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# Development of transfer functions and guidance for modelling irrigation recharge in the Mallee

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# Executive Summary

### *Introduction*

This report summarises the results of a MDBA-commissioned project, that has developed and tested '*transfer functions*' for irrigation areas in the Mallee; and showed how these may be embedded in regional groundwater models used to support salinity management. Transfer functions are unsaturated zone models representing the linkages of irrigation management to recharge into the regional groundwater systems transporting salt to the River Murray. This report also integrates the findings to provide guidance to salinity modelling in the future and describes some of the implications for salinity management of this region.

The aim in this study was to *develop and test approaches for simulating irrigation recharge within an uncertainty framework as a guide for future modelling assessments, rather than being prescriptive*.

### *The issue*

A review of previous approaches to recharge modelling in the Mallee (Currie et al. 2017) highlighted that existing approaches can potentially lead to biased predictions of the salt loads to the River Murray with large uncertainties; and thereby affect decisions on salinity management.

The main problem identified by Currie et al. (2017) is the use of mainly piezometric data to calibrate parameters within groundwater models. This has the potential to cause '*non-uniqueness*', in which widely varying sets of parameters, that adequately fit observations, provide a range of predictions. Non-uniqueness is generally addressed in two ways. In the first, other data are used to supplement piezometric data. These are generally flux-based data (e.g. hydrogeologic parameters from pump-tests, pumping volumes or river salinity). The second approach is to constrain the calibration range of parameters using other, sometimes qualitative, information. While both approaches have been used in the Mallee region, they may not adequately address non-uniqueness for salinity management, especially since changed recharge is one of the major drivers for groundwater changes and salt loads.

*Different modelling approaches* have been applied to the South Australian Mallee (SAM), than for the Eastern Mallee (EM) of NSW and Victoria for a range of reasons, including differences in hydrogeology, salinity assessments, data collected, and irrigation management. For example, the depth to regional groundwater underlying major irrigation areas tends to be greater for SAM than for EM, so that time lags between changes in irrigation management and recharge response are greater. Secondly, irrigation infrastructure can be very different, thus affecting the conceptualisation of surface water balances within models. Thirdly, the modelling for SAM for salinity assessments is updated for a small number of irrigation districts, while the EM is subject of decadal updates affecting several irrigation districts. Fourthly, data availability can be very different between EM and SAM.

One of the major initiatives over the last two decades is the use of *district-wide surface water balance models* for recharge estimates. These models are available across most irrigation districts in the Mallee and predict percolation below the surface layer; based on estimates of irrigation water use efficiency. In the EM, these estimates of percolation have been used directly for recharge; while in SAM, they have been used to compare with recharge estimates inferred from the groundwater response, by using the groundwater model. We refer to the former as Forward Modelling (FM), and the latter as Inverse Modelling (IM). For FM, any bias in the estimate of water use efficiency is amplified in the process of estimating recharge from the surface water balance model; which is then built into the groundwater model calibration. Despite the calibration process, any such bias can flow through to salt load estimates. The difficulty with IM is that because recharge is inferred, more information than the normal hydrogeological parameters is being sought from the inversion of groundwater data, and this could exacerbate non-uniqueness. Qualitative matching with surface water balance models and other observational and modelling information, helps to offset this effect. Qualitative matching of this nature, however, can be difficult to replicate and use in uncertainty analyses.

Currie et al. (2017) suggested a shift to a *joint calibration* of groundwater and recharge models for both SAM and EM. This recommendation is supported by the literature review collated for this report.

*A shift to joint calibration is not straightforward*. Three key issues are:

- The need for transfer functions: The main reason why joint calibration has not been used in SAM has been the absence of a suitable transfer function. The previously used model, SIMRAT/SIMPACT, is not suitable for use under irrigation areas for several reasons, but mostly because it cannot represent perched water tables. Perched water tables have underlain most irrigation areas in the Mallee for at least some time.
- If the surface water models are to be continued to be used, water use efficiency needs to be adjusted as part of the joint calibration by relating it to recharge. In parallel with this project, there have been at least two attempts to do this within the EM, and earlier one for the SAM within this project; but none have been convincing.
- There needs to be sufficient data to jointly calibrate groundwater and recharge. Changing the calibration approach, without balancing data requirements may not result in any improvement.

### *Approach*

We consider an *evolutionary change in the modelling approach*, where surface water balance models are still used, and the shift to joint calibration is a variation of the current groundwater models *made possible by the development and deployment of recharge models/transfer functions*. Given the SAM and EM models are very different not only in the calibration approach, but the scale of the model, the frequency of assessments and the data underlying them, the *nature of the changes required for SAM and EM modelling workflows* will be very different.

### *A lumped approach trialled for the Eastern Mallee*

For EM, the district-scale surface water balance model has been modified to incorporate unsaturated zone processes and to allow water use efficiency to be adjusted during the joint calibration process. This is done by relating water use efficiency and recharge to drainage over perched areas and by assuming water use efficiency is similar for perched and unperched areas. While it is not technically a transfer function, the modified surface water balance forms a 'lumped' recharge model that incorporates unsaturated processes and provides a link between irrigation actions and regional groundwater model, thus fulfilling the transfer function requirements that were established at the outset of the research program.

The drainage and surface water diversions data at EM suggest three groupings of irrigation districts:

- Victorian districts, where some perching persisted over the past four-to-five decades;
- Major NSW districts, where perched water tables are likely to have disappeared as water use efficiency improved; and
- Minor NSW districts with negligible perched water tables.

A recharge model (based on the modified surface water balance) that reflects these different irrigation groupings, has been incorporated into the existing EM modelling platform (v2.6), and recalibrated within an uncertainty framework. The results from this analysis were then compared to previous models (Figure ES-1).

The results show that *small changes in water use efficiency and unsaturated zone parameters can result in a wide range of recharge estimates* (Fig. 1a). The *previous approaches did provide recharge estimates at the lower end of the uncertainty range, probably reflecting a bias* (Fig. 1b). The uncertainty range is least for the first grouping of irrigation districts, where recharge is limited by, and hence sensitive to the hydraulic properties of the impeding layer. The third group has the largest uncertainty range, and is limited by, and sensitive to, the water use efficiency; with possible discharge to the land surface increasing the uncertainty.

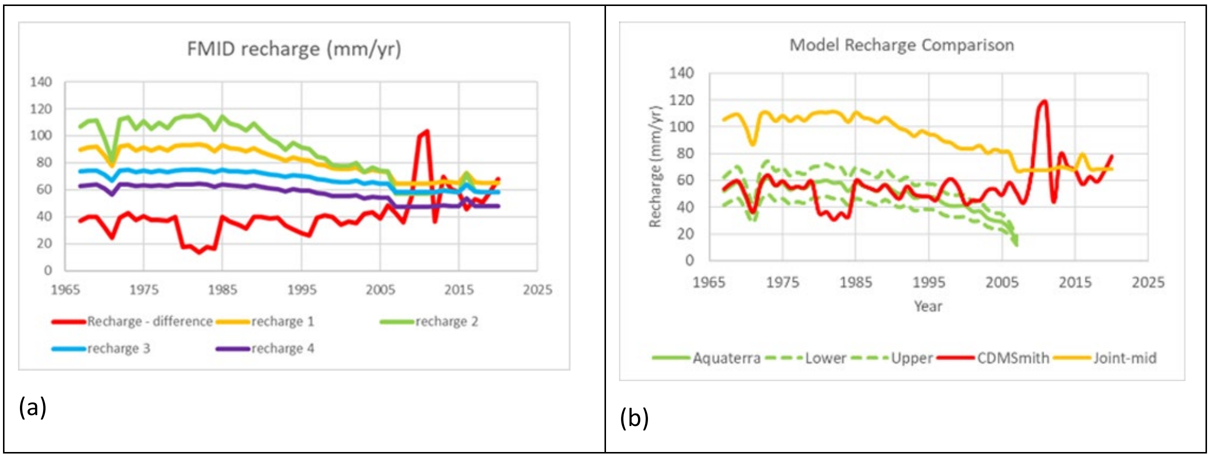


**Figure ES-1 Comparison of recharge estimates for the First Mildura Irrigation District, FMID (a) for the newly developed model using four sets of parameters (green, yellow, blue and violet) compared to CDM Smith EM2.6 study (red); (b) comparison of median value from the newly developed model (Joint-mid) to those derived by earlier studies (EM1 (green), Jacobs(green dashed) and EM2(red).**

it would be untenable not to use an uncertainty approach, or to not adjust water use efficiency and unsaturated zone parameters, as this is likely to create a consistent and strong bias in recharge estimates and hence salt loads. It also highlighted the importance of accessible data on soils, soil salinity and remotely-sensed evapotranspiration. The inconsistencies inherent in previous recharge estimates appear related to errors in the input data (particularly drainage data), and scrutiny of these inputs is required.

Before the next salinity assessment, some further work would be needed to further develop this concept for general acceptance. This would include collation of data for verification, testing of improved models for an individual district nested in the regional groundwater model; and further reviewing.

### *A discretised approach trialled for the South Australian Mallee*

A trial of the transfer function approach at SAM preceded the EM study by three years. It was *only partially successful*.

For SAM, a transfer function, *PerTy3*, was developed to represent unsaturated zone processes under irrigation districts, *both with and without perched water tables*, and provide estimates of recharge over time, allowing for time lags. The model was built upon an understanding of the wetting up processes following irrigation development, changes in irrigation accessions associated with water use efficiency improvements and decommissioning of irrigation. These models have been *benchmarked using FEFLOW*, showing that the model have accurately captured the physical models. Outputs reflected aspects of recharge from the inverse modelling (IM) undertaken previously (Figure ES-2).

This model was tested within a groundwater model for the Loxton-Bookpurnong irrigation districts using three different approaches. The first was to use a calibrated transfer function as input to an already calibrated groundwater model and estimate salt load. The second was to use the same transfer function as input to the groundwater model and recalibrate. The third was to try a joint calibration of the recharge and groundwater model. The results were then compared to those obtained using an IM approach. Both the IM calibration and transfer function model approaches used a large number of recharge zones which became burdensome during calibration.

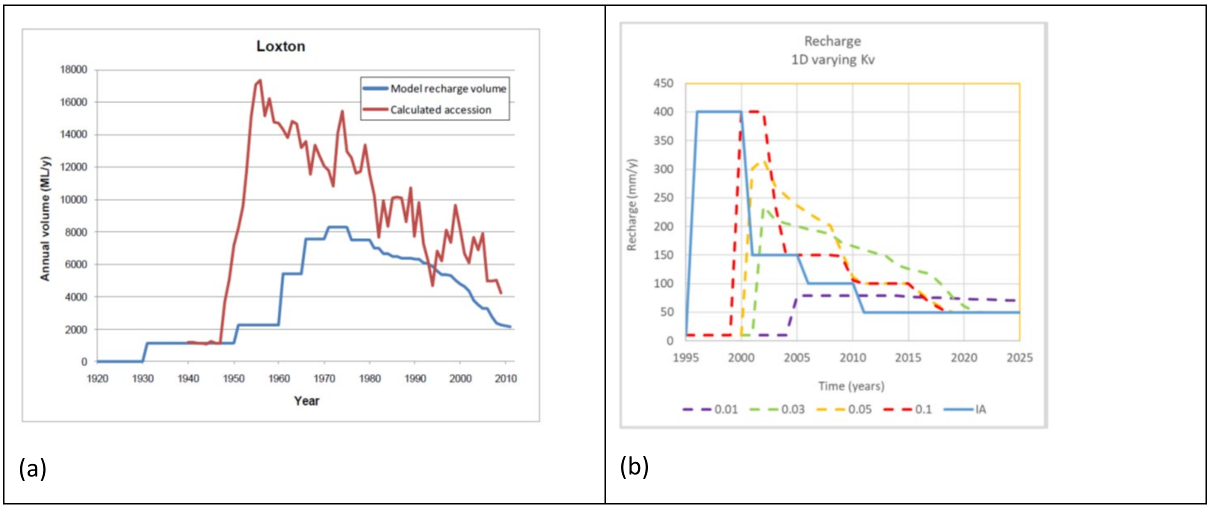


**Figure ES-2 (a) Comparison of the total recharge volumes inferred using inverse modelling for the calibrated groundwater model (blue line) with the calculated accession (red line) from surface water balance model. Figure from Yan et al. (2012a); accessions from Meissner (2011); (b) Plots of modelled recharge estimates from PerTy3 with time for irrigation systems with different values of Kv (i) 0.01 (ii) 0.03 (iii) 0.05 and (iv) 0.1 cm/day in response to a sequence of irrigation actions captured by the plot of irrigation accessions (IA).**

Unfortunately, the experiment showed that the transfer function at that time was *not sufficiently robust for use in an automated calibration*, and so continuous maintenance of the model was required throughout the calibration. Secondly, it is hypothesised that the groundwater rise under the irrigation district led to *interception of groundwater by the drainage network*; a process which had not been represented in the existing model, but significantly affects irrigation recharge to the groundwater. This would also complicate a direct comparison of inferred recharge from IM with the simplified surface water balance model. Thirdly, the same issue complicated the joint calibration of recharge and groundwater models. Somewhat surprisingly, the models provided salt load and recharge estimates comparable to that from IM. Discrepancies were mostly explicable due to the interception of groundwater within the drains. This *provided some confidence in the approach* once difficulties were remedied.

Since this modelling experiment, the transfer functions were reprogrammed to be more robust. More importantly, the process of *superposition*, in which transfer functions for individual actions (e.g. irrigation development, efficiency change) could be simply combined to provide an adequate fit to the overall recharge. Superposition is not self-evident because of thresholds related to perching and drainage, but with care avoids the main issues affecting the robustness of the transfer function. A further simplification, in which *approximants* for the transfer function was successfully trialled, enabling conceptual models to be used in a similar fashion to those used in shallow water table areas, yet be sufficiently physically realistic. Finally, an adaptation of the modelling approach for situations of *shallow water tables* has been developed, enabling representation of groundwater mounds affecting drainage. While these updates should improve the performance and have been benchmarked against a numerical model, they *have not been trialled within a regional groundwater modelling framework* for Mallee irrigation districts. Generally, testing can be more comprehensive for the more physically based, spatially distributed models of SAM, than for the lumped conceptual models of EM, noting that some simplification of the number of recharge zones is warranted given the difficulties encountered during the transfer function pilot trial at Loxton-Bookpurnong.

*No particular bias* was found for the Loxton-Bookpurnong IM implementation. We hypothesise the main reasons for this were the complex iterative process used in manual IM calibration to qualitatively match surface water balance model outputs and other observations and modelling studies; and the proximity of the Loxton research station, at which many water use efficiency studies were conducted. This suggests a *lesser urgency to change* to a joint calibration process than for EM, that could be delayed until updated transfer functions have been trialled. There are, however, strong arguments to eventually move to a joint-calibration method. The complex iterative process used in manual IM calibration is difficult to replicate, and difficult to implement in an uncertainty analysis. There is subjectivity in defining specific irrigation actions (e.g. improved efficiency) for forward modelling purposes. And some other irrigation districts (e.g. Woolpunda) do not have the same level of data as at Loxton (e.g. on drainage) meaning that the same level of qualitative checking will not be possible; hence increasing the likelihood of bias. *Ultimately, a change to joint calibration method is warranted*, but as the Loxton-Bookpurnong trial showed, such a change could be done *in an evolutionary fashion*, that fits into the salinity register assessment cycle.

### *Status of transfer function development*

Within the project, there has been much progress in the development and testing of transfer functions for application to Mallee irrigation areas, but the nature of modelling means that these can be further improved. The different scales and purposes for which the modelling has been applied, and will be applied in the future, means that *a single set of transfer functions for all situations is not feasible*. The typology, in which Type 1 represents situations with no perching, Type 2 perched water tables over shallow regional groundwater, Type 3 perched water tables over deep regional groundwater and Type 4 for multiple perched water tables, was useful in the development, but has been largely discarded, for the simple reason that irrigated fields may change from one type to another. Similarly, transfer functions needed to address the whole evolution of irrigation districts from initial development to final decommissioning, rather than be single purpose. However, the use of superposition means that it is easier to combine single purpose transfer functions to represent this evolution.

It is *unlikely that the models for EM and SAM will be fully consistent in the near future*, although a shift to a joint calibration within an uncertainty framework may facilitate comparisons between the regions. The use of transfer functions means a greater focus on unsaturated zone and irrigation water balance processes in groundwater modelling, while the joint calibration approach means a greater emphasis on calibration and uncertainty methodologies.

### *Recommendations*

1. Future salinity assessment in the Eastern Mallee should apply a joint calibration process, in which the water use efficiency and unsaturated zone parameters are adjusted within an uncertainty framework. Before the next assessment, some further work would be required on improving the methodology and supporting data, for one or more irrigation districts.

2. For the South Australian Mallee region, there should be further testing of the simplified transfer function methodology for a South Australian irrigation district within a groundwater model, as a step towards joint calibration into the future.

3. The use of easily accessed remotely sensed data for evapotranspiration for the joint calibration should be explored, as this is likely to constrain uncertainty and reduce bias. Improved collation and interrogation of other irrigation and soil data (e.g. drainage data) to support surface water balances and the development of transfer functions should also continue in parallel. While this could occur as a regional initiative across the Mallee, it is best embedded in individual modelling assessments; since the data collation and review process assists in the development of unsaturated zone conceptualisations and in the design of groundwater modelling approaches to robustly simulate irrigation recharge.

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**No table of contents entries found.**

# Document history & status

| Revision | Date issued | Reviewed by | Approved by | Date approved | Revision type |
|---|---|---|---|---|---|
| V0 | 19 July 2023 | G. Walker | D. Currie | 19 July 2023 | Draft |
| V1 | 23 November 2023 | Ray Evans<br>Juliette Woods<br>Prathapar S. | D. Currie | 23 November 2023 | Draft |
| | | | | | |
| | | | | | |

# Distribution of copies

| Version | Date issued | Quantity | Electronic | Issued to |
|---|---|---|---|---|
| V0 | 19 July 2023 | 1 | 1 | E. Xevi |
| V1 | 23 November 2023 | 1 | 1 | E. Xevi |
| | | | | |
| | | | | |

| | |
|---|---|
| **Last Saved:** | 18 June 2024 |
| **File Name:** | 1001335-RPT-Guidelines for modelling irrigation recharge-v1 |
| **Author:** | Glen Walker and Dougal Currie |
| **Project Manager:** | Dougal Currie |
| **Client:** | Murray-Darling Basin Authority |
| **Document Title:** | **Development of transfer functions and guidance for modelling irrigation recharge in the Mallee** |
| **Document Version:** | V1 |
| **Project Number:** | 1001335 |

# Section 1 Introduction

The maintenance of the salinity registers for the Basin Salinity Management strategy (BSM2030) in the Mallee region requires robust modelling approaches to quantify groundwater fluxes and salt loads to the river that result from irrigation. These models need to simulate processes in both the saturated and unsaturated zones to connect on-ground actions (such as irrigation development and/or efficiency improvements) with their influence on river salinity at regional scales.

A review of traditional approaches to the treatment of irrigation recharge within salinity register modelling (Currie et al. 2017) highlighted some issues and inconsistencies in how irrigation recharge is determined and noted a significant limitation in traditional approaches; namely, there is no direct modelling of the unsaturated zone to account for the perching on clays and time lags that are known to occur. The existing recharge model for the unsaturated zone, SIMRAT (Fuller et al. 2005), is unable to simulate these processes. In the absence of an appropriate modelling tool to simulate unsaturated zone processes, there is a disconnection between the simulation of on-ground actions and an assessment of their salinity impacts. These issues conspire to make the salinity register review process less transparent and open to challenge due to inconsistencies in methodology, which slows down the review process and adds to the overheads of maintaining the register. But more significantly, any unintended bias in the modelling may lead to a substantial over- or under-prediction in salt loads which could result in under- or over-costing works to manage the impacts and/or inequitable cost sharing arrangements between BSM partner governments.

From 2018 to 2023, the Murray-Darling Basin Authority (MDBA) has commissioned a series of projects to develop unsaturated zone transfer functions (transfer functions) to address these limitations, with the ultimate goal of developing a robust and consistent framework for the treatment of irrigation recharge within salinity register models. This report presents a summary of this work program to:

- Review the existing groundwater modelling practices to identify areas and opportunities for improvement (Section 2).
- Describe the new recharge models that have been developed and how they can be applied (Section 3).
- Discuss the application of the new recharge models within salinity register models at Sunraysia (Section 4) and Loxton-Bookpurnong (Section 5) to highlight the capabilities and limitations of these techniques.
- Provide a series of recommendations to represent irrigation recharge more robustly within groundwater models for salinity register purposes (Section 6).

This document is intended as a resource for groundwater modelling practitioners, independent reviewers and those responsible for commissioning and overseeing salinity register reviews in the Mallee region. It is based on the MDBA-commissioned work, which has been described in detail within a series of papers and reports (Currie et al., 2017; Currie et al., 2020; Walker et al.,2020a, 2020b; Walker and Currie, 2022; Walker et al., 2023). The findings from these studies are summarised here; and have been further integrated to provide guidance for a range of modelling across the Mallee region. They are intended to supplement Australian modelling guidelines (Barnett et al., 2012; Peeters and Middlemis, 2023) by providing a focus on recharge modelling in the Mallee to support decision-making on salinity management.

The context for modelling salinity impacts in the South Australian Mallee (SAM) and the Eastern Mallee (EM) in Victoria and New South Wales can vary due to different hydrogeology, history, irrigation management and policy. There is a need from the perspective of the BSMS decision-making to consider these within a common framework that respects these differences; but is also transparent. Because of these differences, this report is not intended to be prescriptive. Also, too prescriptive a document may deter potential innovations and adjustments by groundwater modellers for their particular problem.

# Section 2 Current modelling practices

## 2.1 Forward and inverse recharge modelling

This section describes modelling and calibration workflows in the context of current and potential groundwater modelling strategies to support salinity management in the Mallee Region. The main aim of this modelling is to estimate historical and future salt discharge to streams for a range of scenarios to support the Salinity Register and provide advice on options. The basic structure of these programs is shown in Figure 2-1 and consists of two broad model components:

1. The recharge module calculates the unsaturated zone water outputs (especially recharge to regional groundwater system, but sometimes drainage volumes, crop evapotranspiration and discharge of perched water to the land surface), using water inputs (especially irrigation diversions and rainfall and sometimes others such as channel losses) and a range of soil, vegetation, climate and irrigation management parameters; and
2. The groundwater model calculates a range of outputs (discharge to rivers and irrigation drains, groundwater ET and sometimes groundwater pumping volumes and recharge) using recharge and river levels as model inputs and incorporating a range of hydrogeological and hydraulic parameters).

The scenarios involve changes in water use efficiency, groundwater (salt interception) pumping and river management and climate scenarios. These scenarios are generally reflected by the inputs and parameters to the combined recharge module/groundwater model. Here, 'input' refers to a time series, often fluxes; while 'parameter' refers to a characteristic of the system, e.g. soil physical properties or vegetation parameters.

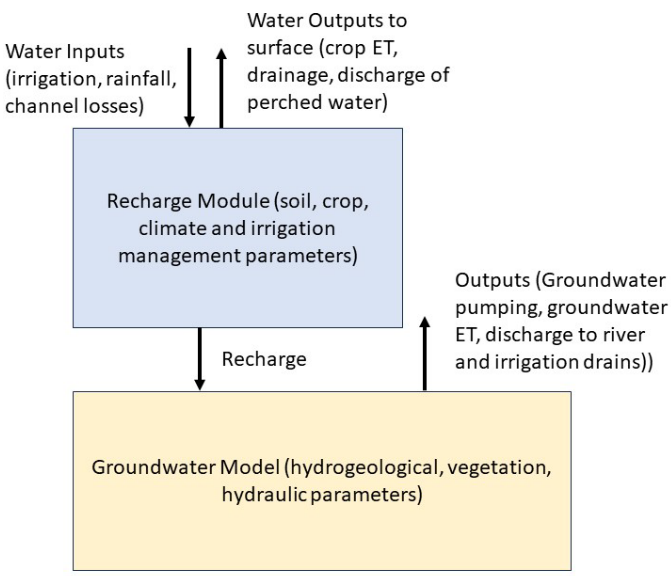



**Figure 2-1 Schematic diagram showing the relationship between recharge module, groundwater model and the various water fluxes.**

Both the recharge module and groundwater model need to be parameterised. We describe three different approaches in the way parameter values can be calibrated or assigned:

1. Forward modelling of recharge (FM). The parameters of the recharge module are set independently of the groundwater model. The calibrated recharge model is then used to provide input to the calibration of the groundwater model and subsequent applications. An example of this for the Mallee region is the EM2.3 model (Aquaterra, 2009)).

2. <u>Inverse modelling of recharge (IM)</u>. The groundwater model is calibrated without explicit inputs from recharge modelling. Not only are the hydrogeological parameters calibrated, but also recharge across recharge zones for a range of times. The derived recharge can then be compared qualitatively with independent surface water balance and unsaturated zone modelling, and relevant field observations. An example of this in the Mallee region is the Loxton-Bookpurnong model (Yan et al., 2011a,b).

3. <u>Joint recharge-groundwater calibration (JC)</u>. The groundwater and recharge models are jointly calibrated to match field observations. This differs from the IM approach in which only the groundwater model is calibrated; or the FM approach where recharge and groundwater models are calibrated independently. Examples of this 'hybrid' approach in the Mallee include Mallee Model Refinement for Salinity Accountability (Jacobs, 2019), Sunraysia Model Upgrade Project – Eastern Mallee (EM) 2.6 (CDM Smith, 2022) and CDM Smith (2023). The approach has been termed 'hybrid' modelling in works conducted for the transfer function program to date, but JC is preferred from now on as it is a more established term in the broader groundwater modelling discipline and will thus be more readily understood.

The boundaries between these approaches are not necessarily clear. For example, Yan et al. (2012a, b) qualitatively compared the inferred recharge rates from the inversion with recharge modelling and observations and adjusted hydrogeological parameters until both hydrogeological and recharge targets were met). Also, for forward modelling, recharge models may need to be revised if groundwater calibration provides unrealistic numbers. These grey areas could be separated, noting that the qualitative nature of such joint calibration means that the any modelling is not done in an automated mode. This means that any uncertainty or sensitivity analysis may be limited in nature and the calibration process more subjective. For the rest of this paper, these further categories will not be explicitly mentioned, with the gradation between JC and the FM/IM approaches., with the gradation between categories implicitly assumed.

The magnitude of changes in the salt load to the river is intrinsically linked to the changes of recharge to the regional groundwater system. The ability of groundwater models to inform recharge (R) through calibration is hampered by the correlation between recharge and aquifer parameters such as hydraulic conductivity (K) and specific yield (S), and the insufficient information content of observation datasets (Carrera, and Neuman, 1986). This correlation is exemplified by the analytical solution of Hantush (1967), in which the level of groundwater mounding under a uniform increase in recharge is dependent on the ratios of R, K and S to each other, rather than each independently. While this is an idealised conceptual model, the underlying scaling does not disappear with additional complexity. The scaling implies that use of piezometric heads for inversion cannot inform all three variables independently. If one is set, there may be compensating errors in the computation of the other two variables, in the absence of other constraining data.

In the case of the Mallee region, all major irrigation districts have simple land surface water balance modelling based on water use efficiency and channel loss factors to estimate irrigation accessions (percolation) that may become recharge. While such factors are based on local experience and knowledge, there is undoubtedly a degree of subjectivity in assigning values to these variables across irrigation districts over decades. Newman et al. (2009) have collated available information on root zone drainage and water use efficiency, highlighting the degree of uncertainty in using such models for estimating recharge. Newman et al. (2012) showed that there was a discrepancy between estimates of recharge from land water balance approaches and groundwater approaches at that time. For the FM approach, any errors in the recharge estimate will affect the calibration of K and S and bias estimates of salt loads. Because of the general difficulty of measuring recharge at reasonable temporal and spatial resolutions, Voss (2011a) has suggested that generally '*a useful recharge value might best be obtained indirectly, as a result of a modelling analysis based on other hydrologic data such as head or groundwater age. This reverse approach may be preferable to employing a possibly wrong, externally determined value of recharge as the main driver of flow*'.

IM has been increasingly used to infer recharge (e.g. Das Gupta and Paudyal (1988); D'Agnese et al., 1999; Ella et al., 2002; Dickinson et al., 2004; Palma and Bentley, 2007; Knowles et al., 2007; Hashemi et al., 2013). Efforts to overcome parameter non-uniqueness have generally involved two approaches. The first is to use of flux-based or groundwater velocity observations used either as a prescribed stress or as a calibration target in addition to piezometric head data. Examples of this in the Mallee are the salt discharge to the river or groundwater pumping. The second is to impart expert knowledge of aquifer hydraulic properties, such as K, or S, through regularisation, which stabilises parameter estimation process in an otherwise ill-posed inverse problem by providing constraints on parameters.

Uncertainty associated with groundwater model-based recharge estimates is rarely quantified. Knowling (2016) showed, using a steady-state complex parametrised groundwater model, that a reasonable inference of recharge (average recharge error <10%) requires a surprisingly large number of preferred value regularisation constraints (>100 K values across the study area). The introduction of pumping data into the calibration reduces error in both the average recharge and its spatial variability, whereas submarine groundwater discharge (as a calibration target) reduces average recharge error only. Knowling (2016) showed using the same model in a transient mode that reasonable estimates of monthly recharge (<30% recharge root-mean-squared error) require a considerable amount of transient water-level data, and that the spatial distribution of K is known (i.e., through joint R-and-S estimation). The joint estimation of R, S and K, however, precludes reasonable inference of recharge and hydraulic parameter values. These two studies indicate that the estimation of steady-state recharge and temporal recharge variability through inverse modelling may be impractical for real-world settings, limited by the need for unrealistic amounts of hydraulic parameter and groundwater level data. These results echo those of Erdal and Cirpka (2016), who applied the Ensemble Kalman filter to jointly estimate spatially distributed R and K from head observations for a highly simplified synthetic aquifer.

There have also been several examples of JC (e.g. Liu et al., 2008; Lubczynski and Gurwin, 2005; Ebrahimi et al.., 2016). The process of merely combining recharge and groundwater models as part of a joint calibration does not itself address the concerns raised in the previous two paragraphs. If the information content of observations and constraints remains unchanged, then the issues with inverse recharge modelling remain. However, recharge module outputs will generally have both a temporal and spatial structure built in by linking to monitoring time series variables (e.g. rainfall, surface water diversion and drainage volumes and remotely sensed evapotranspiration) and to spatial datasets (e.g. irrigation and drained areas, soil types, depth to water table). They will also generally incorporate an understanding of unsaturated zone processes (perching, time lags) so that information content is greatly increased.

The difference to FM in using this temporal and spatial structure of recharge is that parameter(s) in the recharge module is (are) partially calibrated to match groundwater targets and, as such, provides flexibility for recharge to be modified as part of the calibration approach. It also allows uncertainty and bias of the whole modelling system to be assessed and support the prioritisation of data that would reduce uncertainty. Finally, if the main interest is on the linkage between irrigation management changes and future salt load changes, the combined model transparently shows the cause and effect, and trade-offs in the modelling.

The above considerations led Currie et al. (2017) to recommend a ‘whole-of-system approach’ as the means to advance a more consistent approach to salinity modelling for the Mallee region and to obtain a better understanding of uncertainty and avoid bias. The extent to which a whole-of-system modelling approach could be adopted, will vary for each model will depend on range of factors, including availability of a suitable recharge module, relevant data to parameterise the models and the context for the modelling. The next section discusses the first of these, namely suitable recharge modules.

## 2.2 Recharge modules

Surface water balance models to estimate irrigation accessions are available for all major districts of the Mallee. These have been used regularly, especially in the EM, to estimate recharge. The percolation below irrigation areas that becomes recharge has often been inferred as the small difference between other larger fluxes using simple water balance models that can be cast in the form:

$$R = TWA*(1-W_{eff}) - D - D' \quad (2\text{-}1)$$

where R is the annual percolation flux below any impeding layer, that becomes recharge; D the annual sub-surface drainage per unit irrigation area, D’ is the annual discharge to the land surface from perched water tables per unit area and TWA is the total water availability for agricultural production per unit area (including both rainfall (or effective rainfall) and surface water diversion), and $W_{eff}$ is effectively a district water use efficiency, which lumps together field water use efficiency and other terms such as evapotranspiration from channel losses. As most of the irrigation water and rainfall returns to the atmosphere through evapotranspiration and drainage, small errors in the estimation of these terms can cause large errors in percolation. All terms have errors, but $W_{eff}$ is particularly problematic. Considerations of non-uniqueness would suggest that this uncertainty should be addressed by (1) using these models quantitatively in a JC framework, or qualitatively in an IM framework, to effectively calibrate $W_{eff}$, based on groundwater response; (2) finding independent surface data to calibrate and constrain R irrespective of calibration framework; or (3) find more reliable surface water balance models.

There are several field techniques to estimate water balance and deep percolation, but many are limited in spatial and temporal range. Remotely-sensed ET data has good spatial coverage over recent decades; and will be discussed later. Where such data exists, it could still be used in conjunction with JC and IM approaches, as well as to reduce errors in the estimation of R in the FM framework. More complex physically-based surface water balance modelling approaches could be used, but these would generally require knowledge of (1) irrigation distribution to and within different fields; and (2) more detailed information on evapotranspiration. The detailed knowledge of irrigation water use varies across the states, and irrigation districts and within irrigation districts. that alternative consistent models of using surface water balance for recharge are unrealistic. The approach in this report is to continue to use these surface water balance models, for which there has been considerable investment and knowledge; but (1) seek further data to improve their reliability; and (2) link these models to models of water movement through the unsaturated zone between the root zone of agricultural crops and the regional water table. This zone would include any perched water tables, that might lead to drainage or return of irrigation water to the land surface by ET.

A problem in using estimates of percolation directly for recharge is that there can be significant time lags in percolation becoming recharge. An increase in irrigation accession rates lead to a wetting up of the unsaturated zone. A 'wetting front' effectively needs to reach the regional water table before the corresponding increase in recharge can occur. This is further complicated where a low permeability layer occurs and impedes the vertical percolation of water to form a perched water table. It takes time for a perched head to form, increasing the flux through the impeding layer, and for lateral movement of perched water from the irrigation field, causing an increased area of percolation. Perched water can lead to drainage occurring and further evapotranspiration to the land surface. The presence of drainage is an indicator of these further time lags. If sufficiently low, the vertical conductivity of the clay layer becomes the main controlling factor for recharge, rather than the total amount of water applied to the surface by irrigation (in addition to rainfall). The water tables in SAM tend to be deeper than those in EM due to the river cutting a gorge through the landscape, causing regional water tables to be deeper relative to the land surface. The deeper water tables mean that time lags become much more important. In EM, the time lags are unlikely to be as important; and have largely been ignored in modelling efforts to date.

The unsaturated zone model of choice, SIMRAT, is a variant of the SIMPACT model (Miles and Kirk, 2005; Wang et al., 2005), developed for dryland regions to estimate time lags in change of recharge following clearing of native vegetation. Changes in the percolation below the agricultural zone is conceptualised as leading to the formation of a 'wetting front' that eventually reaches the water table. Recharge only increases once this occurs, a delay determined by the change in percolation due to the change in surface vegetation and the soil physical properties of the unsaturated zone. Field studies have shown that the spatial distribution of percolation over larger areas is reasonably approximated by a log-normal distribution, which when combined with the wetting front model leads to a cumulative log-normal distribution of lag times between change of surface cover and the change in recharge (Figure 2). Where the spatial distribution of recharge is not being considered, the response time would be represented by a step-function. The difficulty in applying SIMRAT to irrigation areas in the Mallee is that this wetting front model does not represent unsaturated zones well, where there is a perched water table. Most irrigation districts in the Mallee have historically had perched water tables and many still do. Also, it had assumed default values for (1) irrigation accessions that represented overly high rates as a precautionary approach for salinity management; and (2) soil physical properties. When applied in this fashion, it cannot also represent irrigation efficiency improvements, as required to support salinity management. Finally, the model cannot represent irrigation decommissioning, increasingly important under the water reforms and associated water trades. The time lags associated with decommissioning can be decades (Walker et al., 2020b), thus delaying any salinity improvement in the River Murray.

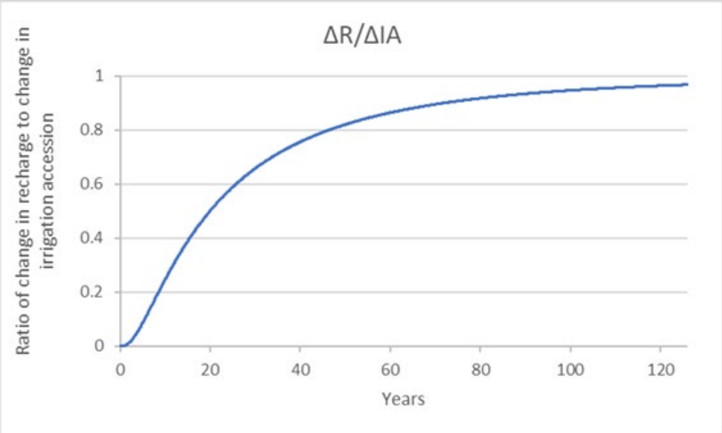



**Figure 2-2 A plot of a normalised recharge output from the SIMPACT model, displaying the properties of a cumulative log-normal probability distribution function of lag times associated with a step-function change in recharge.**

The relationship between the type of recharge module and the calibration approach needs to be considered. In a study of the Dehloran Plain, western Iran, Ehtiat (2016) compared three approaches for the calibration of a groundwater model, that corresponds to the IM, JC and FM approaches, each using different types of recharge models. In the first (autocalibration, Model 1), an IM approach is used for each recharge zone. In the second (empirical return coefficient method, Model 2), a JC approach is used to estimate the coefficients for recharge, when expressed as a linear combination of the three inputs (precipitation, groundwater abstraction for irrigation and groundwater abstraction for urban and industrial purposes). In the third, a distributed hydrological model, Soil and Water Assessment Tool (SWAT, Model 3) is used in FM mode. The three calibrated groundwater-recharge models were then tested in real future scenarios ('validation'). Although Model 1 performed the best in simulating water levels at observation wells in the calibration stage, it did not perform satisfactorily in real future scenarios. Model 3, with SWAT-based recharge rates, performed better than the other models in the validation stage. The study showed the interplay between the calibration approach, representation of physical processes in the recharge module, and the information content in the data used in the calibration of the recharge module. The SWAT model represented physical processes better and while not using groundwater data in its calibration, made good use of other data. The IM approach used nothing but groundwater data, while the JC approach used a very simple empirical recharge model that is easier to implement within JC.

This example shows that adding a recharge model to the inversion process without having data with more information content; or a model with adequate physical representation may not add much value. The consideration of data supports the third recommendation of Currie et al. (2017) that 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) and availability of relevant datasets so that the implications for predictions of a particular representation of the unsaturated zone by the modelling framework can be understood and documented and for the recharge module to be suitably calibrated.' The extension of Equation (1) for the land surface water model to include time lags or to allow the incorporation of $W_{eff}$ into the groundwater calibration, needs to consider the nature of the recharge model, as well as data, that is independent of those used directly in the groundwater calibration.

Previously, the term 'transfer function' has been used by the authors for the development of recharge modules that link irrigation accessions to recharge (e.g. Walker et al., 2020a,b). This term is used in analogy with other areas of science and engineering, where 'transfer function' is used to reflect the correlation between input and output signals from a process. For example, SIMRAT relates a step-change in irrigation accessions to a cumulative log-normally distributed change in recharge over time; that incorporates both an increase in recharge and dispersion of the signal. Irrigation accessions can be represented by a series of step-functions, where those where irrigation accessions increase can be represented by SIMRAT, and some where irrigation accessions decrease by other transfer functions. Through this process, the evolution of an irrigation district over time can lead to a complex array of recharge processes over time and space. This complex array will be dampened and lagged through the unsaturated zone (Cai et al., 1994; Prathapar et al., 1996; Walker et al., 2020b), and exacerbated by perched water tables, that have affected most irrigation areas in the Mallee. Perching can reduce recharge by causing discharge to drains; and the land surface, and increasing time lags. The consideration of irrigation accessions as an input time series and recharge as an output time series enables modellers to conceptualise the various hydrological processes, using a wider range of approaches.

In the scientific literature in this research domain, transfer functions have historically been defined even more narrowly to conceptual models that are fitted to water table fluctuations (e.g. Besbes, and de Marsily, G. ,1984; Morel-Seytoux, 1984; Gehrels et al., 1994, Wang et al., 2009, 2010; Mattern and Vanclooster, 2010; Wang et al., 2016, Collenteur et al., 2021) to represent the relationship of irrigation accessions, as input time series, and R as the output time series. This would be analogous to either the unit hydrograph or conceptual modelling in surface hydrology. The aim is not to physically represent processes, but to find functions that best emulate responses to changes in inputs. For example, a function representing the time lags as an exponential function of depth could be calibrated using fluctuations of water table, without fully representing the soil physical processes. The calibration of such functions is generally well-understood, with such functions providing better prediction, where the form of the function better represents the physical processes. In the Mallee, the regional groundwater systems evolve slowly in response to increased irrigation recharge, so there no water table fluctuations with which to calibrate these 'transfer functions'. The information content is not as great in the gradual rise and fall in the regional water table as it is in shallow water table areas. The inversion of groundwater data to calibrate recharge functions in areas of deeper water tables are likely to require a joint calibration with the groundwater model. As shown by model 2 in Ehtiat (2016), the joint calibration of a conceptual model that does not represent the physical processes well may not provide adequate predictive capability. Before beginning to calibrate any conceptual models using groundwater data, it is important to understand the physical process and the shape of the response function.

One of the best uses for physically-based parameterised models (e.g. Huo et al., 2014), is to provide insights into unsaturated zone processes; and to identify to identify most sensitive parameters (Alexander, et al., 2008). While there have been some efforts to provide regional soil datasets (independent of groundwater data) to calibrate these models (e.g. Cao et al., 2016, Wu et al., 2023), the routine use of complex physically-based models in a calibrated integrated recharge-groundwater model to predict outputs relevant to decision-making is limited due to the complex parameterisation in such a model to account for spatial heterogeneity of soils (both vertically and laterally); irrigation application; and vegetation responses. As shown by model 3 (SWAT) in Ehtiat (2016), physically based models can be used in FM mode, where there are appropriate datasets to calibrate the recharge module, such as surface water water gauging. Unfortunately, there is a paucity of streams in the Mallee The 1D LEACHM model has been used as part of an integrated model in SAM, albeit in a constrained fashion.

An important subset of physically-based models, for situations where time lags are important, is the kinematic wave approach (Sisson et al., 1980, Rossman et al., 2014, Wossenyeleh et al., 2019). These models simplify Richard's equation for soil water movement following the movement of wetting fronts and soil drainage. While simpler in nature than some of the numerical soil models, the critical parameters can still vary significantly. SIMRAT is an example of such a model, where the time lags are estimated using irrigation accession, in conjunction with several soil physical parameters, all of which are sensitive to soil properties, such as texture and organic matter. This implies a high predictive uncertainty for the time lags. However, it is feasible that for areas, where the SIMRAT model was appropriate that the time-lags could be inferred by the delay in groundwater response to new irrigation developments. These inferred time lags can relate to a wide range of different combinations of relevant soil parameters and irrigation accession, implying a lack of uniqueness in the recharge model. In such a case, it may be appropriate to use a simpler functional form for recharge that fits the physically-based model. By understanding the sensitivities to different soil and irrigation parameters, one may be able to calibrate a simpler model spatially and temporally using groundwater patterns in conjunction with known patterns in lithology, depth to water table and irrigation history. This means that there can be a correspondence between complex physically-based models and simpler conceptual models, provided that the conceptual model appropriately represent physical processes and the sensitivities are well-understood. Where this is the case, the simpler models may provide a more efficient and pragmatic approach.

Irrespective of whether a model is conceptual or physically based; lumped or distributed, the number of parameters that can be sensibly calibrated is related to the information content of the data. A more complex model will have more parameters, that may require a greater array of data to calibrate. Conversely, the physical processes may not be adequately represented by a too simple model. Such considerations are best analysed using sensitivity and uncertainty analyses. Conceptual models tend to be simpler in nature and their implementation has meant that uncertainty has been upfront; while the uncertainty analysis of complex numerical groundwater models have only been recently gaining traction (Peeters and Middlemis, 2023). This leads to the fourth recommendation of Currie et al. (2017) that a pilot uncertainty analysis that takes a whole-of-system approach be undertaken that covers the components of the district-scale water balance, recharge, groundwater flow and floodplain processes.

# Section 3 Development of transfer functions

## 3.1 Overview

This section describes the development of transfer functions that occurred during this research program. The main challenge is to provide transfer functions that can be represented at the spatial and temporal resolution of the regional modelling, yet have appropriate data with which to calibrate. The hydrological processes in irrigation areas can be very complex with a range of soils, drainage conditions and crop types. The approach taken was to first understand the processes and sensitivities, develop models that replicate these processes and then consider ways of simplifying these while retaining critical processes. Several phases of model development occurred, as follows:

1. **Discrete unsaturated zone transfer function models.** The initial set of transfer function models developed by this program focussed on simulating recharge as a transfer of an irrigation accession across an unsaturated zone to the regional water table. The models use semi-analytical functions to represent unsaturated zone transmission as occuring within discrete sub-units (spatially and temporally) that can be superimposed across an irrigation district over the required timescale. The models were coded into software, a typology was defined to guide their development and application and models were tested against FEFLOW benchmarking experiments. They have been linked to a groundwater model at Loxton-Bookpurnong to test their application within a JC framework (see Section 5). They are described in detail by Walker and Currie (2022).
2. **Use of approximants as conceptual models.** Walker et al. (2020a,b) explored the use of approximants (i.e. non-physically based functions) to further simplify the transfer functions and their parameterisation requirements.
3. **Lumped surface water balance model.** The testing of recharge modelling at the Sunraysia (EM) pilot trial (see Walker et al. 2023, Section 4) saw the development of a lumped recharge model based on the reformulation of the surface water balance.

The following sections present a brief description of these transfer function models and their capabilities and details can be found in the cited references.

## 3.2 Discrete unsaturated zone transfer function models

### 3.2.1 Framework and typology

The objective of transfer functions is to simulate the effect of various actions (irrigation development, efficiency improvements and decommissioning) on recharge to the regional water table over space and time. The use of a transfer function that link water supplied by diversions from the River Murray and rainfall to recharge to the regional groundwater systems. The initial research program represented the hydrological processes in a physically-based way. The irrigation areas were disaggregated into discrete sub-units (spatially and temporally) that could be superimposed across an irrigation district over the required timescale. For example, an irrigation district could be split up into recharge zones based on the underlying soil profile and irrigation development history, and then the effect of the various actions could be simulated based on the timing of the actions, to produce a time series of recharge to the regional water table.

In parallel, a typology was developed to distinguish the main types of unsaturated zone which occur in the Mallee. Four types of unsaturated zone were defined. Type 1 settings represent unperched situations. Type 2 settings represent a shallow regional water table under a perched water table. Type 3 settings represent a deep regional water table under a perched water table. Type 4 settings represent a deep regional water table under several perched systems. Transfer functions, specific to each Type of setting, were to be developed. The development of Type 4 models was deferred due to its complexity.

The typology provided structure to the development and testing of the transfer function recharge models. However, as the research program has progressed, it has become apparent that the concept is somewhat restrictive and does not need be maintained to guide recharge modelling. For example, testing of semi-analytical functions shows that profiles can switch between unperched (Type 1) and perched (Type 3) situations depending on the irrigation accession rate (see Section 3.2.4), while at Loxton there is evidence of Type 3 settings changing to Type 2 settings over time as the regional water table increases and starts to intersect drainage infrastructure (see Section 5). In such cases, which are not uncommon, maintaining the typology is restrictive and it need not be rigorously applied to transfer function development and application.

### 3.2.2 Irrigation development/wetting up

The UnperTy1_3 model was developed for modelling unperched irrigation situations overlying deep regional water tables (Type 1). This model is intended to update the pre-existing transfer function, SIMPACT/SIMRAT, used to estimate time lags for recharge following irrigation development; and overcome its limitations, especially its inability to simulate conditions of improved water use efficiency and irrigation decommisssioning (discussed in the next section). As discussed earlier, the application of such models to irrigation development, in the absence of perching, predict a step-function increase in recharge after a period of time. The time lag depends on a combination of parameters that together describe the ratio of the difference in the hydraulic permeability of the soil and the the difference in the volume of water in the soil profile for wet and dry conditions. In applying this to real field conditions, there is considerable predictive uncertainty in the time lag as this time lag is sensitive to soil parameters that can vary significantly both laterally and vertically. In practice, the time lag is calibrated using the groundwater response. Over the larger region, there is a distribution of soils and depths to water table which may lead to a smoother distribution of recharge. Models, such as SIMPACT and UnPerTy1_3 can produce spatial coverages of recharge at different times for input to groundwater models.

The comparison with the FEFLOW modelling showed that the kinematic wave assumption was adequate for representing time delays (see modelling experiments 1, 2 and 5 in Figure 3-3; for which the main parameters can be found in Table 3-1). To illustrate the responses to a step change in irrigation accession in a comparable fashion, a normalised transfer function is used, where this is defined as:

$$TF(t) = (R(t) - Ro)/(IA_n - IA_o), \qquad [3.1]$$

where $Ro$ is the initial recharge; $IA_n$ and $IA_o$ are the new and original accession rates respectively. For irrigation developments, $IA_o$ is the dryland recharge, usually insignificant compared to $IA_n$, assumed here to be 10 mm/year. When scaled in this way, the transfer function in the case of no drainage could be considered as a cumulative probability density function of time response for recharge.

**Table 3-1 Benchmarking experiments for 1D modelling of irrigation developments. Kvs2 is the vertical saturated hydraulic conductivity of the impeding layer and IA is the irrigation accession.**

| Model Experiment Number | $IA_n$ (mm/year) | $IA_n / K^v_{s2}$ |
|---|---|---|
| 1 | 100 | 0.30 |
| 2 | 100 | 0.75 |
| 3 | 100 | 1.50 |
| 4 | 100 | 4.00 |
| 5 | 400 | 0.75 |
| 6 | 400 | 1.50 |

The PerTy3 model was developed (Walker et al. 2020a,b) to generalise UnPerTy1_3 from just modelling recharge in unperched situations overlying deep water tables (Type1) to include perched situations (Type 3. ) . The conceptual model for this is shown in Figure 3-1. The top of the layer 1 is the level at which there is significant discharge to drains or the land surface. Walker et al. (2020a) show that there are several stages to the wetting up process, following irrigation development. These can can cause the different forms of the Transfer Function, as shown in Figure 3-1. Modelling experiments 3 and 6 situations with perching, but no discharge to the land surface or drains; and 4 where there is discharge to drains or the land surface. These different situations are reflected by the ratio $IA_n / K^v_{s2}$. Again, there is strong consistency between the semi-analytic PerTy3 and the numerical FEFLOW models, providing confidence in the ability to model these situations. The new equilibrium recharge is less than irrigation accessions (transfer function equilibrating to less than one) when discharge to drains or land surface occurs. The total recharge for two dimensional systems are very similar to the one-dimenional systems for the range of parameters tested. The main difference is some of the recharge occurs external to the irrigation field.

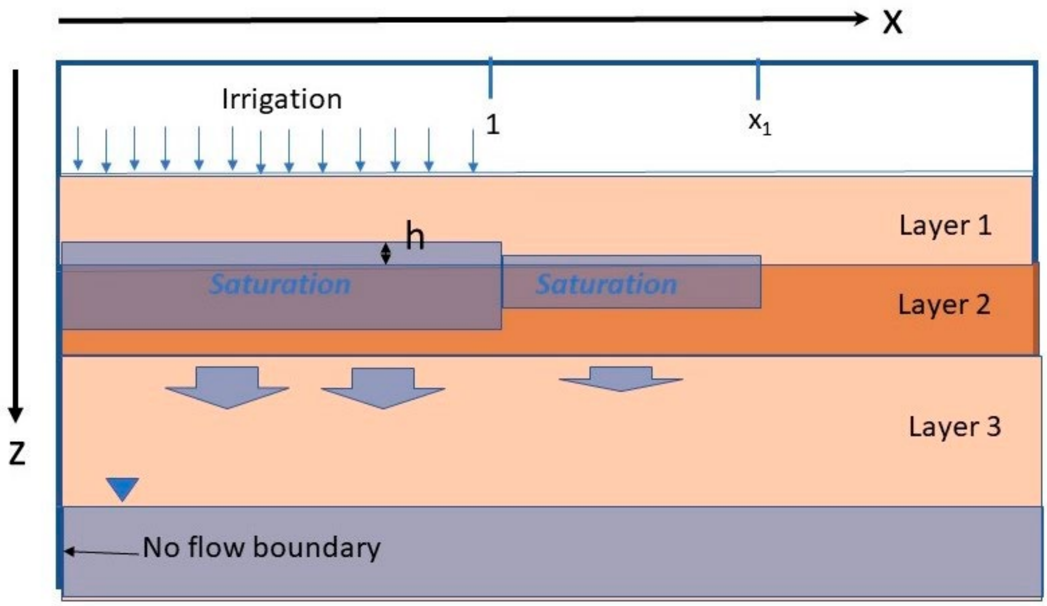



**Figure 3-1** **Conceptual model used to simulate recharge under perched water tables. The left-hand boundary is a no flow boundary, representing a line of symmetry. The variables are non-dimensionalised, with x = 1 being the outer limit of irrigation and x = x1 being the outer limit of perched water. Below layer 3 is the saturated zone of the aquifer.**

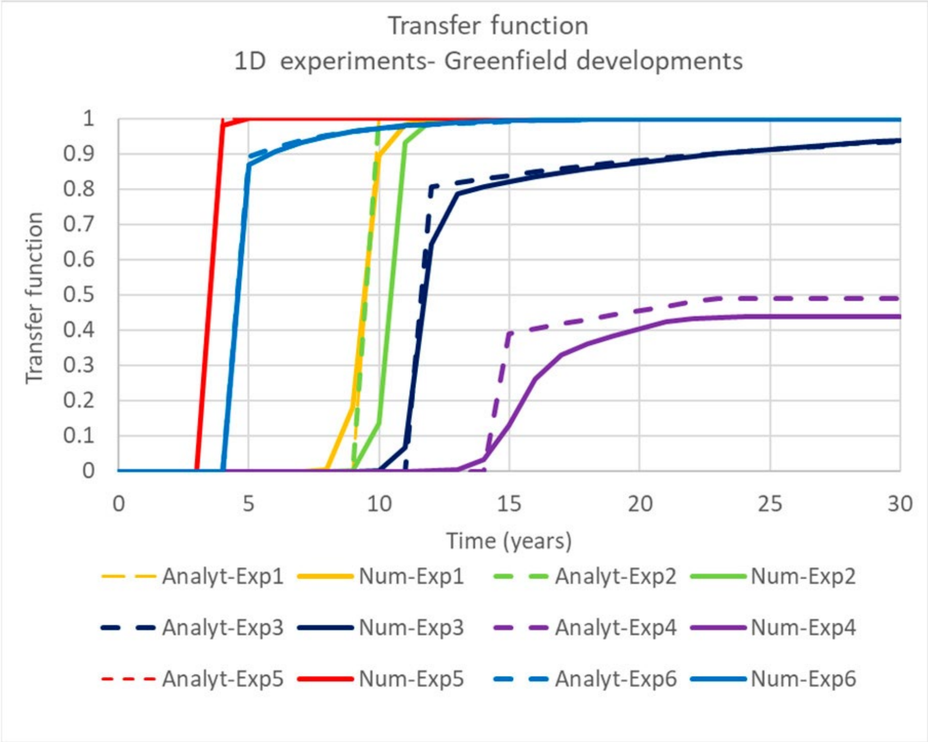



**Figure 3-2** Outputs from one-dimensional outputs from PerTy3 (semi-analytical) (dashed) and FEFLOW (numerical) (solid) models (for transfer functions for modelling experiments with reducing vertical conductivity of the clay layer. Experiments 1, 2 and 5 are situations without perching, 3 and 6 have perched water tables, but no discharge to drains and land surface, while Experiment 4 represents a situation with discharge to drains or land surface. The y-axis represents the ratio of change in recharge to change in irrigation accessions (including drainage).

### 3.2.3 Efficiency improvements / drying

To generalise UnPerTy1_3 to incorporate irrigation efficiency improvements and irrigation decommissioning for unperched soils, a kinematic wave approach was also used to determine time lags for drying soils. Such time lags have generally not been included in modelling to date, especially since the most significant of these, irrigation decommissioning has not occurred. The small level of decommissioning to date has meant that there has not been a priority to change the current practice of ignoring such time lags. Pressure changes for a drying soil do not lead to a sudden increase in recharge, as for wetting soils, but progressively slower reductions of recharge as the soil column dries, up to 1-2 decades. The time lags are much more significant for irrigation decommissioning than for smaller changes in irrigation because the changes in the volumes of water in the soil column are much smaller. A major rehabilitation program may also cause a significant delay. Walker et al. (2020b) describes the generalisation to include perched groundwater systems (PerTy3).

**Table 3-2 2D modelling experiments with water use efficiency improvements.**

| Model Experiment Number | $IA_{o,n}$ (mm/year) | $IA_n / K^v_{s2}$ |
|---|---|---|
| 7 | 230 to 100 | 2.1 to 0.91 |
| 8 | 100 to 50 | 0.91 to 0.45 |
| 9 | 230 to150 (0y) to 100 (5y) to 50 (10y) | 2.1 to 1.36 to 0.91 to 0.45. |
| 10a | 10 to 230 (1996) | 0.09 to 2.1 |
| 10b | 10 to 230 (1921) to 150 (2001) to 100 (2006) to 50 (2011) | 2.1 to 1.36 to 0.91 to 0.45 |
| 10c | 10 to 230 (1996) to 150 (2001) to 100 (2006) to 50 (2011) | 0.09 to 2.1 to 1.36 to 0.91 to 0.45 |
| 10d | Superposition of 10a and 10b | |

Figure 3-3 shows the resulting normalised transfer functions for experiments described in Table 3-2. Experiment 7 represents the change from an equilibrium perched situation to another perched situation; Experiment 8 the change from an equilibrium situation with no perching to another with no perching, while Experiment 9 the change from an equilibrium situation with perching to another without perching. The parameters used are those relevant for the Mallee region. The results show that lag times can be significant. The comparison between the semi-analytical model is not as good as with the wetting situations, but still adequate.

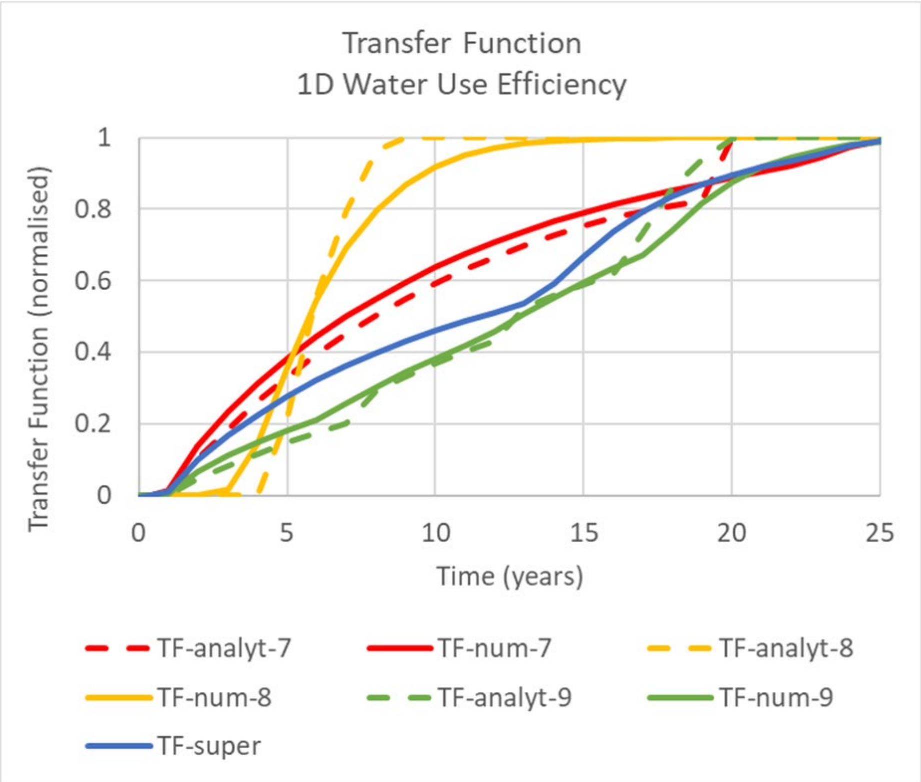



**Figure 3-3 The 1D modelling outputs for Experiments 7 (red), 8 (yellow) and 9 (green). (a) Transfer function (TF). Solid lines indicate FEFLOW (numerical) outputs, while dashed line shows PerTy3 (semi-analytic) outputs. The superposition for the transfer function (Experiment 9) is denoted blue line (super). The y-axis is the negative of the change on recharge to the change in irrigation accession. Experiment 7 represents the change form an equilibrium situation with perching to another situation with perching; Experiment 8 represents the change from an equilibrium situation without perching to another without perching; Experiment 9 the change from a perched situation to an unperched situation.**

### 3.2.3 Assumption of superposition

Irrigation areas are complex spatially and temporally. There are always changes made in terms of new irrigation developments, water use efficiency measures and decommissioning processes. The transfer functions that have been described above have been developed and tested for one action on an irrigation field. To be practical, there is a need to be able to aggregate these for the more real-world situations. The most likely approach is that of superposition, which invokes linearity, so that the recharge for a series of events and irrigation fields is the sum of the recharge for individual events and fields. This drastically simplifies the situation. Unfortunately, the presence of perched water tables is innately a nonlinear process potentially affecting interactions between fields and events. However, testing has shown that within reasonable constraints, the recharge from neighbouring fields is the sum of the recharge from individual fields. Similarly, testing on events, such as that in Figure 3-5 has shown that superposition of different actions is also reasonable within constraints of testing. Superposition vastly simplifies the analysis for irrigation districts.

The numerical testing shows that there is a lack of significant lateral movement over clay layers between irrigation areas; and where there is overlap, superposition appears to be a reasonable approximation. This then allows normal spatial aggregation to be applied leading to the definition of recharge zones, based on soils, irrigation history, drainage, etc; and the aggregation of recharge for these zones. For each recharge zone, a recharge model can be applied to generate recharge for the groundwater model, similar to what occurs now with most groundwater models. The Loxton example described in a later section illustrates how this can happen in practice.

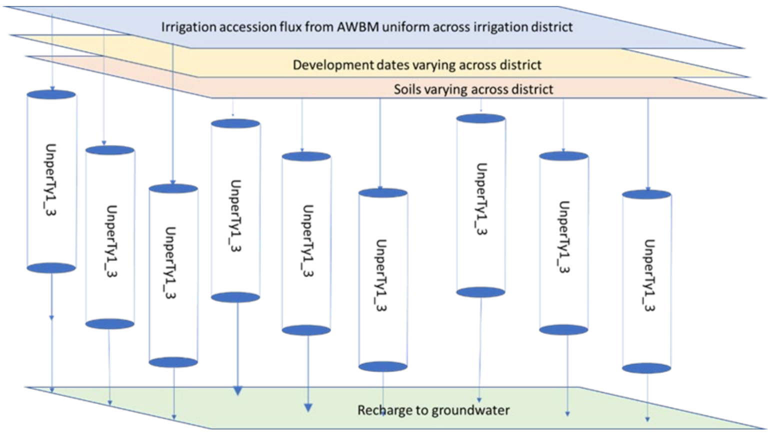



**Figure 3-4 Conceptual diagram showing the spatial interplay of irrigation accession, date of irrigation development and soil properties affecting the vertical movement of hydraulic fluxes, as represented by UnperTy1_3, affecting the spatial and temporal pattern of recharge. UnperTy1_3 applies to several sub-areas across the irrigation district.**

Figure 3-5 for the modelling experiment 10 shows how temporal superposition can work. These figures show the modelled response to a new development and for subsequent water use efficiency improvements both in isolation and combined. In Figure 3-6, the superposition (solid red) resembles the modelled output (red dashed) from PerTy3. The resultant pattern is a smoothed and delayed version of the irrigation accession (shown in blue). Irrigation accession is the input to the model and reflects initially the pre-irrigation conditions, then the irrigation history from 1976 to 2010 and then the assumed final irrigation accession of 50 mm/year from 2010 onwards. The yellow line represents the transfer function for the wetting, while the green is the transfer function for the drying. The peak of the recharge is less than that for irrigation accession and lagged. Mathematically, superposition implies that the aggregate transfer function for a sequence of actions that affect irrigation accession is given by:

$$TF(t) = (\sum_j (IA_{j+1} - IA_j)\, TF_{j+1})/(IA_{p+1} - IA_0) \qquad [3\text{-}2]$$

where $IA_j$ is a sequence of irrigation accessions that occur from $j = 0$ to $j = p + 1$ and $TF_{j+1}$ is the transfer function that applies for a change of irrigation accession from $IA_j$ to $IA_{j+1}$. This equation needs to be modified where the ponded head causes drainage or evapotranspiration to the land surface (Walker et al., 2020b).

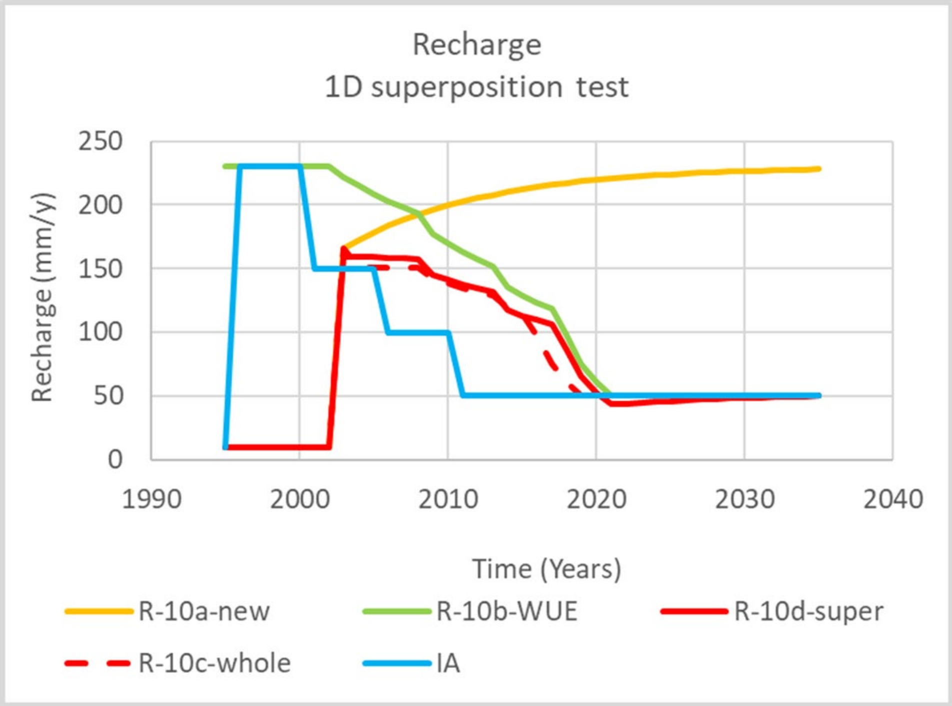



**Figure 3-5 PerTy3 modelling output for Experiment (1D): 10a new development (new, orange line);10b water use efficiency (WUE, green line); 10c (whole sequence of new development and water use efficiency (whole, dashed red line); Experiment 10d recharge for superposition of 10a and 10c transfer functions (super, red solid line); Irrigation accession for Experiment 10c (1D) blue line.**

Superposition vastly simplifies the analysis for irrigation districts. One of the problems for the Loxton study described in the next section was that superposition had not been trialled at the time of the pilot study and this led to overflow of vectors in the recharge module. This required much reprogramming of the transfer functions so they would be more robust under the calibration process. The over-runs were due to keeping track of the various pressure fronts, which tended to merge during wetting, and diverged during drying. While superposition can lead to 'wrinkles' in the recharge time series, these should not cause any problems for the groundwater modelling. As superposition implies that any transfer function is not dependent on earlier 'event', it allows transfer functions to be calculated for different soil types, ahead of collating the recharge time series. As part of the calibration process, soil parameters may need to be change and hence transfer functions would then need to be revised.

However, in using superposition, it is still important to note there are important nonlinear processes. It is necessary to keep account of the irrigation accession at any given time and compare with two thresholds, that necessary for perching and that necessary for drainage or discharge to the land surface. The type of transfer function changes as the system goes from not being perched to being perched or vice versa. Also, the transfer function is zero for situations where there is discharge to the land surface. In modelling the systems at a fine resolution, any additional irrigation accession above the threshold will be removed by drainage or discharge to the land surface rather than form additional recharge. This situation changes in the lumped district-scale modelling described in the next section.

The process is further simplified by noting that apart from major changes in irrigation accessions, such as irrigation development, major rehabilitation and irrigation decommissioning, time lags for pressure fronts to move to the water table from the land surface in unperched situations or from the impeding layer in perched situations can be ignored. This means that the transfer functions for small changes in irrigation accessions for unperched situations can be approximated as step-functions with zero time lags; and in the case of perched situations as exponential functions.

### 3.2.4 Phasing between perched and non-perched situations

The sensitivities of recharge across the irrigation lifecycle is an important input to the calibration process. Figure 3-6 shows the impact of the vertical conductivity of the clay layer on recharge for decreasing values of $K^{v}_{s2}$. A small value for hydraulic conductivity leads to a reduction in the peak of recharge and increasing lag times. Our studies suggest that this is the most sensitive parameter for determining recharge as a time series when perching occurs. A second parameter, B, which reflects the ratio of lateral movement of water above the clay to the vertical movement of water through the clay has an influence on perching and the transition to some water returning to the land surface. Figure 3-* shows how reducing values of $K^{v}_{2s}$ leads to a lagged and smoothed response to irirgation accession.

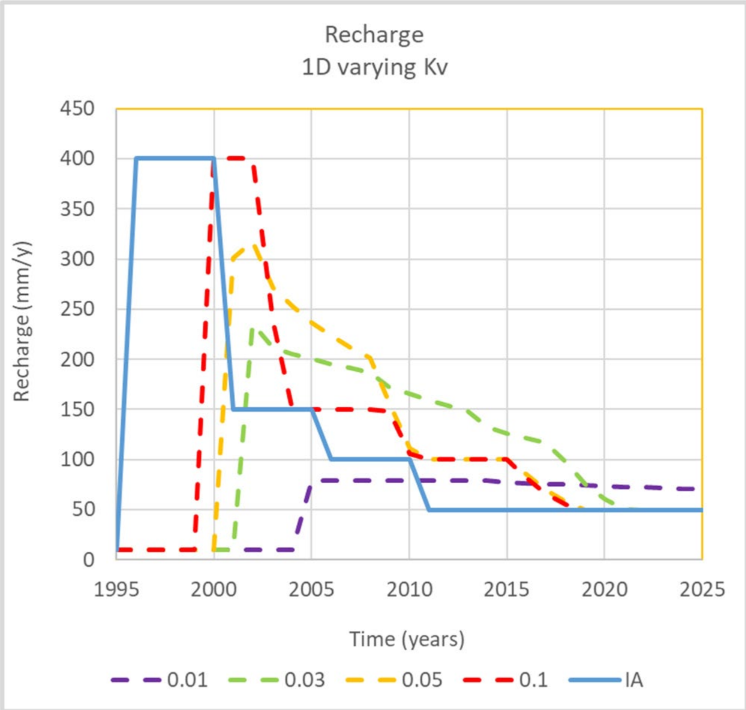



**Figure 3-6 Figure 10. Plots of recharge with time for irrigation systems with different values of $K^{v}_{2s}$ (a) 0.01 (b) 0.03 (c) 0.05 and (d) 0.1 cm/day in response to a sequence of irrigation actions**

## 3.3 Use of approximants

The above section highlighted three simplifications to the use of transfer functions, namely:

- Spatial superposition, allowing normal spatial aggregation of recharge zones,
- Temporal superposition of transfer functions,
- Ignoring time lags associated with movement of pressure fronts below the impeding layers for changes in irrigation accessions due to processes other than irrigation developments, decommissioning or major irrigation rehabilitation. This leads to step-functions

This section introduces one further potential simplification, namely the use of a simple conceptual models, as described in section 2 (e.g. Morel-Seytoux, 1984; Besbes and De Marsily, G., 1984). If approximations to both the semi-analytic functions and numerical equivalents can be developed and found suitable, this would reduce reliance on the current code and potentially provide efficiency in numerical runs.

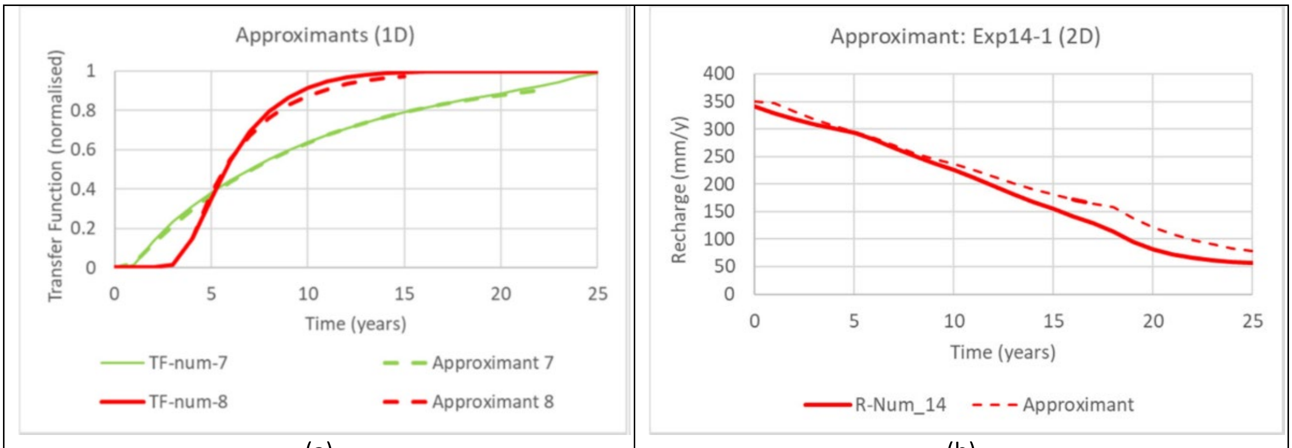
For unperched situations, the transfer functions takes a simple form as an initial step-function increase in recharge after a timelag with subsequent transfer functions being step-functions with no time lags corresponding to changes in irrigation accessions. For perched situations, the exponential function unsurprisingly fitted the transfer function for irrigation development well, allowing for the time lag. Subsequent transfer functions are exponential functions (1-

exp(-λt))with the same decay constant (λ) corresponding to changes in irrigation accessions. Hence, λ becomes an important parameter which is relevant for the entire time the system is perched and hence a suitable candidate for calibration. An exponential moving average (EMA) filter can be used with Equation [3-2] to quantify the recharge time series.

Two threshold parameters mentioned earlier were 1) the irrigation accession required for perching to occur, and indicated by the ratio A of IA to $K^{v}_{2s}$; and 2) the irrigation accession for which drainage and/or discharge to the land surface occurs, as also indicated by A; another non-dimensional parameter B which indicates the degree of lateral movement and the thickness of the top layer relating to that of the impeding layer. For the first situation, perching occurs where there is insufficent vertical conductivity to transmit the irrigation accession. The ponded head above the impeding layer allows more water to be transmitted because of an increased vertical hydraulic gradient and because of lateral water movement, a larger area of infiltration through the clay layer. B indicates the balance between these two processes. Th height of the ponded head is limited by the thickness of the top layer, when drainage or discharge to the land surface begins. These two thresholds may be observed, when relevant, through direct field observations. Where no perching occurs, the recharge is limited by the irrigation accession (and hence $W_{eff}$). Where drainage occurs, recharge is limited by the hydraulic conductivity of the clay layer. In between, the equilibrium recharge is dependent on IA, but time lags will become increasingly dependent on the hydraulic conductivity. In reality, the ponded head can exceed the height of the drain or the minimum height at which discharge to the land surface occurs, especially where the topography of the surface, impeding layer or drainage network is not flat, and distance beteen drains becomes greater. This is more evident for the lumped modelling described later.

Apart from λ, three further parameters are evident in approximating the transfer function for irrigation development; namely 1) threshold flux when a portion of flux returns to the land surface through drainage or evapotranspiration; 2) time delay (years) before recharge can occur; and 3) the value of the transfer function when recharge begins. The fit to the drying transfer function is seen in Figure 3-8b to be adequate. While perching still exists, the same decay constant is used, but then changes, as clay layer and lower soil layer begins to drain. This suggests another parameter, the decay constant, μ, for soil drainage.Three of the five parameters are either of the initial development or final decommissioning of each irrigation field, while two are on-going for the perched lifecycle; one of which is associated with drainage and the other, the return to the land surface.

Each of these five parameters are variably related to $W_{eff}(t)$), $K^{v}_{s2}$;$K^{h}_{s1}$, and other soil parameters or ratios of these. Ratios include A, of IA to $K^{v}_{s2}$ ; and B (which relates ability of water to move laterally across top of impeding layer relative to vertical movement through the impeding layer). Rather than use the full transfer functions, modellers have the ability to fit the five parameters, independently of the knowledge of soil physics and science of perching; or to use this knowledge to suitably constrain these parameters. The recharge will be relatively insensitive to $W_{eff}$, when water is being returned to the land surface; and sensitive otherwise. This means that IA may be inferred from drainage volumes for higher IA fluxes; and recharge at lower fluxes. The two parameters related to irrigation development are sensitive to IA and $W_{eff}$ at the time (see Figure 3-3) with lower IA being associated with longer lag times. The other three parameters are relatively insensitive to IA and sensitive to soil parameters. More work is required in relating the calibration parameters to irrigation and soil parameters, such as $K^{v}_{s2}$.




(a) (b)

**Figure 3-7 (a) Fitted approximants for 1D FEFLOW (numerical) transfer functions for modelling experiments (7) and (8) ; (b) Superposition of a succession of fitted approximants (a) to reductions of irrigation accession from 350 to 200, 200 to 150 (5 years later), 150 to 100 (5 years later) and 100 to 50 (5 years later) and compared to FEFLOW (Numerical) output for 2D modelling Experiment 14-1**

## 3.4 Lumped surface water balance model (DWR method)

The Sunraysia (EM) pilot trial (described in section 5) was initiated to test the application of transfer functions within a JC modelling approach in the Eastern Mallee (EM) region of NSW and Victoria (Walker et al. 2023). Early in the pilot trial, it became apparent that the conceptualisation of drainage processes within the discrete unsaturated zone transfer function models was inconsistent with the observed drainage trends at Sunraysia. Under the discrete modelling approach, drain flows occur as 'rejected recharge' when the top layer of the transfer function model becomes fully saturated. Thus, when drainage is being simulated, the recharge reaches a maximum rate because perched head is at a maximum; and will remain constant until the drain flows completely subside. However, the data at Sunraysia (groundwater levels and drain flows declining at the same time), implied that recharge and drainage were proportional with both processes being driven by the head of the perched water table. An alternative approach was required.

While various approaches could have been used to overcome these limitations (including a revision of the to discrete modelling approach), the approach taken involved reformulating the surface agronomic water balance (AWB) with the inclusion of unsaturated zone processes. Conceptually, this amalgamated AWB-TF model represents a water balance of the perched water table system. It is based on a coarse spatial and temporal resolution, but allows complexity to be added, or resolution to be changed, as required. In the Sunraysia pilot trial it was applied at an irrigation-district scale as a lumped surface water balance model. It is described further in Section 4, where it is termed the DWR (Drainage $W_{eff}$ Relationships) method, as it relies on drainage data, D, which becomes a surrogate variable for the state of the hydrological condition of the unsaturated zone.

While it is not technically a transfer function, the modified surface water balance forms a 'lumped' recharge model that incorporates unsaturated processes and provides a link between irrigation actions and regional groundwater model. It thus fulfils the transfer function requirements that were established at the outset of the research program.

## 3.5 Further development of transfer functions

Several lines of development could be pursued to further develop the transfer function and recharge models described.

### 3.5.1 Refinements to discrete modelling approaches

*Treatment of drainage*

As outlined, there is an inconsistency in how drainage is treated between the lumped and discete recharge modelling approaches. In the lumped approach, the ponded head between drains under higher topography, is assumed to be higher than the base level of the drains or that required to discharge to the land surface. In the discrete approach, the ponded head is bounded by the base level of the drains or that which requires discharge to the land surface. This results from the difference in scale between the two approaches.

At the larger scale of the lumped approach, the topography of the land surface, top of the clay layer and the drainage system become more important. The nominal ponded head (of the perched water table) is conceptualised as an average across the irrigation district above the drain level.

The discrete approach is readily adapted to allow higher ponded heads and better represent drainage processes. However, the implementation requires knowledge of the proximity of the recharge zone to the drains and caissons. With such refinements, it is probable that the problems inherent in the JC approach at Loxton-Bookpurnong (see Section 5) could be avoided.

*Simulating the influence of shallow regional water tables*

The discrete modelling is also readily adapted for the situation of shallow regional groundwater levels, including groundwater interception. The challenge is providing the groundwater levels as input to the recharge model. As in the case of the SA irrigation districts, this could come from historical groundwater modelling, while in topographically low areas, where shallow water tables persist, there would be a need to link, through scripting, the recharge models with the groundwater model outputs.

### 3.5.2 Refinements to lumped modelling approaches

*Simulating deep water tables*

The use of lag times can be incorporated into the district scale lumped models by 1) keeping a register of newly-developed irrigation districts and 2) convoluting the lag time response functions with the history of irrigation development and decommissioning for each irrigation district. The lag times appeared to be less important than for the SA districts, but there are indications of these during phases of major changes at Sunraysia.

### 3.5.3 Consideration of scale

If the lumped model at the resolution of the irrigation district and the fine resolution of the discrete recharge zones within the Loxton irirgation district represent endpoints, an intermediate resolution at the sub-district scale, based around soils and drainage systems, should be explored.

## 3.6 Summary

The understanding and modelling of unsaturated zone models for irrigation areas with underlying perching has been significantly improved with these studies, but falls short of a recipe book for all situations. Most notably,

1. UnperTy1_3 model has been developed to replace SIMPACT for non-perched areas; but avoids the use of default parameters and incorporates representation of decommissioning and major rehabilitation processes;

2. The physics, scaling and modelling of perched water tables have been included within the PerTy3 model, which can model both perched and non-perched systems,
3. Superpositon of recharge changes under different irrigation fields have been demonstrated justifying the use of vertical recharge zones;
4. Superposition of recharge changes due to different events e.g. new developments, decommissioning, water use efficiency developments have been demonstrated, allowing simplification of the modelling of the lifecycle of an irrigation district. It also allows the development of a set of transfer functions prior to each model run, allowing superposition to simplify the runs;
5. Approximants to transfer functions have been developed, potentially allowing a simpler calibration process, not unlike those used in surface hydrology;
6. The similarity between recharge under areas with significant lateral movement over the clay layer and that under areas with limited lateral movement has been demonstrated for the range of parameters explored, simplifying the simulation of irrigation districts through the use of recharge zones;
7. The sensitivity to the vertical hydraulic conductivity of the clay layer, the horizontal hydraulic conductivity of the overlying layer and the thickness of the various layers has been explored, provding a knowledge base for calibration;
8. Implementation of the full transfer functions within the Loxton-Bookpurnong district has been demonstrated.

Aspects for further development and testing include:

1. Implementation and calibration of transfer functions using the superposition of events within an irrigation district;
2. Implementation and calibration of simple conceptual models for an irrigation district. This and the previous dotpoint should be easier than the use of the full transfer function;
3. Implementation of lag times within the irrigation district-scale lumped recharge models;
4. Allow the ponded head to be higher than the discharge height for drains and the land surface within the discrete transfer function; and
5. Development of a sub-district recharge module.

# Section 4 Lumped surface water balance modelling

## 4.1 Overview

This section describes a pilot trial of the transfer function approach in the Eastern Mallee (EM) at Sunraysia (Walker et al. 2023) in which:

- The surface water balance was reformulated as a lumped recharge model for the existing salinity register model (the Eastern Mallee groundwater model, EM2.6) to allow JC in an area where time lags have not generally been incorporated.
- A JC process was applied using this recharge module and EM2.6.

The irrigation districts for EM are shown in Figure 4-1.

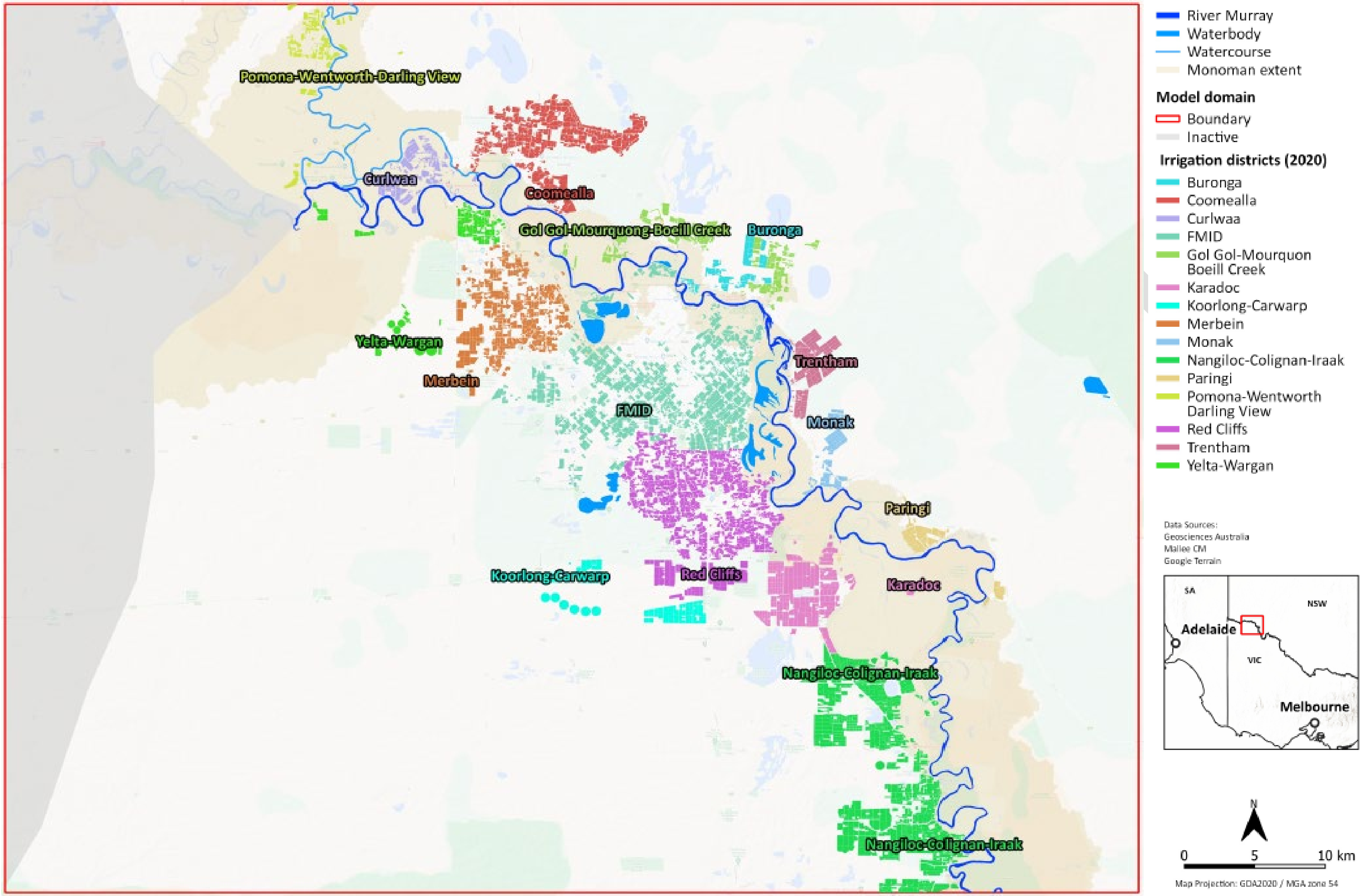



**Figure 4-1 Map of Sunraysia irrigation districts and EMv2.6 groundwater model domain (CDM Smith 2022)**

## 4.2 Previous approaches to recharge modelling in the Eastern Mallee

Equation (1) represents mean annual fluxes and variables for each irrigation district. If it is to be used within a JC, only one variable, $W_{eff}$, can be adjusted as part of the calibration, as others are monitored. There have been three previous approaches to modelling the EM region:

1. WA ($W_{eff}$ assignment): a FM approach using the a priori estimates of a field water use efficiency, $W_f$ and channel loss factors that lump together to form $W_{eff}$ (Aquaterra, 2009). The value of $W_{eff}$ is applied across the whole irrigation district; and variations in monitoring of D reflect the differences in soils and drainage management. D' is not explicitly included and but could be implicitly included as a higher value for $W_{eff}$ for districts where there is perched water, but not an established drainage system.
2. RS (Recharge Scaling): A JC approach, where the recharge that is output from the simple water balance model is simply scaled with the scaling parameter calibrated (Jacobs, 2019) has been used to address any issues of bias. The scaling factor (α) is constrained to between 0.8 and 1.2. Through Equation (1), an adjustment of R through scaling implies a simple adjustment of $W_{eff}$ by (α-1)*R/TWA. Such scaling is still consistent with the scaling of R, K and S. While it allows changing recharge values, there will still be a tendency for non-unique solutions. D' has been implicitly included in values of $W_f$.
3. WF ($W_{eff}$ Fitting): A JC approach, where the normal field efficiency factor, $W_f$ is assumed to be of a particular a functional form with four parameters, which are then calibrated (CDM Smith, 2022). The logistic function (also known as the S-shaped curve) is represented by:

   $$W_f(t) = (W_f^{late} - W_f^{early}) / (1 + exp(-\gamma * (t - t_{mid}))) + W_f^{early} \quad (4\text{-}1)$$

   where is the time in years, $W_f^{late}$, $W_f^{early}$ respectively are for late and early values for $W_f$, γ is a variable that controls the shape of the rising trend, and $t_{mid}$ is the year at the midpoint of the rising trend. This loses any local knowledge built into the a priori estimates of $W_f$. Unfortunately, the calibrated function has sometimes been found to be insufficiently close to the true functional form of $W_f$; leading to negative values of recharge or increase in recharge over time. Such forms are inconsistent with our physical understanding of what should occur under increasing water use efficiency. As discussed in previous section, R can be very sensitive to values of $W_{eff}$ and hence $W_f$. D' has been implicitly included in values of $W_f$.

In the above, $W_{eff}$ and $W_f$ are related by the following equations:

$$TWA = SWD * (1 - L * (1-RF))/A + P \quad (4\text{-}2)$$

$$W_{eff} = ET / TWA \quad (4\text{-}3)$$

$$W_f = (ET - SWD * L * (1-RF)) / (SWD * (1-L)/A + P) \quad (4\text{-}4)$$

where SWD is the annual surface water diversion; L is the proportion of SWD that is not delivered to irrigation fields because of channel losses; RF is the proportion of L*SWD, that percolates deep into the soil; A is the irrigation area; and ET is the evapotranspiration flux from the irrigation district.

In most models in the EM region, D' has been lumped as part of ET and $W_{eff}$. It has been explicitly included in Equation (1), as this process appears to be a significant process in those areas of the Mallee, which do not have sub-surface drainage and perched water discharges to low-lying parts of the land surface (Figure 4-2).

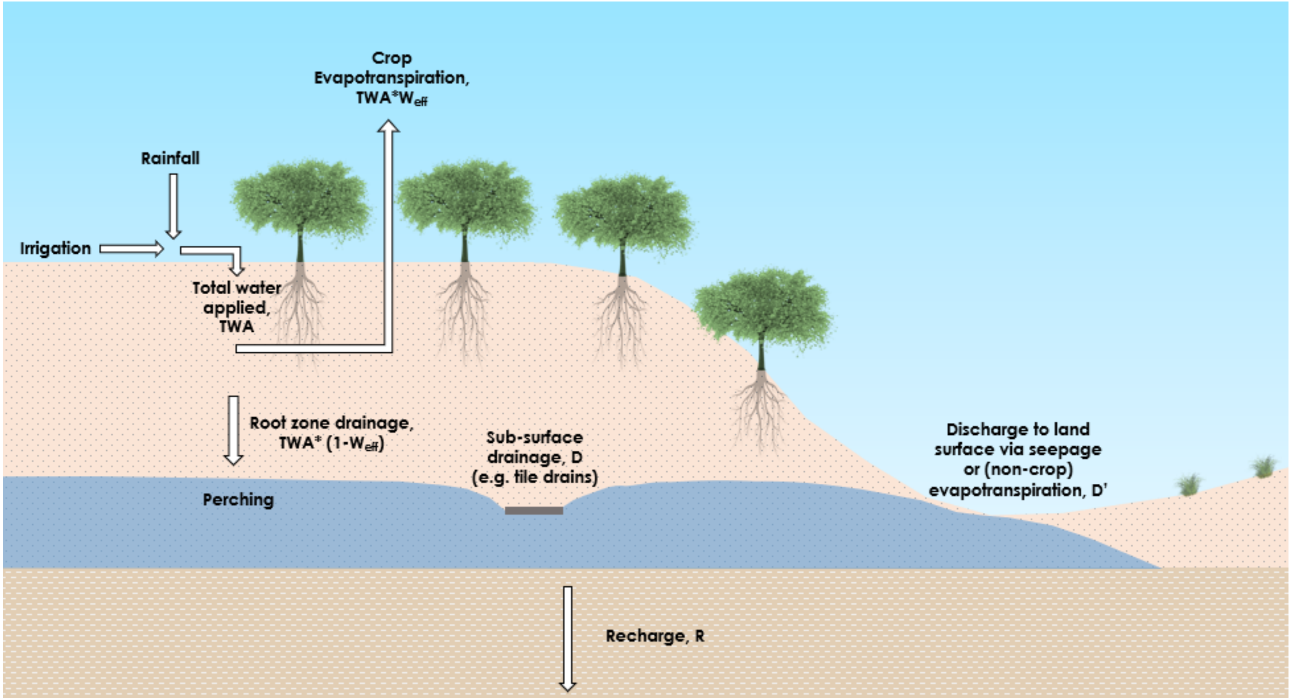



**Figure 4-2 Conceptual model of an irrigation area within Victorian EM, in which the components of Equation 1 are illustrated.**

## 4.3 Water use and drainage data

Before considering further approaches, we first review the spatial and temporal patterns of two of the main non-hydrogeological datasets that have been collated for the area; namely water availability (TWA) and drainage (D) across irrigation districts (CDM Smith, 2022). Figure 4-5 shows that similar time series for 1/TWA across irrigation districts of EM, irrespective of differences in soils and crop type, with one exception (Karadoc). Figure 4-4 (a) shows the time series for D/TWA across the irrigation districts of EM, which suggests that there is a natural division of irrigation districts into 3 categories. The first includes the Victorian districts, for which drainage remains a significant proportion of TWA over 50 years. The second includes the more established NSW irrigation districts for which drainage is initially significant and then declines to almost nothing. The third category are those districts, mostly smaller NSW districts for which there is none or little reported drainage. The Victorian irrigation districts are currently reporting greater drainage volumes than NSW. The variable 1 - $W_{eff}$ under irrigation districts is a linear function of these two variables, one which is increasing over time; and one which is decreasing over time, with the latter mostly dominating.

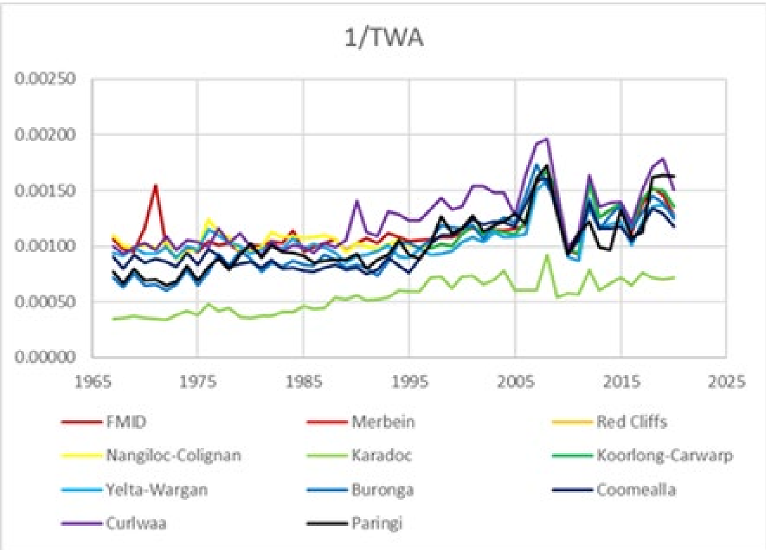



**Figure 4-3 Inverse of Total Water Availability for different irrigation districts.**

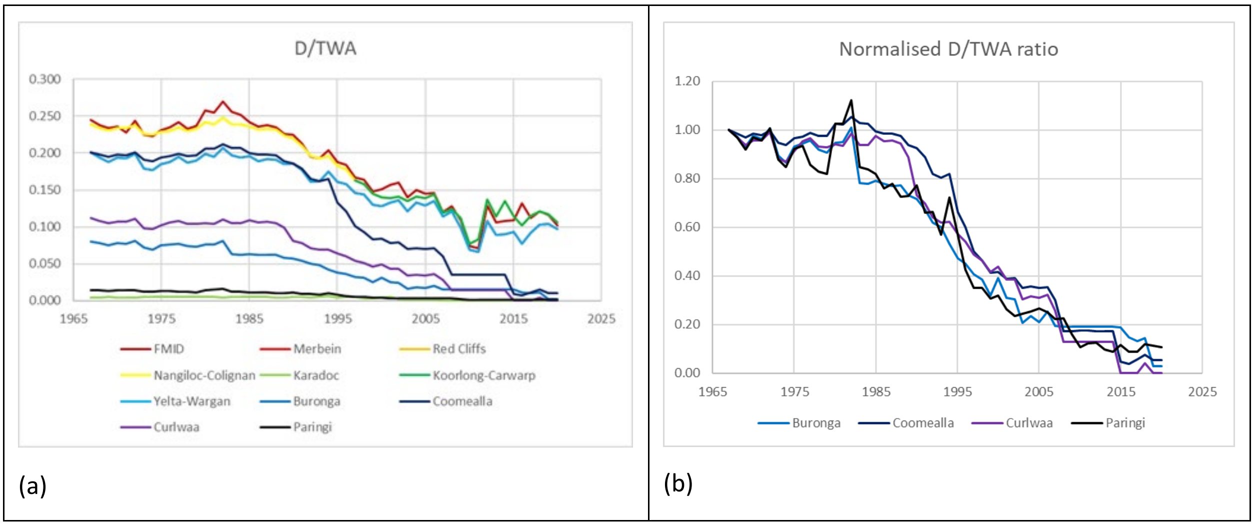



**Figure 4-4 (a) The ratio of drainage volumes to total water availability for all irrigation districts and (b) The ratio of D to TWA for districts of group 2 normalised with respect to initial value.**

Drainage will occur where there is perching on either the Blanchetown or Coonambidgal Clay, with some established irrigation districts having a proportion of both units (see Figure 4-5). Coonambidgal Clay forms as part of the floodplain of the River Murray, while the Blanchetown Clay, is a remnant of an ancient lake, which can be found away from the river, generally on higher ground. An absence of reported drainage could be due to 1) lack of sub-surface drainage infrastructure, with perched water discharging to the surface in lower areas; 2) an absence of perching due to permeable soils allowing percolation to the regional water table; or 3) lack of reporting. Figure 4-4(b) shows that for the more established NSW irrigation districts, the rate of decline of drainage to TWA ratio is similar across all units, indicating a similar process for this decline. The relative irrigation areas of these three types of drainage patterns are approximately 70% for the Victorian districts, 20% for the more established NSW districts and 10% for the remaining areas respectively.

These general trends in EM, when considered with Equation (1), indicate that:

- $W_{eff}$ is similar across irrigation districts,
- The different patterns of D and D' reflect differences in soils, drainage management and reporting across irrigation districts, but can be categorised into three groups;
- Recharge is limited by,
  - the hydraulic properties of underlying clay layers in perched areas and
  - the water use efficiency of irrigation practices in unperched areas.
- Slight differences in (1 -$W_{eff}$) in Equation (1) can cause large differences in R, where D forms a large proportion of TWA (D/TWA>0.1),
- There is little information on regional patterns of water use ($W_{eff}$) over decades to the precision required to avoid bias or recharge sensitivity.

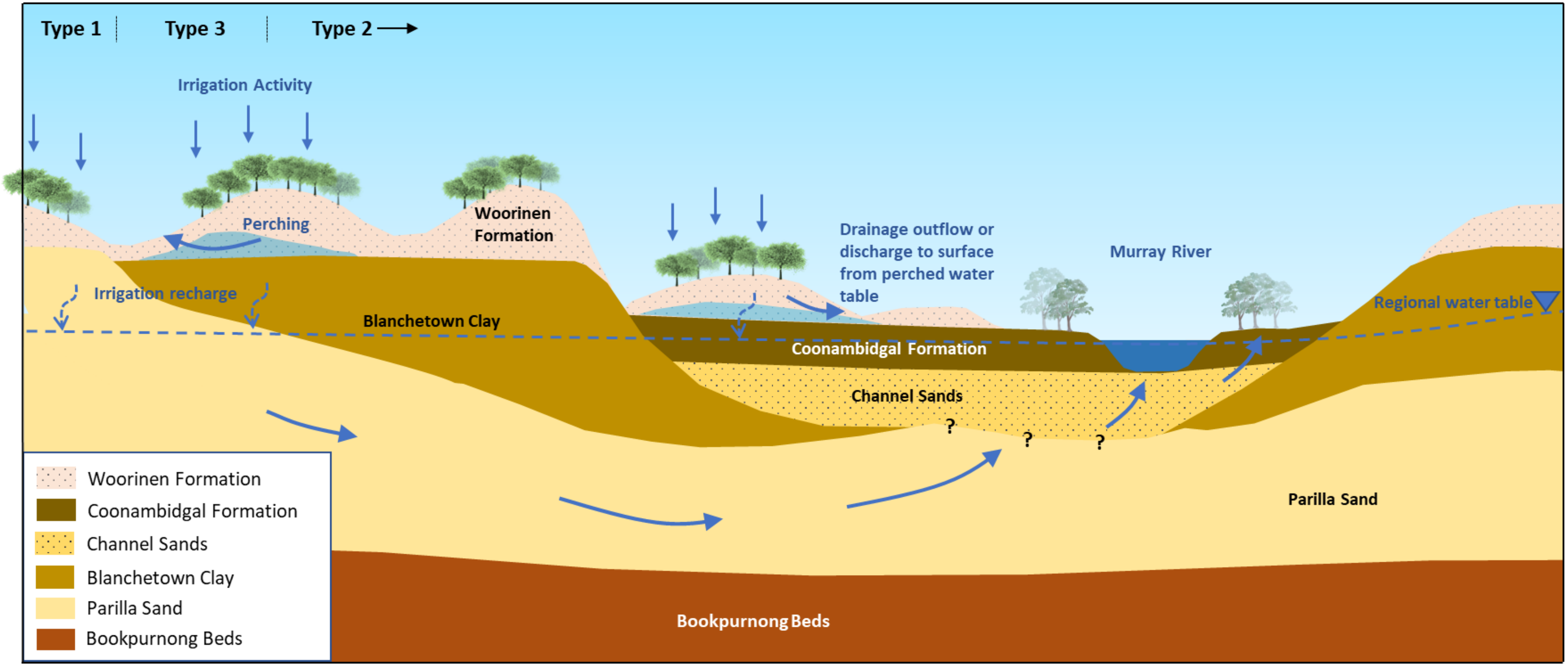



**Figure 4-5 Conceptual hydrogeological model for the Sunraysia region**

## 4.4 Lumped surface water balance model

A fourth approach for estimating recharge at Sunraysia (EM), termed DWR (Drainage $W_{eff}$ Relationships), was devised by Walker et al. (2023). It is based on three broad principles:

1. For areas underlain by perched water tables, the R, $W_{eff}$ and D' are linearly related to D. This assumption is based upon physical grounds with R, D' and D being linearly dependent on a conceptual ponded head above clay layer for each irrigation district, allowing Darcy's Law and linear reservoir assumptions to be applied;
2. $W_{eff}$ is considered to be similar for both areas underlain by perched water tables and those are not;
3. A power law relates the proportion of irrigation district underlain by perched water tables and the mean drainage across the irrigation district.

Analytical solutions are then found for R, $W_{eff}$ and D' in terms of 1/TWA and D/TWA, using six variables, that are then calibrated or assigned. Thus, D becomes a surrogate variable for the state of the hydrological condition of the unsaturated zone.

Such a model is conceptual and direct correspondence to physical processes needs only be sufficient to justify the linear relationships. The actual ponded head will vary temporally in response to irrigation and spatially in relation to topography, drainage and irrigation. It is not explicitly used in the calculations as R and Weff are directly related to D in a linear fashion. Also, real coefficients, such as $K^{v}_{2s}$ will vary spatially, so that the coefficients of the lumped model should be considered conceptual and only vaguely related to the real coefficient. A benchmarking process against an established numerical model (such as that which was performed for the discrete transfer functions described in Section 3.2) is therefore not informative or warranted.

## 4.5 JC modelling

The DWR recharge model has been implemented with the groundwater model using an ensemble approach to address calibration and uncertainty, using PESTPP-IES (see Figure 4-6). This produces 100 realisations of the recharge-groundwater model each with a calibration dataset, iterating towards optimising the cost function, which balances the fit to observed hydrogeological data to that of having appropriate target range for $W_{eff}$ (CDM Smith, 2023).

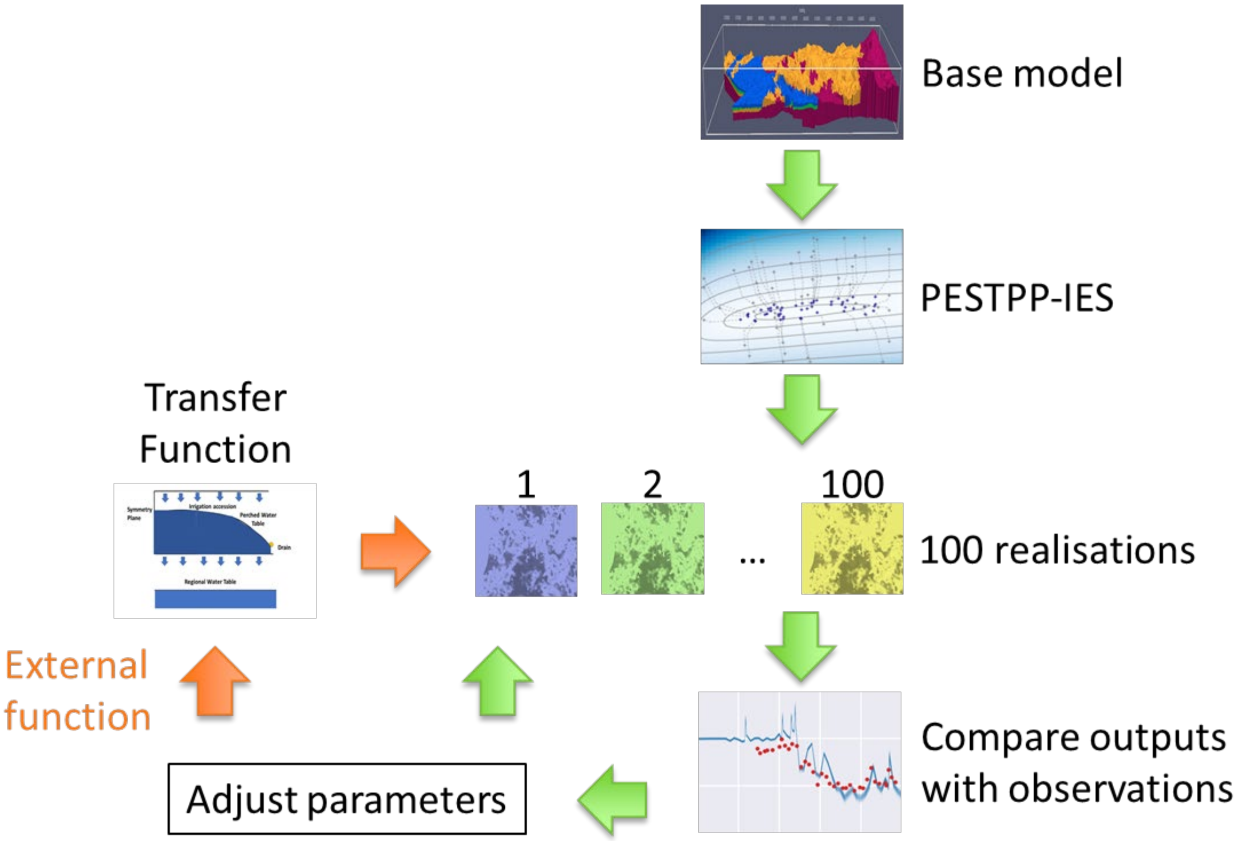



**Figure 4-6 Calibration workflow coupling recharge module (transfer function) with the EM2.6 groundwater model**

## 4.6 Comparison of methods

The results are shown for the FMID irrigation district in Figure 4-7 for both recharge (a-c) and $W_{eff}$ (d-f). FMID is a Victorian irrigation district with a high D/TWA ratio and found by the model to have mostly perched water tables. Figure 4-7 (a) shows a comparison of the median recharge time series for WF (in red) with those of the recharge module for DWR using four sets of parameters. It illustrates the potential range of R, as represented in DWR, while showing unexpected behaviour using WF. The variability of R becomes smaller after 2005. Figure 4-7 (b) shows the full range of R for the ensemble in DWR, illustrating a wider range for R. Figure 4-7 (c) shows a comparison of all 4 approaches., with WA shown in green, the full range of possible results for RS (n green dashes) representing values of $\alpha$ = 0.8 and 1.2, median time series for WF (in red); and median time series for DWR (in orange). The results for WA, RS and WF tend to be at the lower end of the range for DWR before 2005, while that for WF approaches that for DWR after 2005. The results for Figure 4-7 (d-e) show that this variability occurs despite relatively small differences in $W_{eff}$.

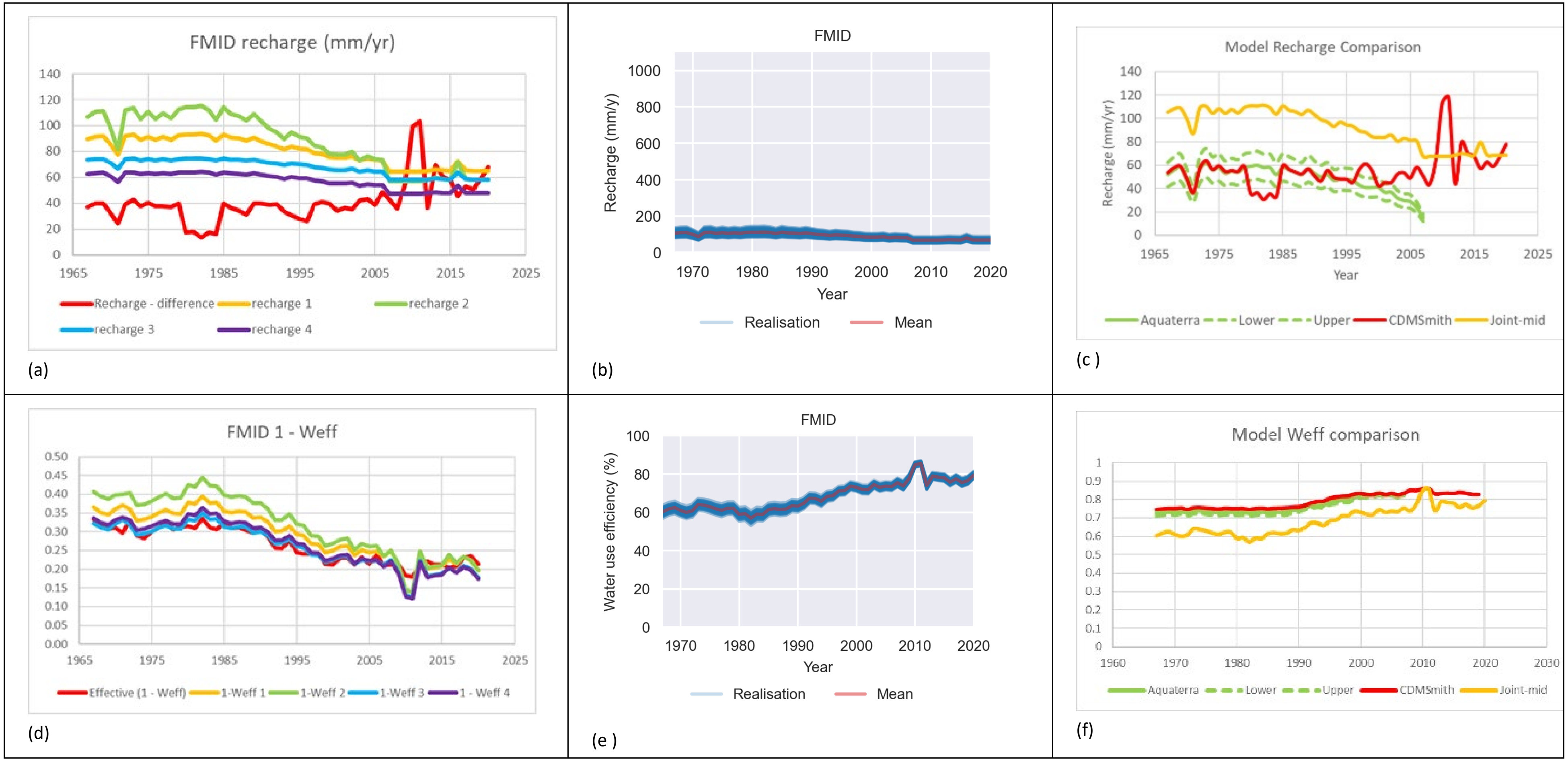



**Figure 4-7** Time series for FMID district showing (a) annual recharge for the recharge module in DWR (CDM Smith, 2023) for four sets of recharge parameters, compared with median value of ensemble for WF (CDM Smith, 2022) shown as red line ; (b) ensemble set of recharge time series for DWR, showing variability across all sets of variables tested in the ensemble; (c) comparison of recharge series for all 4 approaches; i.e. WA in solid green (Aquaterra,2009; range of values for RS in green dashes (Jacobs, 2019) assuming α = 0.8, 1.2 ;the median series in ensemble for WF in red; and the median time series in ensemble for approach 4 in orange (d) 1- $W_{eff}$ for four sets of parameters for recharge module in DWR, compared to median time series for WF; (e) the range of Weff within ensemble for DWR; and (f) comparison of all four approaches for $W_{eff}$ similar to recharge in (c).

All four approaches satisfy Equation (1) and have similar $W_{eff}$ trajectories. Yet, recharge is variable. Figure 4-8 shows the reasons behind the differences. Figure 4-8 (a) shows that recharge is linear with respect to the hydraulic conductivity of the clay layer, $K^v_{2s}$, while Figure 4-8 (b) shows that it is negatively correlated with $W_{eff,}$ as expected with Equation (1). Where $K^v_{2s}$ is high, R is higher and $W_{eff}$ is lower. Thus, the value for $K^v_{2s}$ changes the balance between R and $W_{eff}$. Figure 4-8 (c) shows the parameter distribution for $K^v_{2s}$ , as determined by the ensemble modelling for approach 4, showing a peak at ~45 mm/yr. Results from WA, RS and WF approaches would correspond to values towards the lower end of the distribution, ~10-20 mm/yr.

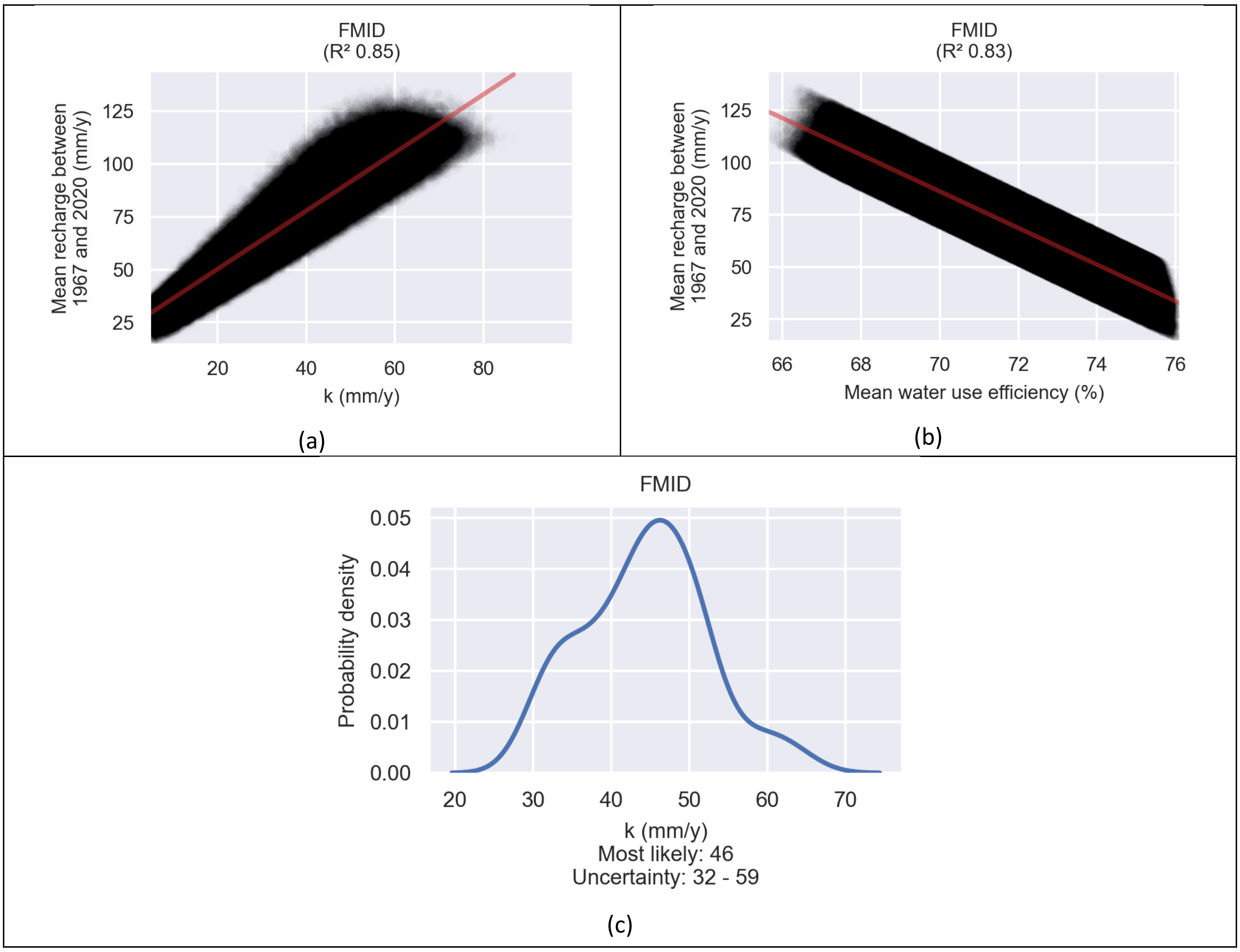



**Figure 4-8 For the DWR method of CDM Smith, (2022), plots of recharge against (a) conductivity of underlying clay layer; and (b) Weff for same irrigation district. (c)Probability distribution function for conductivity after ensemble modelling.**

For other types of irrigation areas, the uncertainties are higher. A smaller ratio of D/TWA means that there is greater unaccounted excess water that can either percolate to the water table or discharge to the land surface. Without other independent data to constrain these processes, uncertainty is higher. While the joint calibration does constrain the parameter values, the uncertainty is still significant. The assumptions about the relationship between $W_{eff}$ and D also become more nebulous as D becomes a smaller fraction of R and more of the irrigation district is not constrained by hydraulic conductivity of the underlying layer. Inclusion of information on soils and extent of waterlogging and salinity may constrain these. While these areas represent a lower proportion of irrigation in EM, the higher uncertainty in recharge estimates for these may dominate the uncertainty from the Victorian areas.

The DWR approach has provided an estimate of 18% improvement in water efficiency across the Sunraysia region from 1988 to 2000 with 12-28% within individual irrigation areas. In response, groundwater recharge has reduced by 28-68% across irrigation districts. The a priori assignment of values for $W_{eff}$ leads to much lower estimates of, and hence potential bias in, recharge than found in this study. The newly calibrated groundwater model can be used to predict future salt loads to the River Murray under various scenarios, as required under the basin salinity strategies.

## 4.7 Discussion

The development of DWR should not be seen as implying that this should be the preferred approach in future, but rather indicating potential future directions and with results to be fully discussed with local agencies. By explicitly representing processes that match the main patterns of 1/TWA and D/TWA; and by incorporating into an uncertainty framework, it allows analysis of approaches and their major pros and cons. It also illustrates the potential for innovation in approaches in moving from setting $W_{eff}$ upfront.

There is room for better use of data to better constrain recharge estimates. In particular:

1. All four methods are prone to errors in monitoring of D, especially when D/TWA>0.1, as errors in D exacerbate uncertainties in Equation (1). The DWR method explicitly used D as a surrogate for determining $W_{eff}$ and R. Inconsistencies in the determination and reporting of drainage volumes will affect the results. For example, Stephens and Thompson (2019) highlight how processes besides irrigation efficiency improvements are affecting drainage. This emphasises the importance of the need for continued collating, reviewing and upgrading drainage information (Rolls, 2007; Telfer and Charles, 2019; Stephens and Thomson, 2019).
2. The results also highlight the use of other regional data to supplement drainage data, the most notable being remotely sensed evapotranspiration. There has been some history of remotely sensed data in the region (O'Connell, et al., 2011; Whitfield, et al., 2011; Abuzar et al., 2014; Whitfield and Abuzar, 2014; Whitfield, et al., 2014); including for recharge estimation (Whitfield, et al., 2019). There are also now large datasets available for use (Guerschman et al., 2022; McVicar, et al., 2022; TERN, 2023) across Australia. There have also been several studies internationally on the use of remotely-sensed data for recharge (e.g. Lubczynski and Gurwin, 2005; Hendricks Franssen et al., 2008; Ebrahimi et al., 2016). However, we emphasise that these approaches supplement drainage information, rather than replace them. Firstly, R is sensitive to $W_{eff}$, so that bias and errors in the remotely sensed ET will be amplified for estimates of R. Secondly, remotely sensed data is not available over all the historical period, to the same extent as D. Gaps and bias in both datasets mean that generalising the approach to use both drainage and remote sensing may provide greater robustness, especially where D/TWA is small.
3. The local knowledge that has been incorporated as part of the a priori estimates of water use efficiency is lost as part of the iteration process in RS, WF and DWR. The documentation of the surface water balance approaches is not comprehensive and does not transparently show critical information. If this is done, such information could be included as part of the regularisation approach. There will also be other data available locally on soils, discharge patterns etc, that have not been included here. Local review will be necessary before using the results more widely.

The results from the DWR method highlight issues with previous approaches:

1. The combination of the WA method to estimate recharge within a FM framework can lead to strongly biased results. However, with data improvements, as suggested in the previous section, and emphasis on evidence-based estimation of recharge, this bias may decrease.
2. The results of the DWR approach show that the RS method for adjusting recharge within an JC framework has set constraints ($0.8<\alpha<1.2$) that are too limited for the change in recharge required. A broader range may also require testing that the values of $W_{eff}$ have not become unrealistic. Also, a mapping of R to F(R ) could be more general than the simple scaling e.g inclusion of a constant term within a linear mapping or even a binomial mapping. There would need for appropriate weighting within the regularisation to ensure both hydrogeological and $W_{eff}$ targets are jointly met.
3. The use of a functional form for $W_{eff}$ within an IC framework appears to have difficulties in consistently producing realistic time series of R. A constraint could be placed in the regularisation scheme to avoid such forms of R.

However, given the sensitivity of R to $W_{eff}$, there is a need to ensure both hydrogeological and $W_{eff}$ targets are met.

4. The target range post-2000 for $W_{eff}$ may have been underestimated for the DWR method. The results show that values of $W_{eff}$ for many irrigation districts was close to the lower end of the chosen range of 0.75. Even allowing for the different definitions of water use efficiency, various studies and estimates have been greater than 0.8. The low value of $W_{eff}$ is due to the large volumes of drainage still found post-2000 in the Victorian irrigation studies. For all methods described above, the setting of target ranges is an important step.

All the above methods have been based on an annual timestep and a spatial unit of an irrigation district. This has occurred through simplification of the very complex processes operating in irrigation areas. Complexity could be added to the model by varying the spatial and temporal resolution. However, additional model complexity without appropriate data may be counterproductive, because of parameter uncertainty. Also, the potential risk may not justify any additional effort in adding complexity and data to match. Noting this, some important issues include:

1. Time lags have been ignored for all four methods. The main time lags involve the change in recharge resulting from commissioning and decommissioning of irrigation areas. While the slow increase in irrigation development may mask some of the time lags for recharge changes from commissioning irrigation districts, the time for soils to drain after decommissioning are evident in drainage data around 2007. The previous section describes the processes affecting time lags and approaches to estimate these. If the spatial resolution remains at the irrigation district scale, there is a need to keep a register of the proportion of districts and the associated changes in recharge.
2. The drainage patterns are most likely due to distributions of clays and their thickness. The DWR approach uses a functional relationship between drainage volume and proportion of irrigation district, which is perched. The distribution of the Coonambidgal and Blanchetown Clay are reasonably well-known, although thickness less so. It is likely that better relationships could be developed using the knowledge of these distributions of soils and their properties. There is an adaptation to DWR that would allow such information to be used, while remaining the same spatial resolution.
3. In some areas, mostly the floodplains, the regional water table is in the clay layer. A shallow regional water table does not allow free drainage and can cause rejected recharge, leading to increased drainage and discharge to the land surface as well as reduced recharge. Under the current fourth approach, this would calibrate to a lower permeability clay layer. There is an adaptation to the DWR method to represent this, but the additional complexity and small area of these situations means that the additional effort in including these in regional modelling would not be justified in the regional analysis.
4. It is possible to split the irrigation district into sub-areas based on soils, irrigation history, drainage patterns, depths to water table and proximity of piezometers to better represent some of the above processes. Such models could be tested by being nested within current model. It is likely that a higher resolution may be required for models supporting more local decision-making. The next section describe modelling based on an even finer resolution.

In summary, this section has shown that an unbiased determination of recharge will require more data, such as remotely-sensed evapotranspiration and transparent documentation of drainage and assumptions within the current simple water- balance modelling. The adjustment of these recharge patterns can be adjusted through a joint calibration process, but care needs to be taken on ensuring realistic recharge or $W_{eff}$ targets are incorporated into the regularisation process, and that the weighting is sufficient to ensure these targets are met. The current spatial resolution of the regional EM groundwater modelling masks the effects of different soils, irrigation history, different depth to water table, etc and a finer resolution should improve representation of these processes in the model, provided there is appropriate data to set parameters for these. A risk-based approach is required to support the assessment of the need for additional effort.

# Section 5 Use of discrete transfer functions in models

## 5.1 Overview

This section describes a pilot trial of the transfer function approach at Loxton-Bookpurnong summarised by Walker et al., (2020a); Walker et al., (2020b); and Currie et al., 2020), and integrates these findings within the broader groundwater modelling of the Mallee. In these studies, a suite of transfer functions has been developed to:

1. Better understand the modelling of the soil physics of perched water systems and time lags through unsaturated zones.
2. Providing simpler conceptual models of these processes.
3. Demonstrate integration of these within the Border to Lock 3 groundwater model for two SA irrigation districts.

It should be noted upfront that this trial was undertaken early in the research program and thinking has since changed.

## 5.2 Site description and previous modelling

Many irrigation districts in the South Australian Mallee (SAM) have deep regional water tables, which can cause significant time lags between actions at the land surface and changes in recharge . Actions, such as changes in irrigation management, including initial development, changed efficiencies and decommissioning, lead to changes in pressure below the agricultural zone or perched layer, which then move to the regional water table. Where a perched water table develops, the perched water table and the associated drainage mean that any pressure signal at the land surface is heavily modified by the time it reaches the regional water table. Previously used models such as SIMPACT and SIMRAT had been found to be no longer appropriate for such situations (Woods et al., 2016).

Due to such problems, groundwater modelling efforts began to use IM to infer recharge rates from the groundwater levels. An example of this the Loxton-Bookpurnong 2011 groundwater model (LB2011), the aim of which was to evaluate salt loads resulting from local, accountable actions such as land clearance, irrigation area development, changes in irrigation practice and the construction of SIS. The recharge was inferred in the following way:

1. The irrigated areas are divided into 42 recharge zones based on irrigation commencement year, initial lag time and estimated recharge rates.
2. During calibration, the recharge zones, initial lag time and recharge rates are adjusted within reasonable ranges until the modelled water level and trend consistently approximates the observed water level and trend.
3. If this leads to a poor match to observed heads, the aquifer properties are also varied within reasonable ranges.

More than 700 model runs were conducted. In this section, we will focus on Loxton.

A conceptual diagram of the hydrologeological setting is shown in Figure 5-1. This setting differs from Sunraysia in that the river is more incised, irrigation occurs on higher areas rather than the floodplain and the regional water table is deeper, below the Blanchetown Clay. Irrigation commenced in 1948 and within four years, salinisation and waterlogging emerged as an issue due to perching on the Blanchetown Clay (Rolls, 2007). Tile drains were installed, with the excess water being disposed to seepage shafts and drainage bores. Such disposal achieved limited success, and a Comprehensive Drainage Scheme (CDS) was completed in 1964. This comprised of gravity main drain pipelines receiving water from the tile drain or agricultural drain systems on each property and delivering the drainage water to open bottom caissons. The percentage of the area that was drained increased from almost none in 1964 to 48% in 1972, 53% in 1992 and 58% in 1997 (Watkins, 1992; Smith, 1997). During this time, irrigation management changed from flood irrigation and drainage bores were used during the 1950’s and 1960’s, to sprinkler and drip systems during the 1970’s; monitoring soil system and improved management of irrigation systems after 1988; and replacement of leaky concrete water distribution channels with pipelines after 2002. A groundwater irrigation mound developed following irrigation, increasingly intercepting the drainage systems and associated caissons (Rolls, 2007). The rehabilitation of the irrigation system resulting in less water delivery, less drainage and a fall in the groundwater mound. These trends were exacerbated by drought and water restrictions after 2005.

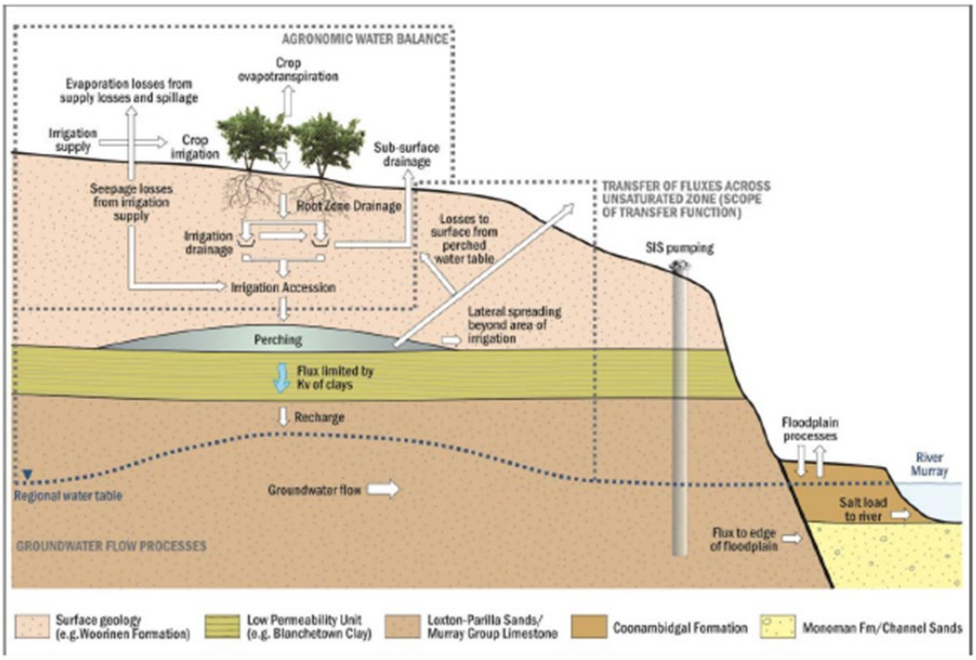



**Figure 5-1 Conceptual model of groundwater returns to the Murray River from the Loxton and Bookpurnong irrigation districts.**

A simple water balance model for the Loxton Irrigation District was developed by Meissner (2011). The values of $W_{eff}$ were assigned based on the history of irrigation management and some field studies, while input water and drainage are from monitoring data. The inverse water availability (1/TWA) is seen to be relatively constant until 2005 and then increases during the drought. The assigned 1 - $W_{eff}$ is relatively constant until 1990, and then falls dramatically during water use efficiency measures and rehabilitation of the irrigation district. D is seen to rise from 1960 until 1972 due to the implementation of the CDS, but continues to rise, presumably due to increased groundwater interception.

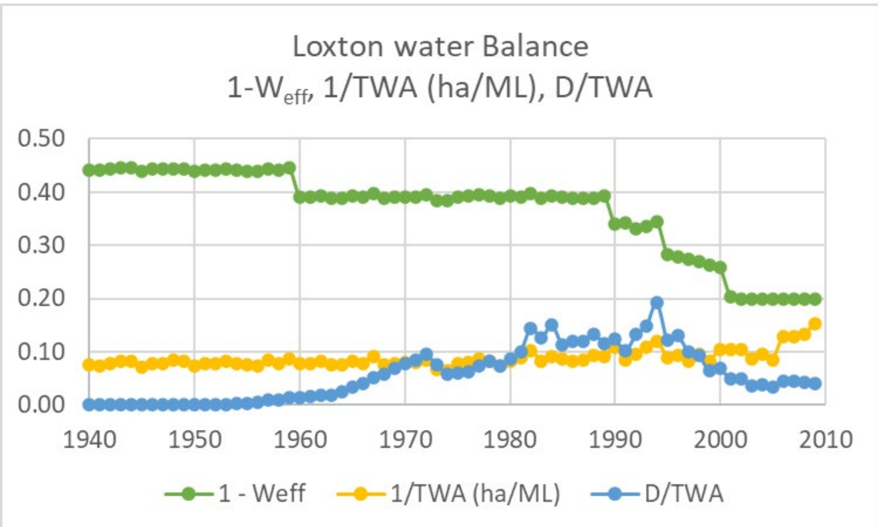



**Figure 5-2 Time series for 1/TWA, D/TWA and 1-Weff from Meissner (2011)**

A comparison of the inferred recharge volume for the Loxton Irrigation District from the inversion of groundwater data and accession rates from simple water balance modelling is shown in Figure 5-3. The irrigation accessions are shown to rise sharply until early 1960s and then fall until 2010. The initial rise is due to the increase in irrigation area and a lack of drainage; while the fall is initially due to increased drained area, then greater groundwater interception and then later to water efficiency improvements. The inferred recharge rates are seen to rise over the 1960s to a peak in 1972 before falling. They appear to match the estimated accessions from 1980. The mismatch before 1970 is likely to be due to a lag time for wetting fronts from irrigation development to reach the water table. The unsaturated zone is wetted up, perched water tables form above the Blanchetown Clay and perched water is discharged to the land surface. The cause of the reduction of recharge from 1970 to 1990 is less clear, but is hypothesised to be related to groundwater interception of drains. The drainage network was set up in the model at 28m AHD, but actual groundwater levels were generally lower than this (see Figure 5-4), as were modelled levels and part of the actual drainage network, including caissons. This means that recharge would need to be lower to mimic the effect of drains.

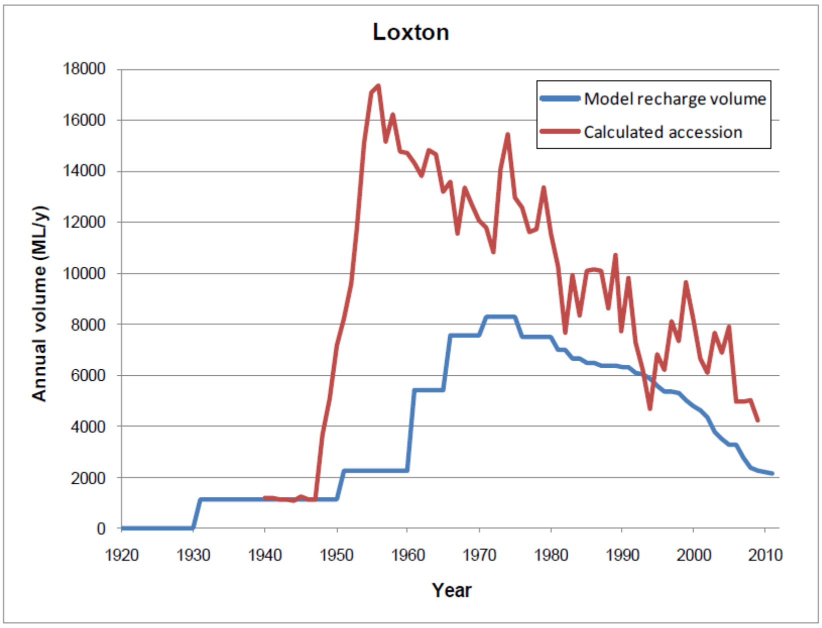



**Figure 5-3 Comparison of the total recharge volumes in the calibrated model (blue line) with the calculated accession (red line). Figure from Yan et al., 2012a; accessions from Meissner (2011)**

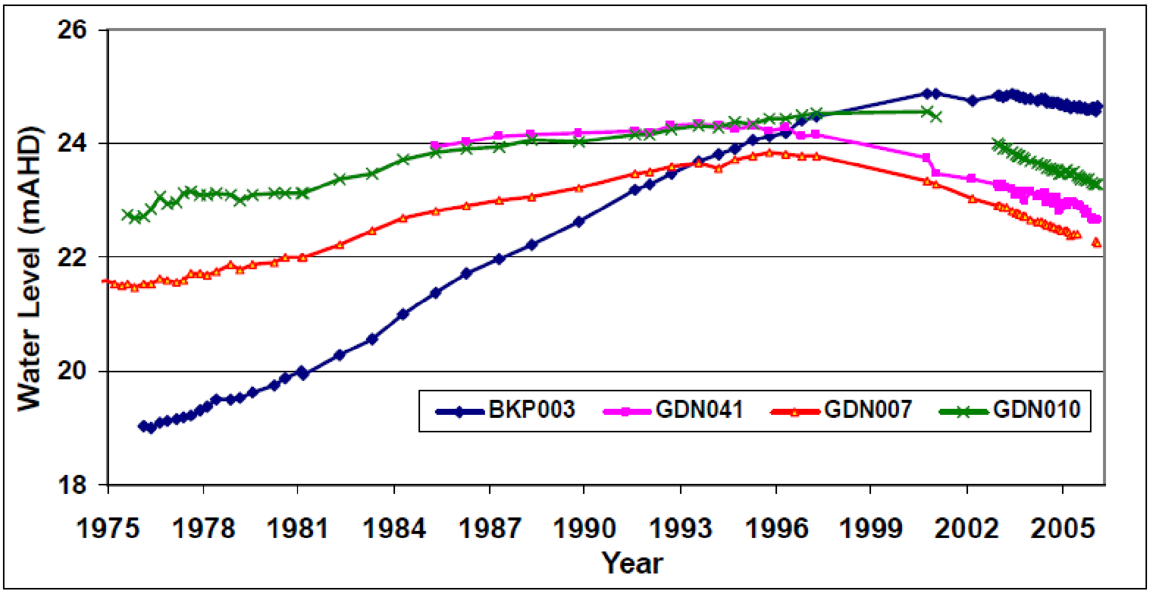



**Figure 5-4 Groundwater levels for the Loxton Irrigation District (rom Rolls, 2007)**

This comparison provides confidence that the total recharge applied in the model is within the reasonable range and is consistent with accession estimates, also recognising that such a comparison was used as part of the groundwater model calibration. The example shows that IM modelling with qualitative assessment, allows reasonable estimates of recharge, without trying to model the complexities of an irrigation area, but still allows interpretation of the processes. It is important to transparently understand the main drivers and processes of change to manage the issue appropriately. However, the inversion process here is difficult to replicate by others; and would be difficult to implement in an automated fashion, as would be required for a predictive uncertainty analysis.

## 5.3 Joint calibration modelling with transfer function

In 2019, a pilot trial of newly developed transfer functions (recharge models) was undertaken at Loxton-Bookpurnong (Walker et al., 2020a; Walker et al., 2020b; Currie et al., 2020). This work pre-dated the Sunraysia pilot trial (Section 4) and did not consider a reformulation of the surface water balance. It does allow for an assessment of how recharge models can explicitly simulate time lags associated with deep water tables. The Loxton-Bookpunong transfer functions had the following key differences to the DWR approach used at Sunraysia:

- Transfer functions were applied at much finer spatial scales. Each irrigation district was split up into numerous recharge zones based on the properties of the unsaturated profile (e.g. depth to clay layer, thickness of clay layer and depth to water table) and the timing of irrigation development, and transfer functions were run individually for each zone.
- Rather than being used as an input to the surface agronomic water balance (as per DWR in Sunraysia), drainage data was set aside and used to calibrate the transfer function as a form of rejected recharge.

In the Loxton-Bookpurnong pilot trial, transfer functions were linked to the pre-existing groundwater model, LB2011 (Yan et al. 2012), the linked model was run using three different approaches (two FM and one JC) as follows:

1. TF-A passed recharge rates derived from transfer function, calibrated against drainage data, into the LB2011 model. The transfer function used a priori setting of Weff and provided an estimate of drainage to compare with observations. The groundwater model was not recalibrated.
2. TF-B passed recharge rates from the transfer function (as per TF-A) to the LB2011 groundwater model which was then recalibrated against groundwater data using PEST.
3. TF-C calibrated the integrated (AWB-TF-MODFLOW) model simultaneously using drainage and groundwater data using PEST and PESTPP. $W_{eff}$ is provided as an estimate. This calibration was only partially successful.

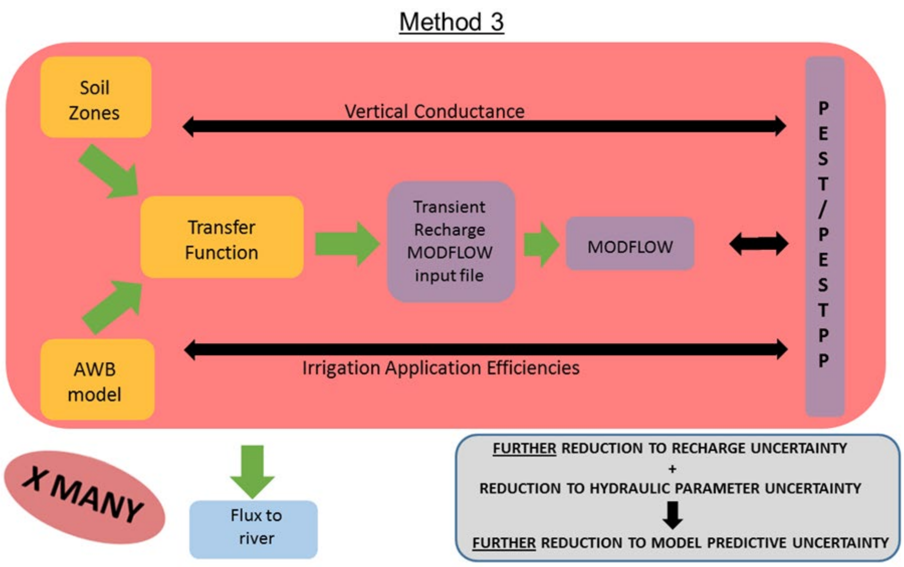



**Figure 5-5 Schematic figure of the process used in TF-C.**

The calibration of the AWB-TF models estimated that $K^v_{2s}$ for the clay layer was well constrained by the drainage targets and only minor adjustments were required from the default value of 0.03 cm/day (109.5 mm/year). Non-negligible discharge to the land surface would occur in areas where drainage infrastructure is absent and clay present.

Figure 5-6 shows a comparison of the recharge and drainage rates derived from the baseline methods and datasets (Meissner, 2011; Yan et al., 2012a) to those derived by the AWB-TF models developed. The AWB-TF models show recharge and drainage outputs that increased substantially in the late 1950s, reflecting the main period of irrigation development and accounting for a short time lag (<5 year), a period of stabilisation between 1960 and 2000, and a decline post-2000 as irrigation efficiency measures were introduced. The calibration focused on the period of late 1990s onwards, as this was where there was more confidence in the available datasets.

When recharge and drainage were combined, the outputs of the AWB-TF models compared reasonably to the combined LB2011 recharge and observed drainage rates (Figure 5-6c). However, there was divergence in the 1960–2000 period when recharge and drainage were considered separately. The LB2011 model had recharge declining from 1980 onwards at a period when drainage rates were increasing, while drainage was increasing. In contrast, the AWB-TF model estimates were flatter. This difference is very likely due to the difference in the way the model results would be affected by groundwater interception by drains. Some of the excess water predicted by the TF models is rejected and becomes drainage.

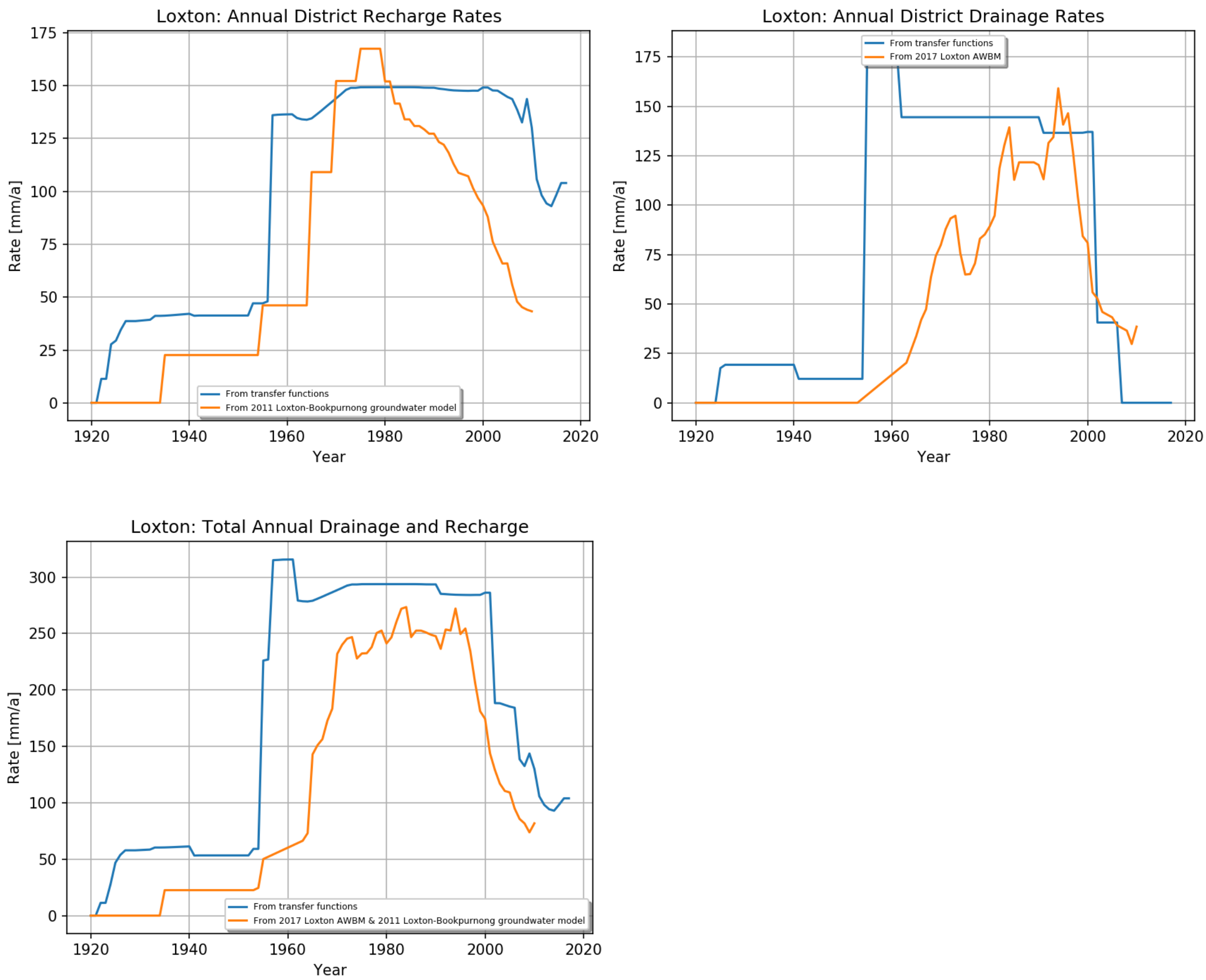



**Figure 5-6 Comparison of recharge and drainage rates derived from existing methods and datasets (plotted in orange) to those derived the new AWB-TF models (plotted in blue) for the Loxton irrigation area, showing: (a) Recharge rates; (b) Drainage rates; (c) Total drainage and recharge rates.**

A range of outputs for the different models have been described in Currie et al. (2020) and are shown below. These include the calibrated horizontal hydraulic conductivities, $K_h$, of the regional water table aquifer for TF-B and TF-C relative to LB2011 (Figure 5-7); recharge map for 1985 comparing TF-A/B with TF-C and LB2011 (Figure 5-8); calibrated $W_{eff}$ for TF-C relative to Meissner (2011) (Figure 5-9); and predicted salt loads to the river for all models (Figure 5-10). These results should be interpreted in terms of three issues with the implementation of the models:

- Representation of the groundwater interception of drains in the various models. The recharge estimated for TF-A/B does not incorporate recharge rejection and this flows through to the calibration of TF-B and salt loads for both models. The difference ban be seen in the difference in recharge distributions between TFA/B and LB2011.
- Some problems with the robustness of the transfer function software within a calibration process, which slowed down the process.
- Instability of the inversion process for TF-C between recharge estimation and drainage conductance in the treatment of groundwater interception. The influence of this can be seen in the calibration of $K_h$ in Figure 5-7c; and in the more spatially homogeneous distribution of recharge in Figure 5-8c;

Despite these problems, there are surprisingly comparable results, for example:

- The spatial distribution of $K_h$ under TF-B was broadly similar to LB2011 despite the conductivity field of TF-B was derived independently of LB2011, this provides some confidence in the new method;
- The inferred estimates of $W_{eff}$ for TF/C is very similar to original estimates in Meissner (2011). The differences prior to 1965 are largely due to including drainage before then in the model;
- The various models obtained comparable calibration statistics. The scaled residual mass statistic (SRMS) was 1.6% for the LB2011 model, 1.8% for TF-A/B, and 1.7% for TF-C;
- The salt loads to the river for LB2011 and TF-B are very similar. The former has a dip in, presumably due to the groundwater interception, and a lagged early (<1960) response.

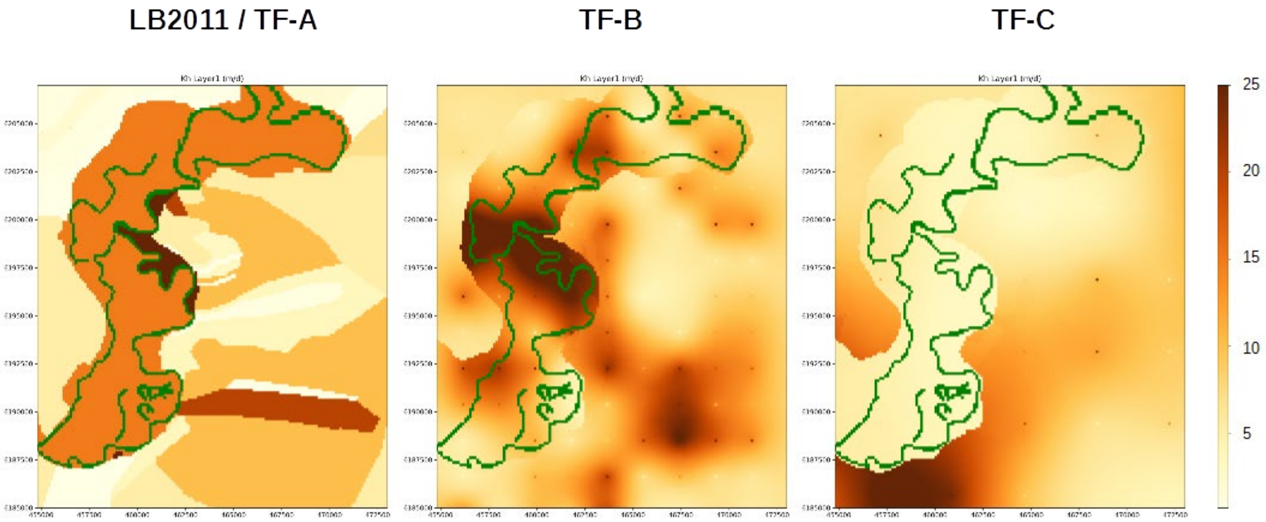



**Figure 5-7 Comparison of calibration for horizontal hydraulic conductivity.**

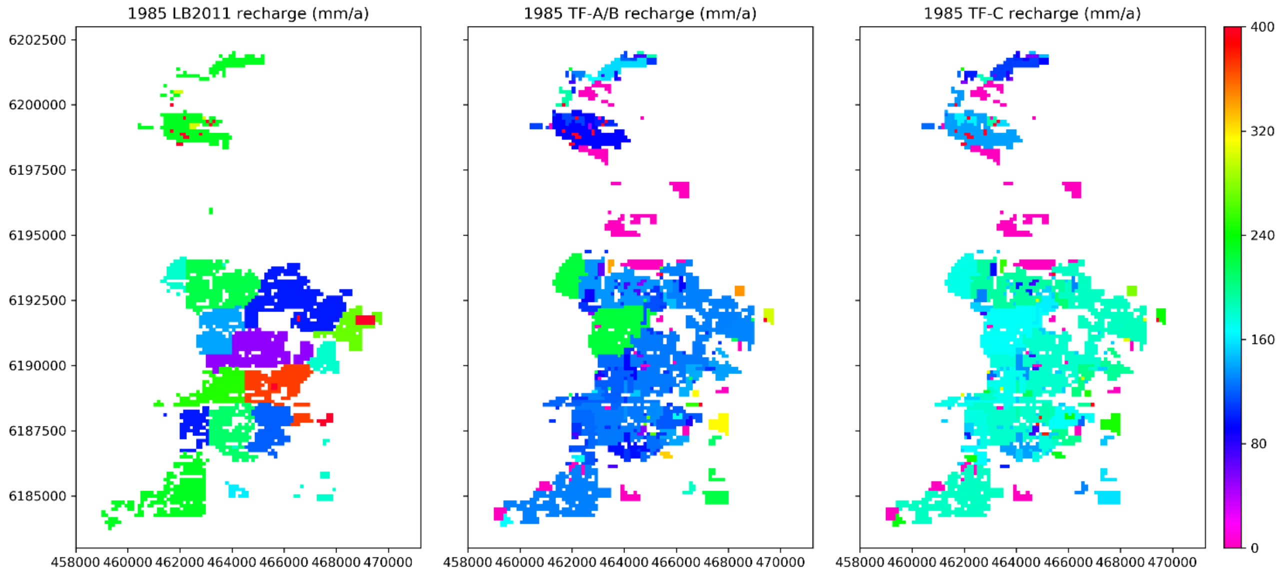



**Figure 5-8** **Distribution of irrigation recharge in 1985 within the existing LB2011 model, the TF-A/B model, and TF-C model.**

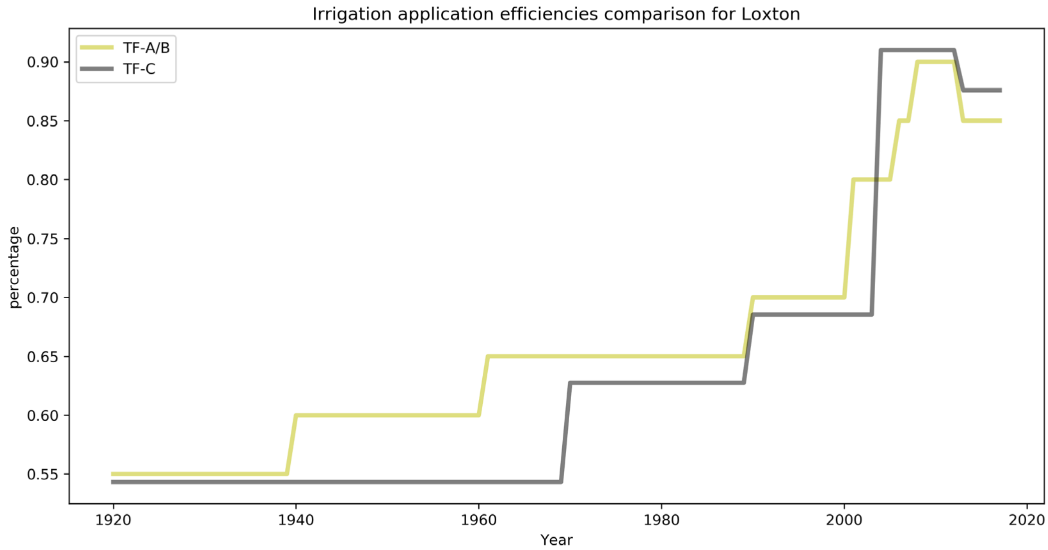



**Figure 5-9 Irrigation efficiency factor used in the TF-A/B and TF-C models**

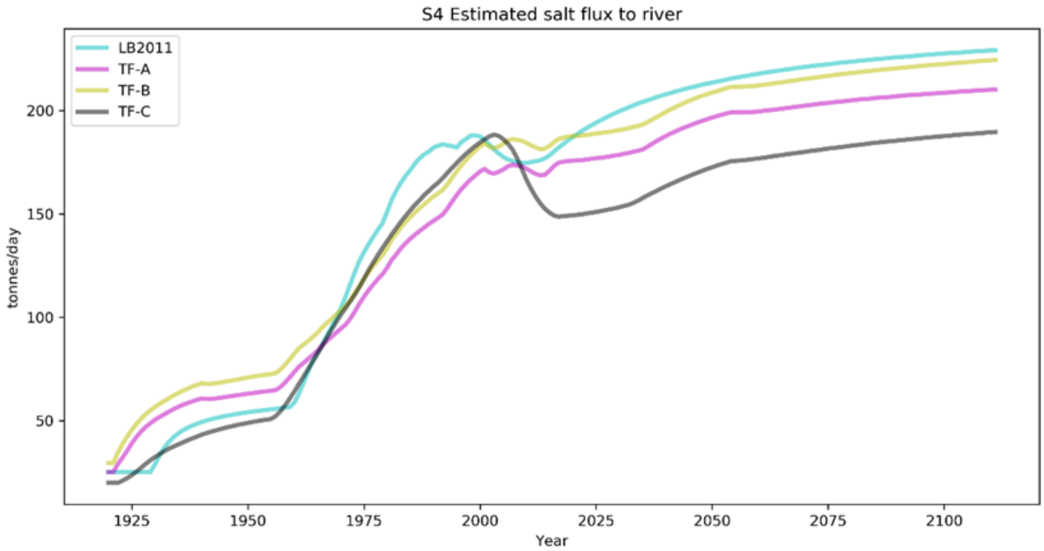



**Figure 5-10 Estimated salt flux associated with groundwater returns to the river for the different models used.**

## 5.4 Discussion

While there had been promising steps with the development of recharge models before 2020, its development was not at the stage of being confident to replace the current methodologies. With the hindisght of the EM example and further development, it would be useful to reflect on some of the issues raised:

1. A priori assignment of $W_{eff}$: the TF-A/B approaches used a priori assignment of $W_{eff}$, while TF-C used a JC approach with a WA treatment of $W_{eff}$. While the values of $W_{eff}$ post-1960 were similar, it is difficult to judge the efficacy of this approach because of the problems with the inversion. The direct use of irrigation accessions from the simple water balance modelling for recharge (AWB) produces estimates that are too high early (Figure 5-6), that is not easily corrected by scaling (RS) or the use of the SIMPACT/SIMRAT model. Using drainage as surrogate for hydrolgical condition is possible; but requires using the modification for shallow water tables, which, in turn, requires information on groundwater levels and height of caissons. Also, not all drainage goes to the Centralised Drainage System. Remotely sensed evapotranspiration may be useful to supplementing this approach.
2. Spatial Scale: The EM work used one unit for each irrigation district while the SAM studies have used 42 (LB2011) and 335 (Currie et al., 2020) units respectively for two irrigation districts. For the EM, the model is more lumped in nature, while for the latter, the approach is more complex. For regional assessments, it is likely that a more lumped approach is appropriate, requiring 1-5 units for each irrigation district. For a more local assessment, a more complex assessment may be appropriate, requiring 5-40 units. This depends on the proximity of the irrigation areas to the river, the timing of their development, the time lags involved and engineering treatments that may be involved. A more complex model could be nested within a regional model that mostly contains simpler representations. We would no longer see the need for hundreds of units within an irrigation district.
3. Addressing groundwater interception by drains: Shallow water tables can lead to reduced hydraulic gradients through clays and in the more extreme case, become intercepted by drains. Shallow water tables are not unique to Loxton, and occurs else in the SAM (Rolls, 2007) and EM (Walker et al, 2023). The presence of shallow water tables could be addressed in different ways:
   a. Use the DWR approach (as per EM) modified for shallow water tables. This requires knowledge of the depth to water table at relevant times. For historical mounds, this could be provided by interpolation of observed groundwater levels. Where shallow water tables have continued, the groundwater levels from the groundwater model could belinked by scripting to the recharge module (Walker et al., 2023).

b. Incorporate drains in a more detailed fashion within groundwater models. The additional complexity may be difficult to justify. Also, the interaction between groundwater drains and recharge calibration may destabilise the calibration, as shown here.

c. Mimic the recharge rejection effect of drains by temporarily reducing $K^{v}_{2s}$. While this could be considered for historical levels, it would not be appropriate for areas where water tables are still shallow.

d. Inversion of groundwater model. Inferring groundwater recharge has been shown to be effective here, provided there is qualitative linkage with recharge information, and appropriate effort to reduce potential non-uniqueness issues. For areas where shallow water tables persist, this approach is problematic for representing future scenarios.

4. JC inversion approaches: This study was only partially successful in calibrating $W_{eff}$ . In comparing with the successes and failures at Sunraysia and here, the choice of strategy is important for success in using JC for this purpose. The DWR was successful not because it was necessarily more accurate but was particularly robust in JC. In the Loxton example case, the presence of drains added to the potential of non-uniqueness. The use of ensemble modelling and better use of targets for $W_{eff}$ in EM also made a difference in Sunraysia.

5. Transfer functions: There was some difficulty in the use of transfer functions in the calibration process, as they were not sufficiently robust at the time. These functions have been made more robust since then, but importantly the use of superposition and simpler more conceptual models make this less a problem.

# Section 6 Recommendations for modelling irrigation recharge

The previous sections have highlighted the progress that has been made over the last few years on understanding and modelling of unsaturated zone processes and incorporating these. This has occurred against the background of progress over the last twenty years on the modelling of salinity impact of actions in the Mallee Region on the River Murray. This section highlights the implications of these studies for the BSMS2030 and recommendations for further actions. This includes:

1. Broad changes required in modelling approaches to provide greater transparency around the Salinity Register with respect to the Mallee region and the Legacy of History;
2. Background data that could significantly reduce uncertainty; and
3. Specific changes in modelling that would improve assessment of salinity impacts.

As with earlier sections, the aim here is not to be too prescriptive, but provide rationale for certain actions.

## 6.1 BSMS2030

The BSMS2030 salinity strategy provides the framework in which further actions must be incorporated. The Salinity Register of Credits and Debits are central to this. While BSMS2030 is a risk management framework, any significant underestimation of uncertainty and bias in larger register items would be a concern. The outputs of the EM modelling show this is possible with current approaches over a large area of the Mallee. This is a region in which significant management actions could take place in the next two decades. In developing approaches to overcome any such problems, it is necessary that these maintain transparency around register entries and their use for management decisions. This means that assumptions are understood, linkage between actions and impacts and between data and assessments are clear. The challenge in doing this is that the effort in making assessments should be proportionate to the risks.

## 6.2 Choice of modelling framework

The review in section 2 shows that a JC framework, in which both groundwater and recharge models are jointly calibrated, should be the preferred choice. This reduces the risks related to non-uniqueness issues. However, it does require adequate recharge models to exist. Until this is done, there may need to be some acceptance of the use of IM approaches, in which there are continual adjustments made until a qualitative agreement is reached between existing information on irrigation accessions. The lack of repeatability (and hence transparency) of such IM approaches and its relation to uncertainty analyses may mean that the current approach needs to be reviewed soon. Also, a clear link between management actions and impact is important. This link is weakened by through the use of a qualitative comparison of recharge information and inferred recharge. This flows through to the choice of scenarios and associated recharge values used for prediction.

The application of a JC framework means that the reliance on the a priori assignment of water use parameters needs to be reduced. While such approaches were major improvements on the assignment of irrigation rates previously used, there is a degree of subjectivity in these estimates, particularly for earlier times. Given that recharge is then estimated as the small difference between larger terms, any error is amplified. The application of this within a FM framework means that such errors can flow through to estimates of salt loads. A JC framework requires that $W_{eff}$ to be adjusted, either explicitly or implicitly through adjustment of other variables. The approach used in the EM study in which $W_{eff}$, D' and R are linearly related to the monitored variable D, provides an example of how this could happen. However, the introduction of other monitored data would require other approaches. It would be unfortunate to lose the useful information contained within the time series of Weff , that has resulted from local knowledge of the history of irrigation and drainage management, and from local field studies. To continue to be useful, this acquired knowledge requires more transparent documentation of the key pieces of information.

## 6.3 Interrogation of data

Most groundwater modelling involves an assessment of the available data to develop hydrogeological conceptualisations. This would generally include recharge, but rarely is this data analysed as in sections 4 and 5, where easily available monitored data can provide insights to recharge mechanisms. There would be certainly more available knowledge on soils, soil properties and discharge to the land surface that would have aided this process. Such information would provide constraints on parameters representing the ratio of discharge to the land surface relative to drains; the proportion of irrigation areas that are perched and how this has changed with improved water use efficiency; the relative proportions of irrigated land overlying Coonambidgal Clay, Blanchetown Clay or relatively minor impeding layers.

Both sections 4 and 5 showed the importance of drainage information for most methods of recharge estimation. For the FM approach, recharge was the small difference between drainage and 1-$W_{eff}$; and hence was very sensitive to drainage. Drainage was also critical for linear relationships between drainage and other fluxes in the DWR approach. Also, most drainage information is for centralised drainage systems; and only poor information exists for private drainage systems. Spatial extent of drainage systems and their topography, including elevation of caissons are important for the definition of recharge models and for developing an appropriate recharge module for shallow water table systems. The collation of available drainage information across all states would improve the efficiency of this step.

The identification of shallow water table areas, both historical and current, is an important component of the conceptualisation; not only where it may intercept groundwater; but where reduced vertical hydraulic gradients through the impeding clay layer may cause recharge rejection and increase discharge to drains.

The use of remotely sensed evapotranspiration appears to be a readily available dataset, that has been underutilised to date. There has been some experience in using remote sensing for such a purpose. The preparation of a dataset tailored for the purpose of recharge estimation would seem well justified.

While uncertainty can be reduced through better conceptualisation, the main reduction will occur with more data, with greater information i.e. through independent forms of data.

## 6.4 Conceptualisation of recharge processes

The previous section described how better spatial and temporal data could lead to better conceptualisation of recharge processes, especially those that affect the magnitude of recharge rather than the timing. All recharge modelling at the current time uses annual timesteps, hence averaging dynamic processes that occur over a year. Better representation of the annual dynamics has not been investigated as part of this work. Decadal trends in drainage and water use reflect the state of the perched water table and the study in section 3 has shown how this can be used to develop a time series of recharge. A linear relationship between fluxes has been used here but if additional data form other sources, e.g. remote sensing the nature of this relationship could be changed. Section 5 showed the risk of using such data when other factors are affecting drainage, such as development of centralised drainage system, shallow groundwater or even urban runoff into drainage systems.

The EM spatial resolution has remained the same as previous studies, i.e. at the irrigation district scale. Such a lumped scale does not cannot adequately represent all processes, but shown here is discharge to the land surface, a proportion of irrigated district that is not perched, and this proportion changing over time. Some improvements could be made while retaining this scale, but it is likely that dividing the unit would be required to substantively improve representation of processes. Such an approach could be tested by nesting within the current groundwater model and recalibrating. Whether the additional resources to change more units is warranted would be part of the test. For the SA Mallee, such an intermediate step may help facilitate the shift from IM, should a decision be made to do so.

The conceptualisation of time lags depends on some of the same issues. Time lags may be only significant for new developments, major rehabilitation of irrigation areas and irrigation decommissioning. The significance of the time lags will depend on the presence of perched water tables, thickness of clay and depth to regional water tables.

## 6.5 Construction of recharge models

Section 3 describes the nature of the transfer functions that could be used in recharge module. Since the Loxton study, simpler approaches based on superposition and/or simpler conceptual models have been developed. Currently, no time delays are used in the Sunraysia model; while in SA, time lags, as calculated from SIMRAT, are used to begin the inverse process. For SA, any impact of a drying or rehabilitation process would be embedded in the inferred recharge from the IM process.

We would suggest that the full transfer function is used for the wetting up, especially for areas of high hydraulic impedance for the clay layer and more recent developments, as this will affect the recharge response following the initial rise. For the drying phase, we would suggest that it matters less whether a simpler model is used. A numerical model could also be used upfront to perform the same role as the semi-analytical function, but care is needed to avoid instability about the clay layer.

As discussed in section 3, shallow water tables can be addressed in different ways. The best representation of this process would be link, through scripting, the groundwater level outputs of the groundwater model to the recharge model. Where the regional groundwater mound occurred in the past, historical levels could be used rather than the outputs of the groundwater mound. We believe that perched shallow water tables will cause recharge rejection in some low-lying areas, but the significance of this process will need to be assessed. The duplication of drainage processes in the recharge module and in the groundwater model should be avoided.

The implementation of the transfer functions and the related conceptual model requires experience in unsaturated zone processes to be part of the team. This would be in addition to experience in irrigation management to conceptualise the development of perching.

## 6.6 Calibration, sensitivity and uncertainty analysis in JC framework

Section 4 illustrates how the recharge module could be calibrated as part of the JC process. The ensemble approach effectively treats each run as a forward modelling exercise and then adjusts the parameter set purposefully for the next run, to minimise the cost function. Some of the examples for the EM run and for Loxton show that selecting the recharge module to make this robust is important. The more complex the recharge module, the more likely there will be difficulties in the calibration.

Section 4 also illustrated how the use of sensitivity analyses before incorporating recharge module within the groundwater model allowed sensitivities for different regions to be well-understood without the long run times of a groundwater calibration. It also helped interpret data, develop conceptual models and pre-empt calibration problems. When drainage is a small fraction of the water balance, the uncertainty is higher. This cannot be addressed without obtaining further data.

The predictive uncertainty of all transfer functions is high as the hydraulic parameters on which the model is based has high uncertainty. As we understand it, the current groundwater modelling practice is to observe the rise in water table following new development in the area. The groundwater response used to calibrate the recharge model in a JC approach would contain the full response to new developments.

The ensemble approach assessed predictive uncertainty for salt loads, while also providing parameter uncertainty estimates. This illustrated the potential for bias in assessing water use efficiency and estimates of salt loads. The approach allowed independent estimates of water use efficiency and provided evidence for the improvement and water use efficiency in conjunction with the estimates of changes in salt load. The choice of parameter sets from the ensemble modelling to implement predictive modelling of future scenarios was not assessed in this project. We note the 50th percentile was used for the Sunraysia modelling.

## 6.7 Primary recommendations

The discussion in this section has suggested several possible ways forward. The primary recommendations are as follows:

1. Future salinity assessment in the Eastern Mallee should apply a joint calibration process, in which the water use efficiency and unsaturated zone parameters are adjusted within an uncertainty framework. Before the next assessment, some further work would be required on improving the methodology and supporting data, for one or more irrigation districts.
2. For the South Australian Mallee region, there should be further testing of the simplified transfer function methodology for a South Australian irrigation district within a groundwater model, as a step towards joint calibration into the future.
3. The use of easily accessed remotely sensed data for evapotranspiration for the joint calibration should be explored, as this is likely to constrain uncertainty and reduce bias. Improved collation and interrogation of other irrigation and soil data (e.g. drainage data) to support surface water balances and the development of transfer functions should also continue in parallel. While this could occur as a regional initiative across the Mallee, it is best embedded in individual modelling assessments as the data collation and review process assists in the development of unsaturated zone conceptualisations and in the design of groundwater modelling approaches to robustly simulate irrigation recharge.

# Section 7 References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