



Recharge and Discharge Estimation in Data Poor Areas Scientific Reference Guide

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Description: Limestone tufa on the Douglas River in Northern Territory.

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EXECUTIVE SUMMARY

Determination of an accurate groundwater balance for a region requires estimation of groundwater recharge and discharge rates and, where possible, knowledge of their spatial distribution. Where the value of the resource warrants it, detailed groundwater recharge and discharge studies are commissioned. These studies provide comprehensive empirical information on the spatial and temporal variability of groundwater recharge and discharge, and the relationship between these with soil, regolith, landform and vegetation parameters. Where the value of the resource does not warrant detailed research, much cruder approaches (such as recharge is a simple percentage of rainfall or discharge is assumed to be non-existent) are used. The aim of the project described in this report was to develop a nationally consistent approach to groundwater recharge and discharge estimation for data poor areas which is a half way house between using simple approximations and carrying out very detailed field and modelling studies.

This project involved two phases, the first of which compiled reviews of groundwater recharge and discharge studies that have been undertaken in Australia. It also involved preliminary identification of the parameters (climate, soils, regolith, near-surface geology, landforms, vegetation etc.) that determine groundwater recharge and discharge rates along with a review of the appropriate scale mapping approaches available for these parameters. The second phase of the project utilised empirical relationships derived from data collected in Phase 1 of the project in a decision tree methodology that guides the user to the most appropriate estimate for groundwater recharge/discharge given the data availability.

The decision tree has parallel pathways directing the user to estimates based on: (i) utilisation of statistically significant empirical relationships; and (ii) simple groundwater recharge and/or discharge estimation methods (e.g. Chloride Mass Balance using groundwater samples). The decision-tree methodology is implemented in two Microsoft Excel spreadsheets for groundwater recharge and discharge estimation

([HTTP://WWW.CSIRO.AU/PRODUCTS/RECHARGE-DISCHARGE-ESTIMATION-SUITE](http://www.csiro.au/products/recharge-discharge-estimation-suite)).

These spreadsheets incorporate various parameters; for example, mean annual rainfall, soil type, vegetation type, evapotranspiration and land use change. Other parameters considered include rainfall chloride flux, groundwater chloride concentration, watertable depth, surface soil and regolith type, and aquifer porosity. Where the user does not have access to these datasets, they are directed to MapConnect Groundwater, a specifically designed web-based data delivery tool ([HTTP://WWW.GA.GOV.AU/MAPCONNECT/](http://www.ga.gov.au/mapconnect/)). A User Guide (Jolly *et al.*, 2011) gives detailed instruction in the use of both the Recharge and the Discharge estimation spreadsheets and the associated GIS datasets made available via the MapConnect website.

This report summarises the science underpinning the groundwater recharge and discharge estimation methods used in these spreadsheets. Specifically, Chapter 2 describes six methods; three used to estimate deep drainage and/or groundwater recharge and three to estimate groundwater discharge. The methods used for groundwater recharge/deep drainage estimates discussed in this document are Method of Last Resort (MOLR; Crosbie *et al.*, 2010b), %Clay/rainfall/land-use relationship (Wohling *et al.*, 2011), and Groundwater Chloride Mass Balance (GCMB; Crosbie *et al.*, 2010a). The three methods used for groundwater discharge estimates are the Groundwater Risk Model (based on the Water Balance Risk Model, (WBRisk; Howe *et al.*, 2006), Ecological Optimality model (based on the concepts of Eagleson (1978)) and a groundwater discharge versus groundwater salinity function (O'Grady *et al.*, 2010). Chapter 2 also details the various datasets required to apply any of the six recharge and/or discharge estimation methods.

Chapter 3 provides worked examples of groundwater recharge and discharge estimation using the estimation tools at two exemplar areas (Wattle Range and Tomago). Estimates

generated using the tools compare favourably with more detailed work undertaken in these areas.

Collectively, the two spreadsheets, the MapConnect Groundwater website, the User Guide, and this Scientific Reference Guide constitute the Recharge Discharge Estimation Suite. The authors are hopeful that the methods presented in the Recharge Discharge Estimation Suite will assist hydrogeologists in their management of groundwater resources and provide consistently derived recharge and discharge estimates and associated uncertainty in areas where no specific recharge and/or discharge studies have been undertaken.

However, the authors stress that the approaches presented here for recharge and discharge estimation are intended for data poor areas and for areas where the value of the resource does not necessitate field based studies. If these are not the case, estimates made using the approaches described here should not be used in lieu of more detailed investigations where such investigations are warranted. It should also be stressed that groundwater recharge and discharge estimations made using these approaches should not be applied in urban or irrigation areas as the land management complexities inherent in such areas are not taken into account in these approaches. Furthermore the methods developed do not attempt to account for recharge or discharge to local or regional aquifers through stream or river beds.

1. INTRODUCTION

1.1. Background

One of the primary requirements of water managers responsible for the allocation of water resources for any region is an understanding of the water balance. Whilst this is readily achievable for surface water, it is much more challenging for groundwater. Understanding the water balance of a groundwater system requires the estimation of groundwater recharge and discharge fluxes and these typically vary in time and space in sympathy with landscape morphology, climate, land use and land management.

The relationships that prevail between surface water systems and groundwater systems are most often quite complex and they vary from one type of groundwater system to another. There will always be fundamental differences in hydrogeological processes consistent with geological and geomorphic settings, aquifer properties and regolith character. It is also understood that groundwater recharge and discharge vary over time in a land with 'droughts and flooding rains'. Recharge and discharge fluxes are not fixed in time, instead they move up and down with the climate.

1.2. The problem

When formulating a water balance for a region water managers deal with the hydrogeological complexity in a variety of different ways. Some commission detailed water balance assessments and go on to assemble fully distributed groundwater models. These studies provide comprehensive empirical information on spatial and temporal variability of groundwater recharge, and the relationship between groundwater recharge rates and soil, regolith, landform and vegetation parameters. However such studies are generally extremely costly and time consuming. At the other end of the spectrum, some water managers make assumptions in simplistic spread-sheet models. In these recharge is often assumed to be a simple percentage of annual rainfall (usually ranging from 2-10%). Moreover, discharge is commonly assumed to be non-existent or is simply neglected.

In moving to a more rigorous national approach there is a need to: (a) recognise that the potential for groundwater recharge and groundwater discharge varies with the geological and geomorphic character of the component groundwater systems that make up the area of concern, and (b) to appreciate that actual groundwater recharge will vary temporally, consistent with climate and vegetation. The former deals with the attributes of the landscape that modulate recharge/discharge fluxes, while the latter deals with the biological and climatic circumstances that drive the same.

The two main problems with the *status quo* system of recharge and discharge estimation in data poor areas in Australia are:

- Consistency of estimation - There is no consistent method for recharge and/or discharge estimation currently available to groundwater managers. As a result, managers are often forced to make estimated guesses that are not easily confirmed nor compared.
- Uncertainty of estimation - To date, there has been no attempt made to assign uncertainties to recharge and discharge estimates in groundwater management.

Whilst groundwater and unsaturated zone modelling are sometimes used for recharge estimation, the wide variability in the robustness of model calibration precludes these methodologies from being suitable for a consistent national approach.

1.3. Project objectives

A Consistent Approach to Groundwater Recharge Determination in Data Poor Areas project is funded by the National Water Commission. It aims to develop a nationally consistent approach that can be applied by groundwater managers to estimate recharge and discharge fluxes in areas that have not been subject to detailed investigations.

The project is divided into two phases (Figure 1).

Phase 1 – This assembles an understanding of (a) previous studies that had established point source estimates of groundwater recharge and discharge in Australia and, (b) the most applicable techniques that could be deployed to map the distribution of recharge and discharge fluxes across Australian groundwater systems.

Phase 2 – Construction of a decision support system that would afford groundwater managers first order estimates of recharge and discharge fluxes. This decision support system references the point source data and landscape context established in Phase 1.

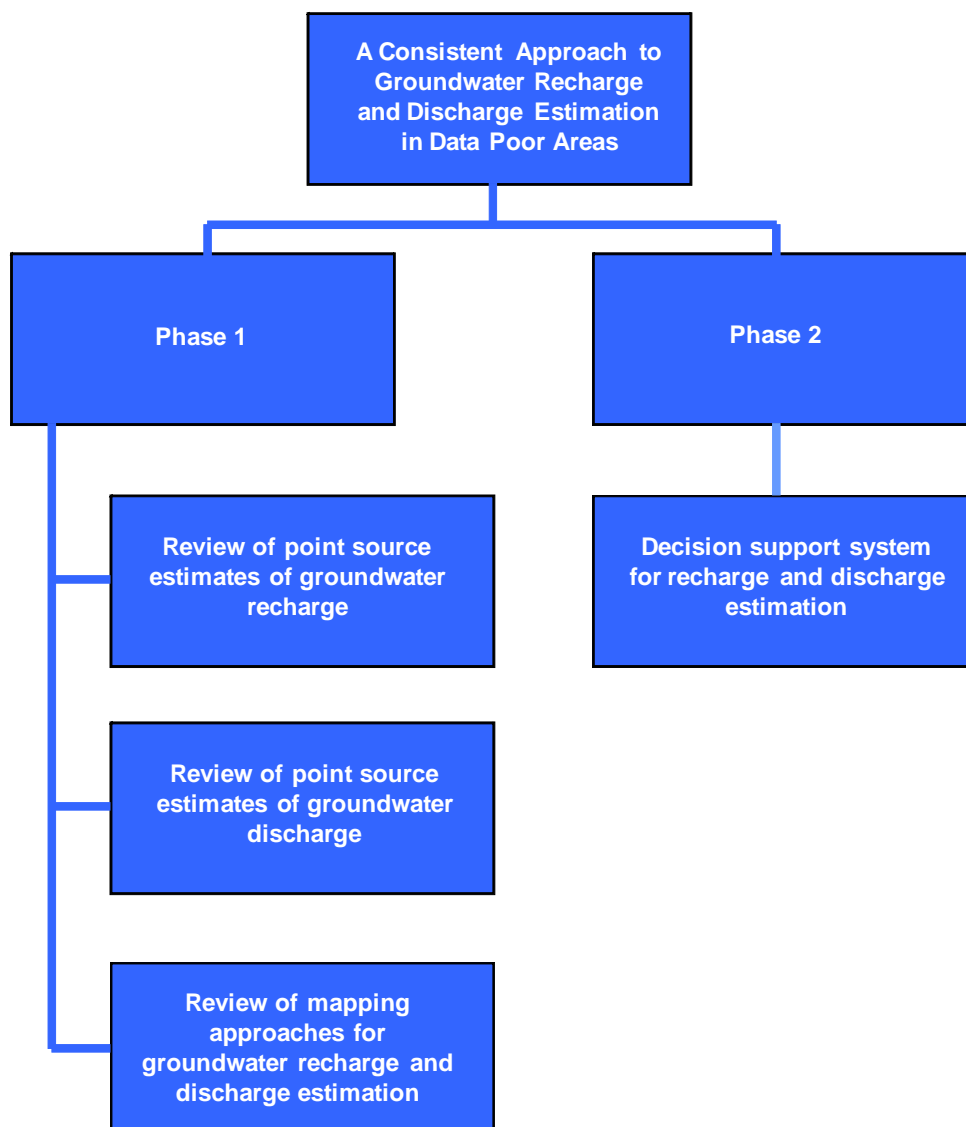


Figure 1. Flow diagram identifying sub-project order.

Note to Users of the Recharge and Discharge methods and spreadsheets.

The methods described in the following chapter endeavour to provide recharge and discharge flux estimations that fall somewhere between using rough guesses (i.e. recharge is 5% of rainfall) and carrying out very detailed field and modelling studies. The authors stress that the approaches presented here for recharge and discharge estimation are intended for:

- 1) data poor areas and
- 2) areas where the value of the resource does not necessitate field based studies.

If these are not the case, estimates made using the approaches described here should not be used in lieu of more detailed investigations where such investigations are warranted. It should also be stressed that groundwater recharge and discharge estimations made using these approaches should not be applied in urban or irrigation areas as the land management complexities inherent in such areas are not taken into account in these approaches. Furthermore the methods developed do not attempt to account for recharge or discharge to local or regional aquifers through stream or river beds.

Groundwater recharge estimation methods and associated uncertainties were based on empirical relationships derived from field based measurements. This was not possible for estimates of groundwater discharge due to the limited number of field based measurements. Consequently a combination of field-based measurements and modelling has been used to develop the Recharge Discharge Estimation Suite described in this Scientific Reference Guide. The development of methods and associated uncertainty of estimation are described in the following chapters.

1.4. Terminology

When discussing groundwater recharge and discharge estimation, it is important to ensure consistent and correct terminology is used. In the past, the term groundwater recharge, along with terms such as deep drainage, have often been interchanged and used incorrectly. For the purpose of this report, we adopt the following definitions (Figure 2):

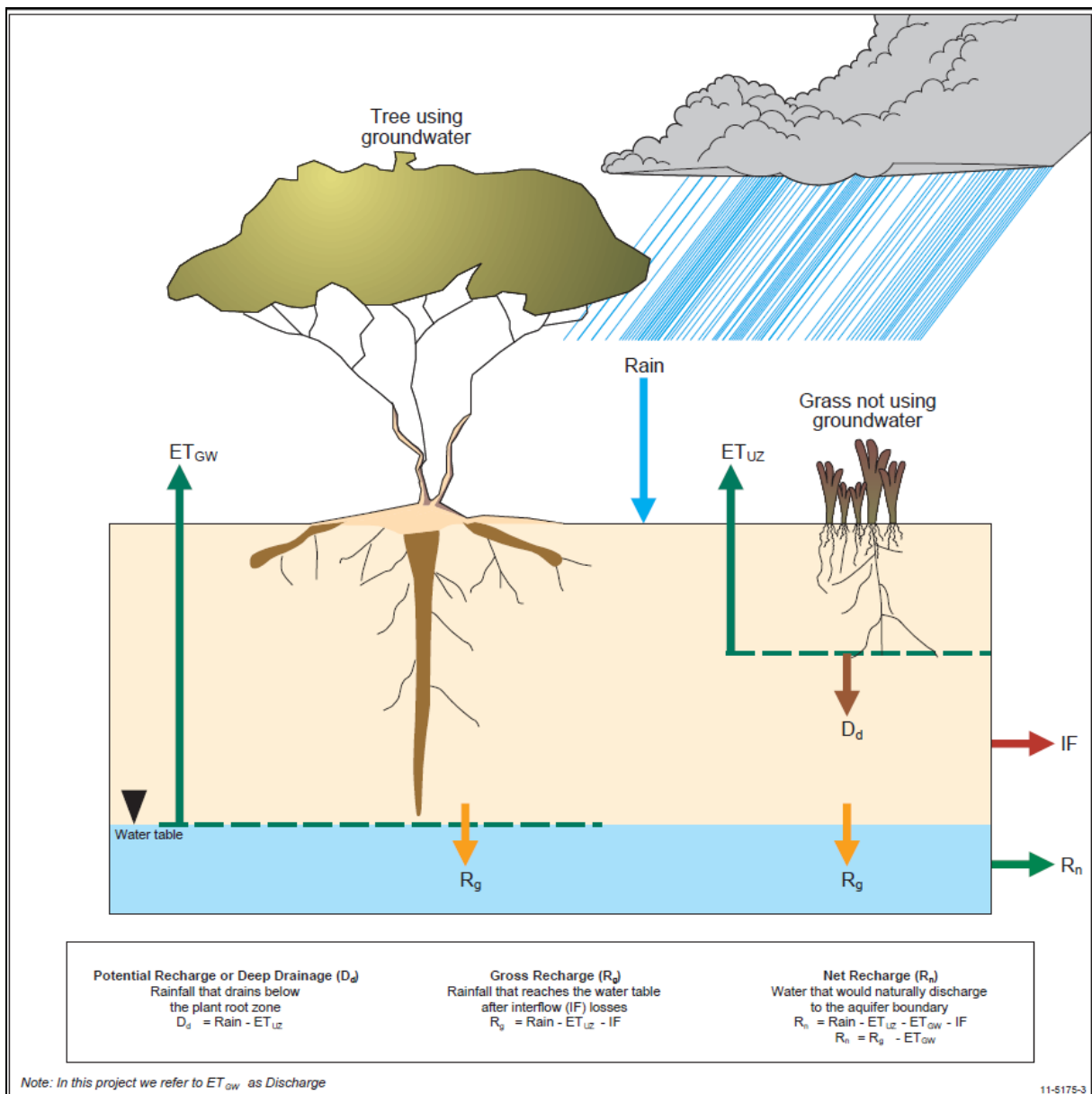


Figure 2. Illustration of the terms deep drainage, gross recharge, net recharge, and discharge by evapotranspiration.

Deep Drainage (D_d) or *Potential Recharge* is rainfall 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 (i.e. causes interflow).

Discharge is any loss of water from the aquifer. In the context of this project we are concerned with loss of water from the aquifer by evapotranspiration by vegetation (ET_{GW}).

Gross recharge (R_g) is the rainfall that reaches the watertable after interflow (IF) losses.

Net recharge (R_n) is the rainfall that discharges to the aquifer boundary after discharge (ET_{GW}) losses.

A time lag can exist between land use changes and associated variations in the rate of deep drainage and when this translates to a change in recharge. This lag time becomes important when determining what can and actually is being measured (as discussed later in this report).

2. METHODS

This chapter will briefly detail Phase 1 of the project before going into greater detail about the various methods that have been developed to estimate recharge and discharge in Phase 2. It will also provide details of the relevant national datasets that provide essential input data to the established methods, why these datasets were selected and where they (or equivalent) can be obtained from.

2.1. Recharge, discharge and mapping reviews (Phase 1)

Phase 1 of the project involved a review of deep drainage, groundwater recharge and discharge studies previously undertaken in Australia and applicable mapping approaches. The review documents also provided preliminary identification of the parameters (climate, soils, regolith, near-surface geology, landforms, vegetation etc.) that determine groundwater recharge and discharge rates and the appropriate scale mapping approaches available for these parameters.

This phase has now been completed and the review documents (Crosbie, *et al.*, 2010A; O'Grady *et al.*, 2010; Pain *et al.*, 2011) can be accessed through CSIRO Water for a Healthy Country website (<http://www.clw.csiro.au/publications/waterforahealthycountry/index.html>).

2.2. Defining the recharge/discharge regimes

Groundwater recharge and discharge are influenced by two distinct processes: 1) the natural propensity of the land to recharge or discharge in accordance with its inherent geological and geomorphic character, and 2) the water balance of the land given dynamic interactions between climate and vegetation.

The geological and geomorphic character of the landscape dictates the nature of a groundwater flow system and this in turn provides insight into areas of potential recharge and potential discharge.

Unlike geological and geomorphic attributes the water balance varies in time and space. Climate and land-use may vary seasonally, from year to year or over several decades. Accordingly, the interactions between rainfall, evaporation and transpiration determine the volume of surface water available to drive groundwater recharge and groundwater discharge processes in any given season and in any given year.

The starting point in investigating the water balance for poorly studied areas should be the disaggregation of the area of concern into component groundwater systems. Various studies have developed methods to divide the landscape and these are detailed in the mapping review (Pain *et al.*, 2011) completed in Phase 1 of the project. Irrespective of the particular method used to disaggregate the landscape, a number of parameters are fundamental – climate, soils, regolith, vegetation and land use change. These spatial datasets are available as a product of Phase 2 via MapConnect (<http://www.ga.gov.au/mapconnect/>) to allow for the identification of sub-areas in the absence of other data, by groundwater managers.

Considerable variability in recharge and discharge rates can arise from changes in these parameters, consequently it is recommended that estimates be calculated for each sub-area. The number of sub-areas used will depend on the detail/resolution of data and the variability of key parameters within the study area. Two examples are provided in Chapter 3. The scale of mapping should also reflect the purpose of the water balance assessment. Investment in very fine scaled landscape definition will only realise a more accurate water balance where the density of point-scale estimates of groundwater recharge and discharge is sufficient to account for landscape variability.

2.3. Recharge estimation

The second phase of the project utilises empirical relationships (derived from data collected in Phase 1 of the project) in a Microsoft Excel-based decision-tree approach to estimate groundwater recharge and/or discharge for a given area. Using the Excel spreadsheet, up to three different groundwater recharge estimation methods may be employed, depending on data availability. No modelled data were used in developing the methods or correlations; instead, the methods have been developed using data for broad scale diffuse recharge and/or deep drainage. Measurements and/or estimates from irrigation areas have not been included because of the added complexities associated with the wide range of possible crops and irrigation management strategies. In addition, measurements and/or estimates for recharge/deep drainage for rivers or floodplains have not been included because no statistically viable relationships to readily available data could be developed for these areas. Also, clearly the recharge/deep drainage estimates are only for watertable (phreatic) aquifers and cannot be applied to confined aquifers except for areas where the aquifers outcrop. Because all of the correlations are derived entirely from measured (and reported) estimates, some of the correlations are limited to certain vegetation, soil types and rainfall ranges.

The decision tree incorporates various parameters; for example, mean annual rainfall, soil type, vegetation type, evapotranspiration and land use change. Through MapConnect groundwater managers will have access to these various datasets at a national scale (see Chapters 2.2 and 2.5). Other parameters of consideration include rainfall chloride flux, groundwater chloride concentration, watertable depth, surface soil and regolith type, and aquifer porosity.

The Excel recharge spreadsheet provides point estimates of groundwater recharge only. The user is encouraged to assess how representative the estimate is in relation to the surrounding landscape by looking at the broader variability of key parameters used to define the groundwater recharge and discharge values. Consequently, before applying the Excel spreadsheet, the user is encouraged to divide the area of interest into sub-areas that have similar parameters pertaining to recharge and discharge. This ensures the true variability is captured. National, regional and local datasets, used in conjunction with local hydrological knowledge can be used to assist in the division of these sub-areas, as discussed in Chapter 2.2.

2.3.1. Estimating deep drainage and recharge

As discussed above, relationships between deep drainage, groundwater recharge and parameters such as soil type, vegetation cover, rainfall, etc. have been formulated from field-based estimates. These correlations have in turn been used to develop methods of estimating deep drainage and recharge in the absence of field-based estimates and are presented in the Excel spreadsheet flow diagram (Figure 3).

Following the Excel spreadsheet flow diagram, deep drainage can initially be estimated using two methods, Method of Last Resort (MOLR) and the %Clay method (Figure 3). Additionally, a number of field-based groundwater recharge and discharge estimates (collated from various published reports and papers) are available via MapConnect Groundwater (<http://www.ga.gov.au/mapconnect/>). If the site being studied is located close to one of these estimates, this measurement should be reviewed to determine whether it is in a similar groundwater recharge/discharge regime as determined by soil type, vegetation and land use history. If so, the previously published value should be employed for that sub-area rather than applying the Excel spreadsheet approach. However, in the majority of cases, particularly in data poor areas, the site will not be on the groundwater recharge/discharge database.

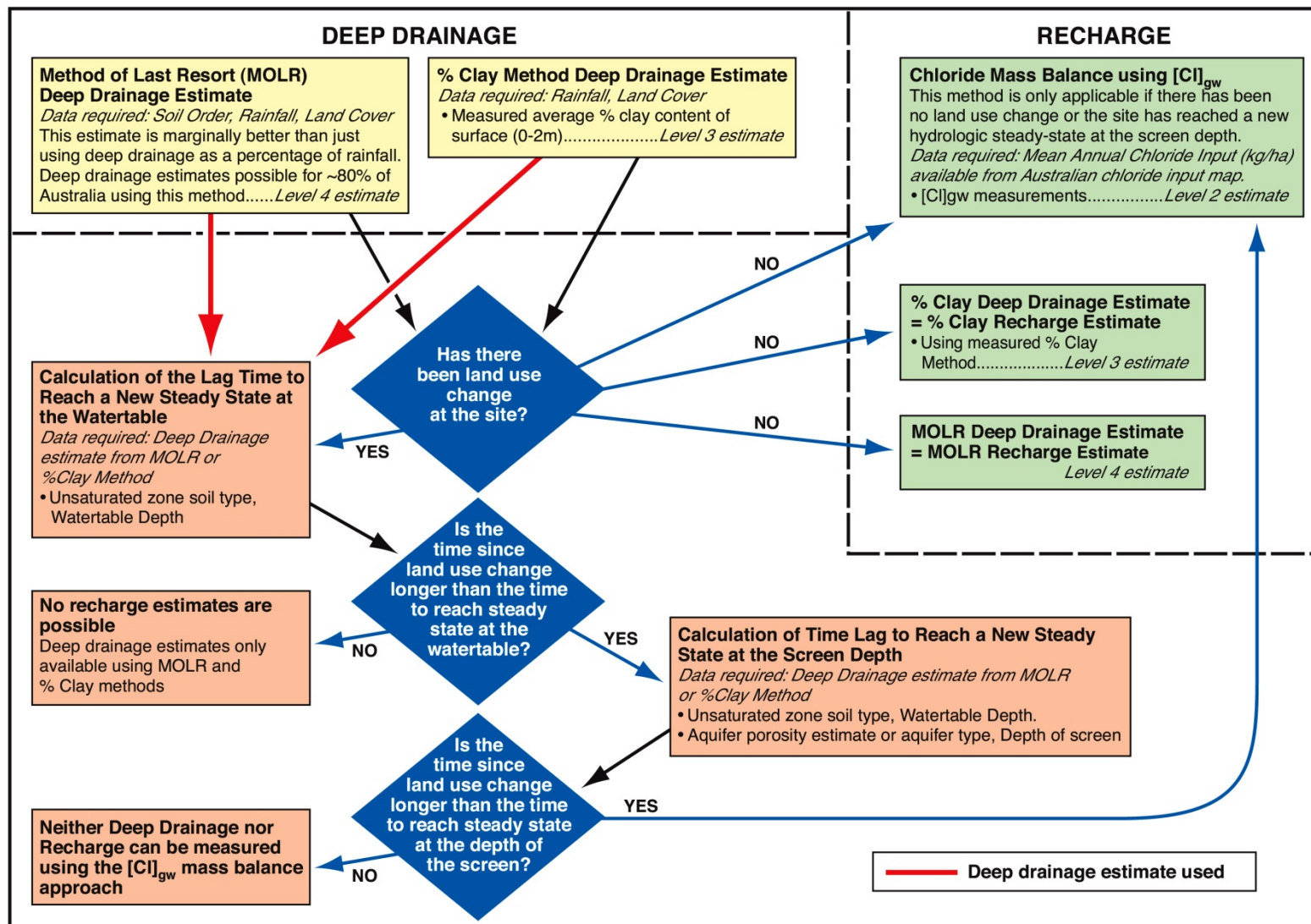


Figure 3. Flowchart showing the deep drainage and recharge estimation methods used in the Excel spreadsheet.

The MOLR is the most widely applicable method and uses the relationship observed between deep drainage and rainfall for different soil orders (as defined by the Australian Soil Classification) and vegetation cover. As the inputs are all national-scale digital datasets, the MOLR has been produced as a nationally consistent spatial coverage. This method has a high degree of uncertainty as the correlations only explain about 60% of the variance in recharge measurements across Australia; uncertainty in the groundwater recharge estimated using these relationships is generally considerably greater than an order of magnitude (Crosbie *et al.* 2010B). An expanded description of the MOLR method is given in Chapter 2.3.3.

Estimates of deep drainage based on empirical relationships with surface soil clay content (0-2m) and rainfall (hereafter known as the %Clay method) have been used in many areas in south-eastern Australia. The method should only be used if the clay content in the top two metres has been measured. Mean annual rainfall can be estimated in a variety of ways as discussed in Chapter 2.5.5. Estimates made using the %Clay method have slightly less uncertainty than the MOLR method. For sub-areas where there has been no vegetation clearing, the rates estimated for deep drainage will also be estimates of groundwater recharge (lateral flow loss below the root zone has not been considered). An expanded description of the %Clay method is given in Chapter 2.3.5.

Overall, the Groundwater Chloride Mass Balance (GCMB) method for estimating deep drainage and groundwater recharge has the least uncertainty of the three methods in the recharge spreadsheet. The GCMB method can only be used when the groundwater at the depth of the screen is at steady-state. Hence, if there has been vegetation clearing at the site, no estimate of groundwater recharge (or deep drainage) is possible until it has been determined that the hydrological water balance has reached a new steady state at the groundwater sample depth. The Excel spreadsheet makes this calculation (lag time) and will either make an estimate based on the GCMB method or indicate that the system has not reached a new steady state (and therefore a groundwater recharge estimate is not possible using the GCMB method). An expanded description of the GCMB method is given in Chapter 2.3.4.

2.3.2. Estimating lag time following vegetation clearing

For areas where there has been vegetation clearing, as established by local knowledge or from GIS data, the Excel spreadsheet allows an estimate of the time to reach a new steady state at the watertable and also at the depth of bore screens that have available measurements of the concentration of chloride in groundwater. It uses a simple one-dimensional piston flow approach (as first described in Cook *et al.*, 1993) to estimate the time for deep drainage to reach the watertable and then also assumes piston flow for vertical recharge to reach the depth of the screen. In reality, watertable impacts are likely to occur before the predicted time lag calculated from the piston flow approach because of the log normal nature of recharge processes (Leaney *et al.*, 2003). The approximations in the approach used here does not allow for a more rigorous lag time estimate to be made.

Deep drainage must be calculated prior to the estimation of lag time. If data availability allows for an estimate of deep drainage from the %Clay method, that value is used. Otherwise, the MOLR estimate of deep drainage is used. Once the lag time required to reach steady-state at the watertable and at the screen interval has been estimated, the user is then given estimates of deep drainage and/or groundwater recharge rates for the various methods depending on whether the sub-area identified has reached new steady state. The time lag calculation assumes that the profile is comprised of up to five layers (two soil layers, unconsolidated material, weathered rock material, and unweathered rock), as shown in Figure 4.

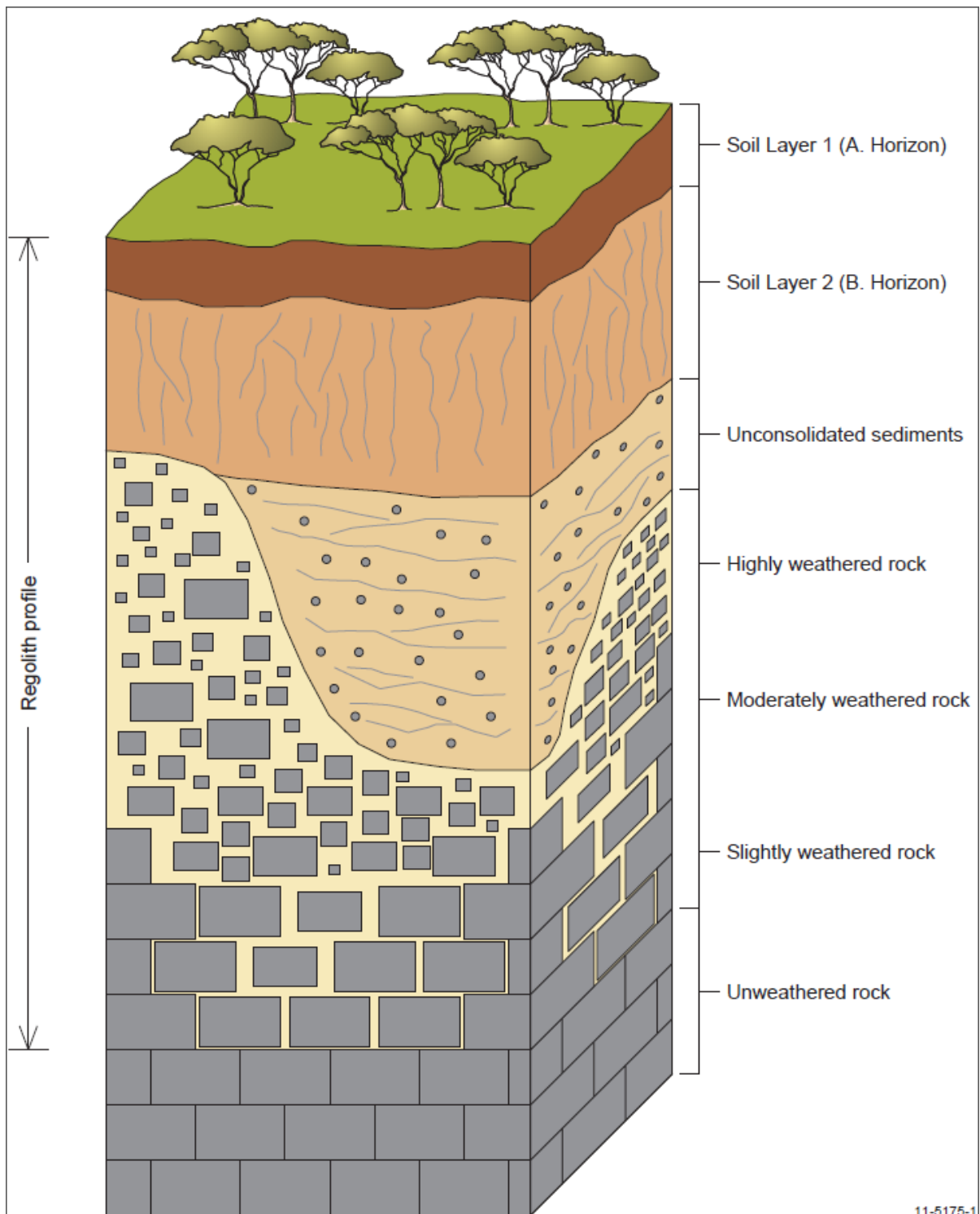


Figure 4. Illustration of the 5 layers comprising the profile used to estimate the time lag following land-use change.

Under pre-clearing conditions, the soil matric suction (and therefore water content of the soil) will be that for soil under the original vegetation. Where the original vegetation consists of deep rooting trees and/or perennials, matric suction has been measured in the range 1000-10000 kPa with a value of ~1600 kPa often used. After clearing of native vegetation and its replacement with shallower-rooting vegetation, the matric suction decreases to ~30 kPa (Jolly *et al.*, 1989). The lag time and associated increase in groundwater recharge at the watertable is the cumulative amount of water required to change the unsaturated zone from a water content associated with pre-clearing conditions (matric suction = 1600 kPa) to that associated with post-clearing (matric suction = 30 kPa) divided by the rate of deep drainage.

Values for volumetric water content at matric suctions of 30 and 1600 kPa from Carsel and Parish (1988) for 11 main soil texture classes (sand, loamy sand, sandy loam, loam, sandy clay loam, silty loam, clay loam, silty clay loam, sandy clay, silty clay and clay) have been used in the Excel spreadsheet (Table 1). The authors believe that this is a reasonable approach for estimation of these parameters for the two uppermost layers used in the spreadsheet (i.e. soil layers). For the deepest layer (unweathered rock), the amount of water required to “wet up” the rock matrix is estimated to be 1% of the porosity. Unfortunately, there is little data available to support this method of estimate. However, for unweathered rock, the amount of water in the rock matrix is generally quite small compared to the layers above and therefore any errors in this estimate should contribute minimally to the overall lag time. Porosity ranges for common rock types are given in the spreadsheet and also in Table 2.

For the unconsolidated sediments and weathered rock layers, it was decided that, in terms of soil water movement, the soil/rock matrix in these layers would act more like a soil than a rock matrix and so the spreadsheet user is asked to assign a soil texture to them. Once a soil texture is assigned, the layers are treated in the same manner as the two uppermost soil layers. The authors accept that it is not always going to be easy to assign a soil type to the unconsolidated sediment and weathered rock layers but some direction is given in the spreadsheet and also in Table 2. In the case of the weathered rock, only the weathered fraction of the rock is considered. Slight, moderate and highly weathered are given the fractions 0.2, 0.5 and 0.9 respectively. Hence, a moderately weathered rock will give 2.5 times the change in volumetric water content as a slightly weathered rock of the same type.

Table 1. Change in volumetric water content between matric suctions of 30 kPa and 1600 kPa for 11 soil texture classes (after Carsel and Parish, 1988).

Soil texture	Volumetric water content at 30 kPa	Volumetric water content at 1600kPa	Change in volumetric water content
Sand	0.046	0.045	0.001
Loamy Sand	0.060	0.057	0.003
Sandy Loam	0.087	0.066	0.021
Loam	0.170	0.088	0.082
Sandy Clay Loam	0.173	0.111	0.062
Silty Loam	0.247	0.103	0.144
Clay Loam	0.274	0.149	0.126
Silty Clay Loam	0.343	0.195	0.148
Sandy Clay	0.271	0.169	0.101
Silty Clay	0.338	0.265	0.073
Clay	0.349	0.270	0.079

Table 2. Suggested translation between soil texture and unconsolidated, weathered rock materials, and porosity ranges for unweathered rock materials. Porosity values are a guide only. * denotes materials that typically have low porosity but potentially very high permeability if fractured, faulted or jointed.

Unconsolidated material (e.g. alluvium, aeolian, lacustrine sediments)	Soil texture
Aeolian sand and clay	sand or loamy sand
Aeolian sand	sand
Sand, silt and clay, minor gravel	loam
Clays; minor sand and silt	clay or silty clay
Sands; minor clay and silt	sand or loamy sand
Weathered rock material	Soil texture
Basalt	clay
Coarse grained intrusives (e.g. granite, diorite, syenite)	loam or sandy clay loam
Fine grained volcanics (e.g. rhyolite, dacite, andersite)	Silty loam or clay loam
Gneiss and other high grade metamorphics	loam or sandy clay loam
Meta-carbonates	clay or silty clay
Sandstone, minor shale and conglomerate	sand or sandy loam
Schist and minor phyllite	clay, silty loam, sandy clay loam
Sedimentary carbonate and calcrete	clay
Shale, mudstone, siltstone; minor sandstone, phyllite and conglomerate	clay or silty loam or silty clay
Fe duricrust and silcrete	sand
Unweathered rock	Porosity (%)
Coarse grained intrusives (e.g. granite, diorite, syenite)	1 to 5
Fine grained volcanics (e.g. rhyolite, dacite, andersite)	1 to 10
Gneiss and other high grade metamorphics	0.8 to 1.6
Meta-carbonates	1 to 10
Sandstone, minor shale and conglomerate	10 to 20
Schist and minor phyllite	0.6 to 1.5
Sedimentary carbonate and calcrete	1 to 20
Shale, mudstone, siltstone; minor sandstone, phyllite and conglomerate	1 to 10
Banded ironstones and quartzite	1 to 5*

In addition to determining the amount of water required to reach the watertable (and hence to reach a new steady state at the watertable), it is also important to determine the amount of water required to reach the screen (and hence a new steady state at the depth of the screen). This is estimated as the amount of water in the saturated zone (depth of screen below watertable multiplied by porosity) added to that required to reach a new steady state at the watertable. The lag time is the total of these, divided by the post-clearing rate of deep drainage. The lag time to reach the screen is often much longer than the lag time to reach the watertable. This limits the applicability of the GCMB method in areas where there has been clearing of native vegetation.

2.3.3. The method of last resort (MOLR)

As described above, in Phase 1 of the project a database of ~4400 recharge and/or deep drainage estimates from 172 studies in Australia was compiled. Crosbie *et al.* (2010B) used a sub-set of data from this database (Figure 5) to determine whether simple empirical relationships could be found that relate groundwater recharge to nationally available datasets and hence whether they can be used to estimate recharge in data poor areas in a scientifically defensible way. It was found that vegetation and soil type were critical determinants in forming relationships between average annual rainfall and average annual recharge, whereas climate zones (Köppen-Geiger climate classification and aridity index) and surface geology (lithology) were not found to be significant determinants.

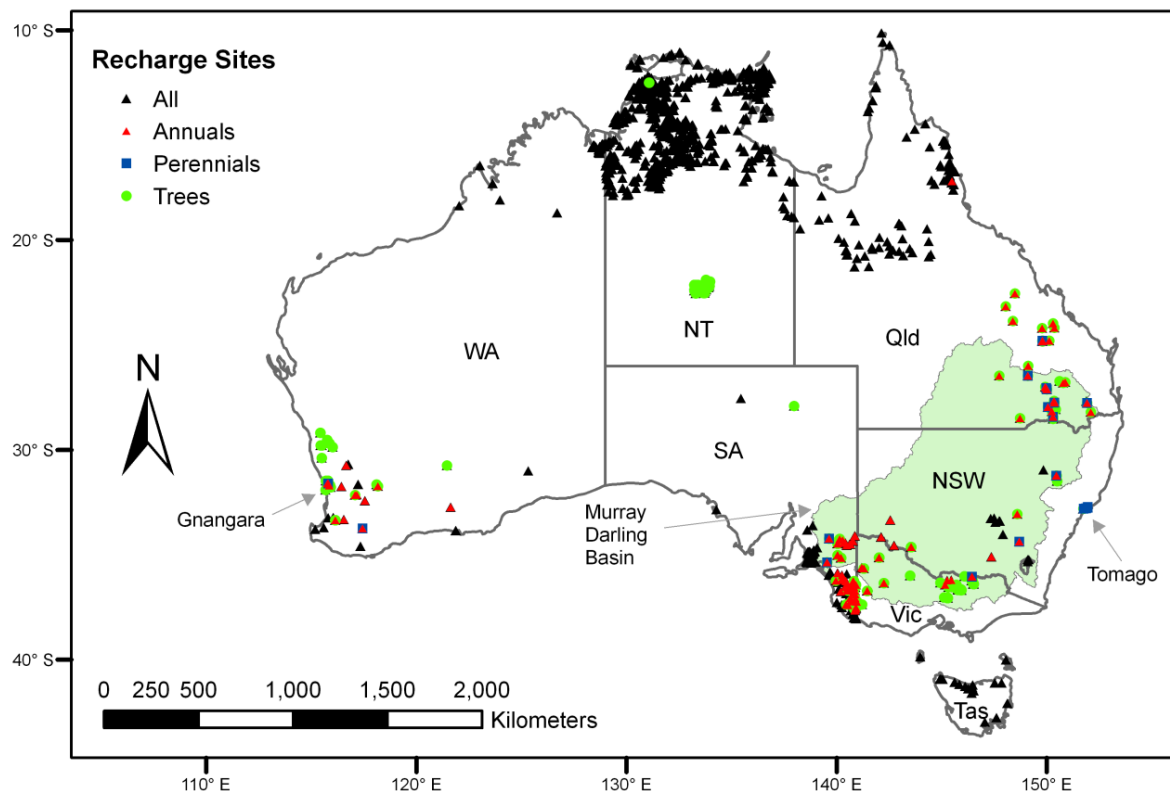


Figure 5. Location of field studies that were used to derive the relationships used in the MOLR. From Crosbie *et al.* (2010B).

The MOLR further simplified the relationships developed by Crosbie *et al.* (2010B) by combining the perennial and tree vegetation types due to a lack of data under these vegetation types. The soils groupings used by Crosbie *et al.* (2010B) have been retained for the MOLR, these are:

- Vertosols (VE)
- Calcarosols (CA), Chromosols (CH), Kurosols (KU) and Sodosols (SO)
- Podosols (PO)
- Rudosols (RU), Kandasols (KA) and Tenosols (TE)
- Ferrosols (FE), Dermosols (DE), Hydrosols (HY) and Organosols (OR)

No estimate of recharge is possible using the MOLR from the last soils group (FE,DE,HY,OR) due to a lack of field studies required to develop the relationships. The

relationships that were developed between recharge and mean annual rainfall, soil order and vegetation type used a two parameter regression model are shown in Equation 1.

Equation 1 $R = 10^{aP+b}$

where a and b are the fitting parameters from a least squares regression between annual average rainfall (P) and the logarithm of annual average recharge (R). Figure 6 shows the relationships observed between average annual rainfall and average annual recharge for the combination of soil and vegetation groups. The annual vegetation class is displayed in red, and the perennials and the trees are displayed in green. In black is all the recharge estimates irrespective of vegetation type. The line of best fit is the bold colour line while the thin black line is the 95% prediction interval about the line of best fit. A line of best fit is only presented on Figure 6 when that line is statistically significant ($p < 0.05$). Table 3 gives the regression parameters used in the MOLR and the rainfall ranges that they apply to (from Figure 6). The regression parameters shown in table 6 are those used in the recharge and discharge estimation spreadsheets (<http://www.csiro.au/products/Recharge-Discharge-Estimation-Suite>). The number of significant figures in the table do not indicate the degree of accuracy (confidence) in the relationships, the same is true for other regression parameters presented in this report.

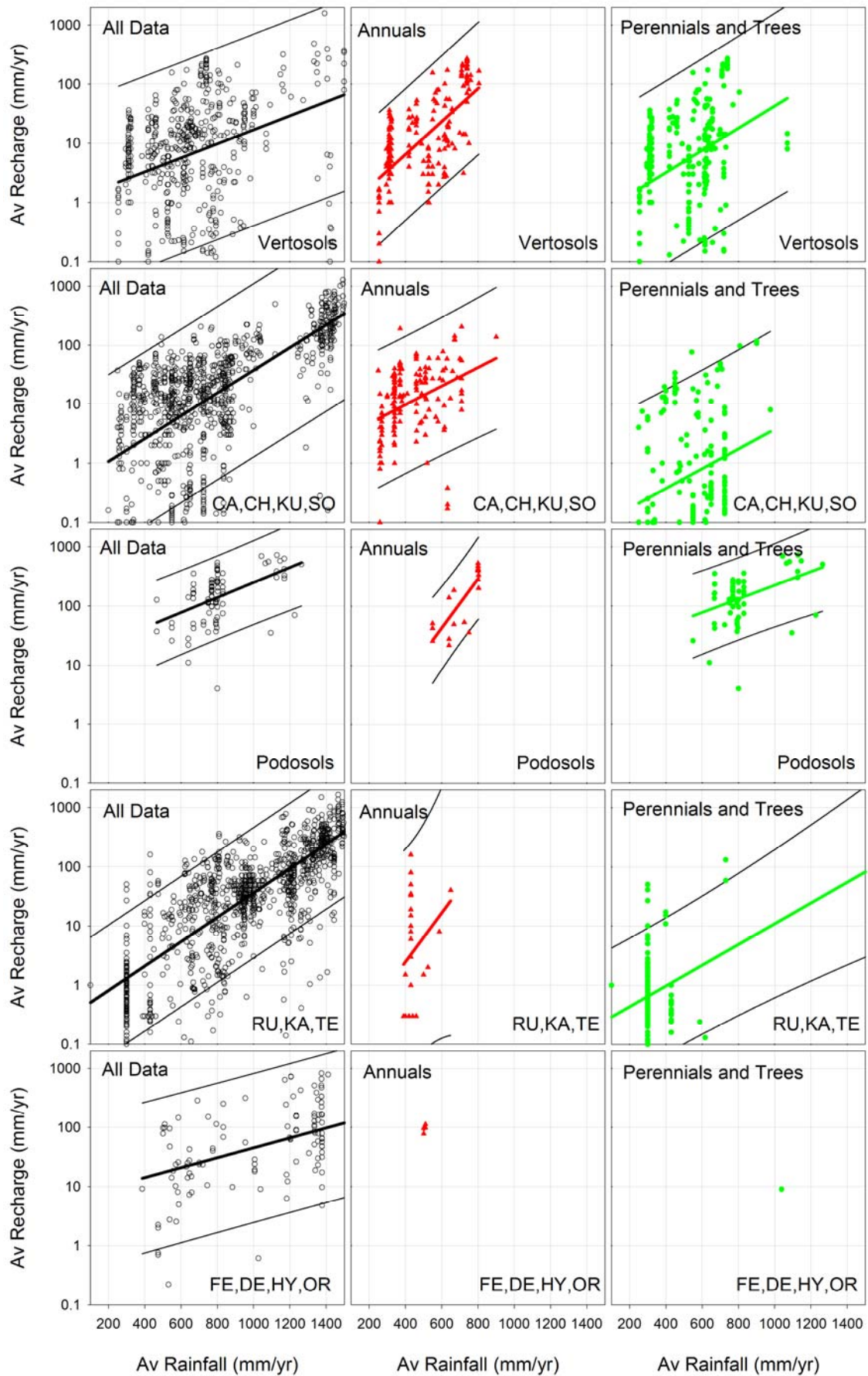


Figure 6. Relationships developed for estimating recharge using the MOLR based upon soil order, vegetation type and rainfall.

Table 3. Regression parameters used in the MOLR and the rainfall ranges that they apply to (from Figure 6). (A is annual vegetation; P & T is perennial and trees vegetation type.)

	best		upper		lower		Rainfall (mm/yr)	
	a	b	a	b	a	b	min	max
VE - A	2.78E-03	-3.02E-01	2.79E-03	8.05E-01	2.77E-03	-1.41E+00	255	805
VE - P & T	2.83E-03	-1.51E+00	2.88E-03	-2.44E-01	2.79E-03	-2.77E+00	255	1070
CA,CH,KU,SO - A	1.58E-03	3.57E-01	1.63E-03	1.50E+00	1.52E-03	-7.85E-01	250	901
CA,CH,KU,SO - P & T	1.67E-03	-1.09E+00	1.69E-03	5.69E-01	1.64E-03	-2.75E+00	250	976
PO - A	4.10E-03	-8.05E-01	3.94E-03	5.27E-03	4.25E-03	-1.62E+00	550	803
PO - P & T	1.32E-03	1.08E+00	1.37E-03	1.71E+00	1.28E-03	4.43E-01	550	1265
RU,KA,TE - A	4.14E-03	-1.26E+00	5.54E-03	1.37E-03	2.73E-03	-2.53E+00	390	650
RU,KA,TE - P & T	1.75E-03	-7.10E-01	1.97E-03	3.53E-01	1.53E-03	-1.77E+00	100	1585

2.3.4. The groundwater chloride mass balance (GCMB) approach

The GCMB method is the most widely used method for estimating recharge in Australia because it is very simple conceptually and the analytical costs are comparatively cheap. 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 groundwater recharge because chloride can continue to be concentrated in the saturated zone if vegetation is exploiting this source of water. However, as described above, the GCMB method can only be used when the groundwater at the depth of the screen is at steady-state. Hence, if there has been vegetation clearing at the site, no estimate of recharge (or deep drainage) is possible until the hydrological water balance has reached a new steady state at the depth of the point where the groundwater sample has been sampled.

The only unknowns when using the GCMB method are an estimate of the chloride deposition rate at the ground surface and the chloride concentration of the groundwater as shown in Equation 2.

Equation 2 $R = D / C_{gw}$

where R is recharge (rate or equivalent depth units?), D is chloride deposition rate and C_{gw} is the concentration of chloride in the groundwater.

The assumptions inherent in the method are that:

1. The chloride in the groundwater originates from precipitation (not rock weathering or halite dissolution).
2. The chloride imported or exported via runoff or runon can be accounted for.
3. The 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 regions of Australia such as the Mallee, Gngara 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 previously been applied in the Mount Lofty Ranges, South Australia 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. Therefore it can be assumed to be a conservative tracer in most cases.

The concentration of chloride in groundwater is estimated over the residence time of the water in storage, therefore the estimate of groundwater recharge made from it is an estimate averaged over the residence time of the groundwater. In Australian aquifers, this can be many thousands of years. For an accurate estimate of groundwater 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 one to two 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.

2.3.5. The percent clay method

Kennett-Smith *et al.* (1994) presented data that suggested that a log-linear relationship exists between deep drainage under cropped land and the percent clay content of surface soils. Their study used estimates of deep drainage derived from the chloride peak displacement method using soil cores sampled from the unsaturated zone in the Murray Mallee. The rainfall at the study sites ranged from 250 to 400 mm y⁻¹. SKM (2002) used what was predominantly the same dataset to determine the best correlation between deep drainage estimates and mean %Clay content when the clay content was averaged over a depth interval of 0-2 m (rather than 0-1 m or 0-3 m). The initial motivation for this work was to estimate the increase in deep drainage rates that results when land use is changed from deep-rooting mallee-type vegetation to shallow-rooting crops and pasture. The authors found that deep drainage in mallee areas could increase by two or more orders of magnitude from <0.1 mm y⁻¹ under mallee vegetation to >10 mm y⁻¹ under pasture. Subsequent studies (Leaney *et al.* 2003) identified that a lag time exists between when land use change occurred and when it impacted as increased groundwater recharge at the watertable. This lag time could be as short as a few years but could extend beyond a century in areas with very heavy (or 'clayey'? or 'high clay content'?) soils.

Since the publication of Kennett-Smith *et al.* (1994), numerous similar unsaturated zone studies have been undertaken at sites throughout South Australia and Victoria (e.g. Leaney *et al.* 1999; Leaney and Herczeg 1999; Leaney 2000; Leaney 2001; Leaney *et al.* 2004; Wohling *et al.* 2006; Wohling 2007). In many of these studies, relationships were developed between the average percentage clay content of the top 2 m of soil and deep drainage (as estimated by the chloride peak displacement method). These studies extended the mean annual rainfall range beyond 250-400 mm y⁻¹ but each study only used data from the area being studied. In addition, it was always assumed that the best deep drainage vs mean %Clay content correlation was for clay content averaged over the 0-2 m interval.

Most recently, Wohling *et al.* (2011) interrogated a significantly larger deep drainage database (202 sites from 11 studies throughout Australia) and identified a trivariate correlation between deep drainage, rainfall and % clay content for sites with pasture/cropping and those that were covered with native tree vegetation. The database covered a significantly larger area than the original Kennett-Smith *et al.* (1994) and SKM (2002) studies and included data from a much greater rainfall range.

The regression equations from Wohling *et al.* (2011) are shown below (Equation 3).

Equation 3 $\log d = y_0 + (b \times \text{clay}) + (a \times \text{rainfall})$

where y_0 , b and a are fitting parameters (but do they also relate to intercept, rainfall and clay, as presented in Table 4 below?). Another improvement over previous work by Wohling *et al.* (2011) was the assessment of the uncertainty in the relationships; this was achieved by assigning 95% prediction intervals to the estimates of deep drainage. These relationships have been used in the Excel approach and are summarised in Figure 7 and Table 4.

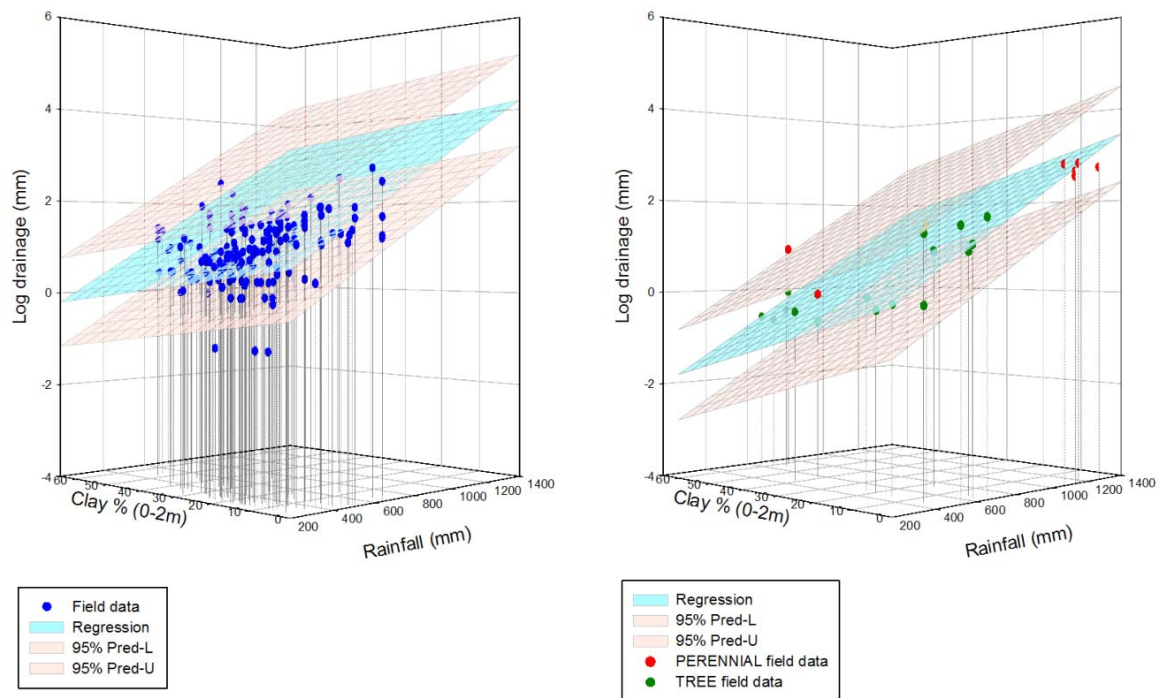


Figure 7. Plot of regression equation developed for annual vegetation (LHS) and combined perennial and tree vegetation type (RHS) also showing 95% prediction intervals. (From Wohling *et al.*, 2011).

Table 4. Best fit multiple linear regression results with 95% prediction limits for deep drainage under annuals and trees/perennial vegetation types.

	Annuals			Perennials & Trees		
	Best	Upper	Lower	Best	Upper	Lower
Coefficient – Intercept (y_0)	-0.039	0.915	-0.993	-0.723	0.225	-1.671
Coefficient - b (clay)	-1.19E-02	-1.19E-02	-1.19E-02	-2.74E-02	-2.72E-02	-2.76E-02
Coefficient - a (rainfall)	3.03E-03	3.06E-03	2.99E-03	2.99E-03	3.08E-03	2.92E-03

2.3.6. The watertable fluctuation method

During the recharge review (Crosbie *et al.*, 2010A), the watertable fluctuation method was considered as a potential method to be incorporated as part of the recharge estimation suite. The method, however, did not lend itself to presentation in spreadsheet form; furthermore, it required temporal monitoring of the watertable depth over an extended period, which would not be consistent with a data poor area. As a result, it is only summarised briefly in this report.

The watertable fluctuation method relies on rises in the groundwater level being related to recharge events (Equation 4).

Equation 4 $R = S_y \times \Delta h / \Delta t$

where S_y is the specific yield of the aquifer, and Δh is the change in water level over a period of time Δt . A thorough review of the watertable fluctuation method was given by Healy and Cook (2002). They identified the following limitations to the method:

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 groundwater recharge where recharge is almost constant. If both the groundwater recharge and drainage away from the watertable are almost constant then Δh will be equal to zero and, as per the above equation, 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.

Because of the site specific nature and complexity of the method, it is not possible to implement it generically in the Excel spreadsheet.

2.4. Discharge estimation

In contrast to the extensive datasets on groundwater recharge, there has only been a handful of studies that have characterised groundwater discharge in Australia and detailed studies are concentrated in only a few locations. For example, groundwater uptake by *Eucalyptus camaldulensis* (red gum) and *E. largiflorens* (black box) trees on the Chowilla floodplain and by *E. globulus* (blue gum) trees in south-eastern South Australia has been extensively studied. As a result, the processes governing groundwater discharge remain poorly resolved and the lack of observations makes the development of empirical generalisations relating to groundwater discharge difficult. The total number of discharge estimates captured in Phase 1 of this project is significantly less than recharge estimates by approximately two orders of magnitude (4 400 vs 45). Despite this, the Phase 1 discharge review identified widespread groundwater discharge in both native and managed forests, highlighting not only the lack of detailed knowledge related to the spatial and temporal patterns of groundwater discharge but also need to develop a consistent and robust framework for estimating this component of the groundwater balance. A simple tool for estimating groundwater discharge in data poor areas has been developed. Given that the tool is designed to be implemented in data poor areas, we have aimed to keep data inputs to a minimum. As with the recharge estimation tool, the discharge toolbox is an Excel spreadsheet, that depending on data availability, will provide up to three estimates of groundwater discharge based on three approaches (Figure 8);

- Groundwater Risk Model;
- Ecological Optimality, and;
- A groundwater discharge groundwater salinity function.

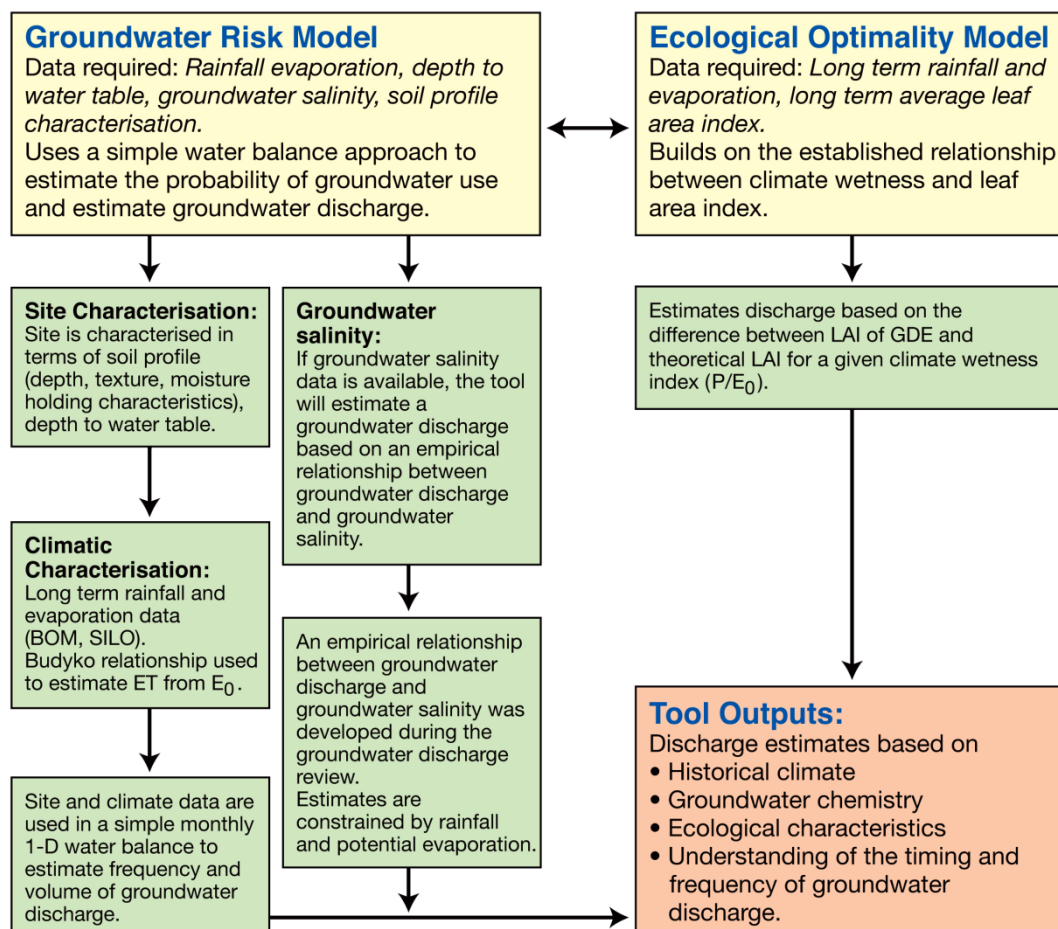


Figure 8. Flow chart describing the layout of the groundwater discharge estimation in data poor areas toolbox.

2.4.1. Groundwater risk model

The groundwater risk model (*WBRisk*) was initially developed as part of an assessment of the extent and degree of ecosystem groundwater dependency in the Pioneer Valley in North Queensland (Howe *et al.*, 2006). This simple water balance modelling approach has been further developed to estimate not only the likelihood of groundwater discharge but provide an estimate of groundwater discharge based on long-term climatic conditions and an understanding of the soil profile, and thus soil water storage. The model provides point scale estimates of groundwater discharge and as per the recharge estimation tool described previously, the user is encouraged to divide the area of interest into sub-areas that have similar parameters pertaining to recharge and discharge. This ensures the true variability is captured. National, regional and local datasets, used in conjunction with local hydrological knowledge can be used to assist in the division of these sub-areas, as discussed in Chapter 2.2.

The water balance of a system is described in Equation 5:

Equation 5 $P = ET + R + D_d + \Delta S$

where P is precipitation, ET is evapotranspiration (and is the sum of transpiration, evaporation from soil and litter and interception losses, i.e. rainfall that wets plant surfaces and is evaporated directly back to the atmosphere), R is runoff, D_d is deep drainage and ΔS is the change in soil water content between two measurement times (all units are usually expressed as depth equivalents, mm). The groundwater risk model developed in this phase of the project uses this simple water balance approach in conjunction with historical rainfall and evaporation data to estimate the probability of the soil reservoir being sufficient to supply evapotranspiration requirements. Thus, although the toolbox models the capacity of the soil profile to supply water for evapotranspiration, it does not explicitly model water uptake by vegetation. The soil profile consists of five layers and these are represented diagrammatically in Figure 4. The user is required to define the soil profile in terms of its textural characteristics of each layer down to the defined watertable depth. Textural classes used in the model are adapted from the Australian Soil and Land Survey Field Handbook (McDonald *et al.*, 1998) and moisture characteristics for the textural classes are taken from (Saxton and Rawls, 2006).

Thus the tool models changes in soil water availability. The magnitude of soil moisture storage is constrained according to Equation 6:

Equation 6 $0 \leq S \leq DTW \times PAWC$

where S is the soil water storage, DTW is the depth to the watertable and $PAWC$ is the plant available water capacity of the soil (mm/m).

The model runs on a monthly time step and groundwater discharge occurs whenever ET exceeds rainfall and the capacity of the soil profile to supply the difference between ET and rainfall, i.e., whenever depletion of the soil moisture store occurs. The preferred modelling approach is to use actual estimates of ET , however we recognise that these data are unlikely to be available in most data poor areas. In the absence of actual ET estimates, ET is instead estimated from evaporation using the Budyko framework (Budyko, 1974). Budyko's framework describes the effect of energy and water limitations on the partitioning of

precipitation into actual evapotranspiration and stream flow. In this context, water-limited environments are described as environments where the energy available for evaporation exceeds the availability of water for evaporation, i.e. $P/E_0 < 1$, where P is precipitation and E_0 is the reference evaporation rate. In contrast, in energy limited environments, the converse is true, i.e. water availability exceeds the energy available for evaporation, $P/E_0 > 1$. Thus, in water limited environments, actual ET approaches P and in energy limited environments ET approaches E_0 .

Because transpiration is often the largest component of ET , this framework implicitly incorporates the effects of biological processes and provides a powerful framework for analysing ecohydrological processes within different environments (Donohue *et al.*, 2007). As the main inputs to this framework are rainfall and evaporation (both of which can be readily obtained from national databases such as SILO) this framework is used to estimate actual evapotranspiration from the relation between the ratio of E_a/E_0 and P/E_0 . The relationship that describes this partitioning is known as the “Budyko curve”. While there are a number of formulations for this curve, Yang *et al.* (2008) have justified the use of the Choudhury (1999) version of the Budyko equation which assumes steady state conditions and formulates a long-term E_a as a function of P and E_0 . More specifically in the spreadsheet we use the Choudhury-Yang formulation of this equation (Equation 7; cited in Roderick and Farquhar (2009)):

Equation 7
$$E = \frac{PE_0}{(P^n + E_0^n)^{1/n}}$$

where E is actual evapotranspiration, P is precipitation, E_0 is potential evaporation and n is a fitting parameter that determines the shape of the curve. Determining n *a priori* is difficult (and is currently attracting a concerted research effort), however a useful rule of thumb is that for Climate Wetness Index ($CWI = P/E_0$) > 0.3 , n approximates $1/CWI$ and for $CWI < 0.3$, n is approximately 1.8 (Randall Donohue, CSIRO Land and Water, pers. comm. 2011).

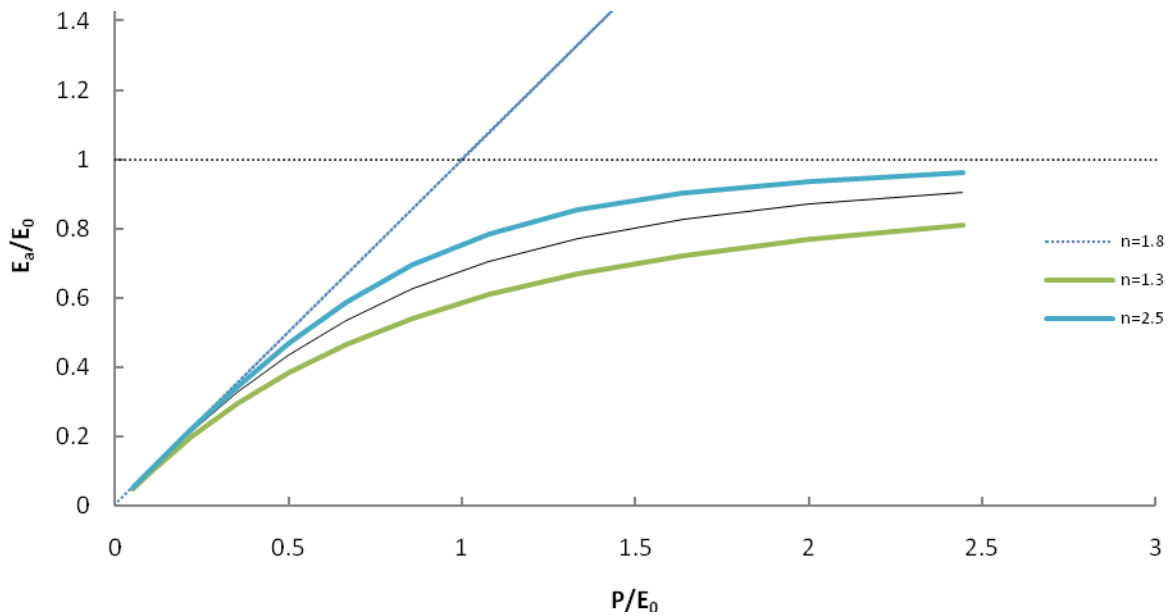


Figure 9. Partitioning of E_a and E_0 as a function of climate wetness index (P/E_0) as per the Choudhury-Yang formulation of the Budyko framework (for $n=1.8$, $n=1.3$, $n=2.5$).

The model is run using rainfall and estimated ET as inputs and a simple water balance is calculated to determine changes in the soil water availability. The model accommodates 100 years of monthly climate data and makes the following assumptions:

- Soil moisture stores are at saturation at the beginning of the simulation.
- Soil water will be used in preference to groundwater, and that low $PAWC$ will trigger groundwater use during dry periods.
- Maximum rooting depths are unconstrained, i.e. roots are able to exploit the soil profile to the watertable depth.
- Watertables do not fluctuate.
- Steady state ratios of E_a/E_o are used to partition E_o on a monthly timestep (this may violate steady state assumptions of the Budyko framework, however discharge is estimated over a 100 year data record).
- If pan evaporation is used as the reference evaporation then $E_o = 0.75$ times the pan evaporation rate (Roderick and Farquhar, 2009).

2.4.2. Estimating groundwater discharge using ecological optimality

The concept of ecological optimality was first introduced by Eagleson (1978) to explain relationships between climate, soils and hydrology. The ecological optimality framework proposes that vegetation responds to interactions of site and climatic conditions to optimise productivity while at the same time minimising water stress. Eagleson's optimality approach predicts three outcomes (cited in Hatton *et al.* (1997)):

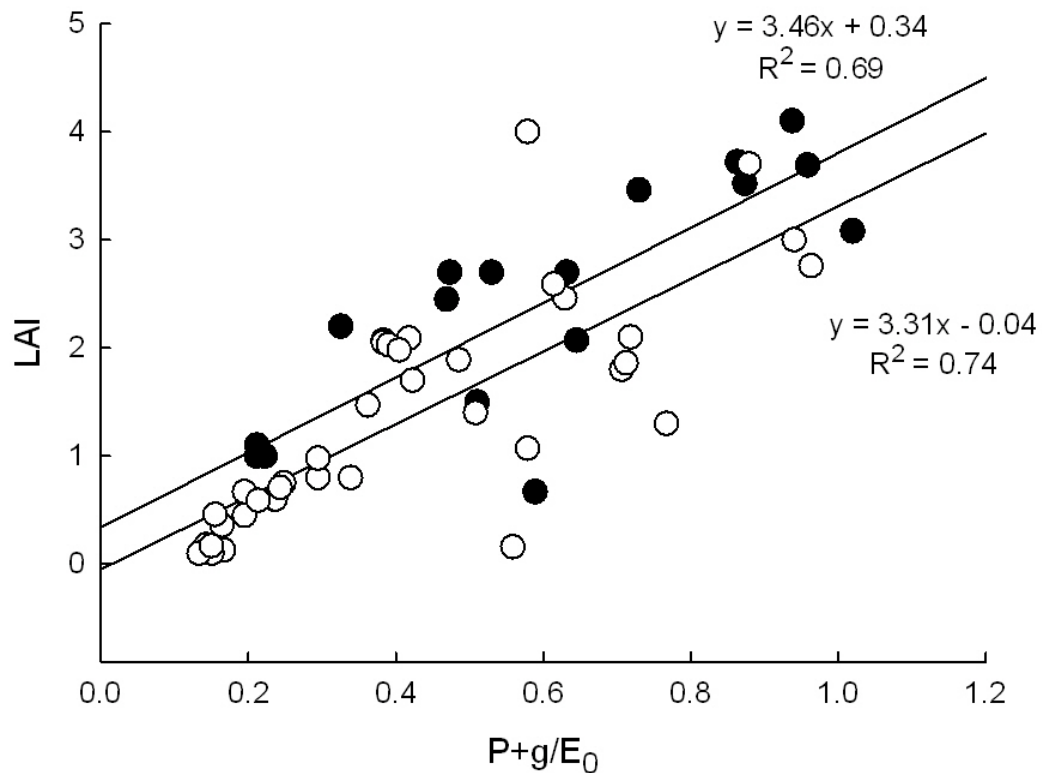
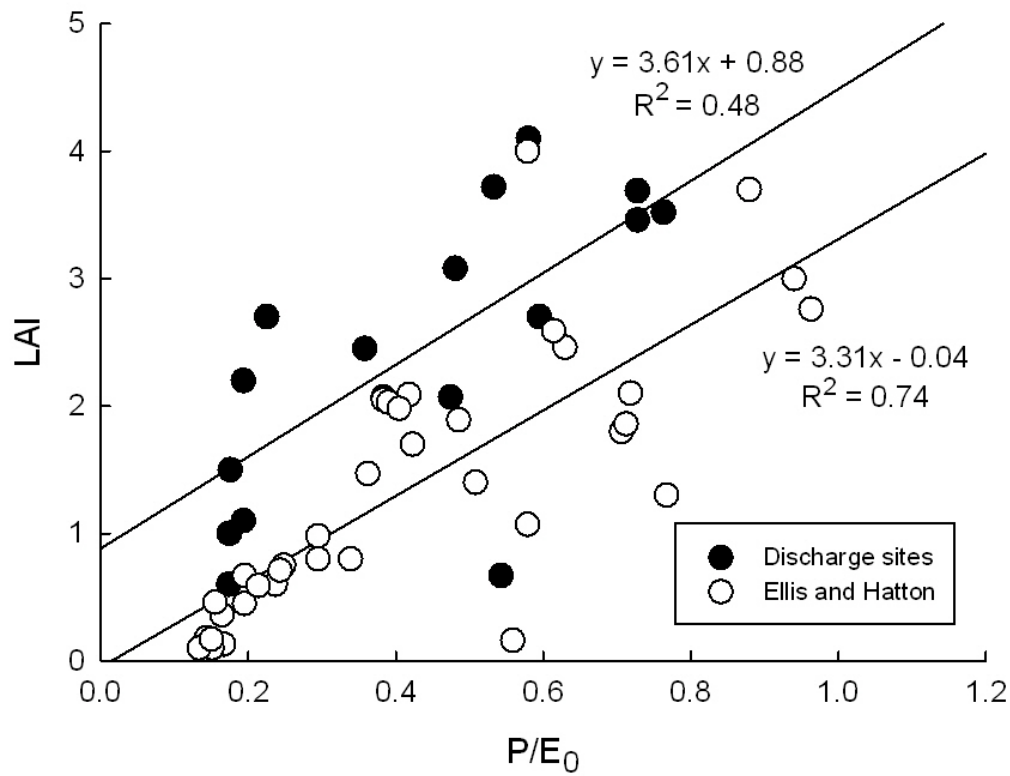
- Over short time scales (i.e. one to a few generations) the vegetation canopy density will equilibrate with the climate and soil to the value at which equilibrium soil moisture will be maximised (minimising water stress),
- Over longer time scales (i.e. many generations) species whose potential transpiration efficiency results in the maximum equilibrium soil moisture will be selected, and
- Over much longer time scales (i.e. evolutionary timeframes), vegetation will alter soil physical properties towards equilibrium values which maximise canopy density (and productivity).

Native vegetation is thought to be in equilibrium with the existing hydrological regime, although there is some evidence that this may not be the case for plantations (White *et al.*, 2010). That is, in water limited environments vegetation structure and function is constrained by the existing hydrological regime. Australia is predominantly a water-limited environment and vegetation responds to factors that alter the availability of water, for example rainfall. A common response to variation in water supply is adjustment of leaf area index (LAI; Grier and Running 1977; Carter and White 2009). LAI is commonly defined as the one-sided projected leaf area per unit ground area and is a fundamental variable in many physiological and hydrological models.

Recently, Ellis and Hatton (2008) reviewed leaf area index data from natural vegetation communities around Australia and found a strong relationship between community LAI and the simple climate wetness index (CWI, i.e. P/E_o). In the groundwater discharge review for this study (O'Grady *et al.*, 2010) the relationship between LAI and groundwater discharge was examined. It was hypothesised that sites with access to groundwater within a given climatic envelope should have a higher LAI than sites with a similar climatic envelope without access to groundwater. The review confirmed this hypothesis, finding that sites with access to groundwater tended to have a higher LAI for a given CWI than sites without access to groundwater (Figures 10). This finding provides a simple basis for estimating groundwater discharge using three parameters: LAI in the area of interest, average annual rainfall and average annual evaporation; the latter two datasets being available through the Bureau of Meteorology. Thus for a given CWI, LAI is calculated as (Equation 8; Ellis and Hatton, 2008):

Equation 8 $LAI = 3.31 \times CWI - 0.04$

In the toolbox, the Ellis and Hatton (2008) relationship is used to predict equilibrium LAI based on the historical rainfall and evaporation record. If available, this value can then be compared to the LAI data used as an input into the model,. The toolbox then calculates the CWI that would be associated with this groundwater dependent LAI using equation 8. The groundwater discharge component can then be estimated by comparison of the two CWI's for a common evaporation regime, and a value of discharge estimated as the difference in rainfall. While this “ecological optimality approach” appears promising, we acknowledge that data for groundwater discharge studies are sparse and thus this framework may require more rigorous testing.



Figures 10(a) relationship between Climate Wetness Index and LAI for ecosystems with access to groundwater in comparison to ecosystems without access to groundwater (as observed by Ellis and Hatton, 2008) and 10(b) relationship between Climate Wetness Index with groundwater discharge included ($(P+g)/E_0$) and LAI in relation to studies reviewed by Ellis and Hatton (2008).

2.4.3. Groundwater discharge salinity function

Salinity significantly impacts on the availability of water within the environment via its impacts on osmotic potential. Thorburn (1996) observed a correlation between decreasing water uptake in vegetation with access to groundwater and increasing groundwater salinity. This is not surprising; salinity reduces the ability of plants to take up water (Munns 2002) to such an extent that the impacts of salinity on growth and productivity are similar to those in plants experiencing water stress. Discharge of saline groundwater has been shown to result in reduced leaf water potentials (Mensforth *et al.* 1994; Holland *et al.* 2008), reduced water use (Sun and Dickinson 1995; Akeroyd *et al.* 1998; Raper 1998) and reduced growth and leaf area (Bacon *et al.* 1993; Munns 2002). In the discharge review for this study a negative, albeit weak, relationship was observed between groundwater discharge and groundwater salinity. At sites where water quality was high and watertables shallow, up to 100% of ET was sourced from groundwater; however, at sites where groundwater salinity was high, groundwater contributed only a fraction of the water required for ET.

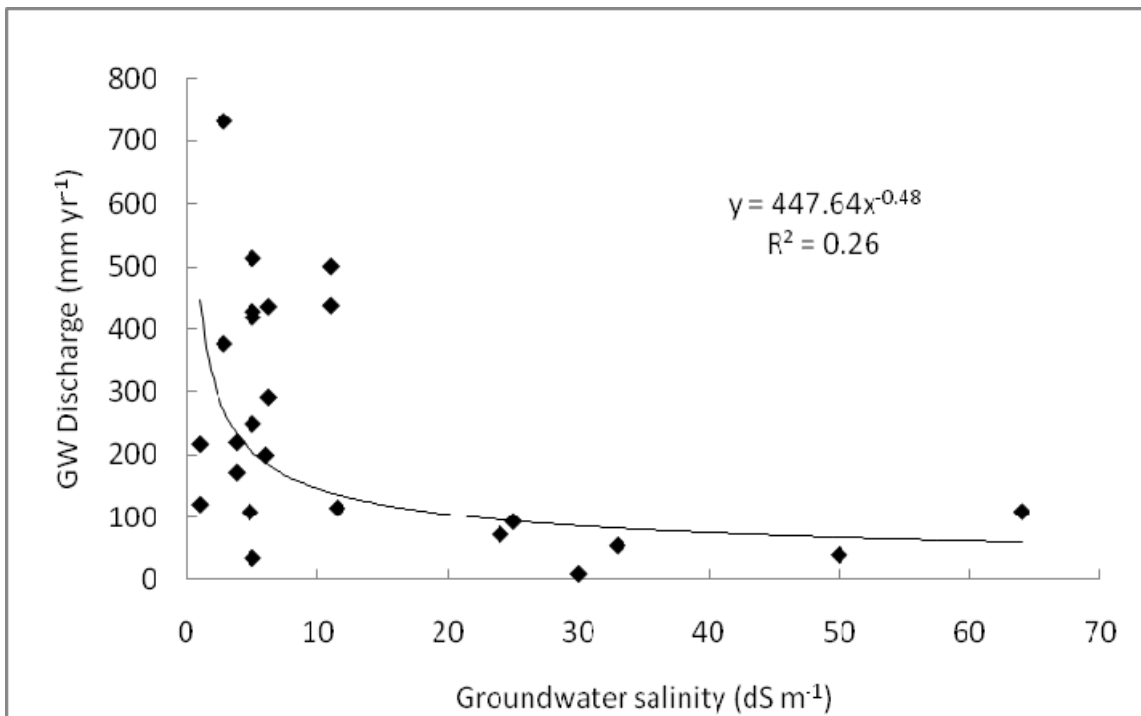


Figure 11. Groundwater discharge as a function of groundwater salinity from O’Grady *et al.* 2010.

In the toolbox, an estimate of groundwater discharge based upon groundwater salinity can be obtained using this equation:

Equation 9 groundwater discharge rate = $447.64 * \text{groundwater salinity}^{-0.48}$

where the rate of groundwater discharge is provided in units of mm/yr and groundwater salinity is approximated via electrical conductivity in units of dS/m.

Discharge estimates are constrained by evaporation and rainfall to prevent unrealistically high estimates of discharge that might result from extrapolation of this function. However, it is important to note that, at low groundwater salinities, there is considerable variability in the estimates of groundwater discharge, and this approach should only be used cautiously.

2.5. Input datasets

2.5.1. Vegetation type

There have been numerous studies illustrating the relationships between vegetation and groundwater (Dodd and Bell, 1993; Benyon *et al.*, 2006; Grieve, 1956; Lamontagne *et al.*, 2005; Tolmie *et al.*, 2003). Vegetation plays an active role in the hydrogeological dynamics of groundwater systems. This may include the ability of specific vegetation to exploit groundwater at depth, specific rates of transpiration and release of vaporised water back into the atmosphere, or the extent of foliage cover and interception of rainwater. Consequently land cover type should be considered by water managers when attempting to estimate levels of recharge and/or discharge.

Vegetation types can be divided into three broad classifications: (1) annuals; (2) perennials; and (3) trees. These classifications were originally used by Petheram *et al.* (2000, 2002) as a way of simplifying the wide variety of vegetation types. This classification method has been recognised and used by other authors in recent works (Crosbie *et al.*, 2008, 2010A, 2010B).

Annual plants lack a deep penetrating root system, and thus are unable to gain access to deep groundwater resources. Most annual crops are shallow rooted with rooting depths <2.7 m below surface (Canadell *et al.*, 1996). Annuals crops are especially reliant on irrigation or higher rates of rainfall to survive. Consequently, in this study the classification of plants into the annual category has generally been restricted to agriculture and heavily managed lands. Bare and/or cleared land has also been added to the annual vegetation category. This can be justified by the assumption that recharge is even greater for bare ground than annual crops. It is also assumed that negligible water will be lost through ground surface evaporation due to lower radiation levels and cooler air temperatures (Finch, 1998) during winter groundwater recharge.

In Australia there are few endemic vegetation associations that are dominated by plants that can be classified as “annuals” (there are numerous native understorey plants that are annual, e.g. native lilies, everlasting daisies, etc.). This is mainly due to the climate of the continent; much of Australia is dominated by semi-arid to arid conditions with smaller temperate zones in coastal regions, alpine areas, and southern latitudes (i.e. Tasmania). This has led to the evolution of dominant vegetation types that are capable of withstanding hot and dry conditions by developing deep root systems that tap into groundwater sources (O'Grady *et al.*, 2010). There are very little available recharge data for perennials in Australia and so the MOLR method considers them as one vegetation class. Although a distinction can be made between perennials and trees based on the location of the plants, their size and to some extent their genus or species, for the purposes of this study both classes were grouped together.

The MODerate Resolution Imaging Spectrometer (MODIS) was selected as the most suitable dataset for providing a national vegetation classification. MODIS is an instrument on the Terra (EOS AM) and Aqua (EOS PM) satellites. Terra was launched in December 1999, while Aqua was launched in May 2002; consequently MODIS has been in use since 2000 and continues to function today. MODIS consists of 36 visible bands from the near infrared to the far infrared, covering an electromagnetic spectrum of 0.4-14.4 μm . Of these 36, seven are used for the study of vegetation and land cover (Zhao *et al.*, 2009), with a swath width of 2330 km. MODIS is capable of covering the entire Earth's surface every one to two days.

A MODIS Land Cover map (Lymburner *et al.*, 2011) was used as the input dataset for identifying vegetation type. This dataset mapped land cover classes nationally based on 12 time series coefficients that represent the statistical, phenological and seasonal characteristics of the vegetation dynamics. The time series was generated from over two-hundred cloud-free images of vegetation greenness for every 250 m² area across the Australian continent. Images were taken every 16 days.

The advantages of this dataset over others are that it provides cloud-free, consistent national scale coverage, has a high resolution of 250 m, and will be revised in subsequent versions (based on the most recent data available).

A Vegetation Type dataset was consequently developed with two classes: annuals and perennials/trees.

2.5.2. Vegetation clearing

Whether or not there has been land use change, and if so, when it occurred, can impact upon recharge and deep drainage in two ways. Firstly, land use change, and more specifically, the clearing of native vegetation, leads to changes in deep drainage rates. Eventually, after a lag time, this impacts reaches the watertable as groundwater recharge (as described in Chapter 2.3.2). Secondly, whether or not land use change has taken place is important when determining whether the Groundwater Chloride Mass Balance method can be employed. If clearing has occurred then the Chloride Mass Balance method needs to take into account the period of time required for the system to return to (hydrologic?) equilibrium.

For the purposes of this study, 'clearing' relates specifically to land that has been converted to either annual cropping or to bare ground.. It can be assumed that all vegetation identified as 'annuals' in the Vegetation Type data (Chapter 2.5.1) has experienced land clearing. However this particular dataset has a spatial resolution of 250 m and thus generalisation within pixels occurs and areas of land clearing have been missed. To incorporate the higher resolution land cover data generated by the states/territories the MODIS-derived dataset was combined with the Integrated Vegetation Cover (IVC) dataset. The IVC dataset was produced by Australian Bureau of Agricultural and Resource Economics and Science and provides information on the distribution of major vegetation cover types in Australia. The 2009 IVC dataset was selected as it combined a number of datasets including:

- 2007 National Forest Inventory dataset produced by Bureau of Rural Sciences (BRS),
- National Vegetation Integrated Systems (3.1) produced Environmental Resources Information Network,
- Catchment-scale land-use change datasets produced by BRS, and
- 2008 IVC (where gaps still existed in the 2009 coverage).

Inaccuracies occur in both datasets; therefore by combining both, matches and discrepancies between the two can be observed. Where both datasets agree, either a 'yes' or 'no' response (relating to the occurrence of clearing) is assigned. Where the datasets disagree or there is ambiguity the user is encouraged to further investigate these sites and verify the land clearing history. Additionally, if higher resolution land clearing information is available to the user, they are encouraged to refer to that, in place of the national scale data discussed here.

If no land clearing has occurred then deep drainage is assumed to equal groundwater recharge and no lag time calculations are required.

2.5.3. Regolith and geology

Regolith is a general term for the layer of fragmental and earth material, residual or transported, that overlies bedrock. Soils therefore describe the upper part of the regolith profile; typically the top 2 m (or less where bedrock is within 2 m of the surface). It includes saprolite (weathered rock in place), alluvium and aeolian deposits. These weathered materials typically have markedly different hydrological characteristics from the bedrock from which they were derived. In many cases an increase in porosity and decrease in permeability may be observed as the bedrock weathers to clay and other secondary components. For the purposes of this study, we have split the weathered component into soils and regolith. Regolith in this context is the unconsolidated, weathered, and sometimes indurated bedrock materials that occur beneath the soil layer. The regolith component of the model can be tens

of metres thick and is used to estimate water holding capacity and lag times associated with recharge and discharge processes. Bedrock composition, fabric and structure also influence water storage and infiltration. In fractured bedrock terrain the user needs to be aware of the potentially huge differences in hydraulic conductivity associated with local-scale preferential flow features; for example, faults, fractures and various bedding/foliation patterns.

Lithological information is provided by the 1:1m national surface geology map of Australia. The Surface Geology of Australia (2010 edition) is a seamless national coverage of outcrop and surficial geology. The data maps outcropping bedrock geology and unconsolidated or poorly consolidated regolith material covering bedrock. The dataset has been compiled by merging the seven State and Territory 1:1 000 000 scale surface geology datasets released by Geoscience Australia between 2006 and 2008, by correcting errors and omissions identified in those datasets, by addition of some offshore island territories, and by updating stratigraphic attribute information to the best available in 2010 from the Australian Stratigraphic Units Database (<http://www.ga.gov.au/oracle/stratnames/index.jsp>). The map data were compiled largely from simplifying and edge-matching existing 1:250 000 scale geological maps. Where these maps were not current, more recent source maps, ranging in scale from 1:50 000 to 1:1 000 000 were used. In some areas, where the only available geological maps were quite old and poorly located, some repositioning of mapping using recent satellite imagery or geophysics was employed. These data are freely available from Geoscience Australia under the Creative Commons Attribution 2.5 Australia Licence (http://www.ga.gov.au/minerals/research/national/nat_maps/nat_geol_maps.jsp).

Table 5. Classified geology schema for recharge and discharge estimation. Classes broadly ordered in decreasing silica content and grainsize.

Bedrock type	code
Quartzite, chert, ironstone, quartz veins (sand)	1
Sandstone, minor shale and conglomerate (sandy loam)	2
Coarse grained intrusive rocks (loam)	3
High grade metamorphic rocks (loam – clay loam)	4
Fine grained volcanics (silty loam)	5
Schist and minor phyllite (loam – silty clay loam)	6
Shale, mudstone, siltstone; minor sandstone and conglomerate (clay – silty clay loam)	7
Coarse grained mafic rocks (clay loam – clay)	8
Basalt (clay)	9
Meta-carbonate rocks (clay – silty clay)	10
Sedimentary carbonate rocks (clay loam – silty clay)	11
Unconsolidated materials	
Indurated materials (sand)	12
Aeolian sands (sand)	13
Aeolian sands and clay (sand – sandy loam)	14
Sands; minor clay and silt (sand – loamy sand/silt)	15

Sand, silt and clay; minor gravel (loam)	16
Clays; minor sand and silt (clay – silty clay loam)	17
Anthropogenic (loam)	18

For application in assessing groundwater recharge and discharge the geology has been classified based on broad textural classes. For example, aeolian sands are separated from alluvial and colluvial sediments because the two latter types typically have a high proportion of silt and clay. In the case of bedrock materials, categories have been defined based upon the silica content and grain size of the parent material. Silica content and grain size are important factors in determining the hydrological character of the bedrock, particularly as it weathers. For example, highly siliceous rocks such sandstone weather largely to sand whereas fine-textured mafics (low silica) like basalt will largely weather to clay. The geology classification schema is shown previously in Table 5. The textural classes used are from the Australian Soil and Land Survey Field Handbook (McDonald *et al.*, 1998) which are shown in Figure 12.

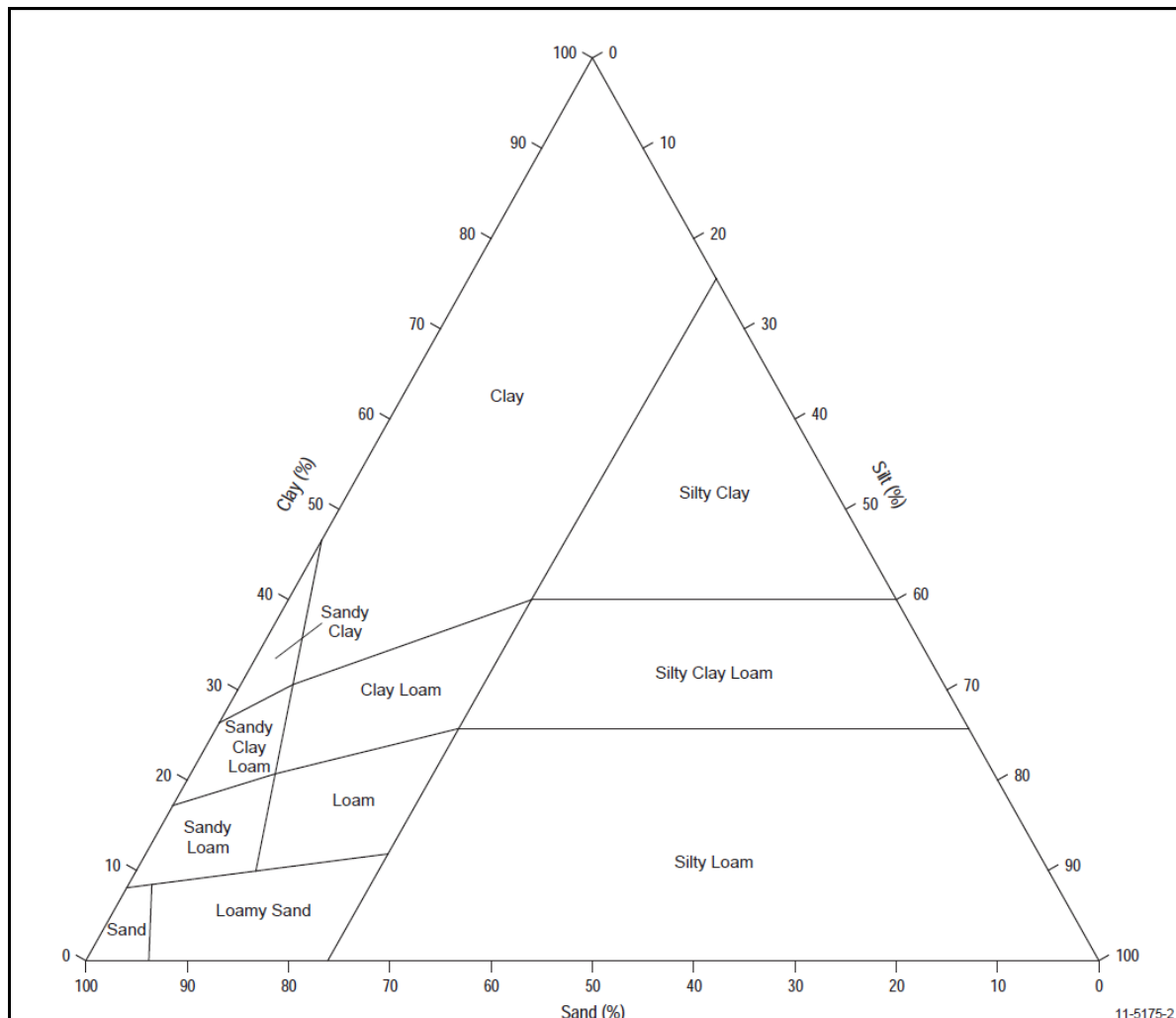


Figure 12. Triangular texture diagram based on international fractions (adapted from Figure 16 of McDonald *et al.*, 1998).

Not all geological polygons are 'pure' in terms of their lithological type and as such the classification should be used as a guide only. Where two or more lithologies occur in the one polygon the most common lithology is used to define the class. Each of the lithological classes has a corresponding weathering over print option. The user can choose one of three

weathering intensity options, including slightly, moderately and highly weathered. In addition to the bedrock types, indurated regolith materials including silcrete and iron (Fe) duricrust, can also be selected.

2.5.4. Soils

Soils can affect the amount of leakage by controlling the balance between water holding capacity and soil drainage. Sandy or rocky soils store little water, thus associated deep drainage or discharge is typically greater than in heavier clay or loam soils. Additionally, the amount of deep drainage depends on the drainage characteristics of the soils and sub-soils; for example, some sub-surface clay may be less permeable and thereby prevent water from draining into the groundwater system. Under these circumstances, water may move laterally instead of draining vertically into groundwater systems (Walker *et al.*, 2007).

Specification of soil order classification is required by the MOLR recharge method. Thirteen soil orders are recognised over the Australian continent (excluding anthroposols, i.e. soils formed by humans). The Atlas of Australian Soils (Northcote *et al.*, 1960-68) was compiled by CSIRO in the 1960's and describes soil information at 1:2 million scale – although many of the original compilations were at scales from 1:250 000 to 1:500 000. To download the digital Atlas of Australian Soils go to <http://www.asris.csiro.au/themes/Atlas.html>. The soil order classes used in estimations of recharge and discharge are described below (descriptions in part based on McKenzie *et al.*, 2004):

Organosols – are identified by more than 0.4 m of organic materials within the upper 0.8 m. The required thickness may either extend down from the surface or be taken cumulatively within the upper 0.8 m, or have organic materials extending from the surface to a minimum depth of 0.1 m. These either directly overlie rock or other hard layers, partially weathered or decomposed rock or saprolite, or overlie fragmental material such as gravel, cobbles or stones in which the interstices are filled or partially filled with organic material. These soils are largely restricted to the west coast of Tasmania.

Podosols – are identified by B horizons dominated by organic matter and aluminium with or without iron. These are sandy textured and therefore typically highly permeable unless indurated hard pans are present. Most soils are highly siliceous with small amounts of clay minerals present.

Vertosols – are identified by their shrink-swell nature and overall high clay content. They have a clay field texture of 35% or more throughout the solum. In places they may have a thin, surface crusty horizon 0.03 m or less thick. When dry these soils typically crack to a significant depth. This may result in preferential water pathways. B horizons are usually well structured with clay mineralogy often but not always dominated by smectite. These soils are also known as Black Earths and Grey, Brown and Red Clays. They often have Gilgai microrelief associated with them.

Hydrosols – are saturated with water in the major part of the solum for at least 2-3 months in most years (e.g includes tidal waters). These soils can vary greatly in terms of their morphological characteristics. Kaolinite and iron oxides (hematite and goethite) are common. Soils are common in coastal environments and along sluggish drainage lines.

Kurosols – are identified by a clear or abrupt textural B horizon and in which the major part of the upper 0.2 m of the B2 horizon (or the major part of the entire B2 horizon if it is less than 0.2 m thick) is strongly acid. The B horizon is typically mottled with massive to well developed columnar structures. They exhibit a range of permeability characteristics with clay mineralogy dominated by kaolinite and variable amounts of illite.

Sodosols – identified by a clear or abrupt textural B horizon and in which the major part of the upper 0.2 m of the B2 horizon (or the major part of the entire B2 horizon if it is less than 0.2 m thick) is sodic and is not strongly subplastic. Sodosols display a wide range of

morphologies. B horizons are typically clayey with restricted permeability caused by the dispersive nature of the sodic clay.

Chromosols – key feature is a clear or abrupt textural contrast between A and B horizons. B2 horizons range from massive to highly structured fabrics. Subsoil clays can include kaolinite, illite and smectite. Chromosols can grade into Sodosols and Kurosols depending on Exchangeable Sodium Percentage and pH.

Calcarosols – identified by the presence of pedogenic calcium carbonate. Soils are calcareous throughout the solum - or calcareous at least directly below the A1 or Ap horizon, or within a depth of 0.2 m (whichever is shallower). Carbonate accumulations must be judged to be pedogenic, i.e. are a result of soil forming processes in situ (either current or relict) in contrast to fragments of calcareous rock such as limestone or shell fragments. These soils do not have a clear or abrupt textural B horizon; texture typically increases gradually with depth. Calcarosols are commonly restricted to arid to semi arid regions with average annual rainfall between 200-350 mm.

Ferrosols – these soils are similar to Dermosols but have B2 horizons containing free iron oxides greater than 5%. The B horizons are characterised by very fine granular or blocky structural fabrics. The B horizons typically have well developed peds. Clay content is usually high (up to 70%) however most soils are very permeable.

Dermosols – key feature is the lack of a distinctive texture contrast between A and B horizons. The B2 horizons are usually clay rich and are moderately to strongly structured. These soils are generally well drained and can grade into a number of other soil orders including; Calcarosols, Chromosols, Kandosols, Vertosols and minor Ferrosols.

Kandosols – are identified by a lack of a clear or abrupt textural contrast B horizon. The B horizons are massive or weakly structured with clay content rising to around 35-50% at depth. Well-drained, permeable soils with clay mineralogy dominated by kaolinite (minor illite) and iron oxides. Soils are usually mottled with a bleached A2 horizon. Kandosols were previously known as Red, Yellow and Grey Earths.

Rudosols – are identified by a lack of pedological development. They have negligible (or rudimentary) pedological organisation apart from the minimal development of an A1 horizon or the presence of less than 10% of B horizon material (including pedogenic carbonate) in fissures in the parent rock or saprolite. The soils are apedal or only weakly structured in the A1 horizon and show no pedological colour change apart from darkening of an A1 horizon. There is little or no texture or colour change with depth unless stratified or buried soils are present. Cemented pans may be present as a substrate material. These soils can develop on alluvial sediments, siliceous sands and over bedrock (lithosols). Their textural characteristics therefore can vary according to the composition of the underlying parent materials.

Tenosols – are widespread and exhibit only weak pedological development with the exception of the A horizon. They can develop on a range of different parent material types. These soils are most common over the western part of the continent where they occur as red and, to a lesser extent, yellow soils on sandplains.

2.5.5. Rainfall

The effects of climate and rainfall on groundwater recharge can be simplified into two different types:

1. In wetter areas, normal rainfall can exceed potential evaporation for a period of the year, leading to deep drainage when the excess water cannot be stored in the soil.
2. In drier areas, deep drainage is likely to occur mainly as a result of exceptional circumstances, such as intense rainfall and flooding that may only occur once every 3-20 years (Walker *et al.*, 2007).

In determining deep drainage, the distribution of rainfall should generally be considered equally as important as the total amount of rain. However, this could not be shown to be the

case in a review of the recharge/deep drainage estimates made in Australia (Crosbie *et al.*, 2010A). Hence, the relationships developed in the groundwater recharge estimation suite for deep drainage do not consider temporal or seasonal variations in rainfall; instead, they simply refer to mean annual rainfall for the sub-area of interest. Long-term average annual rainfall (1900 to 2009) is (generally) available from the Bureau of Meteorology website. This dataset is required for the MOLR recharge method. Temporal (monthly) changes in rainfall are required in the modelling approach used for groundwater discharge estimation. This information can be obtained from a variety of sources; for example, the Bureau of Meteorology provides Australia-wide, monthly gridded data spanning 1900 to 2010 at a 5 km spatial resolution.

2.5.6. Evaporation

Terrestrial groundwater discharge can occur through capillary rise and direct evaporation (E) from the soil, via transpiration (T) through vegetation, or as discharge into rivers and streams. While this study does not consider the latter, evapotranspiration (ET) has been included. Transpiration is controlled by both physical and biological processes and is tightly coupled to the rate of photosynthesis, as stomata provide the pathway by which carbon dioxide enters plant leaves (Glenn *et al.*, 2007). In general, ET is the second largest term in the terrestrial water budget after precipitation; at sites with access to groundwater, ET can be larger than rainfall. Over 80% of terrestrial ET can be attributed to transpiration of water from plants.

Potential evaporation can be combined with mean annual rainfall and a climate wetness index in order to calculate actual ET. Long-term (1981-2006) average annual Penman potential evaporation (Donohue *et al.*, 2010) has been used in this study. For full details of the data refer to Donohue *et al.* (2009). Selection of the Penman method over similar potential evaporation methods (e.g. Priestley-Taylor, Morton, Thornthwaite) was based upon the study undertaken by Donohue *et al.* (2009). They found that, of the five potential evaporation datasets tested, only the Penman formulation displayed realistic values of potential evaporation rates and trends.

2.5.7. MOLR

The MOLR estimates the annual average recharge from the annual average rainfall for a given soil and vegetation type. A groundwater recharge surface has been generated using the MOLR and applied to vegetation, soil and rainfall data (discussed in Chapters 2.5.1, 2.5.4 and 2.5.5 respectively). This surface is shown in Figure 13 along with the 95% prediction intervals using the regression parameters in Table 3. These are accessible via MapConnect; directions to access these data are detailed in the companion user guide (Jolly *et al.*, 2011).

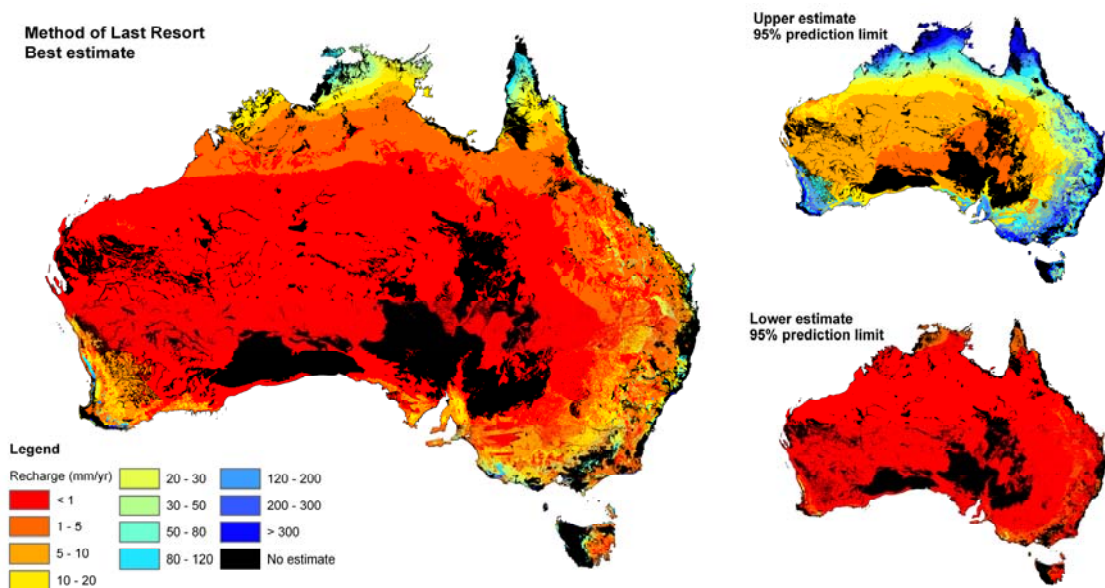


Figure 13. Maps of dryland diffuse recharge estimated using the MOLR (largest) and the upper and lower 95% percentiles of the MOLR estimates.

2.5.8. Chloride in rainfall

The high solubility and conservative behaviour of chloride makes it ideal for use as an environmental tracer of water and salt movement through the hydrologic cycle. These properties of chloride can be applied to the estimation of catchment scale, groundwater recharge rates using the Groundwater Chloride Mass Balance (GCMB) method. For more details on this method, refer to Chapter 2.3.4.

The GCMB method requires measurements of the chloride deposition rate at the ground surface and the chloride concentration of the groundwater. Measurements of chloride in groundwater can be obtained from suitable groundwater bores but measurements of chloride deposition are much less common and often estimates are used instead. For such estimation the spatial distribution of chloride deposition in rainfall (the average chloride concentration of rainfall multiplied by the average annual rainfall) at a suitable scale must be known.

A number of authors have used point data (acquired from field studies of chloride deposition around Australia) to construct relationships between chloride deposition and distance from the coast, thereby allowing an interpolation to any point in Australia. In this project this has been taken a step further with the development of a chloride deposition map for Australia which includes an upper and lower 95% percentile assessment (Figure 14).

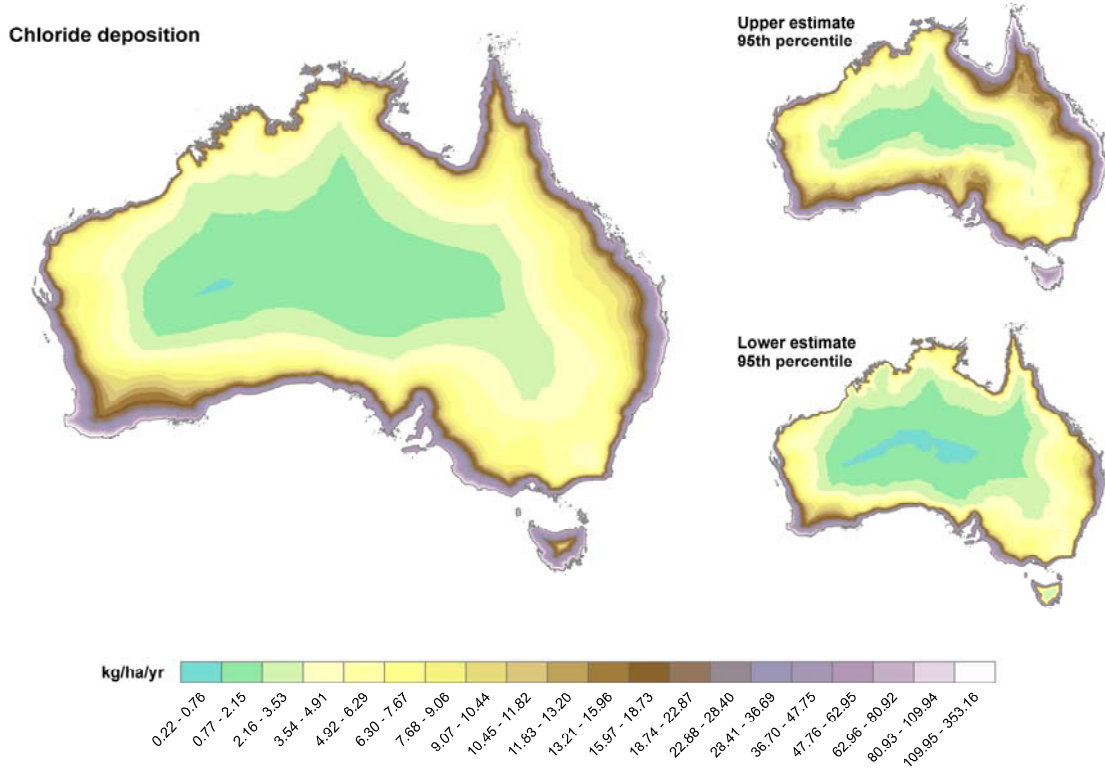


Figure 14. Maps of interpolated rainfall chloride deposition for Australia (largest) and the upper and lower 95% percentiles of interpolated estimates.

A literature review identified 291 point measurements of chloride deposition over the past 60 years (Davies *et al.*, 2011); these were spread unevenly across all states. The point observations identified in the literature review have been used to develop a map of chloride deposition in rainfall across Australia in an attempt to quantify the spatial distribution of chloride accession at a national scale. The relationship developed by Keywood *et al.* (1997) between chloride accession and distance from the coast was used as the basis for this modelling. An empirical relationship for the mass of chloride deposited at a given location (D) is described by the sum of two exponentials: (Equation 10).

$$\text{Equation 10} \quad D = A_1 \exp(-d/\lambda_1) + A_2 \exp(-d/\lambda_2)$$

where A_1 , A_2 , λ_1 and λ_2 are fitting parameters and d is distance from the coast.

Surfaces were interpolated for each of the four parameters using a pilot point regularisation approach within PEST (Doherty, 2005) with the aim of minimising the sum of squared residuals between observed and modelled values of chloride deposition. The pilot points were selected to be located between known observations of chloride deposition and at such a density as to capture the spatial variability present in the parameter values. A best estimate chloride deposition map, based upon a 0.05 degree grid cell, was developed from the resulting surfaces. The correlation coefficient of the measured versus modelled chloride deposition was 0.96 demonstrating the excellent fit of the model.

The uncertainty in the chloride deposition surface was quantified as the upper and lower 95th percentile of 791 calibrated models produced via Null Space Monte Carlo analysis within PEST, full details on the generation of the chloride deposition surface is contained in Davies *et al.* (2011).

2.5.9. Chloride in groundwater

There is a large amount of historical groundwater chloride data managed by the States and Territories (Figure 15) which obviates the need to estimate groundwater chloride from measurements of electrical conductivity.

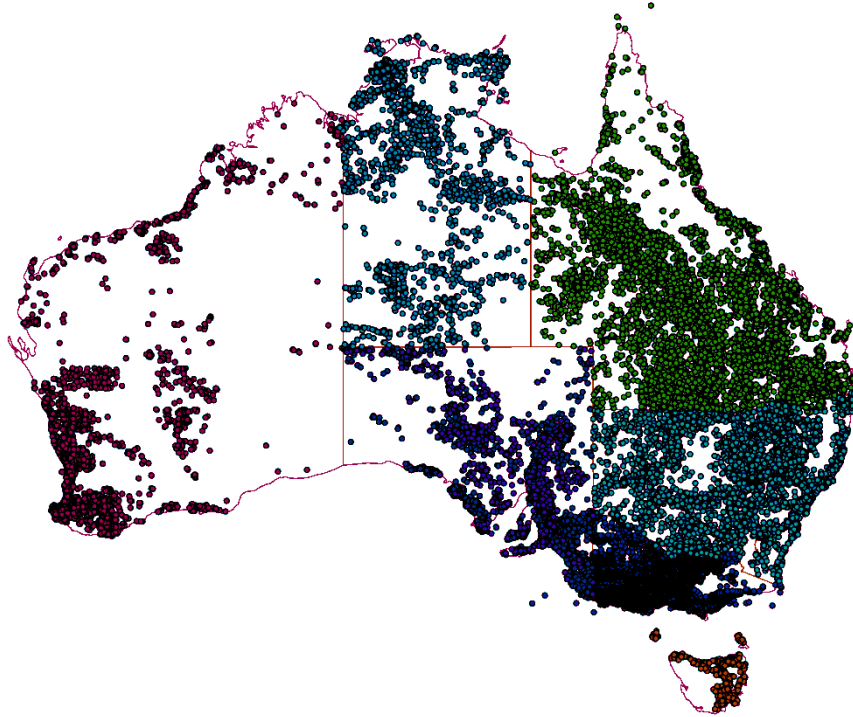


Figure 15. Groundwater chloride data available in State and Territory databases.

3. CASE STUDIES

3.1. Introduction

Two exemplar sites were selected to test the methods discussed in Chapter 2.3 and 2.4. The criteria for site selection were:

- Known recharge and discharge field measurements that could be used to verify any calculated estimates.
- No or minimal irrigation as estimates at these locations are outside the scope of this project.
- Sites should be from varying climatic conditions and from different states and/or territories.

Two sites deemed suitable were the Tomago region near Newcastle in New South Wales and the Wattle Range region near Millicent in South Australia (Figure 16). In this chapter, some background information will be provided about the two exemplar sites and each of the various recharge and discharge estimation methods will be applied and discussed.

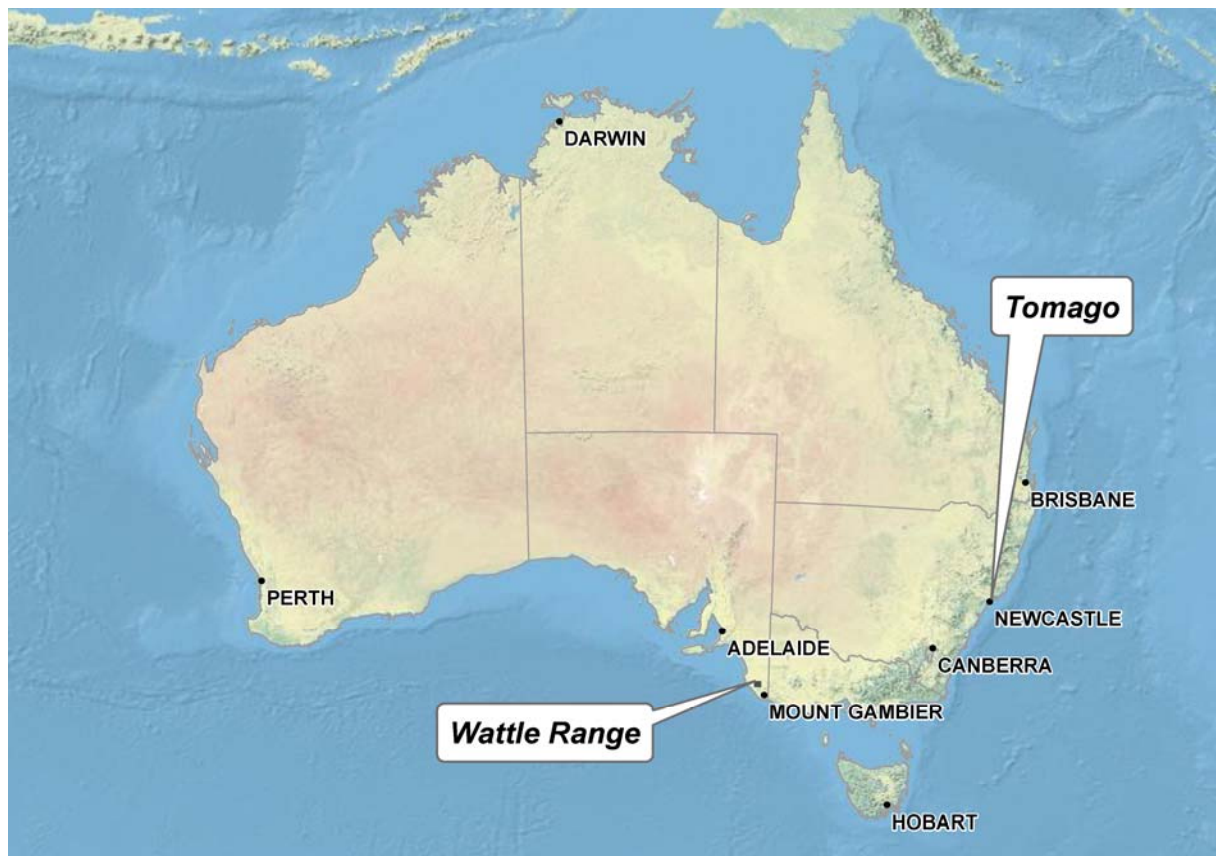


Figure 16. Locations of the 2 exemplar sites.

3.2. Wattle Range

3.2.1. Background

The Wattle Range exemplar site is located north of Millicent in the south-east of South Australia (Figure 17) and is ~1036 km² in area. It is part of a larger area in SE South Australia known as the Green Triangle. It comprises the Hundreds of Coles, Short, Fox and Kennion in the north-east, south-east, north-west and south-west quadrants of the area respectively. The surface geology of the Wattle Range region is comprised of north-west trending Quaternary beach-dune ridge systems, separated by a series of inter-dunal corridors. These overlie the unconfined Tertiary Gambier Limestone aquifer of the Otway Basin. The average annual rainfall varies from ~650 mm in the north-east of the region to ~730 mm in the south of the region.

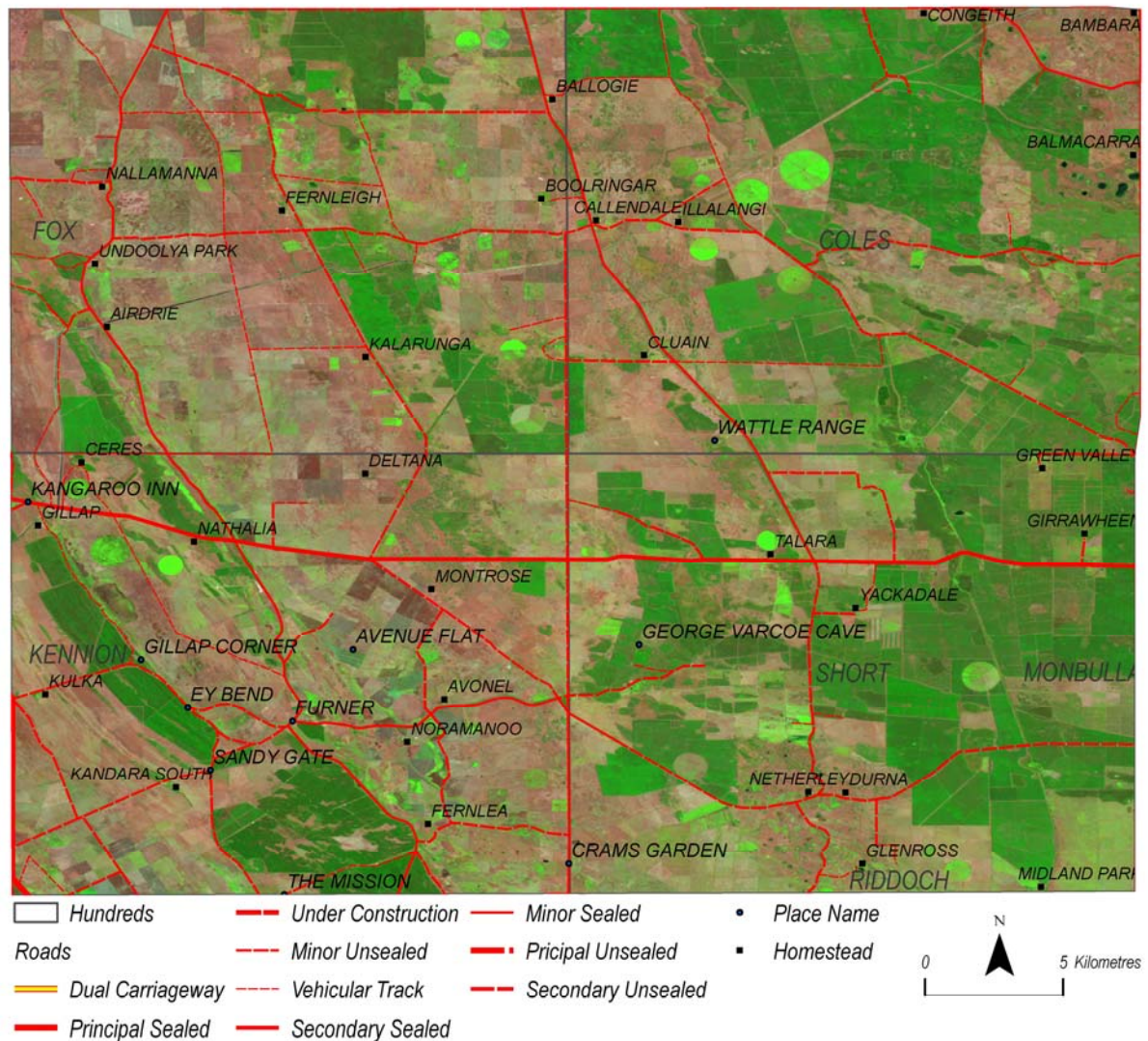


Figure 17. Location map of the Wattle Range exemplar site.

Land use is predominantly grazing/modified pastures although hardwood Blue Gum plantations were introduced in 1998 and now cover approximately 37 % of the area. There are also small areas of pine (softwood) plantations and irrigated agriculture as well as numerous groundwater dependent ecosystems (wetlands). Prior to clearing, the native vegetation cover was rough-barked manna gum/swamp gum, wet heath and open heath wetland habitat (prickly tea-tree), brown stringybark and hill gums on the sandy rises, with

pockets of red gum and damp woodland (Mark Bachmann, SA Department of Environment and Heritage, Pers Comm, 2005).

Two studies have estimated groundwater recharge and/or groundwater uptake by vegetation at or near the Wattle Range site. As detailed in two publications, the first of these studies estimated groundwater uptake using a water balance/sap flow methodology. The approach was applied at two sites where pine forestry had commenced at least 40 years prior (Benyon and Doody, 2004,); and at four sites where Blue Gum forestry had commenced less than 11 years prior (Benyon, 2005). Two estimates, 0 and 600 mm/yr, were made within the pine forestry at 5-6 m depth to water. The significant variation in groundwater discharge estimates was attributed to the likely presence of a low permeability stratigraphic unit, resulting in low associated groundwater uptake. Estimates of groundwater uptake at the blue gum forestry sites ranged from 0 to 640 mm/yr, with an average value of 315 mm/yr.

The second study commenced in 2004/2005 following land use change concerns, principally relating to the expansion of hard and softwood plantations and possible adverse affects on water dependent ecosystems (e.g. wetlands) (Leaney *et al.*, 2006). The authors collected soil cores from 19 sites in this area and in the Nangwarry area, ~30 km further to the South-East. Five of the sites were in areas that had been cleared of vegetation, two were in areas with native vegetation still present, four were in areas where pine plantations had been established 35-79 years beforehand, six in areas where blue gum plantations had developed 7-17 years ago and two were in irrigated areas. Several of the cored holes were also completed as shallow bores.

Using a Chloride Mass Balance approach and soilwater chloride data, groundwater recharge estimates of 0 and 8 mm/yr were calculated for native vegetation sites and between 40 and 375 mm/yr at the cleared sites (without forestry plantation). At the sites cleared of native vegetation and without forestry, the soilwater chloride profiles showed no evidence of elevated levels of chloride throughout the unsaturated zone. Hence it was assumed that the system had reached a new steady state at the watertable and that the deep drainage estimates at those sites equated to groundwater recharge estimates.

Within the pine plantations, the amount of groundwater uptake was estimated assuming that the chloride bulge above the watertable had resulted from accumulation of chloride in the unsaturated zone following extraction when “pure” water was taken up from the capillary zone by tree roots. In this method, the estimate is an average based over the majority of the forest lifetime. Groundwater uptake at the pine sites ranged from >40 to >390 mm/yr (average ~140 mm/yr). The estimates agreed well with those of Benyon (2005) for sites close to each other. Groundwater uptake estimates at the blue gum sites ranged from 0-1000 mm/yr (average ~290 mm/yr) but featured much broader confidence intervals because the methodology was compromised for forests planted within the last 1-2 decades. Again there was reasonable agreement at most of the blue gum sites common to the Benyon (2005) study.

For the purposes of estimating groundwater recharge and discharge, the study area was divided into sub-areas; each was expected to feature a unique groundwater recharge/discharge regime. For both groundwater recharge and discharge estimation, soil order, vegetation type and rainfall were used, while for groundwater discharge estimation, geology was also included. The spatial distribution of key input datasets is shown in (Figure 18). The mean annual rainfall for the study area ranges from ~626-733 mm/yr. Four rainfall ‘sub-areas’ were identified: 652, 673, 716 and 733 mm/yr; these were used in the estimation of groundwater recharge and discharge (Figure 18). Two vegetation types were identified: perennial/trees and annuals. Two soil orders were used: sodosol and vertosol, as defined by the Australian Soil Classification.

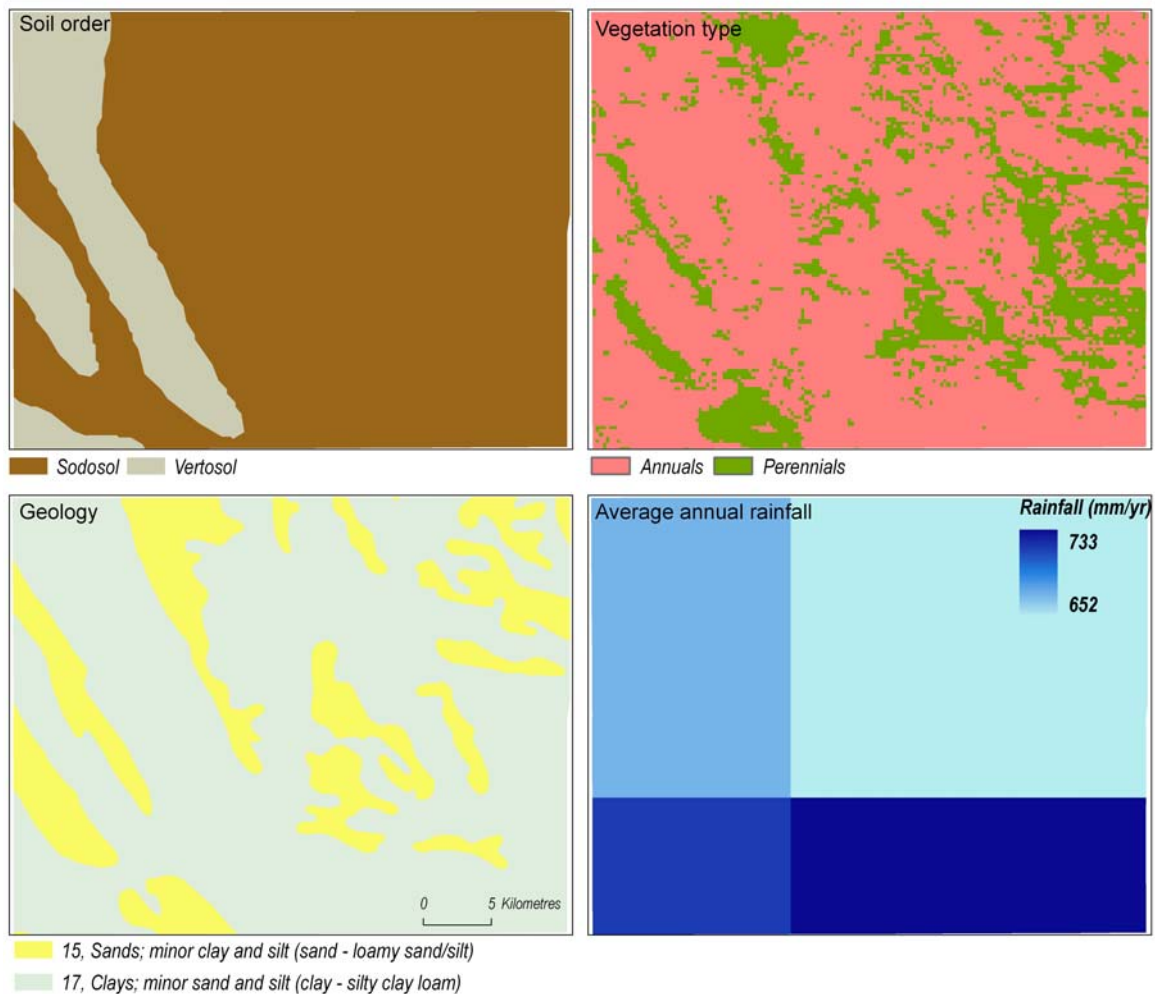


Figure 18. Spatial distributions of four key variables (soil, geology, vegetation and rainfall) at the Wattle Range study site. These datasets were used to divide the study area into sub-areas in order to estimate lag times and/or groundwater recharge/discharge rates.

3.2.2. Recharge estimation

The following discussion designates sub-areas based on national scale mapping; however we recognise that water managers may have better mapping data available and, if so, we suggest that these should instead be used when defining land use sub-areas.

Two vegetation types were identified in the Wattle Range study area: perennials/trees and annuals. Mapping suggests that annual vegetation covers about 77.6% of the study area with the remaining 22.4% identified as perennial/trees (Figure 18). Perennials/trees also include forestry as a significant difference could not be identified between estimates of deep drainage or groundwater discharge for perennials/trees and for commercial forestry.

In contrast to mapping data, South Australian Department for Water records suggest that 37% of this perennial vegetation is composed of commercial plantations and 10% remnant native vegetation. Together this suggests that perennial vegetation covers 47% of the project area, significantly more than the estimate identified during the mapping. It is important to stress here that the Vegetation Type dataset is mapped at a national scale using a remotely sensed approach; consequently there can be some issues with the identification and appropriate classification of various vegetation communities. One possible explanation for the difference (~25%) observed here is that new blue gum forestry, with high growth rates and productivity, has been falsely identified as annuals.

Two soil orders, sodosol and vertosol, are present in the study area (Figure 18). Through combinations of the two soil order classes, four rainfall divisions and the two vegetation

types, the study area was divided into 16 sub-areas. Four of the potential combinations either do not exist in the study area or have insignificant surface extent to warrant investigation, resulting in a total of 12 sub-areas for groundwater recharge/discharge estimation (Table 6).

Table 6. Twelve sub-areas identified for the Wattle Range study site, based on a combination of two soil orders (sodosol and vertosol), two vegetation types (annuals and perennials) and four rainfall zones. Area and percentage of the total study site are also shown.

Sub-area #	Soil order	Vegetation type	Average annual rainfall (mm)	Area (km ²)	% of total area
1	sodosol	annuals	652	224	21.4
2	sodosol	annuals	672	228	21.8
3	sodosol	annuals	716	106	10.1
4	sodosol	annuals	733	108	10.3
5	sodosol	perennials	652	92	8.8
6	sodosol	perennials	672	51	4.8
7	sodosol	perennials	716	22	2.1
8	sodosol	perennials	733	40	3.8
9	vertosol	annuals	672	104	9.9
10	vertosol	annuals	716	43	4.1
11	vertosol	perennials	672	13	1.3
12	vertosol	perennials	716	16	1.5

MOLR deep drainage estimates range from 24 to 49 mm/yr at the sites with annual vegetation and from 1 to 3.3 mm/yr at the forestry sites (Figure 19). Estimates of % clay (at 0-2m depth) from cores are available from eight sites in the hundred of Short in the study area. They are all located within the 733 mm/yr rainfall area and all feature sodosol soils and hence are in sub-areas 4 and 8. The average % clay estimates for the 0-2 m surface soil depth interval range from 2.1 to 17% with an average value of 10% (Leaney *et al.*, 2006). Percent clay-based estimates of deep drainage for sub-areas 4 and 8 using maximum (17%) and minimum (2.1%) estimates of %clay content range from 93 to 140 mm/yr for the cleared areas and from 9.8 to 25 mm/yr for forested areas (Table 7). These estimates are 3-4 times greater than the MOLR estimates for the cleared areas and 7-18 times greater than the MOLR estimates for the forested areas.

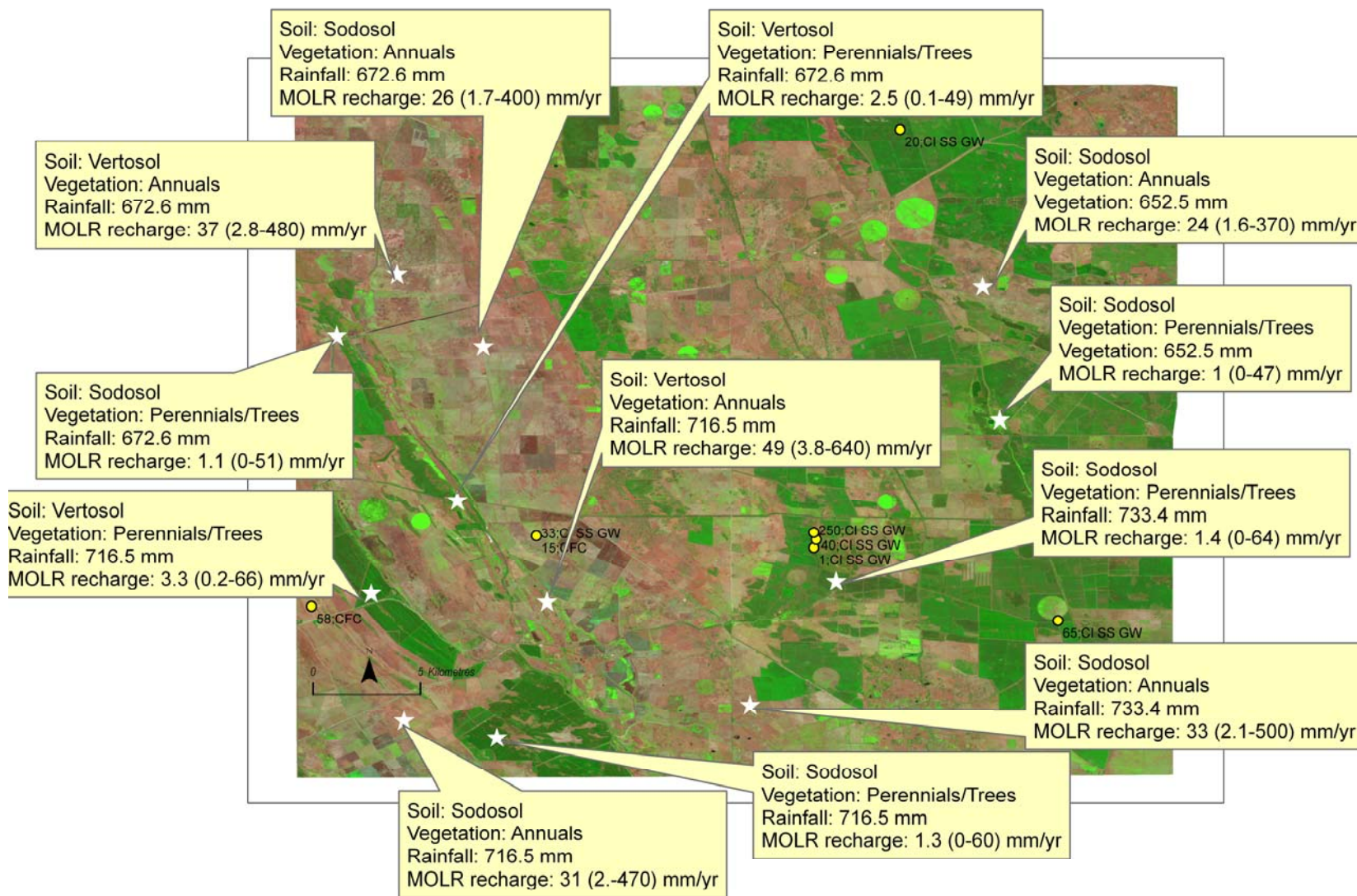


Figure 19. MOLR estimates based on the soil, vegetation and rainfall input datasets.

Table 7. Estimated recharge (mm/yr) for the Wattle Range exemplar area using the MOLR, %Clay and Groundwater Chloride Mass Balance (CMB) approaches. 95% confidence intervals are also provided for MOLR and %Clay estimates. The mean and median are provided for the CMB method.

Sub-area #	MOLR			%Clay (minimum)			%Clay (maximum)			CMB	
	mean	upper 95%	lower 95%	mean	upper 95%	lower 95%	mean	upper 95%	lower 95%	mean	median
1	24.0	1.6	370.0							28	18
2	26.0	1.7	400.0							28	18
3	31.0	2.0	470.0							28	18
4	33.0	2.1	500.0	93.0	9.8	730.0	140.0	15.0	730.0	28	18
5	1.0	0.0	47.0								
6	1.1	0.0	51.0								
7	1.3	0.0	60.0								
8	1.4	0.0	64.0	9.8	1.0	100.0	25.0	2.5	260.0		
9	37.0	2.8	480.0							63	23
10	49.0	3.8	640.0								
11	2.5	0.1	49.0								
12	3.3	0.2	66.0								

Where vegetation clearing has occurred and a new recharge regime has not reached steady state, current recharge rates will be significantly less than deep drainage. The Excel recharge estimation spreadsheet calculates lag times from measurements of depth to watertable, unsaturated zone soil texture and deep drainage rate estimates. The spreadsheet uses deep drainage rates estimated by the MOLR or, if %clay data are available, deep drainage rates estimated from the %clay relationship. For the Wattle Range study area, %clay data and hence %Clay deep drainage estimates were only available for two of the six sub-areas with annual vegetation (Table 7). In order to provide consistency between the different sub-areas, the MOLR deep drainage estimates were used in (all?) lag time calculations. Depth to watertable values range from approximately 2 to 15 m; however for most of the area the watertable is less than 6 m. A watertable depth of 10 m was chosen for the study area in order to calculate a conservative (i.e. maximum) value for the lag time. Particle size analyses of unsaturated zone soil cores collected in the study area indicated that soils were in the loamy sand to sandy loam range (Leaney *et al.*, 2006). The sandy loam soil type was used in the spreadsheet and was assumed to be constant throughout the unsaturated zone. Again, this is a relatively conservative approach resulting in a maximum estimate for lag time. Lag times of 3-5 years were subsequently calculated for areas with annual vegetation cover.

Small-scale land clearing in the Wattle Range area (particularly in the Hundreds of Coles and Short) began in the 1950s. Massive-scale land clearing occurred after commencement of the Anderson Drainage Scheme in the early 1960s (which was completed in 1970). The construction of drains in the area and improved the suitability of land for grazing. As most land clearing occurred between 30 and 60 years ago, a new groundwater recharge regime has likely reached steady state for sub-areas cleared of native vegetation. Flushed soilwater chloride profiles of the cores collected as part of a study by Leaney *et al.* (2006; Figure 5) confirm this to be the case. Consequently, estimated values of recharge (24-49 mm/yr) in cleared areas (featuring annual vegetation) are the same as estimated deep drainage values (Table 7).

In order to determine whether the Groundwater Chloride Mass Balance method can be used to estimate recharge rates in areas of land use change, it is necessary to determine not only whether recharge has reached a steady state rate at the depth of the watertable but also at the depth of the bore screens. Existing bores with measured groundwater chloride concentrations (at depth of less than 20 m from the ground surface) were queried. In general, the top of the watertable aquifer was reported in sandstone or weathered sandstone material. For bore screen lag time calculations the following variables were used: 10 m depth to

watertable (with sandy loam in the unsaturated zone) and a 20 m depth of screen (with weathered sandstone) from the watertable to the screen depth. We have not included a second soil layer, unconsolidated layers or unweathered layers in the calculations (i.e. the thickness of each was set to zero in the spreadsheet) and have used the same rates of deep drainage as discussed earlier for watertable lag time calculations.

Using these data in the Excel spreadsheet, lag times to reach a steady state at a screen depth of 20 m were estimated to range from 32 to 42 years for areas with sodosol soils and 21 to 28 years for areas with vertosol soils. These lag times are in the similar range to the time since clearing, hence a new steady state at the screen depth of selected bores is probable but not certain. These calculations do not take into consideration more recent land use change; specifically, reforestation of large areas of the study site over the last 10-20 years. While this land use change is likely to have altered the groundwater recharge/discharge regime (as discussed further in Chapter 2.4), minimal impact on groundwater chemistry is expected. Hence, current groundwater chloride data are indicative of groundwater recharge rates that existed under cleared conditions. A total of 163 bores featuring salinity observations were identified in the study area (Figure 20). Of these, 128 were in areas with sodosol soils and 35 were in areas with vertosol soils. Using the groundwater CMB method, mean and median groundwater recharge rates for areas with sodosol and vertosol soil orders are 28 and 18 mm/yr and 63 and 23 mm/yr respectively (Figure 21; Table 7). Estimates for individual bores using the CMB method are also given in Figure 20.

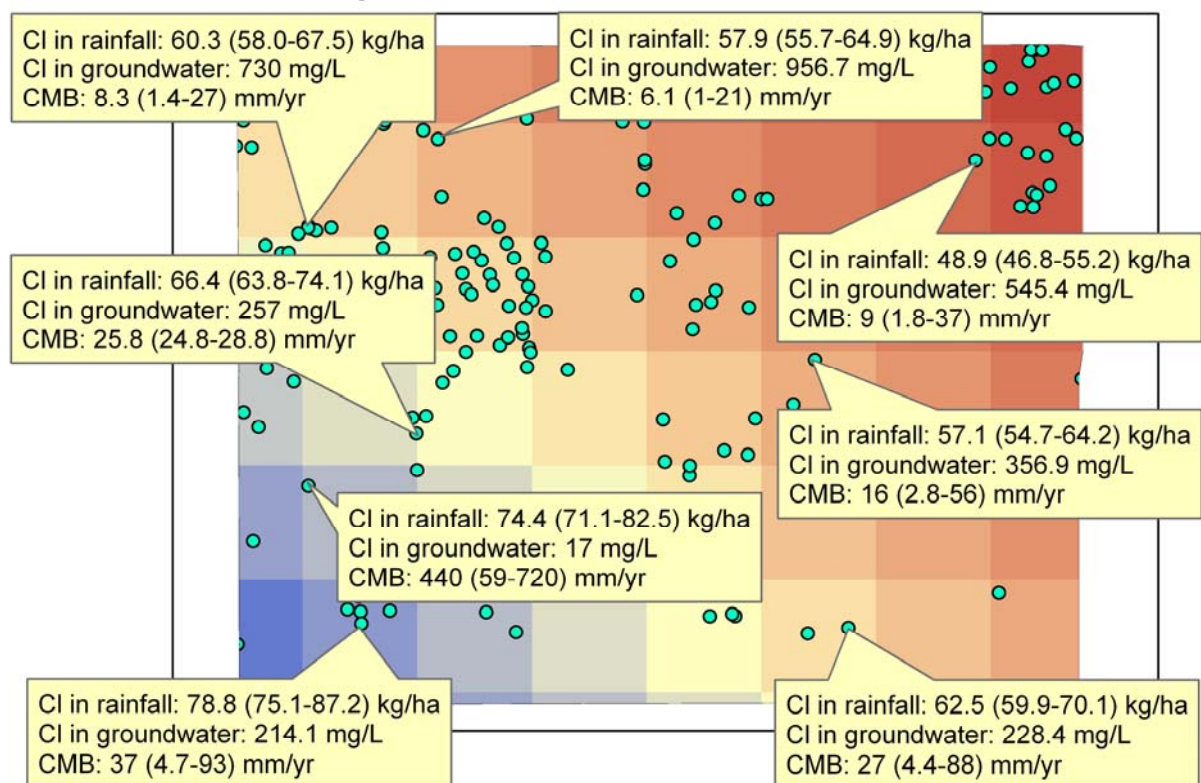


Figure 20. Chloride Mass Balance groundwater recharge flux estimations for the Wattle Range exemplar site. (The background colour is the chloride deposition raster, increasing to the south-west).

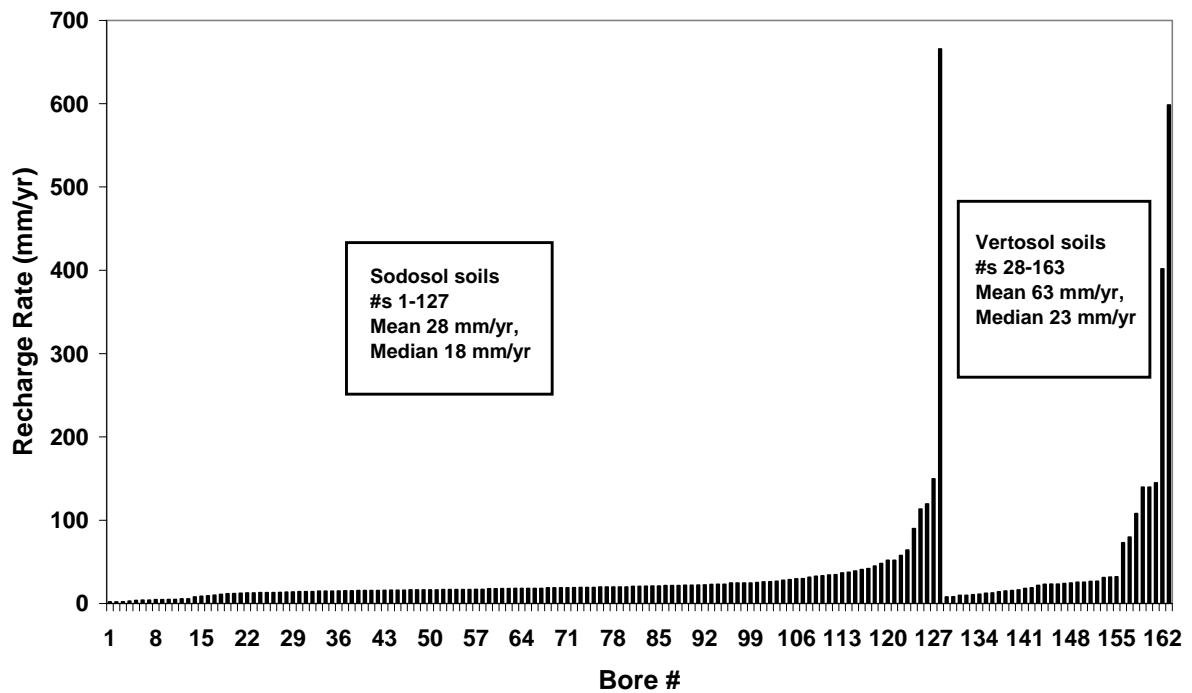


Figure 21. Recharge estimates using the groundwater CMB approach for areas cleared of native vegetation. The area is divided into those in areas with sodosol and vertosol soils.

In summary, sub-areas with annual vegetation are likely to have reached new steady state groundwater recharge rates following clearing of native vegetation several decades ago. In areas that have been cleared and more recently reforested with blue gum plantations, a new steady state recharge regime would have been reached prior to the revegetation. However, recharge rates would have decreased significantly since reforestation, although the groundwater chloride concentrations appear to reflect the recharge regime immediately post-clearing and not the current recharge regime.

Groundwater recharge rates estimated using the MOLR and CMB methods for areas with annual vegetation display very good agreement. No estimates were possible using the CMB method for areas where native vegetation was present because it was not possible to differentiate these areas from areas that had been cleared and then reforested. The groundwater recharge estimates for areas with annual vegetation made using point measurements of %clay and the %Clay method were 3-6 times greater than those estimated using the MOLR and CMB methods for sub-area 4. The difference is even greater for perennials when using the %Clay method, with groundwater recharge estimates an order of magnitude greater than those estimated using the MOLR method for sub-area 8. This is not surprising, given that the %Clay estimate relies on a limited number of point measurements of %clay, which may not provide an accurate representation of the true values and variability of soil clay content within the study area.

The 95% prediction intervals for any individual estimate, as determined using statistics associated with development of the estimation relationships, are up to 1-2 orders of magnitude from the estimated mean (Figures 19 and 20). Comparisons of 95% prediction intervals are at least an order of magnitude worse than the agreement between mean estimates using the different methods (Table 17).

3.2.3. Discharge estimation

Soils in the Wattle Range region are dominated by two orders: sodosols and vertosols. The area is characterised by sandy soils with high hydraulic conductivity and low soil water holding capacity. While variation in rainfall across the site is not significant, rainfall does

decline in a north-easterly direction and, as described above, our analysis delineated four rainfall zones across the region (Figure 18). In total, eight groundwater discharge sub-areas were identified in the Wattle Range study sites. Measured estimates of groundwater discharge (Benyon and Doody 2004) in the study area varied from 2 to 440 mm/yr (Figure 22). In general, depth to the watertable in the Benyon and Doody study was approximately 2 m, although depth to watertable at a site with 2 mm/yr (measured?) discharge was approximately 10 m. In contrast, depth to groundwater at most sub-areas used in the scenarios presented here was approximately 5 m. For sub-areas featuring depths to water greater than 5 m, discharge estimates ranged from 42 to 63 mm/yr (Figure 22).

These values are consistent with those previously reported for south-east South Australia (Benyon and Doody 2004; Holland and Benyon 2010). Groundwater discharge varied from 2 mm/yr to almost 700 mm/yr across the greater Green Triangle region. A threshold of 6 m depth to watertable was identified for groundwater uptake, below which groundwater discharge is assumed to be non-existent. The majority of sites in this analysis were close to this “threshold” depth and may help explain the lower average values of groundwater discharge when compared with those reported by Benyon *et al.* (2006). Additionally, the Benyon *et al.* studies were conducted over a relatively short time frame, generally 1-2 years. In contrast, this analysis considers a longer climatic period (up to 100 years) and, as such, estimated rates of groundwater discharge are considered to be reasonable. At sites with deeper watertables, groundwater discharge is estimated to be in the order of 15 mm/yr, which is higher than previous estimates for the region.

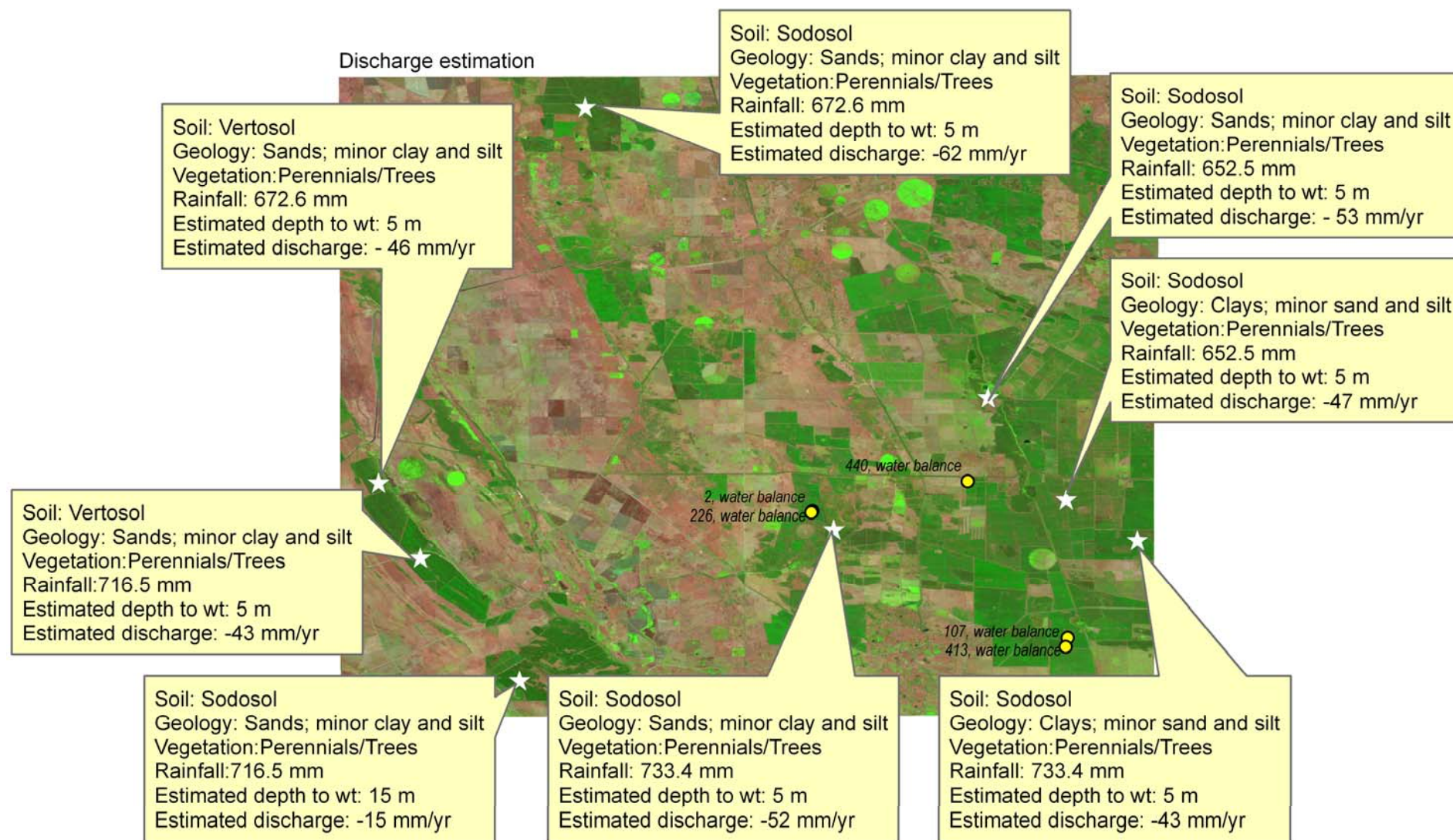


Figure 22. Estimated groundwater discharge flux values for the Wattle Range exemplar site. Actual (reported) groundwater discharge measurements in mm/yr and associated method are also shown.

3.3. Tomago

3.3.1. Background

The Tomago exemplar site is located approximately 15 km north of Newcastle in New South Wales. The Tomago sand beds are an unconsolidated, unconfined aquifer consisting of aeolian deposits of fine to medium sand. The aquifer has:

- a surface areal extent of 152 km²;
- an average thickness of 18 m;
- an average depth to water of about 2 m; and
- a hydraulic conductivity of 23 m/d (Crosbie, 2003).

The aquifer is replenished by rainfall and discharges to the Hunter River to the west, Tilligerry Creek to the south and Port Stephens to the north-east (Woolley *et al.*, 1995) (Figure 23). At the Williamstown RAAF meteorological station in the centre of the aquifer, the average annual rainfall is 1127 mm and the average annual pan evaporation is 1715 mm. A rainfall gradient exists, in which rainfall is higher in the east and lower in the west.

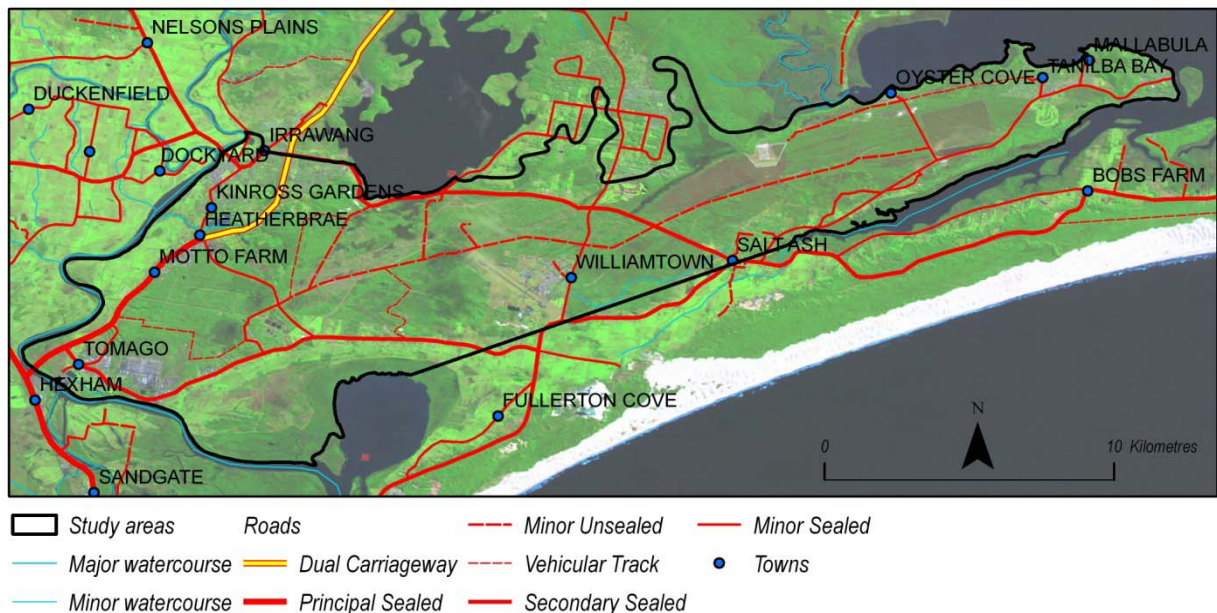


Figure 23. Location map of the Tomago exemplar site.

This aquifer provides about 25% of the potable water supply to the 470 000 residents of the Newcastle Region. The Tomago sand beds were first proposed as a source of water for the city of Newcastle in 1915 but were not developed until 1939 (Corlette, 1944). This exemplar site is considered a 'data rich' area with a history of investigations into the water balance going back more than 60 years.

Recharge rates at Tomago were first estimated using lysimeters (HDWB, 1957). The authors estimated the drainage below the root zone to be between 292 and 632 mm/yr. Several years later the Chloride Mass Balance method was used to estimate recharge at 293 mm/yr (i.e. 25% of rainfall; HDWB, 1957) but details of the method used are sparse. The most recent estimates of recharge at Tomago (Crosbie, 2003; Crosbie *et al.* 2005) focused upon upscaling point-based estimates to the entire aquifer. Estimates of both gross recharge and net recharge estimates were produced.

The watertable fluctuation method was applied at six locations over a period of three years. Estimates of gross recharge varied between 505 and 696 mm/yr. Surprisingly, vegetation

type was not found to significantly influence the magnitudes of gross recharge estimates (Crosbie *et al.*, 2005). Monthly results from the watertable fluctuation method were used to identify a relationship between gross recharge and depth to watertable on a seasonal basis. Using data from the extensive Tomago monitoring network, monthly time series of depth to watertable maps were created, with associated spatial estimates of gross recharge. This process resulted in a spatially averaged gross recharge estimate of 469 mm/yr over 22 years (Crosbie, 2003).

The Groundwater Chloride Mass Balance method was used to estimate net groundwater recharge. Over the past 50 years, more than 9 000 groundwater chloride measurements have been recorded for the Tomago aquifer. In this case, vegetation type was found to be significant in the estimation of net groundwater recharge. In areas of Tomago where land clearance has occurred, recharge was found to be 34% of rainfall. In areas of heath vegetation, net recharge was found to be 27% of rainfall, while in forested areas the net recharge was found to be 18% of rainfall. Using vegetation maps of Tomago as a co-variate, the spatially averaged net recharge was estimated to be 278 mm/yr (Crosbie, 2003).

There have not been any direct measurements of the discharge of groundwater by vegetation at Tomago. However, the difference between gross recharge and net recharge can be assumed to be equal to discharge via ET; this was estimated as 205 mm/yr (Crosbie, 2003).

For the purposes of estimating groundwater recharge and discharge, the study area was divided into sub-areas; each was expected to have a different groundwater recharge/discharge regime. For both groundwater recharge and discharge estimation, soil order, vegetation type and rainfall were used, while for groundwater discharge estimation, geology was also included. The spatial distribution of key input datasets is shown in Figure 24. Two rainfall zones, two vegetation types (annuals and perennials/trees) and two soil orders (dermosols and podosols) were identified.

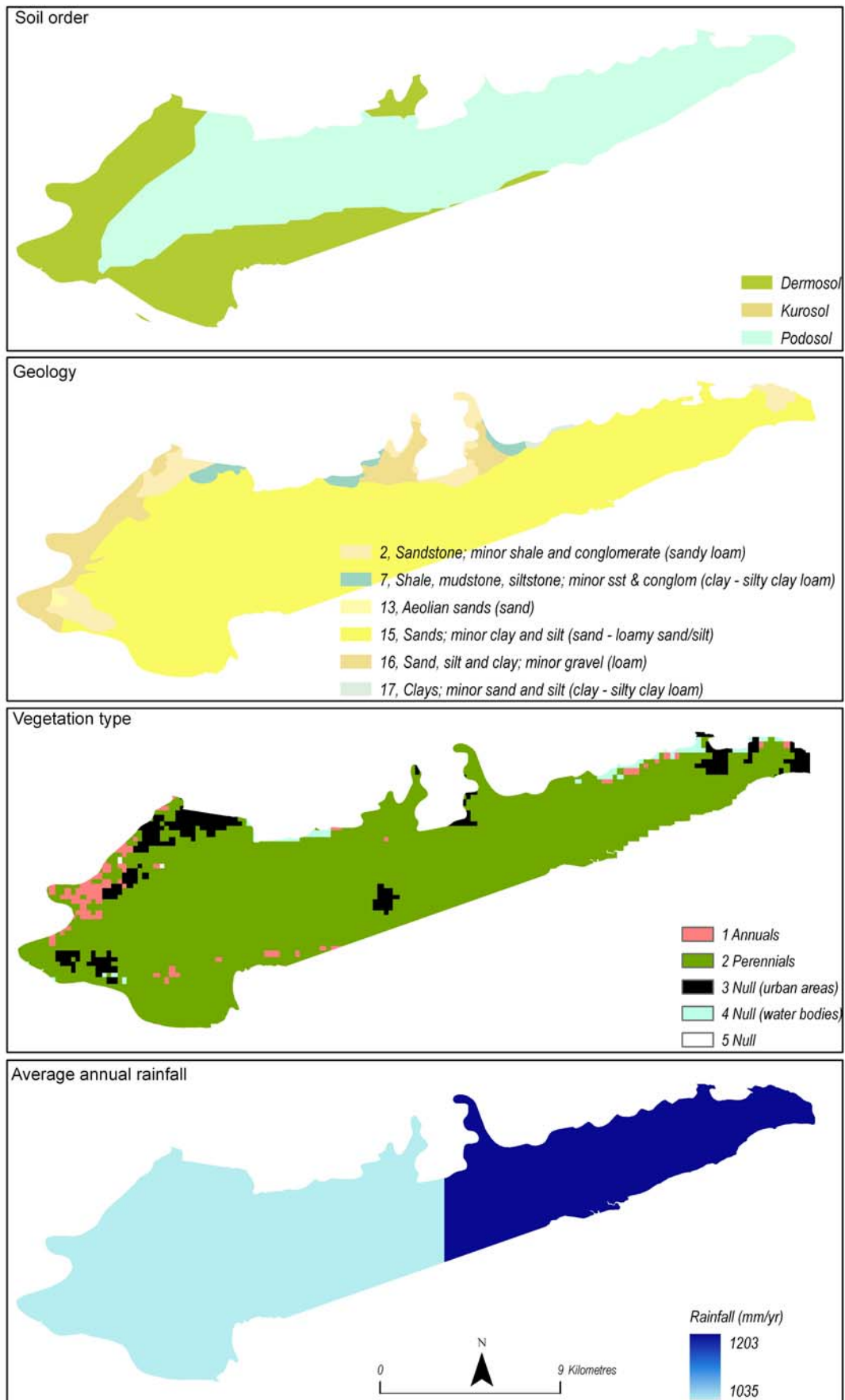


Figure 24. Spatial distributions of four key variables (soil, geology, vegetation and rainfall) at the Tomago exemplar site. These datasets are used to divide the study area into sub-areas in order to estimate lag time and/or groundwater recharge/discharge.

3.3.2. Recharge estimation

The majority of the Tomago aquifer has not been cleared of native vegetation (perennials in Figure 24). Therefore it may be assumed that the hydrological regime is in equilibrium with the climate and the calculation of lag times is not required. In the few sub-areas that have been cleared (annuals in Figure 24), the soil type and geological materials are used to estimate lag times; however, the very high recharge rates estimated at Tomago suggest that equilibrium conditions at the watertable are attained within a year after vegetation clearance (calculations not shown).

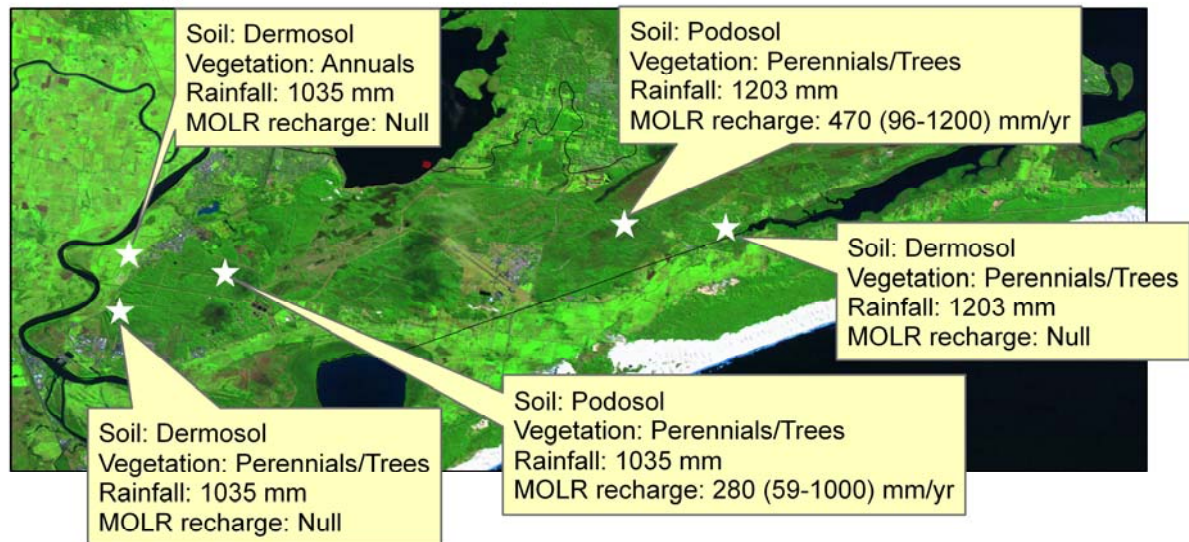
To estimate recharge using the MOLR, three inputs are required: soil type, vegetation type and the annual average rainfall (Figure 24). Two soil orders are present at the Tomago site: podosols occupy most of the region while dermosols are present in some areas on the periphery of the aquifer. The majority of the aquifer is covered by native vegetation and so has been classified as perennials/trees. Small isolated areas of annuals also exist as well as some urban areas, for which the MOLR cannot be used. The distribution of average annual rainfall has been classified using two zones: in the west the average annual rainfall is 1035 mm/yr while in the east it is 1203 mm/yr.

Rates of recharge estimated using the MOLR are shown in Figure 25. For the combination of perennial/tree vegetation and podosol soil type, recharge has been estimated for both rainfall zones. In the west the estimated recharge is 280 mm/yr with 95% confidence intervals of 59 and 1000 mm/yr. In the east the estimated recharge is 470 mm/yr with 95% confidence intervals of 96 and 1200 mm/yr. No estimate of recharge is possible using the MOLR for dermosol soils because there were insufficient available field data upon which to base a regression equation (see Chapter 2.3.3).

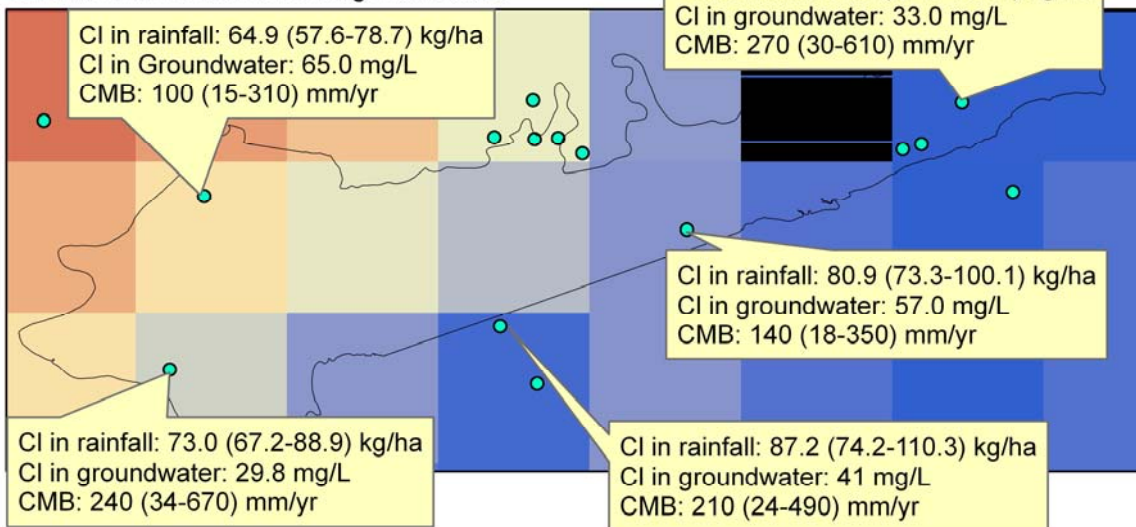
Use of the Chloride Mass Balance method at the Tomago site was possible since groundwater chloride concentration estimates were available (from the NSW Office of Water database). As Tomago is located close to the coast, a strong chloride deposition gradient exists: in the east the rate of chloride deposition is over 90 kg/ha/yr while in the west this falls to about 60 kg/ha/yr (Figure 25). Five bores for which groundwater chloride measurements were available were selected; chloride concentrations ranged from 30 to 65 mg/L. Net groundwater recharge estimates range from 100 (15-310) mm/yr to 270 (30-610) mm/yr, where the numbers in brackets represent the 95% confidence intervals about the recharge estimate due to the uncertainty in chloride deposition measurements.

Estimates of recharge produced using the MOLR and Chloride Mass Balance at Tomago are not significantly different from past field-based estimates (Figure 25).

MOLR recharge estimation



Chloride mass balance recharge estimation



Actual (measured) recharge

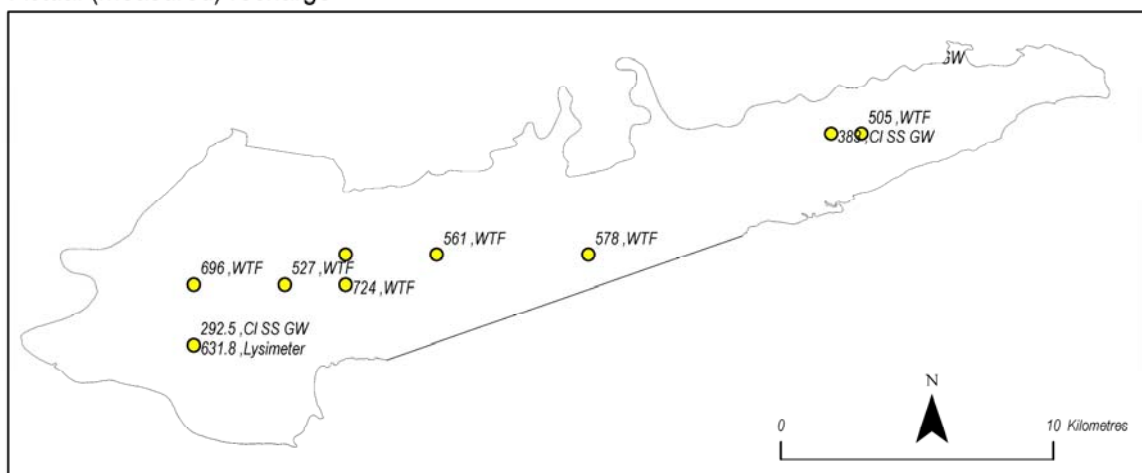


Figure 25. Estimated recharge flux values (from MOLR and CMB methods) and past measurements of recharge flux for the Tomago exemplar site. (The background colour in the middle plot is the chloride deposition raster, increasing to the east).

3.3.3. Discharge estimation

Groundwater discharge estimations used many of the same datasets as used for recharge estimation. As previously discussed, there are two soil orders present at Tomago (podosols and dermosols), two vegetation types (primarily perennials/trees and some annuals); and two rainfall zones (higher rainfall in the east and lower rainfall in the west) (Figure 24).

Geologically, the majority of the region was texturally classified as 'sands; minor clay and silt', although there are small areas with differing geology. The combination of these four parameters resulted in nine unique combinations; groundwater discharge (via vegetation) was estimated for each.

Estimated discharge rates ranged from 38 mm/yr where the watertable was deep (5 m) to 199 mm/yr where the watertable was shallow (1 m) (Figure 26). No known discharge measurements exist for the Tomago; hence estimates could not be compared. Using the calculated difference between gross and net groundwater recharge, Crosbie *et al.* (2005) estimated that groundwater discharge was in the order of 205 mm/yr. This agrees well with the upper end of estimates derived using the groundwater discharge tool. These estimates are also conceptually similar to estimates of groundwater discharge at sites on sandy profiles over shallow (i.e. depth to watertable < 6 m) watertables in other regions, (O'Grady *et al.* 2010).

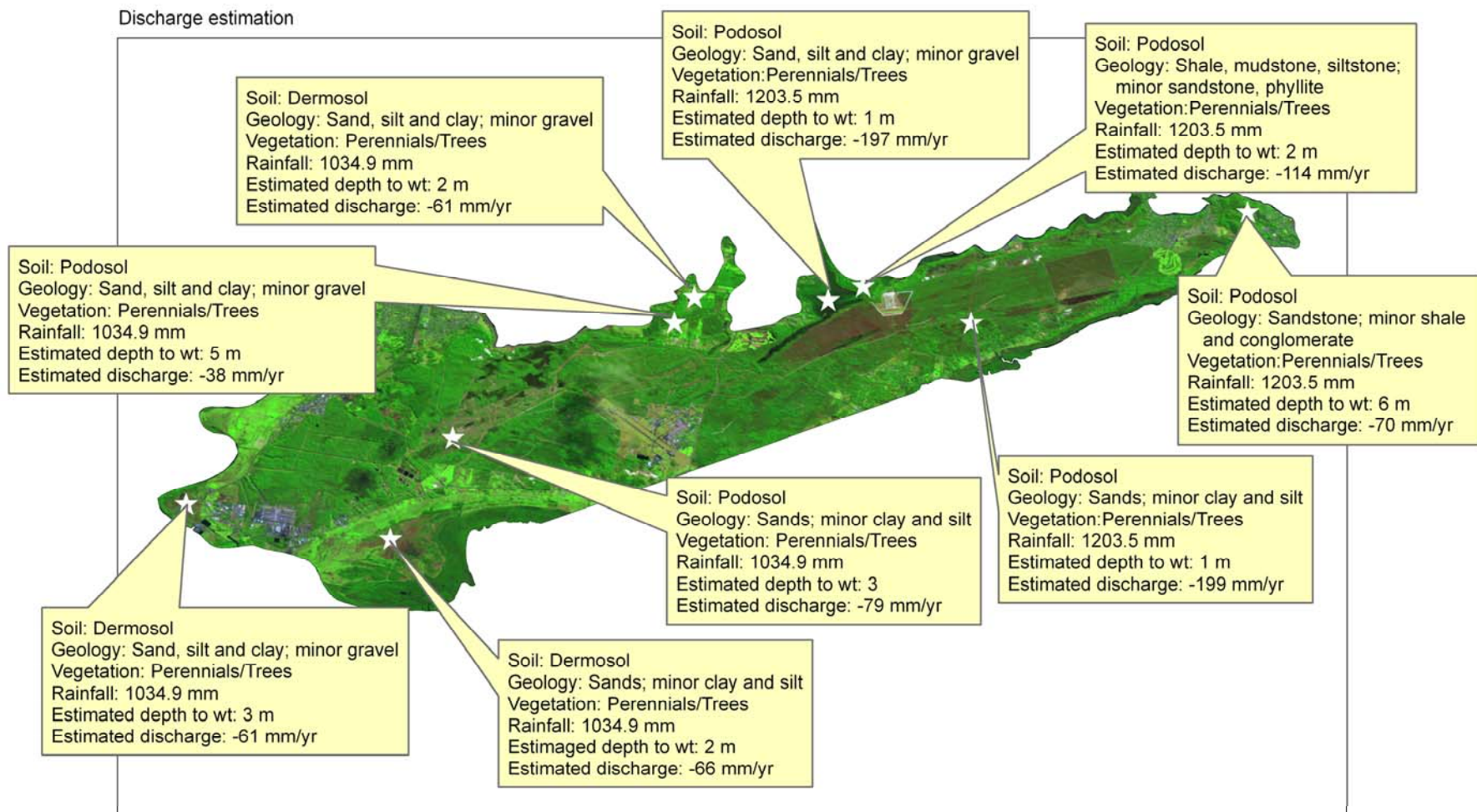


Figure 26. Groundwater discharge estimation sites with associated groundwater discharge estimates. No known (published) groundwater discharge estimates are available for this site.

4. CONCLUSIONS

This Scientific Reference Guide details the technical information used when developing recharge and discharge relations used in the Recharge Discharge Estimation Suite. This suite has been developed for use in data poor areas where preliminary assessment is required and the value of the resource does not necessitate more rigorous field based estimates to be made.

The recharge estimation spreadsheet uses empirically based relationships to develop and/or refine three methods for recharge estimation: Method of Last Resort (MOLR), %Clay and Groundwater Chloride Mass Balance (GCMB). The methods use readily available information on land use, soil type, groundwater chloride data and geology. The MOLR was developed using relationships identified from over 4400 field-based estimates of recharge, as presented in the review by Crosbie *et al.*, (2010A). In addition to estimated values, the methods also address the uncertainty of estimates by providing 95% prediction (confidence?) intervals. These intervals are up to two orders of magnitude from the mean for the MOLR, slightly less when using the %Clay method and significantly less when using the GCMB method. Also included in this Guide is a description of the method used for calculation of the lag time required for a new recharge regime to reach steady state at the depth of the watertable and at the depth of bore screens following clearing of native vegetation and establishment of crops and/or pasture.

The discharge estimation spreadsheet adopts a different approach to that described for recharge estimation. A lack of published field studies, such as those compiled for recharge in Crosbie *et al.* (2010), hindered the identification of empirical relationships. Instead, a simple water balance modelling approach has been developed, based on access to long term climate data. Actual evapotranspiration is estimated from evaporation using the Budyko framework (should this be referenced here?). Discharge rates estimated for the Wattle Range exemplar site using this approach are consistent with previously published field-based estimations. Long term rainfall and evaporation data are available for all of Australia, which, when used in conjunction with nationally available geology datasets developed in this project, facilitate the use of this tool in data poor areas. In addition, this project has highlighted the utility of simple ecohydrological models for the estimation of groundwater discharge. The simple empirical relationships identified between variables such as LAI and climate highlight the potential of these ecohydrological approaches, especially in water limited environments such as many regions of Australia. However a lack of available datasets currently constrains the widespread implementation of these techniques.

In addition to describing the methods used in the Recharge Discharge Estimation Suite, this Scientific Reference Guide summarises how to access default input databases required to populate the recharge and discharge spreadsheets. The input datasets include vegetation type, vegetation clearance, regolith and geology, soils, rainfall, evaporation, rainfall chloride input and groundwater chloride concentrations. It is recommended that the user should draw upon data which is of the highest resolution and accuracy available. This may or may not be the default national scale datasets available through MapConnect Groundwater.

The methodologies developed for recharge and discharge estimation have been applied in two exemplar sites, Wattle Range, south-eastern South Australia, and Tomago, near Newcastle, NSW. Results were compared with those from field based studies undertaken in the same areas. The recharge and discharge estimates using the different methods are internally consistent (i.e. they agree with each other) and are also in good agreement with previous estimates at the sites. In fact, the agreement for recharge estimates is usually within a factor of 2 or 3.

The authors are hopeful that the methods presented in the Recharge Discharge Estimation Suite will assist hydrogeologists in their management of groundwater resources in data poor areas and provide a consistent basis for recharge and discharge estimates (and the

associated uncertainty) in areas where no specific recharge and/or discharge studies have previously been undertaken.

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

- Akeroyd, M.D., Tyerman, S.D., Walker, G.R. and Jolly, I.D. 1998. Impact of flooding on the water use of semiarid riparian eucalypts. *Journal of Hydrology*, 206, 104-117.
- Bacon, P.E., Stone, C., Binns, D.L., Leslie, D.J. and Edwards, D.W., 1993. Relationships between water availability and *Eucalyptus camaldulensis* growth in a riparian forest. *Journal of Hydrology*, 150, 541-561.
- Banks, E., Wilson, T., Green, G. and Love, A., 2007. Groundwater recharge investigations in the Eastern Mount Lofty Ranges, South Australia. DWLBC Report 2007/20, Department of Water, Land and Biodiversity Conservation.
- Benyon RG, Doody TM. 2004. Water use by tree plantations in Southeast South Australia. Final report September 2004. Client Report No. 148. (26 Pages).
- Benyon, R.G., Theiveyanathan, S. and Doody, T.M., 2006. Impacts of tree plantations on groundwater in south-eastern Australia. *Australian Journal of Botany*, 54, 181-192.
- Budyko, M.I., 1974. *Climate and Life*, New York, Academic.
- Canadell, J., Jackson, R.B., Ehleringer, J.B., Mooney, H.A., Sala, O.E. and Schulze, E.D., 1996. Maximum rooting depth of vegetation types at the global scale. *Oecologia*, 108(4), 583-595.
- Carsel, R.F. and Parish, R.S., 1988. Developing joint probability-distributions of soil-water retention characteristics. *Water Resources Research*, 24(5), 755-769.
- Carter, J.L. and White, D.A., 2009. Plasticity in the Huber values contributes to homeostasis in leaf water relations of a mallee Eucalypt with variation to groundwater depth. *Tree Physiology*, 29, 1047-1418.
- Cartwright, I. and Weaver, T.R., 2005. Hydrogeochemistry of the Goulburn Valley region of the Murray Basin, Australia: implications for flow paths and resource vulnerability. *Hydrogeology Journal*, 13(5-6): 752-770.
- Cartwright, I., Weaver, T.R., Stone, D. and Reid, M., 2007. Constraining modern and historical recharge from bore hydrographs, ^3H , ^{14}C , and chloride concentrations: Applications to dual porosity aquifers in dryland salinity areas, Murray Basin, Australia. *Journal of Hydrology*, 332, 69-92.
- Choudhury, B.J., 1999. Evaluation of an empirical equation for annual evaporation using field observations and results from a biophysical model. *Journal of Hydrology*, 216, 99-110.
- Cook, P.G., Telfer, A.L. and Walker, G.R., 1993. Potential for salinisation of the ground water beneath mallee areas of the Murray Basin. CGS Report # 42 Flinders University. EWS (South Australia) Report # 93/6.
- Corlette, J.M.C., 1944. Water Supply for Newcastle, NSW, from the Tomago Sandbeds. *Journal of the Institution of Engineers, Australia*, 16(7-8 & 9), 3-23.
- Crosbie, R.S., 2003. The Regional Scaling of Groundwater Recharge, PhD Thesis, University of Newcastle, Callaghan, NSW, Australia.
- Crosbie, R.S., Binning, P., and Kalma, J.D., 2005. A time series approach to inferring groundwater recharge using the watertable fluctuation method. *Water Resour. Res.*, 41(1), 1008.
- Crosbie, R.S., Jolly, I.D., Leaney, F.W., Petheram, C. and Wohling, D., 2010A. Review of Australian groundwater recharge studies, CSIRO Water for a Healthy Country National Research Flagship, Canberra.
- Crosbie, R.S., Jolly, I.D., Leaney, F.W. and Petheram, C. 2010B. Can the dataset of field based recharge estimates in Australia be used to predict recharge in data poor areas? *Hydrology and Earth Systems Sciences*, 14, 2023-2038.
- Crosbie, R.S., McCallum, J.L., Walker, G.R. and Chiew, F.H.S., 2008. Diffuse groundwater recharge modelling across the Murray-Darling Basin: A report to the Australian

- Government from the CSIRO Murray-Darling Basin Sustainable Yields Project, CSIRO, Canberra.
- Davies, P. Crosbie, R. And Cresswell, R., 2011. Spatial distribution of chloride deposition across Australia (in prep).
- Dodd, J. and Bell, D.T., 1993. Water relations of understory shrubs in a Banksia woodland, Swan Coastal Plain, Western Australia. *Australian Journal of Ecology*, 19, 159-168.
- Doherty, J., 2005. PEST: Model Independent Parameter Estimation. Fifth edition of user manual. Watermark Numerical Computing, Brisbane, Australia.
- Donohue, R.J., Roderick, M.L. and McVicar, T.R., 2007. On the importance of including vegetation dynamics in Budyko's hydrological model. *Hydrology and Earth Systems Science*, 11, 983-995.
- Donohue, R.J., McVicar, T.R. and Roderick, M.L., 2009. Generating Australian potential evaporation data suitable for assessing the dynamics in evaporative demand within a changing climate. In: *Water for a Healthy Country National Research Flagship: CSIRO*.
- Donohue, R.J., McVicar, T.R. and Roderick, M.L., 2010. Assessing the ability of potential evaporation formulations to capture the dynamics in evaporative demand within a changing climate. *Journal of Hydrology*, 386, 186-197.
- Donohue, R.J., T.M. McVicar, L. Li and M.L. Roderick 2010. A data resource for analysing dynamics in Australian ecohydrological conditions. *Austral Ecology*. 35, 593-594.
- Eagleson, P.S., 1978. Climate, soil and vegetation: 1. Introduction to water balance dynamics. *Water Resources Research*, 14, 705-712.
- Ellis, T.W. and T.J. Hatton 2008. Relating leaf area index of natural eucalypt vegetation to climate variables in southern Australia. *Agricultural Water Management*. 95:743-747.
- Finch, J. W., 1998. Estimating direct groundwater recharge using a simple water balance model - sensitivity to land surface parameters. *Journal of Hydrology*, 211, 112-125.
- Green, G., Banks, E., Wilson, T. and Love, A., 2007. Groundwater recharge and flow investigations in the Western Mount Lofty Ranges, South Australia. DWLBC Report 2007/29, Department of Water, Land and Biodiversity Conservation.
- Grier, C.C. and Running, S.W., 1977. Leaf area of mature northwestern coniferous forests - relation to site water-balance. *Ecology*, 58, 893-899.
- Grieve, B.J., 1956. Studies of the water relations of plants. 1. Transpiration of Western Australian (Swan Plain) sclerophylls. *Journal of the Royal Society, Western Australia*, 40, 15-30.
- Hatton, T.J., Salvucci, G.D. and Wu, H.I., 1997. Eaglesons optimality theory of an ecohydrological equilibrium: quo vadis? *Functional Ecology*, 11, 665-674.
- HDWB, 1957. Water Supplies from Underground Sources. *Conference of Professional Officers Representing the Authorities Controlling Water Supply and Sewerage Undertakings Serving the Cities and Towns of Australia*, Newcastle, 13-29.
- Healy, R.W. and Cook, P.G., 2002. Using groundwater levels to estimate recharge. *Hydrogeology Journal* 10(1), 91-109.
- Herczeg, A.L., Dogramaci, S.S. and Leaney, F.W.J., 2001. Origin of dissolved salts in a large, semi-arid groundwater system: Murray Basin, Australia. *Marine & Freshwater Research*, 52(1), 41-52.
- Holland, K.L., Jolly, I.D., McKewan, K.L., Doody, T.M. White, M., Berens V. and Souter, N., 2008. The 'Bookpurnong Experiment': will groundwater management and flooding improve the health of floodplain vegetation? In 2nd International Salinity Forum, Adelaide, Australia.
- Howe, P., Cook, P.G., O'Grady, A.P. and Hillier, J., 2006. Analysis of groundwater dependent ecosystems water requirements. In Howe, P. (Ed.) *Pioneer Valley Groundwater Assessment*. Adelaide, Queensland Department of Natural Resources and Mines.

- Jolly, I.D., Cook, P.G., Allison, G.B. and Hughes, M.W., 1989. Simultaneous water and solute movement through an unsaturated soil following an increase in recharge. *Journal of Hydrology*, 111, 391-396.
- Jolly, I., Gow, L., Davies, P., O'Grady, A., Leaney, F., Crosbie, R., Wilford, J. and Kilgour, P., 2011. Recharge and Discharge Estimation in Data Poor Areas: User Guide for the Recharge and Discharge Estimation Spreadsheets and MapConnect. CSIRO: Water for a Healthy Country National Research Flagship.
- Kennett-Smith, A., Cook, P. and Walker, G., 1994. Factors affecting groundwater recharge following clearing in the south-western Murray Basin. *Journal of Hydrology* 154, 85-105.
- Keywood, M.D., Chivas, A.R., Fifield, L.K., Cresswell, R.G. and Ayers, G.P., 1997. The accession of chloride to the western half of the Australian continent. *Australian Journal of Soil Research*, 35(5), 1177-1190.
- Lamontagne, S., Cook, P.G., O'Grady, A. and Eamus, D., 2005. Groundwater use by vegetation in a tropical savanna riparian zone (Daly River, Australia). *Journal of Hydrology*, 310(1-4), 280-293.
- Leaney, F., 2000. Groundwater Salinisation In The Tintinara Area Of SA: Results Of Field Investigations, April 2000. CSIRO Land and Water Technical Report 34/00, Adelaide.
- Leaney, F., 2001. Estimation Of Recharge Under Irrigated Lucerne And Irrigated Olives Near Kynoch, South Australia. Unpublished report for South Australian Department of Water, Land and Biodiversity Conservation.
- Leaney, F.W.J. and Herczeg, A.L., 1999. The Origin Of Fresh Groundwater In The SW Murray Basin And Its Potential For Salinisation. CSIRO Land and Water Technical Report 7/99, Adelaide.
- Leaney, F., Walker, G., Knight, J., Dawes, W., Bradford, A., Barnett, S. and Stadter, F., 1999. Potential For Groundwater Salinisation In The Tintinara Area Of SA: Impacts Of Planned Irrigation Allocations. CSIRO Land and Water Technical Report 33/99, Adelaide.
- Leaney, F., Barnett, S., Davies, P., Maschmedt, D., Munday, T. and Tan, K., 2004. Groundwater Salinisation In The Tintinara Highland Area Of SA: Revised Estimates Using Spatial Variation For Clay Content In The Unsaturated Zone. CSIRO Land and Water Technical Report 24/04, Adelaide.
- Leaney, F.W., Herczeg, A.L. and Walker, G.R., 2003. Salinisation of a fresh palaeo-groundwater resource by enhanced recharge. *Ground Water* 41 (1), 84-92.
- Leaney, F., Mustafa, S. and Lawson, J., 2006. Salt Accumulation And Water Balance Under Different Land use In Bakers Range Area. CSIRO Land and Water Science Report 05/06, Adelaide.
- Lymburner, L., Tan, P., Mueller, N., Thackway, R., Lewis, A., Thankappan, M., Randall, L., Islam, A. and Senarath, U. 2011. The National Dynamic Land Cover Dataset. *Geoscience Australia Record* 2011/31.
- McDonald, R.C., Isbell, R.F., Speight, J.G., Walker, J. and Hopkins, M.S., 1998. *Australian Soil and Land Survey Field Handbook*, Second Edition. CSIRO, Canberra.
- McKenzie, N., Jacquier, D.W., Isbell, R., Brown, K., 2004. *Australian Soils and Landscapes — an Illustrated Compendium*. CSIRO Publishing, Melbourne.
- Mensforth, L.J., Thorburn, P.J., Tyerman, S.D. and Walker, G.R., 1994. Sources of water used by riparian *Eucalyptus camaldulensis* overlying highly saline groundwater. *Oecologia*, 100, 21-28.
- Munns, R., 2002. Comparative physiology of salt and water stress. *Plant Cell and Environment*, 25, 239-250.
- Northcote, K. H. with Beckmann, G. G., Bettenay, E., Churchward, H. M., Van Dijk, D. C., Dimmock, G. M., Hubble, G. D., Isbell, R. F., McArthur, W. M., Murtha, G. G., Nicolls, K. D., Paton, T. R., Thompson, C. H., Webb, A. A. and Wright, M. J., 1960-1968. *Atlas*

- of Australian Soils, Sheets 1 to 10. With explanatory data (CSIRO Aust. and Melbourne University Press: Melbourne).
- O'Grady, A., Carter, J. and Holland, K., 2010. Review of Australian groundwater discharge studies in terrestrial systems, CSIRO Water for a Healthy Country National Research Flagship, Canberra.
- Pain, C., Gow, L., Wilford, J. and Halas, L., 2010. Review of mapping approaches to recharge and discharge studies, CSIRO Water for a Healthy Country National Research Flagship, Canberra.
- Petheram, C., Walker, G.R., Grayson, R., Thierfelder, T. and Zhang, L., 2002. Towards a framework for predicting impacts of land-use on recharge. 1) A review of recharge studies in Australia. *Australian Journal of Soil Research*, 40(3), 397-417.
- Petheram, C., Zhang, L., Walker, G.R. and Grayson, R., 2000. Towards a framework for predicting impacts of land-use on recharge: A review of recharge studies in Australia. Technical Report 28/00, CSIRO Land and Water, Canberra.
- Raper, G.P., 1998. Agroforestry water use in Mediterranean regions of Australia. In *Water and Salinity Issues in Agroforestry NO2*, p. 71.
- Roderick, M.L. and Farquhar, G.D., 2009. Water availability and evapotranspiration in the Murray Darling Basin: A look at the past and a glimpse into the future. Murray Darling Basin Authority, Canberra.
- Saxton, K.E. and Rawls, W.J., 2006. Soil Water Characteristic Estimates by Texture and Organic Matter for Hydrologic Solutions. *Soil Sci Soc Am J*, 70, 1569-1578.
- Sinclair, Knight, Merz, 2002. An Estimation Of Groundwater Recharge In The Mallee and Wimmera (South-Western Murray Basin): A Land System Approach. Sinclair Knight Merz Report, Melbourne.
- Sun, D. and Dickinson, G.R. 1995. Salinity effects on tree growth, root distribution and transpiration of *Casuarina cunninghamiana* and *Eucalyptus camaldulensis* planted on a saline site in tropical north Australia. *Forest Ecology and Management*, 77, 127-138.
- Thorburn, P., 1996. Can shallow watertables be controlled by the revegetation of saline lands? *Australian Journal of Soil and Water Conservation*, 9, 45-50.
- Tolmie, P.E., Silburn, D.M. and Briggs, A.J.W., 2003. Estimating deep drainage in the Queensland Murray-Darling Basin using soil chloride. Queensland Department of Natural Resources and Mines, Toowoomba.
- Walker, G. R., Cook, P. G. & Gilfedder, M., 2007. Recharge/discharge determination. In: *Australian Groundwater School. Fundamentals of groundwater science, technology and management: Volume 2 - Technology*. Perth: Centre for Groundwater Studies.
- White, D.A., Battaglia, M., Mendham, D.S., Crombie, D.S., Kinal, J., McGrath, J.F. 2010. Observed and modelled leaf area index in *Eucalyptus globulus* plantations: tests of optimality and equilibrium hypotheses. *Tree Physiology* 30, 831-844
- Wohling, D., 2007. Minimising Salt Accession To The South East of South Australia. The Border Designated Area And Hundred of Stirling Salt Accession Projects. Volume 2 – Analytical Techniques, Results And Management Implications. South Australian Department of Water, Land and Biodiversity Conservation Report DWLBC 2008/23, Adelaide.
- Wohling, D., Leaney, F., Davies, P. and Harrington, N., 2006. Groundwater Salinisation In The Naracoorte Ranges Portion Of The Padthaway Prescribed Wells Area. South Australian Department of Water, Land and Biodiversity Conservation Report DWLBC 2005/27, Adelaide.
- Wohling, D. Leaney, F.W. and Crosbie, R.S., 2011. Improving confidence in drainage estimates using multiple linear regression with percent clay content and rainfall. Submitted to *Hydrology and Earth Systems Sciences*.

- Woolley, D., Mount, T., and Gill, J., 1995. Technical Review of the Tomago/Tomaree/Stockton Groundwater. NSW Department of Water Resources, Sydney.
- Yang, H., Yang, D., Lei, Z. and Sun, E., 2008. New analytical derivation of the mean annual water-energy balance equation. *Water Resources Research*, 44, W03410, doi:10.1029/2007WR006135.
- Zhao, B., Yan, Y., Guo, H.D., He, M., Gu, Y. and Li, B., 2009. Monitoring rapid vegetation succession in estuarine wetland using time series MODIS-based indicators: An application in the Yangtze River Delta area *Ecological Indicators*, 9, 346-356.



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