BSM2030 Knowledge Priorities
Mallee Legacy of History
Salinity Impacts from Pre-1988 Irrigation

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This report reviews the approaches and assumptions used to estimate the salinity impact of pre-1988 irrigation development in the Mallee region (the Legacy of History, LoH, impacts), focussing specifically on how irrigation accessions and recharge are estimated and implemented by the salinity register groundwater models.

The current suite of salinity register models have used a variety of approaches and assumptions to estimate groundwater recharge from irrigation, the principal difference being the approach used to estimate recharge during the calibration ("model history match") process:

- A forward modelling approach in which recharge rate over time is estimated via a district-scale water balance and hydrogeological parameters are varied during model calibration;
- An inverse modelling approach in which recharge is varied during calibration, with minimal changes to hydrogeological parameters, and the calibrated recharge rates are subsequently checked for consistency with irrigation accession estimates from district-scale water balances.

Additionally, there has been limited quantification and reporting of uncertainty.

The differences in approach, in the context of uncertain predictions, can be a point of contention amongst stakeholders, creating perceptions of inconsistency in model outputs. This report seeks to explore these areas of apparent inconsistency, unpack uncertainty related to recharge in irrigated areas and provide options for a way forward to guide future modelling efforts.

There are a number of challenges associated with estimating irrigation recharge which provide context to the treatment of recharge within groundwater models. First, the estimation of irrigation accessions (the net downwards flux of water below an irrigation district) is done via district-scale water balances, which rely on multiple datasets and assumptions that are prone to measurement error and potential bias. Second, there is currently no simple and robust transfer function that (for a wide range of scenarios) appropriately simulates the transmission of irrigation accessions to the water table to define recharge that results from irrigation. While the SIMRAT model is appropriate for dryland settings, it is not appropriate for use where perching occurs (which was widespread in irrigated areas prior to 1988). Third, the complexity of the unsaturated zone suggests that it may not be possible to develop a simple and robust transfer function for areas of deep water table with thick clays.

Part of the rationale as to whether a forward or inverse modelling approach is followed is related to the complexity of the unsaturated zone and how irrigation accessions are transmitted to the water table. Where the water table is shallow and a close relationship between irrigation accessions and recharge can be demonstrated, then a forward modelling approach can be undertaken. But where the water table is deep and long time lags are apparent, a forward modelling approach may not be feasible and an inverse modelling approach can be undertaken.

The forward modelling approach directly uses irrigation accession calculations to derive recharge. A benefit of this approach is that it provides a direct link between changes in irrigation practice and recharge. The approach, however, is exposed to the uncertainties associated with the district-scale water balance calculations.

The inverse modelling approach to recharge estimation is a valid technique that produces a well calibrated model with very good history match to the observed record. This is self-evident. It does not rely on an over-parameterised unsaturated zone model, where a lack of data introduces considerable uncertainty. The inverse modelling approach essentially integrates all potential errors into the derived recharge rate (e.g. it requires no judgements about irrigation efficiency or lag time). The approach, however, introduces other uncertainty due to incomplete observed water level data and non-uniqueness of aquifer parameters and recharge choices between the various recharge zones. Additionally, the inverse modelling approach does not rely on a process model to derive recharge and therefore cannot predict recharge into the future due to specific differences in irrigation practice; but it can make broad estimates of recharge in this regard.

Either of these approaches, <u>when applied appropriately</u>, can be used to develop valid and fit-for-purpose models for the estimation of LoH irrigation impacts. Neither approach is systematically biased; however, both approaches are susceptible to bias due to inherent subjectivity and, in both cases, efforts should be made to reduce the potential for bias by using as much data as possible from multiple lines of evidence to constrain the models.

There are three main areas of uncertainty regarding the estimation of LoH salinity impacts:

- The estimation of irrigation accessions over time and space;
- The estimation of recharge over time and space; and
- Parameter uncertainty in the groundwater models.

All three areas of uncertainty combine to influence the predictive uncertainty of the groundwater models and their resultant estimates of salinity impact to the River and their timing.

A preliminary analysis of uncertainty undertaken by this project, using the Loxton Irrigation District as an example, suggests that the uncertainty in the modelled recharge could be 60-150% of the true value. This level of uncertainty is directly transferable as a flux to the edge of the floodplain, but may not result in a linear response to the LoH salt load estimate (register entries) due to floodplain dynamics.

In terms of timing, non-unique model solutions—represented by a range of possible recharge functions—have equivalent response times through the groundwater system. However, in the absence of observed groundwater level data, an incorrect representation of recharge may influence salinity impact estimates. For instance, if an irrigation mound is allowed to grow too quickly then this brings the impact of irrigation forward, potentially over-estimating the impact at 2000 and thus underestimating the incremental change post-2000 (i.e. the register entry).

Given that data sources are more sparse for the pre-1988 period, the uncertainty associated with Legacy of History actions will be larger than that for post-1988 actions. However, ongoing model refinement using post-1988 data can be used to better constrain model calibrations and predictions to reduce this uncertainty.

A risk for register entries is if there is significant bias one way or the other, and the risk is greatest if the modelling consistently underestimates salt load predictions. The use of as much data as possible within either modelling approach (e.g. flux estimates, in-river salinity data, pumping test data) to provide some checks and balances to avoid bias should be the focus of future modelling efforts.

A whole-of-system approach is recommended as the means to advance a more consistent approach to modelling and to obtain a better understanding of uncertainty and avoid bias.

As part of a whole-of-system approach, a hybrid method represents an optimal solution. A hybrid method considers the uncertainty of irrigation accessions (over an irrigation district scale) as a function of time (as determined by the errors for each data source used to derive the accession estimate) and this function is then used to generate a range of plausible recharge functions to be included in the groundwater model. Effectively, this embeds the components of the district-scale water balance (and their errors) within the model and the LoH prediction, providing for greater transparency to link cause and effect. The output of this method would be a range of predictions around a median value used as the register entry.

Additionally, the hybrid method could be conceived as a part-forward and part-inverse modelling approach in which the parameters from the district-scale water balance and transfer function are included within the model calibration procedure.

The hybrid method requires the connection between irrigation accessions and recharge (via a transfer function or otherwise) and this may not be feasible where the unsaturated zone is complex and inverse modelling approaches are required. Nevertheless, the inverse modelling approach can still include the principles of the hybrid method by undertaking a district-scale water balance, describing in detail how the irrigation area and practice has varied over time, and providing a detailed description of the unsaturated zone so that links can be drawn between irrigation activity and the recharge implemented in the model.

In all cases, the unsaturated zone should be described in detail (e.g. the extent, thickness and properties of hydrostratigraphic units and the depth of the water table) so that the implications for LoH predictions of a particular representation of the unsaturated zone by the modelling framework can be understood and documented.

The extent to which a whole-of-system modelling approach is adopted will vary for each model will depend on range of factors (e.g. data availability and cost). A range of options were presented at the project workshop and the following steps to support a whole-of-system modelling approach describe the preferred way forward:

- A) Maintain the status quo with ongoing scheduled model refinement being driven by efforts to avoid bias through a more explicit recognition and documentation of uncertainty and the connections between irrigation accessions and recharge. As part of this, it is recommended that model protocols be updated to require a district-scale water balance and a description of how irrigation area and irrigation practice has varied over time. Additionally, further efforts to constrain models and limit non-uniqueness are recommended (e.g. comparison of modelled fluxes to run-of-river data and salt-load time series, floodplain ET), because hydrogeological parameters (K and S) are time invariant and this will assist in limiting uncertainty in recharge estimates for all time periods.
- B) In addition to point A), with the states each selecting one model for a comprehensive uncertainty analysis by defining the recharge uncertainty envelope and using all available datasets to constrain the range of plausible parameter sets. The derivation of LoH impact estimate for register purposes would require the use of a single recharge function as a fixed input (i.e. not varied during calibration), with the process used to select the fixed function being a policy decision (e.g. the median is an option, but all parties would have to agree on this).
- C) In addition to point A), with the investigation of a transfer function connecting irrigation accessions to recharge.
- D) Where a transfer function is feasible, based on investigations, a hybrid modelling method can be developed whereby the uncertainty of irrigation accessions is considered as a function of time (as determined by the errors for each data source used to derive the accession estimate) and this function is then used to generate a range of plausible recharge functions to be included in the groundwater model.

Subsequent investigations are recommended to support the implementation of the whole-of-system modelling approach:

- A review of the datasets that can be used to constrain the groundwater models;
- The investigation and development of a transfer function that connects irrigation accessions to groundwater recharge and is appropriate for situations where perching occurs or has occurred in the past;
- Studies to conceptualise and quantify the influence on the apportioning of salt loads to the river from regional drivers (e.g. from irrigation) to better understand and predict how a flux to the edge of the floodplain is routed through the floodplain to drive a change in river salinity;
- A pilot uncertainty analysis that takes a whole-of-system approach, covering the components of the district-scale water balance, recharge, groundwater flow and floodplain processes.

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1. Introduction and problem definition

1.1 BSM2030 KNOWLEDGE PRIORITIES CONTEXT

The Murray-Darling Basin Authority (MDBA) is considering a new approach to the salinity accountability framework beyond 2030 as part of the development of the Basin Salinity Management 2030 strategy (BSM2030). In 2014, a general review of the current salinity management arrangements was undertaken as an initial step in this process (MDBA, 2014). The review highlighted, as a strategic knowledge priority, the significant uncertainties of estimated salt loads to the River Murray (the River) that result from past actions (dryland clearing and pre-1988 irrigation) and underpin a projected increase in River salinity, unless they are offset by compensatory actions. The uncertainty surrounding these 'Legacy of History' (LoH) estimates are of most significance in the Mallee region where their contribution to River salinity is greatest. The key elements of BSM 2030 and its strategic knowledge gaps are listed in Figure 1.

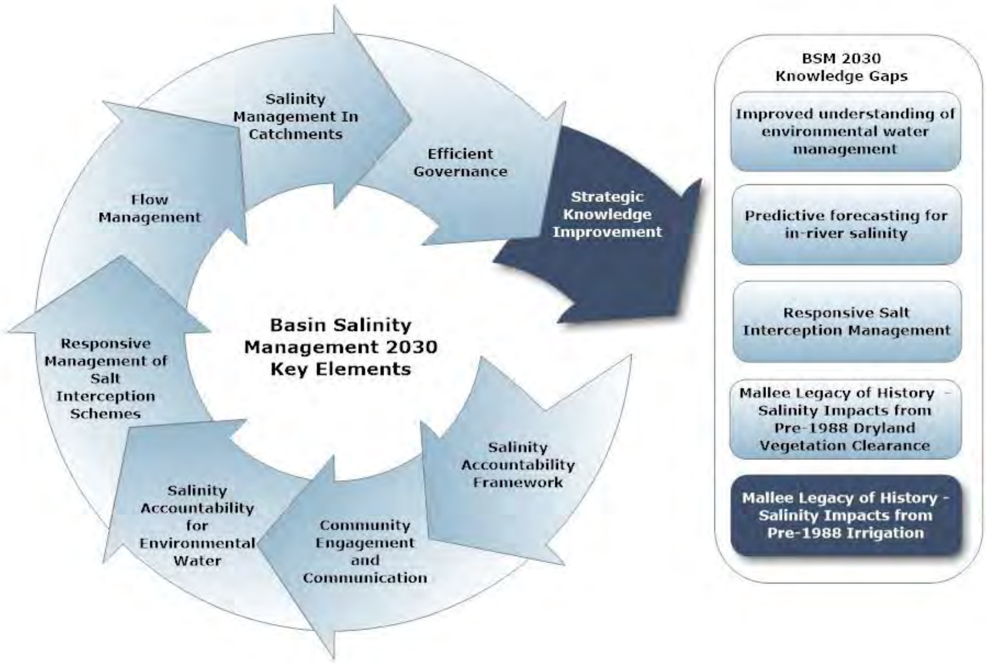


Figure 1 - BSM2030 Strategic Knowledge Priorities

In June 2016, a workshop was convened to discuss these issues (Cummins, 2016) and it was recommended that investigations be undertaken to review:

- the approaches and assumptions used to estimate the Mallee LoH impacts; and
- to determine whether these approaches and assumptions could be applied more consistently across jurisdictions.

Hydrogeologic Pty Ltd and project partners have been engaged by the MDBA to undertake this review, in relation to pre-1988 irrigation.

1.2 SALINITY STRATEGY BACKGROUND

The 1988 Salinity and Drainage Strategy (S&DS) inter-jurisdictional agreement (MDBMC, 1999) was a no regrets approach that allowed for new irrigation development activities, provided their salinity impacts were offset. Simply put, irrigation districts were permitted to acquire the right to dispose of saline drainage water, provided they undertook to build and operate salinity mitigation works and measures and/or collaborate financially to do so. The subsequent Basin Salinity Management Strategy (BSMS) 2001-2015 (MDBMC, 2001) expanded this strategy, and established end-of-valley and Basin water quality targets under an integrated catchment management philosophy. Essentially these Basin-scale partnership strategies have at their core a salinity impact trading scheme, whereby if participants wished to implement works or measures that involved salinity impacts (debits), they need also to implement works or measures to reduce or offset salinity impacts (credits), provided the salinity of the River Murray did not exceed an agreed value (<800 EC for 95% of the time as modelled) and the credits exceeded the debits.

The 1988-2000 S&DS invoked the no regrets principle by acknowledging that past actions had driven the current river salinity regime, and that unpicking this was counter-productive to future management of the system. Rather, a baseline date (1 Jan. 1988) was agreed that ruled off on past actions, and that all future actions would be held accountable in terms of their salinity impacts, evaluating them against benchmark conditions (1975–85 for the S&DS and 1975–2000 for BSMS. Despite reductions in salinity arising from the Strategy, it became apparent that the baseline as agreed was not constant. Some actions taken prior to the 1988 agreement were still able to have a salinity impact after 1988.

Under the 2001-2015 BSMS, the salinity impacts of pre-1988 actions were termed Legacy of History (LoH) impacts and parties to the agreement were held jointly responsible. The salinity impact effects were assessed using models and an agreed climatic/hydrologic sequence, the 'benchmark period' 1975-2000, and baseline conditions were defined as the agreed suite of conditions that contribute to the transport of salt in place within the catchments and rivers on 1 January 2000 (MDBA, 2015).

To implement this approach, a new salinity Register (Register B) was instituted within the BSMS framework as the vehicle to explicitly acknowledge the LoH impacts and these were specifically defined as a salinity impact which occurs after 1 January 2000 but is attributable to an action taken or decision made before 1 January 1988. The part of the impact that occurs after 1 January 2000 is entered in Register B and the part which occurs before 1 January 2000 becomes part of the baseline conditions. The Register B entry is calculated as the incremental change in salinity compared to 2000 (Figure 2 after MDBC (2005), Chart 3.2).

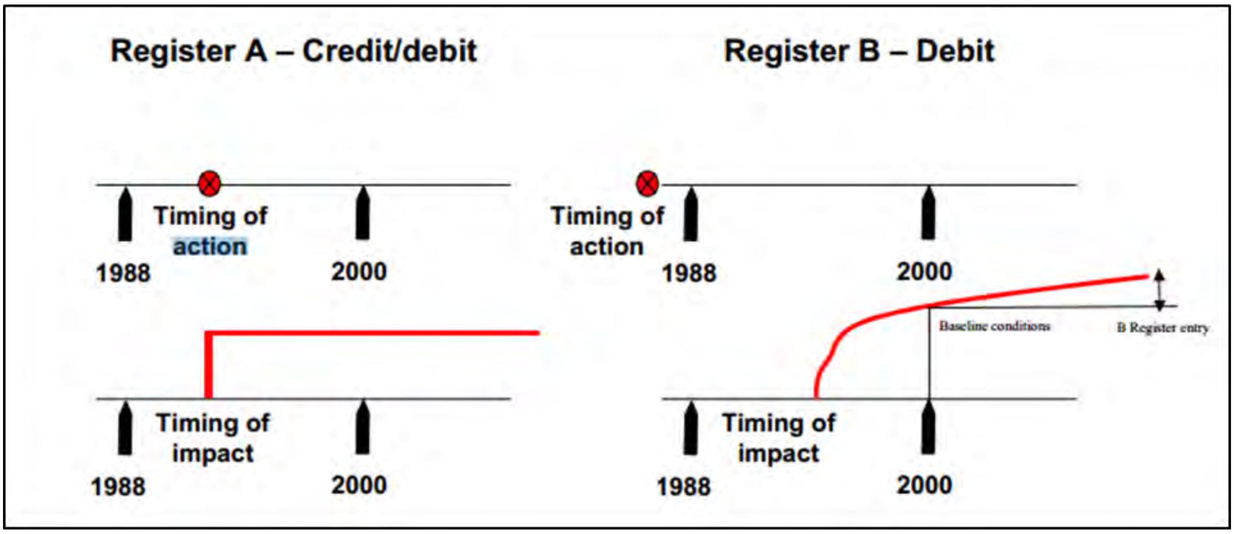


Figure 2 - Timing considerations for salinity register entry calculations

The LoH actions were effectively of two types: dryland actions and irrigation area actions. By their very nature, the salinity impacts of these actions were difficult to quantify, and large uncertainty was attached to the impact estimates. Nevertheless, the impacts were derived and incorporated into the BSMS registers.

1.3 ESTIMATING LOH IMPACTS

Current approaches to estimating LoH irrigation impacts involve the generalised procedure outlined in Figure 3.

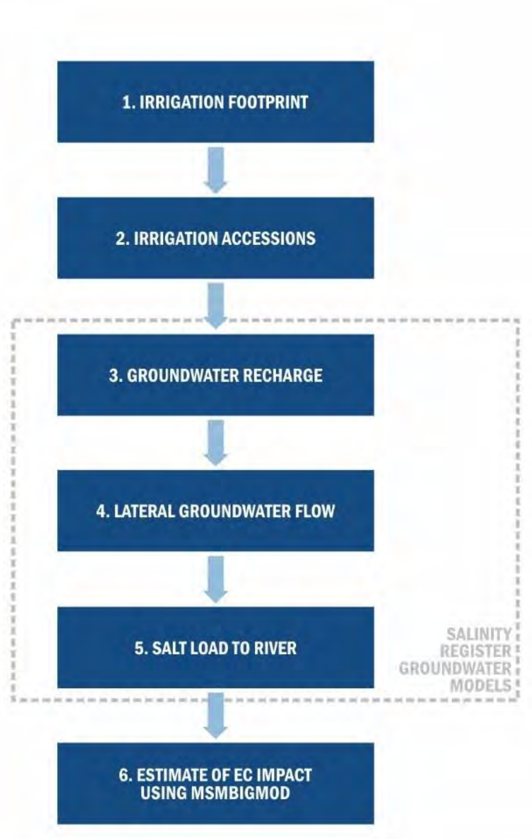


Figure 3 Generalised procedure used to estimate LoH irrigation impacts

Stage 1 requires data on the area of irrigation footprint and the application rate over time, up until 1988. Stage 2 is an estimate of irrigation accessions which is defined as the net downwards flux of water below an irrigation district and is driven largely by Root Zone Drainage (RZD). The downward flux of water takes time to be transmitted through the unsaturated zone and a portion of this water is held in pore spaces, and some may become perched and flow laterally away from the soil column rather than entering the water table and becoming recharge. Stage 3 takes account of these time lags and water losses to estimate recharge to the water table.

Recharge is a primary input to a series of groundwater flow models that are used to simulate lateral groundwater flow (Stage 4) and the discharge of saline groundwater to the River (Stage 5). In Stage 6, the salt loads calculated by the groundwater flor models are converted to a salinity impact, the salinity effect (EC) and cost effect ($m/y) by BIGMOD and the results are summed to calculate the register entries for each jurisdiction.

Several assumptions and simplifications need to be made at each stage of this procedure, to simulate physical processes which are highly variable in space and time. While best efforts are made to calibrate the models, there is uncertainty associated with parameterising the models (such as recharge rates and hydrogeological parameters) and the simplifications required in modelling such large areas. This uncertainty propagates through the models such that their resultant predictions are deemed to be uncertain.

To date, there has been limited quantification and reporting of uncertainty in the register models. Additionally, the register models use different approaches and assumptions to estimate groundwater recharge from irrigation (Stage 3), which (in this context) is the key process in mobilising saline groundwater to the River. One approach is to directly estimate recharge based on estimates provided by Stage 1 and Stage 2 (a forward modelling approach). An alternative approach is to inversely estimate recharge using observed groundwater level data as part of model calibration procedures (an inverse modelling approach).

This report seeks to unpack these issues.

1.4 SCOPE OF THIS STUDY

The scope of this study has been developed to address the workshop recommendations (Cummins, 2016) that were made in relation to LoH irrigation impacts, the major objectives being:

- To review the assumptions underpinning the existing register entries and associated assessment methods, including modelling;
- To provide an improved understanding of the uncertainties inherent in the assessment methods; and
- To determine whether the assumptions and modelling approaches could be more consistently applied across jurisdictions.

The focus of this study is on Stages 1 to 4 of the assessment procedure outlined in Figure 3 and is illustrated in Figure 4; specifically, the study focusses on the assumptions and approaches used to estimate irrigation accessions and groundwater recharge in irrigated settings pre-1988 and how they drive a change in groundwater flux to the edge of the floodplain.

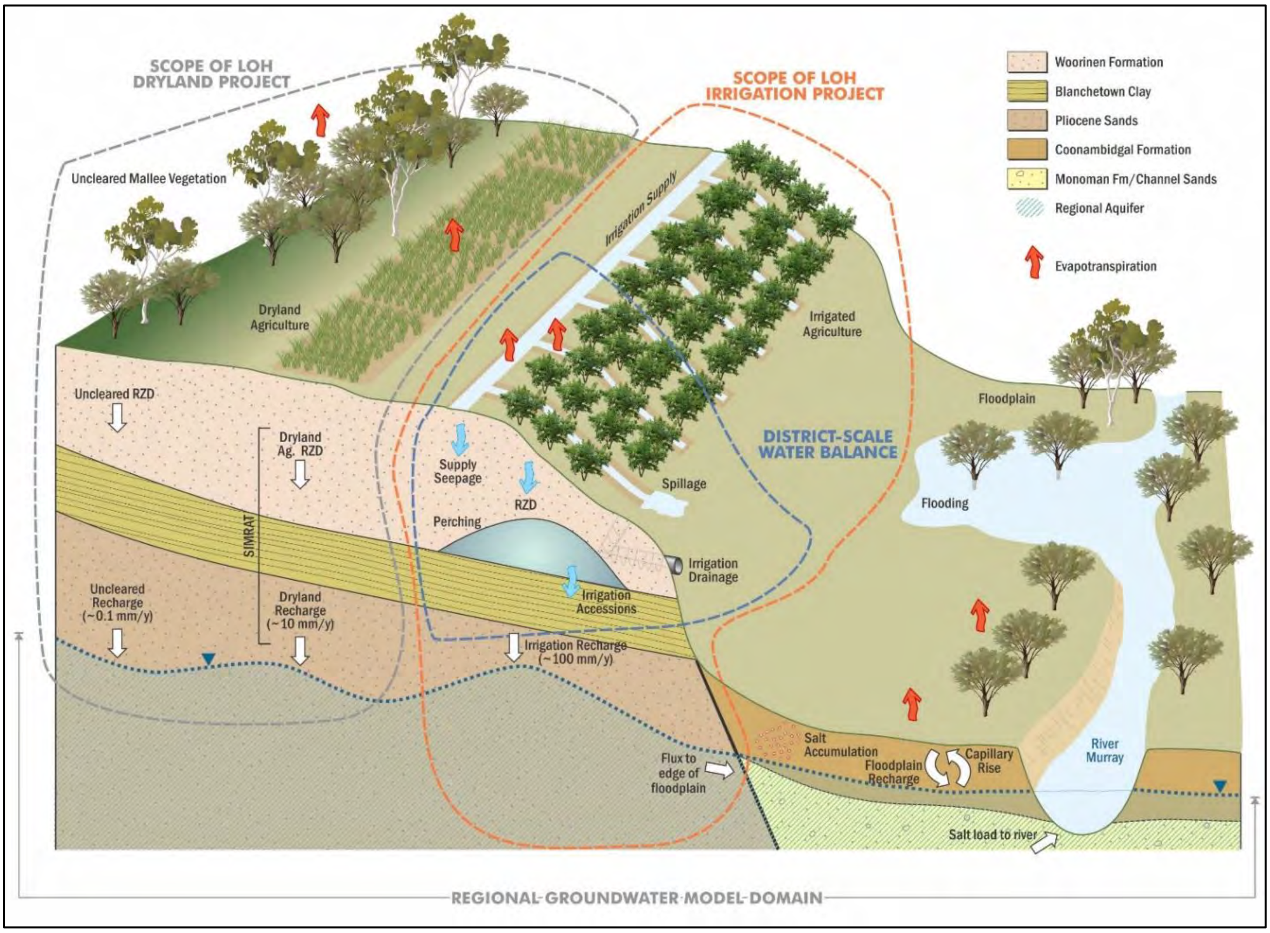


Figure 4 Mallee zone conceptual model for dryland, irrigation and floodplain

The focus of this study is essentially on the driving processes related to pre-1988 irrigation activity which may cause a change in river salinity, post-2000.

While the focus of this study is on recharge processes, the parameterisation of groundwater flow processes in models is also considered due to its relationship with recharge as part of model calibration. Thus, the driving processes related to irrigation activity extend to the edge of the floodplain.

Floodplain processes (due to their complexity) are not being reviewed as part of this study, but their role in influencing the conversion of a flux at the edge of the floodplain to a salt load in the river is discussed (Stage 5), as it is important for this work to consider, in broad terms, the Register implications for a set of modelling assumptions for irrigation recharge. The assumptions and calculation procedures undertaken by BIGMOD (Stage 6) will not be reviewed as part of this exercise.

1.5 THIS REPORT

This report has been structured to align with the physical processes involved in the generation of salinity impacts that result from irrigation activity; i.e. the discussion proceeds from a description of irrigation history, to the quantification of root zone drainage and irrigation accessions, to the transmission of fluxes across the unsaturated zone, to the treatment of irrigation recharge (via forward or inverse modelling approaches) in groundwater models.

The following topics are discussed and explored:

- The concepts and definitions that underpin irrigation accessions and recharge (Section 2);
- Unsaturated zone processes in irrigated areas, describing: the history of irrigation development, the quantification or root zone drainage and irrigation accessions, and the transmission of fluxes across the unsaturated zone (Section 3);
- The treatment of irrigation recharge by groundwater models, describing the forward and inverse modelling approaches and their implications for predictions of LoH salinity impacts (Section 4);
- Identification of sources and magnitude of uncertainty in recharge estimates and their implications for estimates for predictions of LoH salinity impacts (Section 5);
- Options to advance a more consistent approach to the estimation of salt impacts associated with recharge in irrigated areas (Section 6); and
- Conclusions and recommendations (Section 7).

2. Concepts and definitions

The following sections outline some key concepts and definitions regarding irrigation recharge processes and register entries, and provide an overview of the groundwater models used to calculate the register entries.

2.1 IRRIGATION RECHARGE PROCESSES

A conceptual model of irrigation accessions and groundwater recharge in irrigated settings is illustrated in Figure 4, which is expanded in the process diagram shown in Figure 5. Three main elements are involved:

- A land surface water balance;
- Unsaturated zone processes which influence the transmission of irrigation accessions to the water table; and
- Recharge to groundwater and the saturated zone processes which govern groundwater flow.

The purpose of the conceptualisation presented is to frame the understanding of physical processes and to define the terminology used and it will become the basis for a discussion on uncertainty later in the report. It is not meant to represent a modelling approach as such.

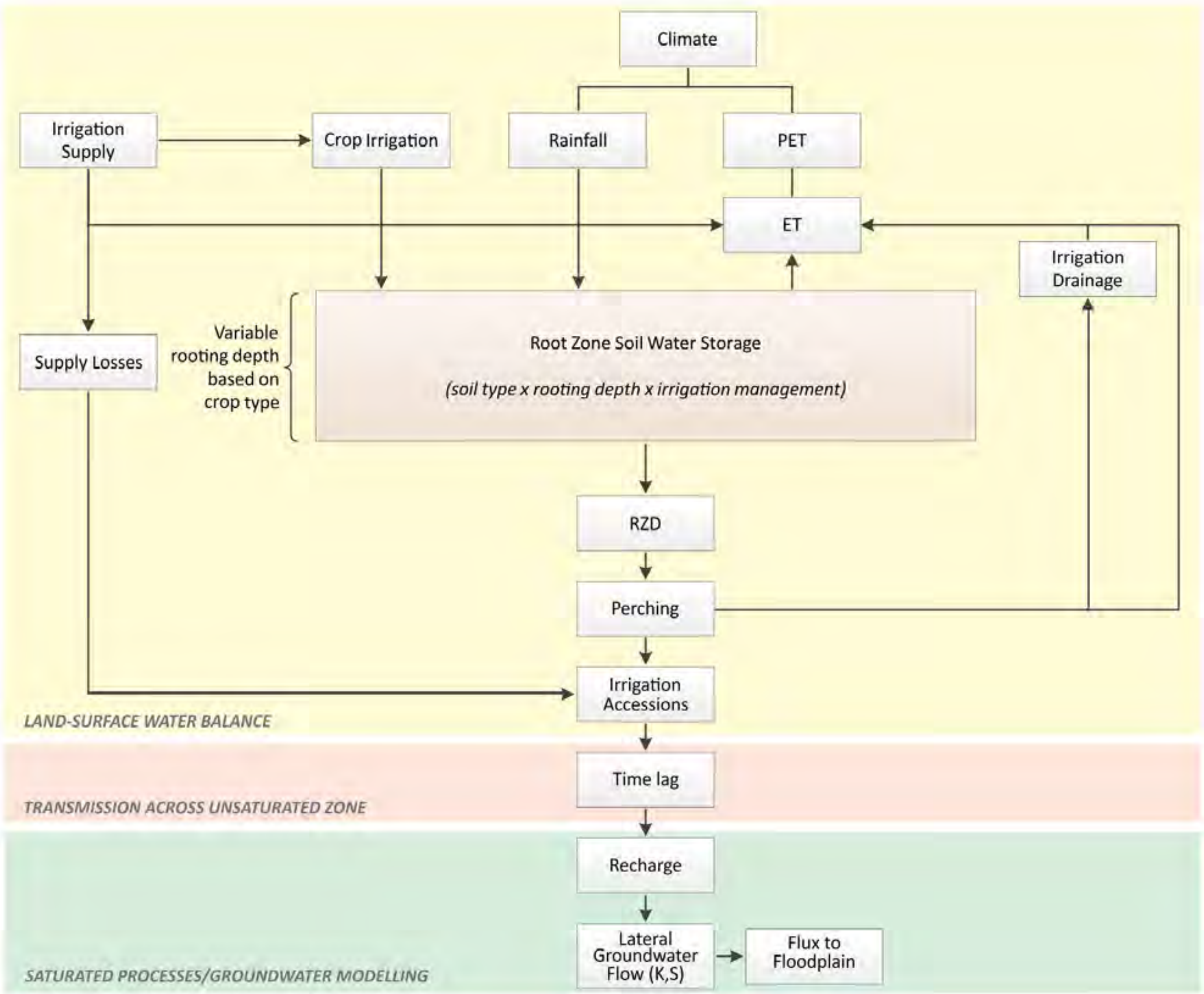


Figure 5 Irrigation accessions and groundwater recharge processes

2.1.1 Land surface water balance

The land surface water balance describes the dynamic in which water from irrigation diversions and rainfall is partitioned into fluxes associated with supply losses, crop irrigation, evapotranspiration (ET), root zone drainage, and sub-surface irrigation drainage. The following definitions apply.

Irrigation supply represents diversions from the River used for irrigation. The conveyance systems for delivering the irrigation supply have changed with time, shifting from a network of lime mortar or concrete-lined channels and sluice gates to a pressurised piping system (Adams and Meissner, 2009). The older channels were subject to *supply losses* associated with evapotranspiration (*ET*), channel leakage and spillage[1], and a portion of this water entered the unsaturated zone.

The total amount of water applied to a crop (*application rate*) is made up of *crop irrigation* and *rainfall*[2]. Much of this water is consumed by ET, but a portion of water may drain below the rooting depth of the crop as root zone drainage (*RZD)*. The quantum of RZD depends heavily on irrigation management, with the relationship between RZD and irrigation efficiency typically[3] described by the following equations:

Equation 1

$$Irrigation\ efficiency = \frac{Crop\ ET}{Application\ Rate}$$

Equation 2

$$RZD = Application\ rate * (1 - Irrigation\ efficiency)$$

RZD is often described as a percentage of the applied water being equivalent to:

Equation 3

$$RZD\ \% = 1 - Irrigation\ efficiency\ \%$$

Early irrigation practices commonly led to the development of perched water tables on the top of sub-surface clays (e.g. the Blanchetown Clay) and the resultant waterlogging led to the establishment of sub-surface drainage schemes (using tile drainage predominantly) to drain the root zone.

Where *irrigation drainage* schemes are present, a portion of RZD may be intercepted before the remaining water moves more deeply into the unsaturated zone. Therefore, total *irrigation accessions* comprise the leakage from supply losses and the balance of RZD and the amount of water intercepted by drainage schemes.

Irrigation accessions may be defined as the total quantum of water that enters the upper bounds of the unsaturated zone and is not lost directly by ET or drainage schemes. This quantum of water is the residual of the land surface water balance.

Discussion of how the land surface water balance has been applied at an irrigation district-scale in the Mallee region is provided in Section 3.2

[1] Losses associated with water flowing out of the end of the concrete channel or that which remained in channel after an irrigation shift ended.

[2] Rainfall can either be defined as total rainfall or effective rainfall. Effective rainfall is the amount of rainfall that infiltrates the rootzone and can effectively be used by the crop; i.e. it is the amount of rainfall that is neither lost to runoff or to root zone drainage (Brouwer and Heibloem, 1986).

[3] There are a variety of definitions of irrigation efficiency in the agronomic literature which can be based on crop yield or a variety of definitions of water applied. This project will use Equation 1 as the preferred term.

2.1.2 Unsaturated zone transmission

Irrigation accessions are subject to time lags and potential further losses (via lateral flow) and reductions in flux before they enter the regional water table as *groundwater recharge* (R).

The nature of the time lags depends heavily on the nature of the unsaturated zone. Where the water table is shallow (i.e. the unsaturated zone is thin), time lags will be short and groundwater recharge may be equivalent to irrigation accessions. However, where the water table is deep and low permeability units (e.g. the Blanchetown Clay) are present and continuous, irrigation accessions may be subject to substantial time lags (in the order of decades) and perching processes may be an influence, which may cause the groundwater recharge rate to be less than the irrigation accession rate because it will be limited by the hydraulic conductivity of the low permeability units. Thus, the relationship between recharge and irrigation accessions may be summarised by the following equation:

Equation 4

$$Recharge_t \leq Irrigation\ accessions_{(t-tl)}$$

Where t is a point in time and tl is the time lag associated with the transmission through the unsaturated zone.

Discussion on the processes that influence the transmission of irrigation accessions across the unsaturated zone is provided in Section 3.3.

2.1.3 Saturated zone processes and model calibration approaches

Groundwater flow is controlled by aquifer characteristics that are parameterised in groundwater models principally by two hydrogeological parameters:

- the hydraulic conductivity (K) which describes how readily water can flow through an aquifer; and
- the storage coefficient (S) which describes the volume of water released or taken into an aquifer for a unit change in head per unit of surface area.

The rate at which groundwater heads rise and fall due to changes in recharge, R(t), is determined by the relationship between R(t), K and S. This relationship is the core of groundwater model calibration in which modelled groundwater heads are matched to observed data from monitoring wells, and ultimately determines the discharge component from the groundwater model which, in this case, is the flux to the floodplain.

There have been two broad approaches to groundwater model calibration to estimate LoH impacts:

- A forward modelling approach in which R(t) is fixed according to land surface water balance calculations, and K and S are determined through model calibration; and
- An inverse modelling approach in which K and S are fixed according to pumping test data, and R(t) is determined through model calibration.

The solutions to obtain an acceptable model calibration are, however, non-unique. That is, different combinations of values for R(t), K and S can yield equivalent calibration performance. An explanation of non-uniqueness and its implications is provided in Figure 6.

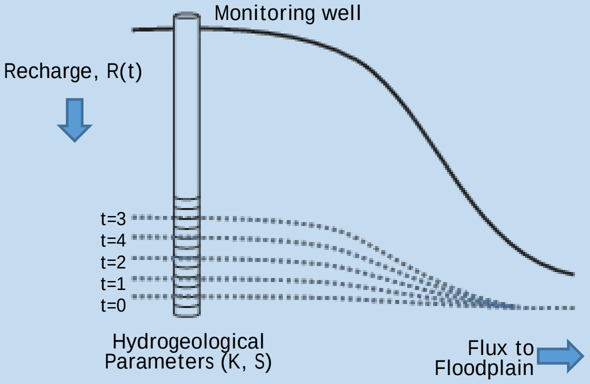
Discussion on saturated zone processes, and the approaches to model calibration and the treatment of recharge in models is provided in Section 4.

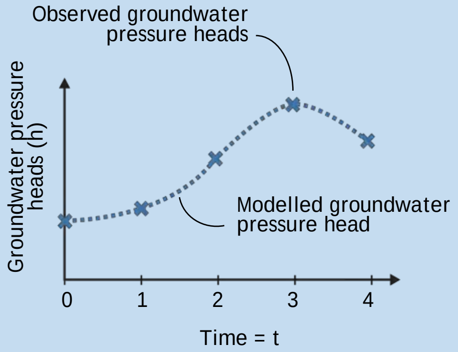
WHAT IS NON-UNIQUENESS?

- Groundwater model calibration attempts to match modelled heads with observed heads by varying (primarily) three main factors: R(t), K and S.
- But the solution is non-unique; e.g. the following parameter sets give equivalent calibration performance,

$$\{R(t), K, S\} \equiv \{0.5R(t), 0.5K, 0.5S\} \equiv \{2R(t), 2K, 2S\}$$

- Using this example, recharge could be 50% or 200% of its true value and the modelled hydrographs would be identical.

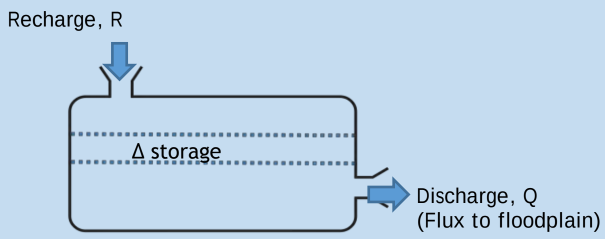




SIGNIFICANCE OF NON-UNIQUENESS

- Consider the groundwater balance in which,

$$Recharge\ (R) = Discharge\ (Q) - \Delta\, Storage$$



- In the context of this project, the discharge term (Q) is the flux to the floodplain.
- Where there is observed groundwater pressure head data, the change in storage is known and does not vary between alternative calibrations, which means that the flux to the floodplain (Q) will vary directly in accordance with the recharge input.
- Using the above example of non-uniqueness, the flux to the floodplain can, therefore, vary by 50% to 200% of its true value despite model calibration.

CONSTRAINING NON-UNIQUENESS

- The above example of non-uniqueness arbitrarily selected a range of 50% to 200% around true values of R(t), K and S to illustrate the issue of non-uniqueness.
- Mathematically, an unlimited range of non-unique solutions is possible, but not all solutions will be physically plausible. Only certain values of R(t), K and S are realistic and data can be used to constrain these estimates further.
- For example: pumping test data can be used to constrain K and S; district-scale water balance data can constrain R(t); and run-of-river data can be used to constrain Q.

Figure 6 Explanation of model non-uniqueness

2.2 CALCULATION OF REGISTER ENTRIES

The Operational Protocols under the BSMS identify how to account for the salinity impacts on the River due to irrigation practices. Two types of actions are identified,

> ***Register A*** contains details of any *actions* after a nominated *baseline date* that are considered to have a *significant effect*, excluding those actions that have the express purpose of offsetting *delayed salinity impacts*.
>
> ***Register B*** records *delayed salinity impacts* due to *actions* taken before the *baseline date* applicable to each state (the 'legacy of history' for which the Contracting Governments accept joint responsibility).
>
> BSMS Operational Protocols

The impacts from pre-1988 irrigation actions that manifest after 1 January 2000 are recorded on Register B. Though indirectly related to this discussion, two other actions related to irrigation are worth considering in terms of their relevant Register. Actions associated with improved irrigation practices and irrigation system rehabilitation on the 1988 irrigation footprint ,that specifically offset LoH irrigation impacts, are also recorded on Register B (for South Australia), whereas impacts due to post-1988 irrigation and improved irrigation practices on the post-1988 irrigation footprint are recorded on Register A. The manner in which the actions are treated under specific Registers is shown diagrammatically in Figure 2.

For Register B actions, two dates are critical to understanding accountability. The first is the date the action commenced, in this case irrigation. Pre-1988 irrigation development is dealt differently from post-1988 - the former is on Register B the latter on Register A. For Register B actions, the second critical date is the year 2000.

Any impacts from pre-1988 irrigation development that occurred in the River prior to 2000 are not accountable to the originating jurisdiction, rather they are identified as part of the baseline. It is only impacts in the River that occur after 1 January 2000 and are due to pre-1988 irrigation that are part of the accountable action termed irrigation LoH. Thus for Register B, the impact is calculated as the incremental change post-2000. In the case of a Register A action, the distinction around the year 2000 is not applicable; accountability is required for the full impact.

Awareness of these dates is important for a consideration of time lags (in both the unsaturated zone and in groundwater flow systems) and how these might affect register B entries.

2.3 GROUNDWATER SALINITY REGISTER MODELS

Estimating salt impacts in the River has been undertaken using a series of groundwater flow models representing different areas of the Mallee groundwater flow system, that have been individually upgraded at different times (see Figure 7). The South Australian reach of the Murray has been divided into five regional domains based on hydrogeological differences: Chowilla, Border to Lock 3, Woolpunda, Waikerie to Morgan, and Morgan to Wellington. For the purpose of LoH scenarios, the Victorian and NSW reaches of the Murray between the SA border and Nyah are covered by the Eastern Mallee EM1.2 regional model domain (there is no division of EM1.2 into sub-regional models). The model domain of the EM2 model is also shown because it was for this model that district-scale water balances were derived for Victorian and NSW irrigation districts (Aquaterra 2009b).

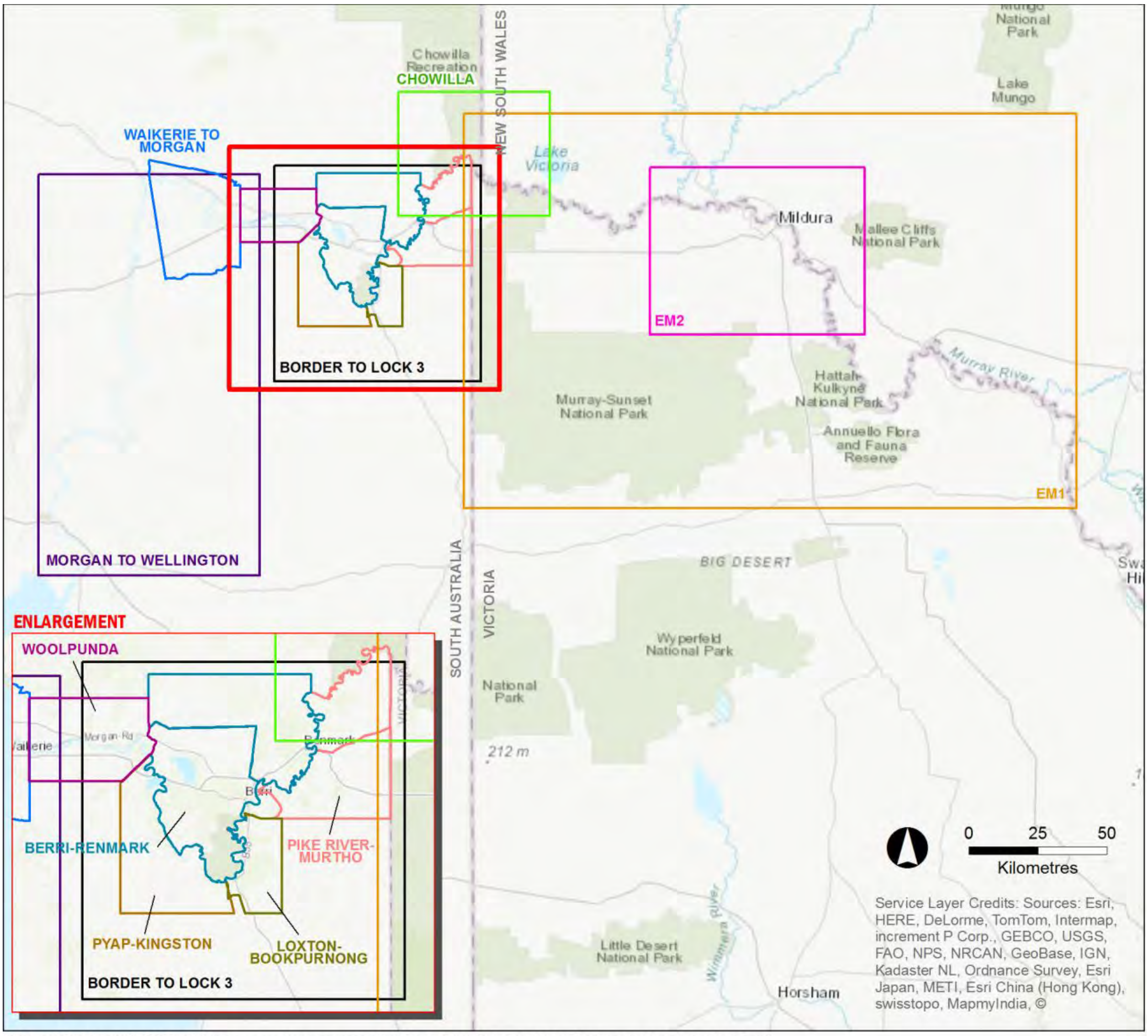


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Figure 7 Groundwater salinity register model extents

3. Current understanding of unsaturated zone processes

The following sections review the current understanding of unsaturated zone processes in relation to pre-1988 irrigation activity in the Mallee. The objective of this review is to summarise what is known about pre-1988 irrigation, the methods and datasets used to quantify irrigation accessions from this historic irrigation, and how the transmission of these fluxes across the unsaturated zone can be modelled to ultimately derive an estimate of recharge for groundwater modelling purposes.

3.1 HISTORY OF IRRIGATION DEVELOPMENT

Irrigation has a long history in the Mallee region, commencing in the 1880s with the establishment of Renmark by the Chaffey Brothers (Cole et al. 2015), who also established the First Mildura Irrigation Trust system (Context 2007). These developments included the installation of pumping stations and the construction of earthen irrigation channels (lined with concrete) through which water could be supplied via gravity flow (on a roster basis) to each farm in the district. Water was applied to crops via flood or furrow irrigation. This system was used for the majority of irrigation systems for the first half of the 20th century.

Until the 1960s, most irrigation occurred by flood or furrow irrigation on set rosters of 4 to 6 irrigations per year (Adams and Meissner, 2010). From the 1960s, new developments and the redevelopment of older districts utilised pressurised pipelines which minimised supply losses, and allowed for the ability to irrigate crops on-demand using sprinklers from the 1950s, and micro-sprinklers and drippers from the 1970s (Cole et al. 2015). The rehabilitation of older systems continued throughout this period until it was completed in 2004.

Early irrigation practices led to overwatering and the development of perched water tables on clayey subsoils. This process was driven by a combination of sandy-textured rootzones with low water-holding capacities, an inflexible irrigation roster system, the use of flood and furrow irrigation, the widespread presence of the Blanchetown Clay below the rootzone, and a lack of knowledge regarding crop water use requirements (Cole et al. 2015).

From the 1930s in Victoria (Mallee CMA) and from the 1940s at Loxton (Cole et al. 2015), sub-surface drainage schemes were implemented to intercept perched water tables and prevent them from rising into the rootzone. In South Australia, drainage was handled either by comprehensive drainage schemes or by bores drilled through the Blanchetown Clay that allowed for leakage to the underlying aquifer (typically the Loxton-Parilla Sands) (Adams and Meissner 2010). In Victoria in the 1990s, a number of drainage disposal schemes were constructed to improve the drainage system.

Significant research programs were initiated in the 1970s (e.g. the Loxton Research Centre) to better understand irrigation water management and since the late 1980s there has been an increasing focus on ways to measure and improve the efficiency of irrigation. The combination of increasing value/scarcity of water, improved infrastructure and delivery systems, the introduction of water allocation planning targets, the implementation of the S&DS and better knowledge and techniques regarding irrigation scheduling (e.g. soil moisture monitoring) has led to an improvement in irrigation efficiency from less than 50 % of the water applied in the first half of the 20th century to 85% or better from 2000 (Adams and Meissner, 2010).

An example of this irrigation history is provided in Figure 8 for the Loxton Irrigation District, noting that the dates of the major shifts in irrigation practice vary across the Mallee region.

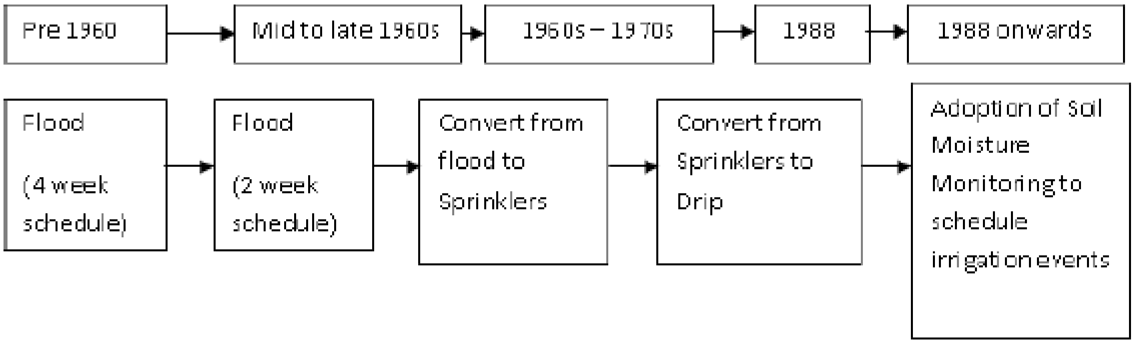

Figure 8 Irrigation history for Loxton Irrigation District (Vears 2010 as presented in Yan et al 2011)

3.2 Estimating irrigation accessions over time

Current approaches to estimating irrigation accession volumes are similar in both Victoria/NSW and South Australia, and involve the conceptualisation and quantification of a land surface water balance undertaken on an irrigation district-scale. A description of these methods, their data sources, assumptions, measurement errors and uncertainties is outlined in the following sections. Note that the irrigation accession estimates in Victoria/NSW are used directly in the groundwater models as irrigation recharge, but they are used only indirectly in South Australia (refer Section 4).

3.2.1 South Australia

In South Australia, a series of district-scale water balances have been performed to quantify irrigations accessions over time. These studies include the estimation of accessions for:

- Waikerie to Morgan (Fordham et al. 2011);
- Woolpunda (Meissner 2012);
- Loxton and Bookpurnong (Meissner 2011); and
- Pike-Murtho (Meissner 2014).

The approach taken by these studies is to calculate the various components of an irrigation water balance, shown in Figure 9, using the data sources and procedure outlined in Table 1. Note that the procedure outlined in Table 1 includes steps to convert the volumes shown in Figure 9 to rates (e.g. mm/y). The irrigation accession rate is the residual of these calculations.

The procedure outlined relies on several patchy data sources and assumptions, each of which being subject to measurement error and potential bias. These errors are greater during early time periods (when datasets are sparse) and will be compounded through the calculations resulting in uncertainty in the calculated irrigation accession rate. Given that the irrigation accession rate is a residual in the water balance and is a small term compared to the other water balance components, it is probable that its uncertainty is considerable and particularly so for early time periods (pre-1988).

See Section 5.1.1 for further exploration of the uncertainty in irrigation accession calculations.

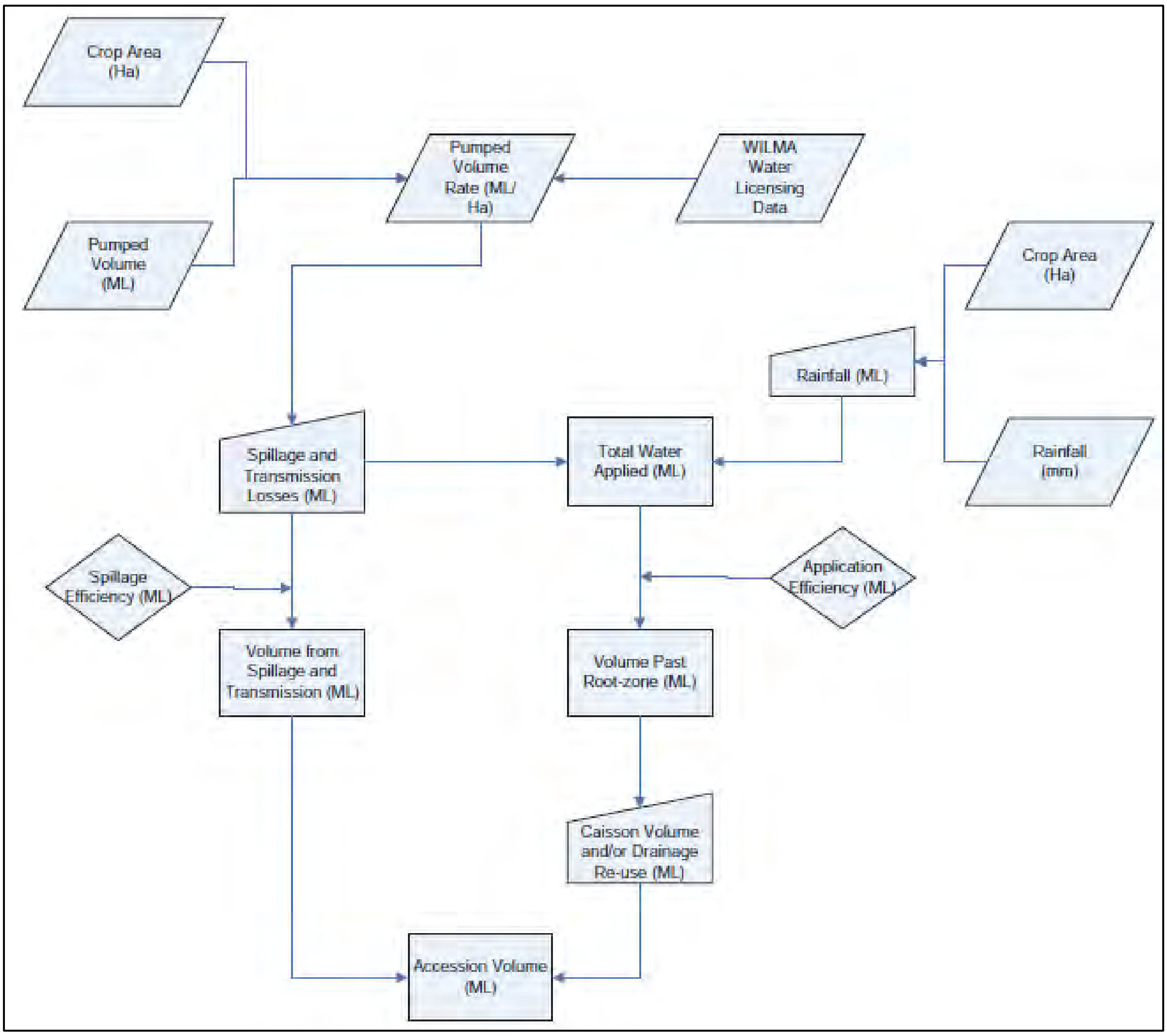

Figure 9 Irrigation water balance used to calculate irrigation accessions in South Australia (source: Fordham et al. 2011)

Table 1 Data sources and calculations for South Australian irrigation accessions

Water Balance component	Data sources / calculation
1. Crop area (CA)	Aerial photos, interpolation and anecdotal
2. Pumped/Diversion volume (Dv)	- estimated pre-metering - metered data post-metering (metering installation variable, circa late 70s to 90s)
3. Pumped/Diversion volume rate (DvR)	Derived by 1 and 2: $DvR = Dv \div CA$
4. Spillage % (Sp)	Estimated based on Ayars (1990) as *10%*
5. Transmission loss % (Tl)	Estimated based on Ayars (1990) as *3%*
6. Supply loss % (SL)	Derived by 4 and 5: $SL = Sp + Tl = 13\%$
7. Supply loss seepage rate (SLSr) (Seepage resulting from supply losses)	Estimated by assuming seepage factors of 40% for spillage and 20% for transmission loss, as follows: $SLSr = DvR*(Sp*40\%+Tl*20\%)$

8. Rainfall rate (P)[4]	Weather station data
9. Total water applied (App)	Derived according to 3, 6 and 8: *App = DvR*(1-SL)+P*
10. Irrigation efficiency (IE)[5] (defined as per Equation 1)	Estimated based on studies such as Adams and Meisser (2010) Newman et al. (2011)
11. Root zone drainage rate (RZD)	Derived according to 9 and 10: *RZD = App*(1-IE)*
12. Drainage rate (DR)	Data records (volumes) from comprehensive drainage schemes where available, converted to a rate by dividing volumes by crop area
13. Irrigation accession rate (Ia)	Derived according to 7, 11 and 12: *Ia = RZD+SLSr-DR*

3.2.2 Victoria/NSW

In Victoria/NSW, the calculation of irrigation accessions was developed for the Eastern Mallee 2 model (EM2) (Aquaterra 2009b) and forms the basis of the irrigation recharge applied in the EM1.2 model which is used for LoH impact calculations for Victoria and NSW (Aquaterra 2009a).

The process (outlined in Table 2) is very similar to that applied in the South Australian examples described above. The only difference in approach being the separation of supply losses into transmission losses and spillage rates in South Australia. In Victorian and NSW the seepage component from spillage is specifically excluded from irrigation accessions and accounted for as part of the drainage term.

There are no published confidence estimates or errors regarding the data sources and assumptions used to calculate the irrigation accessions in NSW and Victoria (as reported in Aquaterra 2009b), but they are likely to be at a similar level as those applicable for South Australia.

Table 2 Data sources and calculations for irrigation accessions in Victoria and NSW for the EM groundwater model (Aquaterra 2009)

Water balance component	Data sources / calculation
1. Crop area (CA)	Provided by MDBA and Sunrise21
2. Diversion volume (Dv)	Pumped volumes provided by MDBA
3. Diversion rate (per unit area) (DvR)	Derived by 1 and 2: *DvR = Dv ÷ CA*
4. Supply Loss % (SL)	Based on published estimates in NWC (2008)
5. Supply Loss rate (SLR)	Derived by 3 and 4: *SLR = DvR*SL*
6. Supply Loss Seepage % (SLS) (Proportion of Supply Loss that is seepage)	60% of supply loss is assumed to be channel seepage; remainder of supply loss is assumed to be evaporation and transpiration from fringing vegetation)
7. Rainfall rate (P)	Weather station data
8.Total water applied, rate (App)	Derived according to 3, 4 and 5: *App = P + DvR*(1-SL)*
9. Irrigation efficiency % (IE)	Estimated based on recent crop water use benchmarking studies (e.g. SunRise21 2006; Giddings undated)
10. Root zone drainage (RZD)	Derived according to 6 and 7: *RZD = App*(1-IE)*
11. Drainage rate (DR)	Data available for about 50% of irrigated area from published estimates (SKM 2003; and SKM & AWE 2003), estimated elsewhere with relative differences between districts maintained.
12. Irrigation accession rate (Ia)*	Derived according to 4, 5, 10 and 11: *Ia = RZD+(SLR*SLS)-DR*

*Termed irrigation recharge in Aquaterra (2009b)

[4] Fordham et al. (2011) provides two alternative estimates for irrigation accessions. The first uses total rainfall, which is what has been used in other irrigation districts of South Australia and also in NSW and Victoria (Aquaterra 2009b). The alternative estimate uses effective rainfall by applying a factor of 0.6 to convert total rainfall to effective rainfall. The overall estimates of irrigation accession are about 10% lower when the effective rainfall rate is used.

[5] Estimates of irrigation efficiency are based on standard FAO 56 methodology to estimate crop water use (Allen et al. 1998) at scales where data permits. These estimates are then extrapolated over space and time, as outlined in Newman et al. (2011). This applies for South Australia and for NSW/Victoria.

3.2.3 Water balance outputs

Figure 10 presents a summary of the district-scale water balance outputs for 1967, 1988 and 2000 for NSW and Victorian districts (data from Aquaterra 2009b) and for several (but not all) South Australian districts (data from Fordham et al 2009; Meissner 2011a&b; Meissner 2012). The plots show the outputs of the water balance (supply losses, crop water use, drainage and irrigation accessions), the sum of which is equivalent to the total amount of water supplied to an irrigation district through pumping from the River (diversions) and incident rainfall. The irrigation efficiency percentage used in the calculations (not an output of the water balance) is also shown.

The purpose of presenting these results is to see how the different assumptions made in the water balance calculation may influence the derived irrigation accession estimate, and to look at the variability of the results obtained.

Comparing the water balance outputs for South Australia and NSW/Victoria shown in Figure 10, the following comments are made:

- The total volume of water (per unit area) supplied to irrigation districts is broadly similar, although there is considerable variability between the irrigation districts;
- Supply losses via ET (e.g. evaporation from spillage losses) do not represent a large component of the water balance;
- Crop water use (equivalent to total water applied multiplied by the irrigation efficiency factor) is the largest component of the water balance (as an output);
- The assumed irrigation efficiency is higher in NSW/Victoria, particularly in 1967;
- The drainage rates are much larger and more widespread in NSW/Victoria than what is accounted for in South Australia;
- The estimated irrigation accession rates generally decline by around 50% between 1967 and 2000, although the decline appears greater in South Australia;
- The estimated irrigation accession rates are much larger in South Australia than in NSW/Victoria.

The higher estimates of irrigation accession in South Australia are driven by two factors:

- Irrigation efficiency factors are assumed to be lower (75% to 85% in South Australia in 2000 compared to 85% in Victoria/NSW); and
- Accounted drainage rates are much lower.

Regarding drainage, a key point of difference is that only data from the Comprehensive Drainage Schemes is used in South Australia and if there is no data available drainage is not estimated or extrapolated. In NSW/Victoria, where drainage data is not available (over about 50% of the area) a drainage rate is estimated, driven by the need to take specific account of (i.e. not undermine) pre-existing drainage-related claims (Drying of the Drains, Psyche Bend Lagoon, Lambert Swamp). There is no such accounting need in South Australia and this extrapolation has not taken place. However, there may also be physical reasons as to why drainage rates are higher in Victoria (e.g. a more efficient drainage network, the depth of the Blanchetown Clay relative to the rootzone).

Another difference in the approaches taken relates to pre-1967 data. In South Australia, early irrigation accession rates are estimated using the approach outlined in Section 3.2.1. But in Victoria/NSW, the pre-1967 estimates are scaled as a proportion of the 1967 rates by factors that are applied to account for an assumed growth rate in irrigation area (the factors are: 22% for 1900-1920, 43% in 1920-1950, 87% for 1950-1967).

While the differences between estimated irrigation accession rates in South Australia and Victoria/NSW are of interest, it is re-iterated that the accession rates estimated for South Australia have not been used directly in all of the salinity register groundwater models, while those in Victoria/NSW have been used directly. Thus, these differences only have bearing on some of the SA register entries. Nevertheless, it is important to be aware of how the land surface water balance calculations are made and their associated uncertainty prior to a consideration of how irrigation recharge is treated within groundwater models, which is outlined in Section 4.

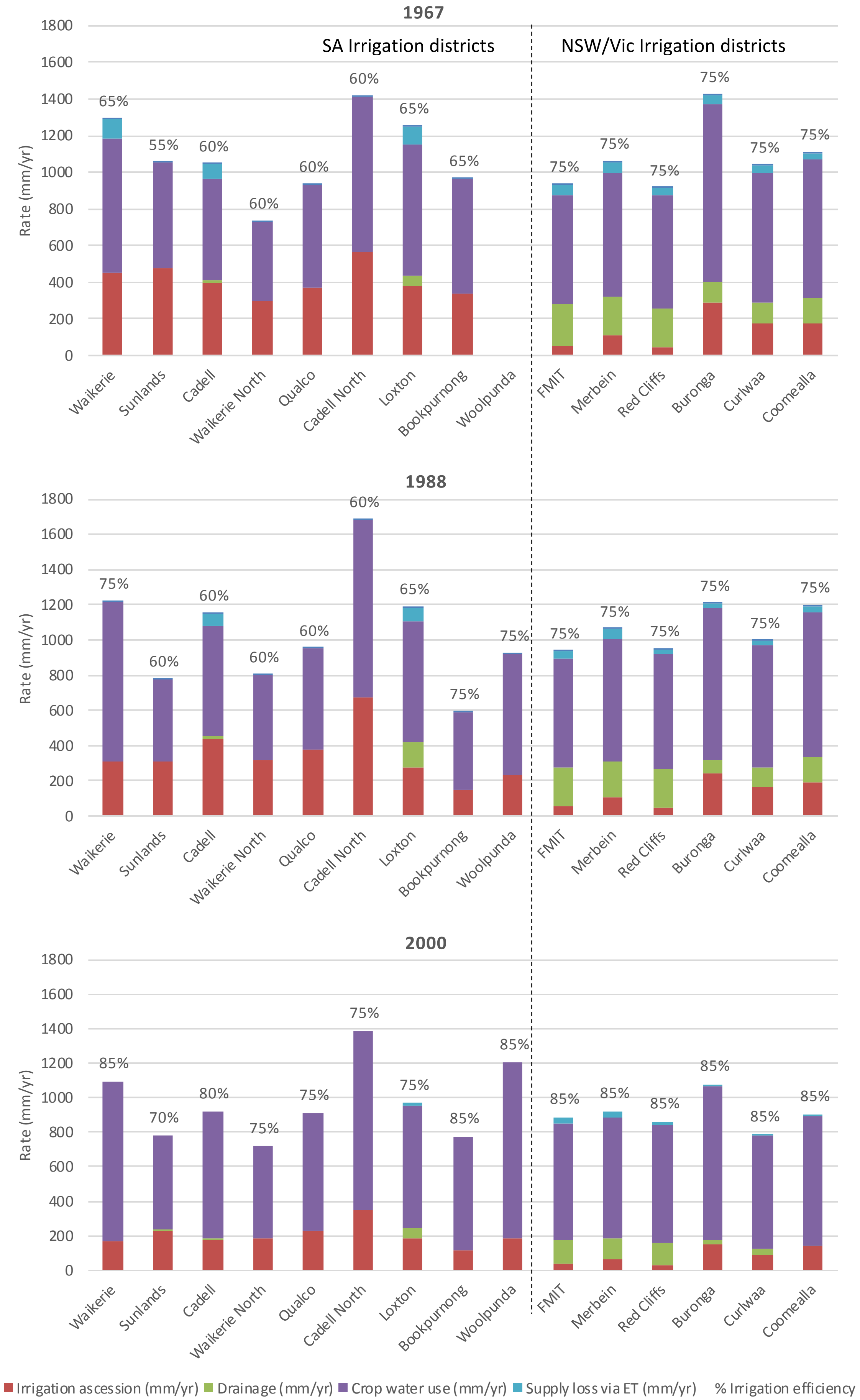

Figure 10 Comparison of loss terms for district-scale water balances in 1967, 1988 & 2000

3.3 Unsaturated zone transmission

3.3.1 Processes

Irrigation accessions are not equivalent to groundwater recharge. As water moves through the unsaturated zone it is subject to a number of processes that cause time lags between irrigation accessions and groundwater recharge and a reduction in the vertical flux. A key process is that of perching on the clay layer that underlies most irrigation areas.

The general assumption in the dryland LoH model predictions was that water moves under gravity to the water table and hence perching will not occur. The reason for this is that the RZD is less than the saturated vertical hydraulic conductivity of all soil layers and hence all soil layers are sufficiently permeable for water to move through it under gravity. A typical conductivity for a clay layer over a broad area is 1 mm/d (365 mm/y), which is at the upper end of RZD for dryland areas but is typically much less than RZD for irrigation areas. This means that perching will be the exception rather than the rule for dryland areas but the opposite is true for irrigation areas.

Sub-surface drainage is often used to take away water from perched water so as to avoid waterlogging. This process has been defined in this report to be accounted for in irrigation accessions. Otherwise water will (a) begin to move laterally and (b) create a ponded head above the clay. Consider the conceptual model shown in Figure 11 of the Waikerie Irrigation district. Water moving past the root zone (irrigation accessions) becomes perched on the Cadell Marl—a low permeability unit at the base of the Loxton Sands (a similar process to what commonly occurs when the Blanchetown Clay is encountered). The perched water table will continue to grow with time until it is offset by:

- Lateral fluxes, which may ultimately lead to cliff seepage and water loss;
- Increased vertical flux through the low permeability unit due to an increase in hydraulic head; and (in this example)
- Losses through drainage bores (which are not accounted for in the district-scale water balance, but they are simulated in the groundwater models).

The vertical fluxes which pass through the Cadell Marl will be subject to further time lags as they are transmitted across the unsaturated portion of the Glenforslan unit until they enter the regional water table as groundwater recharge.

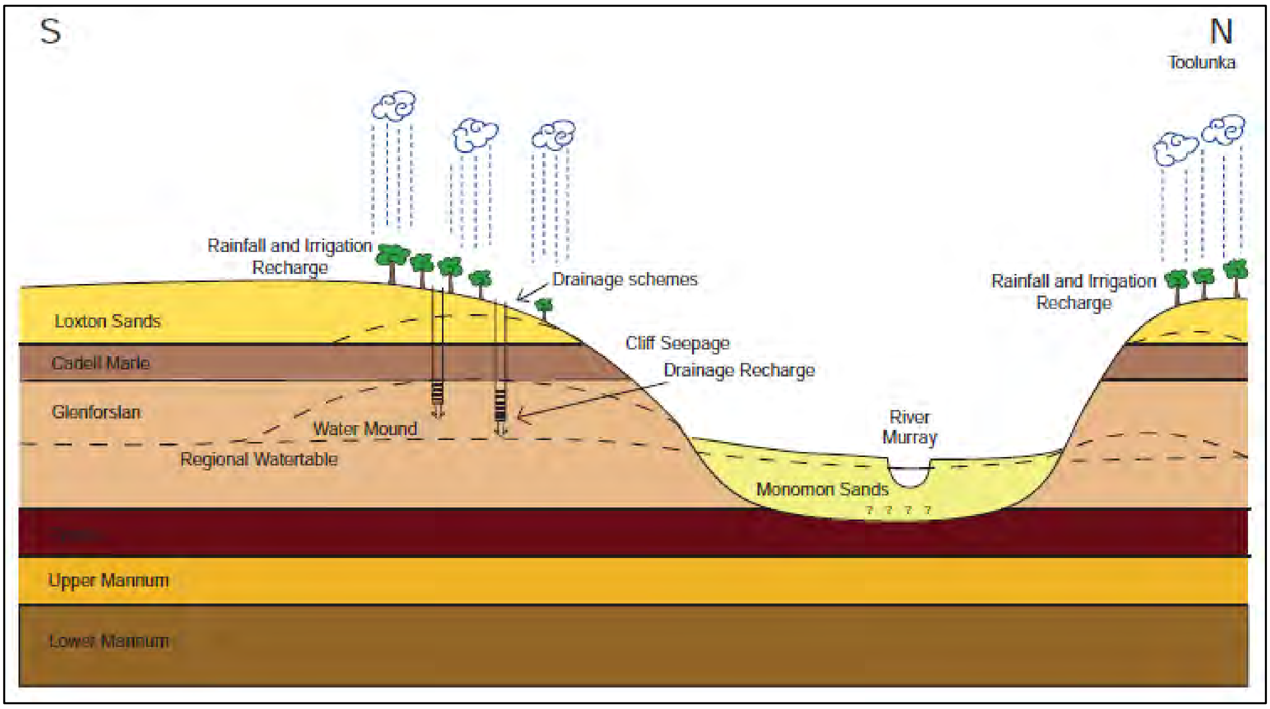

Figure 11 Conceptual model of irrigation recharge for the Waikerie Irrigation District (Fordham et al. 2011)

The time lags inherent in this process are due to the available pore spaces in the unsaturated zone wetting up until a new dynamic equilibrium is established. Thus, the time lags are greatest in response to the initial development of an irrigation area. But once the unsaturated profile has wet up, subsequent changes in the irrigation accession rate (e.g. a reduction due to improved irrigation efficiency) are transferred more rapidly through the unsaturated zone.

3.3.2 Modelling unsaturated zone transmission

The aim of any prediction model for the unsaturated zone is to define recharge rate from the Irrigation Accessions. One of the better-known models for doing this is the Salinity Impact Rapid Assessment Tool, SIMRAT (Fuller et al 2005), which has recently been reviewed (Woods et al. 2016).

SIMRAT

SIMRAT includes a transfer function to simulate the transmission of water from irrigation accessions (termed RZD by SIMRAT) to recharge. The function is based on the methodology outlined in Cook et al. (2001) using a 'time to fill' approach where the unsaturated zone is represented as a storage that gradually fills, and recharge results when it is full. The dimensions of storage are controlled by the initial (θ_i) and final (θ_f) water contents and the depth of the water table (z), and the rate that it fills is controlled by the irrigation accession flux (Ia), to calculate the time lag (t_l) as follows:

Equation 5

$$t_l = \frac{z(\theta_f - \theta_i)}{Ia}$$

Some further complexity is provided within SIMRAT, by applying a log-normal distribution around the mean irrigation accession rate, and including an allowance for a second soil layer (e.g. the Blanchetown Clay Unit). These inclusions effectively smooth the resultant estimates of groundwater recharge, giving it an S-type shape.

SIMRAT had been originally developed as part of a Rapid Assessment Tool for greenfield irrigation developments. The recharge algorithms have been used in early regional groundwater models. It is still included in some models to represent initial wetting up of the unsaturated zones under greenfield sites, and is used in many models during their calibration to estimate time lags.

SIMRAT also includes an optional drying feature, based on Sisson (1980), that simulates how a reduction in irrigation accessions propagates through the unsaturated zone. An analysis of the analytical equations presented by Sisson (1980) suggests that the time lag associated with such a 'drying' event is much shorter (by a factor of about ½), but the recharge reduction may be gradual.

However, the central assumption of SIMRAT is that water moves one-dimensionally down the profile by gravity and does not perch on low permeability layers and flow laterally. Hence it is not appropriate for use in any areas where extensive perching occurs.

SUTRA MODELLING

Some preliminary analysis of time lags and perching processes in the unsaturated zone was undertaken by Armstrong (2011) using a Richards Equation-based numerical model (SUTRA). The modelling provides some insights into the unsaturated flow processes that occur below an irrigation development. Several scenarios were run in which the irrigation accession rate was either maintained or lowered after a period of 50 years. The results from this modelling are shown in Figure 12.

A three-layer model was considered with sand over clay over sand representing a 2 m thick sandy-textured rootzone (e.g. Woorinen Formation) overlying a 5 m thick low permeability unit (e.g. Blanchetown Clay) which, in turn, overlies a sandy-textured unit hosting the regional water table (e.g. the Loxton Parilla Sands) at 25 m below surface.

The nominal irrigation accession rate (200 mm/y) was set considerably higher than the saturated conductivity of the clay layer (36 mm/y), which leads to perching on the clay layer with a thickness of some metres. Water moves horizontally away from the irrigation zone, while water continues to infiltrate into the clay. The perched water will continue to move laterally until the infiltration into the clay becomes equal to the water being added through irrigation rootzone drainage.

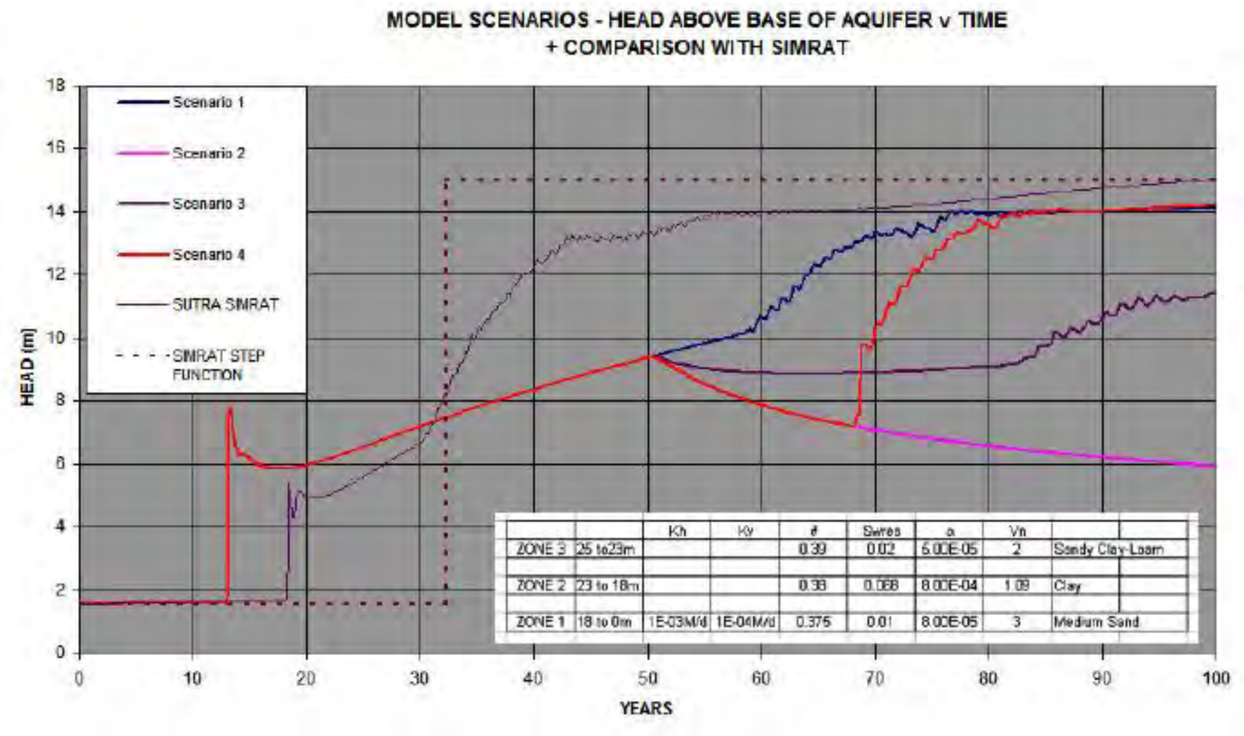

Figure 12 Model outputs showing development of irrigation mound for varying irrigation accession rates with time (Armstrong 2011)

The modelling suggests that the infiltration to the clay is greater than its saturated hydraulic conductivity. This is most likely due to the perching creating a vertical gradient greater than that due to gravity. It could also be due to the sorptivity associated with lateral flow processes (i.e. away from the wetted area). Significant drainage from the clay layer is only likely to occur if the clay is near saturation. A delay is also associated with the sharp texture contrast between the clay and the underlying sand unit, which when dry forms a capillary break (due to its very low unsaturated conductivity) and limits the vertical infiltration until the hydraulic head in the clay is sufficient to drive water downwards.

The transmission through the sand is modelled as occurring through a wetting front mechanism where there is near-saturation behind the wetting front. The near-saturation behind the wetting front could be due to a numerical instability. More likely, there is either of two mechanisms (1) a wetting front (less than saturation) which moves more slowly to the water table or (2) fingering which conduct water more quickly to the water table but across a smaller area. Either way, the flux will be reduced to the water table.

The recharge response occurs about 10-15 years following the initiation of irrigation. The increase in recharge is initially sharp due to sudden removal of the overlying capillary break and it is perhaps overstated due to some numerical instability in the model. This is followed by a long lag that may continue for 100 years or so until a new dynamic equilibrium is established. The zone of recharge gradually increases in area due to the lateral spread of the perched layer.

Several scenarios were also considered due to changes in irrigation accessions.

Under the scenario in which the irrigation is decommissioned (Scenario 2), infiltration through the clay continues until there is no perched water table.

Under the scenario in which improved irrigation efficiency is considered (Scenario 3), irrigation accessions are reduced from 200 mm/y to 100 mm/y. This still exceeds saturated conductivity and a perched water table still exists, but it is expected that perched water table will have a smaller lateral and vertical extent.

In summary, the modelling by Armstrong (2011) shows the processes that occur for an irrigation development with variable irrigation accession rates over time. The initial irrigation accession rate is high and after a short period of time (~10-15 years) there is recharge directly under the irrigation areas. But as the perched area increases, this eventually leads to a larger zone of recharge, with the rates increasing until a new equilibrium is established after about 100 years. If, after some time, there is a reduction in the irrigation accession rate, the perched area will reduce and a reduction in recharge could happen quickly.

Similar unsaturated zone modelling analyses were undertaken by Woods et al. (2013) and Nakai et al. (2010). These studies also showed the development and lateral expansion of perched systems under irrigation.

The studies by Armstrong (2011), Woods et al. (2013) and Nakai et al. (2010) suggest that if perching occurs, SIMRAT should not be used for modelling as its fundamental assumptions no longer apply, because perching leads to: 1) flow that is no longer one-dimensional; 2) flow that is no longer due to gravity; and 3) possibly fingering.

WATER BALANCE MODELLING OF PERCHED SYSTEMS

Accounting for losses between irrigation accessions and recharge, 'missing water', is not commonly evaluated, but with enough data it is possible to develop a simple water balance of the perched aquifer. For example, Yan et al. (2012) mapped an inferred potentiometric surface of the perched aquifer at Qualco and Waikerie in South Australia and used this surface to estimate the total volume of the perched aquifer, the portion of this that extended laterally beyond the irrigation area, and the cliff seepage fluxes. Such mass balance techniques are of assistance when conceptualising and quantifying recharge in irrigated areas.

3.4 IMPLICATIONS FOR GROUNDWATER MODELLING

This section has reviewed the current understanding of unsaturated zone processes in relation to irrigation activity and has shown that:

- Approaches to estimating irrigation accessions through district-scale water balances rely on multiple datasets and assumptions which are prone to measurement error and potential bias. Thus, there is uncertainty in the residual of the water balance (the estimated irrigation accession rate);
- Currently, there is no simple and robust transfer function that (for a wide range of scenarios) appropriately predicts the transmission of irrigation accessions to the water table to define recharge that results from irrigation. While the SIMRAT model is appropriate for dryland settings, it is not appropriate for use where perching occurs (which was widespread in irrigated areas prior to 1988); and
- The complexity of the unsaturated zone suggests that it may not be possible to develop a simple and robust transfer function for areas of deep unsaturated zone with thick clays.

These findings highlight the challenges associated with estimating irrigation recharge for groundwater models, and provide context to whether forward or inverse modelling approaches have been adopted.

4. Current approaches to treatment of recharge within Register models

4.1 Overview

The approach to estimating and assigning recharge rates and lag times under irrigated areas in each jurisdiction is as follows:

- The South Australian models estimate recharge rates are largely based on the inverse modelling approach, i.e. adjusting recharge rates and lag times so the modelled trends in groundwater levels match observed trends. There are some models (either older models or those where observation bore data is sparse) that estimate recharge based on a district-scale water balance; and
- The Victorian and NSW models use a forward modelling approach by deriving recharge estimates from an irrigation district-scale water balance which is input to each model.

4.2 South Australia

Each of the SA domains has a regional groundwater model simulating groundwater levels and flow to the river. Essentially the South Australian reach of the Murray has been divided into five regional domains—Chowilla, Border to Lock 3, Woolpunda, Waikerie to Morgan and Morgan to Wellington. The Border to Lock 3 domain has been used as the basis for the development of four sub-regional groundwater models (see Figure 7). These sub-regional models have been developed at different times and each has a different legacy.

All of these models produce estimates of salt load for the agreed range of scenarios for a specific river reach.

When the time comes for a five-yearly review, the regional domain model is updated (or upgraded) with the latest data from the sub-regional model(s) to provide a suitable platform for new estimates for the relevant accountable actions for that area via updated sub-regional models. For each upgrade, the work focusses on redefining the hydrogeology for the specific area (sub- region), including the latest observation data and recalibrating the model to a refined set of parameters. The full set of scenarios are simulated and salt impacts are provided to MDBA for modelling using BIGMOD and eventual inclusion on the Register.

The South Australian groundwater models used in the estimation of salinity impacts in the River due to irrigation generally estimate the recharge due to irrigation via inverse modelling approaches. There are some exceptions to this, for example, the Woolpunda model (Woods et al. 2013) where a district scale water balance approach is used (see further below for description).

Although three SA groundwater models (2012 Waikerie-Morgan; 2013 Woolpunda; 2014 Pike-Murtho model) have not yet been endorsed by MDBA for the assessment of accountable actions, the MDBA has indicated that the latest results from these models should be considered within the context of this report.

4.2.1 The inverse modelling approach to estimating recharge

The inverse modelling approach is described in detail in the SA groundwater model reports—the Loxton-Bookpurnong model report (Yan et al. 2011) is a good example. The approach follows a number of steps as reported in Yan et al (2011):

- calibration begins with a numerical model incorporating the best available hydrogeological data and an up-to-date conceptual model, at scales appropriate for the project aims (i.e. the sub-regional model is based on the latest refinements to the regional domain model);
- recharge zones are determined by recharge areas, rates and lag times that are based on the best available data and the latest scientific research; these zones are small and are based on the location of historical observation bores;
- during calibration, the recharge rate of each zone is varied within a reasonable range appropriate for that time period's irrigation practices; hydrographs from observation bores

are used to gain a history match between predicted and observed data; if this leads to a poor match to observed heads, the aquifer properties are also varied within reasonable ranges, provided that the hydrogeological data supports such changes;

- the process is iteratively solved as adjoining observation data lead to changes in hydraulic properties and recharge rates; in some cases this involved up to 700 model runs;
- in some cases, recharge zones were further sub-divided to allow a better fit of modelled data to observed values; and
- recharge rates were constrained by values specified from other studies based on knowledge of irrigation practices over time.

The inverse modelling approach is justified on the basis that it assigns recharge directly to mimic observed groundwater behaviour, the inference being that it is therefore more likely to be the actual recharge rate. The approach is further justified by an inference that it is not being subject to the general lack of data on historical irrigation delivery and application volumes, and gaps in the scientific knowledge of unsaturated zone processes. These points are valid; however, as the inverse modelling approach is still constrained by a lack of hydrogeological information, specifically as the matching of modelled recharge to observation data relies on aquifer parameter choices.

The inverse modelling approach is acknowledged as being subject to non-uniqueness problems (see Figure 6), but is seen as appropriately constrained thus limiting the problem. However, one issue that arises is the distribution of observed groundwater level data both temporally and spatially. The approach works best where each recharge zone in the model has one observation bore that has a continuous set of water level measurements for the full time of interest to the predictions. This is not always the case. In some instances, recharge zones have either a truncated record of observations, or have no observations. In these cases, changes are inferred from adjacent recharge zones.

The inverse modelling approach also assumes initially that the hydrograph response in a recharge zone is only influenced by recharge in the zone. To overcome this, the model is run iteratively so that inter-zone influences can be optimised. This optimisation has no single solution, and is uncertain due to both the number of iterations undertaken, and the choice of aquifer parameters.

This inverse modelling approach produces a well-calibrated model; this is no surprise as a great deal of modelling effort is invested in matching modelled to observed heads. The calibrated historical model run is reasonably good and meets all calibration criteria.

The next step in the process requires responses in the groundwater system to be linked to irrigation actions on the ground, so that actions and impacts can be accounted for on the salinity registers. This process involves matching changes in recharge rates as derived from the inverse modelling approach within the model, to changes in irrigation practice on-ground, as derived from historical records.

The final step is to make choices about recharge rates that are to be used for each of the model scenarios. These rates are informed by the calibrated recharge rates and constrained by interpretation of what actions have occurred in each irrigation area.

These two final steps are not straightforward and require some subjective judgement.

Dealing with the issue of tying calibrated recharge rates to on-ground actions first, it is acknowledged in model reports that changes in water table response immediately below irrigation areas: is due to both improvements in irrigation efficiencies, farm management practices, drought effects and the capacity for the drainage infrastructure to intercept root zone drainage before it recharges the water table.

Each of these needs to be unpicked so that the various actions can be simplified for implementation in the scenarios.

Improvements in irrigation efficiencies, rehabilitation of irrigation infrastructure and changes in farm management have occurred in most South Australian irrigation areas over time, especially during the late 1980s and 1990s. It is reasonable to assume that the majority of the hydrograph fluctuation seen in most irrigation area observation bores is driven by this process. Plot scale investigations have shown improved irrigation efficiency over time, and district scale irrigation accession estimation (e.g. Meissner 2011) has also come to the same conclusion.

The issue of drought effects impacting on hydrograph response is slightly more complex. In reality, climatic variation will impact on water levels below irrigation areas. There are two considerations that are relevant. Firstly, irrigation by its nature will smooth out short term climatic events—irrigation applications are intended to supplement rainfall to an effective crop requirement. If it is wet, then lower water diversion and application occurs. Conversely, if it is dry, greater diversion and application occurs (provided water is available). This results in a roughly constant total application rate that meets the crop requirement.

However, in the case of the second consideration, this is less likely to occur where there is an extremely long run of non-average weather. In these cases, especially when there is extreme drought, diversions do not mirror crop requirements. Irrigators will respond in a number of different ways for example, land retirement or crop changes, and this response is likely to be patchy across an irrigation district. It would be difficult to unpick this from an observation bore hydrograph; and it is most likely that the Millennium drought produced exactly this response.

The role of drainage infrastructure in intercepting root zone drainage and therefore impacting on water table response as the infrastructure is turned on or off, or changes efficiency, is also worth considering. Most infrastructure will have reasonable records, at least during early times of operation, of how much water is diverted. This can be incorporated into groundwater models as explicit features and records can be used to calibrate how these features perform. These drainage infrastructure features are represented explicitly in the South Australian groundwater models (and drainage volume data for Sunraysia districts was a key element of the district-scale water balances that underpin the recharge estimates in the Eastern Mallee models).

4.2.2 Estimating lag times with the inverse modelling approach

Lag times measure the time taken for when changes to water application occur at the land surface and when there is a corresponding change in recharge rates at the water table; effectively it is the time for the changed root zone drainage to transit the unsaturated zone. Lag times are important when there is a requirement to manage the impact of on-ground actions on the water table within the context of the BSMS Register framework and its timelines. This is especially so when formulating the different scenarios used to model the impact of accountable actions.

In the case of the South Australian models, lag times as derived from SIMRAT model runs are used as an initial value prior to the inverse modelling approach (noting the commentary in Section 3.3.2 about the inappropriateness of SIMRAT in cases where perching occurs). Modelled lag times are then effectively integrated into the inversely derived estimates of recharge during the hydrograph fitting process. The changes in recharge rate input to the model are then benchmarked with on-ground changes in the irrigation process. There is no reporting on what criteria are used to generate the changed recharge rates (which implicitly incorporate lag times), and there is no reporting on exactly what are the calibrated lag times (because they are integrated into the inverse modelling approach). Lag times incorporated into the inverse modelling approach appear to be shorter than those generated via SIMRAT, and lag times become shorter as the water table rises over time.

Modelled lag times for current day irrigation are essentially zero; that is, there is inferred to be an almost instantaneous transfer of a new water regime across the unsaturated zone.

4.2.3 Strengths and weaknesses of the inverse modelling approach

The inverse modelling approach to recharge estimation is a valid technique that produces a well calibrated model with very good history match to the observed record. This is self-evident. It does not rely on an over-parameterised unsaturated zone model, where the lack of data may introduce high levels of uncertainty. The approach essentially integrates all potential errors and uncertainties into the derived recharge rate (e.g. it requires no judgements about irrigation efficiency or lag time).

Whilst the inverse modelling approach reduces uncertainty from unknown unsaturated zone parameter choices, it introduces other uncertainty due to incomplete observed water level data and non-uniqueness with aquifer parameters and recharge choices between the various recharge zones.

The inverse modelling approach does not rely on a process model to derive recharge and therefore cannot predict recharge into the future. Assumptions are made about how irrigation practices have translated into recharge rates in the past, and these are used to guide the choice of recharge rates into the future. However, for future predictions of efficient irrigation (i.e. once time lags have worked through since irrigation commencement), a rate of 100 mm/year has been adopted consistently in SA model scenarios.

In comparison, in the Sunraysia, the EM1.2 model assumed future irrigation recharge rates at the rate applying at the end of calibration (i.e. capped at 2005 rates, which range from 24 to 126 mm/year across the various districts in Victoria and NSW).

There is no information that suggests the inverse modelling approach either consistently over-estimates or under-estimates recharge rates or lag times. Errors in the estimation process will be driven by the choice of recharge rates and aquifer parameters and how well these are optimised during the iterative matching of modelled to observed data across recharge zones.

4.2.4 Forward modelling approach to irrigation recharge estimation

In some model areas, for instance, Woolpunda, Berri-Renmark, Morgan to Wellington and Pyap to Kingston, a different approach to recharge estimation was undertaken: district-scale water balances. This method was invoked either because the model version was relatively early in the development program (those undertaken prior to about 2010) or model areas where the observed water level data have not shown any responses to irrigation recharge (e.g. Woolpunda). This latter case is due to the relatively recent start of irrigation and the long lag times for transit of changed water regime across the unsaturated zone in some areas. In some model areas, the inverse modelling approach is not possible as there are no observation bores in the irrigation areas.

Modelled recharge rates, in the case of the district-scale water balance method, are based on a review of irrigation data and its estimated water balance. The steps are (as reported in Yan et al, 2007):

- The irrigation recharge analysis began with consideration of GIS information of areas irrigated at specific milestones (1920, 1940, 1955, 1960, 1970, 1988, 1997, 1999, 2001 and 2000). This identified the areas that could potentially have specified recharge rates applied to the model;
- Recharge rates for irrigation districts were estimated based on known application volumes and estimated irrigation efficiencies. Application rates were sourced from various irrigation trusts, indicating the amount of water diverted from the River Murray with time. The water diverted was then assumed to be uniformly applied at a rate per hectare across the irrigation districts;
- An assumption of 85% irrigation efficiency for all time periods was made since it is believed to effectively integrate water use efficiency improvements and farm management practises appropriately on a regional scale;
- The specification of the recharge flux to the water table is dependent on the applicable time lag between irrigation application to the land and the root zone drainage to the water table. Initial estimates of time lags under irrigation areas from the SIMRAT model (where provided) assuming a 120 mm/y irrigation accession rate. The lags were zoned and applied to the numerical model; and
- Modelled recharge rates in some areas were adjusted during the (re-)calibration process to better match the trend seen in the groundwater system.

In some areas (Woolpunda) recharge rates are specified rather than derived; in this instance the recharge rates were assumed to be 100 mm/y for permanent irrigation (irrigation that remains at a fixed location) and 60 mm/y for pivot irrigation (irrigation that is only temporary and does not remain at a fixed location). An exception is made for the small area of irrigation which commenced before 1988, which is assumed to have a recharge rate of 120 mm/y until 1988.

4.2.5 Estimating lag times using the forward modelling approach

Lag times are derived from SIMRAT using a standard irrigation accession rate of 100 mm/y, and applied as an initial estimate of the time lag applying to SA models from the commencement of irrigation to the application of recharge to the water table. In areas of pre-1988 irrigation, this is varied to 120 mm/y to match the assumed irrigation accession rate.

4.3 Victoria and New South Wales

In the case of Victorian and NSW irrigation areas, the regional scale EM1.2 model (Aquaterra, 2009a) was used for Register B LoH scenarios (irrigation and dryland). The EM1.2 model adopted the district-scale water balance that was developed for the EM2.3 semi-regional scale model (EM2.3 was applied to Register A scenarios) to estimate recharge rates.

4.3.1 The forward modelling approach to estimating recharge

The EM-model district-scale water balance method of estimating irrigation recharge to the water table is conceptually and analytically very similar to the SA-model method. It comprises the following elements (Aquaterra, 2009a):

- Irrigated area and extent of irrigation districts and private diverter areas was provided by MDBC and SunRISE21 for the years 1972, 1977, 1980, 1985, 1988, 1997, 2000, 2003, 2006.
- Annual diversion volume data were provided for the irrigation districts of Red Cliffs, FMID, Merbein, Coomealla, Curlwaa and Buronga, and to private diverter irrigation areas. Time-varying supply system loss rates were applied based on available reports, including allowing for infastructure changes (rates applied ranged from 3% to 17%).
- Rainfall was added to the net diversion volumes and the total was applied at a rate per hectare uniformly across each of the irrigation districts and to private diverter irrigation areas (i.e. there is spatial/temporal variation of irrigation applications between districts/areas). Time-varying irrigation efficiency rates were applied based on available reports (rates applied were typically 75%, but ranged from 60% to 86%), and an estimate of evapotranspiration for plant water use was applied.
- Data provided on drainage volumes per district was subtracted from the water balance (i.e. there is spatial/temporal variation of drainage rates between districts/areas).
- The remainder of the root zone drainage is deemed groundwater recharge.

4.3.2 Estimating lag times using the forward modelling approach

In the case of Victorian and NSW irrigation areas, the time lags calculated by the SIMRAT vertical flux algorithm indicated a range of 10 to 40 years. However, the groundwater level monitoring evidence indicated that Sunraysia irrigation time lags are typically of the order of months and up to 2–3 years in some areas. The Eastern Mallee EM1.2 model that was used for Sunraysia LoH scenarios (Aquaterra, 2009a) adopted zero time lag as a simplifying assumption for irrigation recharge. This approach will bring forward impacts, particularly in cases where the water table is deep (noting that deep water tables are uncommon in Sunraysia).

4.3.3 Strengths and weaknesses of the forward modelling approach

The strengths of the forward modelling approach include:

- It links recharge to irrigation accessions and on-ground actions based on independently derived diversion and drainage data to produce a valid calibration; and
- It can be used to predict future recharge rates due to changes in irrigation practices (as it is a quasi-process model). For example, future irrigation in the Sunraysia is based on the rates applying at the end of the calibration history match (2005 rates for the EM1.2 model).

Its weaknesses are as follows:

- Where data is poor (spatially or temporally) subjective judgement requires choices to be made about lag times and recharge rates introducing uncertainty. The approach can suffer from non-uniqueness problems during calibration (described in more detail in Section 5).

- An irrigation efficiency factor is needed to derive irrigation accessions and recharge. This tends to introduce a dependency into the model when it is being used to predict the impacts of efficiency changes as accountable actions. This allows a more direct link between accountable actions and their effects (even though that may depend to some degree on subjective judgement choices in some cases). More discussion on uncertainty associated with the water balances in irrigated areas is provided in Section 5.1.

4.4 Model scenario formulation

As mentioned above, each model simulates a standard set of scenarios for salinity accounting purposes (e.g. those outlined in Table 3). Each scenario is based on the calibrated model, but with the simulated period extended into the future and with certain assumptions applied to represent accountable actions. The set of scenarios has been designed to estimate the impact of each accountable action either by assessing incremental changes over time (for the LoH scenarios) or by comparing scenarios to isolate the influence of an individual action.

For LoH irrigation impacts, the relevant scenarios are 3A and 3C, as follows:

- Scenario 3A simulates what would have happened if irrigation development had remained unchanged from 1988. The incremental change in salt loads to the river post-2000 is used to estimate Register B entry for Pre-1988 irrigation.
- For South Australia, Scenario 3c is also run and simulates what would have happened if the irrigation development had remained unchanged from 1988 but improvements in irrigation practice had still occurred. The difference between Scenario 3a and Scenario 3c in the incremental change in salt loads post-2000 is used to estimate the Register B entry for improved irrigation practices on the pre-1988 irrigation footprint.

Table 3 Summary of the standard salinity register model scenarios for South Australia (Woods et al. 2013)

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

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

Whilst each scenario is standard, the manner in which the recharge input file for each is derived slightly differently depending on which recharge estimation technique is used:

- In models that have used a forward modelling approach, recharge is fixed according to 1988 rates for Scenario 3A as derived by a district-scale water balance (e.g. 120 mm/y in Woolpunda, Woods et al. 2013) and according to pre-determined recharges rates that represent an improvement in irrigation practice for Scenario 3C (e.g. 100 mm/y in Woolpunda, Woods et al. 2013); and

- In models that have used an inverse modelling approach (e.g. Loxton-Bookpurnong, Yan et al. 2011), recharge is fixed according to 1988 rates (as derived by the calibration model) for Scenario 3A and according to time-varying rates from 1988 to the current year (as derived by the calibration model) for Scenario 3C. There are cases where further complexity is introduced. For example in Loxton-Bookpurnpong, recharge rates are modified in areas of Pre-1988 irrigation activity where the wetting front has yet to reach the water table by 1988, and they are also modified during drought years (e.g. 2006–2010) where recharge rates are restricted to be 100 mm or greater so that drought effects do not bias the results.

In the case of the forward modelling approach, the assumptions used to derive the irrigation accession rate from the district-scale water balance (e.g. application rates, irrigation efficiency, supply losses/seepage and drainage) are essentially hard-coded into the recharge estimate. This produces a dependent output as there is no deterministic approach to estimating the influence of irrigation practice (e.g. irrigation efficiency) that contributes to irrigation accessions. In one sense this approach has already predicted the impact of the change as a consequence of using the particular set of assumptions to derive recharge. In other words, the model is not being used to predict the magnitude of the change in recharge due to the irrigation practice changes, it is simply being used to simulate the magnitude of the impact of a pre-ordained change; and by fixing the recharge in this manner, the model calibration will have no bearing on the total quantum of discharge from the model (it will however influence time lags in the saturated zone). It is an *a priori* approach.

In the case of models that use the inverse modelling approach to recharge estimation, irrigation efficiency and the other factors associated with irrigation practice are not defined. Rather, the timing of changes in irrigation practices are matched to changes in recharge rates and causal correlations are invoked. The recharge time series from the calibrated model are then used (in concert with knowledge of the system) to produce the recharge time series used in each Scenario. It is an *a posteriori* approach. This is perhaps a less subjective approach than that used in the district-scale water balance approach; but it is not entirely objective, it is subject to non-uniqueness, and still results in some dependency on choices of recharge in the recharge regime used. For example, the assumed cut-off for drought effects in the Loxton-Bookpurnong model (Yan et al. 2011) of 100 mm/y is subjective.

4.5 Summary

When applied appropriately, either the forward or the inverse modelling approach can be used to develop valid and fit-for-purpose models for the estimation of LoH irrigation impacts. Neither approach is systematically biased; however, both approaches are susceptible to bias due to inherent subjectivity and, in both cases, efforts should be made to reduce the potential for bias by using as much data as possible to constrain the models.

5. Uncertainty

5.1 Sources of Uncertainty

There are three main areas of uncertainty within the scope of this project regarding the estimation of LoH salinity impacts:

- The estimation of irrigation accessions over time and space;
- The estimation of recharge over time and space (accounting for the transmission of irrigation accessions across the unsaturated zone); and
- Parameter uncertainty in the groundwater models.

All three areas of uncertainty combine to influence the predictive uncertainty of the groundwater models and their resultant estimates of salinity impact to the River. The sources of uncertainty within each of these areas is discussed in the following sections and some preliminary analysis is provided as an attempt to quantify uncertainty.

5.1.1 Estimating irrigation accessions over time

The estimation of irrigation accessions over time is done via district-scale water balances, and the uncertainty of these estimates is related to the component data sources and assumptions used with the water balance method (i.e. those listed in Table 1 and Table 2). To date, there has been no systematic attempt to quantify the errors of the component data sources and assumptions, and the overall uncertainty of the irrigation accession rate derived. The following comments are made regarding the errors associated with each component of the district scale water balance:

- Crop/irrigation area is considered to be one of the more robust estimates used in the procedure (Tony Meissner pers. comm., error range of +/- 5 %). The total area of irrigation is based on aerial photography, with historic archives stretching back to the 1940s in New South Wales[6], South Australia[7] and Victoria[8]. While photographs are not available for every single year, linear interpolation is a reasonable approximation to account for these gaps in the record. Prior to the advent of aerial photography, surveying records and anecdotal evidence is used, and these estimates are judged to be less certain (errors much larger than 5%);
- Pumped volume/rate should be considered in two periods. Prior to the installation of irrigation metering, which corresponded to the shift from channel delivery to piping, estimates of total pumped volumes are uncertain. For instance, Meissner (2011a) estimated pumping volumes prior to metered data being available (i.e. pre-1991) using records of electricity consumption and the duration of pumping at the Loxton Irrigation Trust Area pump station. While this approach is a reasonable one to take in the absence of data, it must be subject to error, perhaps in the order of +/- 50 %. After the introduction of metering, confidence in this estimate is greatly improved (error of +/- 10 %). Given that the pumped volume/rate is the largest input component of the water balance (up to 80 %), errors in this term will have a large bearing of the irrigation accession rate derived.
- Supply losses have been estimated based on a limited number of studies (Ayars 1990; NWC 2008) with the results extrapolated to cover areas with different soil types and irrigation channel characteristics (e.g. age, lining material and condition). They are therefore subject to error (+/- 50 %). But given that supply losses form a relatively small component of the water balance (see Section 3.2.3), the influence on the estimate of irrigation accessions is smaller.
- Irrigation efficiency estimates determine the partitioning of total water applied into that which is used by the crop and that which forms rootzone drainage. Given that crop water

[6] http://spatialservices.finance.nsw.gov.au/mapping_and_imagery/aerial_imagery
[7] https://www.environment.sa.gov.au/Science/mapland/aerial-photography
[8] http://delwp.vic.gov.au/parks-forests-and-crown-land/spatial-data-and-resources/imagery-and-elevation/aerial-photography

use is the largest output component of the water balance (see Section 3.2.3), small errors in the irrigation efficiency calculation can translate to large errors in the irrigation accession rate. Again, it is useful to consider the error range over time.

In terms of recent data, CMC (2011) and Adams and Meissner (2010) have collated recent studies (since the 1980s) that have examined irrigation efficiency using a range of methods: daily water balances at the sub-paddock scale (Cole 1985; Cock 1991), farm-scale water accounting reporting (Adams 2003). These studies have been used to derive efficiency estimates by crop type and irrigation method, which are then scaled-up to the district-scale based on the mix of crop types and their area. CMC (2011) reports modern-day estimates of irrigation efficiency[9] ranging from 70% to 85 % (of irrigation and effective rainfall) which translates to root zone drainage estimates ranging between 90 and 280 mm/y across different irrigation districts. Irrigation efficiency is also highly variable within irrigation districts. Consider the data plotted in Figure 13, which shows that for a given rate of irrigation in 1983-84, the measured drainage volume (a surrogate measure of irrigation efficiency) can vary by up to 1 ML/ha which is equivalent to 100 mm. Note also, that there has been an improvement over time in terms of irrigation efficiency and the variability between sites—shifting from 100 mm/y in 1983-84 to ~20-30mm/y in 2007-08.

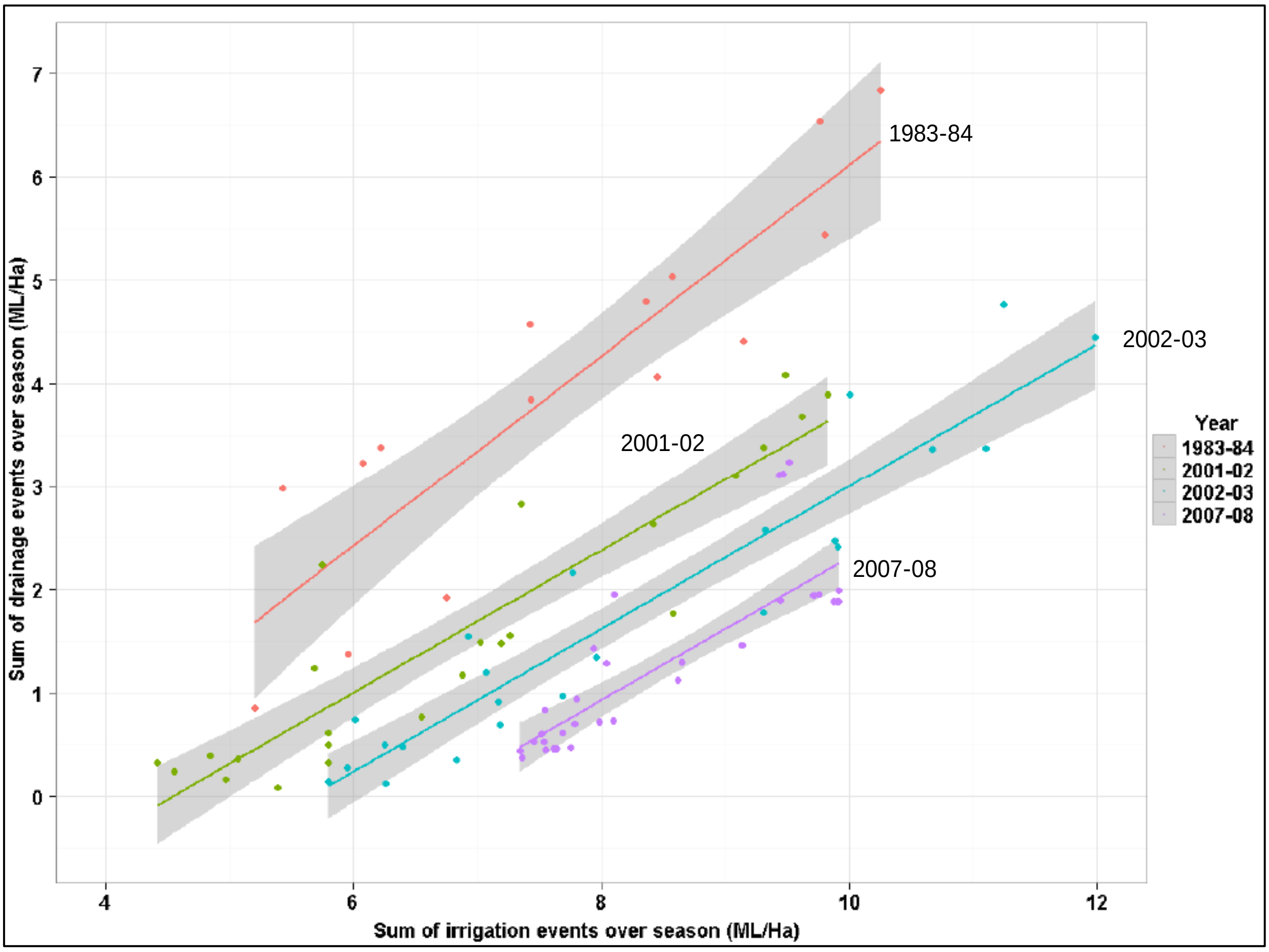

Figure 13 Compilation of irrigation vs drainage water balance estimates from studies of irrigation efficiency in vineyards (Adams and Meissner, 2010)

In terms of earlier periods, when flood and furrow irrigation was widespread, there is much more uncertainty over the irrigation efficiency estimates. These are based largely on theoretical crop water use requirements, such as those outlined in FAO56 (Allen, 1997),

[9] The definition of irrigation efficiency by CMC (2011) is different to that applied by this study. CMC (2011) define irrigation efficiency as the proportion of total water applied by irrigation plus *effective* rainfall, whereas this study considers all rainfall within the calculation. Thus, the estimates of irrigation efficiency listed by CMC (2011) will be comparatively lower.

and anecdotal evidence about irrigation practices (e.g. 'crops being watered until the drains began to flow'). They are regarded as being highly uncertain (Tony Meissner pers. comm.)

- Drainage records across the study area are often patchy and incomplete, aside from those collected by Comprehensive Drainage Schemes in South Australia and the Drainage Disposal Schemes in Victoria. In NSW and Victoria, drainage records were available over about 50% of the area, and extrapolation was required to cover the remaining areas of irrigation (Aquaterra 2009b). In South Australia, this is complicated by the occurrence of drainage bores drilled through the Blanchetown Clay for which no data exists. Given that drainage represents a large component of the water balance, often being larger than the irrigation accession term, its associated error will represent a significant component of the uncertainty in the accession estimate.

In summary, there are large errors involved in the calculation of district-scale water balances which are particularly large during the early years of irrigation development. The key areas of uncertainty concern total pumping rates (before metering was introduced), irrigation efficiency estimates (during early periods of irrigation) and incomplete records of drainage rates. Based on these considerations, it is conceivable that early estimates of irrigation accessions are subject to considerable uncertainty, which is even greater at the property-scale (the scale of relevance for groundwater model calibration efforts due to the reliance on observed groundwater level data).

To explore this further, the district-scale water balance data from Meissner (2011) has been used to calculate a preliminary estimate of uncertainty in irrigation accessions for the Loxton irrigation district, by applying the following assumptions:

- For the irrigated area: an error range of +/- 5% for all time periods;
- For total pumped volume/rate: an error range of +/- 50% for 1940-1969, then +/- 10% for 1970-2009, corresponding to the introduction of metering;
- For supply losses (and associated accession contributions): an error range of +/- 50% for all time periods;
- For drainage rates: an error range of +/- 20% for all time periods;
- For irrigation efficiency estimates: an error range of +/- 20 % for 1940-1979, +/- 10% for 1980-2000, and +/- 5% for 2000-2009; and
- Each of the above error ranges has been applied to the value for each water balance component quoted in Meissner (2011) and compounded through the district scale water balance calculation procedure—for instance, to obtain the lower band of irrigation accessions the crop area is assumed to be 5% larger than the quoted value, the pumping volume is assumed to be 50% less than the quoted vale for 1940-1969 and 10% less for 1970-2009… and so on.

The above procedure was used to estimate a lower and an upper band for irrigation accession estimates over time and the resultant plot is shown in Figure 14. The following qualifications apply to these results:

- The upper and lower bands represent the extremes of possible estimates and there has been no effort made to constrain these estimates by placing some physical limits to the results;
- The upper estimate during early time periods of around 1,200 mm/y is particularly high and not considered realistic over an entire irrigation district (due to pumping constraints) but such rates may indeed be possible at smaller scales; and
- The analysis does not consider probability distributions for each error term (such data is unknown) and all values within the uncertainty range should not be considered as being are equally likely.

Noting these qualifications, this preliminary analysis indicates a high degree of uncertainty in the accession rates. This is particularly the case in early years (pre-1970) when accessions could range by between 33 % and 200 % of the calculated rate. This range reduces somewhat over time as the accuracy around the component data sources has improved. However, even in recent years (post-2000) the error range sits at about 60-150% of the calculated irrigation accession rate, demonstrating how small errors can be compounded through the calculation procedure.

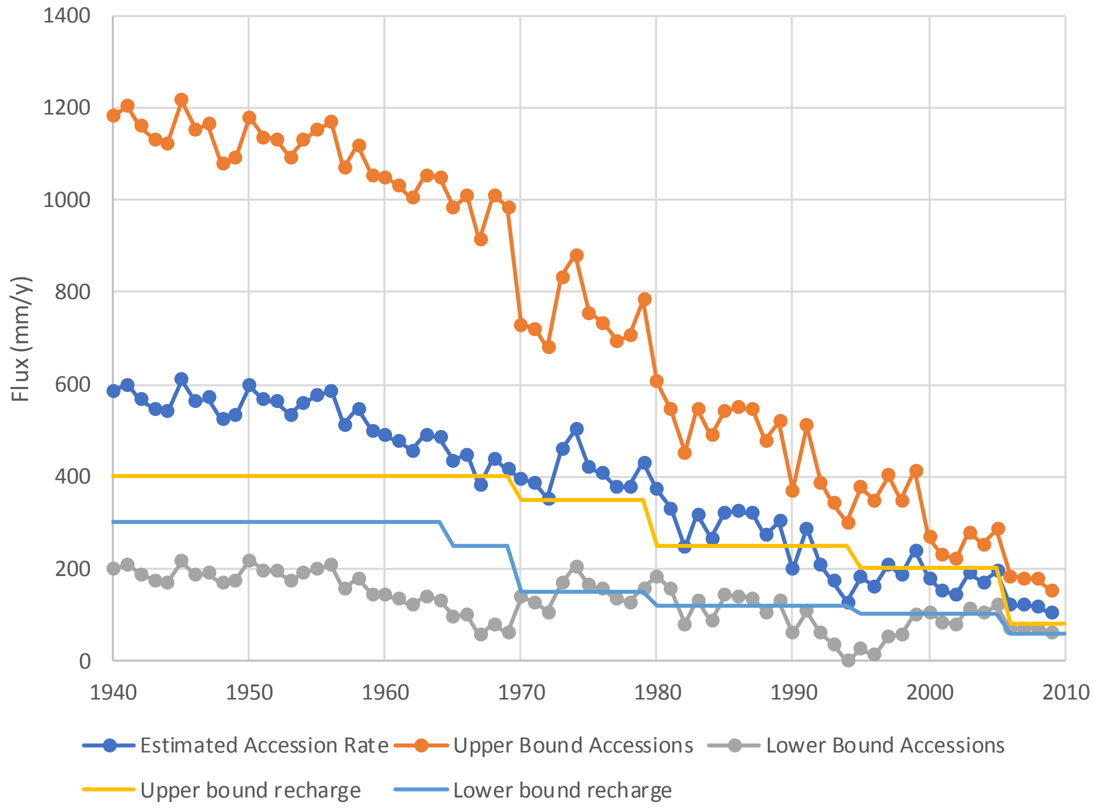

Figure 14 Estimated error range for irrigation accession rates calculated by Meissner (2011) for the Loxton irrigation district compared to the range of recharge rates implemented in the groundwater model (Yan et al. 2011)

5.1.2 Estimation of groundwater recharge over time

The transmission of irrigation accessions across the unsaturated zone will be influenced by a number of factors that include:

- The irrigation accession rate;
- The depth of the water table;
- The presence, thickness and consistency of low permeability units such as the Blanchetown Clay;
- The hydraulic properties of unsaturated zone, such as water retention characteristic and unsaturated hydraulic conductivity functions; and
- The antecedent conditions of the unsaturated zone, such as its moisture content.

All of these factors can be highly heterogeneous meaning that perching and time lags can be highly variable and quite different to the idealised response functions provided by SIMRAT, SUTRA and other modelling options.

The uncertainty associated with the transference of irrigation accessions to groundwater recharge is evident in the modelling approaches taken.

In the EM groundwater model, there is an assumption of zero time lag. While, at first glance, this does not appear to be physically plausible it is perhaps related to relatively late start time of the modelling (1967) compared to irrigation development, whereby the initial wetting up period of the unsaturated zone has passed and subsequent changes to the irrigation accession rate are transmitted through the unsaturated zone more rapidly. Short time lags were also confirmed by observed groundwater level data in nested sites which showed a close correlation between water levels in the perched water table within the Blanchetown Clay and the deeper

Loxton Parilla sands aquifer (e.g. see Figure 15). A relatively thin unsaturated zone below the Blanchetown Clay is noted for the example shown.

By comparison, time lags and the influence of perching appears to be more heterogenous in different irrigation districts within South Australia. For instance, Figure 16 compares the irrigation accession volumes calculated by Meissner (2014) to the recharge implemented in the Pike-Murtho groundwater model for two irrigation districts (Woods et al. 2014). At Lyrup the water table is shallow and there is close comparison between irrigation accessions and recharge, in terms of total volumes and short time lags. However at South Murtho, where the water table is deep and Blanchetown Clay thick, a much longer time lag is apparent and the recharge rate implemented by the model is considerably less than the estimated accession volume; perhaps as a result of perching on the Blanchetown Clay.

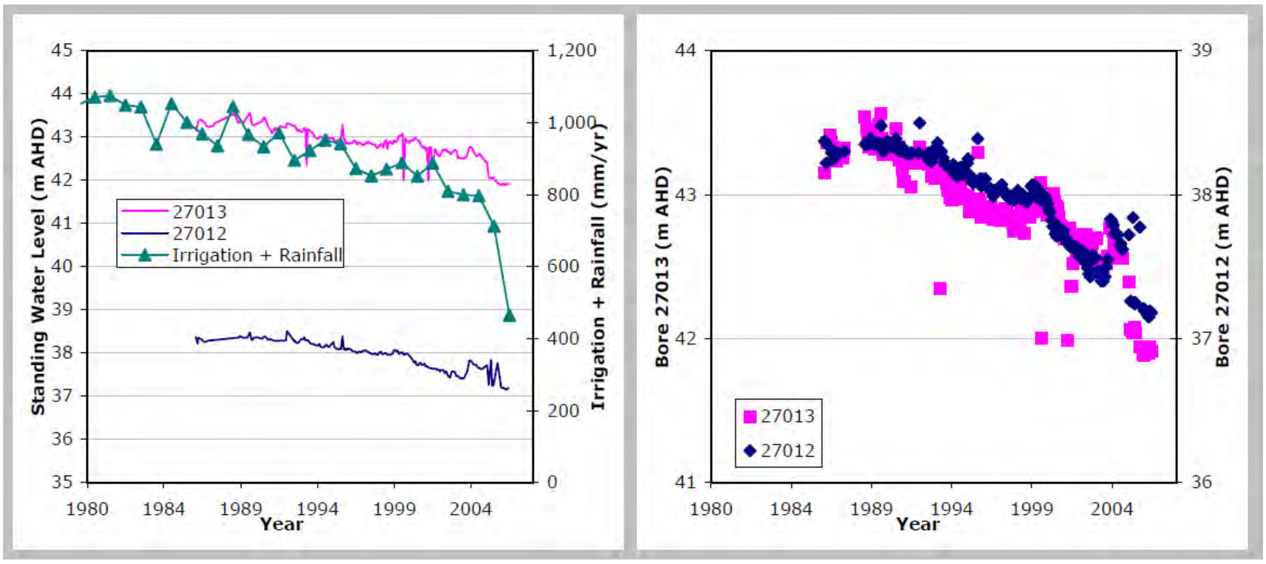

Figure 15 Comparison of groundwater levels in the Blanchetown Clay (perched) (site 27013) vs the regional water table (site 27012) (Aquaterra 2009b)

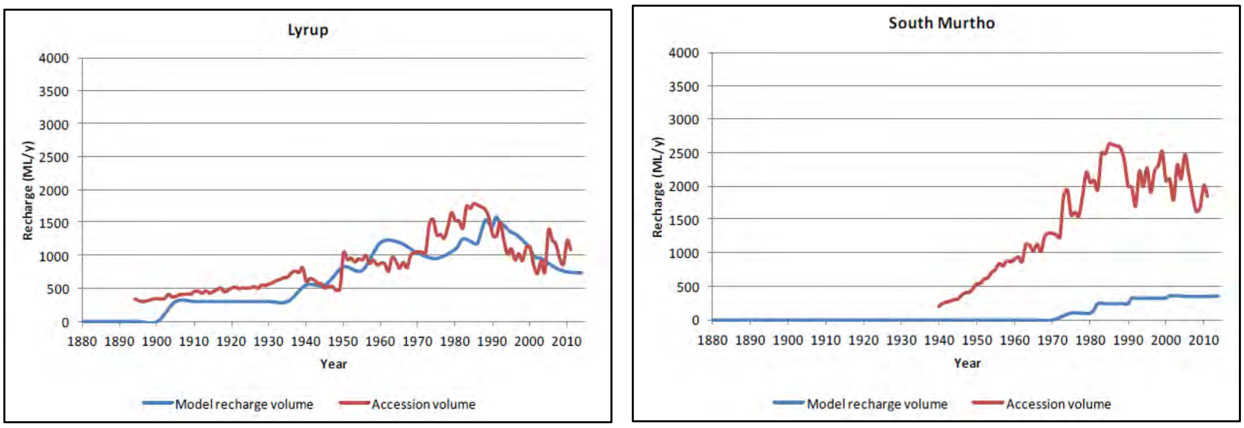

Figure 16 Comparison of model recharge and irrigation accession volumes for the Lyrup and South Murtho irrigation districts (Woods et al. 2014)

Figure 16 plots the range in recharge rates used for the Loxton irrigation district (Woods et al 2011) over time. The variability in the recharge rates used to calibrate the model provides some insight into the uncertainty associated with estimating recharge, noting that the range is +/- 15-40 % of the median recharge rate throughout the pre-1988 period. The modelled recharge rates are within the bounds suggested for irrigation accessions (Figure 14) albeit towards the lower limit of this range.

5.1.3 Groundwater model parameters

A groundwater model entails simplification of the groundwater system, which together with sparse measurements, means uncertainty in the effective hydrogeological parameters (K and S). Calibration is used to estimate these parameters. The calibration process to determine K and S should not be considered to be independent of recharge given that it involves deriving a solution (so that model heads match observed heads, reasonably well) that is highly dependent on the time-varying recharge input. Thus, the uncertainty in establishing the time-varying recharge, or R(t), is closely related to the uncertainty of K and S. The larger the uncertainty band is for R(t), K and S, will result in a greater potential for non-uniqueness where more than one set of plausible estimates of these parameters provides reasonable calibration performance (see Figure 6).

The variability of hydrogeological parameters, which can be large (e.g. see Figure 17), forms part of this uncertainty profile.

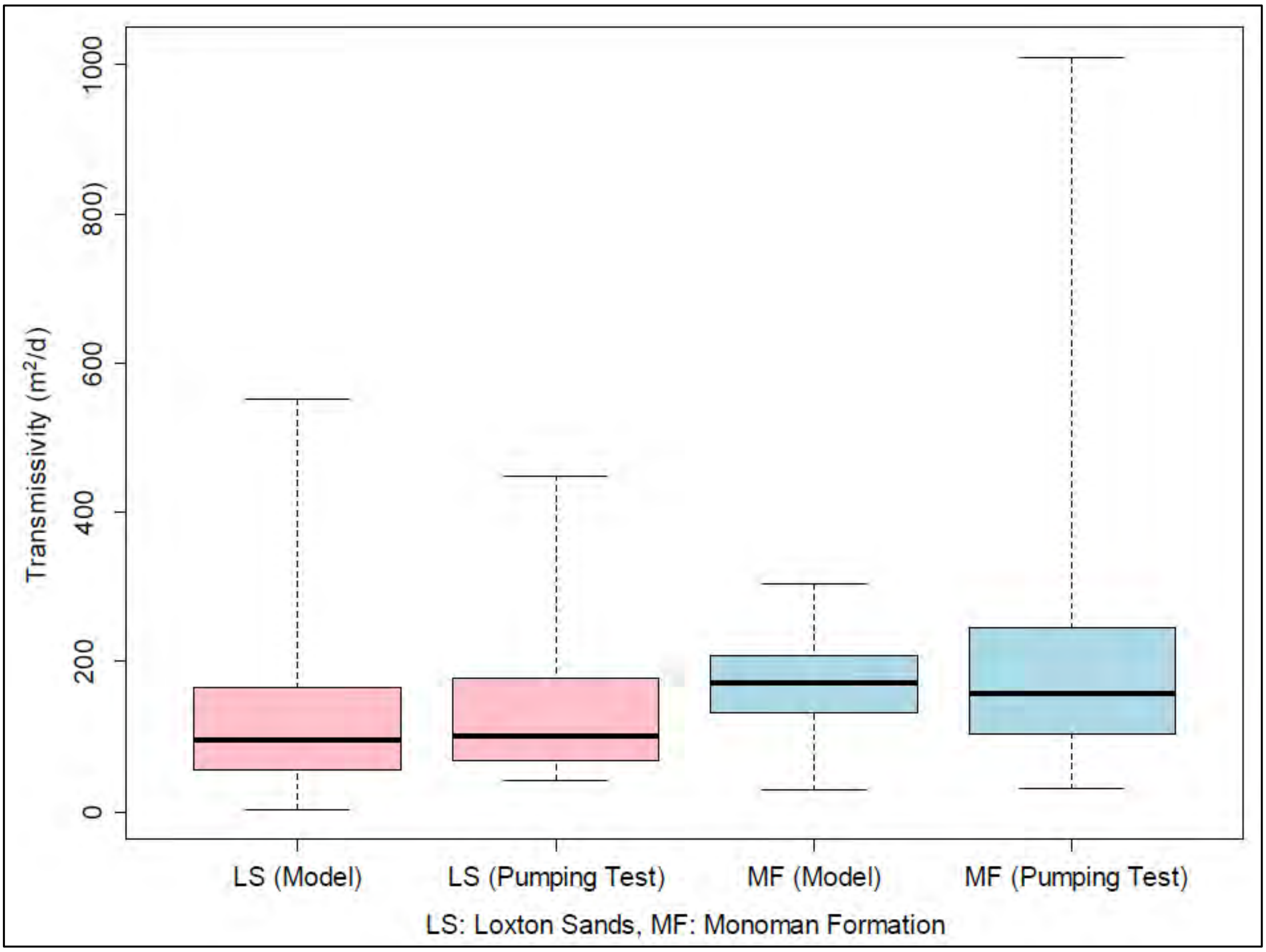

Figure 17 Variability in transmissivity in groundwater model and pumping test for Layer 1 of the Loxton-Bookurnong groundwater model (Yan et al. 2011)

5.2 Propagation of uncertainty through groundwater models

If recharge is uncertain, then it is important to understand how this translates through the groundwater models and influences salinity impacts in the River.

From a water balance perspective, the necessity of calibrating the groundwater models to match observed heads means that the change in groundwater storage is more or less fixed for different solutions of the R(t), K and S relationship. This then means that should recharge be varied by 75% or 150% due to uncertainty in actual recharge then there will be a corresponding 75% or 150% change in discharge (salt load) to the River once the new dynamic equilibrium is established (leaving aside floodplain dynamics for the moment). Thus the uncertainty in the recharge estimate is directly transferable to the salt load estimate to the River.

The question then becomes about timing and whether an over- or under-estimate in R(t) affects time lags through the groundwater system and the register entry calculation. Based on an analysis of the analytical equations of Hantush (1967) which describe the development of a mound under an irrigation area, it would appear not. If R(t) is increased during calibration, then a corresponding increase in K and S is required to accommodate the additional recharge and get a decent curve match. This means the hydraulic diffusivity (D, the ratio of K:S) is more or less unchanged between the non-unique solutions and, according to the Unit Response Equations, URE, provided by Knight et al (2002) there are no differences in timing involved through the groundwater system; i.e. there are no differences in time lags between the non-unique solutions.

This logic also holds when more complex scenarios are envisaged based on changing footprints of irrigation recharge and rates.

The focus then shifts to the uncertainty of the recharge estimate. As an example, consider the Loxton Irrigation District. The uncertainty of the irrigation accession rates might be as large as 33-200% (see Figure 14), the variability of the modelled recharge in the calibrated model is as large as 60-140% of the median rate (see Figure 14) and the variability in the hydrogeological parameters (Figure 17) is of a similar magnitude to variability in recharge, perhaps slightly larger. This preliminary view of the uncertainty profile suggests that the uncertainty in the modelled recharge, and thus the salt load estimate, would be in the range of 60-150%; noting that a more accurate view of the predictive uncertainty of the model could be obtained by running a complete uncertainty analysis which accesses all datasets that can be used to constrain the calibration (e.g. if the model calibrates well to SIS pumping, where the extraction rate is known, it supports that the aquifer parameters are roughly correct).

Regarding time lags in the unsaturated zone and how an incorrect estimate may influence a register entry (due to timing uncertainty), this is not so much of an issue where observed groundwater level data is available (due to the above considerations), but will be an issue where data is lacking. For instance, an assumption of zero-time lag brings the impact of irrigation forward, potentially over-estimating the impact at 2000 and thus underestimating the incremental change post-2000. Again, model calibration and the means to constrain it are key.

5.3 OTHER CONFOUNDING FACTORS

The above discussion of uncertainty in irrigation recharge, R(t), and how it propagates through the groundwater models will be influenced by other factors, most notably climatic variability and floodplain dynamics.

Climate variability can play a role in influencing regional water levels and is relevant where an inverse modelling approach has been used to adjust R(t) during model calibration. Because the observed groundwater level data may be influenced by climatic variability, the adjustment to the R(t) during calibration cannot be solely due to changes in irrigation practice, which is an inference made by the inverse modelling approach when it comes to examining both the expansion of irrigation and the improvements made to irrigation efficiency. Extended wet periods or dry periods (such as the Millennium drought) will confound these inferences and introduce another element of uncertainty.

Floodplain dynamics, while outside the scope of this study, may complicate the relationship between R(t) and resultant changes in salt load to the River. For instance, the above discussion points to a direct relationship between the uncertainty of R(t) and the predictive uncertainty of salt load estimates, but floodplain dynamics may alter this relationship. Given that the floodplain acts as a major salt store and the release of salt is controlled by River flow dynamics and evapotranspiration, a 50% increase in R(t) may not correspond to a 50% increase in salt load to the River. A discussion of modelling floodplain dynamics is provided by Woods et al (2015).

While there are estimates available of the wide range in uncertainty for the recharge estimates, there are few uncertainty assessments in the regional model reports of the effect of variations in recharge. Where they are reported, variations in irrigation recharge rates in the range of 30% to 100% resulted in variations in salt load estimates ranging from 10% to 50% (e.g. Yan et al. (2011, 2012); Woods et al. (2014)). One test with a 300% increase in irrigation recharge resulted in a 265% increase in salt load (Yan et al, 2012). This indicates a relatively non-linear sensitivity relationship between recharge and salt load, due mainly to the interception effect of evapotranspiration on the floodplain.

5.4 WAYS TO BETTER UNDERSTAND AND ADDRESS UNCERTAINTY

An approach to drive both a better understanding of uncertainty and the identification of ways to address it is take a whole-of-system approach to modelling. To determine the impacts of irrigation on River salinity in a robust manner, it is necessary to consider the whole system from irrigation (and water use efficiencies, irrigation accessions), to recharge (magnitude and timing), to edge of floodplain and then to River. Given that there are calibration processes for all of the models there is a need to:

- use as much data as possible;
- describe it carefully and the way it is used;
- put some qualitative bounds on the estimates at each stage; and
- understand how this might affect predictions.

As part of this, it is possible to formulate a hybrid method in which the uncertainty bands around irrigation accessions as a function of time are considered, with the size of this uncertainty driven by an appreciation of the errors for each data source used to derive it (e.g. pumping rates, irrigation efficiency and drainage). Suppose that since the year 2000 the error band is +/- 10 %, +/- 20% for 1980-2000, and +/- 50% prior to this. Taking a forward modelling approach (e.g. the EM model) as an example, if 5 levels of uncertainty are considered to occur across the band, 5 possible R(t) functions would eventuate. If the groundwater model was calibrated using each of these 5 functions, both error analyses and predictions could be compared. The error analyses could be used to indicate optimal or plausible values and a range of predictions. As part of this process, the inclusion of all available datasets (e.g. run-of-river survey data, pumping test analysis, floodplain evapotranspiration) should constrain what is considered a plausible parameter set and limit non-uniqueness. A greater appreciation of the factors driving uncertainty would be an outcome of this process, which could be used to guide efforts aimed at improving uncertainty where possible.

The hybrid method requires a connection between the irrigation accessions and recharge. Where SIMRAT is inappropriate due to perching processes, some other transfer function would be required. Given the complexity of processes in the unsaturated zone, such definition may be difficult. A more comprehensive assessment of this zone is required due to the limited nature of the unsaturated modelling to present.

In all situations, regardless of whether a forward or inverse modelling approach is taken, the factors affecting time lag should be noted: depth to water table, any soil texture information, presence and thickness of Blanchetown Clay, thickness of overlying sand.

6. Options to advance more consistent modelling approaches

As discussed in the earlier sections of this report, the current suite of salinity register models have used a variety of approaches and assumptions to estimate groundwater recharge from irrigation, the principal difference being the use of:

- A forward modelling approach in which R(t) is held (more-or-less) constant and K and S are varied during model calibration; or
- An inverse modelling approach in which R(t) is varied along with K and S during model calibration.

Part of advancing a more consistent way forward is to recognise that either of these approaches, when applied appropriately, can be used to develop valid and fit-for-purpose models for the estimation of LoH irrigation salinity impacts. Conceptually, the approaches are two sides of the same coin; the coin being the relationship between R(t), K and S. The forward modelling approach is more reliant on district-scale water balance estimates of irrigation accessions to fix R(t). The inverse modelling approach is more reliant on hydrogeological parameterisation (to fix K and S) as supported by pumping test data. Neither approach is systematically biased; however, both approaches are susceptible to bias due to inherent subjectivity and, in both cases, efforts should be made to reduce the potential for bias by using as much data as possible to constrain the models.

Part of the rationale as to whether a forward or inverse modelling approach is followed is related to the complexity of the unsaturated zone and how irrigation accessions are transmitted to the water table. Where the water table is shallow and a close relationship between irrigation accessions and recharge can be demonstrated, then a forward modelling approach can be taken. But where the water table is deep and long time lags are apparent, a forward modelling approach may not be feasible and an inverse modelling approach can be taken. The rationale behind the selection of a forward or an inverse modelling approach should be made explicit in the model documentation.

To advance a more consistent way forward, it is recommended that a whole-of-system approach as outlined in Section 5.4 is taken for all of the models. The extent to which this is carried though for each model will depend on range of factors (e.g. data availability and cost) so a range of options were put forward to project stakeholders at a workshop on 30 March 2017, as follows:

<u>Option 1:</u>

- A) Maintain the status quo with ongoing scheduled model refinement being driven by efforts to avoid bias through a more explicit recognition and documentation of uncertainty and the connections between irrigation accessions and R(t).
- B) As in 1A, with the states each selecting one model for a comprehensive uncertainty analysis by defining the R(t) uncertainty envelope and using all available datasets to constrain the range of plausible parameter sets. The derivation of LoH impact estimate would require the use of a single R(t) as a fixed input (i.e. not varied during calibration), with the process used to select the fixed R(t) function being a policy decision (e.g. the median R(t) is an option, but all parties would have to agree on this).
- C) As in 1A, with the investigation and development of a transfer function connecting irrigation accessions to R(t). (Further explanation of the importance of a transfer function is provided in Section 7.5.2).
- D) Where a transfer function is feasible, based on investigations in 1C, a hybrid modelling approach can be developed whereby the uncertainty of irrigation accessions is considered as a function of time (as determined by the errors for each data source used to derive the accession estimate) and this function is then used to generate a range of plausible recharge functions to be included in the groundwater model.

Option 2:

- Full uncertainty analysis required in each and every groundwater model (whether a forward or inverse modelling approach is applied), with the median realisation (or other) being used to determine LoH impacts.

Option 3:

- Mandating a forward modelling approach for all register models with R(t) fixed according to irrigation accession calculations (district-scale water balances). This is not necessarily the best or most scientific approach, but it is the most consistent, and it allows a direct comparison with irrigation efficiency improvements and it can be constrained by data on irrigation diversion volumes and drainage volumes (reducing the non-uniqueness effect).

These options were presented and discussed at the project workshop and Option 1 was identified as the preferred option.

As part of Option 1A, it was recommended that model protocols be updated to require a district-scale water balance and a description of how irrigation area and irrigation practice has varied over time (e.g. conveyance systems, application methods, the existence of comprehensive drainage schemes, drainage bores etc.). This information provides important detail about what has driven recharge in irrigation areas (whether it be derived by the forward or inverse modelling approach). Additionally, further efforts to constrain models and limit non-uniqueness were encouraged (e.g. comparison of modelled fluxes to run-of-river data, floodplain ET), and because K and S are time invariant this will assist in limiting uncertainty in recharge estimates for all time periods.

Pilot uncertainty analysis (1B) was supported. Both South Australia and Victoria expressed interest in a comprehensive uncertainty trial for one or part of a selected groundwater model. An inter-jurisdictional uncertainty analysis should take a whole-of-system approach covering the components of the district-scale water balance, recharge, groundwater flow and floodplain processes.

A transfer function (1C) could conceivably be developed in multiple ways (see Section 7.5.2), but further investigation is required as it provides a link between irrigation accessions and recharge, and if it cannot be developed (due to complexity in the unsaturated zone) then this provides the basis for selecting an inverse modelling approach over a forward modelling approach and a description of the implications for ignoring the unsaturated zone.

The hybrid method (1D) is considered optimal as it provides the most complete modelling approach that represents the land surface water balance and unsaturated zone transmission to generate a range of plausible recharge functions to be included in the groundwater model. It does, however, rely on the development of a transfer function which may not be feasible in areas where the water table is deep.

Option 2 was judged to be expensive and not recommended, unless supported by the outcomes of the pilot uncertainty analysis (1B).

Option 3 was acknowledged as being consistent, but was not widely supported. It was considered unsuitable for South Australia due to the complexity of the unsaturated zone, and it would be a major challenge to get agreement on a consistent set of assumptions for the derivation of irrigation accessions for pre-1988 conditions due to data quality issues of these earlier records.

7. Conclusions and recommendations

This report has sought to explore the different approaches and assumptions made in relation to the derivation of pre-1988 irrigation LoH salinity impacts, focussing specifically on how irrigation accessions and recharge are calculated. The report has also sought to unpack the uncertainty associated with recharge in irrigation areas and provide options for a way forward. The key findings from this assessment are as follows:

7.1 Estimation of irrigation accessions

The estimation of irrigation accessions through district-scale water balances relies on a number of datasets and assumptions, which have different uncertainty profiles in space and time. Early records of total water pumped/diverted, supply losses, irrigation efficiency and drainage have large error bands. These have improved incrementally with time, but even small errors can be compounded through the calculation procedure to create uncertainty in the overall estimate. The uncertainty envelope is greater at the property-scale compared to the district-scale.

7.2 Unsaturated zone transmission

Irrigation accessions are not equivalent to groundwater recharge. As water moves through the unsaturated zone it is subject to time lags and (possibly) perching.

The time lags are greatest in response to the initial development of an irrigation area. But once the unsaturated profile has wet up and a new equilibrium is established, subsequent changes in the irrigation accession rate (e.g. a reduction due to improved irrigation efficiency) are transferred more rapidly through the unsaturated zone.

The transmission of irrigation accessions across the unsaturated zone will be influenced by many factors (e.g. depth of water table, presence and continuity of low permeability units, hydraulic properties of the unsaturated zone) that can be highly heterogeneous. Thus, perching and time lags can be highly variable and quite different to the idealised response functions provided by SIMRAT, SUTRA and other modelling options.

Furthermore, an analysis of SUTRA modelling undertaken by Armstrong (2011) confirms existing advice (as provided in Woods et al. (2016)) that the central assumption in SIMRAT (that water moves by gravity) does not apply where perching occurs. Hence it is not appropriate to use SIMRAT in areas subject to perching.

The uncertainty associated with the transference of irrigation accessions to groundwater recharge is evident in the groundwater modelling approaches taken; e.g. the EM model assumes zero time lag, while several South Australian models estimate time lags inversely as part of model calibration. The complexity of the unsaturated zone is also a reason (not always explicitly documented) as to why an inverse modelling approach has been taken.

This work has postulated that developing a simple and robust transfer function that connects irrigation accessions to groundwater recharge may not be feasible for areas of deep unsaturated zone with thick clays. This means that the forward modelling approach may not be feasible for such areas

7.3 Treatment of recharge within groundwater models

Current groundwater modelling approaches are considered valid and have delivered acceptable calibration performance, with each approach having strengths and weaknesses.

The forward modelling approach directly uses irrigation accession calculations to derive recharge. A benefit of this approach is that it provides a direct link between changes in irrigation practice and recharge. The approach, however, is exposed to the uncertainties associated with the district-scale water balance calculations.

The inverse modelling approach to recharge estimation is a valid technique that produces a well calibrated model with very good history match to the observed record. This is self-evident. It does not rely on an over-parameterised unsaturated zone model, where the lack of data may introduce high levels of uncertainty. The inverse modelling approach essentially integrates all potential errors and uncertainties into the derived recharge rate (e.g. it requires no judgements about irrigation efficiency or lag time). The approach, however, introduces other uncertainty due to incomplete observed water level data and non-uniqueness with aquifer parameters and recharge choices between the various recharge zones. Additionally, the inverse modelling approach does not rely on a process model to derive recharge and therefore cannot predict recharge into the future.

Either of these approaches, when applied appropriately, can be used to develop valid and fit-for-purpose models for the estimation of LoH irrigation impacts. Neither approach is systematically biased; however, both approaches are susceptible to bias due to inherent subjectivity and, in both cases, efforts should be made to reduce the potential for bias by using as much data as possible to constrain the models.

7.4 Uncertainty considerations

To date, there has been limited quantification and reporting of uncertainty in salinity register models.

There are three main areas of uncertainty regarding the estimation of LoH salinity impacts:

- The estimation of irrigation accessions over time and space;
- The estimation of recharge over time and space; and
- Parameter uncertainty in the salinity register groundwater models.

All three areas of uncertainty combine to influence the predictive uncertainty of the groundwater models and their resultant estimates of salinity impact to the River

A preliminary analysis of uncertainty undertaken by this project, using the Loxton Irrigation District as an example, suggests that the uncertainty in the modelled recharge could be 60-150% of the true value. This level of uncertainty is directly transferable as a flux to the edge of the floodplain, but may not result in a linear response to the LoH salt load estimate (register entries) due to floodplain dynamics.

In terms of timing, non-unique model solutions—represented by a range of R(t) in the order of 60-150%—have equivalent response times through the groundwater system. However, in the absence of observed groundwater level data, an incorrect representation of the shape of the R(t) function may influence salinity impact estimates. For instance, if an irrigation mound is allowed to grow too quickly then this brings the impact of irrigation forward, potentially over-estimating the impact at 2000 and thus underestimating the incremental change post-2000 (i.e. the register entry).

Given that data sources are more sparse for the pre-1988 period, the uncertainty associated with Legacy of History actions will be larger than that for post-1988 actions. However, ongoing model refinement using post-1988 data can be used to better constrain model calibrations and predictions to reduce this uncertainty.

7.5 Recommendations

7.5.1 A way forward for modelling

A risk for register entries is if there is significant bias one way or the other, and the risk is greatest if the modelling consistently underestimates salt loads. The use of as much data as possible within either modelling approach (e.g. flux estimates, in-river salinity data, pumping test data) to provide some checks and balances to avoid bias should be the focus of future modelling efforts.

A whole-of-system approach is recommended as the means to advance a more consistent approach to modelling and to obtain a better understanding of uncertainty and avoid bias. In applying this strategy there is a need, during calibration and scenario formulation, to:

- use as much data as possible;
- describe it carefully and the way it is used;
- put some qualitative bounds on the estimates at each stage; and
- understand how this might affect predictions.

As part of a whole-of-system approach, a hybrid method represents an optimal solution. A hybrid method considers the uncertainty of irrigation accessions (over an irrigation district scale) as a function of time (as determined by the errors for each data source used to derive the accession estimate) and this function is then used to generate a range of plausible recharge functions to be included in the groundwater model. Effectively, this embeds the components of the district-scale water balance (and their errors) within the model and the LoH prediction, providing for greater transparency to link cause and effect. The output of this method would be a range of predictions around a median value used as the register entry.

The hybrid method requires the connection between irrigation accessions and recharge (via a transfer function or otherwise) and this may not be feasible where the unsaturated zone is complex and inverse modelling approach are required. Nevertheless, the inverse modelling approach can still include the principles of the hybrid method by undertaking a district-scale water balance, describing in detail how the irrigation area and practice has varied over time, and providing a detailed description of the unsaturated zone so that links can be drawn between irrigation activity and the recharge implemented in the model.

In all cases, the unsaturated zone should be described in detail so that the implications for LoH predictions of a particular representation of the unsaturated zone by the modelling framework can be understood and documented. For instance, if a simplifying assumption of zero time lag is applied, then it will bring forward associated impacts.

Ongoing model refinement and efforts to better constrain models and limit non-uniqueness using post-1988 data are also recommended.

The extent to which a whole-of-system modelling approach is adopted will vary for each model and will depend on range of factors (e.g. data availability and cost). A range of options were presented at the project workshop and the following option was preferred:

<u>Option 1:</u>

- A) Maintain the status quo with ongoing scheduled model refinement being driven by efforts to avoid bias through a more explicit recognition and documentation of uncertainty and the connections between irrigation accessions and R(t). As part of this, it is recommended that model protocols be updated to require a district-scale water balance and a description of how irrigation area and irrigation practice has varied over time. Additionally, further efforts to constrain models and limit non-uniqueness are recommended (e.g. comparison of modelled fluxes to run-of-river data and salt-load time series, floodplain ET), because K and S are time invariant and this will assist in limiting uncertainty in recharge estimates for all time periods.
- B) As above, with the states each selecting one model for a comprehensive uncertainty analysis by defining the R(t) uncertainty envelope and using all available datasets to constrain the range of plausible parameter sets. The derivation of LoH impact estimate would require the use of a single R(t) as a fixed input (i.e. not varied during calibration), with the process used to select the fixed R(t) function being a policy decision (e.g. the median R(t) is an option, but all parties would have to agree on this).
- C) As in 1A, with the investigation of a transfer function connecting irrigation accessions to R(t).
- D) Where a transfer function is feasible, based on investigations in 1D, a hybrid modelling approach can be developed whereby the uncertainty of irrigation accessions is considered as a function of time (as determined by the errors for each data source used to derive the accession estimate) and this function is then used to generate a range of plausible recharge functions to be included in the groundwater model.

7.5.2 Supporting investigations

The implementation of the whole-of-system modelling approach would be supported by the following investigations.

REVIEW OF DATASETS TO CONSTRAIN MODELS

A number of datasets could potentially be used to constrain model calibrations and assist in the avoidance of bias. These include:

- run-of-river salinity surveys;
- toroidal coil data that provides a continuous measure of in-river salinity;
- remote sensing techniques to estimate floodplain ET;
- remote sensing techniques to more accurately map cropping area and type for post-1988 irrigation activity; and
- reported irrigation drainage volumes.

It is recommended that these are reviewed in terms of their costs, accuracy, spatial and temporal dimensions, and their applicability and limitations for groundwater model calibration.

TRANSFER FUNCTION

A knowledge gap within the current modelling regime is a transfer function that connects irrigation accessions to groundwater recharge and is appropriate for situations where perching occurs or has occurred in the past. Further investigation to develop transfer functions is recommended, but it is acknowledged that it may not be possible to develop a simple and robust transfer function that is appropriate for a wide range of scenarios due to complexity of the unsaturated zone; particularly where the water table is deep. This means that the forward modelling approach in which recharge is determined through the application of a district-scale water balance may not be feasible for such areas.

The district-scale water balance modelling should be used as much as possible. Where it is inappropriate or not feasible to model unsaturated zone processes, it is still important to link the extent possible actions that lead to irrigation efficiency improvements to recharge estimates that might be obtained from the inverse modelling approach. It is also necessary to understand the fate of any 'missing water'; i.e. the difference between irrigation accessions and recharge. This has been done for areas such as Waikerie using groundwater models of perched water (Yan et al., 2012). In areas where the unsaturated zone has already been wet-up by previous developments, it may be possible to ignore unsaturated zone processes, when nearby developments are commissioned (e.g. as undertaken by Aquaterra 2009a). However, this needs to be justified as the SUTRA modelling by Armstrong has shown that while changes in fluxes may be transmitted quickly, not all of the change may necessarily be transmitted. This all suggests that a comprehensive modelling of the unsaturated zone be done, building upon the work of Armstrong and Woods in order to:

(a) understand the processes that are operating;

(b) delineate those areas where transfer functions might be used and where they cannot be;

(c) define relevant transfer functions, and

(d) understand the implications of ignoring unsaturated zone processes, where they are ignored

FLOODPLAIN PROCESSES

This project has discussed the importance of floodplain processes as being a key element of LoH prediction modelling. The floodplain exerts considerable influence on the apportioning of salt loads to the river from regional drivers (e.g. from irrigation), and there is a need to better understand how a flux to the edge of the floodplain is routed through the floodplain to drive a change in river salinity. The issue is complex and would benefit from a scoping exercise to clearly articulates the question(s), split the problem into smaller and more achievable steps, and describes an approach to developing solutions which can then be implemented within the LoH modelling framework.

PILOT UNCERTAINTY ANALYSIS

The pilot uncertainty analysis listed as part of Option 1B found favour from workshop participants who were supportive of an inter-jurisdictional uncertainty analysis that takes a whole-of-system approach covering the components of the district-scale water balance, recharge, groundwater flow and floodplain processes.

7.5.3 How to manage uncertainty in the BSMS/BSM2030 context

The BSMS/BSM2030 is a risk-based framework supported by model outputs with some level of uncertainty, and, while not within the scope of this technical assessment, there is a need to gain agreement on how uncertainty in salt load impacts should be reported and how register entries are managed when salt loads would be reported as an envelope of values with lower and upper bounds. It is likely that the level of uncertainty can be as large as some credits and debits.

8. References

Adams, T. (2003). Delivering Improved Water Use Efficiency Across the Murray-Darling Basin Project. I2003 Final Report to Murray-Darling Basin Commission, Primary Industries and Resources, South Australia ISBN 0727 601 X

Adams, A. and Meissner, T. (2010). How Efficient Are We. Report prepared for Department for Water by PIRSA Rural Solutions and Laroona Environmetrics, December 2010.

Allen, R., Pereira, L., Raes, D., Smith, M. (1998). Crop Evapotranspiration: Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No 56, FAO Rome

Aquaterra (2009a). Mallee Zone 5-Year Rolling Salinity Review – B Register 'Legacy of History Assessments – Eastern Mallee Model Version 1.2 (EM1.2). Report to the Murray-Darling Basin Authority.

Aquaterra (2009b). SUnraysia sub-regional groundwater flow model (EM2.3). Final Report. Report prepared for Goulburn-Murray Water and Murray-Darling Basin Authority.

Aquaterra (2013). Sunraysia Eastern Mallee Model Project (SEMMP). Report on EM2.3.2 model, prepared for NSW Office of Water, Mallee CMA, MDBA. May 2013

Armstrong, D. (2011). Lag-Time Study – Sutra Model Based on Loxton Hydrogeological Profile. Prepared for DWLBC by Lisdon Associates May 2010.

Ayars, J. (1990). Improved Water Management in the Riverland of South Australia. Primary Industries South Australia (Internal report).

Barnett, B., Townley, L.R., Post, V., Evans, R.E., Hunt, R.J., Peeters, L., Richardson, S., Werner, A.D., Knapton, A. and Boronkay, A. (2012). Australian Groundwater Modelling Guidelines. Waterlines report 82, National Water Commission, Canberra. URL: http://archive.nwc.gov.au/library/waterlines/82.

Brouwer, C. and Heibloem, M. (1986) Irrigation water needs. Irrigation Water Management, Training manual no. 3. Food and Agriculture Organization of the United Nations, FAO, Rome, Italy.

Catchment Management Consulting (2008). Sunraysia Salt Interception Scheme Investigations Sub- Regional Salt Accessions to the Murray - as represented in the MDBC MSM BigMod Model. A project report to MDBC and Goulburn Murray Water through Australian Water Environments Pty Ltd undertaken in close collaboration with MDBC Office. CMC draft report no.93, Version #6b, Oct. 2008.

Catchment Management Consulting (2011). District scale root zone drainage values for BSMS irrigation salinity impact assessment models for the Mallee region of the lower M-D Basin [MDBA Project #MD 1616]. Prepared by CMC in consortium with Rural Solutions SA, Aquaterra, Ken Smith Technical Services and Laroona Environmetrics for Murray Darling Basin Authority Canberra.

Cole, P. (Ed.) (1985). RMISIP Report Technical Report No. 69, Department of Agriculture, South Australia.

Cole, P., Watson, K., Cock, G., Schrale, G., and Plowman, D. (2015) Irrigation development and management in South Australia's Riverland. Primary Industries and Regions SA, Government of South Australia.
http://www.pir.sa.gov.au/aghistory/left_nav/natural_resources/water_resources_ag_dev/murray-darling_basin/irrigation_development_and_management_in_the_sa_riverland

Cock, GJ (1991) Water Balances of Irrigated Sultana Vineyards in the Riverland of South Australia. River Murray Irrigation and Salinity Investigation Programme Technical Report No. 179, Department of Agriculture, South Australia

Context Pty Ltd (2007). Victorian Water Supply Heritage. Vol 1: Thematic Environmental History. Report prepared by Context Pty Ltd for Heritage Victoria.

Cook P, Leaney F and Jolly I (2001) Groundwater recharge in the Mallee Region and salinity implications for the River Murray - a review. Prepared for the Murray Mallee Local Action Planning Association Inc.

Cummins, T. (2016). BSM2030 Knowledge Priority Workshop 23 June 2016. Mallee Legacy of History Salinity Impacts. Workshop Final Report. Prepared for MDBA.

Fordham, A., Thompson, R., Vears, L., and Meissner, T. (2011). Methodology to estimate irrigation accessions underlying irrigation areas and application of method to the Waikerie to Morgan region. Department for Water. December 2011.

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

Giddings, J. (undated). Winegrape Irrigation Benchmarking 1998-03. NSW Agriculture, Dareton.

Hantush, S. (1967). Growth and decay of groundwater mounds in response to uniform percolation: Water Resources Research, v. 3, p. 227-234

Knight, J., Gilfedder, M. and Walker, G. (2002). Impact of irrigation and dryland development on groundwater discharge to rivers: A unit response approach to cumulative impacts analysis. CSIRO Land and Water Technical Report 3/02.

Mallee CMA (2014). Mallee Salinity Workshop. May 30, 2012.

Meissner, T. (2004). Relationship between soil properties of Mallee soils and parameters of two moisture characteristics models. SuperSoil 2004. Australian New Zealand Soils Conference.

Meissner, T. (2011a). Estimation of Accession for Loxton and Bookpurnong Irrigation Areas. Prepared for Department for Water, February, 2011.

Meissner, T. (2011b). Estimation of Accession Volumes of the Cadell, Qualco-Sunlands and Waikerie Irrigations Areas. Prepared for Department for Water by Laroona Environmetrics, Loxton, Nov. 2011.

Meissner, T. (2012). Estimation of Accession Volumes of the Woolpunda Irrigation Areas. Prepared for Department for Environment, Water and Natural Resources, Adelaide by Laroona Environmetrics, Loxton, October 2012.

Meissner, T. (2014). Estimation of Irrigation Accession Volumes for the Lyrup, Pike and Murtho Districts. Prepared for Department for Environment, Water and Natural Resources Adelaide by Laroona Environmetrics, Loxton, February, 2014.

Middlemis, H., Merrick, N., Ross, J., and Rozlapa, K. (2001). Groundwater Flow Modelling Guideline. Prepared for Murray-Darling Basin Commission by Aquaterra, January 2001. URL: www.mdba.gov.au/sites/default/files/archived/mdbc-GW-reports/2175_GW_flow_modelling_guideline.pdf

Middlemis H, Evans R, Walker G, Cook P, Richardson S, Currie D (2017) Mallee Legacy of History Salinity Impacts from Dryland Vegetation Clearance. Preliminary draft report prepared by Hydrogeologic for Murray-Darling Basin Authority. 2 May 2017.

Murray-Darling Basin Authority (2014) General Review of Salinity Management in the Murray-Darling Basin. 7 October 2014.

Murray-Darling Basin Authority (2014) BSMS Description of Salinity Register Entries 2015 Register. Technical Report no. 2015/20. November 2015.

Nakai, T., Woods, J., and Telfer, A. (2010). Modelling the impact of clays in the unsaturated zone on groundwater recharge. Presentation at Groundwater 2010 conference, Canberra, October 2010.

National Water Commission (2008). National Performance Report 2006-07 Rural Water Service Providers.

Newman, B., Currie, D, Evans, R. and Adams, T. 2009, Irrigated Agriculture in the Mallee: Estimating Root Zone Drainage. Murray-Darling Basin Authority, Canberra.

Sisson, JB, Ferguson, AH & van Genuchten, M (1980) Simple Method for Predicting Drainage from Field Plots, Soil Sci. Soc. Am. Journal, v 44(6), pp 1147 - 1152

SKM (2003) Sunraysia Drying up of Drains. Sunraysia EC Credit Claim. Department of Sustainability & Environment. Final.

SKM and AWE (2003). Integration and Optimisation of Salt Interception in the Sunraysia region. Final Report to Department of Land and Water Conservation.

SunRISE 21 (2006). Mallee Zone Salinity and Irrigation Information Base. Draft Final Report to Murray-Darling Basin Commission.

Woods, J., Telfer, A. and Werner, A. (2013). Recharge and perched aquifers below irrigation areas: a variable-saturation model. Presentation to the National Ground Water Association Summit, San Antonio, Texas, April 2013.

Woods, J (ed.) (2015a) Modelling salt dynamics on the River Murray floodplain in South Australia: Conceptual model, data review and salinity risk approaches, Goyder Institute for Water Research Technical Report Series No. 15/9, Adelaide, South Australia.

Woods, J (ed.) (2015b). Modelling salt dynamics on the River Murray floodplain in South Australia: Modelling approaches, Goyder Institute for Water Research Technical Report Series No. 2015/10, Adelaide, South Australia.

Woods, J., Li, C., Bushaway, K., and Yan, W. (2014). Pike-Murtho Numerical Groundwater Model 2014 Volume 1: Report and Figures, DEWNR Technical Report 2014/05.

Woods, J., Li, C., Bushaway, K., Yan., W. and Peat, V. (2013). Woolpunda Numerical Groundwater Model 2013 Volume 1: Report and Figures, DEWNR Technical Report 2013/12.

Woods, J., Peat, V. and Middlemis, H. (2016). Stage 1 Review of SIMRAT V2.0.1. Prepared for MDBA, May, 2016.

Yan, W., Li, C. and Woods, J. (2011). Loxton-Bookpurnong numerical groundwater model 2011. Department for Water Technical Report 2011/22.

Yan, W., Li, C. and Woods, J., (2012). Waikerie to Morgan Numerical Groundwater Model 2012 Volume 1: Report and Figures, DFW Technical Report 2012/18.

Yan W, Morgan L, Georgiou J, Evans S and Vears L, 2009, Morgan to Wellington numerical groundwater model 2009, DWLBC Report 2009/22.

9. Glossary

Aquifer - An underground layer of rock or sediments that holds water and allows water to percolate through.

Aquifer properties - Those properties of a rock that govern the entrance of water and the capacity to hold, transmit, and deliver water, such as porosity, storativity and permeability.

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; see also potentiometric surface.

Aquifer test — A discharge (or injection) test performed on a well to provide data for analysis of aquifer properties (e.g. hydraulic conductivity, and storativity if nearby observation wells are monitored).

Aquifer, unconfined — Aquifer in which the upper surface is not impervious and the water surface is at atmospheric pressure (i.e. an unconfined aquifer has a water table).

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

Bore — See 'well'.

Basin Plan - Strategy to guide governments, regional authorities and communities to manage the waters of the Murray-Darling Basin sustainably between all users, including the environment; came into effect in November 2012.

BSMS - Basin Salinity Management Strategy 2015; implemented under Schedule B of the Murray-Darling Basin Agreement.

BSM 2030 - updated strategy for Basin Salinity Management for the period to 2030.

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.

Darcy's law - An empirical law which states that the velocity of flow through a porous medium is directly proportional to the hydraulic gradient (assuming that the flow is laminar and inertia can be neglected); after Henry Darcy, 1856.

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

DELWP - Department of Environment, Land, Water and Planning (Government of Victoria)

DEPI - former Department of Environment and Primary Industries (Government of Victoria)

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

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

DPI Water - Department of Primary Industries Water (Government of New South Wales)

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

Diffusivity - the ratio of transmissivity and storativity (T/S) of a confined saturated aquifer (or ratio of hydraulic conductivity to specific storativity (K/S_s) for an unconfined aquifer) that governs the propagation of changes in hydraulic head in the aquifer; hydraulic diffusivity is proportional to the speed at which a finite pressure pulse (e.g. drawdown or recharge) will propagate through the system; large values of diffusivity lead to fast propagation of signals; confined aquifers typically exhibit large values of diffusivity compared to unconfined aquifers; (units of m^2/day).

Drawdown - The vertical distance the water elevation is lowered (or the reduction of the potentiometric surface) due to the removal of water (e.g. via a pumped well).

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.

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.

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

Error – is the difference between a measurement and the true value of the quantity being measured. It is a combination of systematic error and random error.

Floodplain – generically defined as the land adjoining a 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) for spatial and temporal analysis.

Groundwater – Water occurring naturally below ground level or water pumped, diverted and released into a well for storage underground.

Head, hydraulic - The height above a datum plane (such as sea level) of the column of water that can be supported by the hydraulic pressure at a given point in a groundwater system. For a well, the hydraulic head is the distance between the water level in the well and the datum plane. The hydraulic head is the sum of the elevation head and the pressure head (also called static head).

Head, total - The total head of a liquid at a given point is the sum of the static head and the velocity head, thus comprising three components: (a) the elevation head, which is equal to the elevation of the point above a datum, (b) the pressure head, which is the height of a column of static water that can be supported by the static pressure at the point, and (c) the velocity head, which is the height to which the kinetic energy of the water can lift it.

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 (m/d).

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'.

Hydrograph - A time series graph relating level, flow, velocity, or other characteristics of water.

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

Impermeable - A characteristic of some geologic material that limits its ability to transmit significant quantities of water under the head differences ordinarily found in the subsurface.

Infiltration - The downward entry of water into the sub-surface; see also percolation.

Irrigation accessions - the net downwards flux of water below an irrigation district.

Leaky aquifer - Aquifers that lose or gain water through adjacent less permeable layers.

Log-normal distribution - A continuous probability distribution of a random variable whose logarithm is normally distributed.

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 – The repeated measurement of parameters to assess the current status and changes over time of the parameters measured.

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.

Non-uniqueness – Situations where multiple versions of a groundwater model with different parameter sets give equally acceptable fits to observational data.

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

Perched groundwater - Groundwater separated from an underlying body of groundwater (represented by a regional water table) by an unsaturated zone.

Percolation - The downward movement of water through the unsaturated zone.

Permeability - The property of a porous medium to transmit fluids under an hydraulic gradient; see also hydraulic conductivity.

Phreatic surface - see water table.

Piezometer - A devise used to measure groundwater pressure head at a point in the subsurface.

Porosity - The ratio, usually expressed as a percentage, of the total volume of voids of a given porous medium to the total volume of the porous medium [L^3/L^3]

Potentiometric surface - An imaginary surface representing the static head of groundwater and defined by the level to which water will rise in a tightly cased well; where the potentiometric surface is higher than topography, the aquifer is described as artesian (otherwise, sub-artesian).

Probability density - A mathematical function whose integral over an interval gives the probability that its value will fall within the interval.

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 - The process of addition of water to the water table (or saturated zone of a confined aquifer); recharge is also the volume of water added.

Root zone drainage - RZD; 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 - Implemented under the BSMS and maintained by the MDBA; a system for keeping record of accountable actions within the Basin.

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

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

Soil water content (ϴ) - A measure of the amount of water contained within a soil; commonly expressed on a volumetric basis [L^3 / L^3]

Specific storage (Ss) – 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 (Sy) – The volume ratio of water that drains by gravity to that of total volume of the porous medium; [dimensionless].

Storage coefficient (S) – confined aquifer storativity; the volume of groundwater released or taken into storage per unit plan area of aquifer per unit change of head; [dimensionless].

Storativity (S) – the volume of groundwater released or taken into storage per unit plan area of aquifer per unit change of head; virtually equal to the specific yield in an unconfined aquifer; [dimensionless].

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

Transfer function - A transfer function is a mathematical function which describes the relationship between the input and output of a system. In this context, the system is the unsaturated zone, the input is the irrigation accession flux, and the output is the recharge rate used by the groundwater model. Thus, the concept of a transfer function is to define a mathematical relationship between irrigation accessions and recharge that is representative of the influence of the unsaturated zone. The application of a transfer function means that recharge can be computed directly from estimates of irrigation accessions.

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.

Time lag - broadly refers to the 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 becoming recharge at the regional water table.

Uncertainty - the range of values within which a true value is asserted to lie.

Unconfined aquifer - An aquifer which has a water table.

Unsaturated zone - The zone between the land surface and the water table (includes the capillary fringe). Water in this zone is generally under less than atmospheric pressure, and some of the voids may contain air or other gases at atmospheric pressure.

USGS - United States Geological Survey.

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

Watercourse – A river, creek or other natural watercourse; for example, a dam or reservoir that collects water flowing in a watercourse; a lake through which water flows; a channel into which the water of a watercourse has been diverted.

Water table - that surface in a groundwater body at which the water pressure is atmospheric (i.e. upper surface of a zone of saturation except where that surface is a confining unit).

Well – A bored, drilled or driven shaft, or a dug hole, whose depth is greater than the largest surface dimension, constructed for the purpose of obtaining access to underground water.