Review of Australian Groundwater Recharge Studies
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Cover Photograph:

Description: Limestone tufa on the Douglas River in Northern Territory during the dry season.
Photographer: Anthony O'Grady, CSIRO
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EXECUTIVE SUMMARY

The primary requirement for management of water resources in any region is an accurate water balance. This, in turn, requires estimation of groundwater recharge and discharge rates and, where possible, knowledge of their spatial distribution. The amount of time and money water managers are willing or required to spend on estimating recharge/discharge depends on many factors but is primarily decided by the value of the groundwater resource, the likely scrutiny of the decision and data already available.

This report is one of three review reports that constitute phase 1 of the a consistent approach to groundwater recharge determination in data poor areas project funded by the National Water Commission. This report provides background information to address the issues of regional measurement of recharge in data poor areas and, more importantly, estimation in areas where more detailed studies are not deemed warranted. The report reviews studies in Australia where recharge rates have been estimated empirically, excluding those made in irrigation areas and those estimates generated from modelling approaches. A companion report looks at studies in Australia where vegetation discharge has been estimated. As well as providing a comprehensive database of field based measurement, these reviews also identify parameters associated with climate, soils, regolith, near-surface geology, landforms and vegetation that collectively influence recharge and discharge rates. The availability of mapping of these parameters or possible surrogates is addressed in a third report associated with this project. Together, these form the deliverables for Phase 1 of this project.

In this review, a database of 4386 recharge estimates has been compiled from 172 studies throughout Australia. These studies utilised one or more of ten different methods for estimating recharge. About 78% of the estimates were made using a steady-state chloride mass balance approach either of the groundwater (76%) or of the soil water (2%). A further 9% used the transient chloride mass balance of soil water method to estimate deep drainage. The remaining recharge estimates (13%) were computed using the watertable fluctuation, water balance and environmental tracer methods. In spite of the size of the database, the spatial coverage across Australia is inconsistent, with some regions (Mallee) very well represented whereas other regions (e.g. Gippsland) have no published estimates. Most of the more detailed studies are in South-Eastern Australia although there are a considerable number of estimates for Northern Australia (using the steady-state chloride mass balance of groundwater method) as a result of the recent Northern Australia Sustainable Yields project. Recharge estimates to fractured rock aquifers are very poorly represented in the database, particularly for detailed studies. This is a reflection of the difficulties in estimating recharge in these complex environments.

This review has made no attempt to place quality flags/uncertainties on recharge estimates. Part of the reason for this is the difficulty in doing so but, in addition, in many cases it is not so much poor data that is the problem but an understanding of the timeframe/land use/spatial scale over which the estimate applies. This is exemplified by the poor correlation observed between recharge estimates at the same site using different methods of analysis. Each estimation method is most applicable over a specific timeframe and has its own uncertainties and limitations. A consequence of this is that “recharge” estimates may best relate to a flux of water at some depth within the unsaturated zone (i.e. deep drainage), a flux to a watertable (i.e. gross recharge) or the net flux across the water table (i.e. net recharge). Likewise, estimates of recharge may refer to one land use or a mixture of land uses. Moreover, unsaturated zone generally assume water flows through the soil matrix. In areas where large fluxes of water by-pass the soil matrix, these methods are less applicable. All of these limitations will need to be considered in Phase 2 of this project where data from this review will be used to formulate relationships that may be applicable in data poor areas.

Because of its ease of use and minimal data requirements, the steady-state chloride mass balance of groundwater has clearly been the method most often used in Australia to estimate recharge rate. However, there are two main limitations when using this method. If there has been land use change, it is difficult to determine the timeframe over which the estimate applies. Hence, the estimate may refer to the earlier land use, the latter land use, or a
mixture of the two land uses. Therefore, this method should only be used where there has been no land use change or where the rate of recharge is sufficiently high and/or the unsaturated/saturated zone storage sufficiently low to ensure that the measurement definitely applies to the current land use.

The uncertainty of each recharge estimate via the steady-state chloride mass balance methods is proportionally dependent on the uncertainty in the estimate of the chloride flux for the area. Chloride flux is usually estimated using the average chloride concentration in rainfall multiplied by average annual rainfall. Unfortunately, there have been limited long-term measurements of chloride concentrations in rainfall flux and these estimates are not available in collated form. Hence, more often than not, empirical relationships developed from limited data over three decades ago are used to estimate the chloride concentration in rainfall. There are projects underway to help resolve this problem. Results from these projects will be incorporated in suggested methods which will be developed in Phase 2 of this project.

Vegetation type is a critical determinant of recharge rates. From the previous reviews, and the preliminary assessment of the database in this review, it appears that, for the same rainfall and soil type, recharge under annuals is greater than recharge under perennials which in turn is greater than recharge under trees. However, while the amount of data on perennials has increased since the reviews of Petheram et al. (2000, 2002), they are still under represented in comparison to annuals and trees.

Soil texture is also a strong control on recharge with estimates for heavy textured soils generally less than those for lighter textured soils. In the early 1990s, a correlation was developed between deep drainage and surface soil texture (% clay 0-2m) for cropping/pasture areas with 300-400 mm yr\(^{-1}\) annual rainfall (Kennett-Smith et al., 1994). Since then, there have been similar studies undertaken in a range of rainfall areas throughout Australia. Estimates of recharge from the database have been presented as a 3D plot between deep drainage, surface clay content and rainfall in this report. Preliminary results suggest that the 3D relationship developed may be valid regardless of whether the study area is in a winter dominant, lower intense rainfall regime or summer dominant, more intense rainfall area.

In this report, we have also made a preliminary attempt at assessing the recharge estimates in relation to climatic zones using the Koppen-Geiger classification and the aridity index. This looks promising but further work is needed.

Phase 2 of this project aims to use the databases prepared in this review and the companion discharge review to develop relationships that correlate estimates of recharge and discharge rate with readily available parameters such as rainfall, land use, leaf area index, soil type and hydrogeology. It will also utilise the mapping review from Phase 1 that presents regional mapping capabilities for these parameters. The relationships developed will form the basis of methods to be used by groundwater managers dealing with the difficult problem of recharge and discharge estimation in data poor areas. The recharge methods thus developed will have the backing of 4386 field based recharge estimates made over 70+ years of research at 172 sites.
1. INTRODUCTION

1.1. Background

The primary requirement for management of water resources in any region is an accurate water balance. This, in turn, requires estimation of groundwater recharge and discharge rates and, where possible, knowledge of their spatial distribution.

Recharge and discharge rates are largely determined by the interplay of climate, soils, regolith, near-surface geology, landforms and vegetation. Beneath native vegetation, rates of recharge are comparatively low. Land clearing and the development of dryland agriculture have led to significant increases in recharge. In irrigated areas, rates are higher still. In contrast, development of forest plantations in areas of shallow watertables has led to net groundwater discharge in a number of areas. In addition, rates of recharge, sub-surface water movement and discharge are strongly influenced by the nature of landforms, regolith and near-surface geology, and spatially can be highly variable. Some areas may even alternate between being a recharge and a discharge zone. Furthermore, there may be recharge from deeper aquifers into the shallow environment. Thus, in any area there is a complex pattern of recharge and discharge resulting from the interplay of climatic, biologic, and geologic influences.

When formulating a water balance for a region, managers address recharge and discharge estimation in many different ways. The amount of time and money expended depends on many factors but is primarily decided by the value of the groundwater resource, the likely scrutiny of the decision and data already available. In some areas, detailed research projects are commissioned that provide information on spatial and temporal variability of recharge, and the relationship between recharge rates and soil, regolith, landform and vegetation parameters. These projects usually underpin and incorporate a potential spectrum of groundwater modelling approaches all of which have their pros and cons, supporters and detractors.

However, the larger knowledge and data requirements for these more sophisticated modelling approaches means that, pragmatically, simpler approaches are generally used, in which recharge is assumed to be a simple percentage of rainfall (and discharge is often ignored). The percentage rainfall value chosen to compute the recharge rate can vary widely, however (for example, from less than 2% to more than 10%). Often the value used is not justified, and consequently appears to be arbitrary. These types of approaches are subject to very large uncertainty, and lead to major inconsistencies between different water management areas. However, in defence of water managers, when one looks at the knowledge and data requirement for the more sophisticated modelling approaches, it is clear why they often choose such an approach.

The Groundwater Technical Advisory Committee of the National Water Commission (NWC) have been aware of discrepancies in recharge values used for some time and have been concerned about the impact this would have in groundwater management and policy implementation. As a result, they suggested to NWC, the need for a consistent approach to recharge and discharge estimation in areas where specific recharge/discharge studies are neither available nor planned. This phased project aims to provide such an approach over two phases.

Phase 1 of the project consists of three related review reports concerned with recharge estimation, discharge estimation, and mapping approaches that could potentially be used to predict recharge and discharge on a regional basis. This report is the first of these and summarises previous reviews of recharge estimation in Australia, and identifies new work that has been carried out since the last of the comprehensive Australian recharge reviews (Petheram et al., 2002).
In order to gain the greatest benefit from the review, we have developed a comprehensive database containing 4386 recharge estimates from 172 Australian site studies (Figure 1) along with the method used for estimation and data relating to the study site (e.g. site location, rainfall, land use, soil type, etc). The recharge estimates are from site studies only and do not include estimates made using groundwater modelling approaches. They are also limited to non-irrigated areas. The results of a preliminary analysis of the database are described in the Discussion section of this report. The database will be used in Phase 2 of the project to develop relationships between recharge and different climate and landscape attributes (e.g. mean annual rainfall, soil type, land use).

Figure 1-1 Location of recharge studies (green dots) across Australia.

1.2. Recharge estimation methods

There have been a number of summaries and reviews of recharge estimation techniques over the last decade. The most comprehensive summary is the 10 volume CSIRO series on “Studies in Catchment Hydrology: The Basics of Recharge and Discharge” which was edited by Zhang and Walker (1998).

In 2002, Hydrogeology Journal published a Theme Issue on recharge (Volume 10, Number 1) which included comprehensive reviews of recharge processes (de Vries and Simmers, 2002) and estimation methods (Scanlon et al., 2002; Walker et al., 2002). The Theme Issue also has numerous other papers which describe in-depth details of some of the estimation methods, as well as interesting case studies. The reader is referred to the above-mentioned reviews for details of these methods.

During the course of this review, results using the following methods of recharge and/or deep drainage were reported. The methods are listed by order of popular use with the most commonly used method listed first. The acronym used for each of the methods in the data base is provided in brackets.
• Steady-state chloride mass balance of groundwater (Cl SS GW)
• Steady-state chloride mass balance of soil water (Cl SS Soil)
• Transient chloride mass balance of soil water (Cl Transient Soil)
• Watertable fluctuation (WTF)
• Water balance, including lysimetry and soil moisture measurements (WB)
• Carbon-14 ($^{14}$C) groundwater dating (C14)
• Chlorofluorocarbon groundwater dating (CFC)
• Tritium ($^{3}$H) groundwater dating (Tritium)
• Chlorine-36 ($^{36}$Cl) groundwater dating (Cl36)
• Bromide addition and recovery in the unsaturated zone (Br)

A brief description of each of these methods is given in the Discussion section of this report.

1.3. Terminology

When discussing recharge estimation, it is important to ensure consistent and correct terminology is used. In the past, the term recharge, along with terms such as deep drainage, have often been interchanged and used incorrectly. Walker et al. (2002) used the terms deep drainage, recharge and potential recharge to clarify what is meant by each of these terms. De Vries and Simmers (2002) and Scanlon et al. (2002) also defined terms that describe types of recharge (i.e. diffuse (direct) recharge, indirect recharge, localized (focussed) recharge). For the purpose of this report, we adopt the combined definitions of the afore mentioned publications:

*Deep Drainage* is the flux of infiltrated water that moves past the root zone of vegetation. Deep drainage becomes recharge only when no impeding layers exist that would prevent water from moving down to the aquifer.

*Recharge* is the amount of infiltrated water that reaches a specific aquifer.

*Net recharge* is the recharge to the watertable less the amount extracted from the watertable by plant transpiration or direct evaporation.

*Potential Recharge (Deep Drainage)* becomes future recharge. Where a change of land use occurs, a time delay occurs for the recharge associated with the new land use to reach the watertable. This is effectively equivalent to deep drainage but is used to distinguish those cases where the time delay is in the order of years or decades.

*Diffuse (Direct) Recharge* is water added to the aquifer in excess of soil-moisture deficits and evapotranspiration by direct vertical percolation through the vadose zone.

*Indirect Recharge* is percolation to the watertable through the beds of surface water courses and sink holes.

*Localized (Focussed) Recharge* is an intermediate form of groundwater recharge resulting from the horizontal (near-) surface concentration of water in the absence of well defined channels.
2. PREVIOUS RECHARGE REVIEWS

There have already been several reviews of recharge estimates in Australia (Kennett-Smith et al., 1994; Petheram et al., 2000; Cook et al., 2001a; Petheram et al., 2002; Tolmie and Silburn, 2003; Silberstein, 2010). It is not our intention to reproduce these works but rather to summarise their findings and then present studies not included in these reviews. While the different recharge estimation methods utilised in each study will be discussed in this report, the emphasis will be on the recharge rate that was estimated for each area/site and how it relates to factors that can be mapped at the regional scale. Once completed, the relationships generated will form the basis of a method for estimating recharge in data poor areas. The authors understand the difficulty that arises from the spectrum of recharge/discharge regimes available throughout Australia but we stress that the aim of this study is to provide a consistent approach to estimating recharge and discharge in data poor areas and that the relationships derived in this study should only be used where more sophisticated/costly methods are not warranted.

2.1. Summary of Kennett-Smith et al. (1994)

Kennett-Smith et al. (1994) used recharge estimates made using the generalised chloride front displacement method (one of the transient chloride mass balance in soil water approaches); Walker et al., 1991) from 18 studies in the south western Murray Basin. They also used a simple water balance model (WATBAL) to study the importance of factors which affect diffuse recharge in that area (mean annual rainfall, mean clay content in the top 2m of the soil profile, and land use). The recharge method used estimated the average annual increase in potential recharge since clearing of native vegetation.

Kennett-Smith et al. (1994) found that it was possible to develop quantitative recharge relationships. Figure 2-1 shows the relationship between potential recharge and mean clay content to 2 m, for a land use of crop-fallow-pasture rotation in areas with mean annual rainfall of 300-399 mm yr⁻¹. There is clear trend of decreasing recharge with increasing clay content.

![Figure 2-1. Clay content versus potential recharge, for crop rotation sites in the western Murray Basin, with annual rainfall of 300-399 mm. (Figure 3 of Kennett-Smith et al., 1994).](image-url)
cropped (square and plus symbols) from those which are grazed but not cropped (triangle and circle symbols). The relationships are not as clear for data from cropped areas with mean annual rainfall of 300-399 mm yr\(^{-1}\) (plus symbols).

**Figure 2-2.** Clay content versus potential recharge, with mean annual rainfall for sites in the southwestern Murray Basin. The symbols show mean annual rainfall and land use are: Square 250-299 mm C(ropping), Plus 300-399 mm C, Diamond 400-499 mm C, Triangle 250-299 mm P(asture only), and Circle 300-399 P. Also shown are some clay content versus potential recharge relationships predicted by the water balance model. (Figure 4 of Kennett-Smith et al., 1994).

Kennett-Smith et al. (1994) concluded that overall the results showed that:

1. in general, as the texture of the soil became heavier the recharge decreased;
2. under cropped land, as the clay content in the top 2 m of the soil increased from 0 to 20%, recharge decreased by one order of magnitude (from \~30 mm yr\(^{-1}\) to \~3 mm yr\(^{-1}\), for a mean annual rainfall of 310-380 mm yr\(^{-1}\));
3. as mean annual rainfall increased the mean annual recharge increased;
4. sites with a mean clay content of \~10\% in the top 2 m and a mean annual rainfall of 270 mm yr\(^{-1}\) had an estimated recharge of about half that of sites with a similar mean clay content in the top 2 metres but a mean annual rainfall of 310-380 mm yr\(^{-1}\); and
5. data from land which was grazed but not cropped showed similar relationships, however the limited data set did not allow a detailed analysis of the effect of land use on recharge.

### 2.2. Summary of Petheram et al. (2000, 2002)

Petheram et al. (2000, 2002) reviewed over 80 recharge estimation studies in Australia to test whether generic relationships could be developed for assessing the impact of land use change on recharge. Data from 41 of the studies were used to generate a database whereby the recharge estimates were characterised on the basis of broad soil type (sand or non-sand), land use (annuals (shallow-rooted annual crops or pastures), perennials (perennial crops, pastures and native herbaceous vegetation) or trees (very deep-rooted vegetation)) and annual rainfall. Because the collated data represented estimates of recharge at different
temporal and spatial scales as well as at different depths in the soil, they were divided into three groups. Group 1 techniques were those that inferred recharge at depths many metres below the root zone and were generally point scale measurements and averaged over decades. Group 2 techniques were those that inferred recharge from water table changes at the paddock to catchment scale and at a time scale of event to annual. Group 3 techniques were those which estimated potential recharge immediately below the root zone and were generally at the point scale and at a measurement scale of hours to days. For Group 1 and 2 measurements the annual totals were long-term/historical averages, while the yearly totals for Group 3 were for a single year. In order to investigate the effect of soil texture on potential recharge and thus develop generic relationships for assessing the impact of land use change on recharge, Petheram et al. (2002) discarded some of the data where the authors of the original study deemed their measurements to be unrepresentative or erroneous (e.g. due to technical difficulties) or they noted the estimate was made under conditions of preferential flow. Due to the scale and frequency of distribution of preferential flow paths, Petheram et al. (2002) found it difficult to contemplate any relationship that could be applied to such an area because of the difficulty of mapping such features. Data were also discarded where the original study failed to specify soil or vegetation type or if trees less than five years of age were present.

Petheram et al. (2002) found that the development of quantitative recharge relationships was only partially successful due to limited geographical coverage, lack of detail provided by the studies and the variability in their data. Data from the 41 measured studies are presented in Figure 2-3, in which all rainfall and recharge values are annual totals. Figure 2-3 suggests that in the case of the Gnangara Mound in Western Australia there are different factors limiting transpiration/recharge to those applied generally in this study. This region is covered by very deep, coarse sands, and recharge estimates were considerably higher (i.e. sometimes an order of magnitude) than any of those found in the literature from other parts of Australia. That this region has very fresh water and the aquifer is high yielding is indirect evidence that this system is atypical of many Australian aquifers, particularly those that are salinised. The reasons for the very high recharge rates are not clear. It is apparent that this region and other regions with similar soils will need to be examined separately. These data highlight that relationships will not be applicable across all areas, and that it may be possible to identify such outlier areas.

![Figure 2-3. Annual recharge versus annual rainfall for different vegetation types. The hollow data symbols indicate measurements made at Gnangara groundwater mound (GM), Western Australia.](image-url)
Australia. The 1:1 line indicates the point at which all rainfall becomes recharge. (Figure 2 of Petheram et al., 2002).

Figure 2-4 is a subset of Figure 2-3 where data from the Gnangara groundwater mound (3 of the 41 studies) have been excluded. In Figure 2-4, a distinction has been made between single year and long-term average annual recharge and rainfall values.

Figure 2-4. Annual recharge versus annual rainfall for different vegetation types and time scales of measurement. Each symbol represents either an individual measurement or an area-averaged estimate of recharge. Solid symbols represent long-term average annual data and hollow symbols represent single year data. Symbols enclosed by a circle were measurements made under conditions of preferential pathway flow (by mention in cited paper) and were not included in the statistical analysis. Data from the Gnangara groundwater mound have not been included in this figure. (Figure 4 of Petheram et al., 2002).

The influence of different estimation technique groupings on recharge was not investigated for the entire data set because few recharge estimation techniques are suitable for estimating recharge under trees. Figure 2-5 is a subset of Figure 2-4 and shows recharge estimates made using different techniques, but only in respect of the annual vegetation subclass.
Figure 2-5. Annual recharge versus annual rainfall for annual vegetation using different recharge estimation techniques. This figure is a subset of Figure 2-4. (Figure 5 of Petheram et al., 2002).

It was proposed that much of the variation in the data in Figure 2-4 was caused by different soil types and that accounting for this factor may lead to more robust relationships. However, difficulties with categorising soil types meant that soils were ultimately divided into only 2 very broad textural groups: sand and non-sand (Figure 2-6).

Figure 2-6. Annual recharge versus annual rainfall for sand and non-sand soils. This figure is a subset of Figure 2. The 1:1 line indicates the point at which all rainfall becomes recharge. The excess water curves are not illustrated because both long-term and single year data are presented together. (Figure 6 of Petheram et al., 2002).
Petheram et al. (2002) found that attempts to develop quantitative recharge relationships met with limited success because of the limited geographical coverage of the studies, lack of details on the study sites, and high variability in the data. Nevertheless, the following relationships for annual vegetation were found to be statistically valid:

\[
\ln(\text{recharge}) = -19.03 + 3.63 \ln(\text{rainfall}) \quad \text{[for sandy soils]} \quad F(1, 96) = 149.03; \quad R^2 = 0.60
\]

\[
\ln(\text{recharge}) = -12.65 + 2.41 \ln(\text{rainfall}) \quad \text{[for non-sandy soils]} \quad F(1,151) = 46.87; \quad R^2 = 0.23
\]

The low degree of explanation of rainfall for the annual × non-sand data suggested that it is likely that soil structure becomes more important for higher clay content soils. Recharge under trees was negligible compared with that under annuals. Petheram et al. (2002) warned that these relationships should not be used in areas such as those where: preferential pathway flow is the dominant recharge mechanism; rainfall is summer dominant; lateral hydraulic gradients are high; water holding capacities are very low; or there are fresh, high-yielding aquifers.

Petheram et al. (2002) concluded that collectively, the results showed that:

1. rainfall explains a significant proportion of the observed recharge variation;
2. there is a significant difference between mean recharge under trees and annual vegetation;
3. there is a significant difference between mean recharge under annual vegetation on sand soils and non-sandy soils;
4. the land use groups had a greater influence on recharge than the broad soil groups used in the study;
5. there is a lack of annual recharge measurements under perennial pastures/crops, under trees in high rainfall zones (i.e. >600 mm yr\(^{-1}\)) and in areas of summer dominant rainfall;
6. across a broad range of locations, recharge is higher under shallow-rooted annual vegetation than deep-rooted vegetation; and
7. the estimator of Zhang et al. (1999) for ‘excess water’ may provide a useful indication of the upper limit to the long-term average recharge measurements.

Petheram et al. (2002) further concluded that the large variation in the data resulted from a variety of factors including disparity in the recharge techniques used, the coarse soil categories used, failure to account for land management factors, and complications due to macropores and shallow watertables.

### 2.3. Summary of Cook et al. (2001a)

Cook et al. (2001a) summarised all of the recharge estimates from the Mallee region in South Australia, New South Wales and Victoria in order to review the impacts of clearing of mallee vegetation on the Murray River and assess amelioration options. No new attempts were made to relate recharge rates to factors such as soil clay content, land use, and rainfall as this had already been done previously by Kennett-Smith et al. (1994) for this region.

### 2.4. Summary of Tolmie and Silburn (2003)

Tolmie and Silburn (2003) reviewed deep drainage information for dryland cropping systems in the Queensland Murray-Darling Basin and surrounding areas, with a view understanding the future dryland salinity risk in this region. The key factors influencing deep drainage and the data acquisition methods were discussed. They found that there was little quantitative data available for deep drainage under dryland agriculture in this region before about 2002. The limited available data suggested that deep drainage under native vegetation ranged from <0.1 mm yr\(^{-1}\) to 30 mm yr\(^{-1}\), and that post-clearing deep drainage rates were highly variable (< 1 mm yr\(^{-1}\) to 200 mm yr\(^{-1}\)). The limited data prevented the authors from developing any
clear relationships between deep drainage rate and factors such as soil clay content, land use, and rainfall.

2.5. Summary of Silberstein (2010)

Silberstein (2010) reviewed all of the studies of recharge and vegetation water use on the Gnangara groundwater mound, near Perth in Western Australia. The study focussed on the water use by pine plantations as there was concern that the pine trees may be using some groundwater and so net recharge (rainfall recharge to the watertable less the amount extracted from the watertable by plant transpiration or direct evaporation) is the most critical unknown parameter. Silberstein (2010) concluded that recharge declines with increasing basal area, stem density and Leaf Area Index (LAI) (Figure 2-7, Figure 2-8, Figure 2-9).

Figure 2-7. Gross recharge in the Gnangara groundwater mound plotted against vegetation basal area. (Figure 5 of Silberstein, 2010).

Figure 2-8. Gross recharge in the Gnangara groundwater mound plotted against vegetation stem density. (Figure 6 of Silberstein, 2010).
Figure 2-9. Net recharge in the Gnangara groundwater mound plotted against Leaf Area Index (LAI). (Figure 7 of Silberstein, 2010).

However, Silberstein (2010) also concluded that the differences between sites and the disparate results suggest that management of stands of both pine plantations and native vegetation and the soil profile may have such an influence on recharge that simple analysis was not possible. This was demonstrated in plots of gross recharge versus rainfall and depth to the watertable, and net recharge versus depth to the watertable, which showed considerable scatter (Figure 2-10, Figure 2-11, Figure 2-12).

Figure 2-10. Gross recharge plotted against rainfall across the Gnangara groundwater mound for all studies cited. (Figure 2 of Silberstein, 2010).
Figure 2-11. Gross recharge in the Gnangara groundwater mound plotted against depth to the watertable. (Figure 3 of Silberstein, 2010).

Figure 2-12. Net recharge in the Gnangara groundwater mound plotted against depth to the watertable. (Figure 4 of Silberstein, 2010).
3. RECENT RECHARGE ESTIMATES IN AUSTRALIA

There have been a large number of recharge estimates made in Australia since the last of the national recharge reviews in 2002 (Petheram et al., 2002). We summarise below the new data that have become available which can potentially augment the established recharge relationships described in the previous reviews. We also include a few studies that were not included in the previous recharge reviews. For ease of presentation we divide this section up by States. Unless stated otherwise all ‘new’ estimates of recharge discussed in this section were included in the data base.

3.1. South Australia

3.1.1. Overview

There have been numerous deep drainage/recharge measurements made in South Australia. The major study areas have been in the Western Murray Basin and the South-East, both of which are sedimentary aquifer systems, and the fractured rock aquifer systems around Clare in the Flinders Ranges and in the Mt Lofty Ranges. All of the South Australian study areas have winter dominant rainfall climates with mean annual rainfall ranging from 260 mm yr⁻¹ in the Riverland (Western Murray Basin) to 660 mm yr⁻¹ in the Green Triangle (South-East).

All of the recharge/deep drainage measurements made prior to 1993 were included in the Kennett-Smith et al. (1994) review and have formed the basis of the post-clearing deep drainage versus clay content relationship for the 300-399 mm yr⁻¹ mean annual rainfall areas. The more recent studies discussed in this section present data and post-clearing deep drainage versus clay content relationships for lower and higher rainfall areas than those reported by Kennett-Smith et al. (1994). Several of these studies have estimated deep drainage and/or recharge at the same site using up to 4 different methods (steady-state chloride mass balance of soil water, transient chloride mass balance of soil water, chlorofluorocarbon or ¹⁴C groundwater dating and watertable fluctuation).

3.1.2. Western Murray Basin

A number of recharge studies involving the use of electromagnetic induction meters were not included in the previous recharge reviews of Kennett-Smith et al. (1994), Petheram et al. (2000) and Petheram et al. (2002). Cook et al. (1989a) calibrated ground frequency-domain electromagnetic (FEM) meters (Geonics EM31 and EM34) at 4 sites (total of 27 holes) in the western Murray Basin in South Australia. These were used to derive theoretical relationships between electrical conductivity and the estimated total recharge stored in the soil profile to the depth of each hole. Cook et al. (1989b) used the EM34 FEM meter calibrated to recharge rates estimated from chloride profiles (Figure 3-1) to study the spatial variability of recharge in a 14 ha paddock at Borrika with deep and relatively uniform sandy soils.
Figure 3-1. Theoretical relationship between apparent conductivity, determined using an EM34 ground conductivity meter, and recharge rate. Recharge rates determined from chloride profiles directly are compared. Arrows indicate minimum estimates using the transient chloride mass balance of soil water method (Figure 5 of Cook et al., 1989b).

Cook et al. (1992) studied recharge along transects north of Borrika using chloride profiles and both FEM (Geonics EM31, EM34, EM38, and EM39) and transient electromagnetic (TEM) meters. The electromagnetic meters were less successful in predicting recharge rates (Figure 3-2) in this area as they were mostly mapping soil type rather than the chloride leaching profiles that were used to estimate recharge. Cook and Kilty (1992) extended this study to include a multi-frequency helicopter electromagnetic survey of the same site. Correlations between recharge and apparent conductivity (Figure 3-3) were only significant ($R^2 = 65\%$) at the highest frequency (56,000 Hz). It is clear from these studies that EM methods barely work for very uniform sandy soils and so they are unsuitable for more complex heavier textured soils. This is because the soil texture dominates the apparent conductivity rather than the chloride leaching profile which is used to estimate salinity and hence recharge.

![Figure 3-1](image1.png)

Figure 3-2. Comparison of field data relating apparent electrical conductivity to recharge and theoretical model. Model data are shown for 5, 10 and 20% clay contents. (Figure 8 of Cook et al., 1992).
Cook et al. (2004) estimated deep drainage rate (potential recharge) at a further 14 sites in the western Murray Basin in an area with a mean annual rainfall of ~260 mm yr$^{-1}$ and compared them with clay content in the upper 2 m of the soil (Figure 3-4). The deep drainage estimates were made using the transient chloride mass balance of soil water method.

Cook et al. (2004) also plotted them with the Kennett-Smith et al. (1994) estimates for crop rotation sites in the western Murray Basin with annual rainfall of 300-399 mm (Figure 2-1 above), and this is shown in Figure 3-5. They highlighted estimates in the Kennett-Smith et al. (2004) study from nearby sites at Maggea and Murbko which have similar mean annual rainfall as their new sites.

Based on the point estimates of drainage obtained in their study and in previous studies, Cook et al. (2004) developed empirical equations to relate drainage beneath dryland agriculture to soil texture and rainfall. An attempt was made to extrapolate deep drainage across the entire South Australian Mallee region using soil landscape unit mapping. This was
considered to be only partially successful as the average drainage rate measured on the soil cores (2.7 mm yr⁻¹) was less than the average drainage rate predicted from the regional mapping (4.9 mm yr⁻¹).

Figure 3-5. Relationship between soil texture and drainage under dryland agriculture in the 300-399 mm yr⁻¹ mean annual zone (open circles), at Maggea and Murbko (270 mm yr⁻¹; closed circles) and for the study site of Cook et al. (2004) (260 mm yr⁻¹; closed squares). (Figure 3.7 of Cook et al., 2004).

3.1.3. Tintinara

Leaney et al. (1999), Leaney (2000) and Leaney et al. (2004) carried out studies of the potential for groundwater salinisation in the Tintinara area of the Upper South-East of South Australia which has a mean annual rainfall of ~470 mm yr⁻¹. As part of this work they estimated deep drainage rate (potential recharge) at 15 sites using the transient chloride mass balance of soil water method. Leaney et al. (2004) plotted these estimates with the Kennett-Smith et al. (1994) estimates for crop rotation sites in the western Murray Basin with annual rainfall of 300-399 mm (Figure 2-1 above), and the estimates of Cook et al. (2004) and these are shown in Figure 3-6. Leaney et al. (2004) correlated all of the 470 mm yr⁻¹ rainfall zone estimates of deep drainage (D) with % clay content in the top 2 m of soil (C) and obtained the following line of best fit:

\[ D = 10^{(-0.035C+1.9)} \]

This relationship was used with soil landscape unit mapping to extrapolate deep drainage estimates across the entire Tintinara area. It should be noted that, at 2 of the 9 sites, the authors were only able to obtain a minimum estimate for deep drainage. These minimum estimates were included with the other 7 estimates to obtain the line of best fit reported above. At these 2 sites, chloride concentrations were low throughout the unsaturated zone, suggesting flushing of salt from the unsaturated zone as a result of post-clearing recharge.

Leaney et al. (2004) also summarised 6 deep drainage estimates from irrigated sites in the Tintinara area by Leaney et al. (1999), Leaney (2000) and Leaney (2001). Leaney and Herczeg (1999) also estimated deep drainage at several sites in an area 80 km to the north of Tintinara where mean annual rainfall was 100 mm yr⁻¹ less. The limited data and the complexities of irrigation recharge processes, including the wide variety of different management practises meant that they were unable to develop relationships with soil texture, land use or rainfall.
Figure 3-6. Relationship between soil texture and drainage under dry land agriculture in the 270 (closed circles), 300-400 (open circles), and 470 (triangles) mm yr$^{-1}$ mean annual rainfall zones (Cook et al., 2004). The line of best fit was determined for data from the 470 mm yr$^{-1}$ rainfall sites. (Figure 16 of Leaney et al., 2004).

3.1.4. Padthaway

Wohling et al. (2006) estimated deep drainage (potential recharge) at 8 dry land agriculture sites in the Naracoorte Ranges region near Padthaway in the Lower South-East of South Australia. The deep drainage estimates were made using the transient chloride mass balance of soil water method. They correlated the deep drainage (D) estimates with % clay content in the top 2 m of the soil (C) and obtained the following line of best fit:

$$D = 10^{(-0.035C + 2.23)}.$$  

This fit included the estimates used in the relationship established by Leaney et al. (2004) but differed slightly due to the higher mean annual rainfall (~510 mm yr$^{-1}$) and the differing geology of this area. This relationship was used with soil landscape unit mapping to extrapolate deep drainage estimates across the study area.

As was the case at the Tintinara site, it is worth noting that there were 5 further sites (out of a total of 12 sites) where it was possible to only estimate minimum values for deep drainage. Hence, in total, a third of the deep drainage estimates (7 out of 21) used to obtain the above relationship were minimum values. Because the minimum estimates are usually for sites with sandier 0-2 m surface soils, one would therefore also assume that the true slope for the relationship could be considerably steeper (more negative than the value of -0.035 reported) and that the intercept may be considerably greater (more positive than the 1.9 value reported).

3.1.5. Bakers Range

Leaney et al. (2006) estimated potential recharge under native vegetation (2 sites) and pasture (5 sites) in the Bakers Range region in the hundreds of Nangwarry, Short and Penola in the Lower South-East of South Australia. The potential recharge estimates were made using the chloride mass balance of soil water approach (Allison and Hughes, 1978). Whilst they also measured % clay content in the top 2 m of the soil at each site, no attempt was made to relate these data to the estimated potential recharge values.

3.1.6. Border Designated Area and Hundred of Stirling

Wohling (2007) estimated deep drainage and recharge under native vegetation, dryland agriculture and irrigation in the Border Designated Area and the Hundred of Stirling in the
Lower South-East of South Australia. In the Hundred of Stirling estimates were made using water balance, daily soil water balance, steady-state chloride mass balance of soil water method, transient chloride mass balance of soil water method and 1-D recharge and LEACHM (Hutson, 2003) modelling techniques. In the Border Designated Area, the transient chloride mass balance of soil water method, steady-state chloride mass balance of soil water method and 1-D recharge modelling techniques were applied. In total soil cores were collected from 34 sites in the Border Designated Area and 17 sites in the Hundred of Stirling. The deep drainage estimates (D) made at all of their dry land agriculture sites were combined with those given in Leaney et al. (2004) for Tintinara (Figure 3-7) and correlated with % clay content in the top 2 m of the soil (C) to obtain the following line of best fit:

\[ D = 10^{(-0.026C+1.91)} \]

This relationship was used with soil landscape unit mapping to extrapolate deep drainage estimates across the study area.

![Graph showing relationship between soil texture and deep drainage](image)

**Figure 3-7.** Relationship between soil texture and deep drainage under dry land agriculture in the Border Designated Area and Tintinara study areas (470-570 mm/year mean annual rainfall zone). (Figure 5.1 of Wohling, 2007).

### 3.1.7 South-East (chlorofluorocarbon groundwater dating and steady-state chloride mass balance of soil water estimates)

Wood (2010) estimated deep drainage at 25 sites in the South-East using steady-state chloride mass balance of soil water and chlorofluorocarbon groundwater dating approaches. Each site was categorised by climate (5 zones), soil recharge potential (low, moderate or high), soil type (clay, sand, loam) and land use and covered a large range in rainfall (460-700 mm yr\(^{-1}\)). The steady-state chloride mass balance of soil water method used soil water chloride concentration at a depth immediately below what was considered the zone of evapotranspiration (usually about 3-4 metres depth). The chlorofluorocarbon groundwater dating method estimated recharge by considering the amount of water to the depth of sampling (depth below SWL multiplied by porosity) and divided this by the time taken to reach that depth (determined from chlorofluorocarbon -12 age). Because the screens used were several metres in length, a range of recharge rates were estimated based on the upper and lower level of the screen at each site.

### 3.1.8 Mt Lofty Ranges

There have been a number of field investigations carried out in the Mt Lofty Ranges to support the development of the water allocation plan for the area (Green et al., 2007, Banks et al., 2007A-C). Most of the study sites were in areas with fractured rock aquifers although,
at some of the sites, (e.g. around Mt. Compass in the Tookyerta Creek catchment study) there has been considerable sedimentary infill resulting in a sedimentary aquifer up to 200 m thick.

The studies measured recharge rates using the steady-state chloride mass balance of groundwater approach at all of the sites. Chlorofluorocarbon measurements were made at most of the study sites but only gave useful results for the Eastern Mt Lofty Ranges study and the Upper Marne catchment. $^{14}$C was also used at one of the sites where there were nested piezometers (Eden valley site). Recharge rate at the site was estimated by using the $^{14}$C gradient from groundwater samples collected from three screens at approximately, 5 m, 10 m and 15 m below the watertable.

3.1.9. Clare

Fractured rock areas are perhaps the most difficult environment of all in which to estimate recharge. Field-based estimates of recharge in fractured rock aquifers are uncommon throughout the world and even more so within Australia.

The Clare studies were undertaken over several years from the late 1990s until about 2003. One approach used was the steady-state chloride mass balance of groundwater method (Love et al., 2002), where estimates were obtained for two sites post-clearing (>50 mm yr$^{-1}$ and >9 mm yr$^{-1}$) and for larger areas pre-clearing (< 2 mm yr$^{-1}$). There were also various combinations of tracer analyses (chlorofluorocarbon -12, $^{36}$Cl, $^{14}$C and $^{3}$H) and hydraulic measurements (Cook and Simmons, 2000; Cook et al., 1999; Cook and Robinson, 2002) used to estimate post-clearing recharge. The use of two or more tracers, along with measurements of hydraulic parameters help constrain the recharge estimates compared to the use of a single tracer as used in the Mt Lofty Ranges study. In general, it was found that constraining the estimates in this way reduced the uncertainty of analysis. The more rigorous studies also suggested that the steady-state chloride mass balance of groundwater approach underestimated recharge because of the potential of diffusion of “old chloride” associated with periods of pre-clearing recharge from the rock matrix.
3.2. Queensland

3.2.1. Overview

The number of field studies of recharge in Queensland is fairly small. The majority have been concerned with assessing the potential impacts of land use change on dryland salinity in central (Fitzroy Basin) and southern (Murray-Darling Basin) Queensland. These studies have generally been in areas with heavy-textured soils which are mostly either of alluvial or volcanic (basalt) origin. The mean annual rainfall of these semi-arid subtropical regions varies from 500 mm yr\(^{-1}\) in the west to 720 mm yr\(^{-1}\) in the east. There has also been one major study in northern Queensland (Atherton Tablelands) on groundwater recharge and stream baseflow. Groundwater in this region is generally obtained from the surface basalts. The mean rainfall in this wet tropical region varies from 970 mm yr\(^{-1}\) in the north to 2580 mm yr\(^{-1}\) in the south.

3.2.2. Murray-Darling Basin

Tolmie et al. (2004) investigated deep drainage under dryland cropping at 13 sites in the Queensland Murray-Darling Basin using soil chloride profiles. The steady-state chloride mass balance of soil water method was used to estimate deep drainage under native vegetation, and transient chloride mass balance of soil water, solved using the SODICS model method (Thorburn et al., 1987), was used to estimate deep drainage under cleared sites. It was found that drainage rates below native vegetation (brigalow, belah or coolibah) were low, ranging from 0.3 to 1.0 mm yr\(^{-1}\). It also found that deep drainage increased after clearing of native vegetation, and under long-term cropping sites it ranged from 2 to 16 mm yr\(^{-1}\), and averaged about 8 mm yr\(^{-1}\). Only three of the sites included pasture treatments, and these showed that deep drainage rates under pasture were higher than under native vegetation but lower than under cropping. The study also found that mean annual deep drainage under long-term cropping sites increased with mean annual rainfall (Figure 3-8), being lower at western sites and higher at eastern sites.

![Figure 3-8](image)

Figure 3-8. Deep drainage (at 1.5 m) related to average annual rainfall for long-term winter crop sites. Native vegetation sites are also presented for comparison. (Figure 17 of Tolmie et al., 2003).

3.2.3. Fitzroy Basin

The Queensland Department of Primary Industries has been running the Brigalow Catchment Study since 1965 where two adjacent catchments initially under native brigalow
(Acacia harpophylla) vegetation were cleared in 1982 for crops and pastures (and a third was left under brigalow) to measure the effects of land development on the hydrology and the soils. The impacts of the clearing on deep drainage was first reported byThorburn et al. (1991), and included in the Petheram et al. (2000, 2002) reviews. Silburn et al. (2009) recently updated the results from this study with soil chloride data collected at four more sampling times over a subsequent 13 year period. They found that the deep drainage under native brigalow had not changed over the 18.4 year sampling period, with the steady-state chloride mass balance of soil water estimates ranging from 0.13 to 0.34 mm yr⁻¹. The transient chloride mass balance of soil water, solved using the SODICS model method, was used to estimate deep drainage beneath the cropping and pasture sites. In the 16.7 years since the establishment of agriculture deep drainage under cropping was found to range from 3.3 to 50 mm yr⁻¹ (mean of 19.8 mm yr⁻¹), with higher values under the lighter textured soils. Over the same time period deep drainage under pasture ranged from -2.2 to 1.4 mm yr⁻¹ (mean of 0.16 mm yr⁻¹), which was similar to the that under native brigalow vegetation. Radford et al. (2009) recently reported on deep drainage under a further 7 sites in the Fitzroy Basin with cracking clay soils. Deep drainage was low under native vegetation (0.2 – 1.7 mm yr⁻¹) but increased under dryland cropping (1.6 – 27.5 mm yr⁻¹). Deep drainage under cropping was found to reduce linearly with increases in plant available water capacity (Figure 3-9).

![Figure 3-9. Relationship between plant available water capacity (PAWC) of different soil types and annual deep drainage under cropping. R² is significant at P < 0.05. (Figure 4 of Radford et al., 2009).](image)

### 3.2.4. Northern Queensland

Cook et al. (2001b) used a combination of tracer techniques (²²²Rn (radon), chlorofluorocarbon -11, chlorofluorocarbon -12, ¹⁴C, δ¹⁸O (oxygen-18), δ²H (deuterium), temperature) and major ion analyses to quantify recharge rates in the unconfined basalt aquifers of the Atherton Tablelands. A steady-state chloride mass balance of groundwater suggested that recharge was highest in the south (440 – 660 mm yr⁻¹; 33% of rainfall) and lowest in the north (150 – 225 mm yr⁻¹; 16% of rainfall). The ²²²Rn and chlorofluorocarbon -11 data suggested that the groundwater flow rates in the basalt aquifers decrease with depth, and the groundwater ages were mostly less than 30 years. The chloride, δ¹⁸O and δ²H concentrations in stream water were similar to those in the adjacent groundwater, suggesting that, apart from extreme storm events, most of the river flow was from groundwater inflows. No attempts were made to generalise these results for use outside of the study area.

Estimates of recharge across the north of Queensland were made using a steady-state chloride mass balance of the groundwater (Crosbie et al, 2009). This is described in more detail under the Northern Territory (Section 3.7.3).
3.3. Western Australia

3.3.1. Overview

There have been only a small number of field studies of recharge in Western Australia since the Petheram et al. (2000, 2002) reviews. These have been concentrated in the wheatbelt, the Darling Range, and the Perth Basin in the south-west of the state. Rainfall in this region varies from ~250 mm yr\(^{-1}\) in the northern and western extremities of the wheatbelt to >1000 mm yr\(^{-1}\) in the Darling Range. The soils of the wheatbelt are often deep sands or duplex in nature (sand over kaolinitic clay) and over shallow saline groundwater. The soils of the Darling Range are also often duplex in nature. Groundwater beneath the sandy coastal areas of the Perth Basin is generally fresh and an important urban water resource. There are few field estimates of recharge in the north of Western Australia.

3.3.2. Wheatbelt

There have been quite a few studies in this area concerned with determining the water balance of crops, pastures and trees. Many have been modelling efforts but there are some examples where deep drainage has been measured/inferred from field studies.

Eastham and Gregory (2000) used soil water balance to infer deep drainage rates over a 3 year period beneath lupin and wheat crops at East Beverley. They found that the deep drainage rates were different each year (ranged from 20 to 67 mm) as a result of differences in winter rainfall (ranged from 244 to 309 mm), but were not influenced by the crop type.

Ward et al. (2001) used soil water balance to infer deep drainage beneath lucerne and subterranean clover pastures over a 3 year period at Katanning. In the wettest year (rainfall was 329 mm) deep drainage beneath the lucerne (27 mm) was significantly less than that under the clover (79 mm).

Lefroy et al. (2001) studied the water balance of an alley cropping system with included lupins, oats and the fodder tree tagasaste (Chamaecytisus proliferus Link.). The study was carried out over 3 years at a site near Moora which had deep sandy soils. Deep drainage was estimated by difference from measurements of rainfall, tree water use, interception and changes in soil water storage. Very high deep drainages were estimated under the crops (42 to 52% of rainfall) whereas under the tagasaste it was much lower (9% of rainfall). The high deep drainages under the crops was thought to be due to the highly transmissive nature of the sandy soils.

Reynolds and Marimuthu (2007) developed a groundwater flow and solute transport model for the Lake Warden coastal wetlands near Esperance. To assist in the development of the model they estimated mean annual recharge using the steady-state chloride mass balance of groundwater. The recharge estimates were highly variable across the model domain (0 to 126 mm yr\(^{-1}\)) due to a combination of a range of land uses (urban, agricultural, native vegetation) and the variability in chloride concentrations in the water bodies. The authors felt that the steady-state chloride mass balance of groundwater approach provides initial estimates of recharge which could be verified in model calibration. Only the chloride mass balance estimates were included in the data base.

3.3.3. Darling Range

The only recent recharge estimates in the Darling Range are those of Wilkes et al. (2004) who studied the hydrogeology of the small (~4,000 ha) Augustus River catchment near Collie. The catchment is close to the Wights/Salmon research catchments whose hydrogeology was intensively studied in the 1970s and 1980s (and the recharge estimates included in the previous reviews of Petheram et al. (2000, 2002)). Wilkes et al. (2004) used steady-state chloride mass balance of groundwater to estimate the mean annual recharge to be about 7% (~80 mm yr\(^{-1}\)) of rainfall. Unfortunately the authors did not describe the land use in the catchment other than to say that it contained an alumina refinery.
3.3.4. Perth Basin

Apart from the numerous studies of recharge to the Gnangara groundwater mound to the north of Perth, as summarised above from Silberstein (2010), there have been several studies of other parts of the Perth Basin which have been carried out since the reviews of Petheram et al. (2000, 2002).

Bekele et al. (2003, 2006) estimated recharge to the Parmelia Aquifer in the Northern Perth Basin using a range of techniques (watertable fluctuation; steady-state chloride mass balance of groundwater, chlorofluorocarbon and $^{14}$C groundwater dating; steady-state chloride mass balance of soil water). Recharge estimates under native vegetation were found to be generally less than 12 mm yr$^{-1}$, whereas under crops and pasture they were generally 20 to 50 mm yr$^{-1}$. In this sandy aquifer a very good relationship was found between the chlorofluorocarbon age and the sample depth below the watertable (Figure 3-10), and from this recharge rates can be inferred quite accurately.

![Figure 3-10. Relationship between chlorofluorocarbon age and groundwater sample depth below the watertable. Theoretical lines indicate different recharge rates for comparison based on a porosity of 26±1% to show the sensitivity. At high recharge rates, the results are more sensitive to porosity. (Figure 4 of Bekele et al., 2006).](image)

Bekele et al. (2006) also compared recharge rates estimated from chlorofluorocarbon groundwater dating with those estimated using the steady-state chloride mass balance of groundwater and found a general correlation but with quite large differences for some sites (Figure 3-11). The authors cautioned that the process of scaling up recharge estimates for this area was compromised by the presence of heterogeneity in the unsaturated zone and that recharge to the watertable had not reached steady-state. A consequence of this is that some of the tracer results may have underestimated recharge.
Turner and Dighton (2008) recently carried out groundwater dating in the Leederville Aquifer in the southern Perth Basin. The sample bores at 10 locations (and up to 3 depths in the aquifer) along a transect from Cowaramup to Busselton. They measured $^{14}$C, chlorofluorocarbons, carbon-13 ($\delta^{13}$C), $\delta^{2}$H, $\delta^{18}$O, $^{222}$Rn and major ion chemistry of the samples. Recharge was estimated from the $^{14}$C measurements and by steady-state chloride mass balance of groundwater. The report is commercial-in-confidence and so it is not possible to present the results. However, the results showed that the steady-state chloride mass balance of groundwater estimates were 1-2 orders of magnitude higher than those from $^{14}$C. The authors concluded that application of the steady-state chloride mass balance of groundwater to this study area was problematic due to incomplete knowledge of the history of chloride concentrations in rainfall, and the chloride export in surface runoff, which together caused the method to over-estimate the recharge.

### 3.3.5. Northern Western Australia

Estimates of recharge across the north of Western Australia were made using a steady-state chloride mass balance of the groundwater (Crosbie et al., 2009). This is described in more detail under the Northern Territory (Section 3.7.3).
3.4. New South Wales

3.4.1. Overview

There have been comparatively few published field studies of recharge in NSW. Groundwater investigations in this State appear to have been dominated by modelling studies. The majority of groundwater extracted for agriculture in NSW is from the inland alluvium; however there are few recharge measurement studies in these areas. The Tomago Sandbeds is the only region studied in detail to the east of the Great Dividing Range. The Western Slopes of the Great Dividing Ranges have had several studies related to dryland salinity investigation.

3.4.2. Coastal Alluvium

The Tomago Sandbeds supply potable water to the city of Newcastle and surrounds and have been extensively monitored since 1915. The first field measurements of recharge were conducted in the late 1930’s and involved the installation of four lysimeters which collected on average 36% of the rainfall (HDWB, 1957). The next recharge study was conducted in 1952 and involved a steady-state chloride mass balance of groundwater. The chloride concentration of rainfall was estimated from two sources: rainfall collected in rain gauges and rainfall collected in household rainwater tanks in the area. The chloride concentration of groundwater was measured in the water extracted from the aquifer. This study found that 25% of rainfall became recharge (HDWB, 1957). A subsequent steady-state chloride mass balance of groundwater study used an extensive dataset of chloride in groundwater from decades of routine monitoring and 5 rain gauges with a year of chloride monitoring. This study found that recharge was 18% of rainfall under native vegetation and 34% of rainfall after clearing. Averaged over the entire aquifer, recharge was computed to be 25% of rainfall (the same as that from the 1952 study) (Crosbie et al., 2002).

A time series variant of the watertable fluctuation method was used to estimate gross recharge at seven locations using high frequency measurements. This study found recharge to average ~60% of rainfall over a three year period (Crosbie et al., 2005). The recharge estimates from this study are not directly comparable to those computed using the steady-state chloride mass balance of groundwater method. This is because the watertable fluctuation method estimates gross recharge and the steady-state chloride mass balance of groundwater estimates net recharge; where there is phreatophytic vegetation net recharge is less than gross recharge. From the watertable fluctuation estimates of recharge a relationship was observed between monthly recharge as a percentage of rainfall and average monthly depth to the watertable (Figure 3-12). Relationships were developed for a 6 month winter and a 6 month summer period and these relationships were then used to upscale the results over the entire aquifer at a monthly time step over a 22 year period. This process resulted in an average gross recharge estimate of 43% of rainfall across the aquifer (Crosbie, 2003).
3.4.3. Inland Alluvium

The inland alluvium is where the majority of groundwater extraction takes place in NSW but there are few field studies in these areas. Near Quirindi, Coram and Jaycock (2003) used three different tracers to estimate recharge, obtaining values between 8 and 14.5 mm yr\(^{-1}\). Berhane (2001) used the watertable fluctuation method to estimate recharge in the lower Namoi, obtaining a value of 58 mm yr\(^{-1}\). Carrara (2005) used the watertable fluctuation method, a chloride mass balance and \(^{14}\)C tracer to estimate recharge in the Bland Basin of between 0.1 and 22 mm yr\(^{-1}\). There are older studies in the inland alluvium that were reviewed in previous reviews.

3.4.4. Western Slopes of the Great Dividing Range

Dryland salinity following land clearing on the western slopes has been the catalyst for many studies into the water use of agricultural systems compared to native vegetation. Many farming systems have been trialled to reduce recharge but few of these studies have actually made estimates of groundwater recharge. A study at Boorowa compared the recharge under annual cropping to that of perennial pastures between tree belts. Using the watertable fluctuation method, the post treatment recharge was estimated to be an order of magnitude less than under annual cropping (~10 mm yr\(^{-1}\) cf ~100 mm yr\(^{-1}\)) (Crosbie et al., 2007). At Brays Flat, the historical recharge under native vegetation was estimated to be <0.5 mm yr\(^{-1}\) using a steady-state chloride mass balance of soil water from deep (~40 m) unsaturated cores (Crosbie, 2006). At the same site, no recharge could be detected using a water balance under annual pastures or tree belts over several years during a drought (Crosbie et al., 2008).
3.5. Victoria

3.5.1. Overview

The have been a reasonable number of field studies of deep drainage and/or recharge in Victoria but only a handful since the studies reported by the Kennett-Smith et al. (1994) review. This is included in a substantial report by Sinclair Knight Merz (SKM) estimation of groundwater recharge in the Mallee and Wimmera in the south western Murray Basin (SKM, 2002). Most data is pre 1994 and has been included in the previous reviews by Kennett-Smith et al. (1994) and Petheram et al. (2000, 2002). The SKM report does, however, include post-clearing rates for deep drainage for areas of rainfall in excess of 600 mm yr$^{-1}$ not previously reported. More recently, there have been several studies where recharge has been estimated for regions in the south east Murray Basin by Cartwright et al. (2007) as part of their dryland salinity investigations.

3.5.2. Mallee and Wimmera (SW Murray Basin)

This report summarises a project that was jointly undertaken by the Rural Water Commission in Victoria and the CSIRO Division of Water Resources in South Australia. It was issued in a draft form by Hydrotechnology in 1994 and completed by Sinclair Knight Merz in 2002 (SKM, 2002). The aim of the project was to estimate local recharge rates under different rainfall/vegetation/soil combinations for the Mallee and Wimmera regions in the south western Murray Basin.

The report tables in excess of 200 estimates of deep drainage and recharge rates in areas with rainfall from 250-700 mm yr$^{-1}$. Most of the estimates were determined using the transient chloride mass balance of soil water method (post-clearing of native vegetation) or using the steady-state chloride mass balance of groundwater or soil water methods (pre-clearing of native vegetation). Some estimates were also made using hydrograph response and tracer studies. Pre-clearing recharge rates and post-clearing deep drainage rates are plotted against rainfall in the three figures below (Figure 3-13, Figure 3-14, Figure 3-15). Post-clearing rates for deep drainage in the 750 mm yr$^{-1}$ rainfall area is up to 260 mm yr$^{-1}$. The report also suggests extremely high estimates of recharge under native vegetation (up to 42 mm yr$^{-1}$) in a 250 mm yr$^{-1}$ rainfall area because of run-on in local depressions. This is similar to the findings by Allison et al. (1985) for recharge through secondary sinkholes, again for a 250 mm yr$^{-1}$ rainfall area.

![Figure 3-13. Relationship between mean annual rainfall and pre-clearing recharge data obtained from field studies. (Figure 4-2 of SKM, 2002).](image_url)
The authors also examined the effect of soil texture (average % clay content) on rates of deep drainage both for native and cleared sites. Under native vegetation, they suggest that recharge is independent of soil texture in areas with annual rainfall less than ~ 400-500 mm yr$^{-1}$. For these areas, excluding areas where run-on occurs, recharge rates are in general less than 0.2 mm yr$^{-1}$. In the 501-600 mm yr$^{-1}$ rainfall areas, there is, what appears to be, a significant inverse relationship between recharge rate and clay content. No data is presented for rainfall areas in excess of 600 mm yr$^{-1}$, presumably because % clay content was not measured for these studies. The recharge versus % clay content relationship is most pronounced when % clay content is measured over the 0 to 2 m depth interval rather than 0 to 0.5 or 0-1.0 m depth intervals (Figure 3-16).
Figure 3-16. Relationship between clay content of the top 2.0m of soil and pre-clearing recharge in areas of different annual rainfall. (Figure 4-7 of SKM, 2002).

Under post-clearing conditions, the deep drainage vs % clay relationship as previously presented by Kennett-Smith et al. (1994) is presented. The authors explore the relationship using % clay content measure over 0-0.5, 0-1.0 and 0-2.0 m depth intervals and see that while there is an inverse correlation observed for all depth intervals, it is more pronounced when a depth interval of 0-2.0 m is used (Figure 3-17).

Figure 3-17. Relationship between clay content of the top 2.0m of soil and post-clearing recharge in areas of different annual rainfall. (Figure 4-10 of SKM, 2002).

3.5.3. Riverine Plain and Adjoining Margin Areas, Victoria

From 2004 to 2007, Cartwright et al. (2004a, 2007a, 2007b) and Petrides et al. (2006), undertook several studies on areas in the Riverine Plain and adjoining margins in Northern Victoria. The emphasis of their work was to determine the origin of dryland salinity, and whether it was primarily of meteoric origin (evaporated rainfall) or via dissolution of salts
present in the aquifer matrix and to establish flow pathways and timeframes particularly near the basin margins.

Using a combination of chemical (mainly chloride to bromide ratio) and isotopic (mainly $\delta^2$H and $\delta^{18}$O signature) analyses on the groundwater samples, the authors concluded that there was very little halite dissolution. Salinity was primarily the result of high rates of evapotranspiration under native vegetation with salt present in rainfall concentrated during the recharge process. This work was consistent with previous studies as summarised by Allison et al. (1990).

Having established that the chloride in the groundwater originated predominantly from rainfall, the authors felt confident in using the steady-state chloride mass balance of groundwater approach to estimate recharge. Estimates of recharge rates using the steady-state chloride mass balance of groundwater approach were made on ~80 samples and ranged from 0.11 to 23 mm yr$^{-1}$. Eighty percent of estimates were less than 1.0 mm yr$^{-1}$ and the authors concluded that this represented predominantly pre-clearing recharge. This was despite the fact that many of these samples were collected from bores where the total bore depth was less than 10 m and the screen within 5 metres of the standing water level.

The authors also used the watertable fluctuation method and a combined $^{14}$C/$^3$H groundwater dating method for recharge estimation. These methods gave much higher recharge estimates, ranging from 4 to 90 mm yr$^{-1}$ and, given the resolution of each method, there was good agreement between the methods. The estimated recharge rates using these methods were considered to represent the conditions following land clearing approximately 200 years ago. The authors also concluded that there were difficulties in using the watertable fluctuation method where the screen depth was greater than 5 m from the watertable surface.
3.6. Tasmania

An extensive study of groundwater in Tasmania was conducted by REM/Aquaterra (2008a-r) that focussed on 18 groundwater assessment areas (GAA). A combination of methods was used to estimate recharge including steady-state chloride mass balance of groundwater, water balance, watertable fluctuation and chlorofluorocarbon groundwater dating (not all methods were used for all GAAs). These studies found recharge to be variable with individual estimates of recharge ranging from 4 to 634 mm yr⁻¹.
3.7. Northern Territory

3.7.1. Overview

There have only been a small number of studies of recharge in the Northern Territory. Most have been carried in the tropical northern areas where nearly all of the > 1100 mm yr\(^{-1}\) rainfall, and hence recharge, occurs during the wet season (November – April). There has been one notable study in the arid Ti-Tree Basin in the south where rainfall is very low (< 300 mm yr\(^{-1}\)) and highly variable, which leads to recharge being highly episodic.

3.7.2. Central Australia

Harrington et al. (1999, 2002) estimated recharge in the arid Ti-Tree Basin near Alice Springs. Early results were included in the reviews of Petheram et al. (2000, 2002) but not the full data set. In this study recharge from flood-outs of ephemeral rivers was estimated using steady-state chloride mass balance of groundwater and \(^{14}\)C dating of groundwater. \(\delta^{18}\)O and \(\delta^{2}H\) in rainfall, soil profiles and in the groundwater were used to determine that recharge throughout the basin occurred only after intense rainfall events (i.e. recharge is episodic). The estimated recharge rates were low, varying from 0.2 to 1.9 mm yr\(^{-1}\).

3.7.3. Top End

The study of Cook et al. (1998a, b, c) was not included in the Petheram et al. (2000, 2002) reviews. This study investigated the water balance of the tropical Howard East Basin near Darwin where development of the groundwater resources was proposed which potentially had impacts on ecosystems. The study measured evapotranspiration from two of the major ecosystems of the Basin (Eucalypt savanna and Paperbark swamp), accompanied by measurements of soil water content and matric suction, watertable fluctuations, and chlorofluorocarbons, \(^{14}\)C, \(\delta^{18}\)O, \(\delta^{2}H\) in groundwater. Based on the chlorofluorocarbon groundwater dating, it was determined that the mean annual recharge was 200 mm, and occurred entirely in the wet season where the mean rainfall was 1585 mm (i.e. recharge was ~13% of rainfall).

In the Daly region, Wilson et al. (2006) investigated groundwater recharge using a steady-state chloride mass balance of groundwater approach. They estimated recharge to vary between 11 and 200 mm yr\(^{-1}\) under native vegetation; however they did note that preferential flow through the unsaturated zone occurred. Also in the Daly region, Jolly (2002) used a water balance method based upon streamflow to estimate average recharge as 90 mm yr\(^{-1}\).

Crosbie et al. (2009) estimated recharge across Northern Australia (including WA and Qld) using a steady-state chloride mass balance of groundwater approach. The chloride in groundwater was extracted from state agency databases where the bore was drilled to less than 20 m below ground. This yielded ~2500 locations where chloride in groundwater had been measured by the state agencies over the past few decades. The chloride in rainfall was estimated using a function of chloride deposition decreasing exponentially with distance from the coast. The results were reported at a regional scale with error bars representing the uncertainty in the estimates (Figure 3-18). The large uncertainty is mainly due to the uncertainty in estimating the chloride deposition. There is a very large range in individual point estimates of recharge (0.09 mm yr\(^{-1}\) to 1900 mm yr\(^{-1}\)).
Figure 3-18. Regional estimates of recharge across northern Australia made using a steady-state chloride mass balance of groundwater approach (Crosbie et al, 2009). The error bars represent a 90% confidence interval about the mean on a regional basis.
3.8. Australian Capital Territory

The only published studies that tried to estimate recharge applied a digital recursive filter to streamflow records to separate baseflow. The assumption was made that baseflow equalled groundwater discharge which also equalled groundwater recharge (Evans et al., 2004a,b,c).
4. DISCUSSION

4.1. Methods of measurement

In this report, the authors have identified 4386 deep drainage and/or recharge estimates made across Australia. The estimates have been made using a wide range of measurement techniques and consequently made measurements pertaining to different timeframes and for different recharge regimes. In order to evaluate these more fully and understand what is actually being measured, it is informative to compare the different methods for estimating deep drainage and recharge.

Deep drainage is defined here as the flux of infiltrated water that moves past the root zone of vegetation. Recharge is defined as the amount of infiltrated water that actually reaches the aquifer. Deep drainage becomes recharge only when no impeding layers exist that would prevent water from moving down to the aquifer. However, there is often a time lag between deep drainage becoming recharge in situations where land use has changed. This is because it takes some time for the pressure front created by the increase in deep drainage to move downward through the soil to the groundwater. It is only when the pressure front reaches the water table that recharge occurs at the same rate as the new deep drainage rate (see Jolly et al., 1989).

The time lag depends on the depth to the groundwater, the new deep drainage rate and the soil texture. Time lags can vary in duration from a few hours/days to tens of years. Consequently, deep drainage only equals recharge when there has been no land use change or the time since land use change exceeds the lag time, and the system has no impeding layers which can re-direct the water back to the surface.

When the framework for this review was planned, we did not envisage a review of recharge methodologies, only a review of the actual recharge estimates themselves. However, because the method of measurement has such a strong bearing on what is actually being measured (recharge, deep drainage, net recharge) and the timeframe to which it pertains, we believe the following discussion not only useful but necessary.

4.1.1. Steady-state chloride mass balance of groundwater (Cl SS GW)

A steady-state chloride mass balance of groundwater is the most widely used method for estimating recharge in Australia, with 45% of studies using it to make 76% of recharge estimates identified by this study (Figure 4-1). The reason for its popularity is because it is very simple conceptually and the analytical costs are comparatively cheap. There is also a large amount of historical analysis of chloride in groundwater held by the states, so desktop recharge studies are possible with existing data (e.g. Crosbie et al., 2009). The method is valid because chloride in pore water is excluded by evaporation and transpiration leaving it to concentrate in the unsaturated zone, and eventually reach the groundwater via advection. It is a method for estimating net recharge because chloride can continue to be concentrated in the saturated zone if vegetation is exploiting this source of water.

The only unknowns are an estimate of the chloride deposition rate at the ground surface and the chloride concentration of the groundwater:

$$ R = \frac{D}{C_{gw}} $$

where $R$ is recharge ($LT^{-1}$), $D$ is chloride deposition rate ($ML^{-2}T^{-1}$) and $C_{gw}$ ($ML^{-3}$) is the concentration of chloride in the groundwater. The chloride deposition rate is often estimated as the average chloride concentration of rainfall multiplied by the average annual rainfall.
Figure 4-1. Location of studies that have used the steady-state chloride mass balance of groundwater method.

The assumptions inherent in the method are that:

1. the chloride in the groundwater originates from precipitation (not rock weathering or halite dissolution)
2. chloride imported or exported via runoff or runon can be accounted for
3. chloride is conservative in the system
4. the chloride deposition rate has not changed over time

There have been many studies investigating the origin of chloride in groundwater and the most common source is from precipitation, even in very saline groundwater (e.g. Herczeg et al., 2001; Cartwright et al., 2005). Therefore the first assumption can usually be met.

The second assumption becomes irrelevant in deep sands where there is no runoff. In places such as the Mallee, Gnangara and Tomago, chloride exported in runoff has been assumed to be zero. When the steady-state chloride mass balance of groundwater method is used in upland areas, runoff can be significant and should be accounted for. This has been done in the Mount Lofty Ranges by assuming a percentage of rainfall becomes runoff and carries with it an equivalent proportion of the chloride (Banks et al., 2007; Green et al., 2007). In reality, the uncertainty associated with accounting for runoff will be small compared to the uncertainty in chloride deposition.

Conservatism of the chloride ions is generally assumed without any investigation. Vegetation is generally very efficient at excluding chloride from water taken up from the soil and so any loss through vegetation is negligible. In most cases chloride does not interact geochemically with the soil, there are usually no sources or sinks within the soil. In most cases chloride can be assumed to be a conservative tracer.
The concentration of chloride in groundwater is estimated over the residence time of the water in storage, therefore the estimate of recharge made from it is an estimate averaged over the residence time of the groundwater. This can be many thousands of years in many aquifers around Australia. This can cause problems in areas with a land use change where the recharge estimate may be for the native vegetation rather than the current land use. This was acknowledged as the reason why the steady-state chloride mass balance of groundwater and watertable fluctuation methods gave different results in northern Victoria (Cartwright et al., 2007).

For an accurate estimate of recharge, the chloride deposition rate should also be averaged over the residence time of the groundwater. This is usually not practical. In studies where the chloride deposition has been measured it is generally only over a 1 or 2 year period. This is then assumed to be representative of a much longer time period. The fourth assumption is frequently violated but rarely (if ever) acknowledged.

An example of how the deposition rate of chloride has changed over time can be seen in three published studies at Katherine, NT. The first investigation of the chloride deposition found a deposition rate of 1.7 kg ha\(^{-1}\) from 1958-1960 (Wetselar and Hutton, 1963), the second study recorded a deposition rate of 2.5 kg ha\(^{-1}\) from 1992-1994 (Keywood et al., 1997) and the most recent study found a deposition rate of 5.0 kg ha\(^{-1}\) in 2005 (Wilson et al., 2006). The highest recorded deposition rate is three times the lowest deposition rate; this transfers linearly through to the recharge estimates.

In many studies the chloride deposition is not measured but inferred from literature values. There have been many field studies of chloride deposition around Australia and these are used frequently in lieu of collecting more data. Many authors have used point data to construct relationships for chloride deposition with distance from the coast; this allows an interpolation to any point in Australia. An example is shown in Figure 4-2 for Northern Australia where the uncertainty in the chloride deposition can be greater than the chloride deposition rate itself.

Figure 4-2. Example of the uncertainty in using a regression equation to estimate chloride deposition in areas where the chloride deposition has not been measured (Crosbie et al., 2009).
As well as temporal changes in chloride deposition, one must, when using the steady-state chloride mass balance of groundwater method, consider the implications of temporal changes in recharge rate as a result of climate change. The chloride concentration in groundwater is related to the chloride deposition rate at the time recharge occurred. If the groundwater is a paleo-resource, the estimated recharge rate may be that estimated for a period many thousands of years ago and may bear no resemblance to current day recharge. This is the case for a fresh water resource found beneath the Big and Little Deserts in the South Australia and Victoria Mallee region. The groundwater in that area was found to have originated during a wetter climatic phase more than 20,000 years ago and was at least an order of magnitude greater than the estimated rate of recharge over most of the last 20,000 years (Leaney et al., 2003).

Even with the limitations outlined above, the steady-state chloride mass balance of groundwater is one of the most generally applicable methods available for recharge estimation and it is envisaged that it should continue to be one of the most widely used due to its cost effectiveness.

4.1.2. Steady-state chloride mass balance of soil water (Cl SS Soil)

The steady-state chloride mass balance of soil water (Figure 4-3) is not used as frequently as the steady-state chloride mass balance of groundwater method. It is conceptually very similar except that the chloride concentration of groundwater in Equation (1) is replaced by the chloride concentration of the soil water in the unsaturated zone. This method may give a different value for recharge than the steady-state chloride mass balance of groundwater method in relatively shallow groundwater areas because it is an estimate of deep drainage whereas the steady-state chloride mass balance of groundwater method is an estimate of net recharge. The difference is due to any uptake of water from the saturated zone by the vegetation.

The method is subject to the same assumptions as the steady-state chloride mass balance of groundwater method with an additional assumption in that the flow of water through the soil is via matrix flow and not preferential flow. Preferential flow can occur due to soil structure with cracking clays, old root channels, animal burrows or karstic features.
4.1.3. Transient chloride mass balance of soil water (Cl Transient Soil)

The transient chloride mass balance of soil water has the advantage over the steady-state chloride mass balance of groundwater and of soil water, in that it can be used in situations where there has been a land use change. It has been used extensively in studies investigating the changes in recharge following clearing of native vegetation for agriculture in areas under threat from dryland salinity (Figure 4-4). Estimating recharge using the transient chloride mass balance of soil water is usually done using one of two different methods, the generalised chloride front displacement method and the SODICS version method.

The generalised chloride front displacement version of the method (Walker et al., 1991) relies on observations of the movement of a particular chloride pattern with depth which retains its shape during the leaching process. The amount of movement of the pattern is used to infer the rate of movement of water. Unlike the steady-state mass balance methods, there is no need to estimate a chloride deposition rate, (one of the major unknowns when using steady-state chloride mass balance method) nor does it assume that piston flow is occurring. The major limitation of the generalised chloride front displacement method is the need to have a control site nearby in which the vegetation and soil conditions are believed to match those which existed at the site of interest prior to the change in land use. This is required to determine the position of the chloride front in the soil profile before the land use change occurred. It is this limitation, plus difficulties in understanding how to apply the method due to the complex mathematics, that have meant that the method has not been used as widely as it could. The majority of recharge estimates using the generalised chloride front displacement method have been undertaken in South Australia and Victoria.
The SODICS model version of the method (Thorburn et al., 1987) is based on comparing the mass of chloride to some depth at two or more different times. Consequently, there needs to be significant changes in the chloride mass for the method to be accurate. Unlike the chloride front displacement method, the SODICS model requires an estimate of the chloride deposition rate and the model assumes that the chloride concentration of the drainage water is proportional to the average concentration in the root zone - this does not always hold. The majority of recharge estimates using the SODICS model have been done in south eastern Queensland.

![Location of studies that have used the transient chloride water balance of soil water method.](image)

**4.1.4. Watertable fluctuation**

The watertable fluctuation method for estimating recharge has been used in many areas of Australia (Figure 4-5). The method relies on rises in the groundwater level being related to recharge events:

\[
R = S_y \frac{\Delta h}{\Delta t}
\]

where \( S_y \) is the specific yield of the aquifer, \( \Delta h \) is the change in water level over a period of time \( \Delta t \). A thorough review of the watertable fluctuation method was given by Healy and Cook (2002). The limitations of the method that they identified were:

1. The method is best applied to a shallow watertable that displays sharp water level rises
2. The observation wells should be placed in representative areas of the aquifer that are not influenced by extraction
3. The method cannot be used to estimate recharge where recharge is almost constant. If both the recharge and drainage away from the watertable are almost constant then $\Delta h$ will be equal to zero and, as per Equation 2, the calculated recharge will also be zero.

4. The cause of the rise in water level needs to be known. Barometric effects, earth tides, and the Lisse effect need to be filtered out.

5. The greatest source of uncertainty in the method is in finding the appropriate value for the specific yield.

Figure 4-5. Location of studies that have used the watertable fluctuation method.

The watertable fluctuation method has been used at a variety of time scales from hourly (Crosbie et al., 2005) to annual (e.g. Cartwright et al., 2007). Longer time scales are the only option when using routine monitoring data that has been collected manually because the data is generally only available on a monthly basis at best. Higher frequency estimates of recharge require water levels to be logged continuously. Using the watertable fluctuation method on an annual basis is likely to underestimate recharge because small recharge event peaks will not be included, only the longer seasonal trends.

The estimation of $S_y$ is likely to be the greatest source of uncertainty in the methodology. In some cases a single value is assumed based upon literature values (e.g. Wood, 2008), the next step is acknowledging the uncertainty in this parameter and using a range of likely values (e.g. Cartwright et al., 2007). A further complication is the apparent specific yield decreasing as the watertable approaches the surface; this was overcome in a method applied by Crosbie et al. (2005).
4.1.5. **Water balance**

The Water balance method as it has been categorised here is a collection of diverse methods. These include lysimetry, soil moisture measurements and recharge as a residual from a water balance. The locations where these methods have been applied are shown in Figure 4-6.

![Figure 4-6. Location of studies that have used the water balance method.](image)

A lysimeter is perhaps the only method of actually measuring deep drainage rather than inferring it from another measurement. Calculating recharge as the residual from rainfall, runoff and ET estimates is the least direct method of estimating recharge. Water balance methods are best suited to areas with high recharge where the errors in the other terms in water balance do not dominate the uncertainty in the recharge estimates. In semi-arid/arid areas these methods are not appropriate as the recharge estimate could be several orders of magnitude less than the rainfall and ET estimates so that the errors in these estimates make the uncertainty in the recharge estimates very large.

4.1.6. **Carbon-14 (\(^{14}\text{C}\)) groundwater dating (C14)**

Estimation of recharge using groundwater dating tools usually involves estimating the age of the groundwater at the depth of sampling (screen depth) and estimating the amount of water in the aquifer between the screen and the watertable. This approach is the basically the same when using any of the dating tools discussed in this and the following sections. Recharge may be considered to be totally vertical or have a component of lateral flow. With the latter, one needs to consider the relative contributions of lateral and vertical (recharge) flow and this is usually done by some form of mixing model.

The use of \(^{14}\text{C}\) analyses of dissolved inorganic carbon in groundwater to determine the age or more often “mean residence time” of groundwater commenced in Australia in the 1970s.
Given that this method has been available for over 30 years, there have been relatively few studies where recharge rate has been estimated using $^{14}$C. The useful dating range for $^{14}$C is usually considered to be ~2,000-30,000 years although analysis via accelerator mass spectrometry (AMS) has pushed this range to greater than 40,000 years. Hence, in recharge studies, it is most usefully applied in areas where recharge rates are very low or to determine the timeframe for palaeo-recharge. Studies are therefore confined to estimates of recharge under native vegetation in semi-arid or arid areas (Figure 4-7).

![Map of Australia showing location of studies that have used the $^{14}$C groundwater dating method.](image)

**Figure 4-7. Location of studies that have used the $^{14}$C groundwater dating method.**

When using $^{14}$C, the dating clock usually starts when water enters the saturated zone. Hence, if recharge is taking place at a site, groundwater age will increase with depth below the watertable. In its most simplistic application, recharge is considered vertical and piston flow and recharge rate is the amount of water between the screen and the watertable divided by the water age. However, there are problems with this approach because groundwater at any depth is usually the combination of different flow paths. The method is also not applicable where preferential/by-pass flow is a dominant process. This problem is enhanced when sampling from bores with long screen intervals or an open hole, which is usually the case when sampling from existing bores. Another consideration when using $^{14}$C is the need to correct the initial $^{14}$C activity or the recharge water for water-rock interaction. This is not always a trivial process and can increase the overall uncertainty in recharge estimation.

Furthermore, the fact that $^{14}$C age is a log function of $^{14}$C concentration means that a small component of modern recharge can change the mean “age” of the water considerably. Several studies (e.g. Cartwright *et al.*, 2007) have used multi parameter/tracer analysis to try to overcome these problems in dual-porosity aquifers.
4.1.7. Tritium ($^3$H) groundwater dating (Tritium)

Analytical facilities for measurement of tritium, $^3$H, concentration in groundwater were established in Australia in the early 1970s. Dating of groundwater usually relies on matching the $^3$H concentration measured in the groundwater with that in rainfall at the time recharge took place after allowing for radioactive decay (half-life = 12.3 years). From 1952 to 1963, the concentration of many naturally occurring radioactive tracers ($^{14}$C, $^3$H, $^{36}$Cl) increased following above ground atomic bomb tests in the northern and southern hemisphere. For $^3$H, this resulted in an increase in concentration by about two orders of magnitude. Hence, to determine the groundwater age one may either match with pre or post bomb $^3$H concentrations in rainfall (after allowing for $^3$H decay). When using $^3$H for recharge or deep drainage estimates, it is important to remember that the clock starts when the rain falls and not once the water reaches the aquifer. Analyses on samples of soil water from the unsaturated zone, therefore are a measure of deep drainage while analyses on groundwater samples measure the time taken to move through the unsaturated zone to the depth of the screen.

There are relatively few estimates of recharge using $^3$H (Figure 4-8). Most have been where post-clearing recharge rates have been estimated in southern Australia. Despite improvements in detection level, it is becoming increasingly more difficult to use $^3$H because it has now been four half-lives since the peak levels of the early 1960s and it is difficult to differentiate natural levels from levels associated with decay from bomb-peak $^3$H.

![Figure 4-8. Location of studies that have used the $^3$H groundwater dating method.](image)

Estimation of recharge using $^3$H dating is subject to many of the same problems as recharge estimation using $^{14}$C (i.e. sampling from different flow paths, by-pass and dual matrix flow). This, when combined with the vastly different time frame over which $^3$H and $^{14}$C apply, often
causes interpretation problems when groundwater is shown to have a component of modern day recharge (from \(^3\)H results) but a mean \(^{14}\)C residence time of hundreds or thousands of years. However, by combining, \(^{14}\)C and \(^3\)H results, for example, it is possible to suggest the relative components of “old” and modern recharge for a particular site and depth (Le Gal La Salle et al., 2001, Cartwright et al., 2007). The same type of approach can be used when results from \(^{14}\)C are combined with other dating tools such as chlorofluorocarbon (or in the future SF\(_6\)).

4.1.8. Chlorine-36 (\(^{36}\)Cl) groundwater dating (Cl\(_{36}\))

There have been very few studies using \(^{36}\)Cl to estimate recharge or deep drainage and all have been undertaken when developing estimation methods (Figure 4-9). The theory is principally the same as when using \(^3\)H but uptake of the method has been limited by the high cost of analysis and the ability to use other less expensive tracers (e.g. chlorofluorocarbons, \(^3\)H) to get similar results. Also, as with \(^3\)H, what is measured (deep drainage, recharge or something in between) depends on the time it takes to move through the unsaturated zone and the point of collection in the unsaturated/saturated zone.

Figure 4-9. Location of studies that have used the \(^{36}\)Cl groundwater dating method.

Work by Cook and Robinson (2002) combined chlorofluorocarbon -12, \(^{36}\)Cl, \(^{14}\)C and \(^3\)H with hydraulic measurements to refine estimates of recharge rates in the fractured rock system at Clare, South Australia. The Cook and Robinson (2002) study highlighted the difficulties in estimating recharge rates in such an environment and the potentially large errors that may arise if, for example, diffusion from the rock matrix is not considered when estimating recharge.
4.1.9. Chlorofluorocarbon groundwater dating

As is the case for $^3$H and $^{36}$Cl, chlorofluorocarbon concentrations in the atmosphere have changed as a result of anthropogenic activity and it is these changes that make the environmental tracers useful as dating tools. For chlorofluorocarbons, their atmospheric concentrations increased from the early 1960s as a result of increased use of chlorofluorocarbons in refrigeration and air conditioning. The ban on use of chlorofluorocarbons in the mid 1990s resulted in slowing the increase of chlorofluorocarbon concentration in the atmosphere resulting in peak concentrations in 1994 for chlorofluorocarbon -11 and 2003 for chlorofluorocarbon -12. Since then, chlorofluorocarbon concentrations have slowly started to decrease.

The useful age range for chlorofluorocarbon groundwater dating (approximately 1965-2000) is also similar to that using $^3$H and $^{36}$Cl meaning that it is useful only in areas with reasonably high rates of recharge. One slight difference, however, is that greater chlorofluorocarbon concentrations in groundwater indicates younger groundwater and therefore higher rates of recharge. Another difference is that, when using chlorofluorocarbon concentrations to date groundwater, the clock starts at the watertable and hence one is always measuring recharge and not deep drainage using this method.

Several site studies are currently underway using chlorofluorocarbon groundwater dating to estimate recharge rate in various areas around Australia. However, reported studies are limited predominantly to South Australia with a few case studies in Tasmania and one in the Northern Territory (Figure 4-10).

![Figure 4-10. Location of studies where the chlorofluorocarbon groundwater dating method has been used.](image-url)
As a method for recharge estimation, it has the same problems as the aforementioned tracer methods but there are some additional considerations. Groundwater samples collected from close to the watertable will be in equilibrium with the atmosphere and, as such, will result in near modern ages. It is important that the laboratory sampling guidelines are followed when sampling because if the groundwater has even a small amount of contact with air during sampling the measured age will be younger than it should be. For this reason, it is particularly important to treat ages close to detection level (~1965 for CSIRO laboratory) with caution. The difference between a reported age of 1966 or 1967 and <1965 could be the result of slight problems when sampling. Furthermore a reported age of <1965 means that it could in theory be several thousand years old

### 4.1.10. Bromide addition and recovery in the unsaturated zone (Br)

This method is the only method reported where a tracer has been intentionally added to the soil in order to estimate deep drainage. This method is only applicable where rates of deep drainage are likely to be very high and the reported study (Sharma et al., 1991) is in an area with very sandy surface soils and reasonably high rainfall (Figure 4-11).

![Figure 4-11. Location of studies where the bromide method has been used.](image-url)
4.2. Comparison of results using different methods

It is evident from the previous section that there are numerous factors that need to be considered when estimating deep drainage and/or recharge. It is also evident that no methodology comes without its problems and limitations. This section compares recharge/deep drainage estimates made using different methods. In order to ensure no systematic bias, estimates of recharge made using different methods are only compared where the data are from the same author, location and site. As is the case with all data presented in this review, no effort has been made to edit data that may be questionable for a variety of reasons (inappropriate conditions for use of method, analytical errors, etc.). As a result, all of the comparison discussion is made on face value for the data.

In the first six comparisons shown in Figure 4-12, recharge estimates using the most commonly applied estimation method, steady-state chloride mass balance of groundwater (X axis), are compared with a range of other methodologies (Y axis). All of the methods shown in the first 6 figures estimate recharge rate (as opposed to deep drainage rate) and hence, as a first approach, one would expect all data to fall on the 1:1 line. However, this is the case for less than half the data with the remaining steady-state chloride mass balance of groundwater method recharge estimates in general less than recharge estimates using the other methods (excluding chlorofluorocarbon groundwater dating vs steady-state chloride mass balance of groundwater plot). In many cases, this difference is up to two orders of magnitude (i.e. for watertable fluctuation, water balance, transient chloride water balance of soil water and $^{14}$C groundwater dating methods).

The most likely reason for these differences is that the steady-state chloride mass balance of groundwater method is measuring recharge under native vegetation in most of the studies whereas there is the potential for most of the other methods to be measuring at least a component of recharge under a more recent recharge regime following land use change. Excluding commercial forestry, changes in land use usually result in increased recharge as observed in the comparison plots. It is also worth noting that, at some sites, estimates of recharge using the $^{14}$C groundwater dating method are higher than those made using the steady-state chloride mass balance of groundwater. It is likely that in most studies these two methods would have utilised the same groundwater sample. However, the high estimates of recharge rate were probably made using estimates of $^{14}$C age that were relatively modern (<2000 years old) and $^{14}$C groundwater ages over that range are potentially very inaccurate.

The third row of plots in Figure 4-12 display the results for estimates of recharge or deep drainage estimation using steady-state chloride mass balance of soil water, transient chloride mass balance of soil water and watertable fluctuation methods (Y axis) plotted against those using a water balance approach (X axis). The steady-state chloride mass balance of soil water method gives estimates of recharge/deep drainage that is up to two orders of magnitude less than those using the water balance method. This comparison is unexpected and may be the result of recharge via preferential flow accounted for by the water balance method but not by the steady-state chloride mass balance of soil water method which assumes water moves through the soil matrix. It may also, however, be due to the discrepancy in spatial and temporal scale between the two methods. The deep drainage estimates using the transient chloride mass balance of soil water method compare well to the water balance approach. However, this may an artefact of the method where the transient chloride mass balance of soil water method data were calibrated to the water balance data. There were only two data points comparing the water balance vs water table fluctuation methods.

Recharge estimated using $^{14}$C is one to two orders of magnitude less than recharge using watertable fluctuation (plot 10 in Figure 4-12). This is most likely the result of recharge being measured over different time periods and under different types of land use (i.e. current land use for the watertable fluctuation method and historic land use for the $^{14}$C method) and hence, is not unexpected. The chlorofluorocarbon groundwater dating and water table fluctuation methods both measure recharge over similar spatial scales and relatively short time periods (weeks to months for watertable fluctuation method and up to 5 decades for
CFC). Results from the two methods agree well (Plot 11, Figure 4-12). This is presumably because they both measure recharge over time frames when land use did not change.

Plot 12 in Figure 4-12 compares the transient and steady-state approaches to deep drainage estimation using analysis of soil water chloride. The steady-state approach uses soil water chloride measurements from below the root zone but above the depth of peak displacement and assumes piston flow and complete flushing of the unsaturated zone under the new deep drainage regime. This is rarely the case and any remnant chloride left in the soil profile will result in an underestimate of deep drainage as seen in this comparison. The final comparison shows a good correlation between the chlorofluorocarbon groundwater dating and transient chloride mass balance of soil water methods. This comparison is surprisingly good given that the transient chloride mass balance of soil water method estimates deep drainage and the chlorofluorocarbon groundwater dating method measures recharge.

In summary, the comparisons of methods here do not, in general, show anything that is not intuitively obvious given knowledge of the methods and their limitations. Further interrogation of this comparison data, and other recharge estimates in the database will need be undertaken before finalising relationships in Phase 2 of this project.
Figure 4-12. Comparison of recharge estimates where different methods were used by the same author at the same location and site. The abbreviations for each method are as defined in Section 1.2 of this report. (The red line on the plot represents a line where both methods are equal.)
4.3. Relationships

In this section we present some of the relationships emerging from the database developed during the review, and make some preliminary visual observations. A more detailed statistical analysis of the data will occur during the Phase 2 of the project.

4.3.1. Relationship between rainfall and recharge

The relationship between average annual recharge and average annual rainfall is shown in Figure 4-13 in the same manner as that of the major reviews of Petheram et al. (2000, 2002). The plots include all data from the database which has sufficient information. The data is separated into two very broad soil texture groups (sand and clay), and presented for all studies, and individually for annuals, perennials and trees. Data from the Gnangara groundwater mound, and the Tomago Sandbeds, a not-dissimilar coastal sand aquifer with high rainfall (~1200 mm yr\(^{-1}\)), have not been excluded from the plots (as was done by Petheram et al., 2000, 2002).

It appears that recharge on sandy soils is generally higher than that on clay soils for the same rainfall. Recharge also appears to increase with rainfall but there is considerable scatter; the clearest relationship is for perennials on sandy soils. Distinguishing differences due to vegetation type is difficult, and in particular the high recharge data for trees need to be viewed in light of the following. The recharge rates >200 mm yr\(^{-1}\) at a rainfall of ~800 mm yr\(^{-1}\) are for the Gnangara Mound where the soil has virtually no clay in it at all. The recharge rates of ~200 mm yr\(^{-1}\) at a rainfall of ~1200 mm yr\(^{-1}\) (and in areas with shallow watertables) are net recharge values for the Tomago Sandbeds, whereas those >500 mm yr\(^{-1}\) are gross recharge values for the Tomago Sandbeds.

![Figure 4-13. Updated version of Petheram plots.](image-url)
4.3.2. Comparison of recharge under different vegetation types

Many modelling studies have shown that annual vegetation has greater recharge than perennial vegetation which is in turn greater than recharge under trees; these relationships are not obvious from Figure 4-13. To try and distinguish recharge under different vegetation types, we have plotted only the data which has been reported by the same author at the same location and site. In doing so we are trying to remove any differences due to rainfall, soil type and estimation method. These plots are presented in Figure 4-14 and appear to show that recharge under annuals is greater than that under perennials which in turn is greater than that under trees.

![Comparison of recharge under different vegetation types](image)

Figure 4-14. Comparison of recharge under different vegetation types where reported by the same author at the same location and site. (The red line on the plot represents a line where both vegetation types are equal.)

4.3.3. Relationship between recharge and percent clay content of the surface soils

In the previous studies described in Sections 2 and 3 there have been attempts at a range of sites to relate recharge/deep drainage to clay content in the upper soil zone (most commonly 0 to 2 m, but not always). The sites cover a range of average annual rainfalls and vegetation types. Figure 4-15 plots in three dimensional space the average annual recharge/deep drainage versus rainfall versus % clay in the upper soil zone (0 to 2 m) for each of the main vegetation types (annuals, perennials and trees). While there are few estimates of recharge under perennial vegetation, and we have not carried out any statistical analyses, recharge/deep drainage under trees and annual vegetation appears to be related to both rainfall and clay content in surface soils. There are too few estimates of recharge under perennial vegetation to draw conclusions for this vegetation type.
4.3.4. Relationship between climate zones and recharge

The Köppen-Geiger climate classification has been used for over a century for delineating different climate zones. It is a very simple classification based only upon temperature and rainfall and the seasonality (Peel et al., 2007). In this section the recharge estimates in the database were classified by climate class (Table 1) and analysed (Figure 4-16, Figure 4-17). The recharge by Köppen class shows that the tropical classes (Köppen A) have the highest recharge, followed by the temperate classes (Köppen C) with the arid classes (Köppen B) having the lowest recharge.

Table 1. Köppen-Geiger climate classes within Australia.

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Af</td>
<td>Tropical, rainforest</td>
</tr>
<tr>
<td>Am</td>
<td>Tropical, monsoon</td>
</tr>
<tr>
<td>Aw</td>
<td>Tropical, savannah</td>
</tr>
<tr>
<td>Bsh</td>
<td>Arid, steppe, hot</td>
</tr>
<tr>
<td>Bsk</td>
<td>Arid, steppe, cold</td>
</tr>
</tbody>
</table>
BWh  Arid, desert, hot
BWk  Arid, desert, cold
Cfa  Temperate, without dry season, hot summer
Cfb  Temperate, without dry season, warm summer
Csa  Temperate, dry summer, hot summer
Csb  Temperate, dry summer, warm summer
Cwa  Temperate, dry winter, hot summer

Figure 4-16. Koppen Geiger climate classes for Australia (Peel et al., 2007) with the location of the recharge studies overlaid.
Another climate classification that could be useful is the aridity index (UNEP, 1992). This is the ratio of potential evapotranspiration to rainfall and classifies climate into five categories:

- Hyper-arid <0.05
- Arid 0.05 < 0.2
- Semi-arid 0.2 < 0.5
- Dry sub-humid 0.5 < 0.65
- Not arid > 0.65

Figure 4-18 shows the aridity index classes for Australia and the field studies overlaid. The aridity index was calculated using the Penman PET of Donohue et al., (2010) and the rainfall from SILO (Jeffrey et al., 2001). There is a clear increasing trend in the geometric mean of the recharge measurements within the classes with decreasing aridity (Figure 4-19).
Figure 4-18 Aridity Index for Australia showing location of field studies of recharge.

Figure 4-19. Plot of geometric mean of recharge for each aridity class and a plot of P/PET versus R/P.
4.3.5. Relationship between aquifer type and recharge

The principle hydrogeological divisions (GA, 2000) were investigated to see if they relate to recharge (Figure 4-20, Figure 4-21). From the field studies collected here it would appear that they do not. This is not a surprising result as the hydrogeological divisions are not surface geology. For example, the low recharge estimates on vertosol soil types in the Fitzroy Basin in Qld (Radford et al., 2009) sit above the Great Artesian Basin which is a porous extensive highly productive aquifer, this aquifer is confined and the recharge estimates on top of it are not the source of recharge.

Figure 4-20. Principle Hydrogeological Divisions for Australia (GA, 2000) with the location of the recharge studies overlaid.
As the principal hydrogeological divisions were not an adequate method of grouping the recharge studies surface geology was investigated (Figure 4-22). The surface geology of Australia has recently been mapped seamlessly across the country by GA (Liu et al 2006; Raymond et al 2007a; Raymond et al 2007b; Raymond et al 2007c; Stewart et al 2008; Whitaker et al 2007; Whitaker et al 2008). As there are thousands of lithological types in the attribute table, these were simplified into 9 groups:

- Volcanic
- Plutonic
- Metamorphic
- Weathered
- Carbonates
- Unconsolidated – coarse
- Unconsolidated – fine
- Consolidated – coarse
- Consolidated – fine

The results here were mixed (Figure 4-23). The coarse grained material had more recharge than the fine grained material as would be expected. However, the carbonates had comparatively low recharge when it could have been expected to be higher due to karstic systems.
Figure 4-22. Surface geology of Australia with recharge sites overlaid. For the legend to the colours see the original surface geology map.
Figure 4-23. The geometric mean of the field estimates of recharge for each of the groups of surface geology.
5. CONCLUSIONS

1. There has been a large number of recharge measurements over the last decade.
   a. We have identified a total of 4386 deep drainage and/or recharge estimates from 172 studies and these have been compiled into a data base.
   b. In spite of the size of the data base the spatial coverage of recharge estimates across Australia is incomplete and the density of studies is highly variable, with some regions (i.e. Mallee) very well represented whereas others (i.e. Gippsland) are completely lacking in any estimates.
   c. Fractured rock aquifers are very poorly represented and this reflects the difficulties in estimating recharge in these complex environments.

2. The estimates utilise 10 different methods. All of the methods have limitations that constrain the extent to which they can be applied. Inappropriate use of methods makes comparisons of recharge estimates and development of generic relationships difficult.
   a. In particular, different methods apply to different time frames (i.e. the water table fluctuation method applies to time scales from hourly to annual whereas the \(^{14}\text{C}\) groundwater dating method applies to timescales of 100s to 1000s of years).
   b. Moreover, by-pass/preferential flow is generally not accounted for in the unsaturated zone methods and this reflects the difficulties in characterising these complex processes.

3. Of the 10 methods in use, steady-state chloride mass balance of groundwater is by far the most commonly utilised (76% of the estimates) as it is easy to apply and cost effective. However, it does have the potential for being misused and misinterpreted as outlined in the Discussion section.

4. There is a substantial amount of rainfall chloride deposition data that has been collected over the past few decades that is not currently being utilised to its full advantage when practitioners use steady-state chloride mass balance methods. These data need to be collated and assembled into a data base. This will be done during Phase 2 of this project.

5. Vegetation type is clearly a critical determinant of recharge rates.
   a. From the previous reviews, and the preliminary assessments of the data base in this review, it appears that for the same rainfall and soil type, recharge under annuals is greater than that under perennials which in turn is greater than that under trees.
   b. While the amount of recharge data for perennial vegetation has increased since the reviews of Petheram et al. (2000, 2002) they are still under-represented in comparison to annuals and trees.

6. Soil type is clearly a critical determinant of recharge rates with estimates for heavy textured soils generally less than those for lighter textured sandy soils. This is because heavy textured soils have a greater plant available water capacity and so there is less opportunity for rainfall to become deep drainage below the root zone.

7. Correlation of recharge with rainfall, clay content and vegetation type.
   a. Over the last decade initial relationships in the Mallee (i.e. Kennett-Smith et al., 1994) have been extended to other areas.
   b. We have carried out some preliminary assessment of the data (see Discussion) but a more rigorous statistical analysis needs to be undertaken (planned for Phase 2 of the project).
8. We have also made a preliminary attempt at assessing the recharge estimates in relation to climatic zones using the Koppen-Geiger and aridity index classifications. This looks promising but further work is needed.

9. Considering the review in its entirety, and the preliminary relationships developed, it should be possible to proceed to Phase 2 of the project which is aimed at developing tools for estimating recharge and discharge in data poor areas.

10. We were unable to find any field studies of recharge from rivers, in some areas this is the dominant recharge mechanism. This is due to the methods required for this are currently under development, this is an active area of research and will require more effort in future.
GLOSSARY

Aquifer: Saturated permeable soil or geologic strata that can transmit significant quantities of groundwater under a hydraulic gradient.

Aquitard: Saturated soil or geologic strata whose permeability is so low it cannot transmit any useful amount of water.

Discharge: Loss of water from an aquifer (i) to the atmosphere by evaporation, springs and/or transpiration, or (ii) to a surface water body (in the case of rivers it is generally referred to as base flow) or the ocean, or (iii) by extraction.

Groundwater: Sub-surface water in soils and geologic strata that have all of their pore space filled with water (i.e. are saturated).

Hydraulic gradient: Change in hydraulic head in an aquifer with either horizontal or vertical distance, in the direction of groundwater flow.

Recharge: Addition of water to an aquifer, most commonly through infiltration of a portion of rainfall, surface water or irrigation water that moves down beyond the plant root zone to an aquifer.

Vadose or unsaturated zone: Zone between land surface and the watertable within which the moisture content is less than saturation (except in the capillary fringe).

Watertable: Level of groundwater in an unconfined aquifer. The soil pores and geologic strata below the watertable are saturated with water.
REFERENCES


