

**BSM2030 Knowledge Priorities
Mallee Legacy of History
Salinity Impacts from
Dryland Vegetation Clearance**

Prepared for:

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GROUNDING IN WATER



This project critically reviews the adopted hypothesis that mallee vegetation clearance and its replacement with shallow-rooted dryland farming systems results in enhanced root zone drainage and increased (but delayed) groundwater recharge that would drive more salt into the River Murray.

Before summarising the evidence and empirical equations, it is worthwhile reviewing some anecdotal comments about the timing and magnitude of these delayed recharge impacts. **Comments such as “we are not seeing the salt in the river” and “the salinity effects are being pushed out into the future by the models”** are often repeated but are at odds with the facts. Regional groundwater model predictions of salinity impact due to dryland vegetation clearance have always showed low salt loads reaching the river prior to about 2040/2050. The regional models show a significant future increase in salt loads only from about 2040 due to the inherent time lags (due to the depth to groundwater and intervening clay layers). It is not possible for river flow and salinity measurement methods to differentiate the specific effect of the low salt loads due to mallee clearance. **As we cannot “see the salt in the river”,** models are used to unpack the effects. This report explores the model concepts, evidence and complexities.

The link between land clearance and river salinisation was first described by Wood (1924) in the Western Australian wheatbelt. Scientific research in the Mallee region established the empirical Cook paradigm (Cook et al. 2001, 2004) that clearance of native mallee vegetation has disturbed the delicate hydrological balance and led to increased root zone drainage (RZD):

1. prior to clearing, the perennial, deep-rooted native vegetation used most of the rainfall, root zone drainage (RZD) was very low (order of 0.1 mm/year) and in equilibrium with delayed recharge at the water table;
2. post-clearing, the shallow-rooted crops and pastures that replaced the native vegetation used less of the rainfall, and deep drainage below the root zone was greatly increased;
3. the increased drainage moves (slowly) under gravity and causes a wetting front;
4. when the wetting front reaches the water table, recharge occurs (i.e. delays involved);
5. additional recharge at the water table below cleared dryland areas generates increased groundwater flux and salt load to the floodplain and river (this point relates to lateral flow processes, is fundamental and is not challenged, in that regional models are fit for this lateral flux purpose).

There is strong evidence that the Cook paradigm of increased vertical drainage due to native mallee vegetation clearance applies generally (but not uniformly) across the Mallee:

- the leaching of salt (chloride profile measurements) provides a contemporary indicator of the vertical process (continuing in many areas) that is used to quantify the RZD rate;
- RZD under native vegetation was found to be consistently 0.1 mm/y or less;
- RZD under agriculture was found to be much greater (typically 1-50 mm/y, or 1.0 to 2.5 orders of magnitude higher than under native mallee);
- the exception is low rainfall areas that had been thinned for predominantly grazing land use (notably south-western NSW), where no significant difference was observed between RZD under native mallee and RZD under dryland farming;
- significant depths to groundwater and (deep) impeding clay layers in most areas cause long time lags (order of decades to centuries) for increased RZD and deep drainage to become delayed groundwater recharge (Cook et al. 2004; Wang et al. 2005).

The empirical Cook paradigm and algorithms for estimating RZD and delayed recharge:

- are based on the best available science and have been independently verified as statistically significant (95% confidence intervals; Crosbie et al. 2010; Wohling et al. 2012); see section 4.8 for more details;
- provide estimates of dryland recharge suitable for input to regional models to evaluate the salinity impacts of vegetation clearance (i.e. via regional model inputs that use SIMRAT model outputs of dryland recharge rates and time lags that are derived from the Cook paradigm and algorithms; Woods et al. 2016).

Some key implications of the empirical Cook paradigm (encoded in the SIMRAT model) are that:

- the impact of the vegetation clearance action (in BSM2030 terms) is captured in a systematic and quantitative manner via the Cook paradigm and algorithms;
- the Cook paradigm involves a time lag algorithm to account for the effect of (deep) impeding clay layers, whereas alternative methods are designed/applied to estimate RZD only (WAVES, ENSYM, etc.); this makes the alternates not suitable for Mallee conditions where Blanchetown Clay is ubiquitous;
- not all areas of mallee clearance would experience within a reasonable time increased drainage and/or exhibit rising water tables (e.g. low rainfall and/or high clay content in shallow soils results in low rates of RZD and thus long time lags);
- long time lags mean that increased drainage in some areas has not yet reached the water table, and may not reach it in some areas by 2100;
- where drainage has reached the water table, the recharge rates are still quite low (typically 3-9 mm per year, except for areas of sandy soils such as north and east of Robinvale), making it difficult to validate by monitoring bores;
- any rise in groundwater level at any point is not simply due to aquifer recharge occurring at that point; rather it is a result of recharge occurring in the region, with its spatial and temporal variabilities (further increasing the challenge for monitoring);
- the variability/uncertainty in the magnitude and timing of the mapped SIMRAT dryland recharge derived from the Cook algorithms (Wang et al. 2005) is unknown but due mainly to variability in the landscape (soil profile properties and rainfall), specifically:
 - due in small part to uncertainty (around $\pm 50\%$) in the dryland RZD and clay content point drainage relationship of Cook et al. (2004), noting that spatial variability is captured via the mean and variance parameters of the log-normal drainage function, and the integration of the function over time captures temporal variability;
 - due mainly to the application of regional soil maps (necessary to infer clay content), as these maps have inherent deficiencies in how soil type has been mapped spatially, as this mapping groups soil types within landscape relationships rather than individually which would assist in determining drainage properties (i.e. this is fundamentally a data variability/uncertainty issue);
- regional models appear to exhibit low sensitivity in salt loads due to variations in cleared dryland recharge rates (caution: based on only one sensitivity test via the EM1.2 model); overall salt load uncertainty is unquantified, but it is expected to be large (e.g. at least as large as the salt loads themselves); quantitative uncertainty analysis is warranted;
- a number of assumptions are involved in applying Cook paradigm delayed recharge (SIMRAT output) to regional models for estimating salt loads, some of which may lead to over-estimates and some to under-estimates (refer to Table 2 in section 4.7); however, there is no material evidence across most of the Mallee to indicate that the assumptions have resulted in significant bias in groundwater levels or salt load estimates;
 - again, the exception is a potential bias for over-estimating drainage/recharge in low rainfall areas of south-western NSW; however, the predicted SIMRAT recharge rates applying to the small areas of clearing in south-western NSW are mostly low (<12 mm/y), the time lags are long (50-150 years), even for the dune areas with high drainage rates (20-30 mm/y), and the salt loads amount to a very small component of the total mallee clearing salt load, which is itself a small part (5-10%) of the total salt load at all times up to 2100.
- the generally small salt loads predicted due to vegetation clearance scenarios (around 5-10% of the total salt load to the river) is challenging the limit of regional model accuracy (but the scenario difference method applied is appropriate to minimise uncertainty affecting absolute magnitude predictions; Barnett et al, 2012);

- this indicates a low salt load risk context for vegetation clearance (i.e. low relative to irrigation-related impacts), which warrants an adaptive management approach (monitor and review).

Issues/options for further work discussed at the inter-jurisdictional workshop on 29th March 2017 regarding consistent modelling methodologies for vegetation clearance scenarios included the following (roughly in order of decreasing priority):

- status quo: the existing methodology of applying mapped dryland recharge rates and time lags (i.e. SIMRAT output based on the Cook paradigm/algorithms; Wang et al. 2005) to regional groundwater models should continue to be applied to evaluate the potential salinity impacts due to vegetation clearance (including assuming clearing occurred (completely) in 1920, which is a conservative simplification when information indicates that around two thirds of clearing in SA and Victoria was completed by 1930 and south-west NSW is largely uncleared);
- quantify uncertainty: a pilot uncertainty assessment may be warranted for a representative regional groundwater model in each jurisdiction to quantify the range of uncertainty applying to the best estimate (i.e. to objectively quantify the uncertainty applying to the Register entries);
 - comprehensive uncertainty assessments of regional groundwater models are time consuming and expensive, and are thus not warranted every time a salinity impact model is updated, hence the recommendation for a single (pilot) study.
- update the Wang/SIMRAT dataset of mapped recharge and time lags, compare and contrast to new datasets (e.g. WAVES, BoM, CSIRO etc.) and use better data on land use changes (e.g. in south-western NSW);
 - consider alternative recharge datasets and advances in digital data availability.

The workshop (and the project team) supported the status quo of the existing modelling methodology as appropriate given the low salt load risk. Workshop discussions on the considerable effort required to quantify uncertainties relating to mallee clearing recharge effects concluded that it would likely not be commensurate with the low salt load risk (i.e. it is not warranted for each and every modelling study). Although it is not possible to provide definitive uncertainty estimates without a quantified uncertainty evaluation, this report has provided the best guess possible with the information available. A pilot quantitative uncertainty study may be warranted to determine the magnitude of effects on salinity Registers.

Aggregating monitoring recommendations from the current and previous projects suggests that a monitoring and review project is warranted to:

- review the soil chloride profiles at the 14 sites within 20 km of the River in SA investigated by Cook et al. (2004), and confirm which sites may be worth re-surveying (high priority contemporary indicators of enhanced recharge due to clearing);
- review the construction of the bores at the identified 18 priority sites (Middlemis and Knapton, 2015) to confirm their fitness for the purpose of annual monitoring of levels and salinity (lower priority trailing indicators of enhanced recharge due to clearing);
- review gaps in the network (notably in Victoria where few priority sites have been identified) and consider the need for potential new monitoring bore and/or soil chloride profile sites, and the added value of obtaining soil chloride profiles at key/priority monitoring bore sites that are confirmed as fit for purpose.

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1. Introduction

1.1 BSM2030 KNOWLEDGE PRIORITIES CONTEXT

In June 2016, the Murray-Darling Basin Authority (MDBA) convened a workshop to address a strategic knowledge priority (Figure 1) identified in the Basin Salinity Management 2030 strategy (BSM 2030). At issue was the forecast salinity impacts arising due to historic vegetation clearance and from pre-1998 irrigation developments in the Mallee region (Cummins, 2016), labelled as “Mallee Legacy of History” (LoH).

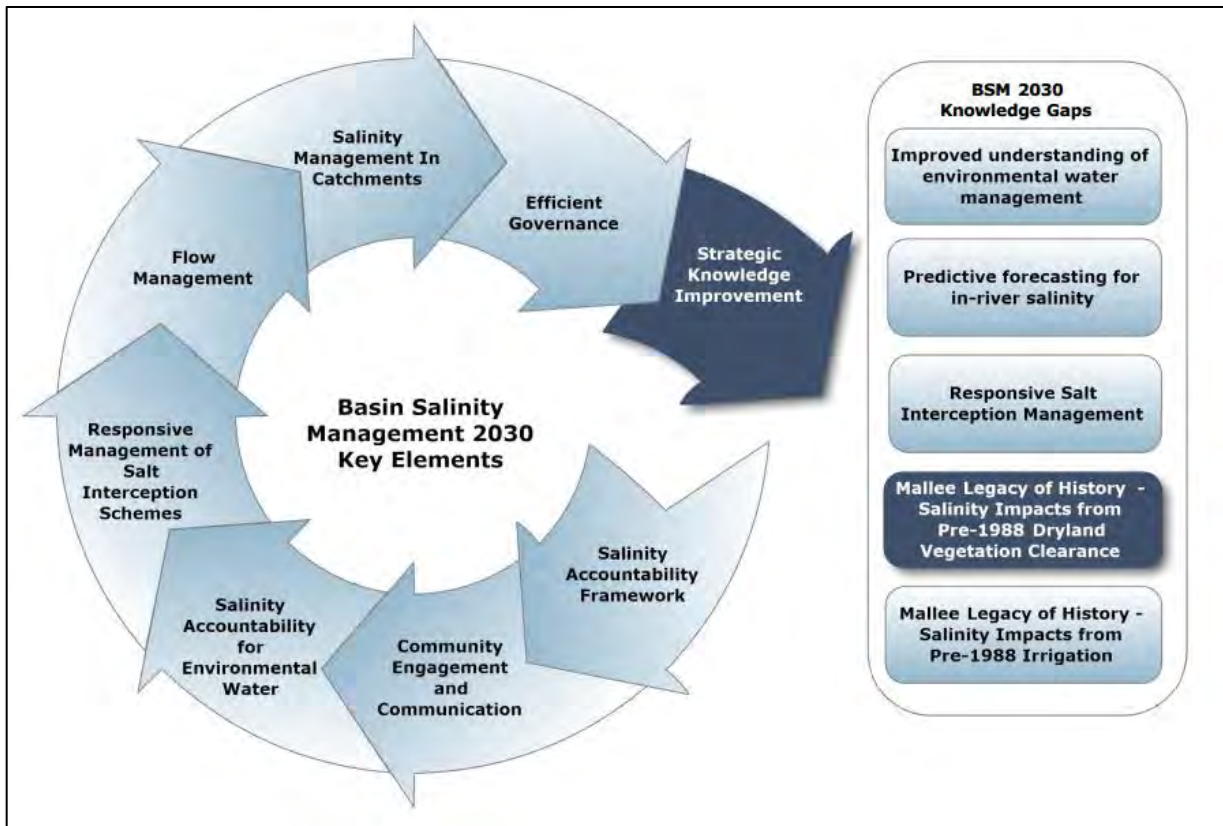


Figure 1 - BSM 2030 Strategic Knowledge Priorities

Mallee Legacy of History salinity impacts result from an action taken, or decision made, in the Mallee region before 1 January 1988, but only that part of the impact that occurs after 1 January 2000 is accountable on Register B (Figure 2; after MDBC (2005), Chart 3.2). The impact that occurs between 1 January 1988 and 1 January 2000 becomes part of the baseline conditions.

The June 2016 workshop recommended investigations to review the current conceptualisation of root zone drainage in the Mallee, to improve the understanding of the drivers of Legacy of History salinity impacts in dryland and irrigation settings.

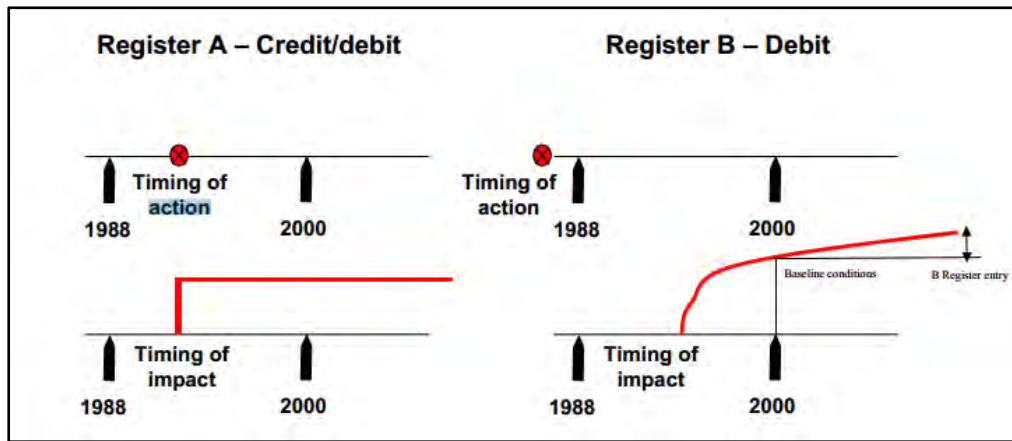


Figure 2 - Timing considerations for salinity register entry calculations

Accordingly, this project critically reviews the evidence for the adopted LoH salinity impact hypothesis that dryland vegetation clearance and its replacement with shallow-rooted agricultural crops results in enhanced root zone drainage, increased (but delayed) groundwater recharge that would drive more salt into the River Murray.

The magnitude of the recharge estimate is highly variable spatially and there can be very long time delays (order of decades) for the recharge to transit the very thick unsaturated zone from the land surface to the water table in most parts of the Mallee (typically tens of metres). Enough time has elapsed and data is available to confirm that the original estimates of enhanced recharge can indeed be very slow to become manifest. The enhanced recharge effect (estimated at 1-50 mm/y) may be manifest in some areas (where short time lags apply) as a subtly rising groundwater level, but it is not so large that it cannot be masked by the effects of other processes (e.g. droughts, floods, agricultural practices). The processes applying are manifestly complex and dynamic, but an improved understanding is warranted to reduce the uncertainties about the future magnitude and timing of salinity risks to the shared water resources.

Although enhanced recharge due to dryland clearing may involve relatively low rates (1-50 mm/y) and hence may have a relatively small effect on groundwater levels compared to other processes, it is quantifiable, and thus it is accountable (in a salinity management context). The effect on groundwater levels due to these relatively low recharge rates can be differentiated from other effects via application of the well-established hydrogeological principle of superposition. This states that the effects of individual processes can be summed to estimate the cumulative effect (USGS, 1984). This also means the effects can be subtracted to unpack individual components. The point is that enhanced recharge due to dryland clearing forms a quantifiable component of groundwater system processes. Even though other processes may have greater (or lesser) apparent effects on groundwater levels, the effects of enhanced drainage and recharge due to mallee clearing form a specific (accountable) component of the cumulative groundwater system processes.

In addition to the innate complexity of the processes applying, it has also become apparent that there may be misperceptions regarding the timing and quantum of these delayed impacts to become manifest, evidenced by anecdotal comments such as:

- “we are not seeing the salt in the river”
- “the salinity effects are being pushed out into the future by the models.”

Such perceptions are at odds with the facts. Predictions of salinity impact due to dryland vegetation clearance have always showed low salt loads reaching the River prior to 2040 and then a significant ramping up due to the inherent time lags (due to the depth to groundwater and intervening clay layers).

Furthermore, the salt loads associated with mallee clearing are small and river conditions so dynamic that it would be almost impossible to isolate a clearing signal from the observed record (hence the need to use models to unpack the effects where river flow, salinity and geophysical measurement methods struggle **to differentiate (“see”) the effect**).

This project is designed in part to help de-mystify such complexities surrounding salinity impacts due to dryland vegetation clearance, but mainly to review the evidence and assumptions for the existing scientific understanding, and to articulate the implications for Register B where the LoH salinity impacts are recorded (Figure 2), the related uncertainties, and to recommend methods for improved and consistent impact assessments.

1.2 SALINITY STRATEGY BACKGROUND

The 1988 Salinity and Drainage Strategy (S&DS) inter-jurisdictional agreement (MDBMC, 1989) was a no regrets approach that allowed for new irrigation development activities, provided salinity mitigation works were implemented. Simply put, irrigation districts were permitted to acquire the right to dispose of saline drainage water, provided they undertook to build and operate salinity mitigation works and measures and/or collaborate financially to do so. The subsequent Basin Salinity Management Strategy 2001-2015 (MDBMC, 2001) expanded this strategy, and established end-of-valley and Basin water quality targets under an integrated catchment management philosophy. Essentially these Basin-scale partnership strategies have at their core a salinity impact trading scheme, whereby if participants wished to implement works or measures that involved salinity impacts (debits), they need also to implement works or measures to reduce or offset salinity impacts (credits), provided the salinity of the Murray River did not exceed an agreed value (<800 EC for 95% of the time) and the credits exceeded the debits.

A baseline (1 Jan. 1988) was agreed that ruled off on past actions, and that all future actions would be held accountable in terms of their salinity impacts, evaluating them against benchmark conditions (1975-85 for the S&DS). Despite reductions in salinity arising from the Strategy, it became apparent that the baseline as agreed was not constant. Some actions taken prior to the 1988 agreement were still able to have a salinity impact after 1988.

Under the 2001-2015 BSMS, the pre-1988 actions were termed Legacy of History (LoH) and parties to the agreement were held jointly responsible. States are accountable for LoH salinity impacts that appear after 01 January 2000 (Figure 2). The salinity impact effects were assessed using models and an agreed climatic/hydrologic sequence; the 'benchmark period' 1975-2000.

The LoH actions were effectively of two types; dryland actions and irrigation area actions. By their very nature, the salinity impacts of these actions were difficult to quantify, and large uncertainty was attached to the impact estimates. Nevertheless, the impacts were derived and incorporated into the BSMS. A new salinity Register (Register B) was instituted within the BSMS framework as the vehicle to explicitly acknowledge the Legacy of History impacts.

1.3 RECENT PRECURSORS TO THIS STUDY

1.3.1 General Review of Salinity Management (MDBA, 2014)

The General Review of Salinity Management (GRoSM) in the Murray-Darling Basin (MDBA, 2014a) concluded (*inter alia*) that:

*...salinity impacts are forecast to gradually increase over time due to the delayed arrival of salt from various landscapes into the river... (however) there are significant uncertainties about the projected extent and timing of salt load accessions and associated river salinity increases...
...based upon the current available knowledge, the largest increases in salt loads are predicted to emanate from the lower reaches of the mallee region arising from relatively recent irrigation development (post-1988) and the delayed salinity impact from past land and water management activities including clearing of native vegetation and historic irrigation development (pre-1988)...*

1.3.2 Mallee Clearing Review (Middlemis and Knapton, 2015)

The GRoSM work led to a subsequent brief investigation (Middlemis and Knapton, 2015), and the June 2016 Knowledge Priority Workshop (Cummins, 2016).

The scope of the Middlemis and Knapton (2015) study was to review groundwater levels and salinity data to test the current conceptualisation of vegetation clearance effects in terms of measurable groundwater level responses to recharge.

Key findings from Middlemis and Knapton (2015) included:

- there is patchy evidence (i.e. not widespread/universal) from dryland monitoring bores of rising groundwater levels post-clearing (mostly less than 1 metre total rise over 20-30 years of record); it is patchy in that wherever a rising groundwater level signal can be identified, there are usually nearby monitoring bores that show flat or falling trends;
- the patchy evidence confirms that the mallee clearing recharge processes have a generally subtle influence on groundwater levels that can be masked by other processes (e.g. changes to agricultural practices and/or climate variability); this is exactly what the original research concluded (Cook et al. 2001);
- monitoring data and analysis difficulties persist, defying simple interpretations (consistent with conclusions from the original research); for example, groundwater level evidence has a subtle influence on water tables, and one that is affected (reduced) by lateral spreading of the water table; this means that groundwater levels alone cannot confirm whether the mallee clearing recharge pulse is yet to arrive at the water table (as the science generally indicates), or whether the pulse has already occurred (e.g. before extensive monitoring began in the 1970s and 1980s); data from soil chloride profiles are also required to be definitive about the current status of the vertical processes;
- recent research (Crosbie et al. 2010b; Wohling et al. 2012) confirmed that the original empirical relationship derived by Cook et al. (2004) between log-normal deep drainage, average shallow clay content (0-2 m below ground) and mean annual precipitation is statistically significant; see section 4.8 for more detail;
- the salt loads attributed to dryland clearing (and the LoH Register entries) are quite low (about 5%-10% of total salt loads across all times through to 2100); this indicates a low risk context (e.g. low compared to irrigation or total salt load impacts);
- given the low salinity impact risk context, the ability to monitor (soil chloride profiles together with groundwater levels), and the long lag times involved, adaptive management was recommended (i.e. monitor and evaluate);
- 18 monitoring bores in dryland areas and within 20 km of the River showing sustained rising groundwater level trends to the present day are priorities for continued monitoring (additional sites were also identified for further research if funding were available); however, as the 2015 study had a focus simply on rising groundwater levels, there are other sites worthy of ongoing monitoring (see recommendations made later);
- as groundwater model calibration performance is relatively insensitive to dryland recharge rates in the order of 1-10 mm/year, modelling cannot be used to determine absolutely whether or not there is a significant influence of mallee clearing on groundwater levels; however, models can be used via uncertainty analysis to investigate the key factors affecting the timing and magnitude of salinity impacts.

1.4 SCOPE OF THIS STUDY

The project brief was developed to address the 2016 workshop recommendation (Cummins, 2016) to review the current conceptualisation of root zone drainage in the Mallee and improve the understanding of a key driver of Legacy of History salinity impacts. The workshop concluded that the patchy (trailing) evidence from monitoring networks of the effect of mallee clearing on groundwater levels, and the inability of models to determine absolutely whether or not there is a significant effect, warranted a critical review of the current conceptualisation of root zone drainage in the Mallee. The review would help to identify if there were a need to adjust any of the assumptions in current model-based salinity impact assessment methodology, and to inform future data acquisition needs. A reconceptualisation would also consider whether other compensating groundwater processes are also occurring.

The scope of work investigated comprises the following, as illustrated in Figure 3:

- Review the conceptualisation of the mallee dryland vegetation clearance processes: deep drainage (below the root zone) and delayed recharge (to the water table).

- Review literature, collate data and convene a workshop to challenge the current paradigm and test alternative hypotheses on groundwater level responses to the clearing of mallee vegetation, with consideration of the underlying assumptions, key factors and uncertainties, including:
 - deep drainage factors (rainfall, root zone average clay content and land use)
 - unsaturated zone properties (storage, hydraulic conductivity and salinity)
 - recharge factors (clearing date, time lags, recharge rates, aquifer storage)
 - other factors (climate variability, drought/wet sequences, agricultural practices, groundwater pumping, post-clearing capillary rise from water tables).
- Consider the implications for vegetation clearance salinity impact Register B entries (magnitude and timing), and scope/prioritise the monitoring and research programs for ongoing testing and validation of adopted conceptualisations.

The focus/scope for this Mallee Legacy of History (LoH) dryland zone root zone drainage (RZD) project (Figure 3) is on the processes and dynamics of vertical drainage below the root zone and delayed recharge to the water table following the clearing of native vegetation and replacement by dryland farming. Matters that are out of scope for this dryland RZD study notably include the following:

- floodplain process issues (although out of scope, it is acknowledged that floodplain processes have a major influence on salt loads reaching the River, and thus they form a key area of uncertainty, one that will be investigated via a separate BSM2030 Knowledge Priority project).
- the capability of the regional numerical models, which are not challenged in terms of their treatment of lateral saturated flow processes (e.g. including local lateral spreading or equilibration of groundwater levels to enhanced recharge).

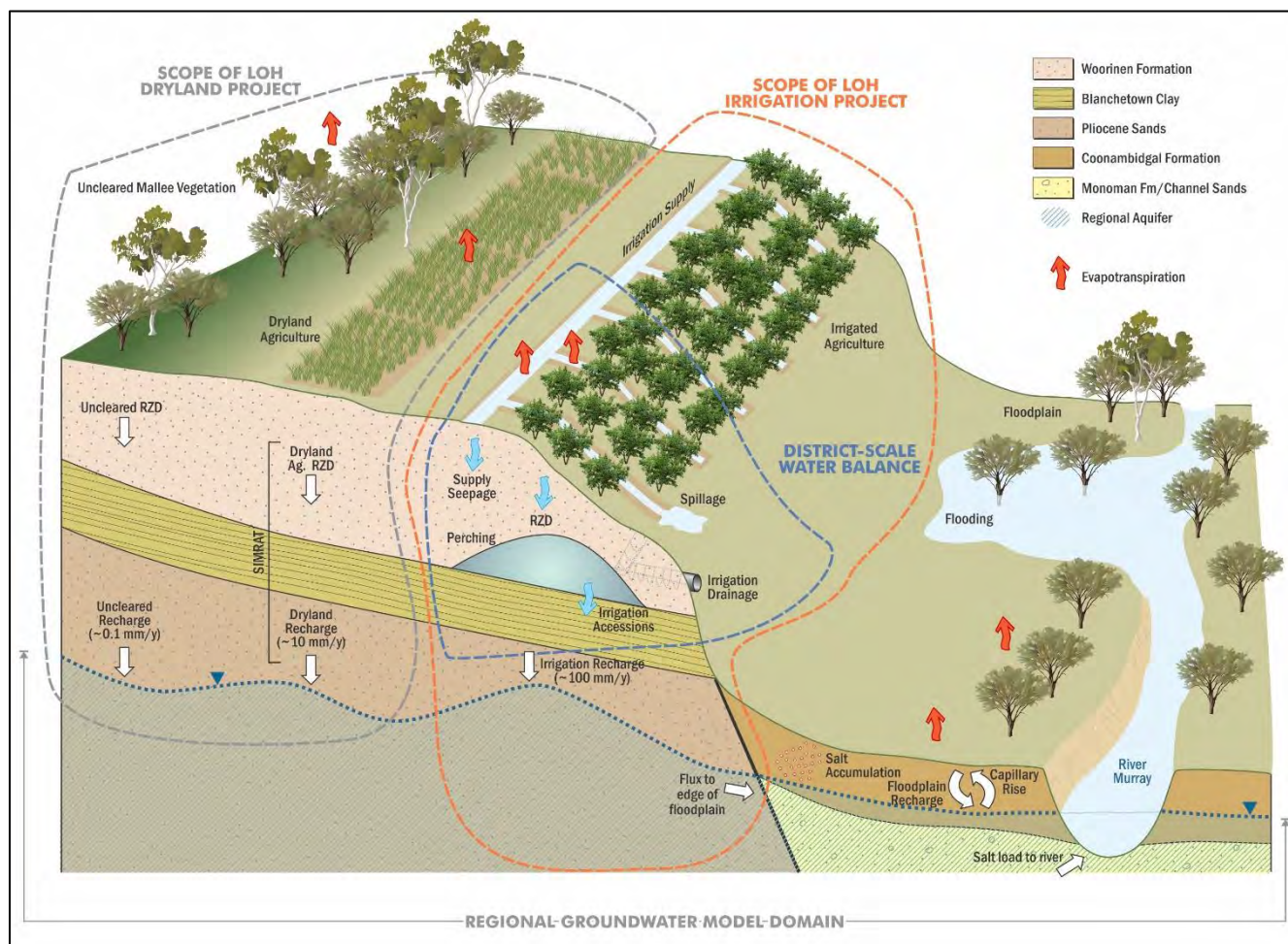


Figure 3 - Mallee zone conceptual models for dryland, irrigation and floodplain

1.5 THIS REPORT

Table 1 - summary of structure and content of this report

Section	Title	Topics discussed and explored
2	Concepts and Assumptions	<ul style="list-style-type: none"> • Firstly, describes the conceptual basic concepts for the empirical Cook paradigm in simple terms (Cook et al. 2004). • Secondly, provides technical detail on the key algorithm elements of the Cook paradigm: RZD estimation, Impeding clay layer (Time lags), Spatial variability, and explores the issue of the Timing of clearing. • Thirdly, describes the Cook algorithms used to derive the mapped recharge reference dataset (Wang et al. 2005) that is encoded in the SIMRAT GIS tool. • Finally, describes how SIMRAT dryland recharge rates and time lag outputs form inputs to regional models for estimating Legacy of History vegetation clearance salt loads to the River.
3	Evidence	<p>Discusses the key evidence datasets:</p> <ul style="list-style-type: none"> • Soil chloride profiles (contemporary indicator). • Groundwater levels & salinity (trailing indicators).
4	Key Assumptions and Alternative Conceptualisations	<ul style="list-style-type: none"> • Discusses technicalities re the key assumptions, including influence of preferential flow, influence of clay layers, date of clearing (1920), soil water content, mallee rooting depth, temporal changes in drainage. • Discusses the implications of assumptions and alternative conceptual models (concludes with validation of Cook paradigm/algorithms).
5	Dryland Recharge in Regional Models	<ul style="list-style-type: none"> • Details how dryland recharge (from SIMRAT) was applied to the SA and Victorian/NSW Register models. • Summarises broad consistencies and minor differences.
6	Uncertainties	<p>Discusses implications of key uncertainty issues, and concludes that there is:</p> <ul style="list-style-type: none"> • Low uncertainty in RZD estimates. • High variability/uncertainty in mapped recharge. • Moderate uncertainty in salt loads.
7	Implications for Salt Loads	Summarises methods, uncertainties and implications for salt loads.
8	Recommendations	<ul style="list-style-type: none"> • Consistent modelling methods. • Monitoring and/or further research.

2. Concepts and Assumptions

This section describes the fundamental research into increased root zone drainage due to mallee vegetation clearance, subsequent groundwater recharge and time lags, and concludes that:

- the Cook paradigm and algorithms are based on the best available science and capture the impact of vegetation clearance action (in BSM 2030 terms) in a systematic and quantitative manner,
- have been independently verified as statistically significant (95% confidence intervals; Crosbie et al. 2010; Wohling et al. 2012; see section 4.8 for more detail), and
- provide dryland recharge data suitable for input to regional models to evaluate the salinity impacts of vegetation clearance (i.e. via regional model inputs that use SIMRAT model outputs of dryland recharge rates and time lags that are derived from the Cook paradigm and algorithms; Woods et al. 2016).

Some key implications of the Cook paradigm and algorithms are described, including:

- not all areas of cleared Mallee would experience within a reasonable time increased drainage and/or exhibit rising water tables (low annual rainfall and/or high clay content (0-2m) result in low rates of RZD and thus long time lags);
- long time lags mean that increased drainage in some areas has not yet reached the water table, and may not reach it in some areas by 2100;
- where drainage has reached the water table, the recharge rates are still quite low (typically 3-9 mm per year in most areas, except in areas of sandy soils such as north and east of Robinvale), making it difficult to validate by monitoring bores;
- the rise in groundwater level at any point is not simply due to aquifer recharge occurring at that point; rather it is a result of recharge occurring in the region, with its spatial and temporal variabilities (further increasing the challenge for monitoring).

Figure 3 (see section 1.4) provides an illustration of the dryland, irrigation and floodplain domains in the Mallee, and the model applications and interactions in the various areas.

2.1 BASIC/SIMPLE CONCEPT

The link between land clearance and river salinisation was first described by Wood (1924) in the Western Australian wheatbelt. Scientific research across the Mallee region of south-eastern Australia over the last 30 years has established that native mallee vegetation clearance has disturbed the delicate hydrological balance and led to increased root zone drainage (RZD) (Allison et al. 1990; Cook et al. 2001).

The basic/simple concept may be summarised as follows:

1. prior to clearing, the perennial, deep-rooted native vegetation used most of the rainfall, RZD was very low (order of 0.1 mm/year) and in equilibrium with recharge to the water table;
2. post-clearing, the shallow-rooted crops and pastures that replaced the native vegetation used less of the rainfall, and deep drainage below the root zone was greatly increased;
3. the increased drainage moves (slowly) under gravity and causes a wetting front;
4. when the wetting front reaches the water table, recharge occurs (i.e. delays involved);
5. additional recharge at the water table below cleared dryland areas generates increased groundwater flux and salt load to the floodplain and river.

While the latter point (5) in the above list is a fundamental hydrogeological principle (one that is adequately represented in regional models) and is not challenged, the first four points of the simple concept are investigated throughout this report. As described later, this review has found that, while these basic concepts are indeed sound, there is variability in the magnitude and timing of enhanced dryland recharge to the water table. This reflects the variability in the soils

and rainfall/climate, as well as land use (clearing, cropping, grazing and other land and water management dynamics). These variabilities lead to uncertainties in the salinity impact estimates.

Further, land use/change data is not captured in detail by the mapping we have available, especially in the pre-satellite era. Recent initiatives may have improved matters (e.g. Sinclair et al. 2012), and other studies are ongoing (e.g. remotely sensed mapping of clearing project in South Australia). However, the current status is that the less than ideal dataset that was available around 2005 has been applied to (adequate but) imperfect models for estimating recharge and time lags, and that recharge model output has been input to regional groundwater flow models to estimate salt loads to the floodplain and River.

These real-world variabilities, data capture issues, and the subsequent model complexities and imperfections, result in uncertainties in estimating salt loads to the River and hence the salinity Register entries. The complexities involved are explored herein.

2.2 MALLEE DRAINAGE/RECHARGE RESEARCH TIMELINE SUMMARY

Research into drainage, recharge and salinization processes in the Mallee began over 30 years ago, and continues to the present, rendering the Mallee one of the most-studied areas of recharge research in Australia. The development of research can be summarised as follows:

- the basic physical processes relating to deep drainage at a point were investigated from 1983 to 1988 (e.g. Allison and Hughes 1983; Cook et al 1988);
- studies from 1988 to 1994 scaled up the processes over large areas in SA, Victoria and NSW (e.g. Jolly et al. 1989; Walker et al. 1991; Cook 1992; Kennett-Smith et al. 1992, 1994) and relationships were developed to estimate deep drainage and recharge from rainfall, soil texture (clay content) and vegetation/land use;
- that information was used to support the first regional groundwater model to investigate mallee vegetation clearance (Barnett, 1989);
- further studies were conducted into Mallee land use change, drainage, recharge and/or salinization processes (e.g. Petheram et al. 2000; Leaney et al. 2004; Wohling 2009);
- by 2005, the drainage/recharge model had been refined firstly using new geophysical and other data (Cook et al. 2004), and then further refined and used to develop spatial predictions of delayed dryland recharge (Miles et al. 2005; Wang et al. 2005), which have been used in all regional Mallee models since 2005 for BSMS purposes.
- the relationships between deep drainage, rainfall, clay content and vegetation that were developed for the Mallee were further analysed (along with other Australian and international relationships) to develop recharge relationships for data-poor areas across Australia (Crosbie et al. 2010; Wohling et al. 2012); these recent studies provided independent confirmation of the validity of the Mallee relationships, as discussed later.

Although the Mallee is one the most-studied areas for drainage and recharge research, it covers a very large area that exhibits large variabilities in climate, landscapes, soil types, vegetation cover, land use and sub-surface conditions. This results in a wide variability in deep drainage and recharge estimates, including the time lag delays between land use change and recharge, and hence there are uncertainty implications for salt loads to the River Murray.

The variability and uncertainty implications in these processes are explored in subsequent chapters, while the following sub-sections present further details on the basic concepts:

- basic concepts for timing of clearing and subsequent root zone drainage and time lags for recharge in sections 2.3 and 2.4 (i.e. basic model points 1 to 4 listed in section 2.1)
- scaling up and modelling in section 2.5 and 2.6
- implications for salt loads in section 2.7.

2.3 TIMING OF MALLEE CLEARING

The main period of extensive clearing of native vegetation was concentrated in the South Australian and Victorian Mallee, while the south-western NSW Mallee has limited cleared areas.

In the South Australian and Victorian Mallee regions, summary histories of clearing are provided in Cook et al. (2001) and Cook et al. (2004), which can be paraphrased as follows.

“Clearing of the native vegetation for agriculture within the Mallee region occurred mainly in the 1910s and 1920s with greatest activity in the periods 1907 - 1914 and 1925 - 1929. Around 55 % of the area [in SA] was cleared in a 25-year period spanning these two decades. Since then, clearing has continued slowly, until restrictions were imposed in the 1980s. Today there are no large areas of mallee vegetation remaining within a 15 km wide strip south of the Murray.”

In the same period, around 72% of the mallee in Victoria was cleared for cropping (Cook et al. 2001). Subsequently, in both states, there was a sudden reduction to the rate of mallee clearing and agricultural development as a result of the economic depression of the early 1930s. Development began to grow again from about the 1950s, and clearing increased until it reduced again in the late 1980s as sustainability principles began to gain importance.

The Mallee lands in the south west of New South Wales are largely uncleared, but with some clearing during the 1960s, 1970s, and early 1980s. Much of the Mallee land in NSW has been operated under leasehold conditions administered by the Western Lands Commission, which has made it relatively unattractive to clear (Kennett-Smith et al. 1991). Although embargoes were placed on clearing in NSW in 1979, which continue to the present, exemptions from the embargo are possible and land clearing is still slowly taking place.

Figure 4 shows the pre-clearing (left frame) and post-clearing (right frame) distribution of vegetation in the Mallee region. Areas of white have been cleared for dryland agriculture, based on National Vegetation Information System (NVIS) data (Department of the Environment, 2012).

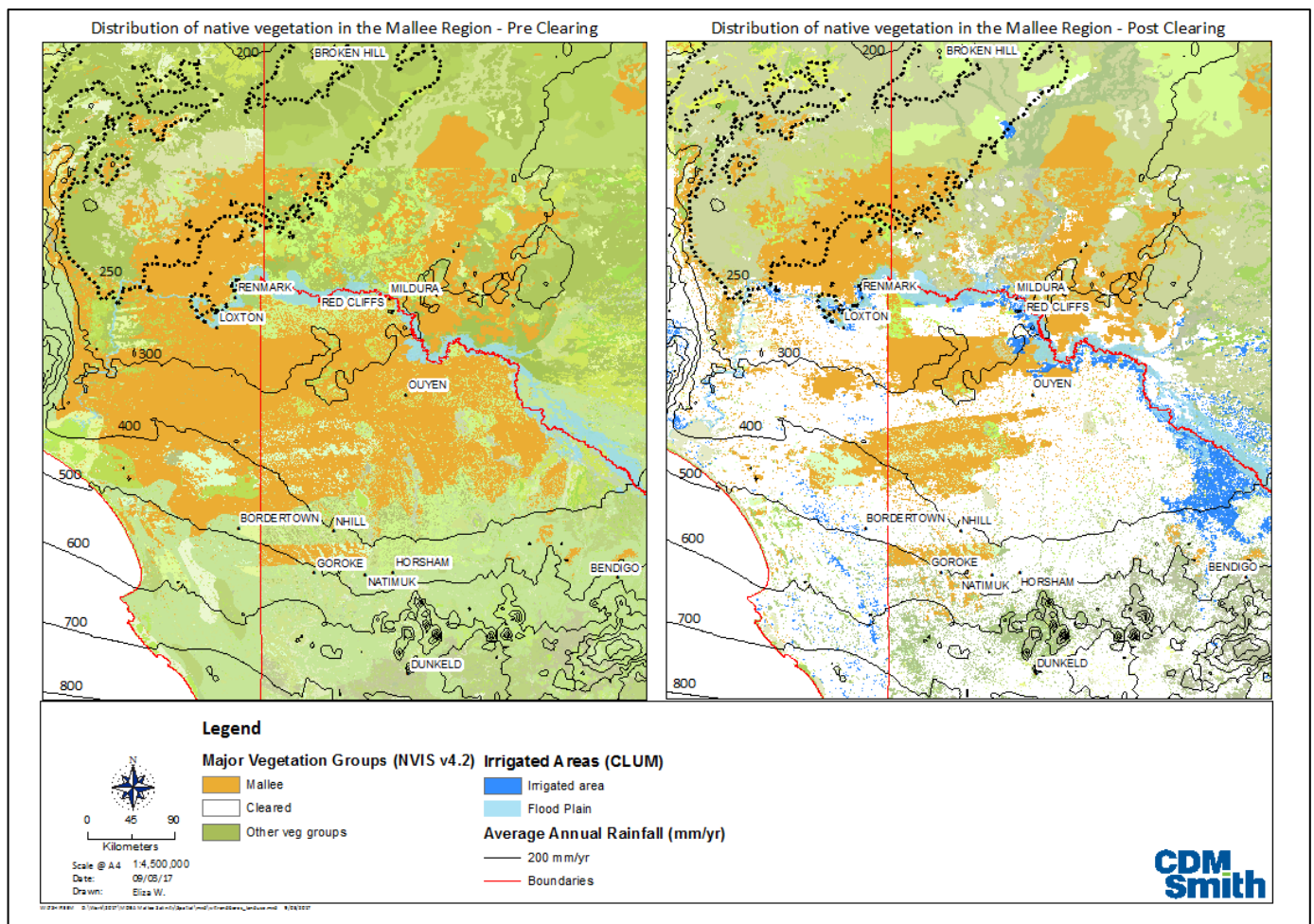


Figure 4 - Distribution of native vegetation pre- and post-clearing (left and right frames)

Despite this understanding, salinity impact assessments usually assume the nominal date of clearing is 1920 (i.e. clearing commenced and was completed instantaneously), and that there was no clearing after 1988. This invokes a data uncertainty, as there is no known documentation of the exact timing and spatial distribution of vegetation clearance. Rather, the current cleared area maps are typically used to assign recharge rate changes and time lags to cleared areas of models, even though there is remote sensing evidence available (e.g. aerial photography since the 1940s, and LandsAT data from the 1980s) that could be used. The timing of clearing is also a modelling uncertainty in that there are no known modelling investigations of the associated uncertainties in terms of the timing and magnitude of salinity impacts that may arise from applying different assumptions.

Nevertheless, there is substantial consistency among the modelling studies in the assumptions **about timing and extent of clearing, and thus a “level playing field” in that regard for Register B entries.** Further discussion is provided in section 4.3.

2.4 DRYLAND ROOT ZONE DRAINAGE AND TIME LAG CONCEPTS

Soil water movement following an increase in root zone drainage associated with the clearance of native vegetation and the development of dryland agriculture has been extensively studied in mallee areas of South Australia, Victoria and New South Wales (e.g. Cook et al. 2001, Cook et al. 2004). The data from these foundational studies were recently analysed in studies by Crosbie et al. 2010, and Wohling et al. 2012, as part of developing recharge estimation methods that can be applied to any location across Australia.

This foundational research compared soil profiles under native vegetation and under dryland farming in adjacent areas. The indication of increased root zone drainage was twofold: measurements of reductions in soil matric potential (indicating wetting) and soil chloride profiles (indicating leaching of salt).

The drainage rate under native mallee vegetation is very small (order of 0.1 mm/year) due to the deep mallee root system in the soil profile. Under agriculture, however, water that is not used by the relatively shallow-rooted crops and pastures and which is not lost to evaporation, will drain under gravity to deeper in the soil profile. Under conditions of piston flow, this infiltrating (**‘new’**) water will push the pre-existing (**‘old’**) soil water ahead of it (**shown by A’ on RHS of Figure 5**). This creates a pressure front, which moves down the profile in advance of the (new) infiltrating water. The result is that the unsaturated zone that was essentially dried by native mallee vegetation becomes slowly wetted up.

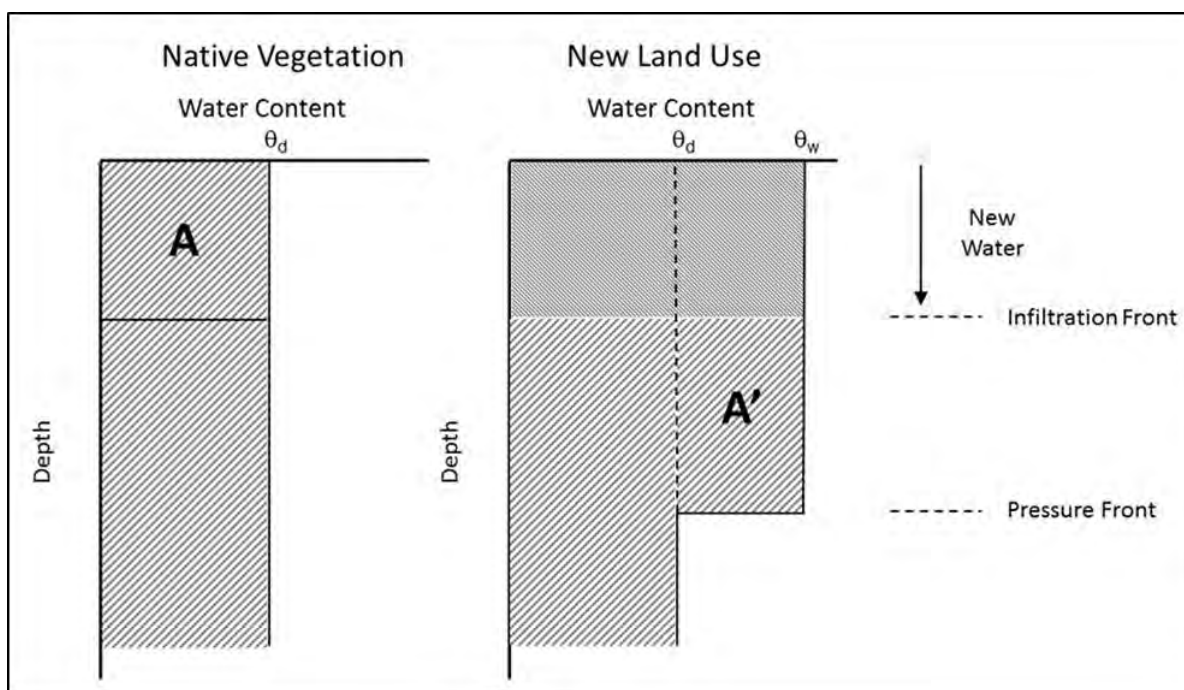


Figure 5 - Water content of the soil under native vegetation and following a change in land use, showing the movement of the pressure front in advance of the solute front

The infiltration front defines the boundary between the ('old') water which was in the soil profile prior to the change in land use, and the ('new') water which has infiltrated since the change in land use. The infiltration front has also been termed the solute front, because this boundary can be distinguished by a change in concentration of chloride solutes in soil water (Jolly et al. 1989). Chloride solutes are usually used for determining the position of the infiltration (solute) front, because the chloride ion is not involved in most soil reactions and is not a significant component of most fertilisers. Matric potential is usually used for determining the position of the pressure front in a soil profile, estimated using the filter paper technique (Greacen et al. 1987). Both the unsaturated zone measurements (soil chloride infiltration front, and matric potential pressure front) are contemporary indicators of the (ongoing) increased deep drainage due to vegetation clearance, whereas groundwater level is a trailing indicator of delayed recharge eventually reaching the water table. This means that, although the groundwater level is much easier to measure, it is not definitive of the status of the deep drainage process without the unsaturated zone measurements (e.g. chloride profiles).

Figure 6 shows an example of chloride and matric potential profiles beneath agricultural land. The site was cleared of native vegetation 9 years prior to sampling, and in this case, the infiltration front is at about 4 m depth, and the pressure front is at about 7 m.

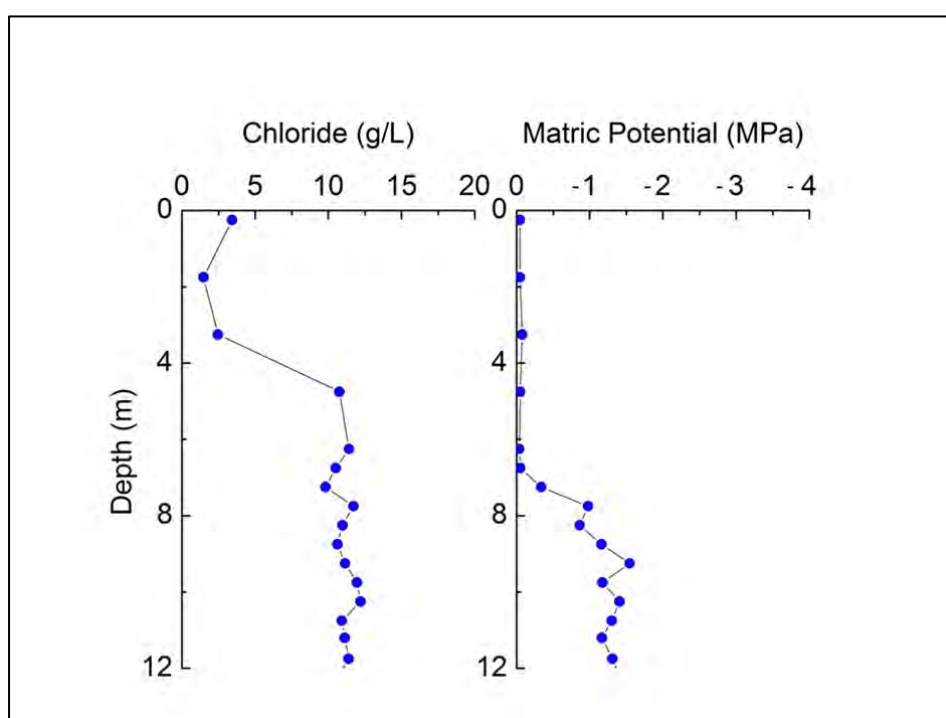


Figure 6 - Chloride and matric potential profiles from a site near Kulkami, South Australia

Until the pressure front reaches the water table, groundwater recharge continues at the same rate as it did prior to the change in land use. Once the pressure front reaches the water table, the recharge rate increases and becomes equal to the rate of root zone drainage (but the salinity of the *in situ* groundwater is effectively unchanged until the solute front arrives; see Figure 6).

A simple mass balance shows that the change in soil moisture storage above the pressure front must be equal to the volume of infiltrating water. Applying this concept to a uniform soil profile, the time lag (t_p) for the pressure front (recharge) to reach the water table can be calculated by;

$$t_p = z_{wt} \frac{(\theta_w - \theta_d)}{D} \quad \text{Equation 1}$$

where z_{wt} is the water table depth, θ_w is the mean volumetric soil water content above the pressure front, θ_d is the mean water content below the pressure front, and D is the rate of drainage (Figure 5).

There is a longer time lag (t_i) for the infiltration (or solute) front to reach the water table (the lower salinity water that has infiltrated since the change in land use; Figure 6), given by;

$$t_i = \frac{z_{wt}\theta_w}{D} \quad \text{Equation 2}$$

For example, Jolly et al. (1989) estimated that it would take about 90 years for the pressure front to reach the water table at 60 m depth following clearing of native vegetation for dryland agriculture at a site in South Australia, and 200 years for the infiltration (solute) front to reach the water table. However, these time lags are strongly influenced by the rate of drainage, which can be highly spatially variable (discussed further in section 2.5).

This means that, over any significant area, there is a distribution of RZD, recharge rates and time lags, due to the spatial distribution of annual average rainfall isohyets, soil types and textures (shallow and deep), and soil water contents.

In summary, the comprehensive research provided strong evidence that the Cook paradigm (points 1, 2 and 3 in section 2.1) of increased vertical drainage due to vegetation clearance holds for most of the Mallee:

- the leaching of salt (chloride profiles) provides a contemporary indicator of the vertical process (ongoing in some areas) and was used to quantify the drainage rate;
- RZD under native vegetation was found to be consistently 0.1 mm/y or less (and in equilibrium with recharge to the water table);
- RZD under agriculture was found to be much greater (1-50 mm/y; or 1.0 to 2.5 orders of magnitude higher);
- the exception is low rainfall areas (**≤250 mm/y**) that had been thinned for predominantly grazing land use (notably south-western NSW), where no significant difference was observed between RZD under mallee and RZD under dryland farming

In chapter 3, we will consider the evidence on how the wetting front becomes recharge at the water table (point 4 of the Cook paradigm described in section 2.1) and the time lags involved (noting that point 5 is a fundamental hydrogeological principle that is not challenged). The following sub-sections explore elements of the Cook paradigm in more detail, including the algorithms to estimate RZD, recharge and time lags.

2.5 THE EMPIRICAL COOK PARADIGM

The fundamental concepts for enhanced dryland root zone drainage due to clearing and delayed recharge to the water table were developed from basic research (section 2.4) at the various investigation sites. The data obtained was used to derive empirical relationships for root zone drainage that incorporated spatial variability and allowed for time lag delays for recharge to reach the water table.

In summary, the empirical Cook paradigm:

- established a correlation between root zone drainage, annual rainfall and average clay content (soil texture) in the near surface soils (0-2 m depth);
- invoked a degree of spatial variability in the deep drainage rate (passing the root zone) by using a log-normal distribution function for mean drainage (distribution mean and variance based on soil core profile data from Cook et al. 2004);
- assumes the water content held in the soil profile is in equilibrium with the drainage rate (i.e. no perching), and applies soil moisture and hydraulic conductivity relationships to calculate the depth of the pressure front and thus the time lag between clearing and recharge at the water table (i.e. water balance basis to calculate time lags);
- allows for an underlying two-layer profile (sand and clay) in the unsaturated zone in the calculation of time lags for drainage to become recharge at the water table.

In simple terms, the Cook paradigm treats the landscape as a set of vertical “columns” in which water moves from the surface to the water table. For any column, root zone drainage can be estimated using average annual rainfall and the mean clay content of the shallow soil (0-2 m). Each column is one member of a population of columns in which deep drainage exhibits a log-normal distribution representative of soil spatial variability.

To map delayed recharge over the Mallee region (e.g. the SIMRAT recharge mapping described in Wang et al. 2005) requires scaling-up the soil column estimates to mean drainage rates for an aggregated area. The log-normal mean drainage rate is calculated using the mean annual rainfall at the site polygon and the mapped soil types (used to infer mean clay content in the upper 2 m), weighted by its proportions within the aggregated area. The deep two-layer (sand and clay) unsaturated zone profile soil texture properties (between the root zone and the water table) are then used to calculate the time lag for the recharge to reach the water table.

These elements of the Cook paradigm and its application to map SIMRAT delayed recharge across the Mallee documented in Wang et al. (2005) are discussed further in the sub-sections below.

2.5.1 Root zone drainage

Rainfall infiltrates from the surface through sandy soils much faster than through clays. The findings from a range of research studies over many years since 1985 were used by Cook et al. (2004) to develop a relationship between the mean root zone drainage rate and mean annual rainfall for near-surface soils (0-2 m depth) with different average clay contents (Figure 7 after Wang et al. 2005, showing the Cook drainage relationship as equation 2). Recent research (Crosbie et al. 2010b; Wohling et al. 2012) confirmed that the empirical relationships are statistically significant (95% confidence); see section 4.8 for more detail.

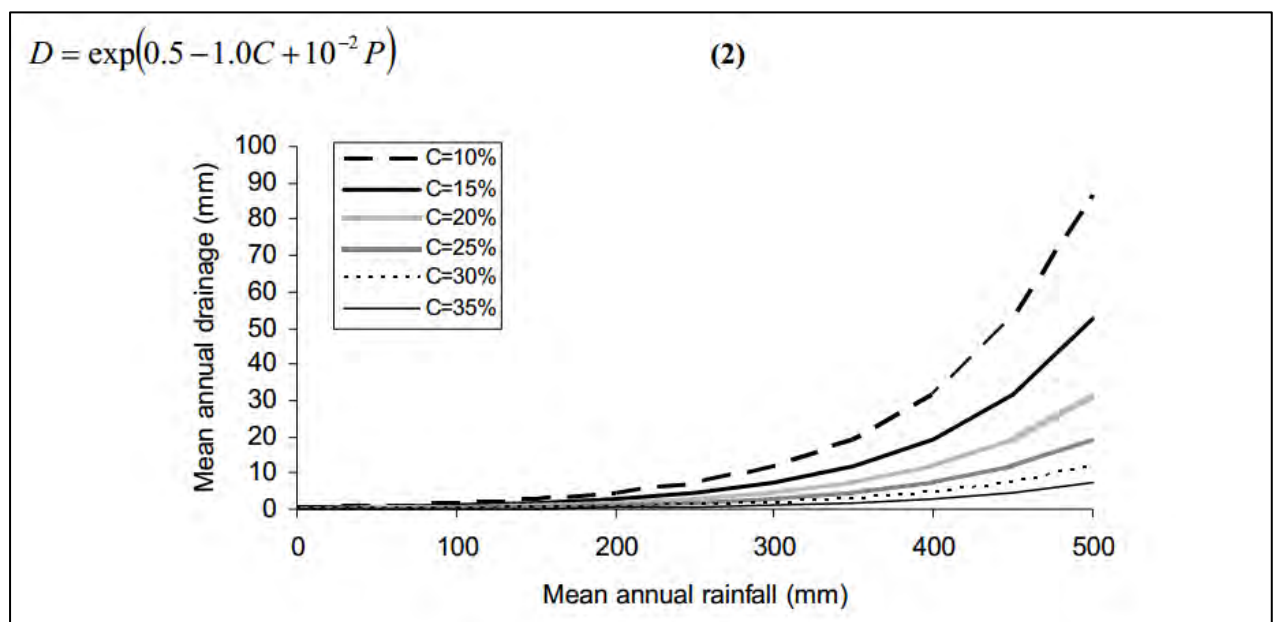


Figure 7 - Relationship between mean annual drainage (D) and mean annual rainfall (P) for soils with average clay content (C) as estimated by equation (2) of Wang et al. 2005

2.5.2 Spatial variability in drainage

While previous sections outline the basic methods used to estimate the mean rate of drainage at a point, this section describes how a log-normal distribution function was applied to account for some spatial variability of drainage.

Basic research has determined that the rate of drainage and rate of recharge are highly variable due to many factors even over small areas for a given soil texture class (Cook et al. 1989b). Further, any rise in groundwater level at any point is not simply due to aquifer recharge occurring at that point; rather it is a result of recharge occurring in the region, and its spatial and temporal variability (Wang et al. 2005).

The main spatial variability problem, however, is that scaling-up of drainage is based on Soil Landscape Unit (SLU) mapping, with its acknowledged limitations for the purpose of determining soil drainage properties. A refinement of Cook et al. (2004) used improved SLU profile mapping (Maschmedt, unpublished) to infer the mean clay content in the upper two metres. This refinement improved the match between the average of the mapped (SIMRAT) recharge rates and the average drainage rates estimated by Cook (1989).

A recent report by Crosbie et al. (2010) described the soils mapping problem succinctly:

“Soils exhibit metre scale heterogeneity and the soil type will vary down a hillslope, all within the same polygon on a map. There will be inaccuracies in the soil that was assigned to each field estimate of recharge but these inaccuracies are consistent with the intended use of the relationships developed.”

This means that, while we may not be able to improve significantly on the existing soils mapping without making more use of new methods such as airborne electromagnetics, the inaccuracies in drainage relationships (including the log-normal spatial variability refinements) reflect to some degree the variability/inaccuracy in the soils/mapping and the landscape.

For example, Cook (1992) showed that the frequency distribution of chloride profile drainage data from 35 soil cores at Borrika obtained over an area of 40 km² in the SA Mallee conforms to a log-normal distribution (Figure 8; after Wang et al. 2005). Furthermore, the spatial variation in drainage was log-normally distributed even for tests on the same soil type.

The rate of drainage has a strong influence on the time delays for recharge to reach the water table. To account for some of the spatial variability in drainage, a probability density function was applied, based on the log-normal distribution. The time series of delayed recharge that reflects the observed spatial variability is calculated by integrating the log-normal distribution of drainage over time (Figure 8), as described in the next section.

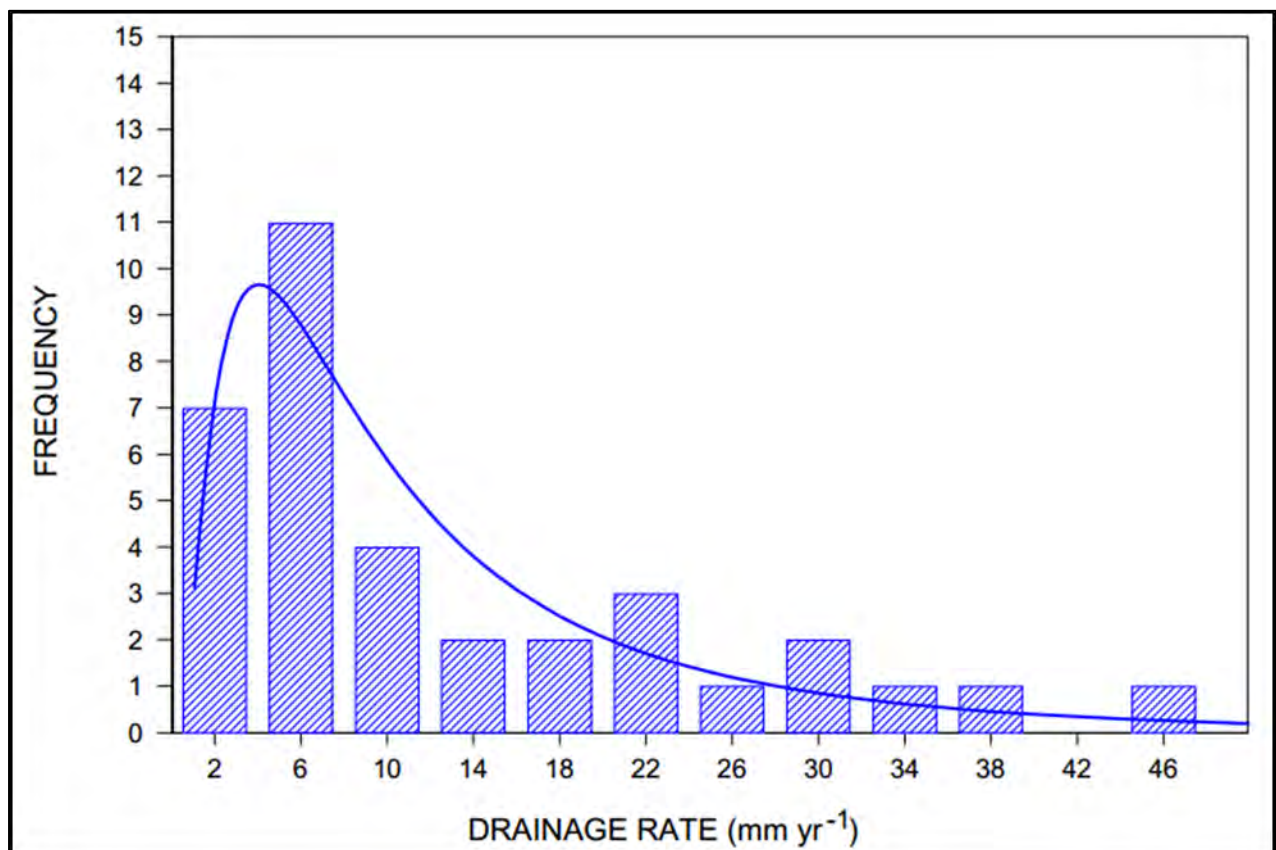


Figure 8 - Log-normal distribution describing spatial variation in drainage

2.5.3 Impeding clay layers and delayed recharge

This section describes the estimation of delayed recharge from drainage rates, and smoothing the transition from pre-clearing recharge (in equilibrium with pre-clearing drainage) to post-

clearing (but delayed) recharge that eventually reaches the water table (i.e. allowing for a smooth transition rather than a step change in enhanced recharge).

A key refinement of the 2004 version of the Cook paradigm (compared to Cook et al. 2001) is to split the (deep) unsaturated zone (between the base of the root zone and the water table) into two homogeneous layers: a sandy loam and a clay. This is a conceptual split, as the algorithm simply calculates the time lag for soil water to drain through an aggregate thickness of sandy loam and an aggregate thickness of clay. The aggregate thicknesses can represent any number of actual layers of sandy loam and clay (in any order) in the unsaturated profile (provided the data input layers have carefully accounted for the aggregation). The effect of the (deep) impeding clay layer is to increase the time lag for drainage to reach the water table and become recharge. A key assumption is that the enhanced drainage rates due to dryland clearing are not so high as to cause perching on the (deep) clay layer.

The allowance for a low permeability layer within the (deep) unsaturated zone profile to impede the downward movement of infiltrating water is warranted, considering the extent and thickness of Blanchetown Clay above the water table across much of the northern Mallee with its otherwise ubiquitous sandy soils. While the Blanchetown Clay is absent in some areas, these areas are mapped and can be accounted for in the algorithm. There are a few other areas where different clay units occur above the water table, but they are well mapped in the northern Mallee, and their effect should be accounted for in aggregating the thickness of intervening clay for the input data layers and/or could be accounted for in future refinements (see also section 4.2).

The drainage rate (see previous sections) and deep soil profile texture type determines the water content that can be held in the deep profile in equilibrium with the drainage rate (Wang et al. 2005). The higher the drainage rate, and the less clay in the deep profile texture, the faster the pressure front will move downwards (i.e. put another way, for every metre of Blanchetown Clay in the deep profile, the time lag for recharge will increase by 2-5 years; Cook et al. 2004).

To account for these complexities, the deep drainage algorithm (Cook et al. 2004) was refined to include relationships between soil water content and hydraulic conductivity:

- **this involves a routine for calculating θ_w** (mean volumetric soil water content above/behind the advancing pressure front; see Figure 5), based on the post-clearing rate of root zone drainage (Cook et al. 2001);
- the relationship of moisture content and hydraulic conductivity (refinement of Cook et al. 2004) can then be applied for the sandy loam properties and for the clay properties (Figure 9; after Wang et al. 2005) that make up the 2-layer deep profile.

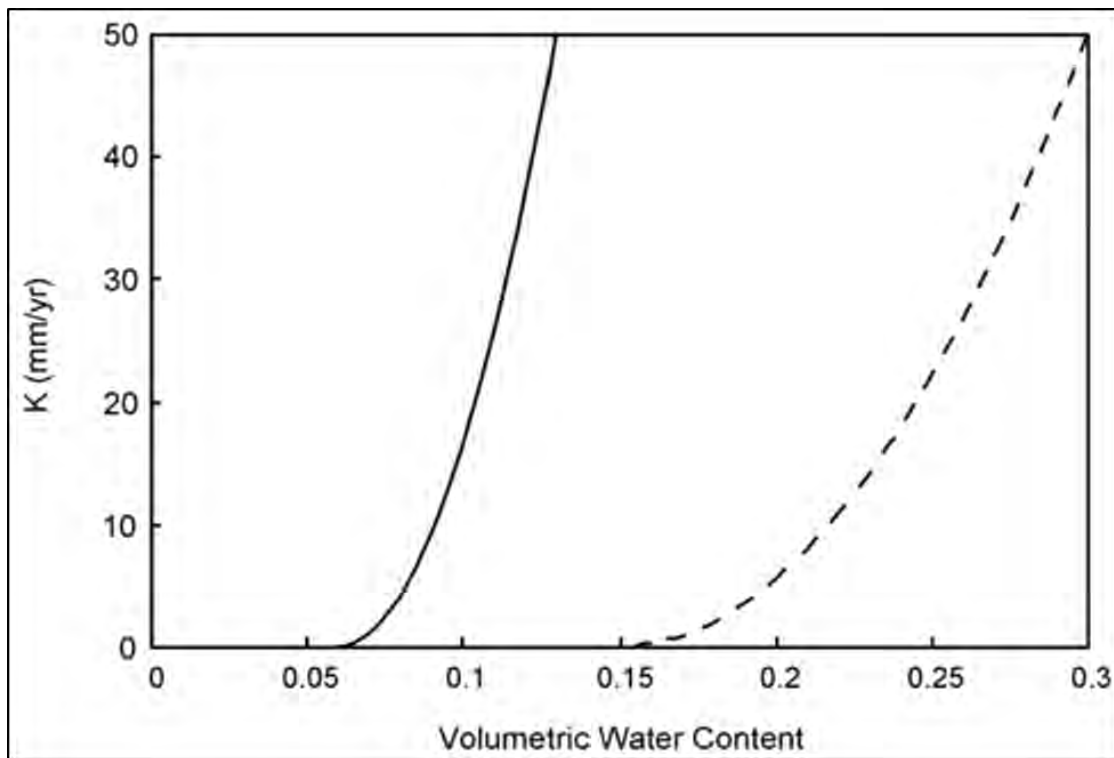


Figure 9 - Hydraulic conductivity versus water content for sandy loam (solid line) and clay soils (broken line)

The time series of delayed recharge is calculated by integrating the log-normal spatial distribution of drainage over time (see Figure 8), accounting for the 2-layer deep profile of sandy loam and clay (Figure 9).

For example, Figure 10 (after Wang et al. 2005; Kittiya Bushaway, DEWNR, pers.comm.) shows time series of recharge rates for zones with a 7-8 mm/y drainage rate (due to similar rainfall and mean clay content (0-2m) properties), but with very different time lags (due to different depths to groundwater and clay thicknesses). Similar plots can be drawn for different maximum drainage rates (due to different rainfall and shallow clay contents) and/or for different lag times (due to different depths to groundwater and intervening clay layer properties).

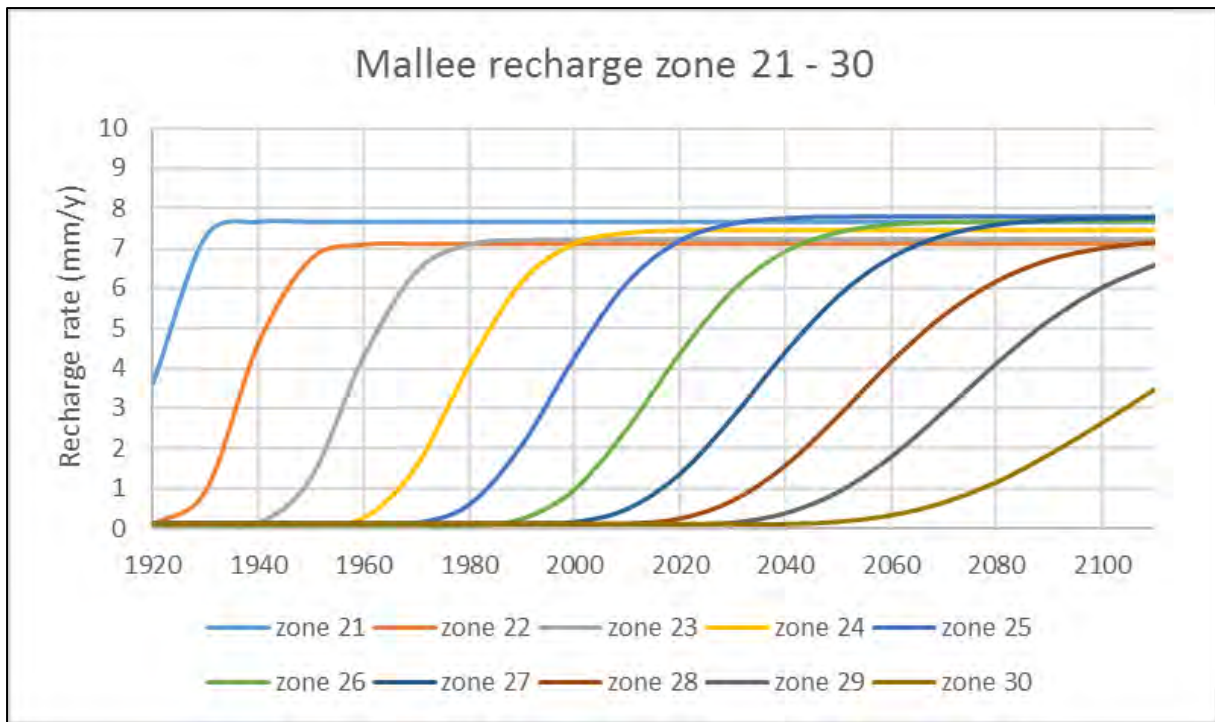


Figure 10 - example of recharge rate time series for zones with different time lags

2.6 COOK PARADIGM BASIS FOR SIMRAT

The algorithm refinements discussed in section 2.5 were eventually coded into the SIMRAT (Salinity Impact Rapid Assessment Tool) GIS tool that is used for mapping dryland delayed recharge estimates (Wang et al. 2005; Woods et al. 2016). Wang et al. (2005) applied these refined algorithms and extrapolated them to map recharge rates and time lags across the SA Mallee. The same methods were applied to extend the recharge mapping east from the SA border by the (then) SA Dept of Environment and Heritage (Matt Miles, DEWNR, pers.comm.). Figure 3 (see section 1.4) provides an illustration of the dryland, irrigation and floodplain domains in the Mallee, and the model applications and interactions in the various areas.

The SIMRAT model uses algorithms from the Cook paradigm and input data for:

- average annual rainfall isohyets (spatially variable);
- soil texture relationships (spatially variable);
 - average clay content in upper 2 m of soil (Figure 7), using data from soils mapping;
 - impeding clay layer properties in the unsaturated zone (Figure 9);
 - log-normal distribution of drainage rates (Figure 8), giving a more gradual wetting process (**“S-curve” of increasing recharge with time**) with spatial variability) see further explanations in previous sections;
- depth to water table data (spatially variable).

The initial stage of a formal review process for SIMRAT (instigated by the MDBA) has been completed (Woods, Peat and Middlemis, 2016). The review investigated the SIMRAT conceptualisation and mathematical basis of the algorithms applied to estimate the effects of vegetation clearance and irrigation, deep drainage, delayed recharge and transmission to the River Murray. They found that SIMRAT continues to be fundamentally suitable for its primary purpose to assess salinity impacts of greenfield irrigation sites in the Mallee region as a rapid assessment tool (**to “explain the maximum amount of change in River salinity impacts with the smallest set of variables”**; Fuller et al. 2005). More importantly for this project, they found that the equations and assumptions are essentially sound where the hydrogeology is relatively simple, and the recharge rates and time lags are suitable for input to regional groundwater models for BSM2030 purposes to evaluate the effects of dryland clearing. They noted that the assumptions are not met in some areas (e.g. where there is perching on clay layers below irrigation areas),

and there are also some uncertainties that should be addressed. Certain of these factors were investigated and the results presented and discussed in Woods et al. (2016), along with discussion of the implications for time lag estimation, and those findings remain valid. Furthermore, all the regional models that use these SIMRAT estimates for dryland recharge and time lags have been independently reviewed, confirming that the model and the recharge data are fit for the purpose of salt load accountability.

2.7 IMPLICATIONS OF FUNDAMENTAL CONCEPTS

In summary, comprehensive research provides strong evidence that the Cook paradigm of increased vertical drainage due to vegetation clearance holds for most of the Mallee:

- the leaching of salt (chloride profiles) provides a contemporary indicator of the vertical process (ongoing in some areas) and was used to quantify the drainage rate;
- RZD under native vegetation was found to be consistently 0.1 mm/y or less (and in equilibrium with recharge to the water table);
- RZD under agriculture was found to be much greater (1-50 mm/y, or 1.0 to 2.5 orders of magnitude higher than under mallee);
- **the exception is low rainfall areas (≤ 250 mm/y) that had been thinned for predominantly grazing land use (notably south-western NSW), where no significant difference was observed between RZD under mallee and RZD under dryland farming**
- not all areas of cleared Mallee would experience within a reasonable time increased drainage and/or exhibit rising water tables (low annual rainfall and/or high clay content (0-2m) result in low rates of RZD and thus long time lags);
- long time lags mean that increased drainage in some areas has not yet reached the water table, and may not reach it in some areas by 2100;
- where drainage has reached the water table, the recharge rates are still quite low (typically 3-9 mm per year in most areas, except in areas of sandy soils such as north and east of Robinvale), making it difficult to validate by monitoring bores;
- the rise in groundwater level at any point is not simply due to aquifer recharge occurring at that point; rather it is a result of recharge occurring in the region, with its spatial and temporal variabilities (further increasing the challenge for monitoring).

This review has found that the Cook paradigm and algorithms for dryland RZD, recharge rate and time lag estimates:

- are based on the best available science and capture the impact of vegetation clearance action (in BSM 2030 terms) in a systematic and quantitative manner,
- have been independently verified as statistically significant (95% confidence intervals; Crosbie et al. 2010; Wohling et al. 2012; see section 4.8 for more detail), and
- provide dryland recharge data suitable for input to regional models to evaluate the salinity impacts of vegetation clearance (i.e. via regional model inputs that use SIMRAT model outputs of dryland recharge rates and time lags that are derived from the Cook paradigm and algorithms, with fit for purpose representation of the spatial and temporal variabilities; Woods et al. 2016).

3. Evidence

The previous section found the Cook paradigm and algorithms to be sound, based on a large number of independent field studies over more than 30 years of investigation, including ongoing comparisons with monitoring that have not identified any anomalous measurements. The Cook paradigm and algorithms provide a sound basis (best recharge estimate) for the purpose of input to regional models to evaluate the salinity impacts of mallee vegetation clearance.

This chapter discusses how the observational evidence available from soil chloride profiles provides support to the Cook paradigm, and how the monitoring bore evidence compares with the SIMRAT recharge estimates that are based on the Cook paradigm.

3.1 SOIL CHLORIDE PROFILES

A recent study into potential salinisation risks in the SA border zone of the southern Mallee (CDM Smith, 2016) is highly relevant. It considered available research on soil chloride profiles in the unsaturated zone and other key factors such as rainfall variability, groundwater level and salinity monitoring, soil texture and land use change effects.

Importantly, the CDM Smith (2016) study confirmed that:

- there is evidence from soil chloride profiles of increased drainage due to vegetation clearance still working downwards towards the water table in many areas;
- some groundwater levels show dynamic changes due to forestry, irrigation drainage and/or pumping (prevalent in the southern Mallee) that largely overwhelm enhanced drainage due to vegetation clearance, and measurement uncertainty is a contributing factor to the variabilities observed.

Other CDM Smith (2016) conclusions included:

- unsaturated zone chloride profiles are contemporary indicators of deep drainage processes, and there is widespread evidence of salt stores in the unsaturated zone being mobilised towards the water table;
 - evidence for this comes from a wide range of research, including recent work by Wohling 2007 and Wohling et al. 2012 that is subsequent to the original Mallee research by Cook and others;
 - this is an important finding that confirms the value of soil chloride profile data in providing objective evidence that verifies the Cook paradigm of enhanced deep drainage and long lag times under vegetation clearance;
- saturated aquifer groundwater salinity and levels are trailing indicators of deep drainage processes that occur over decades, but there is no widespread evidence in the Border Zone of increasing groundwater levels and salinity concentrations, aside from **observations at a few bores (this “patchy” finding from trailing indicator data analysis is consistent with Middlemis and Knapton, 2015);**
- key factors affecting deep drainage rates are land use (clearing of native mallee and subsequent dryland farming), root zone soil texture, depth to groundwater and intervening low permeability layers, while climatic variability and groundwater pumping are processes that can mask changes in deep drainage rates;
- the study was undertaken in an area where groundwater pumping for irrigation is prevalent, and confirmed that this has a much larger effect on groundwater levels than rainfall
 - while groundwater pumping is not a current risk factor in the northern Mallee (i.e. for the focus of this LoH study within 20 km of the River), other than near Salt Interception Scheme (SIS) borefields, future technological developments on water treatment and renewable energy may bring this factor into play in terms of irrigation water supply options, so it should not be ignored;
- there is an underlying climatic variability influence apparent on salt accretion processes over decadal scales, confirming the very slow deep drainage process in train, and re-

visiting soil chloride profiles investigated is warranted to quantify any climatic effects due to recent dry and wet periods:

- since 2007 through to the end of the drought (to 2010);
- the subsequent very wet period (2010-11);
- the relatively average period (2012-15);
- the recent wet period (second half of 2016).
- recommendations for further research (e.g. chloride profiles) and/or monitoring (e.g. bore levels and salinities, and bore design/construction) is warranted at:
 - 14 priority sites within 20 km of the River in SA investigated by Cook et al. (2004);
 - lower priority sites that have been investigated by Jolly et al. (1990), Cook (2001), SKM (2004) and Wohling (2007);
- detailed information on monitoring bore design, construction and contextual siting is required to reduce measurement uncertainties, because:
 - salinity sampled from groundwater bores is only representative of a small area surrounding the bore (scale of tens of metres, consistent with the findings of Cook 1989) and will be influenced by local factors (such as land use and soil texture) that may not reflect the surrounding region;
 - monitoring bore screen intervals need to be placed over a short interval at the water table to reduce groundwater salinity measurement uncertainties, because groundwater mixing processes occur very slowly from the water table down; most monitoring bores tend to sample a broader water column (particularly if the screen interval is long) or may sample from much deeper parts of the aquifer (if the screens are deep).

3.2 GROUNDWATER LEVEL TRENDS

Before considering groundwater level evidence, it is worth summarising the Cook paradigm and related research findings:

- root zone drainage under native mallee vegetation was consistently 0.1 mm/y or less and in equilibrium with recharge to the generally deep groundwater levels across the Mallee;
- root zone drainage under the dryland agriculture that replaced cleared mallee was generally 1.0 to 2.5 orders of magnitude greater (1-50 mm/y);
- the only land use for which there was no significant difference between RZD under native vegetation and RZD under dryland farming was for low rainfall areas (≤ 250 mm/y) that had been thinned for grazing (i.e. notably in south-western NSW).

A quantitative comparison is made below in terms of overlaying the Wang et al. (2005) mapped recharge dataset (i.e. the SIMRAT outputs of time-lagged dryland recharge that are based on the Cook paradigm/algorithms) against the trends in groundwater levels. An exact match should not be expected as the Wang/SIMRAT dataset is a set of one-dimensional (“vertical column”) estimates, whereas the monitoring bores time series trends reflect the 2D/3D aquifer system and are subject to other influences.

3.2.1 Time series trends

The scope of the precursor to this project, Middlemis and Knapton (2015), was to review groundwater levels and salinity data in dryland areas to identify any sustained response to vegetation clearance effects. They used a 10 mm/y cut-off in trend analysis on suitable wells (e.g. more than 4 km from mounds due to irrigation or salt disposal basins and not on the floodplain where shallow water tables occur). The aim was to identify sustained rising trends (i.e. from more than 10 years of record) to the current time, so some short term/early time data was rejected, along with bores with variable trends.

The data on monitoring bore water levels from Middlemis and Knapton (2015) was re-visited for this study, with the following refinements:

- a subjective interpretation of the time series trend was invoked over the basic mathematical trend line (as that is affected by outliers in the data set) to help identify variable trends (not just sustained rising trends), including:
 - long term steady and/or falling trends (including short term effects due to other factors such as drought/wet/flood periods)
 - non-sustained rising trends (e.g. early rising trend but subsequently showing influence of other factors; or not sustained to present day due to data record length).
- Figure 11 shows the results of the monitoring bore time series trend analysis overlaid on annual rainfall isohyets.

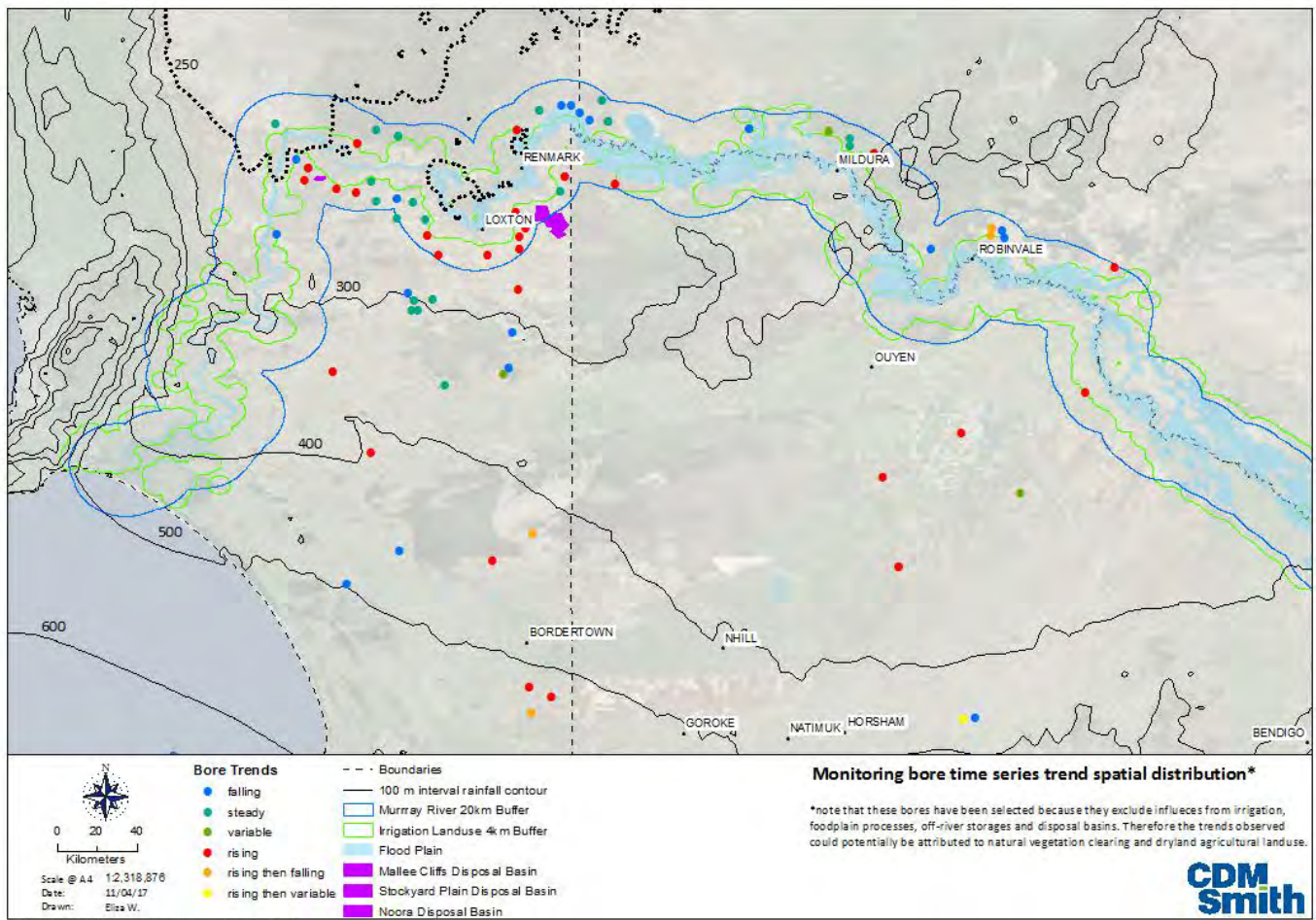


Figure 11 - monitoring bore time series trend spatial distribution

Figure 11 does not show time series trends for bores that have been disqualified (for this comparison purpose) on the basis of completion in Renmark Formation, or proximity to: irrigation, floodplain, disposal basin, Lake Victoria operations, SIS pumping. They represent trends that could potentially be attributed to cleared dryland agriculture areas.

Detailed interpretations of Figure 11 indicate:

- the **“patchy” long term trends** are evident across SA and Victoria, as identified previously (Middlemis and Knapton, 2015):
 - rising and steady trends near the River in the northern Mallee are consistent with the Wang/SIMRAT dataset, as shown in Figure 13 (later);
 - falling trends in SA within 20 km of the River are isolated and likely reflect the spatial variability associated with the processes involved (e.g. Figure 13), and/or the influence of the multi-decadal lower rainfall trend evident in the cumulative rainfall

- deviation plot from 1920-1945 and 1980-present (Figure 12), which shows short term spikes due to very wet periods (e.g. notably 1974 and 2011);
- where falling trends are identified in SA in the central to southern Mallee, these can also be influenced (depending on their location) by groundwater pumping for irrigation or sand mining or Woolpunda SIS (drawdown effects in confined aquifers can be extensive);
 - within the scope and budget of this project, assessment of the available data in the Victorian Mallee region showed trends that were inconclusive, but analysis by others of average trends in groups of monitoring bores in the Victorian Mallee have not identified any significant rising trends (GHD, 2014; SKM, 2014);
 - most bores in NSW within 20 km of the River show long term trends are steady to declining as identified previously (Middlemis and Knapton, 2015), suggesting that the mallee clearing recharge influence on groundwater levels is subdued in south-western NSW, due to the following factors:
 - the limited area of vegetation clearance (Figure 4) and dominant grazing land use,
 - most of the area is mapped as uncleared (i.e. the recharge rate over the majority of the region is very low at 0.1 mm/y; see Figure 13 later),
 - the limited areas of clearing are subject to relatively low recharge (mostly less than 12 mm/y), and the combination of limited area and low recharge rate would generate a low total recharge flux input,
 - long time lags of 50-150 years apply across most of the NSW mallee, even for the sandy soil areas north of Robinvale, resulting in low rates of predicted SIMRAT recharge at 2000, mostly less than 3 mm/y (Aquaterra, 2009a),
 - the multi-decadal declining rainfall trend evident in the cumulative rainfall deviation plot (Figure 12) is punctuated by short term noise that can be attributed to major wet/flood periods, and/or,
 - in recent decades and depending on location, the additional influence of declining groundwater mounds under irrigation, changes to operating rules for Lake Victoria, changes to flows in the Darling Anabranch and/or the River Murray and SIS pumping/disposal, which have an apparent influence on observed groundwater levels in bores many kilometres distant.

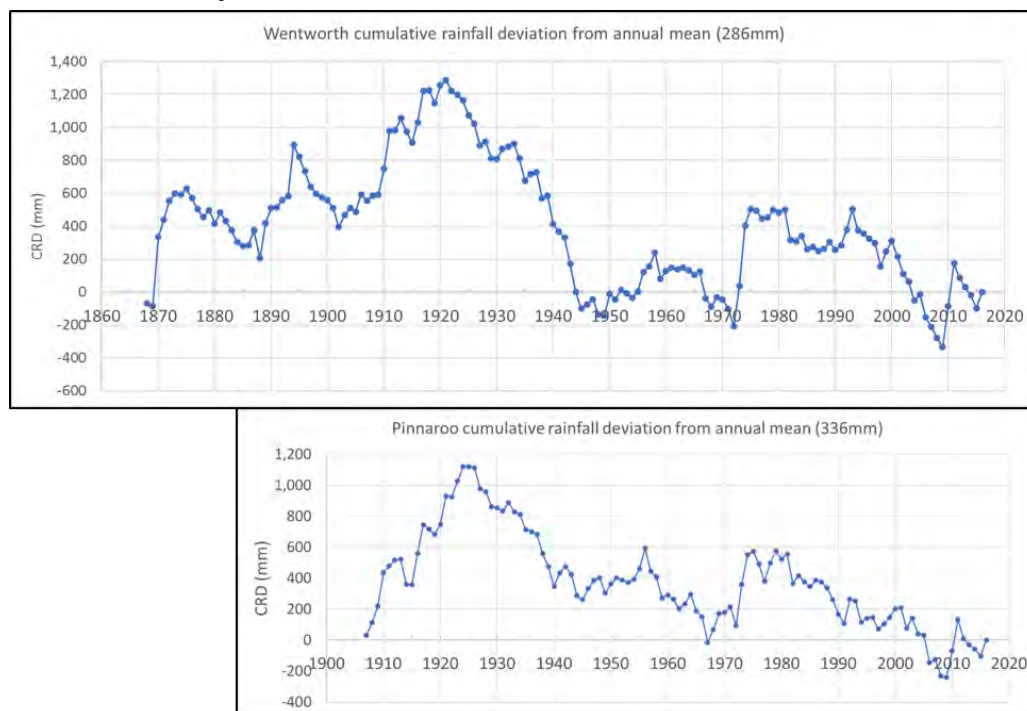


Figure 12 - Wentworth and Pinnaroo cumulative rainfall deviation from annual mean

In summary, there is a wide range of complex confounding factors that makes it extremely difficult to observe changes in the (trailing indicator) groundwater level fluctuations and eventually changes in the river. Key factors relate to changes in rainfall, but more particularly to land use, for which the limited pre-88 data has not been collated into a centralised format that would allow for some interpretations as to the potential drivers for apparent trends. There is more discussion on land use variability in sections 4.3 and 4.6.

3.2.2 Comparison of groundwater level trends with recharge estimates

Figure 13 presents the SA groundwater level trends overlain on the (SIMRAT) map of delayed recharge rates at 2004 (i.e. allowing for time lags) derived by Wang et al. (2005), exhibiting reasonable consistency. The 2004 map of SIMRAT delayed recharge is the only plot available for a recent period (i.e. it is not ideal for comparing to the latest data on groundwater level changes).

Where monitoring bores show a declining trend (open dots) or a low rate of rise (green-blue dots), they are near areas with zero or low rates of delayed recharge at 2004 (i.e. no shading or green/blue shading resp.).

Similarly, bores showing a higher rate of rise are near areas with higher rates of mapped (delayed) recharge at 2004 (purple/yellow shading), noting that there are few areas with more than 9 mm/y recharge predicted.

As there is no raster image available for mapped recharge in NSW and Victoria, the Figure 13 plot cannot be extended into NSW. However, Figure 14 shows a plot of SIMRAT delayed recharge rates calculated using the method of Wang et al. (2005) for the EM1.2 model area that was used for LoH scenarios in Victoria and NSW (after figure 15 of Aquaterra, 2007). The delayed recharge data (Figure 14) shows spatial variability in the rates applied to uncleared (vegetated) areas in NSW and Victoria:

- 1% of mean rainfall for uncleared non-woody veg. (i.e. 1-3 mm/y; shows as olive shading in Figure 14 across certain parts of north-western Victoria and south-western NSW);
- 0.1 mm/y for uncleared woody vegetation (extensive areas of pale blue shading).

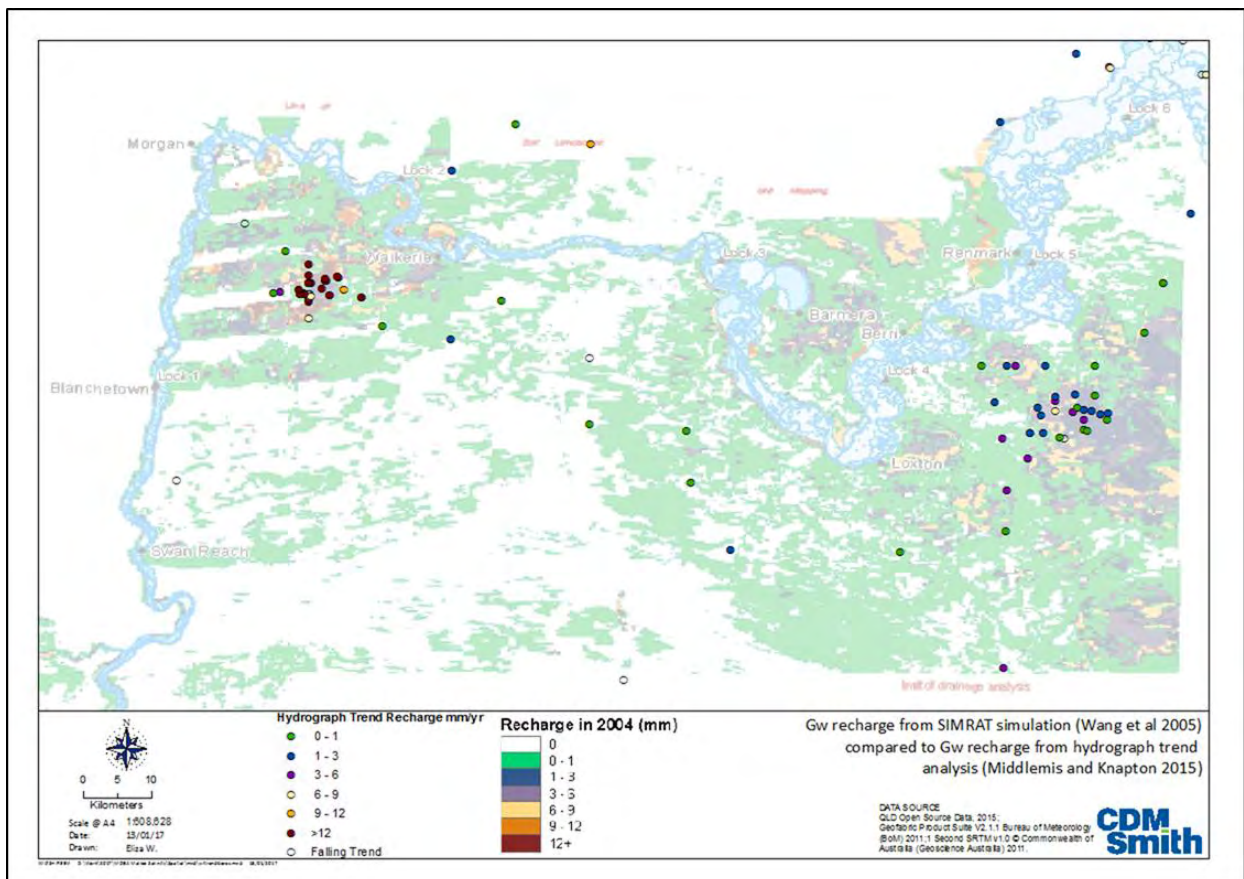


Figure 13 - monitoring bore trends overlaid on SIMRAT delayed recharge at 2004

Figure 14 shows the generally low delayed recharge estimates for the eastern Mallee in Victoria, and especially for most of south-western NSW (the implication is that low salt loads would be expected). In south-western NSW in particular, it reflects the limited area of vegetation clearance (Figure 4) and dominant grazing land use. Research identified an exception to the Cook paradigm (section 2.4) applies in low rainfall areas of south-western NSW that were thinned for grazing in that there is no significant difference between RZD under native vegetation and RZD under dryland farming in these areas. There is also a multi-decadal declining rainfall trend evident in the cumulative rainfall deviation plot (Figure 12). Depending on location, there are additional influences on groundwater levels from declining groundwater mounds under irrigation, changes to operating rules for Lake Victoria, changes to flows in the Darling Anabranch and/or the River Murray and SIS pumping/disposal that help to explain the generally steady to declining bore time series trends observed in south-western NSW (Figure 11). See discussion at section 3.

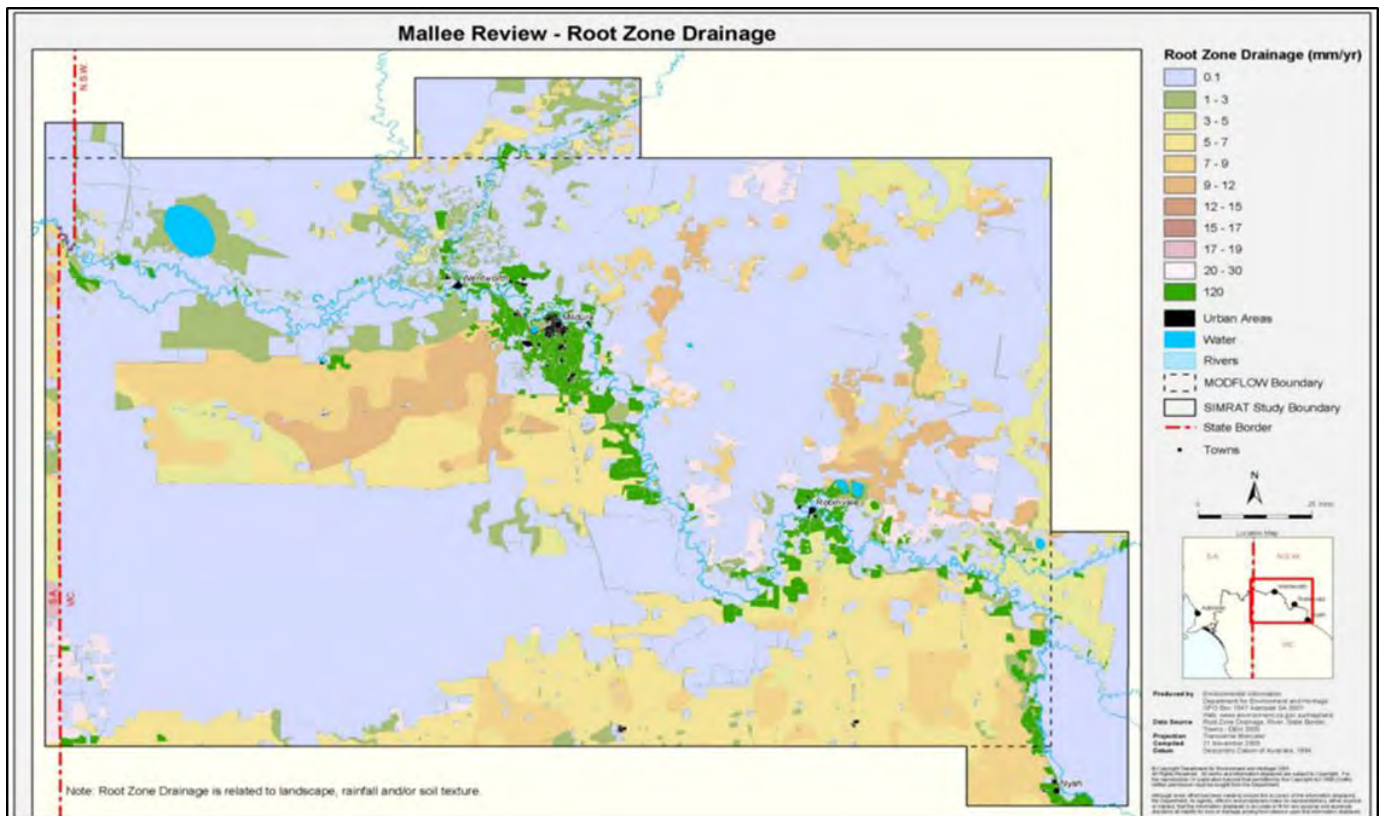


Figure 14 - SIMRAT RZD basis for dryland recharge in EM1.2 model

3.3 FUNDAMENTAL DATA UNCERTAINTIES

Measurement uncertainty affects groundwater monitoring bore data and analysis, defying simple interpretations, as the original and subsequent research has pointed out.

For example, groundwater level evidence is a trailing indicator of the subtle influence on water tables of the vertical drainage process, and one that is reduced further by lateral spreading of delayed recharge at the water table. This means that the trailing indicator of groundwater levels alone cannot confirm whether the mallee clearing recharge pulse is yet to arrive at the water table (as the science generally indicates in many areas), or whether the pulse has already occurred (e.g. before extensive monitoring began in the 1970s and 1980s). Similarly, groundwater modelling cannot be used to rationalise this dilemma.

Contemporary indicator data from soil chloride profiles is required in order to be definitive about the status of the vertical processes. Where soil chloride profile data has been obtained, it confirms that increased drainage due to vegetation clearance is still progressing downwards in many areas.

A small change in recharge (order of several mm/y) is not readily evident in groundwater level hydrographs. For example, recharge at 1 mm/y to an aquifer with 10% storativity would invoke

a maximum 10 mm/y increase in water level, although lateral spreading would likely reduce the effect, and it would require little influence from other factors to over-print on the effect. It would take 10 years at that rate of 10 mm/y to generate a 100 mm rise in groundwater level that would be somewhat apparent on a time series plot.

The following comments by Cook et al. (2001) succinctly describe the data uncertainties involved. They remain valid today (re-confirmed by CDM Smith 2016) and describe a key challenge facing these investigations:

“There are a number of problems that make it difficult to ascertain from bore monitoring data whether or not the watertable within a region is rising as a result of land clearance. For example, some bores may show falls in the watertable because they are in an area where the groundwater is being pumped for irrigation or town water supply. Others may show rising watertable trends because they are in areas where surface water is being used for irrigation, and irrigation drainage has locally increased the rate of recharge to the groundwater. Also, bores in areas with watertables close to the surface may exhibit watertable fluctuations primarily determined by rainfall (i.e. rise during wet periods and fall during dry periods). The success of identifying regional trends and the reasons for these trends relies upon correct interpretation of the individual bore hydrographs and understanding the ‘localised effects’ influencing the hydrographs. It is affected by the number of bores in the monitoring network for the area and the time period over which monitoring has taken place.”

3.4 SUMMARY COMMENTS ON EVIDENCE FOR FUNDAMENTAL CONCEPTS

The evidence available from chloride profiles and groundwater levels supports the fundamental concept that vegetation clearance increases in deep drainage, delayed recharge and groundwater levels, with factors other than dryland recharge potentially influencing water levels to a larger degree in some cases:

- chloride profiles confirm that increased drainage due to vegetation clearance is still working downwards towards the water table in many areas.
- trends in groundwater levels are highly variable across the Mallee; areas of slowly rising and steady levels in the northern (SA) Mallee are consistent with predicted recharge rates and time lags, in that:
 - not all areas of cleared Mallee would experience within a reasonable time increased drainage and/or exhibit rising groundwater levels;
 - time lags mean that drainage in some areas has not yet reached the water table;
 - where drainage has reached the water table, the recharge rates are still quite low (typically 3-9 mm per year), making it difficult to validate by monitoring bores;
 - the rise in groundwater level at any point is not simply due to aquifer recharge occurring at that point; rather it is a result of recharge occurring in the region, with its spatial and temporal variabilities (further increasing the challenge for monitoring);
 - groundwater level trends are possibly influenced by other factors such as multi-decadal trends of declining rainfall (there have not been any long term trends of increasing rainfall).
- analysis by others of average trends in groups of monitoring bores in the Victorian Mallee have not identified any significant rising trends (GHD, 2014; SKM, 2014).
- areas with typically steady to falling groundwater level trends such as south-western NSW are consistent with:
 - research which showed there was no significant difference between RZD under native vegetation and RZD under dryland farming in low rainfall areas that had been thinned for grazing such as south-western NSW;
 - there are much smaller areas of clearing and there is dominant grazing land use in these areas;

- there are other influences including multi-decadal trends of declining rainfall and/or irrigation and river operations (depending on location).
- in the southern Mallee (remote from River), some groundwater levels show dynamic changes due to other factors, including forestry, irrigation drainage and/or pumping that largely overwhelm enhanced drainage due to vegetation clearance, and measurement uncertainty is a contributing factor to the variabilities observed.

The variable spatial groundwater level trend evidence is consistent with the science, and indicates a relatively low salt load risk context (to the River) that is amenable to monitoring and adaptive management (Middlemis and Knapton, 2016).

4. Key Assumptions and Alternative Conceptualisations

The previous sections have concluded that the empirical Cook paradigm and algorithms (conceptualisation and scientific basis) are sound (if imperfect) and consistent with the monitoring evidence. However, there is substantial variability in the magnitude and timing of enhanced dryland recharge to the water table. This reflects the variability in the landscape and climate, as well as land use/change, which may not be captured well by the available mapping.

For example, these points illustrate just a few real-world variability factors (Wang et al. 2005):

- the rate of deep drainage is highly variable over small areas (e.g. paddock scale) for a given soil texture class;
- there are spatial variations evident in soil mapping that does not capture the real-world variability (it is the best we can do in budget-constrained times);
- the rise in groundwater level at any point is not due to aquifer recharge occurring at that point; rather it is a result of recharge occurring in the region, and its spatial and temporal variabilities (the aquifer tends to aggregate/distribute the diffuse recharge inputs).

Real-world variabilities and data capture issues combine with the scientific/modelling assumptions, complexities and imperfections to result in uncertainties around the estimates of salt loads to the River and hence the salinity Register entries.

This chapter discusses key assumptions and simplifications in the Cook paradigm, possible alternative conceptualisations, and related uncertainties:

- sections 4.1 to 4.3 consider alternative conceptual models;
- sections 4.4 to 4.6 consider the physical processes and assumptions relating to root zone drainage and temporal changes in deep drainage rates, and mallee rooting depth and capillary zone factors;
- to summarise, the implications of these alternative conceptualisations and assumptions are discussed in section 4.7 and Table 2;
- sections 4.8 and 4.9 consider alternative recharge datasets and digital data sources.

4.1 PISTON FLOW AND PREFERENTIAL FLOW

The Cook paradigm assumes that soil water movement occurs by piston flow. Piston flow is the uniform downward movement of water, whereby the infiltrating water displaces existing soil water (i.e. without bypassing it). It should be distinguished from preferential flow, which involves the bypassing of existing soil water by more recent rainfall. Preferential flow usually occurs in association with preferred pathways, such as fractures and root channels. It is most likely to occur when saturation conditions exist at the infiltration channel entrance, as might occur where there is ponding at the land surface.

The presence of preferential flow under native mallee vegetation has been observed in dye studies and using radioactive tracers (Nulsen et al. 1986; Allison and Hughes, 1983). However, it appears that this flow is used by the (deep rooted) vegetation before it reaches the (deeper) water table. Under cleared areas, the saturated conditions necessary for preferential flow are unlikely to develop. Radioactive tracer studies beneath agricultural areas within the South Australian and Victorian mallee regions indicate that the volume of water which moves by preferential flow must be small, with the results from seven soil profiles all being consistent with the piston flow model (Allison and Hughes, 1983; Cook et al. 1994). Observed chloride and matric potential profiles obtained on more than 100 soil profiles are also consistent with theoretical profiles based on piston flow conditions (particularly the observed leaching of chloride from the upper part of the profiles), suggesting that preferential flow is limited.

It is difficult to develop an alternative model based on preferential flow. However, the implications can be contemplated with this thought model. If 10% of the root zone drainage water moves rapidly to the water table by preferential flow, then this will cause the rapid recharge to be equal to 10% of root zone drainage immediately following clearing, but with the pulse of additional (subsequent) recharge delayed by 10%. In any case, preferential flow would

then cause some fraction of infiltrating water to reach the water table earlier than the current model suggests. It will also result in a delay in salt leaching, as preferential flow will not efficiently leach salt from the profile (these implications are also summarised in Table 2).

At the inter-jurisdictional workshop, the issue was raised of the effects of dune seepage and swale discharge from the base of dunes, in terms of whether such a process diverts and/or concentrates the enhanced recharge due to mallee clearing and subsequent cropping. It was explained that enhanced deep drainage can still occur under these conditions, as investigated at certain sites (Cook et al, 2001), and as illustrated in Figure 15. More importantly, studies have found that the low density in the landscape of these **localised “dune seepage”** effects are unlikely to significantly change the regional deep drainage regionally across the Mallee (Cook et al. 2001).

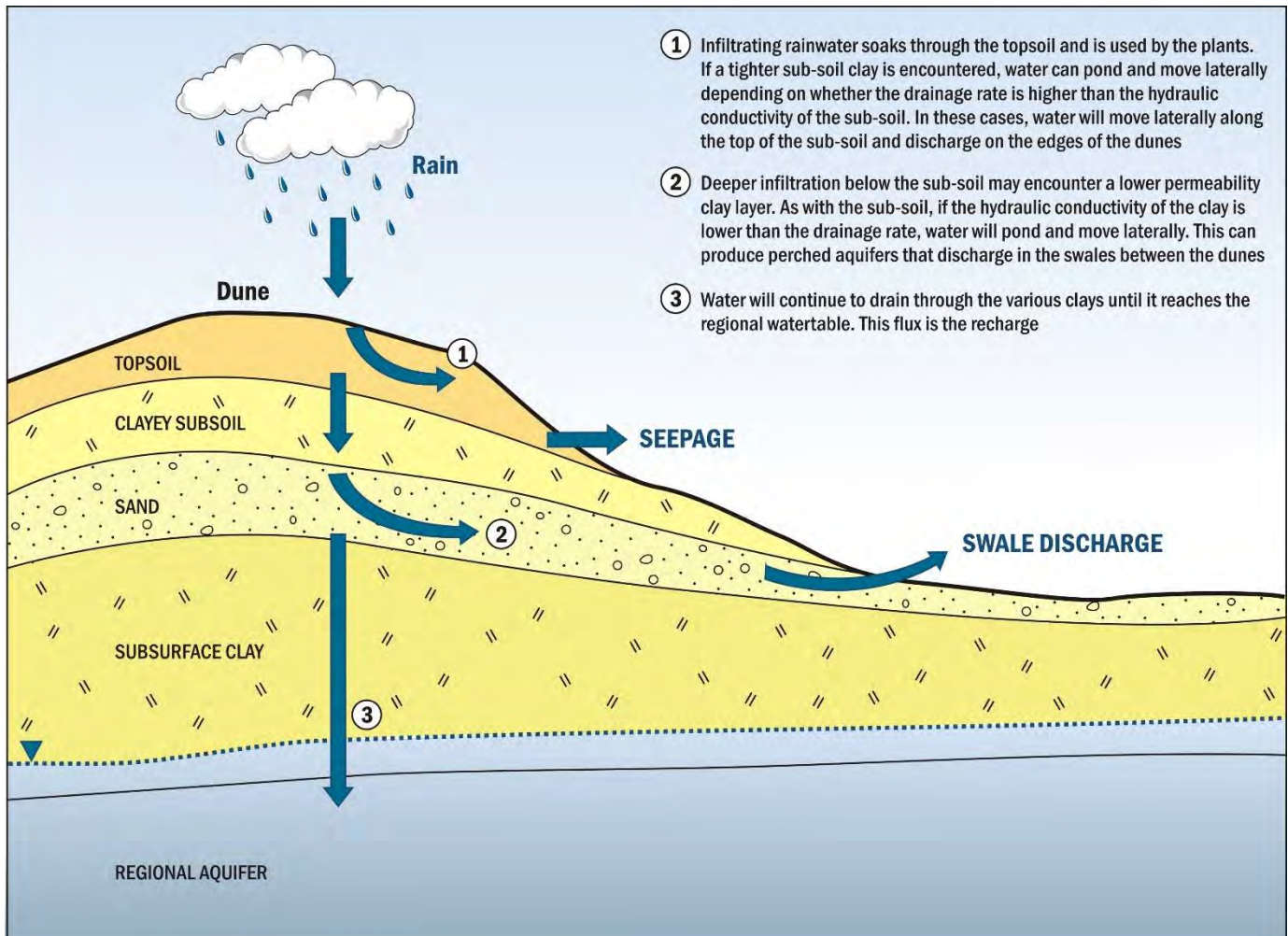


Figure 15 - conceptual model for localised dune seepage processes

4.2 IMPEDING (CLAY) LAYERS

Where low permeability layers (e.g. Blanchetown Clay) occur within the unsaturated zone profile (above the water table), then this can impede the downward movement of infiltrating water and, in some cases, it can lead to the development of perched lenses. Perching will only occur where the hydraulic conductivity of a clay layer is lower than the rate of drainage (unlikely to be extensive in the Mallee given the low dryland drainage rates and the Blanchetown Clay properties).

Where perched lenses do not develop, any clay layers can increase the time lags before recharge occurs, by increasing the soil moisture deficit of the unsaturated zone. This is due to a larger **increase in water content ($\theta_w - \theta_d$)** being required for clay layers than for sand layers (Cook et al. 1994). Equations for predicting this increase in time lag have been developed and incorporated into SIMRAT, but this still requires for the existence of these layers to be identified.

In either case, the existence of clay layers will not decrease the eventual rate of recharge, unless perched water is subsequently lost to evaporation. That will (conceptually) not occur, as the clay layer is accounted for in the (deep) unsaturated zone (i.e. below the upper 2 metres of soil profile and thus beyond the influence of agricultural evapotranspiration).

The Blanchetown Clay is the most significant clay unit, as it is extensive across the northern Mallee, and although there are some areas of absence (“holes”), this is accounted for in the SIMPACT/SIMRAT GIS tools. The Blanchetown Clay is mostly above the water table, with significant thickness and low permeability. There are a few areas where there are other low permeability units also occur above the water table (e.g. Bookpurnong Beds, Lower Loxton Clay, Cadell Marl, mostly in SA between Lock 3 and Lock 1). These areas are well mapped, and their effect should be accounted for in aggregating the thickness of intervening clay for the input data layers.

This calculation provides an estimate of the potential effect of ignoring the impeding effect of clay layers. Based on soil parameters in Cook et al. (2004), we can calculate the increase in time lag that will be caused by the presence of clay layers within the unsaturated zone. For a recharge rate of 5-10 mm/y, water takes approximately twice as long to move through a clay than through a sandy loam.

The implication is that, for every 1 m of clay in the profile, this will increase the time lag by between 2.5 and 5 years.

4.3 ASSUMPTION OF CLEARING IN 1920

Salinity impact assessments usually assume the nominal date of vegetation clearing is 1920 (assumed as instantaneously achieved in 1920 to the mapped extent), and that there was no clearing after 1988. In reality, around two-thirds of the clearing in South Australia and Victoria had occurred by about 1930 (see section 2.3), which means that the 1920 assumption is a conservative one, appropriate for the salinity management context. While there has been some limited clearing since 1988, the effect is not relevant to the pre-1988 context for this Legacy of History project.

This invokes a data uncertainty, as there is no known documentation of the exact timing and spatial distribution of vegetation clearance. Rather, the available maps of (currently) cleared areas are used to assign recharge rate changes and time lags to cleared areas of models, starting from 1920. There is remote sensing evidence available (e.g. aerial photography since the 1940s, and LandSAT data from the 1980s) that could be used to refine this assumption. Recent initiatives may have improved data availability that may be suitable for applying as refinements (e.g. Sinclair et al. 2012), and other studies are ongoing (e.g. remotely sensed mapping project on clearing in South Australia). Application of this new information would involve additional expense and time for data-processing that may not be warranted for the relatively low salt loads attributed to clearing.

The timing of clearing is also a modelling uncertainty in that there are no known modelling uncertainty assessments of how different assumptions on the timing and the magnitude of recharge impacts on salinity. There is one known test (using the EM1.2 model for the Nyah to SA border region including the Sunraysia) that increased and decreased the dryland recharge rate by 50%, with results showing that salt loads varied by 11% in response (Aquaterra 2009a). This suggests that salt loads are insensitive to dryland recharge rates (but this generalisation is not necessarily universally applicable as it is based on one case). In comparison, when the irrigation recharge rates were varied by 50% in the EM1.2 model, the salt loads varied by almost 50%, indicating a near-linear sensitivity response to irrigation recharge. Similar tests on South Australian models indicated non-linear sensitivity to irrigation recharge rate changes, but there has been no testing of dryland recharge sensitivity.

When considered in the context of the relatively low salt loads due to dryland clearing (~5-10% of the total salt loads at all times), the low sensitivity of salt loads to dryland recharge variability (for this one test case on the EM1.2 model) is again indicative of likely low risks. More importantly, there is substantial consistency among the modelling studies in the assumptions about timing and extent of clearing (and the SIMRAT dryland recharge data used), and thus a **“level playing field” in that regard for LoH dryland clearance entries in Register B** (e.g. an overall conservative approach to salinity impact assessment).

4.4 SOIL WATER CONTENT AND MALLEE ROOTING DEPTH

The Cook paradigm for calculating time lags assumes that the soil water contents under mallee are constant with depth (aside from a second deep soil layer incorporated in algorithms to represent the Blanchetown Clay). This is an acknowledged simplification, but is appropriate, as discussed below.

There are no known sites beneath mallee vegetation where there is soil water content and/or matric potential data throughout the profile to a water table that is deeper than 30-35 m. Although the studies that have been conducted in areas where groundwater levels are up to 35 m deep have shown that mallee trees root to within 5-10 m of water table in these areas, this is likely not the case in areas with deeper water tables. Hence it is worthwhile examining errors in the time lags that might arise if the rooting zone of mallee vegetation is significantly less than the water table depth. Figure 16 (after Wang et al. 2005) is relevant to this discussion, as it illustrates the soil water contents in terms of the drained upper limit and lower limit, and the differences between the mallee rooting depths and the much shallower crop rooting depths.

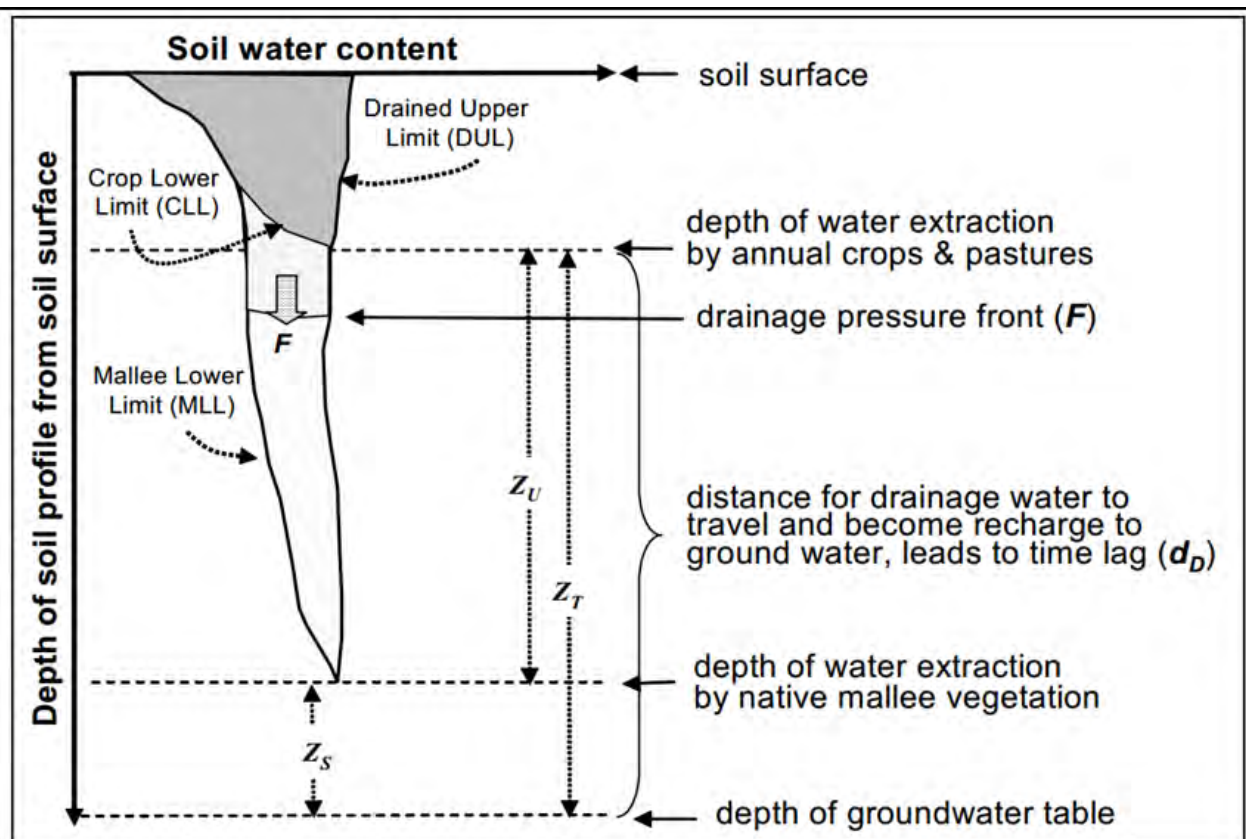


Figure 16 - Soil water content variations and mallee rooting depths

The Cook paradigm assumes that the unsaturated profile under native mallee trees has been largely dried out due to evapotranspiration (Figure 16). This implicitly assumes that mallee trees extend their roots to the water table, which would result in the time lag being linear to water table depth (due to the relationship between volumetric water content and hydraulic conductivity). If the maximum rooting depth of the native vegetation is less than the (deep) water table depth, then the time lag will not be linear. Maximum rooting depths of 20 m and 30 m have been compared with the current model. Allowing for the actual difference in water content above the water table and the wetting front, there could be a decrease of up to 25% in the time for the wetting front to reach a water table at depths of 60 m.

4.5 CAPILLARY ZONE RISE

The model assumes that the soil moisture deficit between the land surface and the water table (which is given by $z_{wt}(\theta_w - \theta_d)$) must be satisfied by root zone drainage, before recharge can occur. However, it is possible that removal of native vegetation can lead to very slow wetting up of the

soils above the water table due to capillary processes (i.e. due to the deep-rooted native vegetation having previously used almost all the available infiltrating water; see Figure 16 previously). Thus, this process might lead to a slight change in the recharge to or discharge from the water table.

This process has not been quantified and is likely not significant, but if it is significant then it will reduce the time lag between land clearance and groundwater recharge (Table 2).

4.6 TEMPORAL CHANGES IN DEEP DRAINAGE RATES

There are two key assumptions in the Cook paradigm that could lead to a bias in predictions:

- **all agriculture is lumped into the single category of 'cleared', whereas there is a range of land use and land management across the Mallee;**
- any temporal variations in root zone drainage will even out in gravity drainage, and so can be assumed to be constant (based on the mean annual rainfall).

The field experiments on root zone drainage have been undertaken where the land use involved rotations of cropping and pastures, as if this is a homogeneous and long term land use and management system.

In the Western Lands of NSW, mallee clearing controls have limited clearing for cropping, and grazing land use predominates (grazing also predominates in most areas north of the River in South Australia). The investigations in south-western NSW have found no evidence of a significant increase in RZD due to the thinning of native vegetation and mainly grazing land use (as has been discussed already).

Moving from north to south across the Mallee, the annual rainfall increases and conditions become more favourable for higher frequency of cropping. Early cropping practices incorporated a long fallow to store soil water prior to cropping. However, issues with wind erosion has discouraged long fallow and encouraged more permanent cover. The initial clearing of native vegetation was also often followed by a long period of fallow to allow the soil to wet up and salt to leach from the root zone. While this could lead to a high bias in RZD, field experiments have shown this effect is only likely to be minor, especially for sandy soils.

While there have been other changes in crop types and cropping practices (e.g. in relation to market, climate and technology dynamics), there are not many estimates of RZD under variable land uses, especially for pre-1988 periods. The limited data that exists indicates that removal of the long fallow and the incorporation of more water-efficient cropping (e.g. Lucerne) into the rotation are likely to reduce RZD. This suggests **that rather than a single category of 'cleared', several different categories may (in principle) better reflect the range of land use and management practices** (for practical reasons, any new categories should represent significant land areas and be measurable in land use datasets). However, it should be remembered that this project has a focus on the effects of pre-88 vegetation clearance, not variations in farming practices as such.

More detailed information is generally available on land use change and dryland farming practices since the late 1980s. However, the salt load impacts to the River from pre-1988 LoH dryland clearing is an accountable action under the BSMS, and these impacts must be quantified for inclusion on the appropriate Register regardless of whether conditions have changed since 1988. Discussion of land use history (though probably warranted in a general sense) is peripheral to the objectives of this report. This project has a focus on methods for evaluating the salinity impacts of pre-1988 vegetation clearance, not variations in dryland farming practices, which would be defined as a different accountable action.

A potentially more significant factor is the rainfall variability shown in Figure 12, especially for Wentworth. The extended dry periods in 1920-1940 and 1990-2009 last for 20 years. These had not only a direct impact on RZD through rainfall but an indirect effect through changed land management. For example, a drier period may make cropping less attractive. Moreover, the early growing season (April-May), when rooting depth is shallow, has been drier over the last two decades (although this cannot be seen in the plot of cumulative deviation from mean annual rainfall). Finally, there has been an intensive effort over the last three decades to reduce the long fallow and retain stubble to avoid wind erosion and to increase productivity (including for areas of wheat on dunes). All of these factors mean that, since the mid-80s, there may have

been a reduction in RZD across the Mallee region. RZD is unlikely to have increased, as that would require extended periods of above average rainfall, and that has not occurred (Figure 12).

It is worth remembering that the Cook paradigm uses mean annual rainfall as an input to estimating RZD (along with clay content). Although the actual RZD during low rainfall periods may be less than the RZD estimated via the mean rainfall Cook relationships, the converse argument can be mounted, that RZD may be underestimated during periods that are wet. The cumulative rainfall deviation plot (Figure 12) shows that wet and dry periods balance out over the period of record, consistent with the mean annual rainfall. More importantly, the BSMS Protocols require average climatic conditions to be applied to groundwater models for salt load predictions. As importantly, the relationships between clay content and RZD also include average rainfall, and have been confirmed as statistically significant (see section 4.8 for more detail).

Calculation of time lags assumes that the historical mean recharge rates (based on mean annual rainfall at any location) can be applied into the future. If root zone drainage rates have decreased over time, either because land management approaches have improved, or because rainfall has decreased, then the time lags in current use may be under-estimates and the recharge rates may be over-estimates. By implication, the associated salt loads may be over-estimates, but that is reasonable because it is consistent with conservative BSMS principles.

The fundamental point is that there is a 1.0 to 2.5 order of magnitude increase in RZD and recharge under an annual crop/pasture rotation dryland farming system compared to under native mallee vegetation, and that is the accountable action investigated by this project. Any differences in RZD due to pre-1988 changes in farming practices or rainfall dynamics are much smaller, and thus the salt load effects would be much smaller than the already relatively small salt loads due to the pre-1988 mallee clearance (around ~5-10% of the predicted total salt loads for all times to 2100).

4.7 IMPLICATIONS OF ALTERNATIVE CONCEPTUALISATIONS

The effects of the assumptions applying to the current conceptualisation and/or to alternative conceptualisations are mostly not significant, as summarised in Table 2.

Table 2 - Possible alternative conceptualisations, and likely impact on timing and magnitude of the recharge and salt load

Alternative Conceptualisation	Implications		
	Current estimate of time lag	Current estimate of recharge at a specific time	Current estimate of salt loads
Non-Piston (Preferential) Flow (likely not significant)	Over-Estimated	Under-estimated	Under-Estimated
Additional impeding clay layer (should be minor effect provided data input layers aggregate clay layer thicknesses)	Under-estimated	Over-estimated	Over-estimated
Clearing after 1920 (potentially significant)	Under-estimated	Over-estimated	Over-estimated
Soil water content limits and reduced mallee rooting depth (likely not significant)	Over-Estimated	Under-estimated	Under-Estimated
Capillary zone rise (likely not significant)	Over-Estimated	Under-estimated	Under-Estimated

As discussed in the sections above, most of the issues (Implications) indicated in Table 2 are considered not significant, apart from (perhaps) the assumed date of mallee clearing (1920).

Nevertheless, there is substantial consistency among the modelling studies in the assumptions **about timing and extent of clearing, and thus a “level playing field” in that regard for Register B entries** (e.g. an overall conservative approach to salinity impact assessment, consistent with BSMS principles).

The conservative over-estimation of salt loads indicated for certain issues in Table 2 (e.g. due to additional clay layers, actual clearing occurring after 1920) may be considered problematic in that it would imply over-investment in salinity management. However, the dryland salt loads form a minor proportion of the total salt load (order of 10%), which would not itself cause over-investment. This issue was considered at the inter-jurisdictional workshop (29th March 2017), including consideration of the potential (small) over-investment. The discussion considered the uncertainty around the analysis and the likelihood that, while this uncertainty may be able to be quantified (subject to a specific project to do so), it is unlikely to be able to be reduced. It was considered that a pilot project may be warranted to undertake a quantitative uncertainty analysis.

As the under-estimation issues (non-piston flow and capillary rise) have very low probability of occurrence (i.e. they are very low risk), further investigation was considered to have a low priority.

4.8 ALTERNATIVE RECHARGE DATASETS

There are several independent datasets available, all of which indicate reasonable matches with the root zone drainage values of the Cook paradigm/algorithms:

- Wang et al. (2005) cite a study by Sadras (2003) that compared the average drainage values of Cook et al. (2001) with simulated values using the farming systems model APSIM (Keating et al. 2003) that found that the simulated (APSIM) values are in the range of observed values.
- Crosbie et al. (2010a) recently compiled and reviewed a database of 4386 recharge and deep drainage estimates over 172 studies across dryland areas of Australia, and developed a tool for use in data poor areas where nationally available datasets can be applied to estimate relationships between recharge and rainfall, soil type and land use.
- Wohling et al. (2012) used the Crosbie et al. (2010a) database and other data to develop an RZD relationship between mean annual rainfall, average clay content (0-2 m) and log deep drainage for various vegetation types (annual vegetation, and combined perennial and tree vegetation), confirming the statistical significance (95% confidence intervals) of the Cook paradigm RZD relationships and providing estimates of the related uncertainty.

Wohling et al. (2012) confirmed key elements of the Cook paradigm relationships, notably that:

- the best metric of the clay content of the shallow soil is the average clay content 0-2 m below surface (as opposed to 0-0.5 m, or 0-1 m, and rather than the highest clay content) in terms of deriving strong relationships for log deep drainage under annual vegetation, and under a combined tree and perennials cover;
- the tri-linear regression relationship that included rainfall in conjunction with log deep drainage and clay content was statistically significant (in terms of the F-test and P-test), whereas simpler linear relationships were not significant (e.g. rainfall versus clay content, or drainage versus clay content, or drainage versus rainfall were not themselves significant).

Another independent dataset is related to the regional groundwater model covering each CMA in Victoria (ecoMarkets/EnSym project), including the Mallee CMA. The basic model purpose is land and water management, including the management of dryland salinity. The EnSym model estimates recharge under historical and potential climate, and that is then applied to the numerical groundwater model to evaluate hydrogeological effects. However, the EnSym model assumes a zero time lag for recharge to reach the water table, so it cannot be directly compared to SIMRAT. The EM3 groundwater model was developed for the Mallee CMA in Victoria under the ecoMarkets project, using the EnSym recharge (Aquaterra, 2010). The study noted that there are some dryland bores (in cleared and uncleared areas) that showed a downward trend contemporary with the drought onset in the 1990s, and other bores that showed no response at

all to the drought, which justified a recommendation for a monitoring review to assist in understanding the key processes (Aquaterra, 2010).

The MDBA also has RZD/recharge estimates from the WAVES model, developed by CSIRO for the MDB Sustainable Yields project. However, it is suggested that, given the spatial variability factors discussed in the sections above, any recharge estimation method that is applied will be subject to a reasonably wide range in uncertainty (i.e. there is no point in changing horses now). The Cook paradigm/algorithms have been found to be sound, based on many independent field studies over more than 30 years of investigation, including ongoing comparisons with monitoring that have not identified any anomalous measurements. The Cook paradigm/algorithms (and the regional mapping of Wang et al. 2005) provide the best recharge estimation method for input to regional models to evaluate the salinity impacts of mallee vegetation clearance.

4.9 ADVANCES IN DIGITAL DATA SOURCES

The water information initiatives of the Bureau of Meteorology (BoM) include GeoFabric, Groundwater Explorer, GDE Atlas, Water Data Online, soil moisture, AWRA recharge and potential and actual evapotranspiration estimates. This information may provide useful data to assist with any future work programs to update or refine the existing modelling tools.

Although floodplain process issues are not within the scope of this project, it is acknowledged that they have a major influence on salt loads reaching the River, in that evapotranspiration discharge is a significant process that intercepts groundwater flux towards the River. It is recommended that the potential and actual evapotranspiration data sets be used in future investigation and modelling programs for salinity impact assessments to benchmark the groundwater model evapotranspiration predictions.

The Australian Geoscience DataCube could also be used by investigation and modelling programs to establish the land use status at 1988, and to quantify the spatial (25m grid) and temporal changes to land use/agriculture since 1988. The MDBA may wish to consider working closely with Geoscience Australia to prepare a dataset from the DataCube that is designed to meet salinity impact assessment (groundwater model) data needs for land use change consistent with BSM 2030 requirements.

Geoscience Australia has also made significant advances in the geophysical interpretation of airborne electromagnetic (AEM), particularly on recharge processes in the Darling River floodplain, and learnings from this work may be very helpful for BSM 2030 modelling purposes. Further information is available from the Broken Hill Managed Aquifer Recharge investigation (www.ga.gov.au/about/projects/water/broken-hill-managed-aquifer-recharge).

Remote-sensed data (e.g. Modis, 250x250 m) is also being applied to estimate a relatively coarse landscape water balance (rainfall minus evapotranspiration) and thus the recharge rate, which could be used as an independent check in areas of deep water tables and no irrigation (as in such areas, the Modis water balance is biased).

5. Dryland Recharge Implementation in Regional Groundwater Models

While regional groundwater models all use SIMRAT estimates for dryland recharge and time lag (i.e. based on the research of Cook et al. 2004 and Wang et al. 2005 that was explored in previous sections), this section explores the differences between the SA models and the Vic-NSW models:

- SA models are calibrated to irrigation recharge only, with uncleared dryland recharge assumed as a background condition, but then apply SIMRAT recharge and time lags to the vegetation clearance Scenario 2 simulation (see section 5.1.2 for a brief description)
- NSW-Victorian models (EM1) are calibrated to irrigation mainly, but with (SIMRAT) dryland recharge specified in cleared areas (and some calibration effort applied there); the effect of the irrigation recharge is unpacked to calculate the Scenario 2 mallee clearance assessment (see section 5.2 for a brief description).

Figure 3 (see section 1.4) provides an illustration of the dryland, irrigation and floodplain domains in the Mallee, and the model applications and interactions in the various areas.

5.1 SOUTH AUSTRALIAN MODELS

5.1.1 Regional model domains and sub-regional models

Groundwater modelling for the purpose of estimating future salt impacts in the River Murray has been undertaken across a series of regional domain models that have been individually upgraded at different times. Essentially the South Australian reach of the Murray has been divided into four regional domains: Border to Lock 3, Woolpunda, Waikerie to Morgan and Morgan to Wellington.

The upstream regional model (Border to Lock 3) has been used as the basis for the development of four sub-regional groundwater models (see section 5.1.2). These models have been undertaken at different times and each has a different legacy.

The sub-regional or regional model, once accredited, produces estimates of salt load for the agreed range of scenarios for the specific river reach. In terms of dryland Legacy of History (LoH), the relevant simulation is Scenario 2 (vegetation clearance), but other accountable actions are also simulated (for other scenarios) and all impacts are included on either the A or B Register.

When the time comes for a five-yearly review, the regional domain model is then updated (or upgraded) with the latest data to provide a suitable platform for new estimates for the relevant accountable actions for that area (including via updated sub-regional models).

5.1.2 Border to Lock 3 model domain

In the case of the Border to Lock 3 model domain, successive upgrades have occurred for the following sub-regional models:

- Berri-Renmark (Yan et al. 2007)
- Pyap-Kingston (Yan and Stadter 2008)
- Loxton-Bookpurnong (Yan, Li and Woods 2011)
- Pike-Murtho (Woods et al. 2014).

These sub-regional models have usually been upgraded from an earlier version. For each upgrade, the work focusses on refining the hydrogeology for the specific sub-regional area, including the latest observation data, and recalibrating the model to a new set of parameters. The full set of scenarios are simulated and the groundwater-based salt load impacts for the defined sub-regional areas are provided to MDBA for modelling salinity impacts to the River using BIGMOD and eventual inclusion on the Register. Although the 2014 Pike-Murtho model review process has not yet been completed for the assessment of accountable actions, for the purpose of this project, the MDBA has indicated that these latest model results should be considered within the context of this report.

There have been no changes made since about 2005 in the way that dryland clearing recharge rates are estimated and then specified in groundwater models (in SA or in Victoria and New South Wales). Therefore, any issues with endorsement of results from the above list of four SA models cannot be attributed to changes in dryland clearing recharge rates or scenarios (as there have been no changes).

Each upgrade has focussed on the salinity impacts on the river due to irrigation development and this is reflected in the calibration approach. Lesser weight is placed on achieving a calibration against dryland bores (in most cases, it is understood that the calibration effort does not attempt to match trends at dryland bores (if any) as the scenarios do not include mallee clearance recharge effects), because there are few of these dryland bores anyway, the dryland recharge rates and groundwater level time series data does not provide a strong signal for model calibration and because the impact from dryland clearing is often masked by the impacts from irrigation mounds (arising from the much higher recharge rates under irrigation).

All model domains simulate changes in dryland recharge due to mallee clearing in a similar fashion. Clearance of natural vegetation is assumed to commence from the 1920s, resulting in increased recharge inputs to the water table, but subject to time lag delays (due to the depth to the water table and intervening aquitard units, e.g. Blanchetown Clay). It is also assumed that no major clearing of native vegetation occurred after 1988. As mentioned earlier, in terms of dryland Legacy of History (LoH), the relevant simulation is Scenario 2.

In SA models, Scenario 2 applies SIMRAT-calculated recharge rates and time lags to cleared dryland areas and applies a native mallee recharge rate of 0.1 mm/y to all other areas (i.e. irrigation areas are not modelled). The scenario results for the year 2000 are subtracted from the results for 2015, 2050 and 2100 to evaluate the LoH Register B impacts of dryland clearing on salt loads to the River.

The Border to Lock 3 model domain has been sub-divided into 41 recharge zones (in one case 42 zones). These recharge zones, recharge rates and time lags were specified by the model developer (Department of Water, Land and Biodiversity Conservation) and were based on studies by CSIRO (Cook et al. 2004) and the then Department of Environment and Heritage (DEH) using the SIMRAT model. For dryland clearing recharge estimation, SIMRAT uses long term annual average rainfall (spatially variable across the Mallee) as input data, along with soil type, depth to groundwater and thickness of Blanchetown Clay (methods described in section 2.5; Wang et al. 2005). The sub-regional model reports for the Lock 3 to Morgan domain also reference the work of Fuller et al. (2005) (developers of the SIMRAT software) as the main source of the dryland recharge data, which specifically indicates long term annual average rainfall (1960-1991) as the spatial dataset input (Fuller et al. 2005, Appendix 1, SIMRAT metadata).

The mallee clearance is assumed to have started in 1920. Recharge rates vary from 0.07 to 11 mm/y. Each model report provides the detailed recharge rates and lag times used in the model. Essentially the different recharge zones are sampled on decadal slices and a recharge rate applied to each model time period.

In all other Scenario simulations in S.A. (that is, other than the Scenario 2 for vegetation clearance) it is assumed that the recharge rate for non-irrigated areas is 0.1 mm/y (and tables in model report appendices show this). This neglects the impact of land clearance in every simulation (including the calibration history match), which is presumed to have a much smaller impact on river salinity than irrigation. This simplification has reportedly been agreed to in discussion with the MDBA when the groundwater models were developed because the task was considered too complex at the time (2006). However, feedback from MDBA on draft versions of this report included statements that their preferred option would be to include mallee clearance in all scenarios (e.g. as has been applied to the EM models for Vic/NSW assessments).

It is not clear from the three model reports (Pyap-Kingston, Berri-Renmark and Morgan-Wellington) what dryland recharge values were used in the calibration run. However, other model reports (Pike-Murtho, Loxton-Bookpurnong, Woolpunda, Waikerie-Morgan) do clarify that the dryland recharge value is 0.1 mm/y for all cases except Scenario 2 (vegetation clearance). It is assumed that the Scenario 2 recharge rates and lag times were incorporated as appropriate, and that Pyap-Kingston, Berri-Renmark and Morgan-Wellington models also apply the 0.1 mm/y uncleared dryland recharge rate as background to the calibration scenarios (and appendix tables to the reports tend to indicate this).

Table 3 summarises the modelled salt impacts in the River from the suite of upgraded sub-regional models, which are calculated for groundwater fluxes towards the river from one side only (the side of the river contiguous with the sub-regional model area; this is appropriate, but it differs from the method applied to the Woolpunda and Walkerie models of the next domain downstream, as those models cover both sides of the river).

Table 3 shows that in most cases the salt load increase is small, especially in early/current time. About 62% of the salt load increase due to vegetation clearance occurs in the period between 2050 and 2100. By 2100, the main impacted areas are predicted to be the Renmark reach and the Pike reach (about 60%). In all other cases the predicted impacts are quite small (confirming the low salt load risk for vegetation clearance scenarios). Table 3 also shows the component of the mallee clearance impact that is part of the baseline conditions (S2 - S1 at 2000 conditions).

Table 3 - Modelled salt load for Border to Lock 3 (provided by MDBA)

River reach	Scenario		2000	2015	2030	2050	2100
			Salt Loads (t/d)				
Murtho	S1 [*]		20.5	20.5	20.5	20.5	20.5
	S2 ^{**}		20.8	20.9	21.0	21.2	22.8
	Mallee clearance	Baseline share [^]	0.3	0.3	0.3	0.3	0.3
		Reg B increment ^{^^}	0	0.1	0.2	0.3	1.9
Pike	S1		31.6	31.6	31.6	31.6	31.6
	S2		34.9	36.7	38.7	41.9	50.9
	Mallee clearance	Baseline share	3.3	3.3	3.3	3.3	3.3
		Reg B increment	0	1.8	3.8	7.0	16.0
Berri	S1		10.1	10.1	10.1	10.1	10.1
	S2		11.9	12.0	12.2	12.4	13.2
	Mallee clearance	Baseline share [^]	1.8	1.8	1.8	1.8	1.8
		Reg B increment ^{^^}	0	0.2	0.3	0.5	1.3
Renmark	S1		10.6	10.6	10.6	10.6	10.6
	S2		11.2	11.4	11.6	13.5	19.4
	Mallee clearance	Baseline share	0.6	0.6	0.6	0.6	0.6
		Reg B increment	0	0.2	0.4	2.3	8.2
Pyap	S1		2.3	2.3	2.3	2.3	2.3
	S2		2.7	2.9	3.3	3.8	5.3
	Mallee clearance	Baseline share	0.4	0.4	0.4	0.4	0.4
		Reg B increment	0	0.2	0.6	1.1	2.6
New Residence	S1		0.3	0.3	0.3	0.3	0.3
	S2		0.9	1.3	1.6	2.1	3.3
	Mallee clearance	Baseline share	0.6	0.6	0.6	0.6	0.6
		Reg B increment	0	0.3	0.7	1.2	2.4
Moorook	S1		0.8	0.8	0.8	0.8	0.8
	S2		1.1	1.3	1.4	1.6	2.0
	Mallee clearance	Baseline share	0.3	0.3	0.3	0.3	0.3
		Reg B increment	0	0.2	0.3	0.5	0.9
Kingston	S1		0.3	0.3	0.3	0.3	0.3
	S2		0.5	0.5	0.5	0.6	0.6
		Baseline share	0.2	0.2	0.2	0.2	0.2

	Mallee clearance	Reg B increment	0	0.0	0.0	0.1	0.2
Loxton	S1		2.7	2.7	2.7	2.7	2.7
	S2		3.5	3.9	4.3	5.1	7.8
	Mallee clearance	Baseline share	0.8	0.8	0.8	0.8	0.8
		Reg B increment	0	0.4	0.8	1.6	4.3
Bookpurnong	S1		22.2	22.2	22.2	22.2	22.2
	S2		22.4	22.5	22.7	23.1	25.1
	Mallee clearance	Baseline share	0.2	0.2	0.2	0.2	0.2
		Reg B increment	0	0.1	0.3	0.7	2.7
Total Border to Lock 3	S1		101.4	101.4	101.4	101.4	101.4
	S2		109.9	113.4	117.3	125.3	150.4
	Mallee clearance	Baseline share	8.5	8.5	8.5	8.5	8.5
		Reg B increment	0	3.5	7.4	15.3	40.5

* S1 (Scenario 1) Pre-development salt loads (uncleared native vegetation, no irrigation)

** S2 (Scenario 2) Dryland clearing salt loads (no irrigation, no SIS)

^ Salt loads due to Dryland clearing that occurred after 1 Jan 1988 and before 1 Jan 2000

^^ Register B Incremental salt loads due to clearing calculated as increase above 2000 levels from Scenario 2

5.1.3 Lock 3 to Morgan region (Woolpunda and Waikerie to Morgan)

Model predictions for the salt impacts for accountable actions in the Lock 3 to Morgan region have undergone a similar evolution as those for the Border to Lock 3 domain. Initially a regional model was developed and accredited in 2005 (the Lock 3 to Morgan model developed by Aquaterra and Rural Solutions). Over time, two stand-alone regional models have been developed to simulate accountable actions: Waikerie-Morgan (Yan, Li and Woods, 2012) and Woolpunda (Woods et al. 2013). Although the 2012 Waikerie-Morgan model and the 2013 Woolpunda model review process have not yet been completed for the assessment of accountable actions, the MDBA has indicated that these latest results should be considered within the context of this report.

There have been no changes made since about 2005 in the way that dryland clearing recharge rates are estimated and then specified in groundwater models (in SA or in Victoria and New South Wales). Therefore, any issues with endorsement of results from the Woolpunda and Waikerie-Morgan models cannot be attributed to changes in dryland clearing recharge rates or scenarios (as there have been no changes).

Both upgraded models (Woolpunda and Waikerie-Morgan) use the same dryland recharge formulation as those upgraded sub-regional models in the Border to Lock 3 domain - see previous sub-section for details. Recharge zones, rates and time lags were specified using output from the SIMRAT model, which specifies long term annual average rainfall (1960-1991) as the key input data, along with soil type, depth to groundwater and thickness of Blanchetown Clay. As with the upgraded models for the Border to Lock 3 domain discussed in section 5.1.2, the supporting technical reports state that annual average rainfall (spatially variable isohyets) was input to derive lag times associated with the calculated the dryland recharge rates.

It appears from the Woolpunda and Waikerie model reports that the salinity budget zones used in the modelling are inclusive of groundwater flux from both sides of the river (appropriate for these reaches). Therefore, salt load impacts derived from the Woolpunda and Waikerie-Morgan models are inclusive of all groundwater flux for the entire model domain and provide fully updated salt loads to BIGMOD. This is slightly different to the sub-regional model upgrades in the Border to Lock 3 reach (which do not apply upgraded salt loads to the full river reach within the specific model domain).

The Woolpunda and Waikerie-Morgan models have been calibrated with a focus on the immediate river area around the irrigation areas and the salt interception schemes. Calibration in the dryland areas away from the river is not as good as elsewhere in the model, though individual

history matches to observed records can be good (even though little to no calibration effort is usually applied to non-irrigated areas).

Table 4 summarises the modelled salt impacts in the River from the upgraded Woolpunda and Waikerie-Morgan models. Table 4 shows that in most cases the salt load increase is small, especially in early time. It can be seen that the majority of the salt load is predicted to occur evenly across the broader Lock 3 to Morgan domain, and at both 2015 and 2100. Again, the 2015 salt loads are quite low, and most increases (70%) occur between 2050 and 2100 (reflecting the time lag influence). There are very small salt load increases for Hogwash to Morgan.

Table 4 - Modelled salt loads Woolpunda and Waikerie-Morgan (provided by MDBA)

River reach	Scenario		2000	2015	2030	2050	2100
			Salt Loads (t/d)				
Woolpunda	S1*		190.9	190.9	190.9	190.9	190.9
	S2**		191.6	191.9	192.3	193.1	201.8
	Mallee clearance	Baseline share^	0.7	0.7	0.7	0.7	0.7
		Reg B increment^^	0	0.3	0.7	1.5	10.2
Holder to Lock 2	S1		5.6	5.6	5.6	5.6	5.6
	S2		6.3	6.9	8.1	10.5	16.8
	S2 incremental	Baseline share	0.7	0.7	0.7	0.7	0.7
		Reg B increment	0	0.7	1.9	4.2	10.6
Lock 2 to Hogwash	S1		13.5	13.5	13.5	13.5	13.5
	S2		14.0	14.6	15.3	16.9	22.5
	Mallee clearance	Baseline share	0.5	0.5	0.5	0.5	0.5
		Reg B increment	0	0.6	1.2	2.9	8.4
Hogwash to Morgan	S1		4.6	4.6	4.6	4.6	4.6
	S2		4.6	4.7	4.7	4.7	5.0
	Mallee clearance	Baseline share	0	0	0	0	0
		Reg B increment	0	0	0	0.1	0.3
Total Woolpunda and Waikerie to Morgan	S1		214.6	214.6	214.6	214.6	214.6
	S2		216.5	218.1	220.4	225.2	246.1
	Mallee clearance	Baseline share	1.9	1.9	1.9	1.9	1.9
		Reg B increment	0	1.6	3.8	8.7	29.5

* S1 (Scenario 1) Pre-development salt loads (uncleared native vegetation, no irrigation)

** S2 (Scenario 2) Dryland clearing salt loads (no irrigation, no SIS)

^ Salt loads due to Dryland clearing that occurred after 1 Jan 1988 and before 1 Jan 2000

^^ Register B Incremental salt loads due to clearing calculated as increase above 2000 levels from Scenario 2

5.1.4 Morgan to Wellington model domain

The third regional model domain developed is for Morgan to Wellington. This model was developed in 2009/10 and is a large regional model that has not been upgraded either as an entity or via sub-regional models since its development.

Dryland recharge rates and time lags for cleared Mallee areas for use in Scenario 2 have been derived from the same SIMRAT source as for all other models in South Australia.

As with the two upgraded sub-regional models in the Lock 3 to Morgan domain, the Morgan to Wellington regional model includes salt load zones for both sides of the river. Therefore, salt

load impacts derived from the model are inclusive of all groundwater flux for the entire model domain and provides fully updated salt loads to BIGMOD. This is the same as for Lock 3 to Morgan immediately upstream, but slightly different to the model upgrades in the Border to Lock 3 reach.

Table 5 summarises the modelled salt impacts in the River from the Morgan to Wellington regional model. Table 5 shows that the salt load increases steadily to 2100, with larger relative impacts at the upstream and downstream reaches.

Table 5 - Modelled salt loads Morgan to Wellington (provided by MDBA)

River reach	Scenario		2000	2015	2030	2050	2100
			Salt Loads (t/d)				
Morgan to Lock 1	S1*		2.8	2.8	2.8	2.8	2.8
	S2**		3.3	4.3	6.5	10.6	19.5
	Mallee clearance	Baseline share [^]	0.5	0.5	0.5	0.5	0.5
		Reg B increment ^{^^}	0	1.0	3.2	7.4	16.2
Lock 1 to Mannum	S1		8.4	8.4	8.4	8.4	8.4
	S2		10.1	10.4	10.8	11.2	13.2
	Mallee clearance	Baseline share	1.7	1.7	1.7	1.7	1.7
		Reg B increment	0	0.3	0.6	1.1	3.1
Mannum to Murray Bridge	S1		0.2	0.2	0.2	0.2	0.2
	S2		21.1	21.7	22.4	23.4	26.7
	Mallee clearance	Baseline share	20.9	20.9	20.9	20.9	20.9
		Reg B increment	0	0.7	1.3	2.3	5.6
Murray Bridge to Wellington	S1		2.7	2.7	2.7	2.7	2.7
	S2		26.9	29.4	32.0	35.9	45.7
	Mallee clearance	Baseline share	24.2	24.2	24.2	24.2	24.2
		Reg B increment	0	2.5	5.1	9.0	18.8
Total Morgan to Wellington	S1		14.1	14.1	14.1	14.1	14.1
	S2		61.4	65.8	71.7	81.8	105.1
	Mallee clearance	Baseline share	47.3	47.3	47.3	47.3	47.3
		Reg B increment	0	4.5	10.2	19.8	43.7

* S1 (Scenario 1) Pre-development salt loads (uncleared native vegetation, no irrigation)

** S2 (Scenario 2) Dryland clearing salt loads (no irrigation, no SIS)

[^] Salt loads due to Dryland clearing that occurred after 1 Jan 1988 and before 1 Jan 2000

^{^^} Register B Incremental salt loads due to clearing calculated as increase above 2000 levels from Scenario 2

5.1.5 SA modelling approach implications

In summary, the SA regional models show relatively low salt loads at 2015 (Table 6) for the Legacy of History dryland vegetation clearance scenario (i.e. low compared to pre-development and/or irrigation impacts). The salt load more than doubles between 2050 and 2100. This is not a new/recent result, and it reflects the effect of time lag influence associated with the SIMRAT recharge rates.

The results indicate a relatively low salt load risk from vegetation clearance until beyond 2050.

Table 6 - SA Legacy of History vegetation clearance salt loads summary (source: MDBA)

River reach	Scenario	2000	2015	2030	2050	2100
-------------	----------	------	------	------	------	------

		Salt Loads (t/d)				
Total Border to Lock 3	S1 [*]		101.4	101.4	101.4	101.4
	S2 ^{**}		109.9	113.4	117.3	125.3
	Mallee clearance	Baseline share [^]	8.5	8.5	8.5	8.5
		Reg B increment ^{^^}	0	3.5	7.4	15.3
Total Woolpunda and Waikerie to Morgan	S1		214.6	214.6	214.6	214.6
	S2		216.5	218.1	220.4	225.2
	Mallee clearance	Baseline share	1.9	1.9	1.9	1.9
		Reg B increment	0	1.6	3.8	8.7
Total Morgan to Wellington	S1		14.1	14.1	14.1	14.1
	S2		61.4	65.8	71.7	81.8
	Mallee clearance	Baseline share	47.3	47.3	47.3	47.3
		Reg B increment	0	4.5	10.2	19.8
Total SA LoH vegetation clearance	S1		330.1	330.1	330.1	330.1
	S2		387.8	397.3	409.4	432.3
	Mallee clearance	Baseline share	57.7	57.7	57.7	57.7
		Reg B increment	0	9.6	21.4	43.8

* S1 (Scenario 1) Pre-development salt loads (uncleared native vegetation, no irrigation)

** S2 (Scenario 2) Dryland clearing salt loads (no irrigation, no SIS)

[^] Salt loads due to Dryland clearing that occurred after 1 Jan 1988 and before 1 Jan 2000

^{^^} Register B Incremental salt loads due to clearing calculated as increase above 2000 levels from Scenario 2

5.1.6 Deriving lag times and dryland recharge rates for SA models

Cleared dryland recharge rates in the South Australian models are based on data that was supplied by the (then) SA Department of Environment and Heritage in 2005. It includes the dryland recharge rate over time and the initial lag time between a change in root zone drainage and a corresponding response in recharge at the water table.

Woods et al. (2016) state that:

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

At least for the models in South Australia, this statement **about “RZD estimated outside SIMRAT”** appears to be somewhat misleading. The dryland recharge rates used in all SA models were derived by the SA agency using the SIMRAT GIS tool (Matt Miles, DEWNR, pers.comm.), although there may be no specific description of exactly how this was achieved. Despite the lack of specific documentation, it is reasonable to assume that SIMRAT was applied based on the methods documented by Wang et al. (2005) for the specific purpose of deriving a time series of cleared dryland recharge rates (i.e. allowing for time lags after the assumed clearing date of 1920) for input to the regional models. It is also possible that the SA agency received a time series of spatially variable post-clearing dryland recharge rates (e.g. from CSIRO), and the SIMRAT GIS tool was used to map those rates and to provide data sets for regional groundwater model input.

The lack of adequate reporting of exactly how this data was derived introduces a potential inconsistency in the way in which cleared dryland recharge rates have been derived and applied. This should be rectified (e.g. by re-running SIMRAT and/or re-importing the dryland recharge rates and time lags to the groundwater models for Scenario 2). A consistent approach within Scenario 2 implementation would be to adopt the recharge rates and lag times for cleared areas from Wang et al. (2005).

5.1.7 SA model uncertainty

There are no errors stated for the various model predictions, but the generally small salt loads to the River from mallee clearance (Scenario 2 increments) across most of the river reaches in the models must be near the limit of simulation accuracy. This leads one to conclude that the uncertainty of the estimates is large, and that by summing all these small estimates across all the models, the uncertainty will remain large, possibly the same order of magnitude as the estimates themselves. As the salt loads are relatively small (~5-10% of total salt loads), this tends to confirm the relatively low salt load risk context for the LoH dryland vegetation clearance scenario.

5.1.8 Post-processing of SA model results

Within the groundwater model environment, salt load changes due to the different scenarios are post-processed using the principle of Superposition - in effect, it is the differences between the Scenario runs that are important. This allows the impacts of individual and discrete actions to be resolved from the general set of salt loads derived from the models. The salt loads from different Scenario runs are passed to MDBA for further processing. The MDBA calculates, from the salt load time series provided, the salt loads for 2000, 2015, 2050 and 2100 and updates the existing register entries based on the new figures. The salt loads are adjusted to account for a baseline share (those salt load impacts that occur in the River prior to 2000), and a set of Register B increments for post 2000 impacts. For example, Table 6 provides the set of salt load impacts for the various regional models (or groupings of sub-regional model outputs) for SA. Each regional model entry shows the different salt load impacts due to the two Scenarios of interest (Scenarios 1 and 2), and the difference between these two Scenarios resolved into baseline share and Register B increment components.

As each sub-regional model area is not the full area of the regional model salt impact estimates, the salt impacts for discrete sections of the river are updated/upgraded in BIGMOD over time resulting in a series of updated/upgraded salt impact estimates for different reaches of the River at different time. Some simulations provide estimates for one side of the river whereas the estimates for accountable actions on the other side may come from a different model.

For example, the Berri-Renmark model is used to estimate salt loads for the northern side of the river, whereas the salt loads for the southern side of the river are provided by three other models: Pike-Murtho, Loxton-Bookpurnong or Pyap-Kingston. As the default setting for groundwater model output is flux to both sides of the river, some data processing is required to:

- ensure that the groundwater model output (to update BIGMOD) is sub-reach salt loads for the appropriate side of the river,
- aggregate the salt loads from the various sub-regional models appropriately within the BIGMOD data files for the scenarios that underpin the Register entries.

The sub-regional modelling approach raises a risk that a set of salt loads is miss-assigned to either one side of the River or to both sides of the River when it should not be.

More generally, there are no explicit protocols or procedures for how the outputs from the various models are to be processed by MDBA to eventually appear on the Register as impacts. Further work is required to better document the procedures that are applied; this will provide a common understanding to all stakeholders and provide more assurance to the Register B entries.

5.2 VICTORIA AND NSW (EASTERN MALLEE) MODEL EM1.2

Model predictions for the salt impacts for Legacy of History accountable actions in the New South Wales and Victorian reaches upstream from the SA border have been based on the Eastern Mallee v1.2 regional model domain (Aquaterra, 2009a).

The EM1.2 model domain extends east/upstream from the SA border to Nyah, south to Ouyen in Victoria and north to near Pooncarie in NSW (i.e. covering the northern half of the Mallee CMA area, and extending 20-100 km into NSW). As the EM1.2 model domain extends north and south of the River Murray, the salinity budget zones used in the modelling are inclusive of groundwater flux from each side of the river (appropriate for these reaches and similar to the Woolpunda and

Waikerie reaches in SA). Therefore, the LoH salt load impacts derived from the EM1.2 model are inclusive of all groundwater flux for the entire model domain (Nyah to the SA border) and provide fully updated LoH salt loads to BIGMOD.

The EM1.2 model has undergone a similar evolution as to those for the SA model domains. Initially a regional model was developed (EM1; Aquaterra, 2007), and this was upgraded with new data (e.g. LiDAR data on the floodplain and irrigation recharge estimates from the EM2 sub-regional model (Aquaterra, 2009b)). The EM1.2 model was calibrated with equal effort applied to the dryland areas as to the immediate river area around the irrigation areas and salt interception schemes (it benefitted from insights gained from the EM2 model around Mildura).

The EM1.2 model (and the EM1 model before it) uses the same SIMRAT-based dryland recharge formulation as the SA models. The SIMRAT dryland recharge data set (developed initially for SA; Cook et al. 2004) was extended eastwards across the Eastern Mallee model domain in northern Victoria and south-western NSW (by the SA Department of Environment and Heritage). Inputs to SIMRAT comprised the standard data on average annual rainfall, soil type, depth to groundwater and thickness of Blanchetown Clay for the Eastern Mallee model domain (and related parameters, as described in section 2). Unsaturated zone lag times and recharge rates were calculated using the Cook et al. (2004) methods, as further detailed in Wang et al. (2005), and as described in **section 2. The outputs (SIMRAT v2.01, run “m_rev”, 5th December, 2005; Matt Miles, DEWNR, pers.comm.)** were input to the EM1.2 model cleared dryland areas.

However, there are a few key differences in the implementation of dryland (and irrigation) recharge in the EM1.2 model compared to the SA models:

- EM1.2 applies recharge to non-irrigated (dryland) uncleared areas as follows:
 - uncleared dryland areas with woody vegetation receive 0.1 mm/year;
 - uncleared dryland areas with non-woody shrubland receive 1% of mean rainfall;
- cleared dryland areas in EM1.2 receive SIMRAT recharge rates and time lags for the calibration history match model runs, and for the prediction scenarios (except for the S2 vegetation clearance run, where EM1.2 replaces the cleared area SIMRAT recharge with the uncleared rate of 0.1 mm/year, and uses scenario differences to calculate the incremental mallee clearance salt loads);
- recharge to irrigation areas of EM1.2 is based on the district-scale water balance analyses developed for the EM2 model (Aquaterra, 2009b), including assuming zero time lag for irrigation recharge (as a simple/robust assumption based on analysis of monitoring bore time series).

For the record/in comparison, the SA model calibration runs apply the uncleared dryland recharge rate (0.1 mm/year) to all dryland (non-irrigated) areas (whether cleared or uncleared), as described in section 5.1. SA models only apply SIMRAT recharge rates and time lags to cleared dryland areas for the S2 vegetation clearance scenario. For irrigation recharge, SA models apply initial time lags based on SIMRAT estimates, but then usually shorten those time lags subsequently during calibration; more information is given in the accompanying study on irrigation root zone drainage (Currie et al. 2017).

Table 7 summarises the modelled salt impacts in the River from the EM1.2 model. Table 7 shows that most salt load increases are small at early time, but then increase substantially from 2050 to 2100, again reflecting the time lag influence, with little difference between NSW and Victoria.

Table 7 - NSW and Victoria Legacy of History vegetation clearance salt loads summary (provided by MDBA)

River reach	Scenario	2000	2015	2030	2050	2100
		Salt Loads (t/d)				
Total Victorian component	S1*	268	268	268	268	268
	S2**	308	311	315	323	349
	Baseline share^	40	40	40	40	40

	Mallee clearance	Reg B increment^^	0	3	7	15	41
Total NSW component	S1		174	174	174	174	174
	S2		206	208	211	218	236
	Mallee clearance	Baseline share	32	32	32	32	32
		Reg B increment	0	2	5	12	30
Total Vic and NSW LoH vegetation clearance	S1		442	442	442	442	442
	S2		514	519	526	541	585
	Mallee clearance	Baseline share	72	72	72	72	72
		Reg B increment	0	5	12	27	71

* S1 (Scenario 1) Pre-development salt loads (uncleared native vegetation, no irrigation)

** S2 (Scenario 2) Dryland clearing salt loads (no irrigation, no SIS)

^ Salt loads due to Dryland clearing that occurred after 1 Jan 1988 and before 1 Jan 2000

^^ Register B Incremental salt loads due to clearing calculated as increase above 2000 levels from Scenario 2

5.3 SIMRAT METHODS CONSISTENT BUT IMPLEMENTED DIFFERENTLY

While the descriptions in sections 5.1 and 5.2 confirm that SIMRAT methods and results are consistent across all three states (e.g. as stated in Woods et al. 2016), there are differences in how the SIMRAT data are applied to the various numerical models for dryland clearing assessments (and also how the SIMRAT time lag data is applied to irrigation recharge).

Despite these quite different dryland recharge approaches, all models calibrate well to measured groundwater levels and other criteria such as run of river salt loads, and all models have passed independent review (Middlemis and Knapton, 2015). This insensitivity of model results to dryland recharge assumptions means that good model performance can be achieved for whichever recharge assumption is adopted, by making small changes to aquifer parameters within a physically realistic range.

5.4 IMPLICATIONS FOR SALINITY REGISTER ENTRIES

The implications for salt loads, and related uncertainties are discussed in section 6.2.

6. Uncertainty

An objective of this report is to consider the implications of adopting the Cook paradigm on the salt load impact as entered in Register B. As the Cook paradigm was being assessed, the issue of uncertainty became evident and specifically how the uncertainties inherent in the various components of the paradigm might influence the final estimate of the impact.

Workshop discussions on the considerable effort required to quantify uncertainties relating to mallee clearing recharge effects concluded that it would likely not be commensurate with the low salt load risk. Although it is not possible to provide definitive uncertainty estimates without a quantified uncertainty evaluation, this report provides the best guess possible with the information available.

Basic research has determined that the rate of drainage/recharge is highly variable due to many factors over small areas for a given soil texture class. The inaccuracies in the drainage relationships developed (including the log-normal spatial variability refinements) reflect to some degree the variability in the soils and the difficulty in applying the soil landscape mapping approach to map drainage rate estimates. The following sub-sections explore key uncertainties relating to the RZD point estimates, the subsequent scaling-up process to map recharge on a regional scale, and the salt load uncertainties predicted from regional models.

6.1 RZD/RECHARGE UNCERTAINTY

6.1.1 RZD relationship to average clay content and rainfall

As discussed in section 2.5.1, recent research (Crosbie et al. 2010; Wohling et al. 2012) confirmed the statistical significance (95% confidence limits) of the original empirical relationship derived by Cook et al. (2004) between log-normal root zone drainage, average clay content (shallow interval 0-2 m below ground) and mean annual precipitation.

Considering the Mallee data subset that formed part of the Australia-wide datasets considered by Crosbie et al (2010) and Wohling et al. (2012), there are differences between the error in the point estimates of drainage and the scaled-up mapping estimates of (delayed) recharge that must be understood. While the scaling-up issues are discussed next, it can be demonstrated that the error in the point estimates of drainage (which form the basis for the Cook paradigm) are relatively small, in the order of $\pm 50\%$ (mainly because the data captures actual measurements of drainage and clay content; Cook et al. 2004); see Figure 17.

There are many factors that have an influence on this drainage relationship, not simply clay content and rainfall. By way of example, consider a study at Pooncarie (Kennett-Smith et al. 1991) north of Mildura that estimated drainage at around 1 mm/y for mean clay content of 15%-18%. The Pooncarie site has mean annual rainfall of 255 mm and the local non-mallee/shrubland vegetation was cleared between 1890 and 1940 with subsequent grazing land use over perennial vegetation cover. Such land use change would tend to result in less recharge than under cropping (Wang et al, 2005). This illustrates a key complexity/uncertainty in the RZD relationship (and one that is very difficult to treat), that land use is itself related to rainfall, especially in low rainfall areas where cropping becomes less economic and grazing predominates.

The implication for very low rainfall areas that are predominantly grazed (i.e. south-western NSW) is that the mapped dryland recharge (Wang et al. 2005) may be over-estimated and thus the time lag under-estimated. However, there is a range of evidence from monitoring bore time series of groundwater levels in south-western NSW (Figure 11) that show a long term steady to downwards trend, with short term responses to significant wet periods (notably 1974 and 2011; Figure 12). This suggests that time lags are relatively short in this area (order of several years).

This is also considered in section 5.2 regarding the performance of the south-western NSW part of the Eastern Mallee EM1.2 model (which applies SIMRAT dryland recharge rates). The generally flat to declining groundwater level trends observed in these NSW dryland areas are slightly over-predicted by the EM1.2 model (i.e. EM1.2 shows generally flat to very slightly rising trends). Although not ideal model performance for this part of the regional model, it can be contextualised as conservative and consistent with BSMS principles. However, this does raise

questions about the potential over-estimation of SIMRAT recharge rates in this area of south-western NSW.

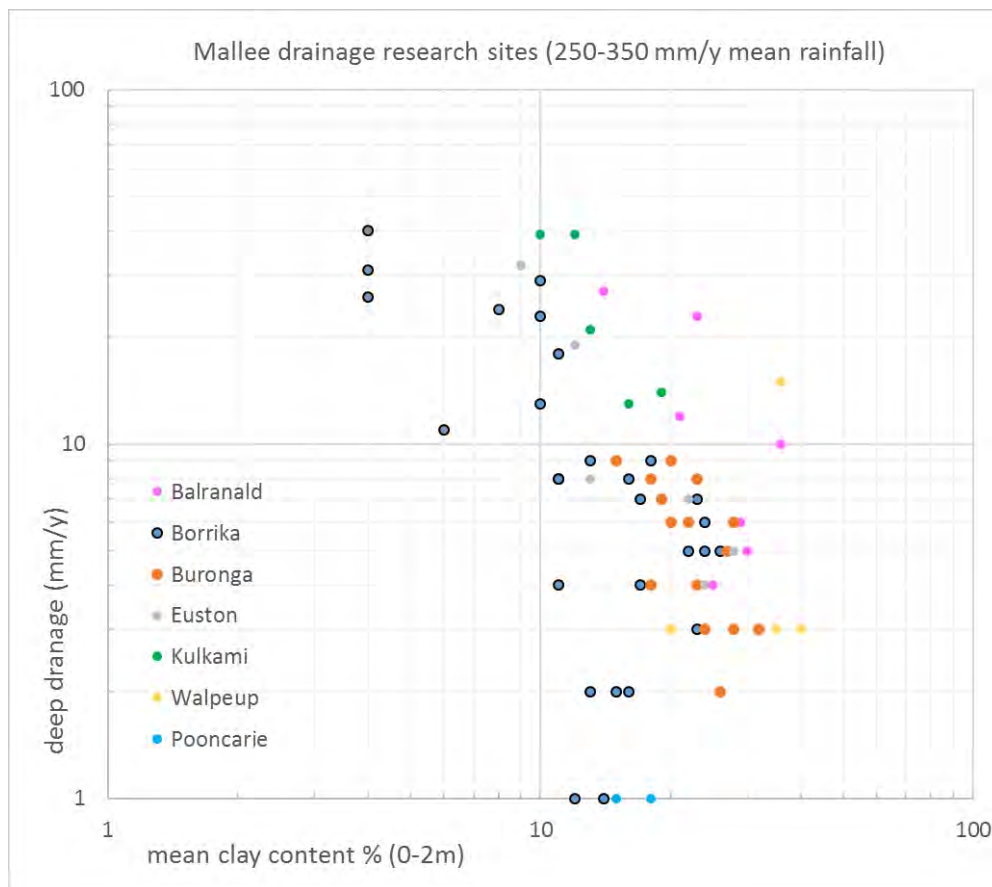


Figure 17 - relationships of drainage and average clay content

6.1.2 Uncertainty in mapped recharge

The error in the regional Mallee (SIMRAT) recharge mapping which uses the Cook paradigm/algorithms (i.e. as documented in Wang et al. 2005) has not been defined. It has been contextualised as follows (Wang et al. 2005):

“...one thing is certain that big differences in drainage exist between native mallee vegetation and the annual crop/pasture rotation system”.

The uncertainty in mapped dryland recharge is due in part to uncertainty in the RZD and (measured) clay content relationship (the point data from research, which has an error of around $\pm 50\%$; Cook et al. 2004). However, the error is greatly increased by the application of regional soil maps (necessary to infer clay content), as these maps have inherent deficiencies (for the purpose of drainage estimates) in how soil type has been mapped spatially, as explained by Crosbie et al. (2010):

Soils exhibit metre scale heterogeneity and the soil type will vary down a hillslope, all within the same polygon on a map. There will be inaccuracies in the soil that was assigned to each field estimate of recharge but these inaccuracies are consistent with the intended use of the relationships developed.

This means that, while we are unlikely to be able to improve significantly on the soils mapping without making more use of airborne electromagnetics, the inaccuracies in drainage relationships (including the log-normal spatial variability refinements) reflect to some degree the variability/inaccuracy in the soils/mapping (for the purpose of drainage estimates).

Wohling et al. (2012) made some very pertinent points about Mallee recharge uncertainty issues:

The unpredictability of recharge due to climatic variability (rainfall and evapotranspiration amount, duration and intensity) combined with spatial variability of soil texture presents difficulties when estimating the spatial and temporal variability of recharge. ...the spatial variability within a land use class may present uncertainties when assessing site specific recharge rates in a broad ranging correlation. For example, annuals encompass a considerable diversity of annual crops and pastures and can represent a variety of farming management practices, including cropping and fallow rotations, direct drill or conventional tillage, and winter crops or summer crops.

Given the range of variables that impact on deep drainage estimates and the resultant level of uncertainty of any such estimate, it would be natural to pose questions over the applicability of scaling up point deep drainage measurements to management scale estimates of deep drainage and associated uncertainty predictions. Up-scaling requires mapping of percentage clay content over large areas. Consequently, the accuracy of deep drainage estimates at management scale boundaries are dependent upon the correlation between the measured soil profile clay content at each investigation site compared to an estimate of clay content from a Geographical Information System (GIS) layer, for example the Soil Landscape Unit (SLU) coverage. A regression through measured soil textural data and SLU soil textural estimates from Wohling (2007) gave evidence that use of such a relationship for up-scaling was not reliable. Consequently, up-scaling using SLU estimates of clay content (0-2 m), which will ultimately depend on a correlation between field and SLU estimates of clay content, should be exercised with caution.

In summary, the uncertainty in mapped Mallee recharge is due in small part to uncertainty in the RZD and (measured) clay content relationship, but it is mainly due the application of regional soil maps (necessary to infer clay content), as these maps have inherent limitations in how the soil landscape mapping approach can be applied to spatial estimates of drainage.

6.2 REGIONAL MODEL UNCERTAINTY

While recharge estimates at a point in the Mallee may vary widely, there are a number of smoothing/mitigation effects involved in the translation of recharge inputs to salt load impacts in the River:

- the aggregation of point estimates to a regional recharge effect is a mathematical integration (smoothing) process;
- the rise in groundwater level at any point is not due to aquifer recharge occurring at that point; rather it is a result of recharge occurring in the region (the aquifer tends to aggregate/distribute the diffuse recharge inputs);
- there is an interception effect of evapotranspiration on the floodplain; for example, the EM1.2 regional modelling study varied dryland recharge by 50% and showed that salt loads varied by 11% in response (Aquaterra 2009a).

The EM1.2 scenario indicates that salt loads are relatively insensitive to dryland recharge rates (but this generalisation is not necessarily universally applicable). There are no other known instances where the dryland recharge rates have been varied in regional models to evaluate salt load uncertainties. There are no known modelling scenarios that have varied the time lag estimates. Quantitative uncertainty assessment is warranted, if for no other reason than it is not otherwise possible to objectively quantify salt load uncertainties.

Another issue that should be considered is that the generally small incremental salt loads due to vegetation clearance across most of the river reaches in the models is challenging the limit of simulation accuracy (section 5). Having said that, the calculation of incremental salt loads by model scenario difference would tend to reduce modelling uncertainties (Barnett et al. 2012). However, the errors involved in measuring salt loads (or indeed stream flows) in the River exceed the small variations in model estimates of salt loads due to these dryland recharge rates.

6.3 SUMMARY COMMENTS ON UNCERTAINTY ISSUES

Despite the variabilities described above and elsewhere in this report, the fundamental point is that there are orders of magnitude increases in RZD under an annual crop/pasture rotation dryland farming system compared to under native mallee vegetation, except in low rainfall areas that are thinned for predominantly grazing land use that show no significant RZD differences.

The impact of the vegetation clearance action (in BSMS terms) is captured in a systematic and quantitative manner via the Cook algorithms, noting further that:

- the RZD relationship has intrinsic point estimate errors of only $\pm 50\%$;
- the RZD estimates capture some spatial variability through the mean and variance parameters of the log-normal drainage function (based on comprehensive research);
- the application of regional soil maps (necessary to infer clay content) invoke uncertainties in mapped (scaled up) recharge due to inherent limitations in how the soil landscape mapping approach can be applied to spatial estimates of drainage;
- mapped recharge rates in south-western NSW are potentially over-estimated, although cleared areas are small and thus salt load implications are minor;
- the estimated RZD rates drive the estimates of lag time for recharge to reach the water table, including delays due to impeding clay layers, and thus any RZD errors are also multiplied through time lag uncertainties;
- regional models appear to exhibit low sensitivity in salt loads due to variations in cleared dryland recharge rates, or at least lower sensitivity than due irrigation recharge (caution: based on only one sensitivity test via the EM1.2 model).
- overall uncertainty in salt load estimates due to mallee clearance is currently unquantified, but it is expected to be large (e.g. at least as large as the salt load estimates themselves);
- definitive uncertainty estimates can only be provided from a quantitative model uncertainty assessment; workshop discussions on the considerable effort required to quantify uncertainties relating to mallee clearing recharge effects concluded that it would likely not be commensurate with the low salt load risk (i.e. it is not warranted for each and every modelling study); however, a pilot study may be warranted to quantify the effects on salinity Registers of uncertainties in mallee clearance recharge estimates.

7. Implications for Estimating Salt Loads

This study has endorsed the strong evidence that the Cook paradigm (Figure 18) of increased vertical drainage due to native mallee vegetation clearance and its replacement with dryland farming systems applies generally (but not uniformly) across the Mallee:

- the leaching of salt (chloride profile measurements) provides a contemporary indicator of the vertical process (continuing in many areas) and was used to quantify the root zone drainage rate;
 - although groundwater levels are much easier to measure, they are trailing and indirect indicators of the process;
- RZD under native mallee vegetation was found to be consistently 0.1 mm/y or less;
- RZD under dryland agriculture was found to be 1.0 to 2.5 orders of magnitude greater (typically 1-50 mm/y);
 - the exception is low rainfall areas that had been thinned for predominantly grazing land use (notably south-western NSW), where no significant difference was observed between RZD under native mallee and RZD under dryland farming;
- significant depths to groundwater and impeding clay layers above the water table in most areas of the Mallee cause long time lags (order of decades to centuries) for increased RZD and deep drainage to become groundwater recharge;
 - alternative RZD estimation methods that exclude the impeding clay layer are not suitable for Mallee conditions where Blanchetown Clay is ubiquitous.

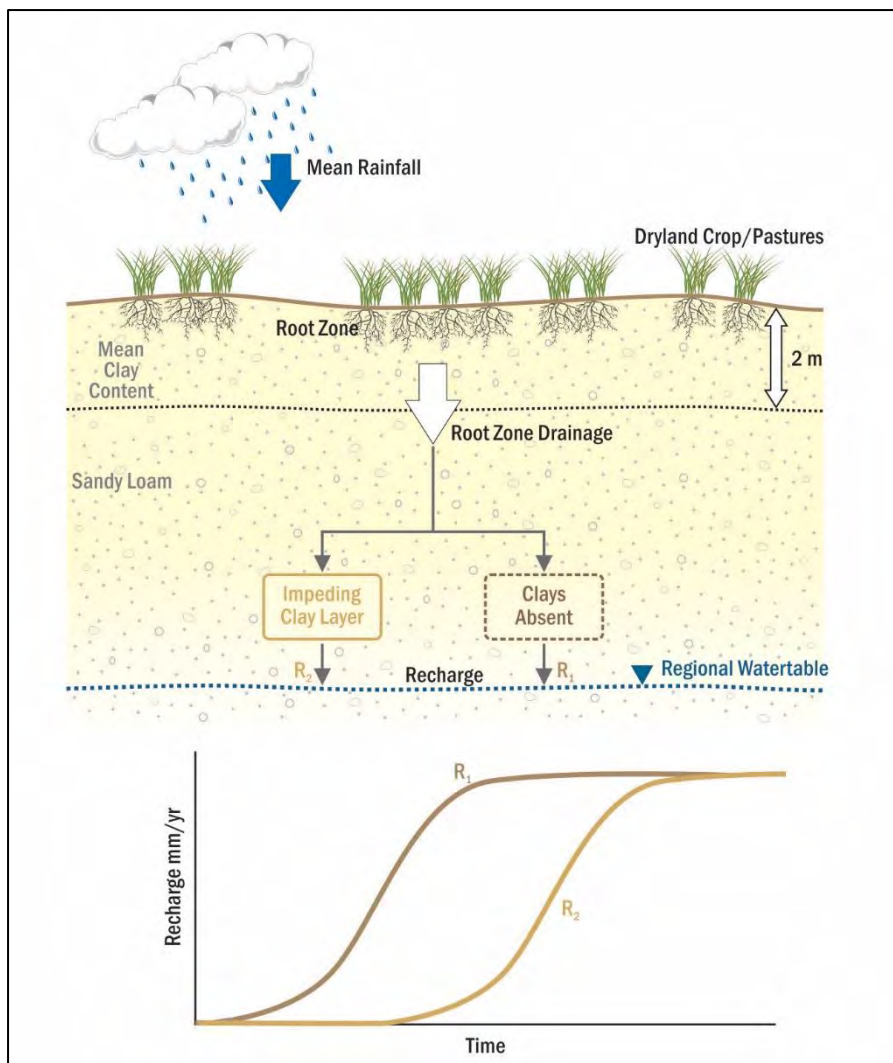


Figure 18 - simple conceptual model of Cook paradigm and SIMRAT recharge

The empirical Cook paradigm and algorithms for estimating RZD and delayed recharge:

- capture the impact of the vegetation clearance action (in BSMS terms) in a systematic and quantitative manner;
- are based on the best available science and have been independently verified as statistically significant at 95% confidence intervals, see section 4.8 for more detail;
- provide estimates of dryland recharge suitable for input to regional models to evaluate the salinity impacts of vegetation clearance;
 - via regional model inputs that all use SIMRAT model outputs of dryland recharge rates and time lags (Wang et al. 2005) that are derived from the Cook algorithms, and all assume clearing occurred (completely) in 1920
 - providing consistency among the modelling studies and thus a **“level playing field”** for Register B entries (e.g. an overall conservative approach to salinity impact assessment, consistent with BSMS principles).

The variability/uncertainty in the magnitude and timing of the mapped SIMRAT dryland recharge derived from the Cook algorithms is unknown but due mainly to variability in the landscape (soil profile properties and rainfall):

- due in small part to uncertainty (of the order of $\pm 50\%$) in the algorithm for (estimated) dryland RZD and (measured) mean rainfall and mean clay content (0-2m)
- due mainly to the application of regional soil maps (necessary to infer clay content), as these maps have inherent limitations in how the soil landscape mapping approach can be applied to spatial estimates of drainage (i.e. this is fundamentally a data variability/uncertainty issue);
- a degree of spatial variability in drainage rates is captured through the log-normal spatial distribution function, and the integration of the function over time provides a time series of delayed recharge to the water table (see section 2).

In summary, real world variabilities and data capture issues combine with the scientific/modelling assumptions, complexities and imperfections to result in unquantified uncertainties in the estimates of salt loads to the River (at least as large as the estimates themselves) and hence the salinity Register entries. It is not possible in cost-effective or practical terms to reduce the real-world and data capture uncertainties to any material degree, but a pilot study of quantitative model uncertainty would provide objective information on the actual range of salt load uncertainty.

As described in this report, a number of assumptions are involved in the methodology for estimating salt loads, some of which would lead to over-estimates and some to under-estimates (refer to Table 2 in section 4.7). However, there is no material evidence across most of the Mallee region to indicate that the assumptions have resulted in significant bias in groundwater levels or salt load estimates.

There are some indications of a potential bias for over-estimating recharge in low rainfall areas of south-western NSW (where mallee was thinned for mainly grazing land use, and where no significant difference was observed between RZD under native mallee and RZD under dryland farming). The Cook paradigm, expressed in the SIMRAT recharge, potentially over-estimates recharge in these areas. However, as discussed in section 3, it is not surprising that there is little evidence of rising groundwater levels in south-western NSW (see also Figure 11), given the predicted SIMRAT recharge rates and time lags applying to the small areas of clearing in south-western NSW, and other factors. Furthermore, as indicated in section 5.2 (Table 7), it is worth noting that the salt loads from mallee clearing in south-western NSW from a very small component of the cumulative mallee clearing salt load, which is itself a small part (5-10%) of the total salt load at all times up to 2100.

While any over-estimation may be considered problematic in that it would imply over-investment in salinity management, the dryland salt loads form a minor proportion (5-10%) of the total salt load, which would not itself cause over-investment. The time lags that apply to dryland recharge mean that substantial salt loads are predicted to be generated from about 2040/2050, which provides scope for application of an adaptive management approach (monitor and review).

8. Recommendations

8.1 OPTIONS FOR CONSISTENT MODELLING METHODOLOGIES

The following options regarding consistent modelling methodologies for vegetation clearance scenarios were discussed at the inter-jurisdictional workshop on 29th March 2017. While this project is endorsing the status quo, some options for improving the methodologies are listed below roughly in order of decreasing priority (should current budget constraints be relaxed):

- status quo: the existing methodology of applying mapped dryland recharge rates and time lags (i.e. SIMRAT output; Wang et al. 2005) to regional groundwater models should continue to be applied to evaluate the potential salinity impacts due to pre-1988 vegetation clearance;
 - the status quo assumes clearing occurred (completely) in 1920, which is a conservative simplification given that information indicates that around two thirds of mallee clearing in SA and Victoria was completed by 1930 and south-west NSW is largely uncleared;
 - recent/ongoing initiatives may improve data on mallee clearing distributions; e.g. Sinclair et al. 2012, and a project using remote sensing to map clearing in South Australia (Peter Kretschmer, DEWNR, pers.comm.)
 - although floodplain process issues are not within the scope of this project, it is acknowledged that they have a major influence on salt loads reaching the River, in that evapotranspiration discharge is a significant process that intercepts groundwater flux towards the River; in the context of BSM 2030 and the Basin Plan, it is likely that the regional models will require upgraded floodplain process capability (e.g. similar to that being developed by DEWNR for the Pike floodplain).
- quantify uncertainty: a pilot uncertainty assessment may be warranted for a representative regional groundwater model in each jurisdiction to quantify the range of uncertainty applying to the best estimate (i.e. to objectively quantify the uncertainty applying to the Register entries);
 - comprehensive uncertainty assessments of regional groundwater models are time consuming and expensive, and are thus not warranted every time a salinity impact model is updated, hence the recommendation for a single (pilot) study.
- update the Wang/SIMRAT dataset of mapped recharge and time lags, compare and contrast to new datasets (e.g. WAVES, BoM, etc.) and use better data on land use changes (e.g. in south-western NSW).

8.2 RECOMMENDATIONS FOR FURTHER RESEARCH AND MONITORING:

Middlemis & Knapton (2016) identified 33 key sites for future monitoring which are confirmed as priorities (18 bores within 20 km and 15 more distant sites that focus on previous research study areas).

CDM Smith (2016) found that there is an underlying climatic variability influence apparent on salt accretion processes over decadal scales, confirming the very slow deep drainage process in train. Hence re-visiting soil chloride profiles that were previously investigated is warranted to quantify any climatic effects due to recent dry and wet periods:

- since 2007 through to the end of the drought (to 2010);
- the subsequent very wet period (2010-11);
- the relatively average period (2012-15);
- the recent wet period (second half of 2016).

CDM Smith (2016) also identified that measurement uncertainty issues can affect many existing monitoring bores.

Aggregating these recommendations from previous projects suggests that a project is warranted to:

- review the construction of the bores at the identified 18 priority sites (Middlemis and Knapton, 2015) to confirm their fitness for the purpose of annual monitoring of levels and salinity (trailing indicators of enhanced recharge due to clearing);
- review the soil chloride profiles at the 14 sites within 20 km of the River in SA investigated by Cook et al. (2004), and confirm which sites may be worth re-surveying (contemporary indicator of enhanced recharge due to clearing);
- review gaps in the network (notably in Victoria where few priority sites have been identified), and consider the need for potential new monitoring bore and/or soil chloride profile sites, and the added value of obtaining soil chloride profiles at key/priority monitoring bore sites that are confirmed as fit for purpose.

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10. Glossary

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

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

Aquifer, confined – **Aquifer in which the upper surface is impervious (see ‘confining layer’) and the water is held at greater than atmospheric pressure; water in a penetrating well will rise above the surface of the aquifer; see also potentiometric surface.**

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

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

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

Bore – **See ‘well’.**

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

BSMS - Basin Salinity Management Strategy 2015; implemented under Schedule B of the Murray-Darling Basin Agreement over the period from 2001 to 2015.

BSM 2030 - updated strategy for Basin Salinity Management for the period from 2016 to 2030.

Capillary fringe - Water held in the soil above the phreatic surface (or water table) by capillary forces.

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

CMA - Catchment Management Authority (State Government of Victoria)

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

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

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

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

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

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

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

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

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

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

- Drawdown - The vertical distance the water elevation is lowered (or the reduction of the potentiometric surface) due to the removal of water (e.g. via a pumped well).
- Dryland salinity – The process whereby salts stored below the surface of the ground are brought close to the surface by the rising watertable. The accumulation of salt degrades the upper soil profile, with impacts on agriculture, infrastructure and the environment.
- EC – Electrical conductivity; 1 EC unit = 1 micro-**Siemen per centimetre ($\mu\text{S}/\text{cm}$) measured at 25°C** ; commonly used as a measure of water salinity.
- Evapotranspiration – The total loss of water as a result of transpiration from plants and evaporation from land, and surface water bodies.
- Floodplain – generically defined as the land adjoining a watercourse that is periodically subject to flooding from the watercourse.
- GIS – Geographic Information System; computer software linking geographic data (for example land parcels) to textual data (soil type, land value, ownership) for spatial and temporal analysis.
- Groundwater – Water occurring naturally below ground level or water pumped, diverted and released into a well for storage underground.
- Head, hydraulic - The height above a datum plane (such as sea level) of the column of water that can be supported by the hydraulic pressure at a given point in a groundwater system. For a well, the hydraulic head is the distance between the water level in the well and the datum plane. The hydraulic head is the sum of the elevation head and the pressure head (also called static head).
- Head, total - The total head of a liquid at a given point is the sum of the static head and the velocity head, thus comprising three components: (a) the elevation head, which is equal to the elevation of the point above a datum, (b) the pressure head, which is the height of a column of static water that can be supported by the static pressure at the point, and (c) the velocity head, which is the height to which the kinetic energy of the water can lift it.
- Hydraulic conductivity (K) – A measure of the ease of flow through aquifer material: high K indicates low resistance or high flow conditions; measured in metres per day (m/d).
- Hydrogeology – The study of groundwater, which includes its occurrence, recharge and discharge **processes and the properties of aquifers; see also ‘hydrology’**.
- Hydrology – The study of the characteristics, occurrence, movement and utilisation of water on **and below the Earth’s surface and within its atmosphere; see also ‘hydrogeology’**.
- Hydrograph - A time series graph relating level, flow, velocity, or other characteristics of water.
- Impact – A change in the chemical, physical, or biological quality or condition of a water body caused by external sources.
- Impermeable - A characteristic of some geologic material that limits its ability to transmit significant quantities of water under the head differences ordinarily found in the subsurface.
- Infiltration - The downward entry of water into the sub-surface; see also percolation.
- Leaky aquifer - Aquifers that lose or gain water through adjacent less permeable layers.
- Log-normal distribution - A continuous probability distribution of a random variable whose logarithm is normally distributed.
- m AHD – Defines elevation in metres (m) according to the Australian Height Datum (AHD).
- Mallee - Region of southern Australia where current landscape (or past landscape) is mallee woodland; often referred to as Mallee region or Mallee zone. Areas of the Mallee have been extensively cleared for agriculture.
- MDBA – Murray-Darling Basin Authority
- MDBC – former Murray-Darling Basin Commission
- Model – A conceptual or mathematical means of understanding elements of the real world that allows for predictions of outcomes given certain conditions.
- MODFLOW - A three-dimensional, finite difference code developed by the USGS to simulate groundwater flow.

- Monitoring – The repeated measurement of parameters to assess the current status and changes over time of the parameters measured.
- MSM-BIGMOD - Flow and salinity routing model used to estimate river salt concentration consequences of changes in saline groundwater discharge in the River Murray and Lower Darling river system.
- Observation well – A narrow well or piezometer whose sole function is to permit water level measurements.
- Perched groundwater - Groundwater separated from an underlying body of groundwater (represented by a regional water table) by an unsaturated zone.
- Percolation - The downward movement of water through the unsaturated zone.
- Permeability - The property of a porous medium to transmit fluids under an hydraulic gradient; see also hydraulic conductivity.
- Phreatic surface - see water table.
- Piezometer - A device used to measure groundwater pressure head at a point in the subsurface.
- Porosity - The ratio, usually expressed as a percentage, of the total volume of voids of a given porous medium to the total volume of the porous medium [L^3/L^3]
- Potentiometric surface - An imaginary surface representing the static head of groundwater and defined by the level to which water will rise in a tightly cased well; where the potentiometric surface is higher than topography, the aquifer is described as artesian (otherwise, sub-artesian).
- Probability density - A mathematical function whose integral over an interval gives the probability that its value will fall within the interval.
- Ready Reckoner - Relates the effects of salt inflows in various reaches of the river on the EC impact at Morgan. The estimates are derived from MSM-BIGMOD modelling.
- Recharge - The process of addition of water to the water table (or saturated zone of a confined aquifer); recharge is also the volume of water added.
- Root zone drainage - RZD; a term used to define the amount of water that passes beyond the crop root zone.
- Salinity - The concentration of dissolved salts in water or soil, expressed in terms of concentration (mg/L) or electrical conductivity (EC).
- Salinity Registers - Implemented under the BSMS and maintained by the MDBA; a system for keeping record of accountable actions within the Basin.
- SIMRAT - Salinity Impact Rapid Assessment Tool; a tool developed and accredited for estimating salinity impacts of accountable actions to support BSMS objectives.
- SIS - Salt Interception Scheme; large scale pumping schemes that divert saline groundwater and drainage water before entering rivers.
- Soil water content (θ) - The ratio of pores in soil that are filled with water; commonly expressed as a volume [L^3 / L^3]
- Specific storage (S_s) – Specific storativity; the amount of stored water realised from a unit volume of aquifer per unit decline in head; units are (m^{-1})
- Specific yield (S_y) – The volume ratio of water that drains by gravity to that of total volume of the porous medium; [dimensionless].
- Storage coefficient (S) – confined aquifer storativity; the volume of groundwater released or taken into storage per unit plan area of aquifer per unit change of head; [dimensionless].
- Storativity (S) – the volume of groundwater released or taken into storage per unit plan area of aquifer per unit change of head; virtually equal to the specific yield in an unconfined aquifer; [dimensionless].
- TDS – Total dissolved solids, measured in milligrams per litre (mg/L); a measure of water salinity.

Transmissivity (T) – a parameter indicating the ease of groundwater flow through a metre width of aquifer section (taken perpendicular to the direction of flow); measured in m²/d.

Time lag - broadly refers to the interval of time between two related phenomena (such as cause and its effect); more specifically for the Mallee it refers to the period of time between water passing the root zone and becoming recharge at the regional water table.

Unconfined aquifer - An aquifer which has a water table.

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

USGS - United States Geological Survey.

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

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

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

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

Wetlands – generically defined as a swamp or marsh and includes any land that is seasonally inundated with water. This definition encompasses a number of concepts that are more specifically described in the definition used in the Ramsar Convention on Wetlands of International Importance, which describes wetlands as areas of permanent or periodic to intermittent inundation, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water, the depth of which at low tides does not exceed six metres.