Using a constant value is simplistic. CMC (2011) RZD rates will depend on complicated site histories, including past and present irrigation practices, and are unlikely to be representative of a newly cleared site that has just commenced irrigation. Intended crop types for a new sites may not be known. Numerical models require many inputs, few of which will be known for a site, and are not suitable as part of a rapid assessment tool.

The assumption of 100 mm/y provides a consistent value for new irrigation areas (also used in the SA Salinity Register models), and we recommend that this assumption be retained for SIMRAT's Salinity Register calculations. However, Victoria does not use SIMRAT and assumes that root zone drainage rates differ by crop type. Hence the Salinity Register entries between the states are not directly comparable.

***Timelag for root zone drainage to reach the watertable as recharge***

The vertical timelags calculated in Stage 2 are critical as they strongly influence, by years or decades, the timing of salt impacts. They are used by SIMRAT and are also routinely used as inputs to numerical groundwater models, for both mallee clearance scenarios (SA, Vic, NSW) and irrigation areas (SA only). Yet there are considerable uncertainties about their calculation. A comparison of SIMRAT timelag estimates with those derived from irrigation area samples from Meissner (2004) shows a high level of uncertainty in the results. NSW and Vic found the timelags unworkable for irrigation areas and do not use them. A study of hydrograph data within the Mallee CMA region in Vic (Aquaterra, 2010) noted that there are some dryland bores (in cleared and uncleared areas) that show a rapid response to drought onset in the early 1990s, and there were also bores that show no response at all to the drought, indicating that a monitoring review is required to understand the key processes (Aquaterra, 2010).

SIMRAT timelags are based on field studies of cleared land and not irrigated land: the curve of hydraulic conductivity to water content may be accurately fitted for the low water contents of cleared dryland, but may not be accurate for the high RZD of irrigated areas. Also, the SIMRAT documentation does not mention what hydrostratigraphic units the soil parameters are based on, but they are most likely upper units such as top soils, Woorinen Formation, Blanchetown Clay, and Loxton Sands. It is not clear whether these parameters are appropriate for lower hydrostratigraphic formations within the unsaturated zone such as the Murray Group Limestone.

SIMRAT soil parameters assume that the site is initially in equilibrium with mallee vegetation conditions, i.e. that the soil profile is close to the residual water content; a greenfield site. This will not be applicable where the site:

- Has been used for dryland farming (i.e. was cleared some years previously)
- Has been irrigated previously
- Is subject to flooding
- Is close to an irrigated area where there may have been lateral spread of drainage, e.g. where the irrigation area underlain by a perched aquifer (as observed at Waikerie–Qualco).

Conceptually, the SIMRAT unsaturated zone model describes purely vertical piston flow under the force of gravity (free drainage). These assumptions neglect soil moisture redistribution effects due to changes in drainage, evaporation and transpiration, which are likely to be important where the watertable is shallow. In addition, free drainage cannot be used to describe conditions where perched aquifers have formed.

It is strongly recommended that the timelag/recharge algorithm be tested and reviewed in further detail, given the uncertainty of the results and its impact on Salinity Register entries. Until the review is concluded, SIMRAT's timelag algorithm remains the best available for a rapid assessment tool and should be retained.

***Groundwater discharge to the discharge edge***

This is calculated using the Unit Response Equation (URE) which assumes purely 1D horizontal groundwater flow in a single layer, non-leaky, homogenous and isotropic aquifer. The only bound on the semi-infinite aquifer is the discharge edge, uniform properties are assumed between the irrigation area and the discharge edge, and it is assumed that the saturated aquifer thickness does not change significantly. There are several areas within Mallee region where these assumptions are not met.

In the following cases, the assumptions of the URE are not met, but there are alternative equations given in Rassam *et al.* (2004) which would calculate the discharge more accurately:

1. Shallow unconfined aquifers where the saturated thickness of the aquifer varies by more than 10% (e.g. Loxton).
2. Areas where there are significant bends in the river, i.e. where the distance between a meander and the irrigation area is closer than four times the closest distance to the river (e.g. parts of Sunraysia).
3. Areas where the width of the aquifer is less than twice the distance from irrigation area to river (e.g. Boeill Creek).
4. Areas where the base of the aquifer is not horizontal, and the aquifer slope is greater than 1.5 degrees (e.g. Wemen and Murtho).

Other situations where the URE is less accurate are areas where there is:

5. A complex hydrogeology involving multiple leaky aquifers, and the source of discharge to the floodplain may be from a different aquifer than the unconfined aquifer which receives the irrigation drainage. This occurs in Waikerie-Qualco, SA.
6. Substantial cliff seepage such as at Trentham Cliffs, Vic
7. Substantial surface evaporation and transpiration close to the discharge edge such as near Lake Alexandrina and Lake Albert, SA and areas in Vic and NSW where irrigation occurs on the floodplain and depth to water is shallow.
8. Significant heterogeneity or geological faulting which may impact flow to the discharge edge (e.g. Overland Corner SA)
9. A groundwater gradient away from the discharge edge, i.e. where the discharge edge (river or floodplain) is losing, in which case the discharge is a reduction in flow from the discharge edge into the regional aquifer.

While SIMRAT results should be used with caution in these situations, there is no other consistent approach suitable for a rapid assessment tool. It is possible that an equation for situation 5 could be developed from examples given in Strack (2014).

It must be stressed that when the errors for some of these situations are compared with an error range due to a twofold uncertainty in aquifer diffusivity, the error due to the conceptualization is less (Rassam *et al.,* 2004). In many locations, greater improvements are likely to come from improving the SIMRAT Data Atlases rather than improving the algorithms (Fuller *et al.,* 2005c).

SIMRAT assumes 1D horizontal flow within the aquifer and hence that all discharge occurs to a single point on the discharge edge. The discharge is multiplied by a salinity value typical for the point on the discharge edge. In practice, the discharge will spread radially from the irrigation area and pass into the discharge edge along a reach. Rassam *et al.* (2004) plotted the distribution. 50% of the applied flux passes through a reach of the discharge edge that is $2a$ wide, where $a$ is the distance between the area of increased recharge and the discharge edge. The assumption of discharge to a point is only of concern if there are significant changes in salinity along a discharge edge. SIMRAT could be modified to allow for the radial spread of discharge and subsequent range of groundwater salinities.

***River connectivity and floodplain attenuation***

These are parameters which attempt to account for complicated processes occurring within the floodplain that may limit groundwater discharge to the discharge edge from reaching the river. The discharge is multiplied by the river connectivity factor (a percentage), then by the floodplain attenuation factor (also a percentage).

The river connectivity factor represents the resistance to groundwater flow between the river bed and the aquifer, which may be due to the properties of the river bed itself or the properties of the material that the river partially or fully penetrates, for example, if a clay layer separates the River Murray from the regional Parilla Sands aquifer. The Data Atlas river connectivity layer was developed on the basis of expert knowledge and there is no documented approach to the development of this layer. The assumption of partial river connectivity in Vic is not consistent with the analytical methodology applied to develop salinity impact zones in Victoria.

The river connectivity factor is not used in practice. If a state provides a sound reason for its use, then the river connectivity layer would need to be reviewed to ensure consistency in approach across regions and states. This would require contribution from expert hydrogeologists across SA, Vic and NSW. Otherwise, it is recommended that it be removed from SIMRAT.

The floodplain attenuation factor (FAF) accounts for storage of salt in the floodplain. This attenuation process describes the storage of groundwater and salt in the floodplain aquifers and backwaters at low flows that are mobilized to the river at high flows (Fuller *et al*., 2005c); it is currently set as 100% (full connection, i.e. no salt stored permanently in the floodplain) everywhere. Unless there is compelling evidence that salt is stored permanently in parts of the floodplain, it is suggested that the floodplain attenuation be removed from SIMRAT entirely. The conservative assumption is to assume that all additional groundwater salt flowing through the discharge edge will eventually flow into the river.

***EC impacts at Morgan and economic costs***

Calculations are based on an MDBC Ready Reckoner derived from MSM-BIGMOD. The SIMRAT documentation does not discuss the detail of how these values were derived. This should be documented.

**Errors and undocumented assumptions in the current implementation**

There is an error in SIMRAT-XL's calculation of the recharge wetting function which is severe when RZD rates are small. The sensitivity plots given in Fuller *et al.* (2005c) were developed using SIMRAT-XL and will contain errors for low drainage cases.

There is an undocumented assumption in both SIMRAT-XL and the GIS version of SIMRAT. For each year, SIMRAT multiplies the discharge from the URE by the average recharge for that decade (rather than the recharge calculated for the year). The decadal time steps for the recharge were most likely chosen because it reduces computational overheads; however, this is not documented so the SIMRAT outputs are easily misinterpreted.

**Data Atlas**

The Data Atlases contain minimal detail on how the layers were developed. For example, the diffusivity layer is calculated from aquifer transmissivity and storativity but the datasets to support those transmissivity estimates are not given. Some data layers are based on extrapolation from little data.

The clay thickness layer is based on estimates of Blanchetown Clay thickness only. This is not appropriate for areas where there are other low-permeability units in the unsaturated zone, e.g. Lower Loxton Clay, Bookpurnong Beds, Upper Mannum Limestone or others. This should be amended. The clay thickness in Vic and NSW should be updated to consider more recent data, particularly for NSW where a single value is applied to the highland and a single value applied to the floodplain. Areas in Vic where the clay is absent should be reviewed to consider more recent drilling in those areas (such as Red Cliffs). More recent data such as isopachs of the Blanchetown Clay mapped for the ENSYM project should be considered when updating this layer. Although SIMRAT is not used in Vic for salinity impact assessment, it is used to estimate timelags for Mallee clearance recharge. Updating the aquitard thickness layer could improve those estimates

SIMRAT assumes that depth to water is constant. In fact, depth to water has changed over time, increasing as new irrigation areas are developed and lowering where irrigation efficiencies have been implemented. The Data Atlas depth to water is based on depth to water in 2000 and 2001. As the depth to watertable has changed since then, it is recommended that this data layer be updated. Note that this approach is both suitable and conservative in instances where SIMRAT is used to assess the impact of new irrigation developments as part of the Pilot Interstate Water Trading area. However, where SIMRAT timelag calculation is used in calibrating numerical groundwater models, particularly in older irrigation areas, the timelag may be overestimated or underestimated due to historical changes in the watertable. Timelags for Mallee clearance will depend on where the watertable was at the time the wetting front approaches the watertable.

The diffusivity data layer should be updated to consider pathways for discharge to the floodplain. For example, at some locations in SA the uppermost aquifer receives the irrigation drainage however it is the deeper confined aquifer that contributes the majority of discharge to the floodplain. The diffusivity layer should then reflect the parameters of the confined aquifer.

The river connectivity layer needs to be justified with a consistent and well-documented methodology. The floodplain attenuation layer should be removed as it is not used.

One or more new data layers should be developed which indicate the broad level of uncertainty in the SIMRAT result, due to data availability and the hydrogeological complexity. This is discussed further under Recommendations (Sect. 8).

**GIS update**

The GIS version of SIMRAT currently operates on an ArcGIS platform that is no longer supported, therefore there is a requirement for SIMRAT to be moved to a new platform. Based on initial investigations it is considered that standard ArcGIS for Desktop v10.2 is the most appropriate alternative platform for SIMRAT, given that the states (SA, Vic and NSW) are familiar with this software and are working toward upgrading to a common version (ArcGIS v10.2) within the next 12 months. Python is considered the most efficient and appropriate programming language to recode SIMRAT. It is recommended that the Stage 2 scope is clearly defined during the initial phase of the project, as the scope will strongly influence how the new SIMRAT program is designed. The scope should be constrained to only consider the future intended uses of SIMRAT and how much user interaction is required. Within the scope and costing for Stage 2, it is recommended that consideration is given to testing the SIMRAT program and verifying its outputs. The outputs should be benchmarked against original outputs for a combination of input parameters. The management of SIMRAT input and output data should also be considered in Stage 2 of the project.

# 8 Recommendations

SIMRAT continues to be fundamentally suitable for its primary purpose as a rapid assessment tool for salinity impacts of greenfield irrigation sites in the Mallee region. However, there is an immediate need to rewrite the SIMRAT code as the language it is implemented in is no longer supported.

SIMRAT's Stage 2 algorithm is critical for Salinity Register entries, as it strongly influences, by years or decades, the timing of salt impacts. The algorithm is used in SIMRAT's rapid-assessment entries for new irrigation areas in SA and NSW, and it routinely provides inputs to numerical groundwater models, for both mallee clearance scenarios (SA, Vic, NSW) and irrigation areas (SA only). Yet there are considerable uncertainties about its use and its timelags for irrigation areas are no longer used in NSW and Vic. It is based on field studies of cleared land and not irrigated land: the curve of hydraulic conductivity to water content may be accurately fitted for the low water contents of cleared dryland, but may not be accurate for the high RZD of irrigated areas. These major uncertainties about its timelag estimates should be addressed.

Further, many minor improvements to SIMRAT's methodology and datasets could be made to improve its accuracy and ensure appropriate use and interpretation of results. Fuller *et al.* (2005a) made recommendations about the use and review of SIMRAT, principally, that there is a 'need for strong hydrogeological input and review as part of model operation. *SIMRAT should not be treated as a "black box" model and run by users unfamiliar with the hydrogeological setting and information associated with trade sites'*. In practice, this has not always proved feasible, with SIMRAT run as a rapid assessment tool without further hydrogeological oversight. Several of the recommendations below aim to reduce the need for day-to-day detailed hydrogeological oversight by incorporating more hydrogeological knowledge upfront, improving the methodology where possible and mapping where SIMRAT is likely to be less accurate and why.

## 8.1 Recommendations for SIMRAT review Stage 2

Recommendations in order of importance:

1. Rewrite SIMRAT in Python for ArcGIS for Desktop v10.2.x (ArcPy). This will ensure that SIMRAT can continue to be used, as the currently-used AML language is no longer supported by the software currently used by the SA, NSW and Vic governments. Detailed suggestions on its implementation are given in Section 5.
2. Undertake a more extensive review of the validity of the Stage 2 timelag algorithm and parameters:
    a. Compare SIMRAT timelag estimates against hydrographs of observation wells. For mallee clearance, compile hydrographs of wells at cleared sites, distant from irrigation areas, and compare with timelag estimates from SIMRAT. For irrigated areas, compile hydrographs within more recently-developed areas (i.e. greenfield sites). This would be useful in benchmarking SIMRAT outputs against actual conditions seen in the Mallee.
    b. Compare SIMRAT timelag estimates against timelag estimates derived from the calibration of the Salinity Register models to hydrographs.
    c. Consult with soil science experts to confirm the need for a review of algorithms and parameters, particularly in the context of SIMRAT as a rapid assessment tool. Conduct further research, including field studies and numerical modelling, to compare SIMRAT estimates against empirical and modelled estimates for a number of sites and conditions.
    d. Consider whether there is a need for a drying algorithm and investigate whether there is a method that would be useful, given the lack of data available on irrigation history for most sites.
3. Update the Data Atlases. This has already been done for SA but has not yet been formally adopted. However SA should consider updating the clay thickness data layer as per findings in Section 4. Similar works should be undertaken for NSW as more detailed information may now be available. Data layers such as thickness of clay and depth to groundwater should updated for Vic as they may improve estimation of timelag for Mallee clearance recharge. Detailed suggestions regarding specific datasets are given in Sections 1.1.2, 2.4.3, and 3.2. The updated data layers should be reviewed by expert hydrogeologists and the accompanying documentation revised to include greater detail about the sources and values of the data used to compile the data layers.

4. Develop new data layers which indicate the overall confidence, for each cell in use of the model at that location, whether the SIMRAT assumptions are reasonable for that location, whether a different form of the URE would be more accurate, or whether SIMRAT assumptions are not appropriate and the results are liable to have a large error. Some areas may need to be masked.
5. Use the updated SIMRAT model (updated data and code) to map timelags for a variety of historical RZD rates. These would provide a better starting point for the initial timelags used in numerical models.
6. Include alternate forms of the URE in SIMRAT when the code is rewritten. While this is likely to make only modest improvements in accuracy, compared to an updated Data Atlas, initial investigations suggest that this would not require much additional work, however this should be confirmed during Stage 2. The following should be considered:
    a. The URE variations provided in Rassam *et al.* (2004)
    b. A leaky aquifer solution, if possible, based on Strack (2014)
    c. A spatial distribution curve for discharge along the discharge edge, replacing the current 1D assumption of discharge to a point, which does not account for changes in groundwater salinity along the discharge edge. Rassam *et al.* (2004) again provide details.
7. The states should confer on the aim and definition of the River Connectivity data layer. A consistent methodology should be developed and implemented, or, if the layer is agreed to have no purpose, it should be omitted (see Section 3.2).
8. The states should confer on the aim and definition of the Floodplain Attenuation data layer. A consistent methodology should be developed and implemented, or, if the layer is agreed to have no purpose, it should be omitted (Section 3.2).
9. Update the EC impacts at Morgan and costs to downstream users' data layers, as these Ready Reckoner values differ from those in the BSMS Operational Protocols.
10. It would be possible to undertake a sensitivity analysis for each trade. This would require the development of additional data layers to give the minimum and maximum value for each parameter to be tested, such as root zone drainage or diffusivity. This should only be implemented if the usefulness of this output is judged commensurate with the effort required to develop it.

## 8.2 Other considerations

These items are not recommendations for SIMRAT but are considerations for the MDBA and states raised by this review of SIMRAT. They concern the lack of consistency across states in applying rapid assessment tools for irrigation Salinity Register entries.

1. The states adopt different approaches to timelag for irrigation areas. SA applies a timelag to mallee clearance and irrigation, while NSW and Victoria apply timelag to mallee clearance impacts, but not irrigation impacts. It may be entirely appropriate to assume zero timelag where irrigation occurs in areas of shallow watertables or complicated land use history. Literature review and compilation of hydrograph and irrigation site histories would assist in confirming whether zero timelag is considered appropriate for all irrigation areas.
2. The states adopt different approaches to calculating discharge. The methodologies should be discussed and compared between states to determine when and how the results are directly comparable.
3. Consistency regarding RZD assumptions across states should be discussed, for example, Victoria adopts different RZD for different crops, while a single RZD value is applied for all crop types in SIMRAT. Changes to RZD assumptions would need to be adopted in BSMS Operational Protocols. Reasonable ranges of RZD could be determined through field studies at greenfield sites and numerical modeling.

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# 10Appendices

## A. Derivation of the timelag equations used in Stage 2

The derivation of the equations is easiest to understand by first considering the timelag mean and distribution for a single soil layer, then generalising to multiple layers.

### *Single layer – homogenous soil*

The analytical equations described in this section are described in Cook *et al*., (2004) and Wang *et al*., (2005). The key assumptions for the unsaturated zone, described below, are:

1. Homogeneous conditions
2. A modified Brooks-Corey equation for the hydraulic conductivity
3. A Darcy-Buckingham equation for unsteady, 1D vertical flow
4. Free drainage conditions
5. The root zone drainage rate is less than the saturated vertical hydraulic conductivity.

In unsaturated soil conditions, flow occurs primarily in those pores filled with water and the unsaturated soil hydraulic conductivity $K(\theta)$ is a function of the soil water content $\theta$ (Kutilek & Nielsen, 1994). A variety of equations have been developed to describe this function. SIMRAT assumes a quadratic relationship between unsaturated soil hydraulic conductivity and soil water content, referred to as a modified Brooks-Corey equation (Brooks & Corey, 1964):

$$\frac{K(\theta)}{K_r} = \left(\frac{\theta - \theta_0}{\theta_r - \theta_0}\right)^2$$

where, $\theta_0$ is the mean soil water content beneath native Mallee vegetation. $\theta_r$ is the reference soil water content and $K_r$ is the reference soil hydraulic conductivity such that $K(\theta_r) = K_r$. Note that $\theta_r$ is not necessarily the maximum water content and $K_r$ is therefore not necessarily the saturated hydraulic conductivity. This equation describes a quadratic relationship between unsaturated soil hydraulic conductivity and soil water content.

Buckingham (1907) modified Darcy's equation to obtain vertical unsaturated flow $q_z$ as a function of the unsaturated hydraulic conductivity and the hydraulic gradient:

$$q_z(z,t) = -K(\theta)\frac{\partial H(z,t)}{\partial z}$$

where the total head $H$ is the sum of the pressure head $h$ and the gravitational head $z$. The flow $q_z$ and total head $H$ are functions of depth z and time $t$.

Free drainage is flow by the force of gravity, and occurs when the pressure head $h$ is constant for all depth:

$$\frac{\partial h(z,t)}{\partial z} = 0$$

and the water content $\theta$ is uniform with depth (Radcliffe & Šimůnek, 2010). Since the gravitational head gradient is unity (e.g. decreasing at a rate of 1 cm per cm of vertical depth below surface) then the hydraulic gradient is equal to one and the Darcy-Buckingham flow equation simplifies to:

$$q = -K(\theta)$$

Based on this assumption of free drainage, as long as the root zone drainage $R(t)$ is less than the hydraulic conductivity at maximum water content $K_m$, $R(t)$ can be substituted for $K(\theta)$, i.e. $R(t)=-K(\theta)$.

If the irrigation drainage and the unsaturated sediments below it are spatially homogeneous, then drainage is a step function and the timelag is constant throughout the irrigation area. If the time since the change in drainage is less than the timelag, then recharge has not yet reached the watertable and the recharge rate is zero. However if the time since the change in drainage is greater than or equal to the timelag, recharge *R(t)* has reached the watertable and that recharge is occurring at a rate equivalent to the increased root zone drainage rate $D_1$:

$$R(t) = \begin{cases} 0 & t < t_L \\ D_1 & t \geq t_L \end{cases}$$

Substituting this into the modified Brooks-equation yields an equation describing the soil water content, when in equilibrium with the root zone drainage, in terms of soil parameters:

$$\theta = \sqrt[n]{\frac{D_1}{K_s}}(\theta_s - \theta_r) + \theta_r$$

An increase in drainage leads to two fronts moving through the unsaturated zone. The solute front represents the physical movement of the drainage since the change in rate. Some recharge to the watertable occurs before the solute front reaches the watertable. This is the pre-change water in the soil column being pushed downwards first, and is termed the pressure front (Cook, Walker & Jolly, 1989).

Assuming one-dimensional vertical piston flow with a sharp wetting front, as described by Green and Ampt (1911) in Radcliff and Šimůnek (2010), the depth of the pressure front $z_{pf}(t)$ at any time t since the increase in drainage can be given as the drainage volume *Dt* divided by the increase in saturation per unit volume:

$$z_{pf}(t) = \frac{D_1 t}{\theta - \theta_0}$$

If the velocity of the pressure front remains constant, the timelag $t_L$ between an increase in drainage and the increase in aquifer recharge is:

$$t_L = \frac{z_{wt}(\theta - \theta_0)}{D_1}$$

where $z_{wt}$ describes depth to the watertable. Combining equations and rearranging for $t_L$ gives the timelag in terms of depth to water and soil parameters:

$$t_L = \frac{z_{wt}}{\sqrt[n]{D_1 K_s}}(\theta_s - \theta_r)$$

Rearranging for *D* gives the minimum drainage rate contributing to aquifer recharge at time *t*:

$$D(t) = \frac{z_{wt}^{n}(\theta_s - \theta_r)^{n}}{t^{n} K_s} = \frac{L}{t^{n}}$$

Where *L* is a constant that depends on the depth to water and on soil properties.

### *Single layer – small, lateral heterogeneity*

SIMRAT has two options regarding the distribution of the wetting timelag. It can either be treated as a step function or as a gradual function. The step function, described in the previous section, assumes that the drainage rates and soil properties in the layer are homogeneous.

The gradual recharge function assumes that small heterogeneities in the irrigation drainage and unsaturated zone properties will lead to variations in timelag within the irrigation area. Water movement in the unsaturated zone is characterized by significant spatial variability in soil properties and perhaps drainage rates, hence recharge to the watertable is spatially variable. The mean timelag is the same as the step function, but it is given a log-normal distribution.

Cook, Walker and Jolly (1989) and Cook (1992) studied the frequency distribution of drainage at Borrika in the Mallee region in South Australia using chloride and electromagnetic techniques. They found that drainage varies considerably spatially, even for very similar soil types. They showed that recharge may fit a log-normal distribution. The probability density function *f(y)* for a log-normal distribution is described as:

$$f(y) = \frac{1}{y\sigma\sqrt{2\pi}} e^{-\frac{(\ln y - \mu)^2}{2\sigma^2}}$$

The probability density function of the log normal distribution has parameters $\mu$ and $\sigma$ which are the mean and standard deviation of the variable's logarithm, respectively. These parameters affect the shape and magnitude of the function and are related as follows:

$$\mu = \ln(\bar{y}) - \frac{1}{2}\sigma^2$$

Where if $y$ is a log-normally distributed variable, $\bar{y}$ is its expected value (the arithmetic mean):

$$\bar{y} = e^{\mu + \frac{\sigma^2}{2}}$$

Recharge rate $R(t)$ will be the cumulative integral over the minimum drainage rate contributing to aquifer recharge $(L/t^2)$ to infinity. In the SIMRAT documentation, this is referred to as the wetting gradual recharge function. The cumulative integral of a lognormal distribution *f(y)* is:

$$R(t) = \int_{t}^{\infty} y f(y)\, dy$$

$$R(t) = \frac{1}{2} e^{\mu + \frac{\sigma^2}{2}} \left(1 - \operatorname{erf}\left(\frac{\ln t - \mu - \sigma^2}{\sigma\sqrt{2}}\right)\right)$$

### ***Layered soil***

The same mathematical formulations are applied for layered soil. Consider that the unsaturated zone between the root zone and the watertable is not homogenous but contains two homogenous soil layers *a* and *b*, that have respective thicknesses $z_a$ and $z_b$ such that $z_{wt} = z_a + z_b$.

The water contents in equilibrium with the drainage are:

$$\theta_a = \sqrt[n_a]{\frac{D}{K_a}}(\theta_{s,a} - \theta_{r,a}) + \theta_{r,a}$$

$$\theta_b = \sqrt[n_b]{\frac{D}{K_b}}(\theta_{s,b} - \theta_{r,b}) + \theta_{r,b}$$

The timelag between drainage and recharge is the sum of the time delay through each individual soil layer:

$$t_{?} = ??(\theta^{?} - \theta^{??})D^{-?} + \quad ??(\theta^{?} - ??)D^{-?}$$

The minimum drainage rate contributing to aquifer recharge at time t is expressed as:

$$D(t) = \frac{(??(\theta_{?} - \theta_{?}) + ??(\theta_{?} - \theta_{?}))}{t_{??}} = \frac{?}{?}$$

The formulation of the recharge wetting function does not change, only the value of L is different.

## B. Derivation of the groundwater discharge equations used in Stage 3

The analytical equations described in this section are from a review of Knight *et al.*, (2002) and Rassam *et al.*, (2004). The key assumptions are:

1. The aquifer is laterally infinite,non-leaky, homogeneous and isotropic
2. Flow is unsteady and 1D horizontal
3. If the flow is unconfined, changes in the saturated thickness are small in comparison with the mean saturated thickness
4. A change in recharge occurs at a distance from a discharge edge (floodplain edge or river) of constant potentiometric head.

### *The linearised Boussinesq equation*

The Boussinesq equation is a non-linear partial differential equation describing unsteady flow in a homogenous, isotropic unconfined aquifer (Fetter, 2001). The Boussinesq equation for 1D horizontal flow is:

$$\phi \frac{\partial H}{\partial t} = K \frac{\partial}{\partial x}\left(H \frac{\partial H}{\partial x}\right) + N(x,t)$$

where *Φ* is the porosity, *K* is the hydraulic conductivity (a constant as the aquifer is isotropic and homogeneous), *H* is the height of the watertable or saturated thickness (a dependent variable), *x* is distance along the horizontal plane and *t* is time. *N(x,t)* is a source or sink term, describing how groundwater is added or removed (e.g. via surface recharge or wells).

As the Boussinesq equation is a non-linear partial differential equation, deriving an analytical solution is possible only for very simple circumstances. If we simplify the equation by assuming that fluctuations in the watertable *h*, and therefore changes in saturated thickness, are minor compared to the average saturated thickness of the aquifer $\bar{h}$, then H= $h + \bar{h}$ and the Boussinesq equation can be linearized to give:

$$\phi \frac{\partial h}{\partial t} = K\bar{h}\left(\frac{\partial^2 h}{\partial x^2}\right) + N(x,t)$$

This equation is an example of the diffusion or heat equation, a linear partial differential equation that is often encountered in the theory of heat and mass transfer (Haitjema, 1995). The exact solution depends on the initial conditions, boundary conditions, and forms of *N(x,t)*. The equation is also identical to the governing equation for confined flow if Φ represents storativity rather than porosity (Haitjema, 1995), hence the same equation can be applied to both unconfined and confined aquifers.

One important property of this linearized equation is that the *principle of superposition* applies. If functions $h_1$ and $h_2$ are solutions to the linearized Boussinesq equation then the following function is also a solution:

$$h(x,t) = C_1 h_1(x,t) + C_2 h_2(x,t)$$

where $C_1$ and $C_2$ are scalars. The superposition principle only holds for linear problems (e.g. the saturated thickness of the aquifer does not change significantly over time). This is the basis for such groundwater modeling approaches such as the Analytical Element Method (Strack, 2014). In essence, this means that the head at a given location is the net sum of the individual impacts of various groundwater processes, such as regional flow, wells, and recharge.

### *Change in potentiometric head due to an instantaneous increase in recharge*

We wish to calculate the impact of recharge at a new greenfield site that is distance *a* from a feature of constant potentiometric head (the discharge edge). That is, we want the solution for a continuous source (step function) *N(a,t) = R* for *t>0* and *R* is the increase in root zone drainage. This is derived in several steps. There is a known analytic solution for the case where *N(x,t)* involves an instantaneous point source at time *t=0*. A boundary condition representing the discharge edge is then imposed. Once the change in head over time is known, Darcy's Law is used to determine the additional discharge to the river/floodplain due to the instantaneous point source. The discharge for a continuous source (such as an irrigation area) can be thought of as the sum of instantaneous sources provided the principle of superposition applies. Hence the change in discharge due to a continuous source is the integral over time of the change in discharge due to an instantaneous point source. Finally, the discharge for the continuous unit source is multiplied by the increase in root zone drainage and the groundwater salinity to obtain the salt load to the river over time. Further details are provided below.

If *N(x,t)* is an instantaneous unit point source at time *t=0*, i.e. *N(x,t)=0* for all *x* and *t* except *N(a,0)=1,* where, then an analytical solution has been developed that satisfies the 1-d linear Boussinesq equation for the initial condition *h = 0* at *t= 0*:

$$h_1(x,a,t) = \frac{1}{2\phi\sqrt{\pi D t}} e^{-\frac{(x-a)^2}{4Dt}}$$

where *D* is the diffusivity of the aquifer, which is the transmissivity of the aquifer divided by the specific yield (for an unconfined aquifer) or storativity (for a confined aquifer). This is the *change* in head due to the change in recharge at an instantaneous point source located at *x=a*.

### *Discharge edge boundary condition*

We now wish to impose a boundary condition: a discharge edge at *x = 0* where *h=0* for all values of *t* (at all times). The discharge edge represents either the edge of the floodplain or a river. The potentiometric head along the discharge edge is constant over time.

To satisfy this boundary condition, the method of images is applied. The method of images is a combined use of the superposition principle and symmetry (Strack, 2014). Recharge at point *x=a* will cause a rise in watertable at *x = 0*. However, to satisfy the discharge edge boundary condition, the solution for change in head *h* at *x=0* must be *h=0* at all times. The method of images introduces a point source of negative recharge at a mirror image location *x = -a*. Recharge at the image location is not real but is merely used as a means to obtain the solution (Strack, 2014). The change in head due to the mirrored source/sink at *x = -a* is:

$$h_2(x,a,t) = -h_1(x,-a,t) = \frac{-1}{2\phi\sqrt{\pi D t}} e^{-\frac{(x+a)^2}{4Dt}}$$

In this way, the rise in watertable caused by recharge at point *x=a* is counteracted by the decline in watertable caused by negative recharge at point *x = -a*. The two solutions cancel each other out at the location of the discharge edge at (x=0) so that the boundary condition always remains a fixed head (h = 0):

$$h_3(0,a,t) = h_1(0,a,t) - h_1(0,-a,t) = 0$$

Hence the equation for the change in head caused by an instantaneous point source at *x=a* in a semi-infinite, homogenous, non-leaky aquifer where there is a discharge edge of fixed head for *x=0* is:

$$h_3(x,a,t) = \frac{1}{2\phi\sqrt{\pi D t}}\left\{e^{-\frac{(x-a)^2}{4Dt}} - e^{-\frac{(x+a)^2}{4Dt}}\right\}$$

### *Discharge to the discharge edge: instantaneous recharge*

However, what we are interested in is not the head but the discharge to the discharge edge. The Darcy equation describing groundwater discharge *Q(x,t)* is proportional to the transmissivity *T* of the aquifer and the hydraulic gradient for flow in the *x* direction:

$$Q(x,t) = -T\frac{\partial h_3(x,t)}{\partial x}$$

where the solution for flux is negative as it is describing groundwater flux to the discharge edge (gaining stream or floodplain).

The partial derivative of head with respect to *x* is:

$$\frac{\partial h_3(\text{?},\text{?})}{\partial \text{?}} = \frac{1}{4\phi\,\text{??}\sqrt{\pi\,\text{???}}}\left(e^{\frac{-(\text{??})^2}{4D\text{?}}}[\text{?}-\text{?}] + e^{\frac{-(\text{?}+\text{?})^2}{4D\text{?}}}[\text{?}+\text{?}]\right)$$

At the river (x = 0) the derivative simplifies to:

$$\frac{\partial h_3(0,t)}{\partial x} = \frac{a}{2\phi D t\sqrt{\pi D t}} e^{-\frac{a^2}{4Dt}}$$

As the diffusivity of the aquifer is the transmissivity of the aquifer divided by the specific yield:

$$D = \frac{T}{\phi}$$

Then groundwater discharge to river/edge (x = 0) in a semi-infinite aquifer due to an instantaneous unit point source at *x*=a can be written as:

$$q(0,t) = \frac{-a}{2t\sqrt{\pi D t}} e^{-\frac{a^2}{4Dt}}$$

### *Discharge to the discharge edge: step function recharge*

To find the groundwater discharge due to a continuous unit source, the flux due to an instantaneous unit source is integrated over time. The integral of an exponential function of the type described in the above equation returns the complimentary error function:

$$F_2(a,t) = \int_0^t q(a,\tau)\,d\tau = -\operatorname{erfc}\frac{a}{2\sqrt{Dt}}$$

This is the **Unit Response Equation**: the groundwater flux to the discharge edge due to a continuous unit source of recharge at *x=a*. That is, it is the discharge due to continuous recharge of 1 unit. The value of $F_2$ can be multiplied by the recharge flux *R* (the recharge rate over an area) to calculate the total groundwater flux to the discharge edge. Impacts are delayed horizontally as a result of the shape of the *erfc* function.

To obtain the salt load to the discharge edge due to the recharge, SIMRAT multiplies the flux by the groundwater salinity at nearest point on the discharge edge.

# 11 Glossary

**Aquifer** – An underground layer of rock or sediments 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

**AML** – Arc Macro Language; scripting language that has been used within ArcGIS in the past but is no longer supported

**ArcGIS** – Specialised GIS software for mapping and analysis developed by ESRI

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

**Bore** — See 'well'

**BSMS** – Basin Salinity Management Strategy; implemented under Schedule B of the Murray–Darling Basin Agreement

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

**CMA** – Catchment Management Authority (State Government of Victoria)

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

**CSIRO** — Commonwealth Scientific and Industrial Research Organisation

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

**DEPI** – Department of Environment and Primary Industries (State Government of Victoria)

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

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

**Diffusivity** – the ratio of transmissivity and storativity of a saturated aquifer (confined or unconfined) that governs the propagation of changes in hydraulic head in the aquifer ($L^2/T$)

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

**EC** — Electrical conductivity; 1 EC unit = 1 micro-Siemen per centimetre (µS/cm) measured at 25°C; commonly used as a measure of water salinity

**ESRI** – Environmental Systems Research Institute; international developer and supplier of ArcGIS software

**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

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

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

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

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

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

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

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

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

**iRAT** – Interim Rapid Assessment Tool developed for the MDBA for point-based assessment of river salinity impacts from trade in water entitlements

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

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

**LEACHM** – Leaching Estimation and Chemistry Model; a suite of simulation models describing the water and chemical regime in the soil root zone, developed by John Hutson and Jeff Wagenet in the Department of Soil, Crop and Atmospheric Sciences at Cornell University, Ithaca New York

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

**Mallee** – Region of southern Australia where current landscape (or past landscape) is mallee woodland; often referred to as Mallee region or Mallee zone. Areas of the Mallee have been extensively cleared for agriculture.

**MDBA** — Murray–Darling Basin Authority

**MDBC** — former Murray–Darling Basin Commission

**Model** — A conceptual or mathematical means of understanding elements of the real world that allows for predictions of outcomes given certain conditions.

**MODFLOW –** A three-dimensional, finite difference code developed by the USGS to simulate groundwater flow

**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

**MSM-BIGMOD** – Flow and salinity routing model used to estimate river salt concentration consequences of changes in saline groundwater discharge in the River Murray and Lower Darling river system

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

**NOW** – Department of Primary Industries Office of Water (Government of New South Wales)

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

**Pilot Interstate Water Trading Area** — area of the Murray Valley in which permanent and temporary water trading has operated to improve efficiency and effectiveness of consumptive water use

**Porosity** – The ratio of an unconsolidated material that contains pores or voids, commonly expressed as a volume ($L^3$ / $L^3$)

**PSA** – former Planning SA (Government of South Australia)

**Python** – A high-level, object oriented computer programming language that is the language of choice for scripting in ArcGIS

**Ready Reckoner** –Relates the effects of salt inflows in various reaches of the river on the EC impact at Morgan. The estimates are derived from MSM-BIGMOD modelling

**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

**RZD** – Root zone drainage; a term used to define the amount of water that passes beyond the crop root zone.

**Salinity** – The concentration of dissolved salts in water or soil, expressed in terms of concentration (mg/L) or electrical conductivity (EC)

**Salinity Registers** – A system for keeping record of accountable actions within the Basin; implemented under the BSMS and maintained by the MDBA.

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

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

**SIMPACT I –** A spatial modelling tool developed in 2001 to support the development of salinity zoning policy in SA

**SIMPACT II** – A spatial modelling tool developed in 2002 in SA ; considered an improvement to SIMPACT I due to more flexibility in input data, refinements in model resolution and incorporation of more robust mathematical equations

**SIMRAT** – Salinity Impact Rapid Assessment Tool; a tool developed and accredited for estimating salinity impacts of accountable actions to support BSMS objectives

**SIMRAT-XL** – Version of SIMRAT written for Microsoft Excel; a point-based assessment tool which can be used for a quick assessment of a locale

**SIS –** Salt Interception Scheme; large scale pumping schemes that divert saline groundwater and drainage water before entering rivers

**Soil water content (ϴ)** – The ratio of pores in soil that are filled with water; commonly expressed as a volume ($L^3$ / $L^3$)

**Specific storage ($S_s$)** — Specific storativity; the amount of stored water realised from a unit volume of aquifer per unit decline in head; units are [$m^{-1}$]

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

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

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

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

**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

**Timelag** – broadly refers to the an interval of time between two related phenomena (such as cause and its effect); more specifically for the Mallee it refers to the period of time between water passing the root zone and recharging the regional watertable

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

**URE** – Unit Response Equation; analytical solution that describes groundwater discharge, developed by Knight *et al*., (2002)

**USGS** – The United States Geological Survey

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

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

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