Accounting for the groundwater impacts of plantation forests in the South East of South Australia

by

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I certify that this thesis does not incorporate, without acknowledgment, any material previously submitted for a degree or diploma in any university; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text.

Darryl Harvey
31 August 2017

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[1] Flinders University and NCGRT

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Abstract

In the South East of South Australia groundwater management now incorporates 145,000 ha of plantation forest as a licensed water user; accounting for 30 per cent of all licensed water allocations administered under a statutory water allocation plan. This is the first time in Australia (and possibly the world) that plantation forests have been required to hold a water licence to offset their hydrological impacts and this has been acknowledged by the United Nations Association with an *Excellence in Water Management Award* in 2016.

It is impractical to measure plantation impacts on groundwater resources at a commercial plantation scale, whether in terms of impacts on groundwater recharge, or extraction from shallow water-tables. Therefore, there is a need for a robust model to account for hydrological impacts of plantation forests at a groundwater management area scale. The 2006 forest water accounting model was developed to account for the hydrological impacts of plantation forests on regional groundwater resources. The model is based on biophysical principles and scientific observations available at that time, however, until this study, no attempt has been made to validate the model outputs and to establish that the model is fit for the intended purpose.

The forest water accounting model was tested by calculating a net annual water-mass-balance for softwood and hardwood plantation sites against 30-years of observed changes in groundwater storage, as indicated by the changes in groundwater level. Five sites, each of 5000 ha, where plantation forests are the main land use, were assessed using an age profile of the plantation forest estate at those sites. The forest age and area profile is assembled from industry data provided when seeking their initial grant of forest water licenses for the plantation forest estate. The granted licenses are for offsetting of the forest impacts on groundwater recharge, and extraction where the plantation forest overlay shallow water tables, which is considered to be 6 metres, or less, below ground level.

The calculated annual net changes in groundwater storage compare well with the actual observed changes in groundwater storage. These results indicate that the adopted water accounting method can adequately estimate the annual net impacts of plantation forests on groundwater resources, concluding that it is fit for the intended purpose of estimating the hydrological impacts of the plantation forest estate at a groundwater management area scale. However, during the study it was found that existing plantation forests are extracting groundwater up to 10 metres below ground level.

The investigation also compared grassland land use impacts on groundwater resources, over the same time period, to further confirm the significance of plantation forest hydrological impacts on groundwater resources, relative to the land uses being replaced by plantation forest as the forest industry expands its activities.

Due to the uniqueness of requiring the regional plantation forest to be accountable for its hydrological impacts with licensed groundwater allocations, this thesis also includes a background of the groundwater policy development and the associated models forest water accounting models.

This thesis also includes some recommendations to refine the forest water accounting model and its application to provide a higher level of confidence in its predictions.

2nd rotation *Pinus radiata*, entering their 3rd year at Comaum Forest Reserve (Edenhope-Penola Road)

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1 Introduction

1.1 Background

A water licence system for accounting for the hydrological impacts of the regional plantation forest estate on the groundwater resource in the South East region of South Australia has recently been incorporated into the water management policies in the Lower Limestone Coast Prescribed Wells Area through a statutory water allocation plan (South East Natural Resources Management Board, 2013)[1]. In applying the adopted accounting methodology, the South East Natural Resources Management Board estimates the regional plantation forest estate of 145 000 ha has a hydrological impact on the local groundwater resource of approximately 308 GL per year, about 30 per cent of the total water allocated for all licensed uses.

Introducing a licensed water accounting system for plantation forest hydrological impacts has not been free of controversy, as it is the first time that such a system has been applied within Australia, for either surface water or groundwater accountability and management. While not confirmed, it is believed to be the first time world-wide that plantation forestry is now accountable for its hydrological impacts through a water licence system, where the water rights are transferable with other uses. This water resource management development was recently noted and acknowledged by the United Nations Association of Australia with an award to the Department of Environment, Water and Natural Resources and the South East Natural Resources Management Board[2].

The regional plantation forest estate is largely based on two species; *Pinus radiata* being the pine or softwood species and *Eucalyptus globulus*, Tasmanian Blue Gum, or the hardwood forest species[3]. These are also known as long rotation and short rotation forests respectively. The two species are planted and managed separately, with the respective wood products generally destined for different markets and uses. The regional softwood plantation industry dates back over one hundred years, whereas the hardwood industry has only existed in the region since the late 1990s (Green Triangle Regional Plantation Committee 2001).

The licensed forest water allocations, which are transferable property right (subject to conditions), were granted to forest managers, as at December 2014, to offset the hydrological impacts of the

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[1] Avey and Harvey (2014) provide detail on the associated legal processes and history.

[2] United Nations Association of Australia Monday, June 6th, 2016. *Excellence in Water Management Award* winner: *Accounting for and managing the water resource impacts of plantation forestry in the Lower Limestone Coast Region of SA.*

[3] This thesis will generally use the terms softwood and hardwood for the two different plantation forest types.

existing regional plantation forest estate on the local groundwater resource. The volumes of water allocated to the forest managers, for the recharge and extraction impacts of each forest compartment[4], have been based on the values calculated by the forest water accounting model described in Chapter 3.

To ensure that the regional groundwater resource can be managed sustainably, as required by the *Natural Resources Management Act 2004*, the substantial hydrological impacts of plantation forests in the Lower Limestone Coast region is now integrated into regional groundwater accounting and management through the South East Natural Resources Management Board's (2013) *Water Allocation Plan for the Lower Limestone Coast Prescribed Wells Area* (water allocation plan).

The forest water accounting system adopted for the Lower Limestone Coast region is an annualised[5] accounting system of the hydrological impacts of the industrial scale plantation forest estate. The annualised accounting approach is premised on individual forest compartments being part of a 'mature' industry where the plantation forest estate is of a mixed age, with the area of the various plantation age classes within the estate being similar, to provide a consistent volume and flow of logs to the various value adding wood product sectors associated with each plantation industry.

The objective of applying an annualised approach is that it is relatively simple for all stakeholders to understand and to administer. Reporting by the plantation forest manager is simplified and compliance requirements are minimal. If the plantation forest estate is operated as a mature industry, with a relatively uniform distribution of forest compartments by area and age, the accounting of hydrological impacts should be sufficiently accurate for groundwater management purposes at an aggregated scale across, or at, a groundwater management scale. Groundwater management areas are generally based on cadastre and vary in size from about 3775 to 55 600 ha. Data published by the South East Natural Resources Management Board (2013) indicates the average groundwater management area is about 24 000 ha.

In this forest water resource accounting approach at a groundwater management area scale, or a sub-regional scale, regardless of forest compartment age, annualised accounting applies an average annual hydrologic deemed value to all plantations of the same forest type (hardwood or softwood).

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[4] A forest compartment is a forest management unit. There is no specific area, but is generally determined by planting date, anticipated productivity class and subsequent management. Data indicates that compartment areas vary significantly in a range from tens of hectares up to several hundred hectares.

[5] 'Annualised' has been adopted by the region as an appropriate accounting term for the applied water accounting methodology, which is essentially the mean annual impact over the full forest rotation period, including site clean-up period after clear felling and prior to re-planting.

The deemed annualised accounting values are outputs of the 2006 forest groundwater accounting model being tested. These values are established by varying the parameterisation for the two forest categories, relative to the forest management practices of the forest managers. When the description of the characterised average forest rotation management is agreed, the parameters in the model are aligned with the industry description of the management practises of the average plantation in the region, in respect to rotation length, the number of thinning operations in the case of softwood plantations, and the form of reafforestation for the next rotation of hardwood plantations.

The depth to the water table under the plantation forest is the only indicator as to whether the subject plantation is considered to extract groundwater (Benyon and Doody 2004).

An alternative annual accounting system would require an annual impact value for each forest compartment, for each year of its life. From a compliance perspective, an annual accounting approach, while perhaps providing a more accurate annual hydrological impact account for each forest compartment, would be demanding in time and cost, on both the forest manager and the water regulator, in terms of data requirements, administration, reporting and compliance. An annual system would be of little additional benefit in delivering water accounting accuracy at the groundwater management area scale, if the plantation estate is managed reasonably consistently with the forest management approach advised by the forest managers at the time of settling on forest management parameters in the adopted forest groundwater model.

The metrics related to plantation forest impacts on groundwater recharge are expressed as a percentage of the recharge that is considered to occur in a grassland landscape in the same management area. Since the late 1970s, when it was no longer legal to clear native vegetation, all new plantation forests occur on grasslands, meaning that there is a reduction in aggregate regional groundwater recharge as the plantation forest industry expands its footprint.

The forest water model is based on the principle that in the Lower Limestone Coast (where the mean annual rainfall across the region ranges from 550 to 800 mm), there is no recharge under a closed canopy forest. As a consequence, any groundwater recharge under plantation forest land use occurs in the period between planting and canopy closure, and in the case of softwood plantations, additional recharge is associated with the plantation thinning operations.

In the Lower Limestone Coast region, diffuse groundwater recharge is a key input for groundwater accounting and hence for the determination of sustainable licensed allocations. In the Lower

Limestone Coast region, groundwater recharge is the residual rainfall after water loss and use associated with regional covering vegetation (Dillon *et al* 2001). Due to this form of accounting, it is not necessary to quantify the evapotranspiration water associated with the covering forest.

The metrics used to quantify groundwater extraction by plantation forests from shallow water tables is an equivalent depth of rainfall, or alternatively, this is expressed as volume of water per hectare of plantation forest (ML/ha). This accounting approach has been based on the findings of Benyon and Doody (2004), when they established a deficit in the accounting of evapotranspiration in closed canopy plantation forests in the Lower Limestone Coast region and attributed the water deficit to groundwater use by the overlaying plantations.

1.2 Literature review

Literature reviews are a continuing process where there is a need to expand knowledge. In the case of the subject of this study there have been three significant periods of literature research and they are; in 2001 at the time of the construction of the first forest water accounting model; when the impacts of forest plantations on recharge was re-considered when the model was reviewed in 2006 and groundwater extraction was incorporated into the model (now adopted by the water allocation plan of the Lower Limestone Coast region); and now, when the adopted forest water model is being tested for its accuracy and suitability for its intended use.

During these periods of literature review, a number of points have become clear and these can be categorised as follows:

- Many studies have sought to understand the impact of plantation forests on surface water catchment yields
- Most studies undertaken are at a small scale; plots scale, some in tens of hectares and a small number in the hundreds of hectare scales
- Many of the studies are conducted over a short period, relative to the long life cycle of a plantation forest being in the order of 30-40 years, in the case of softwood plantations
- Few studies have been directly related to the impact of plantation forests on groundwater resources, but the most informative of these studies have been applied to the development of the 2006 forest water model and its current testing.

The Holmes and Colville (1970) identification of an imbalance in the water-mass-balance estimations for the south-east region of Australia, provided an insight that plantation forest may be extracting groundwater, however this remained an unquantified aspect in regional groundwater resource management for over 30 years. The literature review of Dillon *et al* (2001) refers to the work of Holmes and Colville and the high probability that groundwater extraction by plantation forests was occurring to some extent at some locations in the south east of South Australia. The review by Dillon *et al* (2001) provided confidence to the state and regional groundwater resource manager to adopt the management principle that there was minimal recharge under a closed canopy plantation forest (Avey and Harvey 2014). Consequently, this was applied in the model as a principle, that no groundwater diffuse recharge is considered to occur under closed canopy plantation forests. In the case of hardwood plantations, canopy closure is considered to occur three years after planting and six years for softwood plantations. The development of the Zhang curve, also referred to by Dillon *et al* (2001), while not directly related to forest impacts on groundwater, provides generalised relationship between forest evapotranspiration and rainfall (Zhang *et al* 1999). This remains to be a useful robust test for the magnitude of plantation forest land use impact on local hydrology.

In regard to building on the proposition by Holmes and Colville (1970a and 1970b) that plantation forests extract groundwater, the work by Benyon and Doody (2004) provides key evidence that quantifies the extraction of groundwater where closed canopy plantation forests have access to shallow water tables. The work of Benyon and Doody (2004) is a significant factor in the development of the 2006 forest water accounting model, the subject of this thesis. Subsequent work by Benyon and Doody (2009) has provided further support for the principle that there is minimal recharge under closed canopy plantation forests and that where weed control is practised at the time of reforestation with another forest rotation, there is likely to be a higher rate of recharge than that is considered to occur under grassland land use.

Whilst Benyon and Doody (2004), provide significant observed information, this is limited to a relatively short period (two to three years), relative to the life of a commercial plantation rotation, which can be in the order of 30 to 40 years for a softwood plantation, or up to 20 years for a hardwood plantation that is managed for paper pulp wood chip production.

A considerable amount of forest hydrology has been investigated and reported from South Africa and this has clearly been influential in that jurisdiction pursuing a form of management control in regard to managing the transition of grasslands to plantation forests. However, these studies have a focus on the impacts on stream flow (Scott *et al* 2000, Scott and Prinsloo 2008, and Scott and Smith 1997). Other forms of study have been the impact of regeneration of native forests on catchment yields, such as that undertaken by Bosch and Hewlett (1982) and Langford (1976), while Ruprecht and Schofield (1989) have investigated the impact of forest clearance on stream flow in south west

Western Australia. All these studies, and others related to comparing forest catchments with grassland catchments, under the same or similar climatic conditions, confirm that the evapotranspiration characteristics of forests (plantation or native) are greater than grassland land uses, and while not stated by an authoritative source, similar losses of rainfall to forest evapotranspiration could be expected to occur in a groundwater recharge zone (where there is no catchment runoff), such as in the Lower Limestone Coast region.

A further literature review was conducted by Prosser and Walker (2009). This work was commissioned by the state water resource manager and has a focus on the relevance of forest land use impacts on surface water and groundwater hydrology. An outcome of this review reinforces that plantation forests use more water than agricultural land covers such as pasture, cereals and other crops, and that plantations could have a negative impact on wetlands. Their advice has a significant focus on management approaches to manage the risk and uncertainty associated with the change of land use from grassland to plantation forests.

However, from the available literature, it seems that the hydrological impact of plantation forests cannot be quantified over a full plantation life cycle and particularly, at the forest industrial scale (thousands of hectares) where the plantation forest estate is based on mixed ages, resulting in a continuous cycle of reforestation. Full accountability is a special need in the Lower Limestone Coast region where plantation forests are a significant component of the local water budget and are now offset with a transferable licenced water property right.

As result of the literature reviews undertaken, it is concluded that other than for the work undertaken by Benyon and Doody (2004) and (2009), there is limited scientific work available that quantifies the extraction of groundwater by plantation forests from shallow water tables. While very informative, the work of Benyon and Doody is generally limited to periods of two to three years of a forest life. As a result, it is believed that a significant knowledge gap exists in respect to the full hydrological impact of industrial scale plantation forests on groundwater resources over a plantation forest life cycle.

In order to test the suitability of the adopted forest water accounting model, which was developed to fill this accounting gap, some of the above-mentioned literature has again been reviewed as preparation for this current investigation. Dillon *et al* (2001) has provided support in the use of some of the hydrogeological parameters being applied in the model and its testing. These have included recharge rates, storage coefficients and the selection of a 4 km radius of the study sites.

In addition, literature reviewed to incorporate the latest available knowledge around the connection between the unconfined and confined aquifers in the Nangwarry area is considered necessary because of the possibility that this may interfere with softwood study sites. In this regard, the work of SKM (2012) and Somarante *et al* (2016) has been considered; both confirming there is likely to be some diffuse recharge from rainfall passing from the unconfined Tertiary Limestone Aquifer to the Tertiary Confined Sand Aquifer at parts of the landscape in the Nangwarry area, where two study sites are located.

1.3 Objectives

The objective of this research is to assess whether the forest water accounting model that underpins the forest water accounting system in the regional water allocation plan[6] adequately reflects, for management purposes, the hydrological impacts of plantation forests on groundwater resources in this South Australian region.

While the model and the related parameterisation are agreed between key stakeholders, the model output values have not been tested for accuracy, and hence, their suitability for accounting for, and assisting in the management of groundwater resources in the Lower Limestone Coast Prescribed Wells Area[7] (Lower Limestone Coast region), an area of about 1.45 million hectares, where plantation forests are a significant land use.

This forest water accounting model analysis is necessary for stakeholder confidence in any related groundwater technical assessments and subsequent management responses, where plantation forests have a significant influence on regional or sub-regional groundwater resources. Under the current prescription regime, all future plantation forests will now need to offset their hydrological impact with an appropriate water licence, the source of which will be through a market and transfer system. This provides another reason to validate the hydrological deemed impact values for plantation forests. Validation is also important for confidence in the associated water licensing system which involves a valued transferable water property right. For these reasons, it is important to test whether the forest water accounting model can be considered ‘fit for purpose’.

Subject to the outcome of testing the predicative capability of the forest water accounting model, for estimating the hydrological impact of plantation forests on groundwater resources, knowledge

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[6] This water allocation plan is a statutory document which was adopted by the Minister for Sustainability, Environment and Conservation on 26 November 2013, pursuant to section 80(3)(a) of the *Natural Resources Management Act 2004*. The Plan was prepared by the South East Natural Resources Management Board.

[7] This is the legal name given to the prescribed groundwater resource area in the lower South-East region of South Australia.

gains may assist in refining the model to improve its accuracy, or provide a better understanding of its constraints.

1.4 Scope of the study

The annual components used in constructing the forest water accounting model are an essential component in estimating the aggregated net hydrological impact of the plantation forest estate, over its life, as continuous harvesting and replanting of the compartments in the forest estate occurs.

The analysis undertaken tests whether the assumptions and the parameters applied in the forest water accounting model are reasonable for estimating the hydrological impacts of plantation forest life cycles at a management area scale in the Lower Limestone Coast region. The aggregation of these annual components then determines the model output and its relative accuracy in the deemed annualised accounting values for the recharge and extraction impacts of the region’s two forest types.

This research will enable a testing of the sensitivity of some of the assumptions and the applied parameters, such as the groundwater recharge rate assigned to plantation forests, the extinction depth for groundwater extraction by the plantation forests and the appropriateness of the management regime of the characterised ‘average’ plantation forest.

Using the annual hydrological components of the forest water accounting model for recharge and extraction impacts, this study tests a calculated net annual mass-water-balance, as a prediction of a net change of groundwater storage, against the observed net annual changes in groundwater in storage, as indicated by the changes in the depth to the water table. This is conducted at five different sites where plantation forests are the main land use. The area of each study site is approximately 5000 ha, resulting in 25 000 ha of land use, which includes over 17 000 ha of mixed aged plantation forests being observed for recharge and extraction impacts for periods of 30 years in the case of softwoods and up to 20 years for hardwood plantations.

The focus of the forest water accounting model is on quantifying the combined impacts of the plantation forests on groundwater recharge and extraction where they overlay shallow water tables. The plantation forest recharge impact is expressed as a factor of the diffuse groundwater recharge that would occur in the agricultural landscape (referred to as grassland in this thesis) replaced by the forests, whilst plantation forest groundwater extraction is expressed as a volume per hectare of plantation forest. Collectively, these forest hydrological impacts contribute to aggregated annual recharge and discharge components in the water-mass-balance for each study area, with the net impact affecting the volume of groundwater in storage at each site.

In addition to reviewing the performance of the forest water accounting model, a comparison of water table trends at non-forested sites, over the same time period, is undertaken for some grassland sites to provide an additional line of evidence of plantation forest impacts on the regional groundwater resource. This approach could be considered to be similar to the ‘paired catchment’ approach taken by researchers such as Scott and Prinsloo (2008), and Walker and Zhang (2001) in the assessment of forest impacts on run off in surface water catchments.

2 Study area and key assets

2.1 Land resources and climate

South Australia is considered to be Australia's driest state with only about 2 per cent of its area receiving 600 mm, or more, of annual rainfall. About a half of this area occurs in the Lower Limestone Coast region of the state. This region has a Mediterranean climate with a generally reliable winter rainfall, cool winters and warm to hot dry summers. The region covers an area of about 1.45 million hectares and the mean annual rainfall ranges from about 550 mm in the northern area to just over 800 mm in the higher elevated country west of Mount Gambier (refer to Appendix 2a for a sample of regional mean annual rainfall data).

Broad scale land clearance commenced in the region over 150 years ago, and continued until the late 1970s when the remaining native vegetation became protected by state law. Only about 12 per cent of the Lower Limestone Coast Prescribed Wells Area landscape remains covered in native vegetation (Brown *et al* 2006). Most of the remaining land is used for agricultural activities and plantation forests, with forests covering about 10 per cent of the total area, or about 17 per cent of the land that receives 600 mm, or more, of annual rainfall, and under planning regulations is available for agricultural or plantation forest land uses.

It should be noted, that unlike many jurisdictions, South Australia does not allow the harvesting of natural native forests for commercial purposes, meaning that all South Australian forest products are from plantation grown timber.

A mean annual rainfall of 600 mm is generally regarded to be the minimum requirement for commercial industrial scale plantation forestry (Zhang *et al* 2007). The regional map at **Figure 2.1** shows the distribution of plantation forest development, the groundwater management area boundaries and significant rainfall isohyets. The map also shows the Border Designated Area, a 20-km wide strip, each side of the Victorian state border that is subject to collaborative groundwater management with Victoria, under a formal agreement with supporting legislation in each state[8].

In general, the regional terrain can be considered as flat to gently undulating and is mostly covered with free draining sandy soils over limestone with some karst features[9]. There are several streams crossing from the state of Victoria into the region, but there are no natural streams discharging

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[8] *Groundwater (Border Agreement) Act 1985* for both South Australia and Victoria.

[9] Geological formations shaped by the solutional erosion commonly developed on carbonate rock, often associated with distinctive features such as cenotes and dolines (or sinkholes).

surface water into the marine environment[10]. The streams that cross from Victoria terminate within about 30 km of the state border, and subject to the rainfall characteristics at the time, are generally seasonal to episodic streams.

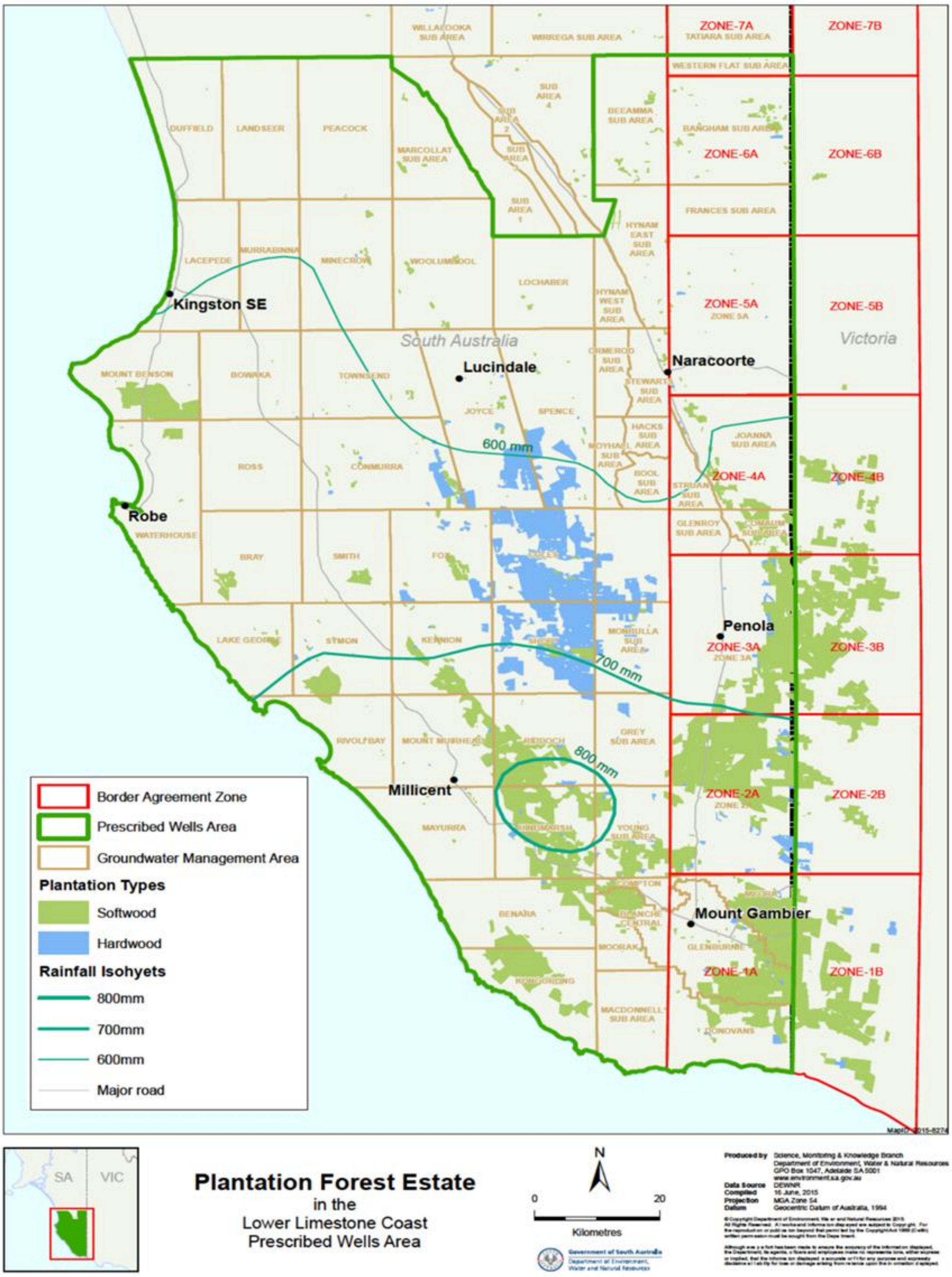

Figure 2.1: Lower Limestone Coast region with the plantation forest estate distribution

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[10] Eight Mile Creek transfers groundwater discharge to the marine environment.

Due to the underlying geology, the topography and the reliable rainfall, the main natural water resource is found in the unconfined Tertiary Limestone Aquifer. The groundwater in the unconfined aquifer is of good to high quality and provides reliable supplies for livestock, irrigation, industrial and public uses. As a result of these natural attributes, the region plays an important role in the state's primary production, with diverse agricultural, pastoral and forest activities. Many crops and pastures are dry-land grown, but others, including high production pasture, seed crops, horticulture and viticulture are irrigated from the local groundwater resource.

2.2 Regional groundwater resource

The hydrogeology of the south-east region of South Australia has been extensively studied and documented during recent years. Some of these include Stadter (1989), Bradley *et al* (1995) and Brown *et al* (2001). The regional groundwater resources occur in what is considered to be two separate aquifer systems, an upper unconfined aquifer known as the Tertiary Limestone Aquifer and the deeper Tertiary Confined Sand Aquifer.

The unconfined Tertiary Limestone Aquifer is a productive extensive aquifer stretching across the south east of the state from the Dundas Plateau in south west Victoria towards the coast. Groundwater flow is towards the coast, generally from east to west, however in the southern part of the region, the flow direction trends southwards. As the topography is considered to be flat to gently undulating and the soils are generally highly permeable, Dillon *et al* (2001) notes that most of the rain that falls to the ground infiltrates the soil, resulting in very little surface runoff, and that part of rainfall passing below the root zone becomes groundwater recharge in the generally thick limestone aquifer.

The region has a number of karst features and whilst these can present as features for point recharge, in regard to the broader scale, these recharge volumes are considered negligible in comparison to the regional diffuse recharge from infiltration (Dillon *et al*, 2001).

A topographic and geological feature of the region are the ancient stranded coastlines that run parallel to the present coast. These dune structures of Bridgewater Formation are a legacy of the glacial and interglacial phases in the Quaternary period. Other than for the Dundas Plateau, the stranded coastal dunes and an elevated area in the Mount Gambier area, the depth to the unconfined saturated zone is considered to be relatively shallow. The depth to the water table, at

June 2004[11], is indicated in **Figure 2.2**, with the greater depths being generally reflective of the geological features mentioned above.

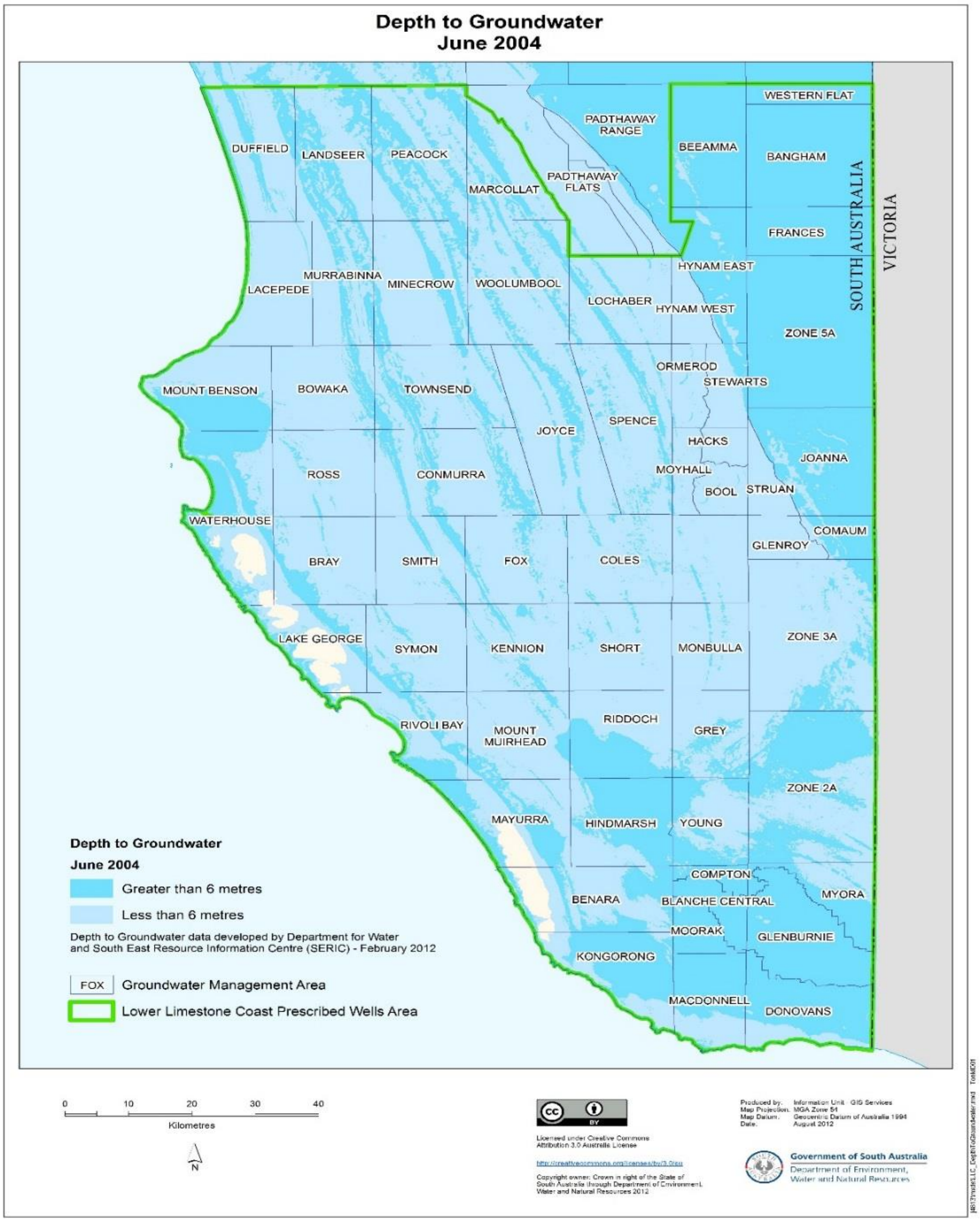

Figure 2.2: Depth to the water table (unconfined aquifer) in the Lower Limestone Coast Prescribed Wells Area

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[11] The water table at June 2004 is the adopted reference point for the granting of the foundation licensed water allocations to offset the extraction by the plantation forest estate existing at 2014. This is a policy decision that aligns with the introduction of the *Natural Resources Act (2004)*. (Avey and Harvey 2014)

2.3 Regional surface water

Whilst the surface water component of the regional water balance is considered to be relatively inconsequential for, and relative to, the groundwater system (Dillon *et al*, 2001), there is a significant network of constructed drains in the region. In the lower South East of the state, drains were constructed to remove excess surface water to the coast. These drains are often regarded as facilitating the diversion of 'rejected' groundwater recharge out of the area. A feature of this infrastructure is to facilitate the surface flows through the remnant coastal dunes towards the coast. In the northern area, generally termed the mid and upper South East of the state, drains were constructed to remove rising saline groundwater to the marine environment.

In general, most of the region's softwood plantation forests do not occur in areas where the south east drainage system occurs. Most of the region's hardwood plantations occur in the Wattle Range area, west of Penola, and this area is traversed by several main drains, one being Drain M and the other is the southern portion of the Bakers Range Drain. **Figure 2.3** locates the constructed drains and natural water courses in the south east of the state.

Drain M was constructed to carry flood water from Bool and Hacks Lagoons to the marine environment. These lagoons receive water from Mosquito Creek that crosses from Victoria. A water management balance is sought for managing these lagoons as there is an international obligation under the Ramsar Convention to maintain a wetland regime in these lagoons[12]. Once full, a regulator at the head of Drain M manages water flows to maintain water levels in the lagoons, without flooding adjacent agricultural land. Prior to the construction of Drain M, flood water from Mosquito Creek would fill the lagoons and then flood the surrounding agricultural land. With the natural water table being at very shallow depths[13], it could be postulated that the subsequent flood water was a mix of surface water from Victoria and rejected groundwater recharge from the area surrounding the lagoons.

Prior to plantation forests becoming a significant land use in the area, surplus surface water, or rejected groundwater originating in some of the now forested areas, provided some of the inflow to the Bakers Range Drain in the Wattle Range area. Since the development of plantation forests in the

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[12] The **Ramsar Convention** is an international treaty for the conservation and sustainable use of wetlands. It is also known as the **Convention on Wetlands**. It is named after the city of Ramsar in Iran, where the Convention was signed in 1971

[13] At Obswell ROB009, SWL below ground level generally has ranged from 1.6 m to 4.0 m below ground level between 1970 and 2015. This well is on farm land near the southern edge of Bool Lagoon

Wattle Range area, there have been limited flows in the southern portion of the Bakers Range Drain. This is coincidental to the forest estate development but can be mainly attributed to a period of reduced rainfall commencing in the mid-1990s.

In general, the floor levels of the Wattle Range drains are at levels similar to the historic groundwater levels in the pre-plantation forest period[14]. Since the establishment of hardwood plantations in this area in the late 1990s, groundwater levels are now lower. Under these circumstances, should there be a flow in the Wattle Range drains, any natural leakage or discharge from these drains could be considered as groundwater recharge. Comment on the Wattle Range drains and their hydrological influence is presented later in this thesis.

The Upper South East Dryland Salinity and Flood Program was initiated in the early 1990s to address concerns about dryland salinity, and waterlogging caused by a period of rising groundwater. The rising groundwater in this area was the result of two unrelated events, but occurring at about the same time. One was a significant change in the composition of the broad acre pastures in the late 1970s caused by the accidental introduction of two foreign aphids[15] which decimated the extensive dry land lucerne pastures. For many years, this deep-rooted perennial, which replaced much of the native vegetation, had ‘provided’ a hydrological balance mechanism in the upper South East region. A number of years passed before lucerne varieties that were aphid tolerant were established across the landscape. In this intervening period, due to loss of deep rooted perennial vegetation, diffuse groundwater recharge from rainfall increased, contributing to a rise in the local water table.

The second event was the flooding of two surface water streams crossing from Victoria. Floods in 1981 in the Tatiara and Nalang Creeks coincided, and the combined outflow at the confluence flooded widely and provided a recharge surge to the local groundwater system, part of which in the Keith area already had naturally high levels of salinity. While there is no specific geographic boundary between the lower, mid and upper regions of the South East, based on functional differences, Lucindale could be considered the northern area of the lower South East.

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[14] As an example, Obswell CLS003, which is located near to Drain M, has a depth to SWL of 0.47 m to 2.5 m during the 1970s. Obswell CLS009, which is located near to Bakers Range Drain has a depth to SWL bgl of 0 m to 2.0 m in the period from 1970s to 1990.

[15] Spotted alfalfa aphid and the blue-green aphid from USA

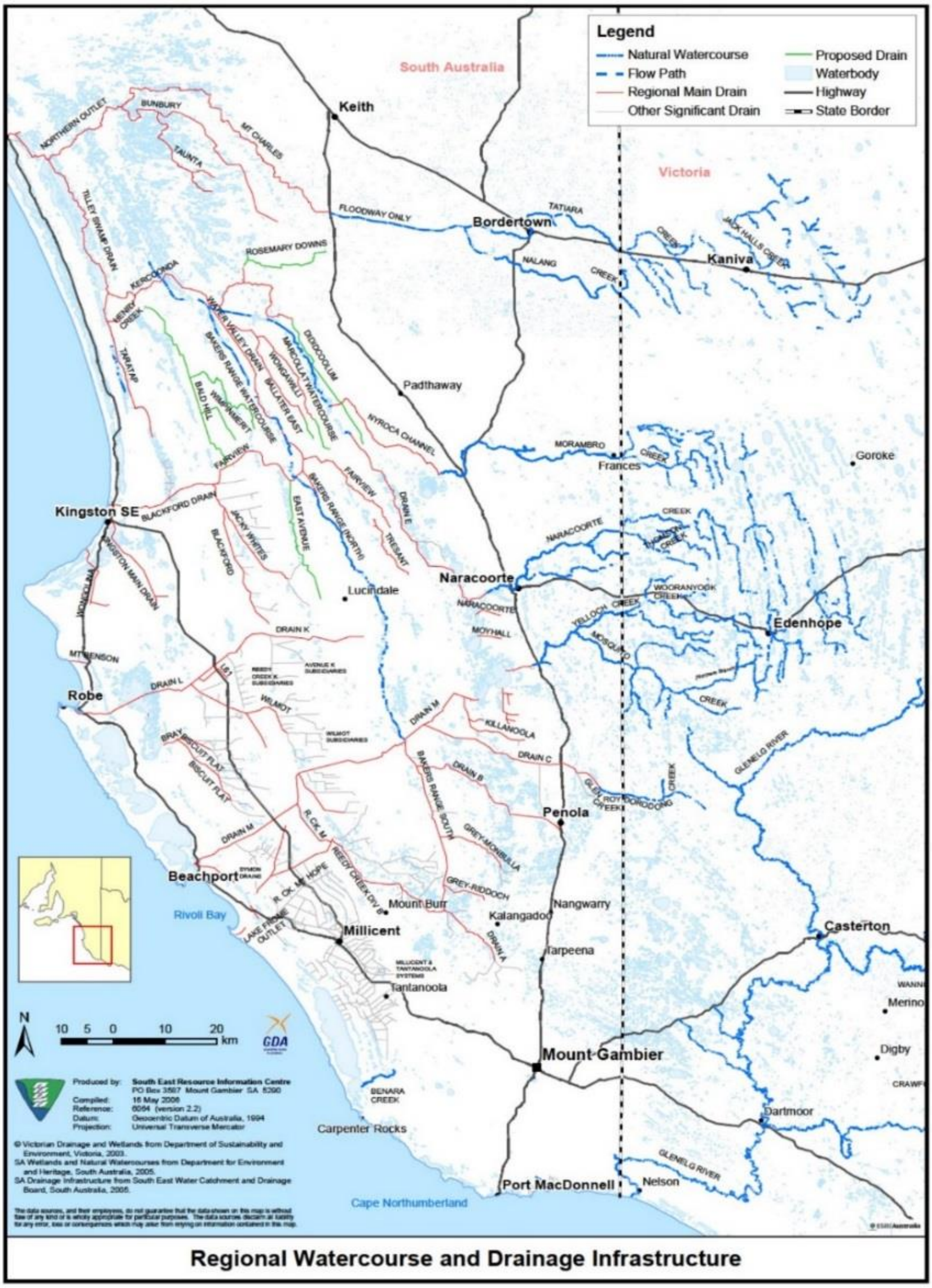

Figure 2.3: Constructed drains and natural water courses in the south east of South Australia

2.4 Regional groundwater management and monitoring network

The formal regional management of groundwater commenced in the border zone with Victoria in 1986. This was the consequence of a bilateral agreement between the two states to equitably share the common groundwater resource in a 20-km zone each side of the state border. The bilateral arrangement with Victoria remains administered under the *Groundwater (Border Agreement) Act 1985* (Avey and Harvey 2014).

The decision to proclaim[16] part of the region in 1986 and place it under formal groundwater management, with a water licensing system, was believed necessary because some declines in the water table were being observed and a trend of expanding irrigation activities. At the same time, in areas adjacent and to the north of the region, groundwater salinity increases were being observed. The objective of introducing a formal management system was to halt the expansion of irrigation activities until detailed assessments of the groundwater resources had been undertaken, and the risk to groundwater sustainability assessed[17] (Avey and Harvey 2014).

By 1997, the remainder of the Lower Limestone Coast was placed under formal groundwater management through the prescription process. Once a water resource is prescribed, legislation requires a technical assessment of the amount of groundwater that can be sustainably extracted. By this time, prescription was not driven by immediate concerns for sustainability but was undertaken as a precautionary measure. Furthermore, while it was not recognised at the time, this was the beginning of a period of reduced annual rainfall in the region[18]. Rainfall variability is taken into account in this study and is discussed in the Methodology Chapter.

The Lower Limestone Coast Prescribed Wells Area is divided into 61 separate management areas, which can be viewed in Figure 2.1. Each is assessed individually for sustainability on the basis of estimated mean annual diffuse recharge to the groundwater resource from local rainfall and the

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[16] 'prescription' and 'proclamation' are legal actions to introduce formal water resource management to an area and this generally requires the adoption of a statutory water allocation plan.

[17] Irrigators existing at the time of proclamation (later it became described as prescription) and those who could demonstrate an existing financial commitment to intended irrigation activities at the time were generally granted licensed water allocations to enable a continuation of existing practices. Access to stock and domestic water was not licensed as this was considered to be a statutory right.

[18] With the benefit of history, it can now be observed that an annual rainfall reduction commenced in about 1993-94 was of the order of about 10 per cent across the Lower Limestone Coast region. Nationally, this period extended to about 2006 and was known as the Millennium Drought.

taking into account of all groundwater extractions, including estimates for stock and domestic uses (Latchem *et al* 2007).

For groundwater management purposes, the lateral groundwater outflow is accounted for as being equal to the lateral inflow; this landscape management policy approach is to maintain natural through flow of groundwater in the aquifer for long term salinity management.

For groundwater accounting purposes, in the period from late 1990s to the early 2000s, it was assumed that groundwater recharge did not occur under plantation forest, regardless of its age, or under native vegetation. For groundwater accounting purposes, recharge was considered to only occur where the land use was agriculture (Brown *et al* 2006)[19], which was mostly pasture with some small areas of cropping. This was a precautionary groundwater accounting approach adopted in the region at that time.

A detailed account of the evolution of formal groundwater management with the supporting administrative structures in the region is described by Avey and Harvey (2014).

The region is serviced by a network of government monitoring wells for observing groundwater levels, with some of these observations dating back to the 1970s. This study utilises observations from monitoring wells in this network. Each of the five study sites in this study is centred on a monitoring well, generally with a 40-year monitoring history. In addition, five monitoring wells with a similar monitoring history, but situated in a predominantly grassland land use environment, provide data comparative to that observed at the study sites where plantation forests are the main land use.

Recent hydrogeological investigations east of Nangwarry, in the border zone with Victoria, have now established a hydraulic connection between the unconfined Tertiary Limestone Aquifer and the Tertiary Confined Sand Aquifer (SKM 2012). This area can now be considered as a recharge zone for the confined aquifer and this is referred to later in this thesis when discussing local water table characteristics and responses to plantation forest impacts. The spatial or quantitative extent of this hydraulic connection between the two aquifers, or its significance, is not known.

Where the water table can be considered to be at a relatively shallow depth, approximately 10 metres or less, the groundwater level responses to changing recharge and discharge processes are relatively rapid in the unconfined Tertiary Limestone Aquifer. Whilst discharge processes are an

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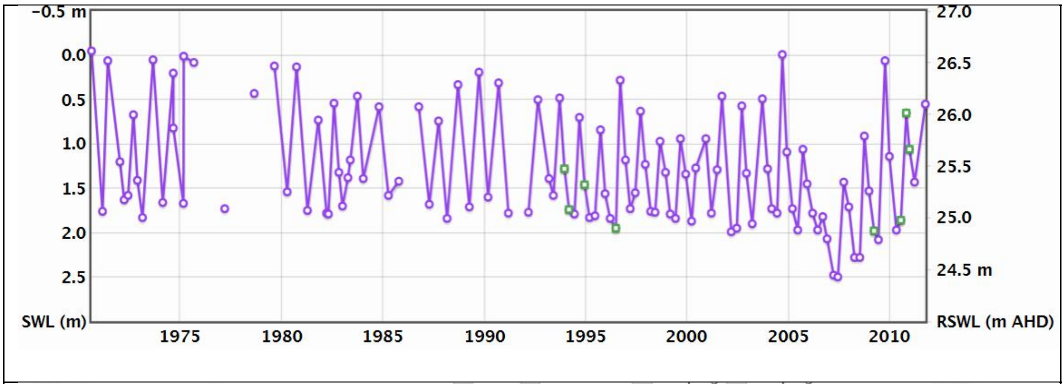
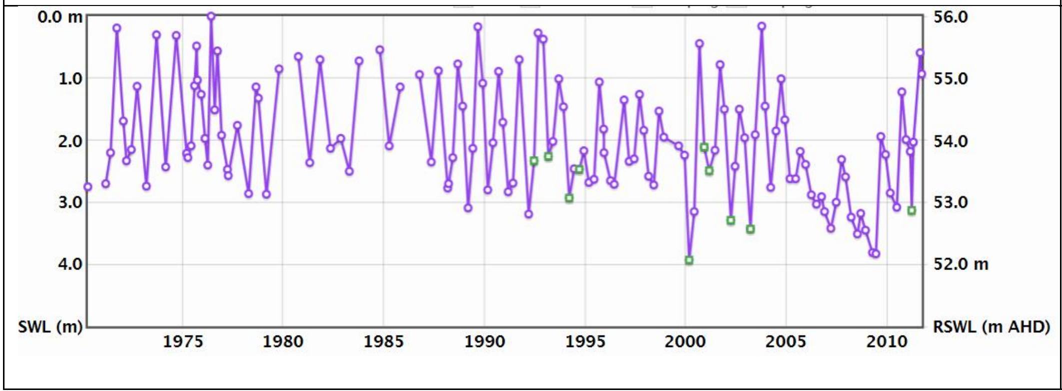
[19] This assumption changed later and is discussed later in this thesis.

important component in the water cycle, a significant impact on water table fluctuations is related to the seasonal variability in rainfall and the resultant diffuse recharge. This is illustrated in **Figure 2.4** in a sample of hydrographs for an extended period (about 40 years) from sites where the main land use is farming and grazing and the sites can be categorised as grassland. The seasonal fluctuations exhibited in these wells provides a mechanism for determining diffuse groundwater recharge; the water table fluctuation method has been applied by Brown *et al* (2006) for water tables about 10 metres, or less, below ground level.

In contrast to long term grassland sites, some hydrographs for observation wells in areas where plantation forests are the main land use are presented in **Figure 2.5**. The area around the two monitoring wells presented, NAN009 and NAN012, was extensively burnt by a bush fire in February 1983 and this can be viewed in the map in **Figure 2.6**. Apart from the loss of human life, some 120 000 ha of land cover was burnt, including approximately 25 000 ha of softwood plantation forest, with about 13 000 ha being in the groundwater management area now identified as Zone 2A. The monitoring wells, NAN009 are NAN012, are near the centre of this burnt forested area.



FOX004

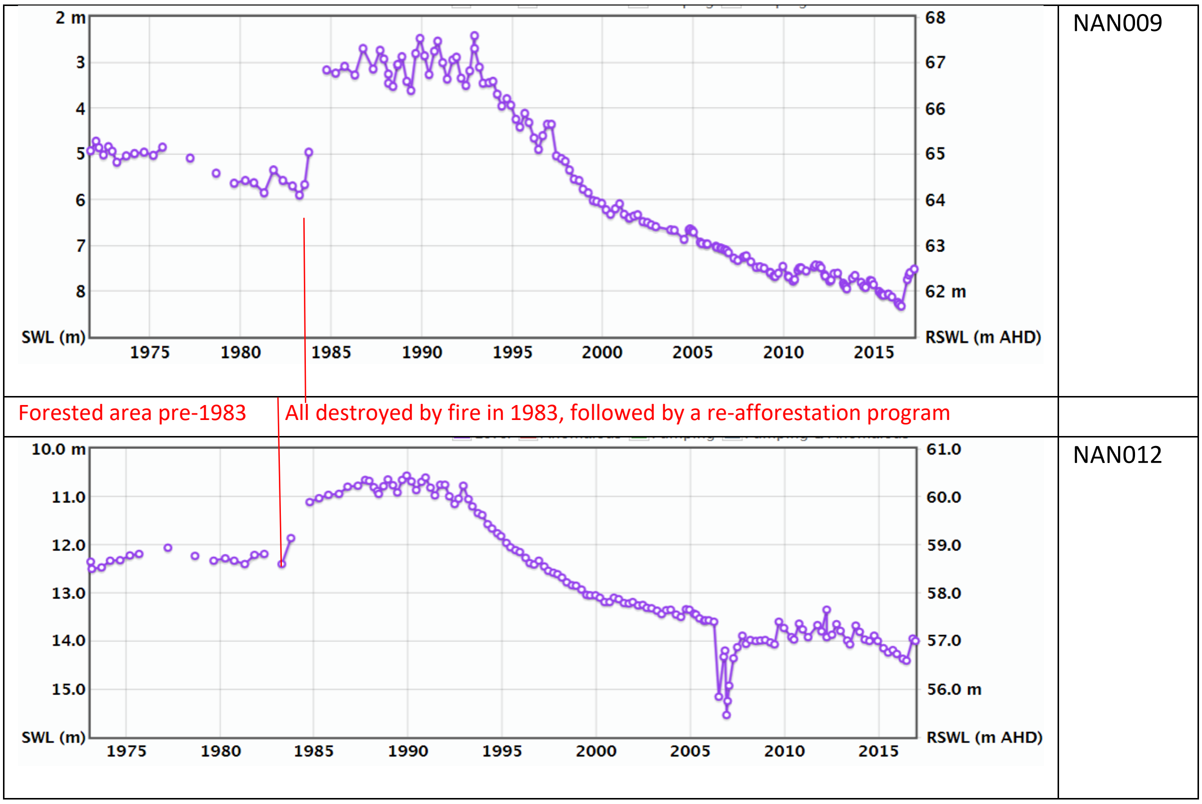


MON004

Source: DEWNR WaterConnect: where it is advised that green markers indicate some pumping observed at that time

Figure 2.4: Comparative hydrographs from monitoring wells in grassland

While the NAN009 hydrograph does not have continuous data, it can be observed that prior to the fire, the water table at NAN009 was showing a gradual lowering, a rate of about 1m over the 10-year monitoring record that existed at that time. During the first winter after the fire, the groundwater level at NAN009 exhibited a 0.94 metre rise. During the next 12 months, there was an additional water table rise of 1.8 metres, bringing the water table within about 3 metres of ground level. This 'elevated' level persisted for about 7 years and during this time exhibited the seasonal trends typical of the surrounding grassland land use sites.



Source: DEWNR WaterConnect

Figure 2.5: Comparative hydrographs from monitoring wells in a fire impacted forest area in groundwater management Zone 2A

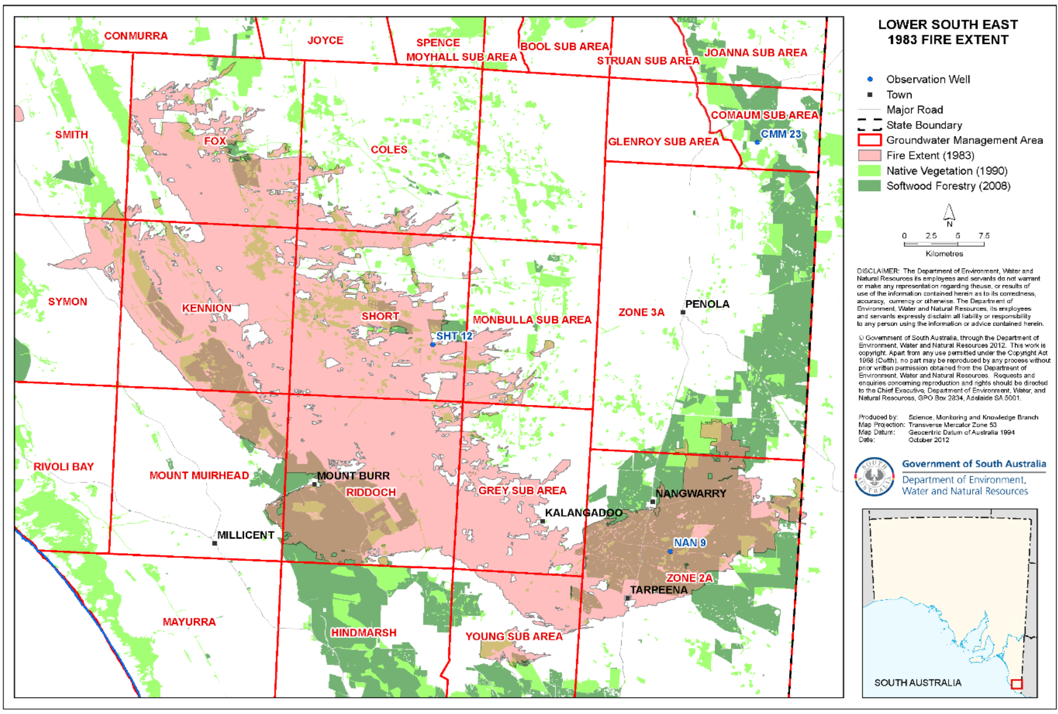


Figure 2.6: Extent of the 1983 bush fire in the lower south east of South Australia

2.5 Plantation forest profile

Softwood, primarily *Pinus radiata*, is the predominant regional plantation type, with the main uses being sawn and finished timber products with some round wood products, mostly from the plantation thinning operations. The softwood plantation life cycle, or ‘rotation’ period, ranges from about 27 to 45 years, during which there can be two to five thinning operations. Each thinning operation results in a reduction of the standing tree population; reducing the population at the first thinning to about 60 per cent and then the removal of about 30 per cent of the remaining population with each subsequent thinning operation. These management decisions are generally determined by the forest productivity and an assessment of the market opportunities for the forest products being removed and the potential of the remaining trees. The first thinning is important to provide access, generally with every fifth planted row being totally removed, for subsequent felling and log hauling.

At the time hardwood plantation forest expansion began in the late 1990s, the softwood plantations in the region covered nearly 100 000 ha, and had an historical average expansion rate of about two per cent a year. The new hardwood industry development saw the total area under commercial plantations increase by about 20 000 ha over a three-year period with more new forests being proposed by the hardwood development companies[20].

2.5.1 The age profile of the softwood plantation forest estate

From softwood forest industry data, the age of forest compartments at the time of clear felling becomes statistically observable when the softwood forest compartments enter the 28 to 37-year age classes. The data indicates that the area of the age classes 27 years and older begins to reduce, at a relatively uniform rate, to the 37-year age class. The aggregate area of trees aged 38 years and older represents only 4.9 per cent of the total softwood plantation estate.

The graph presented in **Figure 2.7** indicates the relative area of each age class, with a 3-year moving average to assist in the observation of an estate expansion trend.

Key statistics observed in the forest age and area data of the Lower Limestone Coast region's softwood forest estate, as at December 2014, are:

- The total softwood plantation estate is 108 046 ha
- The plantation area of unknown age is 1783 ha, or 1.6% of the total estate area
- The estate that is known to be 38 years, or older, is 5306 ha, or 4.9% of the total area
- The estate that is known to be 27 years, or less, is 80 716 ha, or 74.7% of the total area
- The estate area that is between 28 and 37 years old, is 20 241 ha, or 18.7% of the total area
- Except for the last 6 years, there has been a non-uniform but modest expansion in the softwood forest estate area.

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[20] It is believed the industry had intent for land use change to plantation forestry for about an additional 35 000 ha at that time, with about 25 000 ha having planning approval (Avey and Harvey 2014). The industry in its Development Strategy (Green Triangle Regional Planation Committee, 2001), anticipated expanding the hardwood estate by 5000 ha each year.

Figure 2.7: Age class distribution of the regional softwood plantation estate at 2014 (with a 3-yr moving average)

The reduction in the area of the age classes in the 27 to 37-year range is reasonably uniform and this can be further observed in **Figure 2.8**, indicating that clear felling of softwood occurs mainly when trees enter the age range of 28 to 37 years.

In 2001, the Green Triangle Regional Plantation Committee advised that the softwood plantation estate would be expanded by an average of 2000 ha per year for the following 10 years, suggesting the area of softwood plantations would approach 117 000 ha by 2010.

With the exception of the six years immediately prior to 2014, the softwood estate appears to have gradually expanded the area in the 7 to 27-year range. Although there is an increasing area trend in this age range, it is not always consistent and this is probably due to a number of site, seasonal and economic issues that could be occurring at the time. These factors could include variability in seasonal conditions affecting site works, impacts of pests, disease and fire, harvesting timing to optimise market opportunities for wood products and access to new land for plantation expansion.

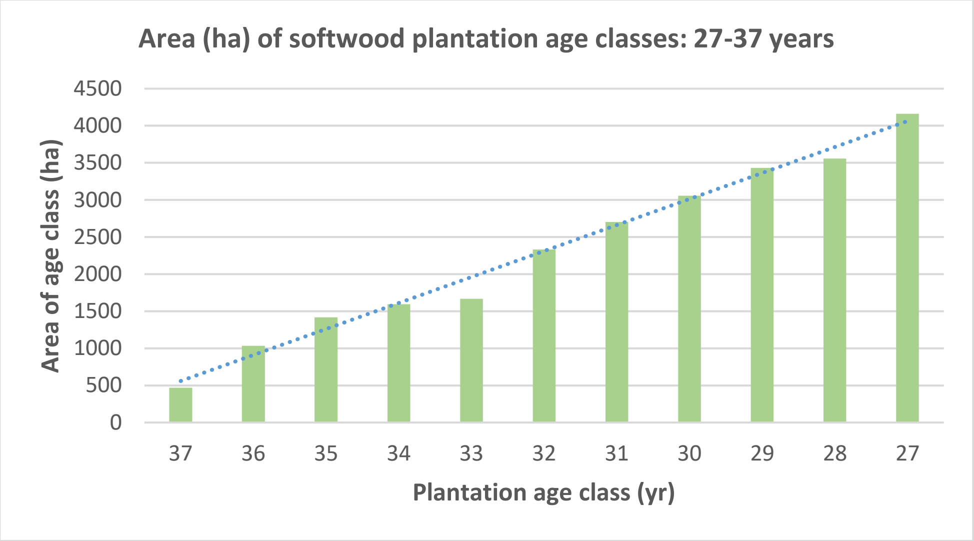

Figure 2.8: Softwood clear felling trend in the 28 to 37-year range

The reduction in replanting and or new plantings during the six years prior to 2014 is possibly due to a combination of commercial factors and these include; a general down turn in the wood product markets, major restructuring of the region's two largest softwood plantation companies (they account for nearly 90 per cent of the softwood forest estate area), and difficulty in accessing expansion land due to increased competition from the agricultural sector from significantly increased livestock returns.

2.5.2 The age profile of the hardwood plantation forest estate

A review of the data available from the forest water licence registration process for the hardwood plantation forest estate does not provide any clarity on the likely age of hardwood trees when clear felled. The age profile of the current hardwood forest estate is presented in **Figure 2.9**. This indicates a bimodal age distribution and an estate that is significantly older than the proposed 10-year rotation described by the hardwood plantation industry in 2006 when the current forest water accounting model was agreed.

The two main age groups are those plantation compartments which are 8 to 10 years and 13 to 15 years old, as at December 2014. These two groupings, in aggregate, make up nearly 80 percent of the total 2014 hardwood estate, with the 8 to10-year age classes representing 26.5 percent of the estate, while the 13 to15-year age class group makes up 53.0 per cent of the total estate. Further detail on the different age classes is presented in **Table 2.1**.

From anecdotal information, it is believed the 2 to 6-year group is from coppiced regeneration and not from planting new material, as proposed by the hardwood plantation forest industry in 2006.

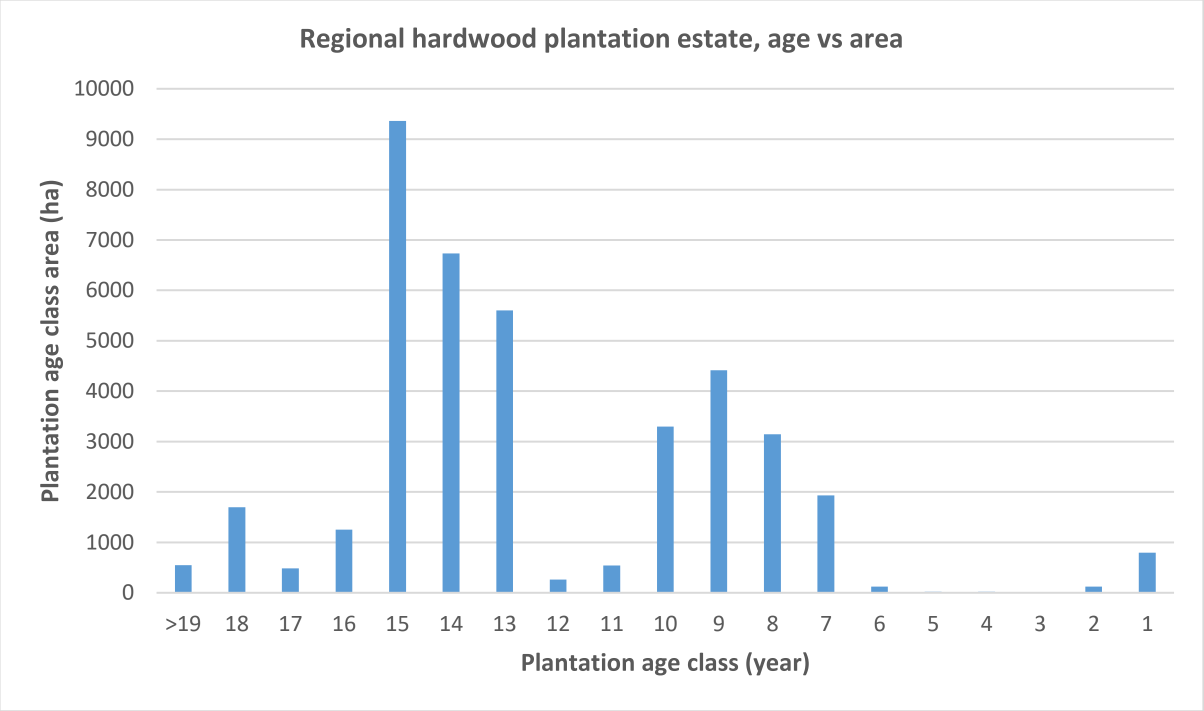

Figure 2.9: Age class distribution of the regional hardwood plantation estate at December 2014

It is believed the large disparity between age classes can be attributed to commercial factors associated with the establishment, and subsequent failure, of the MIS companies[21] making up the hardwood plantation industry in the early 2000s. Plantations aged in the 8 to 10-year category are possibly reflective of the intent to build a mature industry, at the time a paper pulp mill was being proposed at Penola. In 2001, the industry had a target of expanding the hardwood plantation estate by 5000 ha annually, for ten years. Regardless of the earlier industry intent, the reality is the regional hardwood plantation estate is significantly older than that proposed, and accounted for by the South East Natural Resources Management Board in the 2013 adopted water allocation plan.

The spatial distribution of the softwood and hardwood plantation estates can also be viewed in Figure 2.1.

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[21] MIS companies are 'managed investment scheme' companies. These investment companies where established to take advantage of taxation rules applying at the time. This coincided with a Federal Government policy to nationally expand the plantation forest industry.

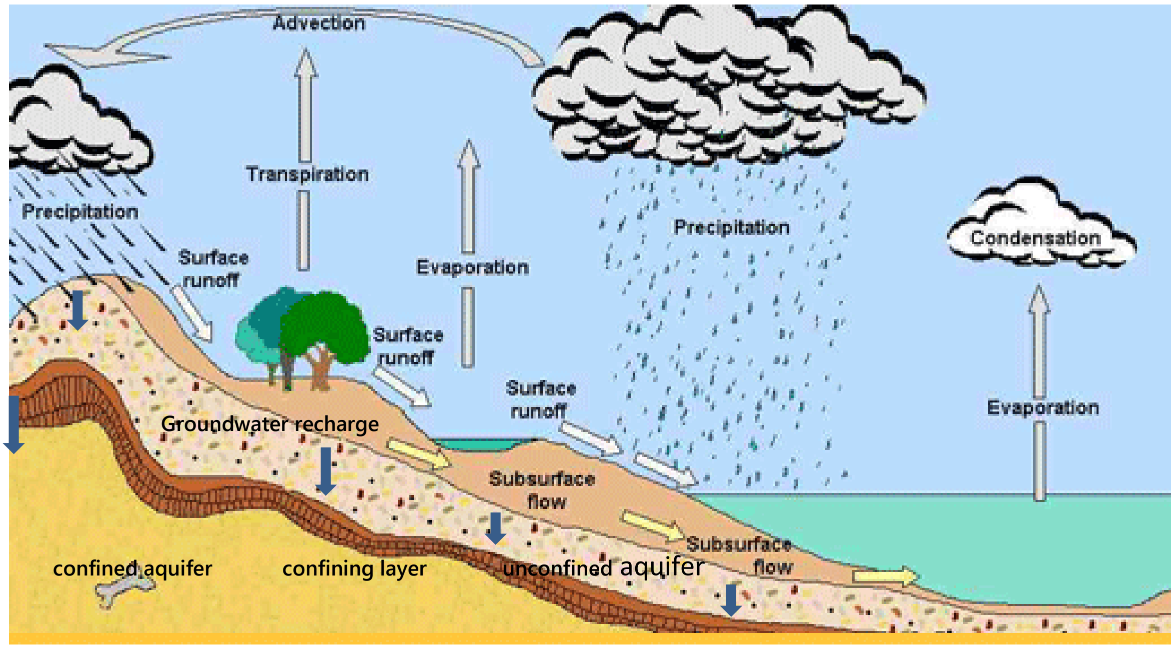
Table 2.1: Area of different hardwood age classes as at December 2014

Age (years)	Area of age class (ha)	Age class as % of total estate	Cohort % of total estate
1	796	1.9%	
2–6	304	0.7%	
7	1932	4.7%	
8	3143	7.7%	26.5%
9	4417	10.8%	
10	3297	8.0%	
11	539	1.3%	
12	265	0.6%	
13	5605	13.7%	53.0%
14	6730	16.4%	
15	9360	22.8%	
16	1250	3.1%	
17	484	1.2%	
18	1700	4.2%	
>19	551	1.3%	
unknown	589	1.4%	
total	40 964	100.0%	

3 Water balance and forest water accounting model

3.1 A generalised hydrological cycle

The hydrological cycle has been adapted and described by many different scientists for a range of different environments, and at different scales, but it is agreed that solar energy drives the recycling of water through the atmosphere and the general landscape as vapour, liquid or solid (ice) and at scale, the water mass remains constant. A generally accepted conceptual model is presented in **Figure 3.1**.



Derived from Gladstone Area Water Board

Figure 3.1: The hydrological cycle

Whilst there are transitional variations in the hydrological cycle, the essential premise is that solar energy causes evaporation of water from the oceans and other water surfaces, and the water vapour condenses forming clouds of moisture which are moved by wind to the land where the condensate falls as precipitation.

The processes in Figure 3.1 can be presented in the water-mass-balance equation 3.1. The equation assumes the hydrological cycle is continuous, with water in its various forms moving through the environment with no water loss, or creation. A form of the equation is:

$$P = Et + I + Q + R \qquad \text{(equation 3.1)}$$

Where, P is precipitation, Et is evapotranspiration, I is interception, Q is surface and sub surface water flow, and R is groundwater recharge.

A water balance is based on the law of conservation of mass; that is, any change in the water mass at a given site, during a specified time period, must equal the difference between the amount of water added and the amount of water withdrawn from it during that same period of time.

3.2 A simplified representation hydrological cycle for the study sites

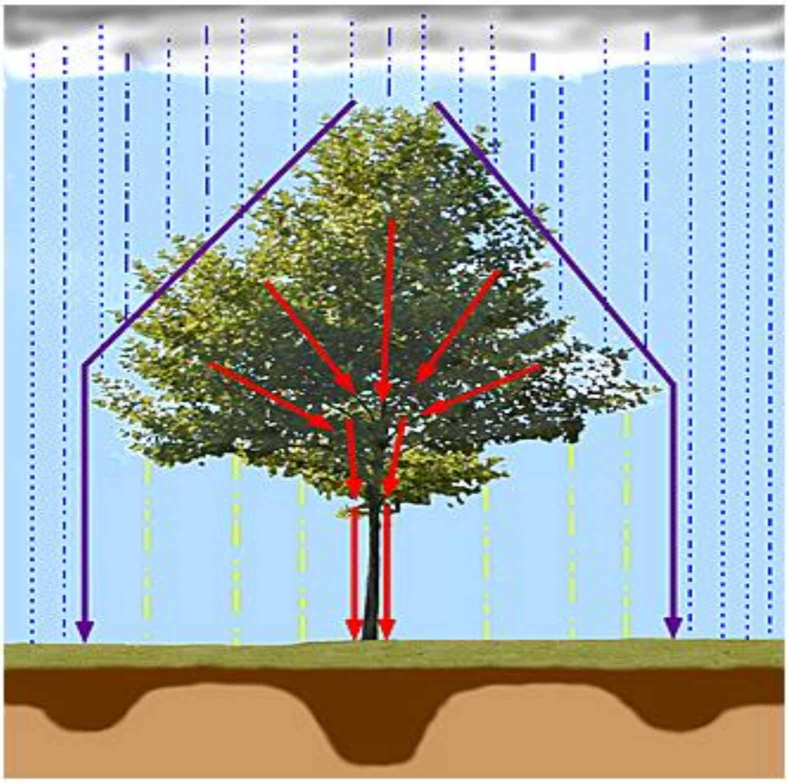
This plantation forest water accounting study is interested in what happens to the precipitation that falls on the regional landscape, and particularly that which contributes to the recharge of the groundwater account and the subsequent changes to the groundwater in storage. A change in the net groundwater account is indicated by a lowering or raising of the water table. In some environments, a significant change in the regional groundwater account can also be accompanied by changes in salinity, but salinity issues are not considered in this analysis. In the region, the balance of the rainfall not transforming to groundwater recharge is assumed to be evapotranspiration related to the covering vegetation. However, it is noted that in periods of high rainfall, some surface water flows out of the region via the local surface water drains.

For simplicity in discussion, all precipitation in this study is considered to be rainfall (but includes variations such as hail). In the general water cycle model, some rainfall is intercepted in the canopy of the vegetation that covers the landscape and is evaporated back into the atmosphere. This can reduce the amount of precipitation falling onto the ground and this can vary significantly between the different classes of vegetation. Some canopy intercepted rainfall can aggregate and flow down stems and tree trunks to the ground. Canopy interception is largely determined by its structure, extent and condition and the character of the rainfall events, in terms of intensity, duration and wind conditions at the time. These characteristics are diagrammatically presented for the forest situation in **Figure 3.2**.

From various studies, it is generally recognised that rainfall interception by grassland and agricultural crops is significantly less than that intercepted by plantation forests. O'Loughlin and Nambiar (2001) advises that interception losses in *Pinus* plantation forests can represent 20 to 30 per cent of rainfall, whereas in *Eucalyptus* plantations it can range from 10 to 20 per cent. This difference is due to factors such as leaf mass, shape, texture and geometry.

In agricultural systems, Lodge *et al* (2001) suggests crop height can be a significant influence for interception loss, with losses in low herbage canopies being in the order of 35 per cent of that in taller canopies.

Rainfall falling directly on the ground surface, by dripping from the vegetation canopy, or as accumulated trunk run-off, can take a number of pathways. These are generally determined by topography, the soil type and depth, the moisture content of the soil, the character of the subsoil and the nature of rainfall events.



Modification of falling precipitation by vegetation. The relative quantity of precipitation entering the soil is indicated in dark brown.

From:

http//www.physicalgeography.net/fundamentals/8khtml

Figure 3.2: Impacts of vegetation type on precipitation fall

The generalised hydrological model considers, that subject to the character of the above parameters, precipitation in the land scape generally converts to increasing soil moisture, with 'surplus' water becoming surface or sub surface runoff, or groundwater recharge. The amount and form of 'surplus' water is influenced by the root zone soil depth, its moisture content, sub soil characteristics, surface gradient and the character of the precipitation event. Water draining past the root zone can be referred to as deep drainage and becomes groundwater recharge.

The generalised hydrological model generally combines evaporation from the soil and vegetation canopy with the vegetation transpiration component to be accounted as evapotranspiration.

According to the general water cycle model, surface runoff can become stream flow. In landscapes that have been modified by anthropogenic activities, some surface flow can be diverted and or stored in dams, for beneficial use at some later time. Stored dam water (and other surface water storages) can also follow a number of pathways. Some evaporates from the water surface, some may transition into sub surface flows, which may result in increasing soil moisture in another part of the landscape, and some may become groundwater recharge.

Due to the topography and the free draining nature of the soils in the Lower Limestone Coast region, and the fact that a Tertiary Limestone Aquifer is generally present at shallow depths below ground level, most of the precipitation that does not add to soil moisture or contribute to the evapotranspiration fraction of the hydrological model, is subjected to gravity and becomes groundwater recharge, after draining below the root zone (Dillon *et al* 2001).

Some relatively small quantities of rainfall can transition to surface water flows in some areas in the region. Depending on soil types and topography, some water can aggregate as perched water in wetlands. In parts of the Lower Limestone Coast region, some rainfall may contribute to episodic flows in the constructed drainage system. Due to study site selection, this possible consequence is minimised, but is discussed later in this thesis for one selected forested study site (SHT012) and two grassland sites (FOX004 and MON004) studied in the same area.

Other than where there are extreme climatic events, groundwater recharge can be considered as the balance of rainfall not benefiting the covering vegetation through evapotranspiration processes. In this simplistic approach, soil moisture changes are ignored as these generally become self-cancelling over a long study cycle.

Under this proposed methodology, this simple approach to water accounting could be described as applying a ‘bucket model’ approach, where only the most important processes are represented to provide insights into the functional behaviour of the local water system. Bucket models are discussed for other environments by Zhang *et al* (2002) and Walker and Zhang (2001).

3.3 Water-mass-balance at plantation forest study sites

As a general principle, a water balance can be calculated for any site environment, ranging from a small scale to an entire catchment. This study is targeted at a scale that can be considered to be appropriate for the groundwater management areas in the Lower Limestone Coast region. There are five study sites of approximately 5000 ha and these are considered sufficiently representative of the spatial heterogeneity that can occur within groundwater management areas, where plantation forests are a significant land use.

In summary, it can be considered that precipitation on the proposed 5000 ha forest groundwater study sites may:

- be intercepted by the covering vegetation and evaporated into the atmosphere
- be evaporated from the soil
- infiltrate the soil and transpired by the covering vegetation
- drain through the soil, past the root zone to become groundwater recharge

In the simplest analogy, the aquifer at the study sites is considered a ‘bucket’ that is filled by diffuse recharge from rainfall that is surplus to evapotranspiration. Discharge processes that remove water from the bucket (representing groundwater in storage) includes pumped extractions and groundwater extraction by plantation forest where the saturated aquifer zone is accessible to plantation roots (directly or by capillary action). An example of such a bucket model is shown in **Figure 3.3**, where the water level rises and falls in response to the balance between recharge and discharge activities for the site being assessed.

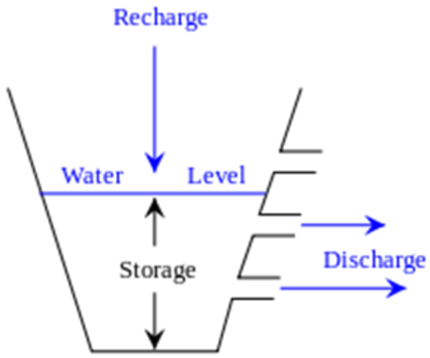


Figure 3.3: Simple bucket model for a water-mass-balance

If the groundwater resource is considered as a store of water, net annual changes to that store need to take account of the annual recharge and discharge. In the study site areas, discharge is generally considered to be from two sources. These are pumped extractions for irrigation, livestock and domestic water uses and extractions by the local vegetation from shallow water tables. In the wider region, other extractions can include water pumped for public supplies and for industrial uses. As previously mentioned, groundwater lateral inflow and outflow are considered equal.

As this study is about estimating the water use by plantation forests, as compared to the agricultural or grassland landscape, the water-mass-balance equation for the relevant study sites can be generalised and expressed as follows:

$$P = Et + R \qquad \text{(equation 3.2)}$$

Where Et now includes the canopy interception losses and R is groundwater recharge and P is precipitation recorded as rainfall. Alternatively, as the hydrological influences of different landscapes is being considered and compared, the equation 3.2 can be alternatively presented as:

$$R = P - Et \qquad \text{(equation 3.3)}$$

The sites selected for investigation are mostly covered in plantation forests, with a lesser area of shallow rooted grasslands or agricultural crops. This shallow rooted vegetation will be referred to as grassland and is the land use that is considered to provide most of the recharge in the groundwater management areas.

While the above equations note evapotranspiration, this study is not investigating this component of the water cycle; the groundwater recharge values are accepted as the rainfall residual after all evapotranspiration processes. From the regional work done by others (such as Brown *et al* 2006 and Dillon 2001), the mean recharge values for each groundwater management area are accepted at the rates specified in the adopted water allocation plan (SENRM Board 2013); a task is to validate forest impacts on groundwater recharge, as a factor of the recharge that would apply to the grassland replaced by plantation forests.

3.4 The analysis approach

An objective of this study is to test the predictive accuracy of the forest water accounting model against the actual observed changes in groundwater in storage at five 5000 ha study sites in the Lower Limestone Coast region over an extended time period. The time period is related to the availability of groundwater and forest data and to approximate the average life cycle of the regional plantation forest estate. This testing is undertaken by developing a net annual water-mass-balance account for each site, using the annual recharge and extraction components from the forest water accounting model (2006 version), for the study areas where plantation forestry is a major land use and is considered to be a reasonable representation of the forest industry activity in the region.

Site selection has focussed on areas where the landscape can be regarded as relatively flat (to minimise the risk of any surface water activity) and there is a history of groundwater level observations, preferably for a period approaching 40 years.

On identifying a suitable monitoring well, where plantation forestry is a significant surrounding land use and where the water table can be considered to be generally within 10 metres of ground level across most of the site, a study site with a 4 km radius is established around the selected monitoring well, to provide a study area of 5026 ha. The various land use classes within the study area are then assigned annual hydrological impact values for groundwater recharge and discharge. These values are initially consistent with the values adopted by the water allocation plan. The resulting aggregated annual recharge and discharge values for each 5000 ha study site then become inputs to a net annual water-mass-balance calculation, which is then expressed as a change in the depth to the water table (from ground level), as a reflection of the net annual change in groundwater storage. These calculated net annual changes, expressed as a depth of groundwater, are then correlated against the actual observed annual changes in the standing water level for each calculated year.

This is a time-trend analysis applied to a relatively large area, where plantation forests are a predominant land use, using existing data for after-the-fact analysis (Zhang *et al* 2010).

The annual recharge components for the water-mass-balance calculations are expressed as a factor of the management area mean annual recharge rate, adopted by the regional water allocation plan (for grasslands). The variants for the annual forest recharge components are derived from the forest water accounting model, described later in this chapter.

The discharge components in the water-mass-balance include the estimated forest extractions, as determined by the forest water accounting model. Any identified pumped extractions for irrigation and stock and domestic uses are also included in the aggregated discharge calculation.

The net impact for the study site on the water-mass-balance is summarised in the equation:

> ΔS (change in groundwater storage) = $\sum R - \sum D$, where R is groundwater recharge and D is groundwater discharge for the study area.

For consistency, the autumn groundwater level is observed and that value is compared to the water-mass-balance calculation for the previous calendar year.

3.5 Early development of the plantation forest groundwater accounting model

In order to manage groundwater resources sustainably into the future, it is necessary to have a reasonably accurate understanding of the net water-mass-balance and the variable factors that can influence the account. In addition, there is a need for an ongoing groundwater monitoring program to maintain a watch on the state and condition of the groundwater resource over time; monitoring groundwater trends and the responses to the management strategies that are in place. A combination of these two instruments assists in explaining any departure of the net water-mass-balance from the seasonal trends, and may provide an early warning for a need to adjust the groundwater management policies.

Given the history of land management prior to the development of hardwood plantations in the Wattle Range region, a basic understanding of the water-mass-balance for the area had evolved and this was supported with the groundwater level monitoring program that has generally been ongoing at some sites since the mid-1970s.

By 2001, about 20 000 ha of hardwood forest had been planted, with indications that another 25 000 ha was to follow over the next few years (Avey and Harvey 2014). At the time, there was concern about the impact of the rapid expansion of hardwood plantations replacing grassland and reducing groundwater recharge on extensive areas which had been providing a significant contribution to groundwater recharge in the region. As per **Figure 3.4**, the groundwater level was showing some decline in the Wattle Range area, but this was mostly attributed to a period of reduced rainfall that commenced in about 1993. However, some local people were of the view that the conversion of grassland to hardwood plantation forest was already beginning to impact on the local groundwater resource.

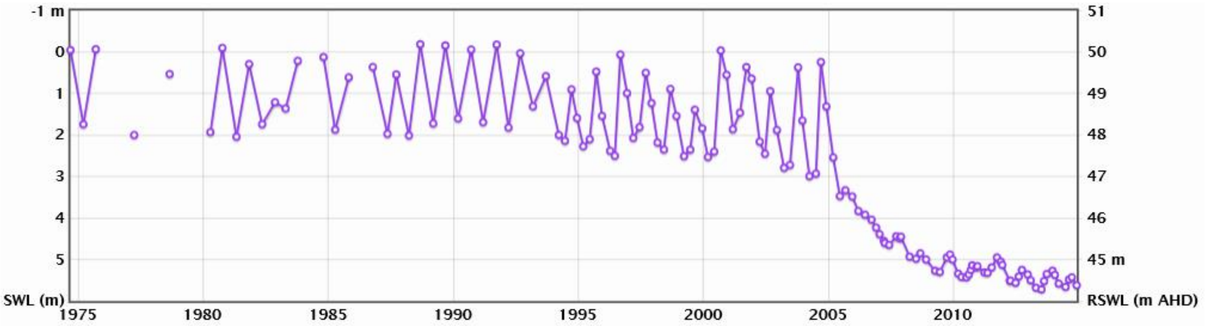


Figure 3.4: Groundwater level trends Wattle Range (MON016) from late 1970s to 2015

Up until this time, regional groundwater accounting had assumed that there was no recharge under any plantation forest (regardless of its age or stage of development); this was considered to be a precautionary approach in accounting for the hydrological impacts of plantation forest, as it was later agreed that the ‘no groundwater recharge’ policy should only apply to a closed canopy forest.

In 2001, key stakeholders and the government water resource manager agreed on a simple forest water accounting model for the estimation of plantation forest impacts on groundwater recharge. The purpose of forest water accounting model was to provide an annual summary, of the mean hydrological impact of a plantation forests on groundwater resources at a groundwater management area scale in the Lower Limestone Coast region.

While the hardwood plantation forest industry was in its infancy, the industry reasoned that with a relatively short rotation period of 10 to 12 years, it would develop quickly into a ‘mature’ industry where there would be a uniform spread of age classes, by area, and therefore, there would be a continuous cycle of harvesting and replanting. With the softwood industry already operating as a mature industry, it was accepted that an **annualised** approach to forest water accounting was a practical approach to groundwater management area accounting of forest hydrological impacts. It was also reasoned that as there was to be plantation renewal every 10 to 12 years, there would be significant recharge phases distributed across the hardwood plantation forest estate; after clear felling and prior to canopy closure of the next forest rotation.

The accounting methodology in the 2001 forest groundwater model was simply based on the agreement there is no groundwater recharge under a closed canopy forest (Dillon 2001) and the model adopted the principle that recharge reduction from the grassland land use to plantation canopy closure was linear, as would be the return of recharge after clear felling.

3.6 Annualised forest water accounting

Annualised accounting was derived by summing all annual recharge components, from the initial land preparation stage (prior to planting), through the planting phase to canopy closure, followed by some recharge in the post-harvest clean up period. This aggregate was then divided by the total number of years in the plantation management cycle to provide an annualised recharge impact.

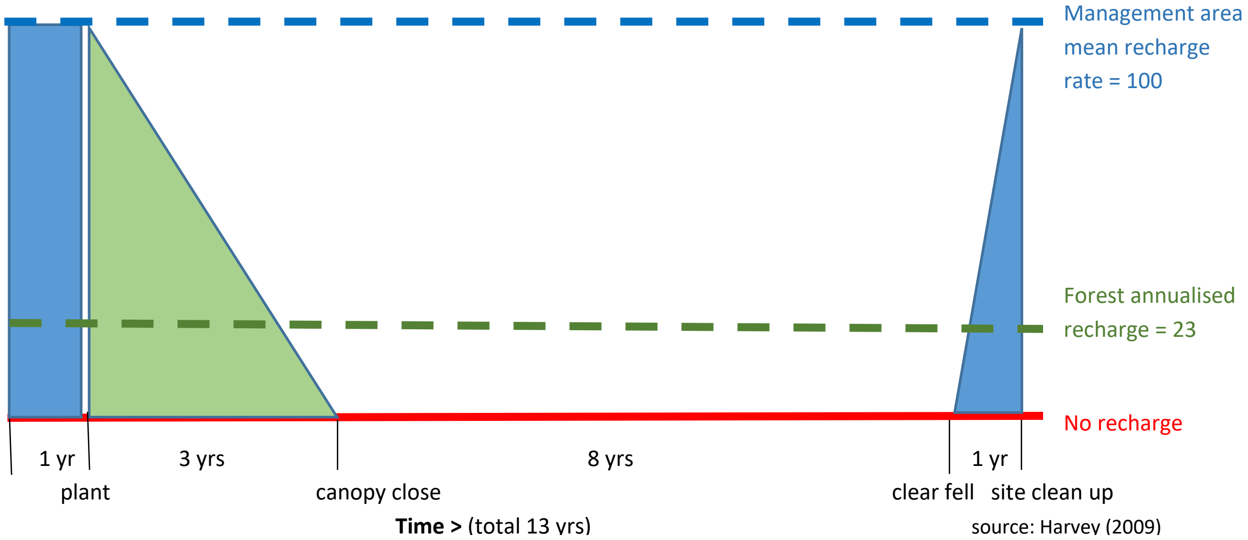
The rotation period was based on the industry’s characterisation of the average plantation management being practised, or intended. The model, when applied to softwood plantations, provided for some recharge immediately following each plantation thinning, where the tree population was reduced. In the case of softwood plantations, the average time from planting to clear felling was considered to be 30 years, during which there were two thinning processes.

The unit of measurement for the annualised plantation forest recharge impact was expressed as a percentage of the recharge that occurred on the grassland land scape which was being replaced by the new forests. The adopted grassland values were the groundwater management area recharge rates which had evolved in the region and adopted by the water allocation plan (Avey and Harvey 2014).

With a statutory requirement to review the regional water allocation plan and with the impact of hardwood plantation forests becoming visible in groundwater trends in the Wattle Range area (refer Fig 3.4), Brown *et al* (2006) carried out a review of groundwater management area recharge rates in the Lower Limestone Coast region. For the shallower water tables (<10m), the water table fluctuation method was the main instrument. Brown *et al* (2006) established a mean management area recharge rate by observing the water table fluctuations over the time period of available groundwater level data and where the main land use was grassland. The determination of a mean recharge value for each management area was generally based on observations at three to four monitoring sites, with some management areas providing up to 11 data sites. As part of this study, the water table fluctuation method is applied to a number groundwater monitoring sites referred to in this study and the resultant values are compared to the Brown *et al* 2006 values.

The 2001 recharge model for hardwood plantations is presented as a diagram in **Figure 3.5**. For an 11-year plantation life, the annualised value is achieved by adding the area of the rectangle and the two triangles in the diagram, representing recharge, and dividing the aggregate by the number of years for the full management cycle. In the following calculation, the adopted management area recharge rate (in the water allocation plan) is represented as 100 mm/yr:

{(100*1 yr) + (3 yr*100/2) + (100* 1 yr/2)}/13 yr = 23% of management area recharge rate.



source: Harvey (2009)

Figure 3.5: The 2001 model of hardwood plantation recharge impacts

The recharge impacts for softwood plantations were calculated using the same methodology, but with some variation to some parameters. Canopy closure for softwood plantations was considered to occur at six years after planting and there was one year of recharge following each of two thinning operations and the time from planting to clear-felling was 30 years. As a consequence, the annualised rate under softwood plantation was calculated to be 17 per cent of the management area recharge rate (the recharge considered to occur on grassland) (Harvey 2009).

Assigning the annualised accounting values to the existing hardwood and softwood plantation forest estates released ‘new’ water (as the previous accounting approach considered that there was no recharge under any forest) to offset some of the proposed forest expansion, where the recharge impacts would be fully accounted. At the time, while there were theories about plantation forests extracting groundwater from shallow water tables, it was agreed that this matter could not be addressed without scientific evidence to quantify any impact (Avey and Harvey 2014).

3.7 Acceptance of softwood plantation forest impacts on groundwater resources

To an observer, the significant attention being given to the hardwood forest development could seem incongruent when there was already approximately 100 000 ha of softwood plantations in the region. The significant differences were the softwood estate had been expanding at very modest rate over 100 years, and up until the mid-1970s, there had been no formal broad scale groundwater level monitoring in place to identify and confirm any significant regional changes in groundwater levels. In addition, other than for the Nangwarry area, a significant portion of the softwood estate was established on deeper water tables (this can be seen from a review of Figures 2.1 and 2.2). Furthermore, much of the softwood estate had replaced native vegetation, where there was already a low level of groundwater recharge. With these factors, by the time that groundwater monitoring commenced, the groundwater levels were relatively stable, although some scientist, such as Holmes and Colville (1970), had noted some unexplained outcomes, with respect to local water balances in forested areas.

3.8 Groundwater extraction by plantation forests

Following the discussions in 2001 that resulted in the first forest water accounting model, an investment was made in investigating whether plantation forests in the region did utilise groundwater resources.

The quantification of plantation forest groundwater extraction by Benyon and Doody (2004) was new information and helped explain some of the anomalous groundwater trends that were evident in some parts of the region, such as that observed at the groundwater monitoring wells NAN009 and

NAN012 following the extensive bush fire in 1983 (hydrographs previously presented in Figure 2.5) and the steep decline in groundwater levels at Wattle Range that began to emerge in the early 2000s. In addition to reducing groundwater recharge in the region, plantation forests were now known to be extracting significant quantities of groundwater from shallow water-tables. The magnitude of groundwater extraction by plantation forests further highlighted the need for transparent water accounting and management of plantation forest hydrological impacts on groundwater resources.

Using concepts applied to the initial 2001 forest groundwater model that only considered forest recharge impacts, the findings of Benyon and Doody (2004) was one of the drivers for revising the forest water accounting model in 2006 to include the accounting for groundwater extraction by plantation forests, where the plantations occurred over shallow water tables. Another reason for a review of the 2001 forest water accounting model related to the forest industry advising that the industry forest management calendars had been reviewed and a revised characterised average forest should be considered (Avey and Harvey 2014).

The outcome provided new insights into the extent of the hydrological impact of the regional plantation forest estate on the local groundwater resources. The full hydrological effect of the regional plantation forest estate on groundwater resources were now considered to be of a similar magnitude to the total volume of all licensed groundwater extractions in the region. At the time, it was estimated that almost all the hardwood plantation forest estate and about 25 per cent of the softwood plantation estate lay over shallow water tables in the Lower Limestone Coast region. It is now known that the total forest hydrological impacts (for recharge and extraction) account for about 30 per cent of all licensed water allocations (South East Natural Resources Management Board 2013). This order of magnitude was significant and required transparent accountability and management.

3.9 The 2006 plantation forest groundwater accounting model

In 2006, the then forest water accounting model (version 2001), which only considered the recharge impacts of softwood and hardwood plantation types, was reviewed to take account of a revision to the forest management calendar of the characterised ‘average’ plantation forest. This work was conducted in parallel with the expansion of the model to account for groundwater extraction by both plantation types, where they overlay shallow water tables. A shallow water table was considered to be 6 metres; this being in line with the findings of Benyon and Doody (2004).

The 2006 forest water accounting model was to remain as an annualised accounting system, derived by summing all annual components, from planting through to clear felling. These recharge and extraction aggregates are then divided by the total number of years in the plantation management cycle to provide an annualised impact for recharge and extraction, where the water table was shallow. The forest rotation management cycle was based on the industry's characterisation of the average plantation management being practised, or intended. The purpose of adopting the annualised accounting approach was to achieve a relatively simple but robust assessment of plantation forest estate hydrological impacts at a groundwater management area scale.

At the time, when the newly established hardwood plantations were immature, it was reinforced by the hardwood industry its intention was to be a long-term industry that would rapidly move to a forest estate that comprised mixed age forest compartments and those age classes would be relatively uniform in area and the age at clear felling would be in the order of 10 years. The industry objective was to ensure a reliable and consistent product flow of wood chips to a paper pulp mill factory that was proposed for the region[22]. The hardwood forest managers also insisted that second rotation forests would be established by the planting of new genetic material, not by coppicing the clear-felled first rotation.

The softwood forest estate management calendar was revised by the plantation forest industry to a 35-year period from planting to clear felling, with four thinning operations, for the industry's 'average' plantation. While this appeared to be a significant change in forest management from the original 30-year rotation with two thinning operations, it did not change the deemed annualised recharge values of the 2001 model. The annualised softwood recharge value was calculated to remain at 17 per cent, or a loss of 83 per cent, of that recharge occurring on the replaced agricultural landscape (considered to be grassland land use), for each year of the forest rotation. This suggested that the model was sufficiently robust for the intended purpose of groundwater accounting of the plantation forest estate at a management area scale.

The revision of the forest groundwater accounting model (now the 2006 version) provided for an increase in the estimated recharge at the time of forest planting as an acknowledgement of the weed control practised at this stage of plantation establishment. The previous 2001 model allowed for some recharge immediately following clear felling, but this was discontinued in the 2006 model,

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[22] There was a proposal to develop a paper pulp mill at Penola. This was supported by government through the *Penola Pulp Mill Authorisation Act 2007.* This legislation later lapsed due to a failure of industry to initiate the pulp mill development.

as it was agreed that in the period following clear felling, and during site clean-up, there would be a period of rebuilding the soil moisture profile to support a higher level of recharge in the year of re-planting, and following through towards canopy closure.

In the 2006 review, the hardwood forest rotation length was adjusted to 10 years. With the higher revised recharge rate applying to the period prior to canopy closure and a reduced rotation length to 10 years, the annualised hardwood recharge value was calculated to be 22 per cent, or a loss of 78 per cent, of that recharge occurring on the agricultural landscape (grassland), for every year of the forest rotation.

The basic feature of the recharge aspects of the model are, there is no recharge under a closed canopy forest and the rate of recharge reduction from the time of planting to canopy closure is linear. Canopy closure for hardwood plantations is considered to occur three years after planting and six years in the case of softwood plantations. A summary of the recharge elements of the forest water accounting model from Harvey (2009) is presented below, noting that the assumptions are based on descriptions of plantation forest industry management proposed by the industry at 2006.

3.10 Recharge under hardwood plantation forests

A summary of the hardwood recharge cycle is described below and presented in **Figure 3.6**.

Hardwood plantation forest management and recharge calculation assumptions:

- Weed control (strip sprayed, representing 50% of the forest compartment area) at time of planting seedling trees, with some recharge benefit continuing until canopy closure.
- Canopy closure occurs three years after planting.
- Clear felling occurs 10 years after planting.
- One year ‘clean-up’ following clear felling.
- An 11-year management cycle for a 10-year forest rotation.

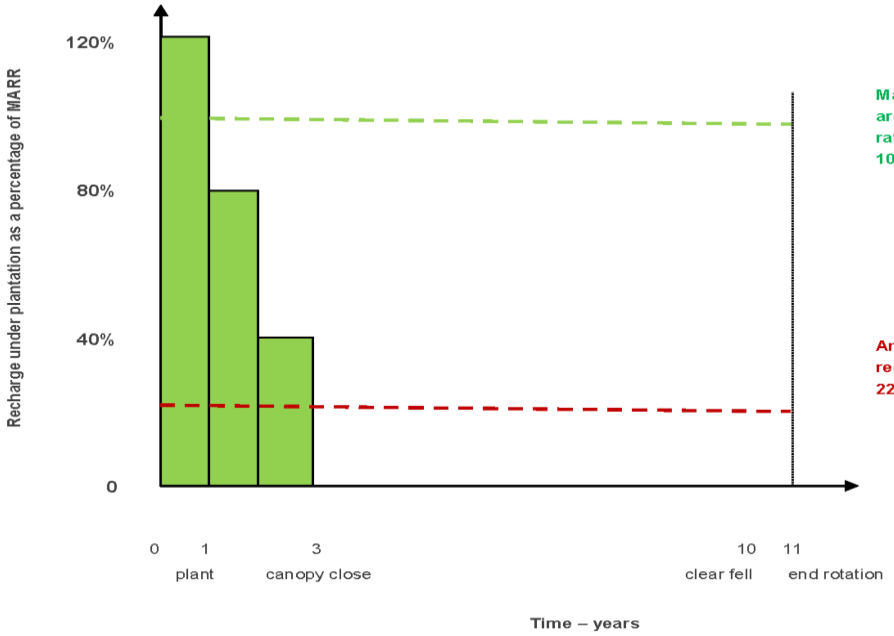
Hydrological impact assumptions based on forest biophysical stage:

- Recharge credit of 120% of management area recharge rate (MARR) in the planting year.
- No recharge under a closed canopy forest.
- Recharge from planting to canopy closure is linear with 120% of MARR for the 1st year and in the subsequent years, recharge is 80% and 40% respectively.
- No recharge in the clean-up year, but recommences in the following year, which is the planting year of the next rotation.

Calculation of annualised recharge impact:

- Recharge impacts expressed as a percentage of MARR.
- Aggregate recharge from planting to canopy closure is [120% + 80% + 40%] MARR
- Sum of all recharge divided by 11 (years) is the annualised recharge for hardwood plantations, expressed as a percentage of MARR. [120% + 80% + 40%] /11

  = 22% MARR



Source: Harvey (2009)

Figure 3.6: Accounting for the groundwater recharge impacts of hardwood plantation forests

3.11 Recharge under softwood plantation forests

A summary of the softwood recharge cycle is described below, with the underlying assumptions and principles, and is presented in a graphic form in **Figure 3.7**.

Softwood plantation forest management and recharge calculation assumptions:

- Weed control (strip sprayed, representing 50% of forest compartment area) at time of planting seedling trees, with some recharge benefit continuing until canopy closure.
- Canopy closure occurs six years after planting.
- Clear felling occurs at 35 years after planting.
- Four thinning operations occurring before clear felling.
- One year clean up following clear felling.

Hydrological impact assumptions based on forest biophysical stage:

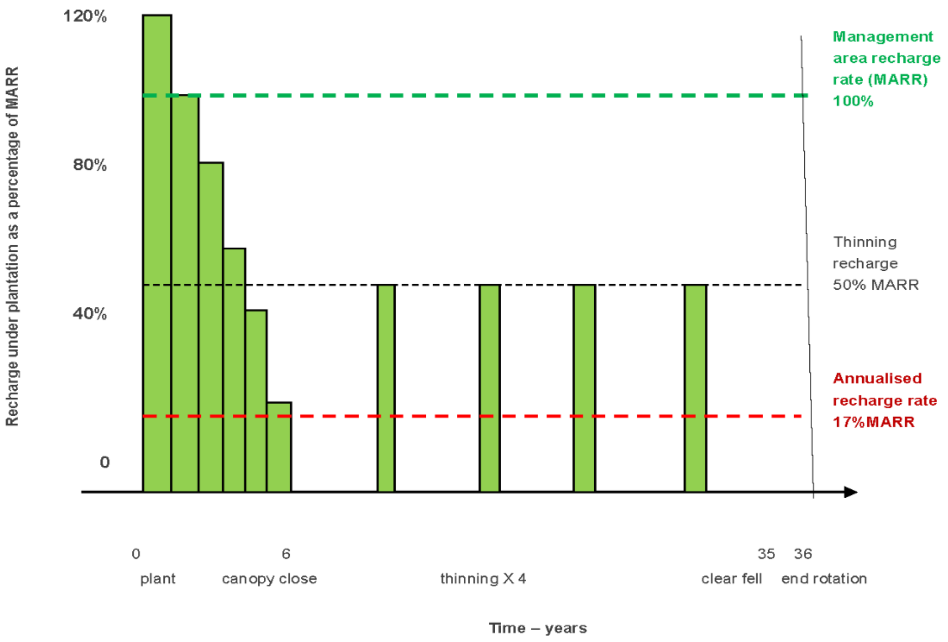
- Recharge occurs at 120% of management are recharge rate (MARR) in the planting year.
- No recharge under a closed canopy forest.

- Recharge from planting to canopy closure is linear with 120% of MARR for 1st year and in the subsequent years, recharge is 100%, 80%, 60%, 40% and 20% respectively.
- No recharge in clean-up year, but recommences in following year, which is the planting year of the next rotation.
- A recharge spike in each year following the four thinning operations is equivalent to 50% of MARR for that year of the thinning operation.
- A 36-year management cycle for a 35-year forest rotation.

Calculation of annualised recharge impact:

- Recharge impacts are expressed as a percentage of MARR.
- Aggregate recharge from planting to canopy closure is [120%+100%+80%+60%+40%+20%] MARR.
- Aggregated recharge following the four thinning operations is [50% *4] MARR.
- Sum of all recharge divided by 36 (years) is the annualised recharge impact of plantations:
  ([120%+100%+80%+60%+40%+20%] + [50%+50%+50%+50%]) /36
  = 17% MARR

The quantum of recharge following forest thinning operations is a vexed issue, without any meaningful scientific observations to provide guidance. As previously advised in section 2.5, the first plantation forest thinning results in a significant reduction of the standing tree population; approximately reducing the tree population by about 40 per cent, with subsequent operations resulting in the removal of about 30 per cent of the remaining tree population. The first thinning generally occurs in the age range between about 10 and 16 years. During the 2006 review of the model, the softwood plantation managers argued that due to the major disruption of the plantations during thinning, there was a period of stifled tree growth following the thinning and therefore it was likely that some recharge from rainfall did occur. This post thinning recharge was conceded to be 50 percent of the regional recharge rate for one year following each thinning operation. This principle has not been technically validated and is therefore subject to questioning.



Source: Harvey (2009)

Figure 3.7: Accounting for the groundwater recharge impacts of softwood plantation forests

3.12 Accounting for plantation forest groundwater extraction

Groundwater extraction parameters were developed in collaboration with industry and key stakeholders at the time of the 2006 model revision. The water resource regulator adopted 364 mm per year extraction for a closed canopy plantation forest, in lieu of the Benyon and Doody (2004) value of 435 mm. This is explained by Harvey (2009), but the decision came down to excluding observations from an investigation site that lay outside of the main commercial hardwood forest estate at the time.

In incorporating plantation forest extraction into the forest water accounting model, it was agreed that extraction would be considered to commence after canopy closure and the rate of increase from nil extraction to maximum extraction, of 364 mm in a year, would be linear and of a similar trajectory as the annual changes in recharge reduction occurring prior to canopy closure. This is illustrated diagrammatically in **Figure 3.8** where, for discussion purposes, the management area recharge rate is assigned at 100 mm/year on grassland.

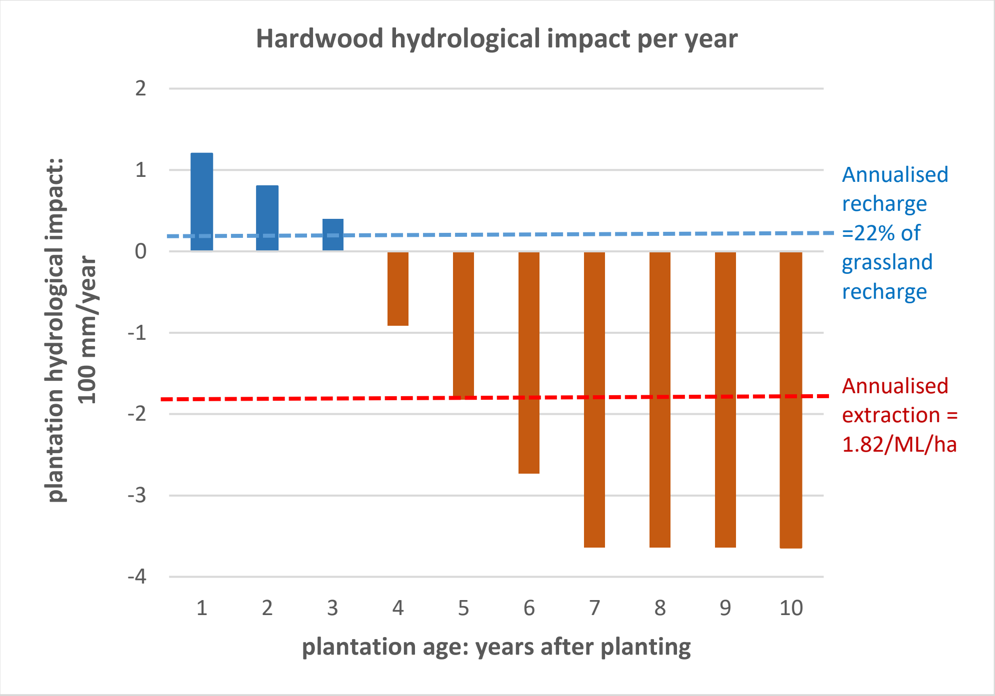


Figure 3.8: Hydrological impact of hardwood plantation forests; relationship between recharge and extraction

3.13 Extraction by hardwood plantation forests

Using a peak extraction rate of 364 mm per year, the annualised groundwater extraction by hardwood plantations from shallow water tables was calculated to be 1.82 ML/ha/year, based on the following assumptions.

Hardwood plantation forest management assumptions:

- Canopy closure occurs three years after planting.
- Clear felling occurs 10 years after planting.
- An 11-year management cycle for a 10-year forest rotation.

Groundwater extraction assumptions based on forest biophysical stage:

- Where there is a shallow water table, no extraction commences before canopy closure.
- Extraction commences after canopy closure and gradually increases until peak productivity in the 7th year after planting, when extraction plateaus at 3.64 ML/ha/year.
- Increased extraction from the 4th year to the 7th year is considered to be linear, but expressed as a discrete volume for each year.
- Extraction ceases with clear felling.

Calculation of annualised extraction impact:

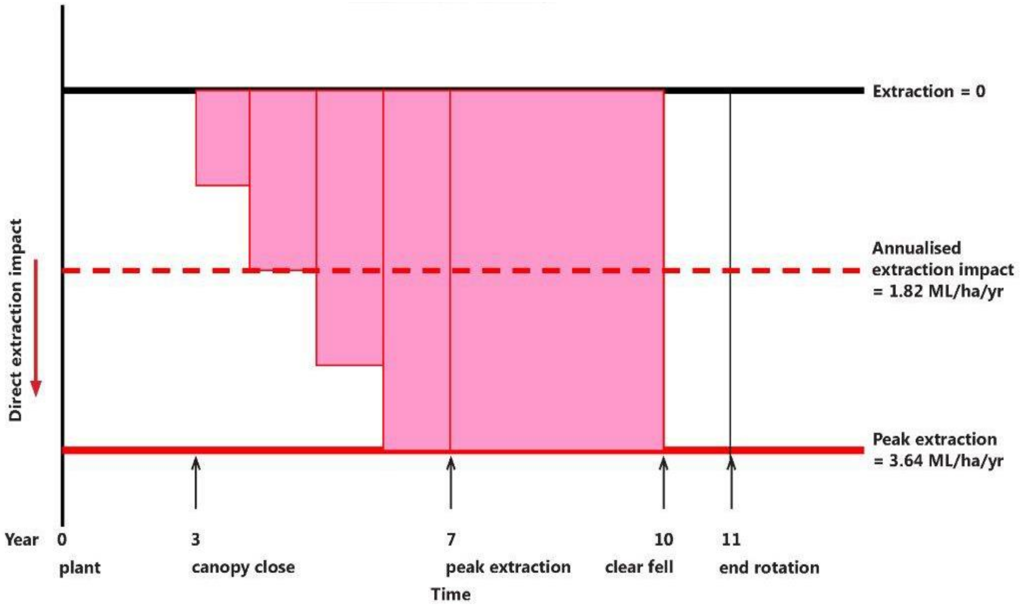
- Annualised extraction is expressed as ML/ha/year.
- Extraction is calculated to be 0.91 ML/ha/year in the year following canopy closure. Extraction for each consecutive year is 1.82, 2.73 and 3.64 ML/ha, respectively (a lineal increase).

- Extraction continues at the peak rate of 3.64 ML/ha for the remaining three years, until clear felling in the 10th year after planting.
- The sum of all extractions divided by 11 (years) is the annualised extraction impact for hardwood plantations: ([0.91 + 1.82 + 2.73 + 3.64] + [3.64 x 3]) /11
  = 1.82 ML/ha/year

A diagrammatic representation of the hardwood extraction components is presented in **Figure 3.9**.

While the hardwood industry advised reforestation would be by replanting new genetic material, extractions by a replacement hardwood plantation established by the coppice method[23] were also considered. This increased the annualised extraction value from 1.82 ML/ha/year to 2.5 ML/ha/year, for the second rotation, where the established root system is assumed to facilitate a rapid return to the forest production phase of the coppiced second rotation.

The forest water accounting model for coppiced regeneration is based on the second rotation being for another 8 years and considers that full extraction occurs at an earlier time in the second forest cycle than in the first rotation (Harvey 2009). This model adaption makes non-validated assumptions about the evapotranspiration characteristics of the coppiced regeneration.



Source: Harvey (2009)

Figure 3.9: Accounting for the groundwater extraction impacts of hardwood plantation forests

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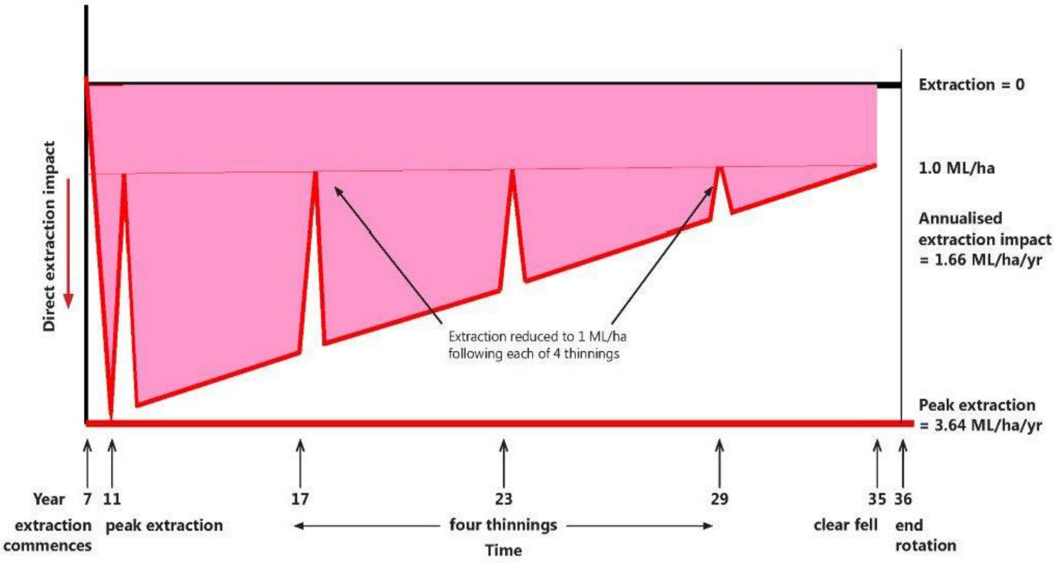
[23] Coppice or coppicing refers to the practice of allowing new epicormic shoots to regenerate from the tree stump after clear felling. These coppiced shoots are generally thinned to two or three main shoots to develop and provide the wood product for the next rotation. This capability only applies to the hardwood plantations.

3.14 Extraction by softwood plantation forests

Parameters for softwood plantation extraction elements in the forest water accounting model are based more on negotiation than established facts. An annualised extraction value for softwood plantations was agreed to be 1.66 ML/ha/year and this lesser extraction, compared to hardwood, is attributed to the ongoing and significant reduction in tree population per hectare, as a result of the forest thinning operations carried out during the life of softwood plantations.

The concept of a reducing tree population (per unit area) reducing aggregated plantation groundwater extraction is presented in a diagrammatic form by Harvey (2009) in **Figure 3.10**. This indicates a gradual, but essentially a linear, reduction in extraction from a peak of 3.64 ML /ha to 1.0.ML/ha at the time of clear felling, with a brief period of relief immediately following each thinning operation. The intention of the figure is to convey the concept of a reducing tree populations reducing total groundwater extraction by the plantation forest per unit area, rather than what is possibly occurring in the plantation, at any point in time.



Source: Harvey (2009)

Figure 3.10: Accounting for the groundwater extraction impacts of softwood plantation forests

The annual extraction components for softwood plantations are presented in **Table 3.1,** where the last column in the table details the accumulative difference between the deemed annualised extraction impacts and those annual components believed to occur. It is noted that the widest disparity occurs in the early stages of the plantation, but by the time the trees are 17-years of age, the differences are minimal (less than 5 per cent of the aggregate extraction volume for the rotation).

Table 3.1: Schedule of softwood groundwater extraction values: annual and aggregated

Age of forest stage: year	Forest thinning and clear felling	Estimated annual extraction: ML/ha	Accumulated extraction: ML/ha	Accumulated annualised: ML/ha	Difference between annualised allowance and accumulation: ML/ha
1	**Plant**	0.00	0.00	1.66	1.66
2		0.00	0.00	3.33	3.33
3		0.00	0.00	4.99	4.99
4		0.00	0.00	6.65	6.65
5		0.00	0.00	8.32	8.32
6		0.00	0.00	9.98	9.98
7		0.73	0.73	11.64	10.91
8		1.46	2.19	13.31	11.12
9		2.19	4.38	14.97	10.59
10		2.91	7.29	16.63	9.34
11	**Thin 1**	3.64	10.93	18.30	7.37
12		1.00	11.93	19.96	8.03
13		2.05	13.98	21.62	7.64
14		2.35	16.33	23.29	6.96
15		2.75	19.08	24.95	5.87
16		3.15	22.23	26.61	4.38
17	**Thin 2**	3.55	25.78	28.28	2.50
18		1.00	26.78	29.94	3.16
19		2.05	28.83	31.60	2.77
20		2.45	31.28	33.27	1.99
21		2.75	34.03	34.93	0.90
22		3.05	37.08	36.59	-0.49
23	**Thin 3**	3.35	40.43	38.26	-2.17
24		1.00	41.43	39.92	-1.51
25		1.90	43.33	41.58	-1.75
26		1.95	45.28	43.25	-2.03
27		2.00	47.28	44.91	-2.37
28		2.10	49.38	46.57	-2.81
29	**Thin 4**	2.15	51.53	48.24	-3.29
30		1.00	52.53	49.90	-2.63
31		1.30	53.83	51.56	-2.27
32		1.40	55.23	53.23	-2.00
33		1.50	56.73	54.89	-1.84
34		1.55	58.28	56.55	-1.73
35	**Clear fell**	1.60	59.88	58.22	-1.66
36		0.00	59.88	59.88	0.00
	aggregate	59.88			
	annualised	**1.663**			

Derived from Harvey (2009)

The accumulative annual extractions are presented in **Figure 3.11**.

The June 2004 depth to the water table (≤ 6m) is the reference point for the granting of forest water allocations to existing plantation forests for groundwater extraction. This was a policy decision based on legislation applicable at the time and the observations advised by Benyon and Doody (2004). In the current water allocation plan, this same reference point (≤ 6m at June 2004) is also used for introducing new plantations into the forest water licence system. The 6-metre extraction depth principle is investigated and discussed later in this thesis.

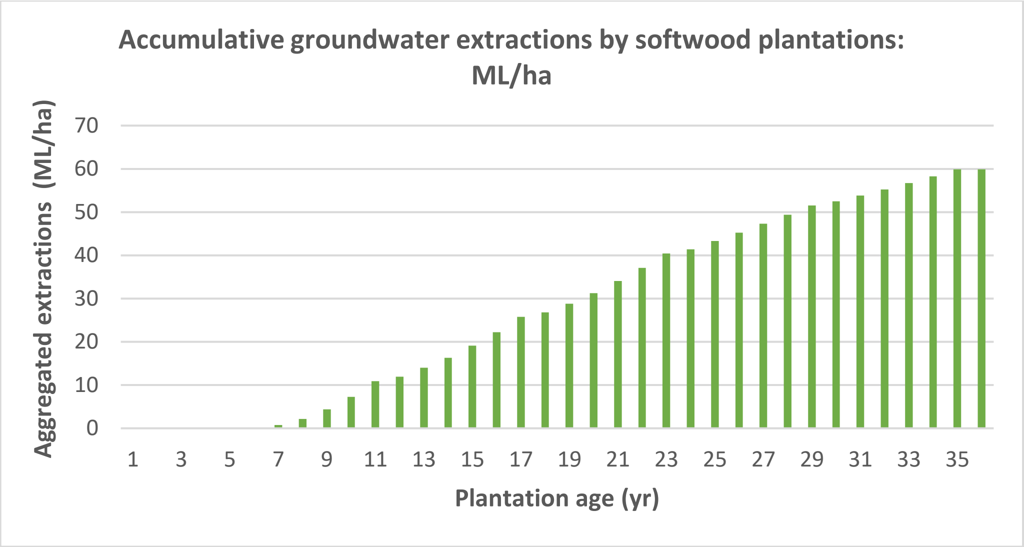


Figure 3.11: Accumulative extraction of groundwater by softwood plantation forests

3.15 Forest water model and groundwater recharge

A key component in the forest water accounting model addressing groundwater recharge impacts is the assumption that there is no groundwater recharge under a closed canopy plantation forest; that is, the total annual rainfall is evaporated from the forest canopy, the soil, or is transpired during this period of a plantations forest's life. Benyon and Doody (2004) observed at their study sites (in the Lower Limestone region in closed canopy forests), transpiration exceeded rainfall where the groundwater was at a shallow depth (≤ 6 m below ground level), confirming the above assumption. While this may be the case in Lower Limestone region, where the mean annual rainfall is generally in the range of 600 to 800 mm in forested areas, it may not necessarily be the case in areas that experience significantly higher rainfall.

The quantum of recharge associated with a plantation forest life cycle must then be related to the recharge that occurs in the early life of a plantation; in the period from planting to canopy closure. The variables to be considered during this period are the recharge that occurs in the year of planting, when plantation water use is at its lowest level, the rate of recharge decline as the plantation grows and approaches canopy closure and the time lapse from planting to canopy closure.

While prevailing weather and soil fertility will also impact on forest growth, the above assumptions are made for mean climatic factors and it is assumed that forest managers will optimise soil fertility conditions to take maximum advantage of the available moisture.

Canopy closure is considered to be a marker for the cessation of groundwater recharge, but this could be contestable, with a considerable mass of forest productivity already being observed by the six-year time point for softwood plantations. Plantation forest development and the groundwater recharge occurring in the first year of plantation is significantly influenced by the effectiveness of weed control in that year. If the weed control is effective, about 50 percent, or more, of the net forest area (stump to stump of the outer perimeter) can be regarded as 'fallow', resulting in recharge on such managed areas being greatly in excess of the recharge occurring on grassland.

In the years after planting, and prior to canopy closure, if the weed control practiced is effective, most of the rainfall can transition into soil moisture, to be transpired by the plantation forest, with surplus water gravitating past the root zone and becoming diffuse groundwater recharge.

In summary, for accounting for the groundwater recharge impacts of plantation forests the parameters that can be varied are, the number of years in a forest rotation, the diffuse groundwater recharge under a grassland landscape, the stage of the forest rotation at which canopy closure is considered to occur, or more particularly, the stage at which recharge is considered to cease. In addition, the amount of recharge that is considered to occur under the weed management that is practised at the time of planting and carries over into the first few years of the rotation. While these parameters can be varied, those being applied in the initial analysis of this investigation (the subject of this thesis), are those set down in the 2006 model and the application of (grassland) recharge rates adopted by the water allocation plan.

Some field work undertaken by Benyon and Doody (2009), while not conclusive due to some variability in the site management history away from the characterised average plantation management and a relatively low number of observations, provides indications that recharge at forested sites where weed control is practised in the year of planting, could be of an order two to three times that for a grassland landscape in the same area. Consequently, a case could be made to propose that recharge in the year of planting could be greater than the 120% allowed for in the forest water accounting model. This is discussed later in this thesis, in the context of the observations made during the investigation that is the subject of this thesis.

3.16 Forest water model and groundwater extraction

A key component addressing groundwater extraction impacts in the forest water model is the maximum annual rate of groundwater extraction by the plantation forest and the trajectory of increasing extraction from the point at which extraction is considered to commence. This commencement period is considered to be after canopy closure under mean rainfall conditions.

An important point, from the perspective of groundwater management, is the depth at which extraction by plantations is considered to be extinguished. The policy adopted by the water allocation plan is that extraction by plantation forests is considered to occur where the water table is 6 m or less, below ground level. This is in line with the summary by Benyon and Doody (2004), however, Benyon *et al* (2006) has observed extractions from a water table 8.9 m below ground level.

3.17 Summary

The annual components of the forest groundwater model are presented in **Figure 3.12** with a summary of the metrics which apply to the various outputs of the model, noting that the outputs that are being applied in the accounting of plantation forest hydrological impacts in the Lower Limestone Coast region are expressed in an annualised form. At a sub-regional scale and assuming the annual components of the model reasonably reflect the hydrological impact of the plantation forest, the relevance of the annualised values depends very much on how close the plantation forest management is aligned to the management strategy embodied in the model parameters.

The purpose of the technical investigation is to determine whether the calculated annual combined impact of plantation forest reducing groundwater recharge and extraction, where the plantations overlay shallow water tables, accurately quantify the net annual change in groundwater storage, as per the following equation:

> ΔS (change in groundwater storage) = $\sum R - \sum D$, where R is groundwater recharge and D is groundwater discharge for the study area.

While the project does not set out to quantify plantation forest evapotranspiration, the model outputs could be extended to estimate the aggregate annual forest evapotranspiration.

<table>
<tr><th>Function and metrics</th><th>Hardwood – short rotation</th><th>Softwood – long rotation</th></tr>
<tr><td>

Recharge

Metric is % of recharge rate for management area. This metric can be translated into mm of rainfall.

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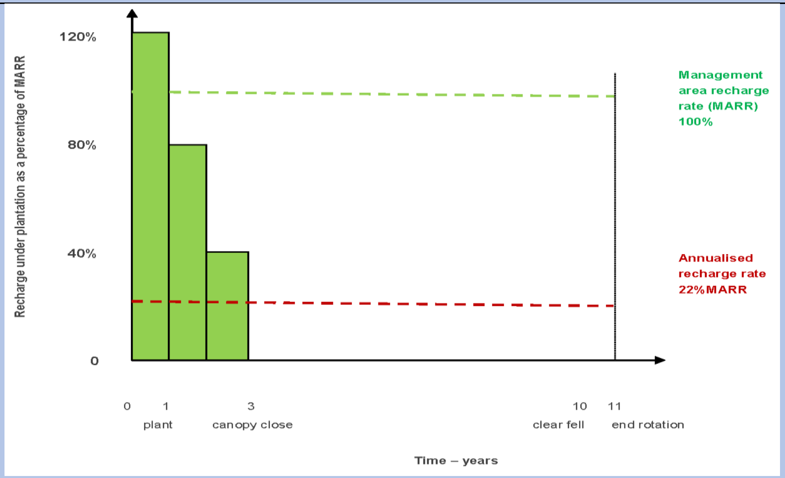

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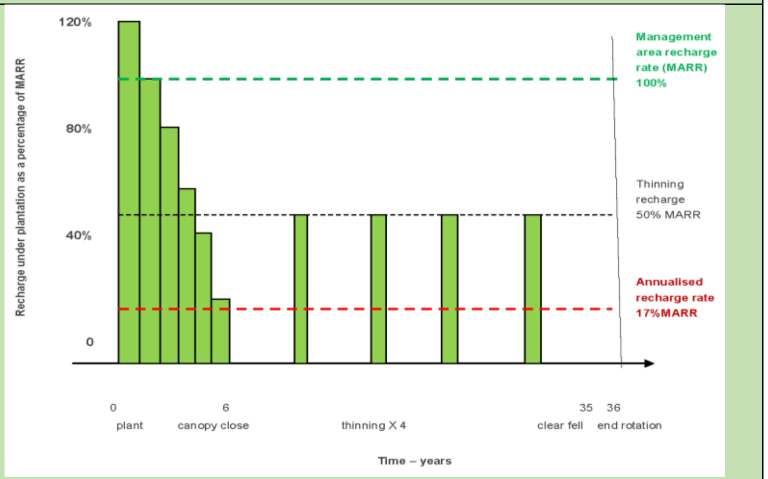

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Discharge

Extraction units are ML/ha

Threshold depth for extraction 6 m below ground level

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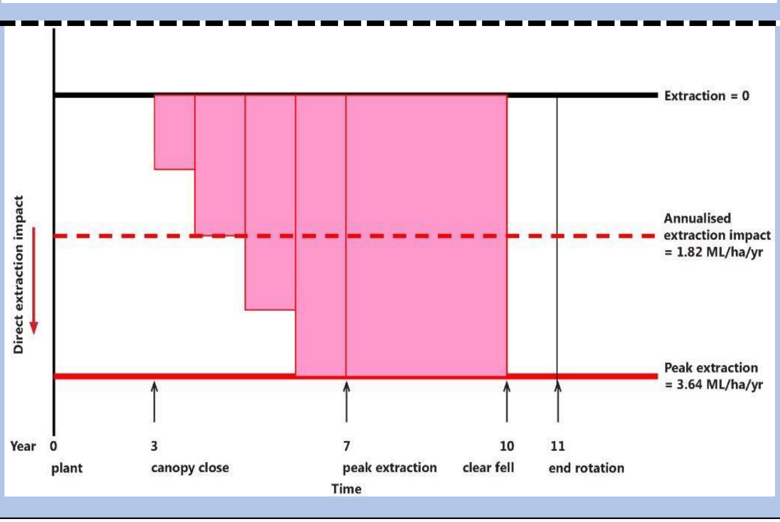

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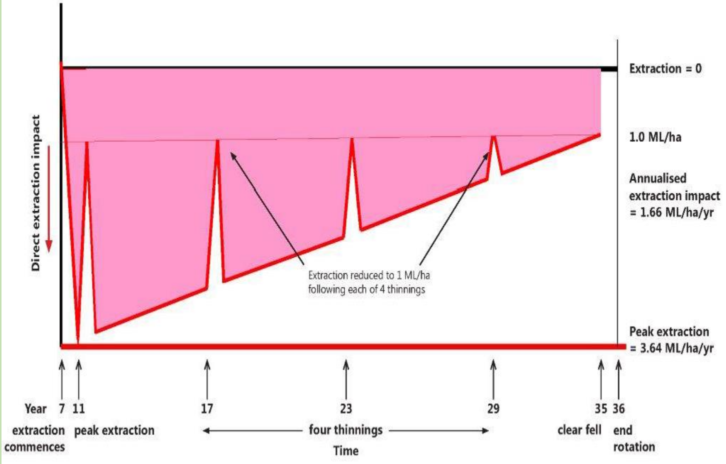

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Figure 3.12: Components of the forest groundwater model source: Harvey (2009)

4 Methodology

4.1 Introduction

As stated in the Introduction to this thesis, the objective of this research is to assess whether the forest water accounting model that underpins the forest water accounting system in the water allocation plan adequately reflects, for management purposes, the hydrological impacts of plantation forests on groundwater resources in the Lower Limestone Coast region.

Using the annual hydrological components of the adopted 2006 forest water accounting model, the study compares a calculated net change in annual mass-water-balance, expressed as a net annual change in groundwater storage, against the observed net annual changes in groundwater in storage, as indicated by the changes in the depth to the water table. This is undertaken at five different sites where plantation forests are the main land use.

The plantation forest recharge impact is expressed as a factor of the diffuse groundwater recharge that would occur in the agricultural landscape (grassland) replaced by the forests, and plantation forest groundwater extraction is expressed as a volume per hectare of plantation forest. Collectively, these forest hydrological impacts contribute to aggregated annual recharge and discharge components in the water-mass-balance for each study area, with the net impact affecting the volume of groundwater in storage at each site.

Underlying this analysis is the assumption that the forest water model annual components, and the related parameters, in aggregate, adequately reflect actual plantation forest hydrological impacts on the regional groundwater resource in the Lower Limestone Coast region, where the mean annual rainfall is mostly in a range of 600 to 800 mm and the groundwater is generally within 10 metres of ground level.

With the exception of the annual groundwater diffuse recharge, in the initial analysis, all parameters applied in the forest water accounting model are held at the levels in the adopted model and as described in Chapter 3. This initial analysis will test whether the forest water accounting model is suitable for estimating the hydrological impacts of plantation forest life cycles at a management area scale in the Lower Limestone Coast region. In this part of the analysis, the adopted groundwater diffuse recharge rates (as defined in the water allocation plan) are adjusted to reflect some of the influences of rainfall variability. This is discussed further in Section 4.3.

While the forest water accounting model deemed outputs are expressed in an annualised form, the calculated net annual mass-water-balance calculation is based on an aggregation of the annual components of the forest water accounting model across the study sites, as it is known that forest management at all the study sites does not align with the characterised average forest management applied in the model. This is considered further in the Results and Discussion chapters.

In addition to the basic question whether the forest water accounting model is suitably accurate for its purpose, this research enables a testing of the sensitivity of some of the assumptions and applied parameters, such as the groundwater recharge rate assigned to plantation forests, the extinction depth for groundwater extraction by the plantation forests and the appropriateness of the management regime of the characterised ‘average’ plantation forest. Subject to the outcome of testing the predicative capability of the forest water accounting model, for estimating the hydrological impact of plantation forests on groundwater resources, knowledge gains may assist in refining the model to improve its accuracy, or provide a better understanding of its constraints. In this regard, a revised forest water accounting model, related to both plantation types, is tested by comparing the predictive ability against observed changes in groundwater storage. This aspect is described and discussed in Discussion chapter of this thesis.

In addition to reviewing the performance of the forest water accounting model, a comparison of water table trends at non-forested sites, over the same time period, is undertaken at some grassland sites to provide an additional line of evidence of plantation forest impacts on the regional groundwater resource.

The area of each forested study site is approximately 5000 ha, resulting in 25 000 ha of land use, which includes over 17 000 ha of mixed aged plantation forests being observed and these observations are extended over 30 years for softwood plantations and 20 years for hardwood plantations.

4.2 Area of study sites

The choice of a 4 km radius for the study sites has been influenced by Dillon *et a*l (2001). Dillon *et al* (2001) comments on the apparent difference in groundwater responses throughout the region, noting that some observation wells exhibit differing response magnitude to recharge events. This was considered by Dillon *et al* (2001) to be the outcome of variable transmissivity and specific yield.

A high aquifer transmissivity, results in a relatively quick transfer of water away from recharge areas to areas down gradient and where the recharge may be less. A higher specific yield between different parts of the aquifer system results in less response in water level changes. Dillon *et al* (2001) explored this *zone of influence* with two different methodologies. While Dillon *et al* (2001) found it difficult to provide a quantified relationship between recharge zones and regional groundwater level responses, the investigation and subsequent discussion by Dillon *et al* (2001) can be generalised as follows:

- Using examples based on bank storage theory and the alternative Hantush intermittent strip recharge, it is difficult to specifically predict response times as a result of plantation forest land change from grassland land use.
- Difficulty is largely due to the high transmissivity characteristics of the unconfined Tertiary (Gambier) Limestone aquifer.
- The effect of the plantation forest is masked by recharge occurring on the forest perimeter and the plantation samples would need to be more than 2000 m across in order to have a measurable response.
- However, in assuming an initial horizontal water table, new gradients can establish over a number of years.

Increasing the radii above the minimum 2000 m was to provide a sufficiently large study area to adequately reflect the land use and forest variability of the region.

4.3 Assumptions

Due to the in-practicality of having complete and accurate site information, many hydrogeological assessments are based on estimated information. These data can be expressed as values accompanied by wide error bands, or presented as mean or default values. As an example, rainfall over a large subject area is often estimated by a single 200 mm diameter rain gauge catchment, but with the knowledge that actual rainfall can vary around those observed values in various parts of any study area. As a consequence, a number of assumptions are made and these include:

4.3.1 Aquifer storage coefficient

It is considered by Stadter (1989) that a reasonable storage coefficient default value for the regional unconfined Tertiary Limestone Aquifer is 0.10. This value has been consistently used in other regional hydrogeological studies as a default value. Simplified, this means that a net discharge, or recharge, of 0.1 metres of free water will represent a change in the groundwater level of 1 metre.

The storage coefficient value of 0.10 is also applied by Brown *et al* (2006) as a robust value for the unconfined aquifer in calculating the management area recharge rates using the water table fluctuation method, where the water table is generally 10 m, or less, below ground level.

While a storage coefficient of 0.1 is considered to be ‘safe’ default value, it is widely understood that storage coefficients can vary across the region and a range between 0.08 and 0.15 (and higher) can frequently apply.

4.3.2 Management area recharge rates

The diffuse groundwater recharge from rainfall is generally regarded as the main input to the water-mass-balance of the unconfined aquifer in this region (Dillon *et al* 2001). Some of the determinants for recharge of the regional unconfined aquifer are rainfall, depth to the water table, soil profile, land surface topography and land use. All these factors can have variations within each category and across the landscape, spatially and over time. They can impact on the quantum of recharge and lag time between a recharge event and the event being observed in the subject aquifer. Consequently, it is necessary to apply a relatively robust value for accounting for groundwater diffuse recharge at scale.

The regional water allocation plan (South East Natural Resources Management Board 2013) assumes that the mean groundwater recharge, other than that occurring under plantation forests, prior to canopy closure, and after thinning operations in softwood plantations, only occurs under the agricultural landscape (or alternatively referred to as grassland). To be consistent with the policies in the water allocation plan, it is assumed there is no groundwater recharge under native vegetation land use, or wetlands. The adopted management area recharge rates, and the processes applied to establish the values, are described by Brown *et al* (2006).

While the Brown *et al* (2006) values are applied, comment is provided for any observed anomalies identified in the water table fluctuations occurring in a period of non-forest land use at the study sites. Any apparent discrepancies, while within a range of acceptability, may also indicate a variation in the storage coefficient between sites, or a leakage of water to the confined aquifer; this being a possibility at the Nangwarry study sites, where recent reporting by SKM (2012) indicates a direct connection between the two aquifers in the area.

In this study, an annual adjustment is made to the adopted recharge rates to reflect some of the consequences of rainfall variability. This adjustment factor is based on the actual observed rainfall during the May-October period in each of the studied years, compared to the long-term mean rainfall for the May-October period (1970-2015). Rainfall observations from the Penola site of the Bureau of Meteorology (BOM 026025) provides data for this purpose.

The long-term rainfall record indicates that almost 70 per cent of the annual rainfall in the region occurs during the 6-month period, May-October. It is also the period when rainfall generally exceeds transpiration, meaning that rainfall is in excess of plant needs and the excess rainfall can drain beyond the plant root-zone to become diffuse groundwater recharge (Dillon *et al* 2001). The rainfall history at Penola is available in Appendix 4a.

While this May-October approach may seem to be a reasonable to reflect rainfall variability, it is recognised that a percentage increase, or a decrease, in rainfall, may not be reflected in actual groundwater recharge to the same proportion. It also recognised that extreme climatic events, particularly rainfall events and their sequence, may further impact and contribute to some apparent anomalous groundwater recharge responses; both in terms of increased and decreased recharge. While a number of variables could interact, the adopted approach is applied to provide a consistent level of recharge variation adjustment away from the mean rainfall situation to partially reflect rainfall variability on diffuse groundwater recharge.

Rainfall data from the Penola rainfall station (BOM 026025), for the period 1970 to 2015, is reviewed and assessed in terms of its annual variability about the period mean annual rainfall. This was also undertaken for the rainfall occurring in the May-October period. This data is presented in a graph in **Figure 4.1** and from this, it can be noted that in regard to the period annual mean, the years from 1970 to 1992 was a time when rainfall was generally above the mean while the latter two decades indicate a period of rainfall below the mean. This observation also applies to the rain that occurred in the May-October periods.

It is also noted, in general, the greatest rainfall deviations from the mean appears to apply to the May-October periods, with the exception being in 2010 and 2011 when the winter-spring period was near the mean value (+3% and -5 %) but the annual values indicate the total rainfall exceeded the annual mean by 14 and 18 percent respectively, meaning a significant amount of rainfall occurred outside the usual seasonal wet period. These general observations are consistent with a general community view of a trend of drier spring periods in recent years.

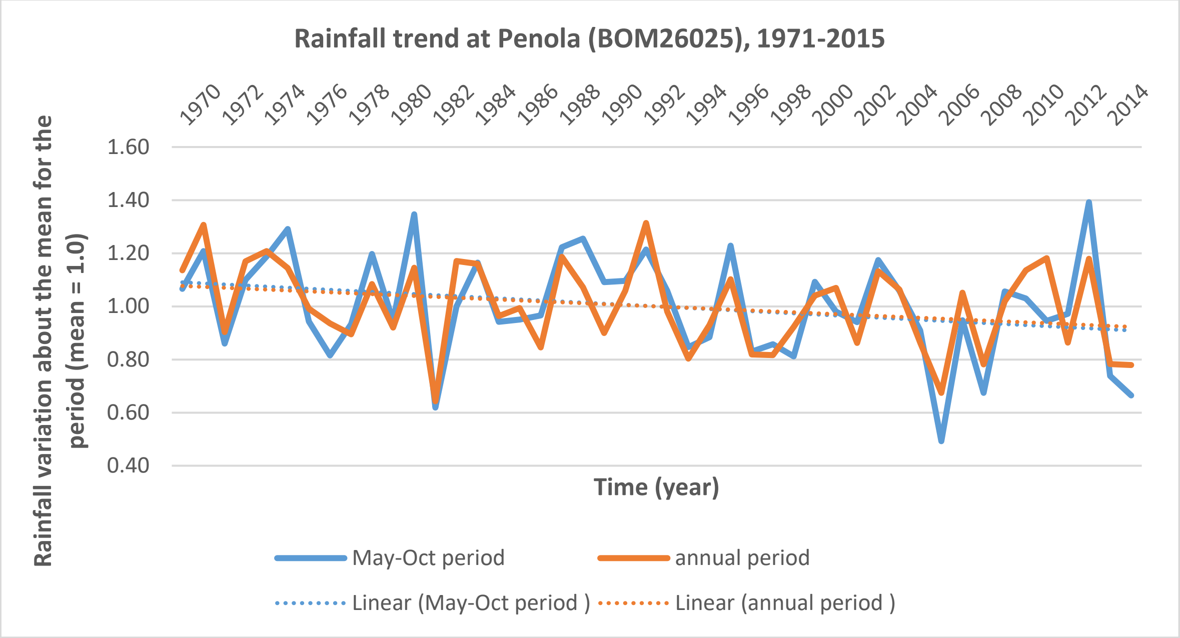

Figure 4.1: Rainfall variation about the mean at Penola (BOM 026025) for 1971-2015

Some observances of anomalous groundwater level responses, not adequately accounted for, in the net annual water-mass-balance calculations, are commented on in the Results and Discussion chapters to follow.

4.3.3 Forest recharge rates

As previously discussed, the forest recharge impacts applied in the water-mass-balance accounting are based on the annual increments in the forest water accounting model. In the model, these are expressed as a percentage of the groundwater management area recharge rates (recharge on the grassland land use) applicable to the management area in which the study site is located. While the management area recharge rates are expressed as a depth of rainfall, these values are converted to a volume per unit area for the area under study. The recharge values are also adjusted for seasonal rainfall variability (in accordance with the discussion in 4.3.2) and the resulting forest recharge is expressed as ML/ha for the net forested area.

4.3.4 Groundwater recharge on other land uses

In association with the plantation forest land use throughout the region, a significant area of fire breaks are maintained by the plantation forest managers. For groundwater recharge accounting of this land use class in this study, fire breaks are considered as grasslands. Areas of road, rail and drain reserves are also treated the same as firebreaks, with respect to groundwater recharge.

4.3.5 Extraction by plantation forests

The adopted policy for the region is that plantation forests that overlay a water table 6 m, or less, below ground level, extract groundwater. In the regional water allocation plan, the point of reference for this parameter is the depth to the water table at June 2004, regardless of the age of the plantation, groundwater trends at that time, or the site geophysical characteristics. It needs to be recognised that the 2004 reference point is an administrative marker to enable the first-time introduction of plantation forests into a legislated water accounting and management system. This has resulted with most of the forest at the Wattle Range study sites considered to be extracting groundwater, whilst in Nangwarry, the forests are deemed not to be extracting groundwater and accordingly have not been granted licensed allocations for extraction.

For the purpose of this study, extraction by plantations is considered to occur across all three Wattle Range sites. Due to the significant variability in the depth to the water table at the Nangwarry sites after the 1983 fire, three approaches have been taken. One is to assume that in accordance with the policy position of the depth to the water table at June 2004 exceeding 6m, no forests are extracting groundwater. The second approach is that all plantation forests extract water at the Nangwarry sites. The third approach is to assume that plantation forest extraction ceases when the depth to the 1990 water table exceeded 10 metres below ground level.

The determination of the area of Nangwarry plantation forest impacted by this 10 metres extraction extinction parameter is determined by the application of available data from a digital elevation model being applied to a calculated groundwater surface for the area at June 1990, derived from a wide scale assessment of groundwater levels (from official state monitoring data and calculated by DEWNR). At 1990, the water table at the Nangwarry sites still exhibited stability following the re-forestation after the 1983 fire.

This study sets out to test the hydrological impacts of plantation forest, and not the policy application, or implications. The 10 metres extraction threshold for plantation forest extraction is a liberal approach to forest extraction, noting that the observations of Benyon *et al*. (2006) indicated that extractions may occur where water tables are observed at depths to 8.9 metres. Discussion on this parameter follows later in this thesis.

Other than the threshold depth to the water table (10 m), the groundwater extraction parameters are considered to be consistent, that is, there is no consideration given to site geophysical variability, or a reducing groundwater take as the water table lowers towards an extinction level. The outcome is that a forest is considered to extract water at the same rate, provided the depth to the water table is less than the threshold depth (10 metres, or less, at 1990). This approach is consistent with the principle applied by Benyon and Doody (2004), where a hard pan site was identified among their study sites, and the outcome was incorporated into the mean extraction value for all plantations overlying water tables 6 m, or less, below ground level.

4.3.6 Pumped extractions

Allowances for groundwater extractions for livestock use has been made on the basis of livestock carrying potential of grassland. This is based on estimated pasture productivity potential which is directly related to the mean annual rainfall for the study areas. An aggregate value for stock water use of 0.03 ML/ha for pasture land use is used for the Nangwarry and Wattle Range sites. Livestock water allowances are only made for the agricultural land, with firebreaks, road, rail and drain reserves being excluded from the livestock carrying potential.

An estimated annual domestic groundwater extraction value has been established for each homestead identified in the aerial image of each study site[24]. This value is based on each dwelling unit having 0.4 ha of irrigated land (a value that is generally applied statewide in prescribed areas for water accounting purposes) and an average domestic water use which is based on SA Water state statistics. An aggregate value of 3.55 ML per dwelling is used for the Nangwarry and Wattle Range study sites. Appendix 4b provides the calculations for livestock and domestic uses.

Licensed pumped extractions are based on metered annual water returns by licensees. Where there are data deficiencies, a volume of 8 ML/ha is applied for each year of the study period for areas identified as irrigation in the aerial imagery. With respect to the chosen study sites, irrigation is identified as a minor land use and only occurring in the Wattle Range area sites.

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[24] All aerial photography is orthorectified and colour image 'tiles' in red, green, blue and near infrared bands using a Vexcel UltraCam D Optical Sensor, radiometrically balanced and mosaicked. Initial acquisition 31 Dec 2012 but updated 25 June 2013

4.3.7 Groundwater lateral flows

While there is a natural lateral flow of groundwater, for this study, the lateral inflows and outflows for the study areas are considered equal. This is based on the principle that groundwater management for the region is premised on maintaining lateral through flows of groundwater regional water allocation plan (South East Natural Resources Management Board 2013). Similarly, groundwater transmissivity is considered to be a constant.

4.4 Variability of parameters

Earlier in this thesis, it was advised that the values and principles that have contributed to the groundwater accounting behind the regional water allocation plan would be applied in this study, but where anomalous outcomes from the analysis is observed, some of the relevant parameters are varied and the results discussed.

While a number of the adopted parameters could be described as ‘default’, or mean values, based on past investigations by others (Dillon *et al* 2001 and Brown *et al* 2006), the suitability of some of these are to be tested for sensitivity, while others will be noted. The appropriateness and relevance of the adopted parameter values will help to determine how robust the forest water model is at scale.

In this study, the relevant scale is the accounting for plantation forest hydrological impacts on groundwater resources at a groundwater management area scale. According to the regional water allocation plan the groundwater management areas vary in extent from about 3775 to 55 600 hectares, with an average area of about 24 000 ha. In this respect, while acknowledging there will be some natural variations within management areas, the adopted site testing of areas of 5000 ha should be adequately appropriate to indicate the plantation forest hydrological impacts at a groundwater management area scale (or a sub-regional scale).

Two hydrogeological parameters that vary across the landscape are diffuse groundwater recharge rates and the aquifer characteristics, particularly the variability of the aquifer storage coefficient. Variability in the aquifer storage coefficient may appear to be significant as this factor determines the change in groundwater level for a change in groundwater volume in storage. While many observers will consider regional aquifers to be homogenous, the reality is they are heterogeneous, constructed of many layers with varying physical characteristics that are not always consistent spatially, or at depth, but this does not prevent a general characterisation of an aquifer to reflect its broad and ‘average’ physical characteristics which are applied in technical assessments, groundwater numerical modelling and subsequent management.

4.5 Data sources

Data describing the plantation forest estate is from information provided by the industry to the regional groundwater administrator, the Department of Environment, Water and Natural Resources. This information was provided by all commercial forest estate managers to register their respective forest estate holdings, as at December 2014, to receive granted forest water licence, as provided by legislation. The data is at a compartment scale and includes forest type, hardwood or softwood, net area of the forest, year of planting and its location in the landscape.

The classification of other land uses is derived from other publicly accessible spatial data and the interrogation of 2013 aerial images. The various land uses are categorised as: pasture, forest firebreaks, roads (public and private), rail and drain reserves, native vegetation (including wetlands), irrigation, and although minor in area, other sundry areas taking account of any dams, industrial or un-identifiable areas.

Groundwater level data is sourced from the government monitoring well network known as the Obswell network. The water level monitoring record for many wells extends back to the 1970s, and generally, the observations have been made quarterly. Apart from selecting wells in the appropriate landscape, with respect to the surrounding land use, wells with a long term and continuous groundwater level record are preferred, where possible for the provision of groundwater level data; however, this is not always achievable. This data is also available to the public via a government web site[25].

The reference point for the change in groundwater storage is the change in groundwater level below ground level. For consistency, the depth to water table observations are those levels observed, as near as possible, during autumn at each site. The autumn level is often the lowest observed level for the year for a grassland land use and this observation period is selected to establish a relationship between ‘cause and effect’, with the observed autumn level being compared to the net water-mass-balance for the previous calendar year. This aligns the reporting periods for forest management and the rainfall year with the net impact of those consequences being observed in the water table in the following autumn.

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[25] https://www.waterconnect.sa.gov.au/Systems/GD/Pages/Default.aspx

Rainfall data from Penola (BOM 026025) is applied in the Wattle Range and Nangwarry studies. Appendix 4a summarises the monthly Penola rainfall and its deviation from long term means, annually and for the May-October periods, for the period 1970 to 2015.

Any gaps in land management data are estimated, after taking advice from available relevant local expert sources. In the case of plantation forestry at Nangwarry, the history of the plantation existing prior to the 1983 bushfire, has not been provided as part of the forest registration process. While annualised forest water accounting values could have been considered for this period, it would have been necessary to exclude it from the statistical analysis due to a lack of historical knowledge of the plantation forest compartments in the pre-fire period. Consequently, some historical standing water level data is provided, but no corresponding calculations of water-mass-balance is undertaken at the Nangwarry sites, pre-fire.

4.6 Forested site selection

A key requirement at each investigation site, is, as near as practical, to have a continuous groundwater monitoring record of water levels extending back as far as possible. The purpose is to observe the impacts of plantation forests and other related land uses over as long a continuous time period as possible. While there are many government groundwater monitoring sites in the Lower Limestone Coast region, the number with a continuous record in areas where plantation forestry is a significant land use is limited. For increased confidence about forest hydrological impacts, it is desirable that observations at the different study sites be for parallel time periods to minimise any disruption from any variable background trends and rainfall in a different period.

Other than the availability of a groundwater level monitoring site in an area where plantation forestry is the predominant land use, to ensure confidence in the water accounting outcome, it is also important to remove, where practical, the possibility of surface water flows and other extraneous activities within the study sites. For this reason, sites that are significantly undulating, or known to have natural streams or drains, have generally been excluded. The location of the South East drainage systems can be viewed in Figure 2.3.

One exception is the site identified as SHT012. This site is dissected by the Bakers Range Drain. The drain transfers surface water from a southern catchment outside the study site, through the study area. Under current conditions, it is not believed to collect any significant surface water directly from the investigation site.

Due to the elevation of the drain floor, relative to the current water table, drain flow when it occurs, is likely to contribute some additional diffuse groundwater recharge to that occurring from rainfall at that location. This lower groundwater level condition is considered to exist since about 2002. In the pre-forest period, when groundwater levels were elevated, it was probable that there was some groundwater discharge into the drain, creating some base flow. The influence of the drain at site SHT012 is a discussion item later in this thesis.

Ideally, it is desirable to observe the water level trends at the study sites prior to forest development as this assists in further demonstrating the hydrological impacts of plantation forests, compared to non-forest land use (grassland) activities. It also aids in the alignment of the water-mass-balance calculations with the observed changes in groundwater in storage. This comparative landscape observation is achieved in the case of the Wattle Range hardwood sites as these plantations have only been established since the late 1990s and on land that was previously pastured, with groundwater monitoring in place during the pre-forest period.

In the case of the longer rotation softwood plantations, much of the current plantation forest estate is 2nd or 3rd rotation forests, and there are no groundwater monitoring observations that can be considered representative of groundwater level responses prior to broad scale softwood plantation land use. However, the unfortunate occurrence of the Ash Wednesday bushfire in February 1983, with the destruction of an extensive softwood forested area, has provided a situation that has assisted in observing a non-forested landscape transitioning to an intensive softwood plantation area. This transition should also assist in aligning the net water-mass-balance account with the groundwater levels at the two Nangwarry softwood investigation sites. Some softwood plantation forest compartments at these sites are now entering the clear-felling stage, followed by reforestation programs, so the study can be considered to cover a period that extends almost across a full forest rotation, albeit having a compressed age structure, rather than being typical of the regional estate with a wider distribution of ages.

The selected forest water accounting study sites represent two different geographic areas and include approximately 5000 ha around each of the following observation wells:

- MON016, SHT012 and SHT014 hardwood sites in the Wattle Range area (west of Penola)

- NAN009 and NAN012 softwood sites in the Nangwarry area (south of Penola)

A map locating the five study sites is presented in **Figure 4.2**, and **Table 4.1** summarises some of the site statistics and characteristics of the selected forest water study sites.

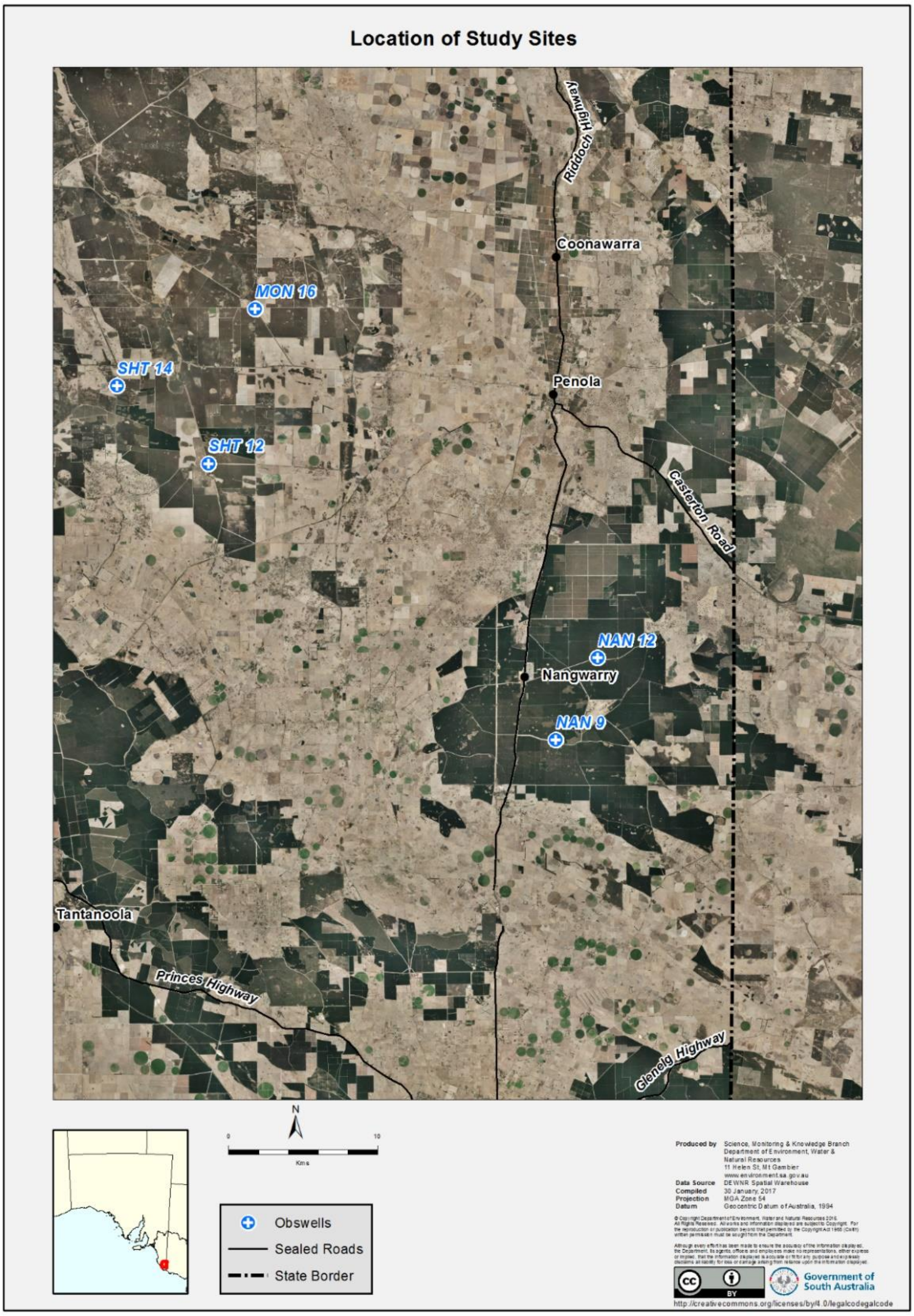


Figure 4.2: Lower Limestone Coast forest water account project study sites

In addition to the above study sites, for which water-mass-balances are created, some monitoring wells in the same vicinity as the study sites are reviewed where plantation forests are not the main land use, and the additional monitoring wells can be considered to be representative of grassland land use accompanied with a long-term monitoring record.

4.7 Grassland 'paired' site selection

Ideally, for observing grassland land use, the site selection should target a minimum of land use change over the study period and to ensure, as much as possible, consistency with the various environmental factors, such as rainfall, the investigation should be carried out over the same time period as the forested study sites. Options for grassland sites with a long term and continuous water monitoring record in the vicinity of plantation forests has been limited, but two sites provide an opportunity for 'paired catchment' observations with the studied forest sites. These grassland sites are based around the observation wells FOX004 and MON004. A water-mass-balance over 5000 ha at each site is assessed against the observed water table fluctuation at each of these grassland sites. Such observations are intended to add further confirmation of the hydrological impact of plantation forests.

In addition to FOX004 and MON004, sites with a minimal percentage of plantation forest land use in the vicinity, observation wells NAN003, MIN009 and MIN020 in the Nangwarry area are referenced. Groundwater level at some confined aquifer wells are also observed in the vicinity where a connection between the unconfined and confined aquifer is believed to occur at Nangwarry. A direct relationship between the unconfined and confined aquifer has recently been established in the border zone east of Nangwarry (SKM2012 and Somarante *et al* 2016). The water level responses at confined aquifer observation wells MIN018, NAN083, NAN084 and NAN085 are considered and discussed later in this thesis.

At the two Wattle Range grassland sites, MON004 and FOX004, while the predominant land use is grassland, there are some other agricultural activities. The east side of the 5000 ha study site of MON004 intrudes into the Coonawarra viticultural area, to the extent of about 600 ha. The MON004 site is also traversed by Drain D, a contributing drain to Drain C (refer Figure 2.3).

The FOX004 site is largely composed of grassland, but the western side does intrude onto the base of one of the ancient remnant coastal dunes referred to in Chapter 2. The site is also traversed by a number of surface water drains, mostly running east-west, with the natural regional gradient, but with some with north-south orientated drains for intercepting local surface water. The Wilmott Drain runs parallel to the eastern foot of the remnant dune range referred to above. Drain M, a major regional drain, cuts across the southern portion of the study site.

Table 4.1: Study site characteristics

Site ID (obswell identification)	**MON016**	**SHT012**	**SHT014**	**NAN009**	**NAN012**
General location	Wattle Range	Wattle Range	Wattle Range	Nangwarry	Nangwarry
Main forest type	hardwood	hardwood	hardwood	softwood	softwood
Net area of main forest type	3320 ha	2928 ha	1813 ha	4061 ha	4119 ha
Total area of plantation forest	3320 ha	3551 ha	2166 ha	4064 ha	4119 ha
Plantation forest as a % of site area	66%	71%	43%	81%	82%
Native vegetation as a % of site area	10%	11%	22%	6%	4%
Study period	1976 to 2014	1983 to 2014	1980 to 2014	1985 to 2014	1985 to 2014
Rainfall data from relevant BOM station	Penola (BOM26025)	Penola (BOM26025)	Penola (BOM26025)	Penola (BOM26025)	Penola (BOM26025)
Depth to obswell standing water level during the study period	2.35–6.18 m	1.66–5.74 m	1.79–4.84 m	5.64–8.05 m	12.28–14.37 m
Water mass balance calculations include forest extraction	yes	yes	yes	yes and no	yes and no
Irrigation activity in study area	28.5 ha	177.6 ha	46.4 ha	no	1.6 ha
Approx. groundwater gradient across the area study sites	0.6/1000 m			0.42/1000 m	
Anomalous characteristics of the site requiring consideration and comment		Study area traversed by Bakers Range Drain		Forest extraction from water table deeper than 6 m	Forest extraction from water table deeper than 6 m

Statistics of the various land uses at the five study sites is available in Appendix 4c

4.8 Testing of the forest groundwater accounting model against groundwater level data

To test the forest water accounting model using observed groundwater level data, it is necessary to convert the water balance into comparable metrics. The calculation for a water-mass-balance at a 5000 ha area site commences with a zero balance and the subsequent calculated net annual outcome becomes a variation about zero. These annual water mass balance values, expressed as ML are converted to an equivalent depth of groundwater in storage. A recharge, or discharge of a volume of water 0.1 m deep is spatially equivalent to a volume of 1 ML per ha. Assuming an aquifer storage coefficient of 0.1, this depth of water therefore represents a 1 m depth of groundwater in storage.

The resulting calculated water-mass-balance is a groundwater volume of what is occurring at each 5000 ha circular site. In general, these sites are reasonably representative of what is occurring in the wider area around the 5000 ha site and consequently similar annual changes will be occurring in the surrounding areas to redistribute any subsequent groundwater gradient. While the lateral movement of groundwater is a slow process, there will be some spatial redistribution of any net change of groundwater volume in storage. It is found that dividing the water-mass-balance outcome by 3 approximates the redistribution of the change in groundwater volume in storage to a depth of groundwater in storage. If an alternative denominator value was applied, the proportional relationship would still remain.

As the annual change in the net water-mass-balance and the subsequent calculated change in groundwater storage commences with a zero balance and the result is to be compared with the actual observed net annual change in groundwater storage at the monitoring well, the two-data set are then aligned, recognising that the calculated net water-mass-balance is to be compared to the autumn groundwater level for the year following the net annual calculation. This data is then presented as a graph for each site, with the calculated or predicted depth to the water table being plotted against the actual observed depth to the water for the same time point.

To achieve this alignment, a period of relative water-table stability (which also relates to a relative constancy in the land use at the study sites) is desirable and a calculated constant value, that is unique to each site, is added to the calculated annual site net-water-mass-balance values. This constant value is derived from establishing a mean depth to the standing water level for a period of about seven to 10 years. Similarly, a mean calculated change in groundwater storage is established for the same time period. The difference between the two mean values is then incorporated, as a constant, to all calculated net annual water-mass-balance values at that site. This alignment occurs generally in a period of non-forestland use, or a period or minimum forest impact period. The alignment period is during the pre-forest period at Wattle Range and in the immediate post fire period at Nangwarry, while much of the area is in the early stage of reforestation and the water table appears to be in a steady state.

The alignment process does not interfere with the net annual water-mass-balance changes or the change in groundwater storage values, but provides for a closer visual relationship between the observed water table (autumn values) against the calculated net annual water-mass-balance, expressed as a depth to the water table, for the same time period.

4.9 The annual water-mass-balance account

In summary, the net annual water-mass-balance is constructed as follows:

The calculated net annual water-mass-balance = $\sum R - \sum D$, where R is recharge, and D is discharge at the 5000 ha study site.

The source of annual recharge is the diffuse recharge from rainfall on the plantation forests and the grassland land uses. Discharge includes the extraction by plantation forest, plus any pumped extractions which includes irrigation water and water for stock and domestic uses. Lateral groundwater inflow and outflow are considered equal therefore become self-cancelling.

The calculated net annual water-mass-balance is considered to equal the calculated (predicted) net annual change in groundwater storage. This is then related to the observed net annual change in groundwater storage, determined by the annual fluctuation in the depth the water table below ground level.

5 Results: Comparison of calculated and observed change in groundwater storage

5.1 Introduction

The investigation of the five forested study sites has resulted in a number of observations. Some observations relate directly to the calculated net annual change in the water-mass-balance and the observed change in groundwater storage, whilst others are relevant to the local land use, particularly the plantation forest management cycles and that relativity to the characterised average plantation forest management that has determined the parametrisation for the different forest types. The data collected and the related observations are grouped as follows to assist discussion:

- Historic regional water table trends
- Correlation between the calculated net annual water-mass-balance and observed changes in groundwater storage
- Threshold depth at which groundwater extraction by plantations could be considered to cease.

In addition to the above matters, observations related to some of the applied parameters and relationships are considered and these include:

- Groundwater recharge variability
- The relevance of the storage coefficient value in the alignment of water-mass-balance calculations with observed water table movements
- Relationship between confined and unconfined aquifer responses at, or near, the Nangwarry study sites
- Management of the characterised average plantation forest.

5.2 Historic regional water table trends

While it is now generally accepted that plantation forests impact on groundwater recharge and plantation forests extract water from shallow water tables, a broader perspective beyond the selected plantation forest study sites is considered with an observance of groundwater trends at grassland sites in the same general area, where forest hydrological impacts can be considered inconsequential over the same time period. This approach can be considered comparable to the ‘paired’ catchment studies where catchment yields under forest land use are compared with surface water yields in a similar, but grassed catchment, under the same climate conditions, as reported by Brown *et al* (2005).

The following site groupings are made on the basis that the only apparent difference between the sites is the surrounding land use; plantation forestry being compared to grassland land use. In the selection, the topographical and geophysical differences are minimised as much as possible and the observed sites are in the same rainfall zone. Consequently, any differences in groundwater trends can be considered to be caused by the difference in land use. The comparative observations between plantation forest land use and grassland land uses are considered in the following groupings:

- Wattle Range forested sites, MON016, SHT012 and SHT014 are compared to the non-forested sites of MON004 and FOX004
- Nangwarry forested sites, NAN009 and NAN012 are compared to the non-forested sites of NAN003, MIN009 and MIN020.

5.2.1 Wattle Range area

In the Wattle Range area, the two observation wells FOX004 and MON004 are located in, and surrounded by, grassland land use and have a similar observation span as the forested site monitoring wells, MON016, SHT012 and SHT014, where hardwood is the dominant forest type. The location of all five wells can be viewed in **Figure 5.1**.

A comparison of hydrographs, using reduced standing water levels expressed as (m) AHD is presented in **Figure 5.2**. While there are some data gaps, the available data provides sufficient indication of the water table trend at each site, and broadly across the Wattle Range area.

It should be noted that the grassland MON004 site is up gradient of the three forest investigations sites, while the grassland FOX004 site is down gradient. Although a very slight declining trend in the water table can be observed after 2002 at MON004 and FOX004, followed by recovery in 2010, the general trend, other than for the natural seasonal recharge/discharge fluctuations, is relatively stable. Monitoring at these two grassland sites ceased in the 2010 -2011 monitoring period.

The three-forested study site monitoring wells all exhibit a similar trend of groundwater level decline which becomes noticeable in about 2000 to 2001, about 3 years after the commencement of broad scale afforestation on land that was previously grassland.

The forested monitoring well site SHT012, which is adjacent to the Bakers Range Drain, shows a slight rise in the water table in 2010 and then some stabilisation before re-commencing a declining trend. This water table recovery coincides with a sequence of two wet years when the rainfall exceeded the mean annual rainfall and the mean for the May-October period, and water was present in the Bakers Range Drain at those times and this is discussed later in this thesis. This wetter period also coincides with the groundwater level recovery in the grassland sites of MON004 and FOX004, whereas, there is no recovery evident in the other forested MON016 and SHT014 sites.

Prior to 2000, when the landscape at the forested study sites (MON016, SHT012 and SHT014) was essentially grassland, these monitoring wells have trends and seasonal responses similar to the grassland wells, MON004 and FOX004. The period between 1994 and 1999, except for 1996, was noticeable for its significant reduction in annual rainfall.

The general water table gradient across the 45 km between the monitoring wells MON004 and FOX004 is relatively flat with an overall net average gradient of about 0.6 m per 1000 m. This relatively flat gradient in the local water table indicates a potential low rate of lateral through flow when the groundwater resource is in a stable condition.

Using observed groundwater level data from the grassland sites, recharge rates for the grassland land use are calculated using the water table fluctuation method, and compared with the management area mean recharge rates adopted by the regional water allocation plan. This is discussed in Section 5.6.

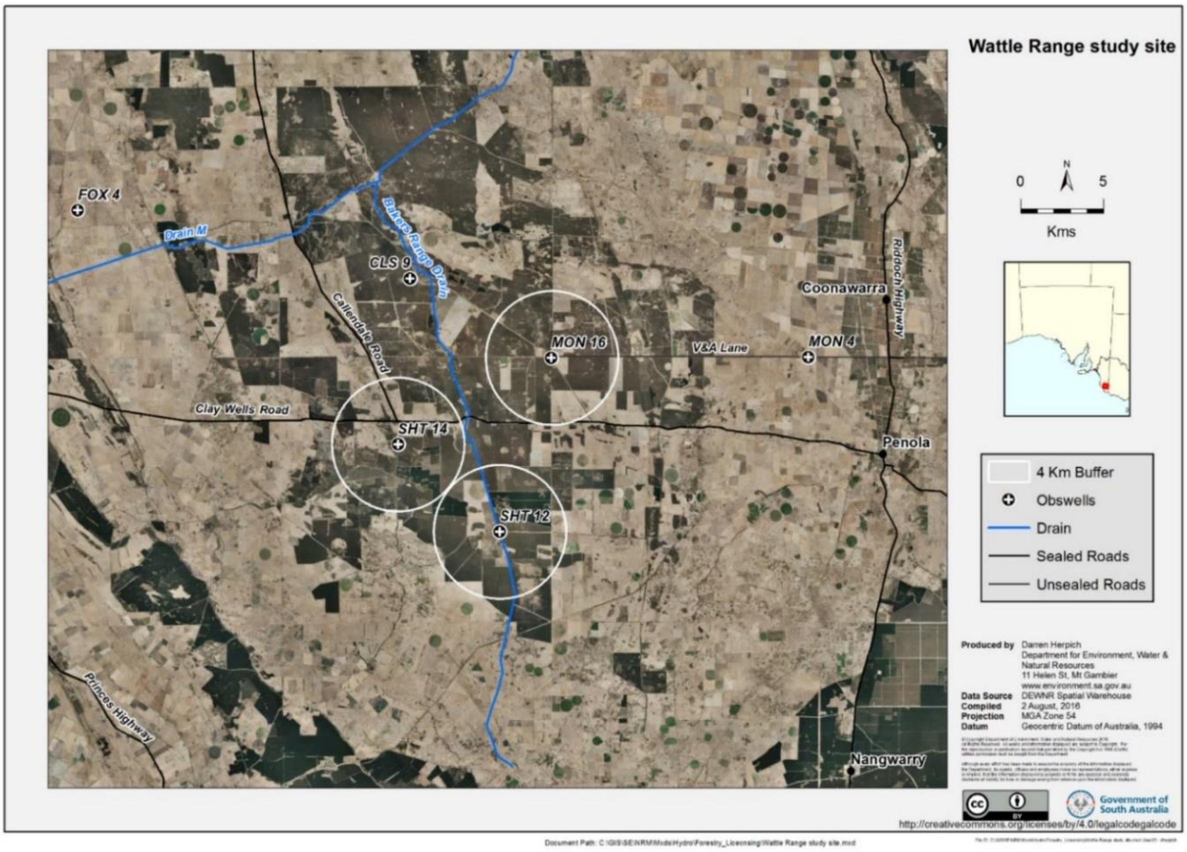


Figure 5.1: Wattle Range monitoring wells: grassland and forested study sites

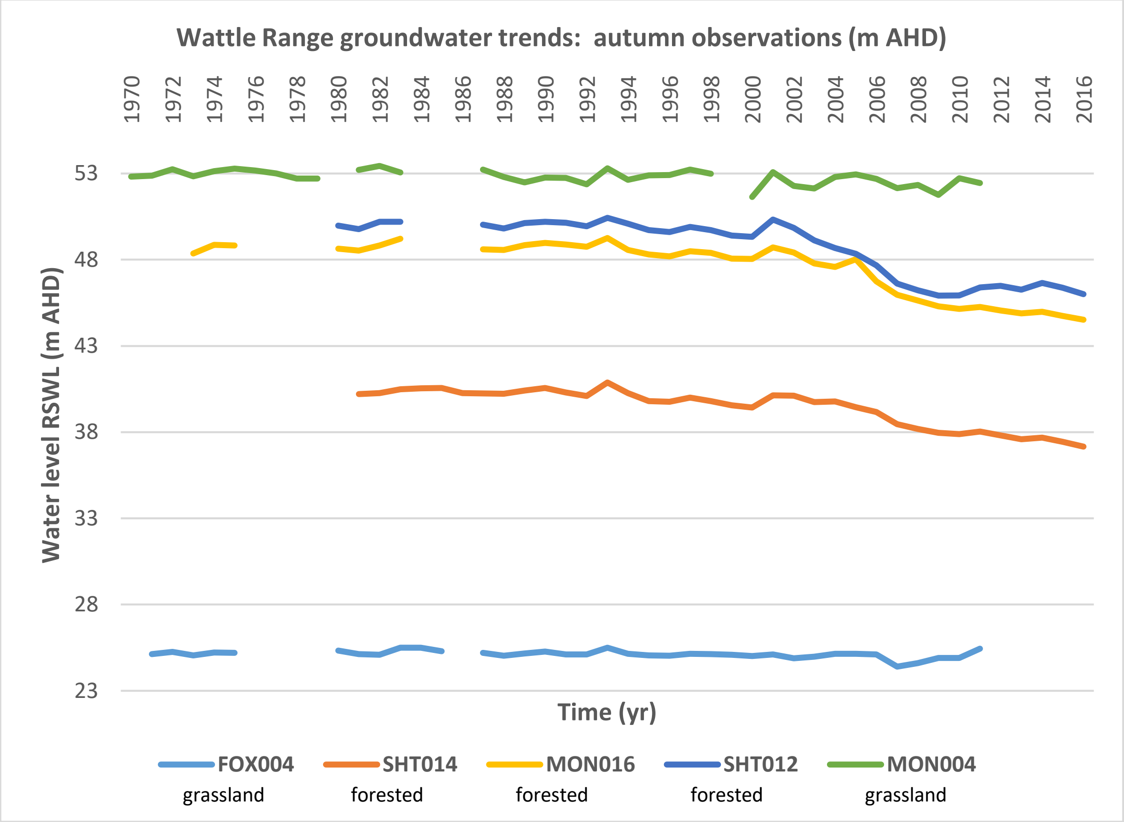


Figure 5.2: Wattle Range groundwater trends

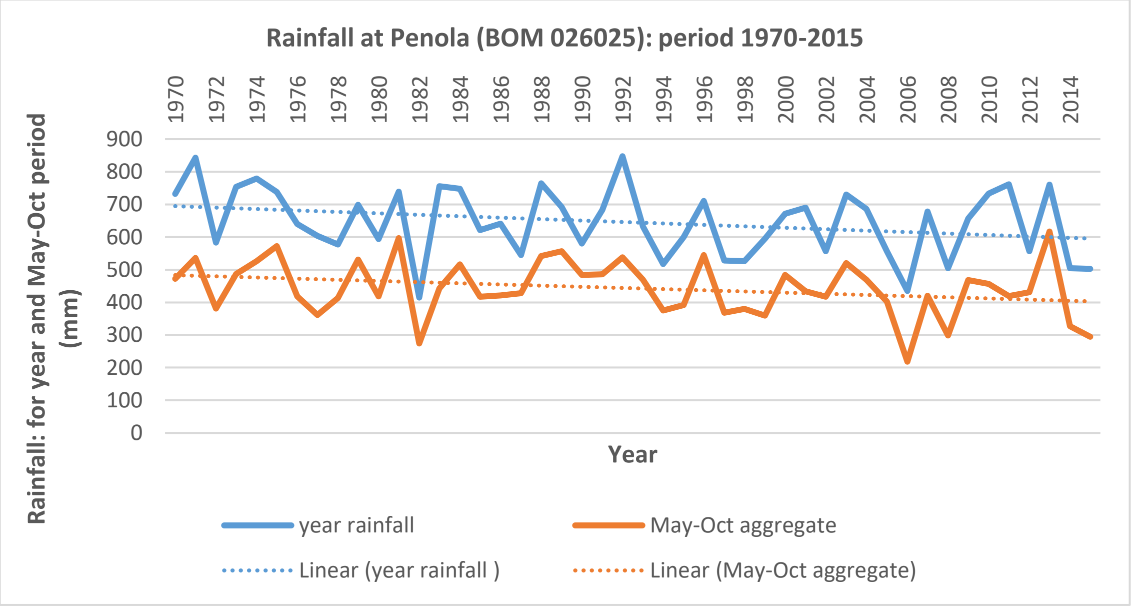


Figure 5.3: Rainfall at Penola (BOM26025) for period 1970 to 2015

The rainfall has a significant influence on groundwater diffuse recharge and the rainfall record for the period 1970 to 2015 is presented in **Figure 5.3**. The data is presented as annual rainfall and the rainfall for the May-October period for each year. The trend for each period class is also included.

Generally, up until about 2001, all observations indicate a general relativity between the water table trends at the five monitoring well sites. All hydrographs exhibit a recharge spike in 1992, when the annual rainfall exceeded the mean by 31 per cent and again in 2000-01 when the rainfall was about the mean for two consecutive years, following three consecutive drier years. The response at the down gradient FOX004 is muted in comparison with the other sites. The start of a significant downward trend of the groundwater level commences at the forested sites in 2002. While at the grassland sites, a temporary decline is observed coinciding with the annual rainfall being 86 percent of the mean. In 2004, the grassland site groundwater levels recover to the long-term levels, while the forested sites continue to decline.

From the higher groundwater levels during the pre-forest period, the groundwater decline at the three forested study sites is of the order of 4.3 m at MON016 to 2.69 m at SHT014 and SHT012 with a 3.97 m decline from 2001 to 2015 (refer Figure 5.2).

5.2.2 Nangwarry area

Identification of suitable grassland monitoring wells in the Nangwarry area is more difficult due to the lack of wells with a continuous monitoring history being located sufficiently distant from plantation forest land use and influence and in the same hydrogeological zone as the forest water study sites NAN009 and NAN012.

The monitoring wells NAN003, MIN009 and MIN020 are identified as having a reasonable monitoring sequence and being partially representative of a grassland land use, noting that plantation forest does exist within about 1000 metres of NAN003, but the forest is down gradient of the monitoring well, while MIN009 abuts a down gradient plantation forest. The location of all the above-mentioned wells, along with a confined monitoring well MIN018, are presented in **Figure 5.4**. The extent of the 1983 Ash Wednesday bushfire is also included in the figure.

A review of a long-term hydrograph for the monitoring NAN009, at **Figure 5.5**, reveals a significant rise in the water table after the bushfire destroyed some 13 000 ha of softwood plantations in the groundwater management area in February 1983. Other than for seasonal fluctuations, the elevated water level then exhibits a relatively stable trend for about 10 years before entering a period of continuing decline; this coincides with the early stages of the reforestation program that followed the fire. As the plantation industry spread the reforestation over about 10 years, the age classes are ‘compressed’, relative to what would be expected with a 35-year characterised average softwood plantation estate.

Prior to the fire, there is a declining water table trend of about 1 m over 10 years at NAN009. Other than knowing that the area was forested at the time of the fire, detail of the age structure of the pre-fire plantations is not known, but it is believed to have been more representative of the characterised average plantation than that plantation established in the 10 years following the fire.

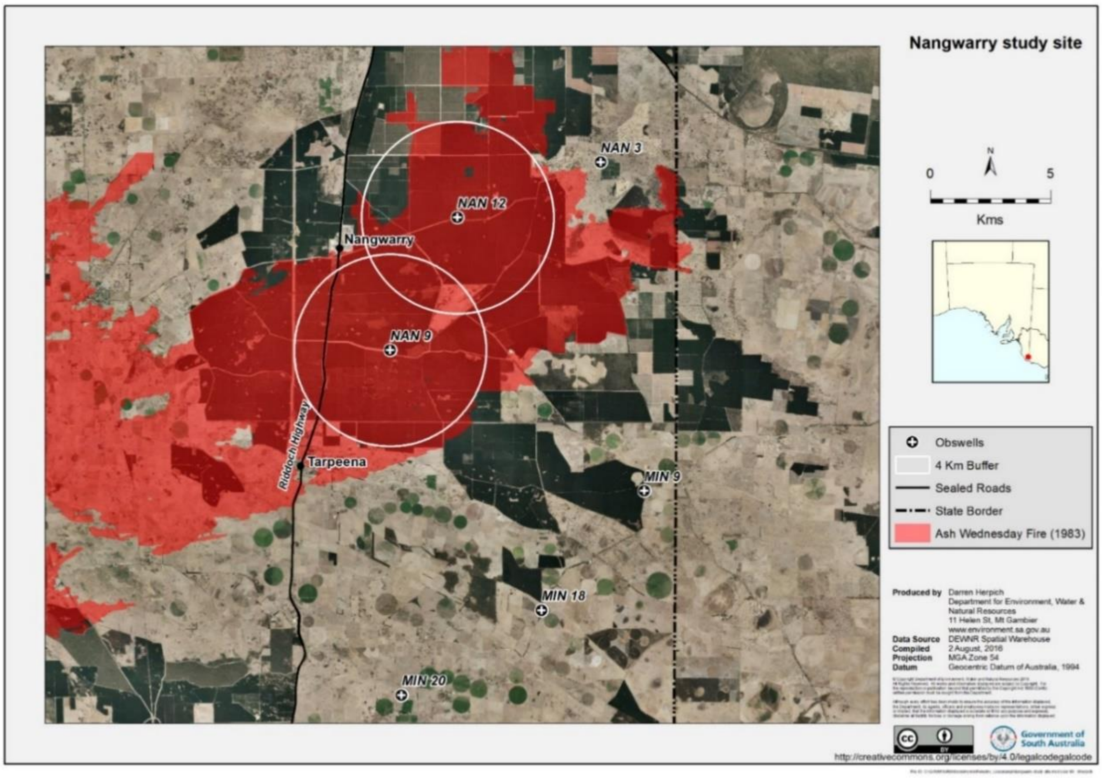


Figure 5.4: Nangwarry monitoring wells: grassland and study sites

By comparison to the 1985 to 1992 post fire period, this earlier period does not exhibit any significant seasonal recharge fluctuations. While the pre-fire monitoring record is not continuous, it does exhibit a similar rate of decline to that observed after about 2000.

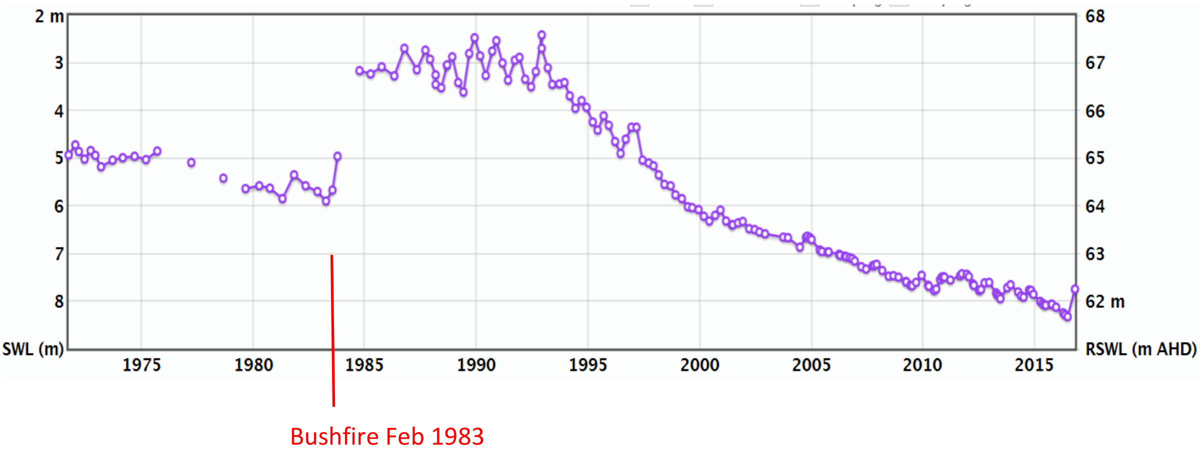


Figure 5.5: NAN009 monitoring well hydrograph

A comparison of reduced standing water levels, expressed as (m) AHD for the unconfined monitoring wells (NAN003, NAN009, NAN012, and MIN020) is presented in **Figure 5.6**. While there are some data gaps, the available data provides an indication of the comparative water table trend at each site, and across the Nangwarry area. While the 'grassland' sites were not impacted by fire, the most significant observation is there is no groundwater level response immediately following the 1983 fire at the grassland sites, as occurred at the forested sites, when most of the plantation forest was destroyed.

From the higher groundwater levels during the immediate post fire and early reforestation period, the groundwater decline at the two forested study sites is of the order of 5.4 m at NAN009 and 3.7 m at NAN012, during the 30-years from 1986 to 2015 (refer Figure 2.5).

At the grassland sites, NAN003 and MIN020, other than for some seasonal fluctuations, the trend is relatively stable for about 20 years prior to 1993. This is followed by a gradual decline, then the grassland sites enter another period of relative stability commencing in about 2009 and until 2015. Both these stable phases generally coincide with periods of mean to above mean rainfall, and the declining trend, with the period of reduced rainfall.

The site MIN009 data indicates a gradually rising water table commencing in about 1988 and continues for about 5 years, before entering a gradual decline until about 2009.

At the forested sites, NAN009 and NAN012, a steep downward trend commences in 1992, nine years after the fire and the commencement of reforestation, with the trend moderating about 10 years later in about 2002, but the downward trajectory continues. The hydraulic gradient across the area is relatively flat at 0.42 m per 1000 m.

In summary, it can be concluded that the water table at the forested sites display a significant recovery commencing in the first winter following the February 1983 fire. The water table at the forested sites continued to rise in the second year following the fire and remained at the elevated levels for about 10 years (recovery in the order of nearly 3 m at NAN009 and 1.7 m at NAN012). The two grassland sites of NAN003 and MIN020 remained stable during this period, while MIN009 exhibited a small rise (<0.5 m) from 1990. It is advised that there were no government groundwater level observations in the autumn of 1983 at any wells, and consequently, the link from 1982 to 1984 is presented as a connecting straight line between the two years in Figure 5.6.

All groundwater levels have declined after 1992-93. The forest sites exhibiting a continuous decline, while the up-gradient grassland sites show some recovery and stabilisation in 2009-10. The down gradient site of NAN003 continues to exhibit a decline. It is noted that other than the recovery of water levels after the fire, the trends at NAN003, NAN009 and NAN012 are similar. In the post fire period, while the forest sites exhibited a significant groundwater rise, the grassland site NAN003 groundwater level remained stable during this period.

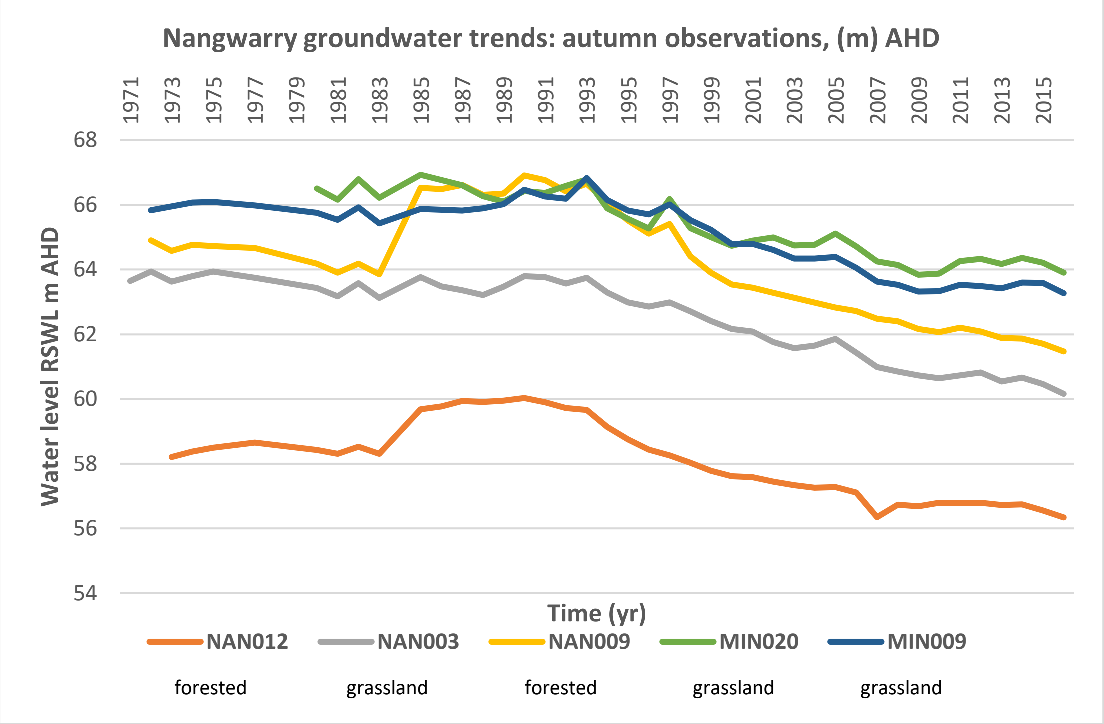


Figure 5.6: Nangwarry unconfined groundwater trends

According to the forest water accounting model, the replanted forests would provide a recharge net gain up until about 1992 as extraction is not considered to commence until the seventh year after planting. Furthermore, according to the forest water accounting model, due to the weed control practiced, recharge under first year forest is greater than grassland and is equivalent to grassland in the second year of plantation establishment.

To summarise, the Wattle Range sites demonstrate that plantation forests do have an overall negative impact on the local water balance, while the grassland sites, other than for any periods of significantly reduced rainfall, maintain a relatively stable water table. The Nangwarry forested sites demonstrate that long term forestation results in a lowering of the water table, compared to a grassland environment. This is starkly illustrated by the significant rise in the water following largescale forest destruction as the result of the 1983 fire. While the burnt forests demonstrate a significant rise in the water table, there is no significant response on grassland during the same period. However, due to some significant differences in groundwater levels following the fire in 1983, and subject to localised transmissivity, some of the significant forest impacts on groundwater may be impacting in some neighbouring areas.

5.3 Correlation between the calculated net annual water-mass-balance and changes in observed groundwater storage

The following graphed observations and statistical analysis (Figures 5.7 to 5.24) present the results from calculating net annual water-mass-balance accounts for each of the five 5000 ha forested study sites. The resulting net change in groundwater storage is expressed as a change in the depth to the water table and, these predictions are compared to the actual observed changes in depth to the water table. As previously explained, the plantation forest hydrological impact accounts are based on the annual component values contained in the forest water accounting model, and the assumptions and parameters referred to in the previous chapter.

Due to the large percentage of plantation forest cover at each study site, the hydrological impacts of forest should contribute to a significant percentage of the total annual net water-mass-balance account and its trends at each of the study sites. Consequently, if there is a good correlation between the calculated net annual water-mass-balance changes and the observed net annual change in groundwater storage, the 2006 forest water accounting model, and its annual accounting values, can be considered to provide a relatively accurate indication of hydrological impacts of plantation forests at a groundwater management area scale.

It then follows, if the plantation forest estate is managed in accordance with the ‘average’ characterised forest management in the 2006 forest groundwater model, the model can then be considered reasonably accurate for estimating the hydrological impacts of the plantation forest estate on the local groundwater resource, on an annualised basis, at a groundwater management area scale.

At the Wattle Range sites, it is observed that plantation forests occupy between 43 and 71 percent of the area at the three 5000 ha study sites, where hardwood plantations are the predominant forest type and land use. The study period incorporates nearly 20 years of pre-forest land use, providing significant confidence that the observed groundwater level changes after the commencement of afforestation at those sites can be related to the land use change from grassland to plantation forests.

In the case of the Nangwarry softwood sites, plantation forests represent a higher percentage of the landscape at the two study sites, with plantations accounting for 81 to 82 per cent of land use. This adds to the confidence that any groundwater trends away from the regional background trend, are related to the impacts of softwood plantation forests at those sites.

As stated earlier in this thesis, the water-mass-balances for the two Nangwarry sites are assessed under three different assumptions. One is that no plantations extract groundwater, the second is all plantations extract groundwater, and thirdly, to consider plantation forest groundwater extraction ceases when the depth to the water exceeds 10 metres below ground level. In the assessment process and to provide a reference point, the 10 metres level was determined for 1990. This was to utilise groundwater contouring data available from the Department of Environment, Water and Natural Resources.

In the following figures, the X axis is the year of the observed autumn water table depth below ground level and the relevant time for the corresponding calculated net annual net water-mass-balance, expressed as a depth to the water table. The Y axis is the calculated (predicted) and observed depths to the water table below ground level at the study site monitoring well.

The time point for the calculated depth to the water table, based on the net annual water-mass-balance calculation, is compared to the following autumn observed depth to the water table to provide the link between the ‘cause’, the calculation, and the observed value being the ‘effect’.

The blue graph links the actual observed water table depth values below ground level, while the green graph is the calculated (or predicted) net annual water-mass-balances converted to a depth to the water table.

The calculated net annual mass-water-balance at each site have been statistically tested against the actual observed annual change in groundwater in storage. The coefficient of determination (R^2) provides a measure of how predictable one variable responds to another. This statistical analysis and the resulting coefficient of determination R^2 values are presented for each study site.

In addition, Root Mean Square Error (RMSE) values (in metres) are provided for each site as a further indicator of proximity between the predicted and the observed depths to the standing water level. These statistical calculations are provided for the period of forestation.

The variables and parameters applied in this first presentation of results are those applied in the 2006 forest water accounting model and adopted in the regional water allocation plan. This includes the recharge rate, which is adjusted to reflect the rainfall variability in the May-October period, and the hydrogeological storage coefficient of 0.1. The forest recharge parameters include the adopted position of canopy closure being the point when there is a cessation of recharge, the rate of recharge in the years between planting and canopy closure, and recharge occurring after softwood plantation thinning.

In respect to groundwater extraction, the parameter is the adopted rate of increasing extraction after canopy closure. Application of some alternative parameters to refine the model are presented and discussed later in this thesis.

A table of calculated annual water-mass-balance values, converted to a depth to the standing water level and the actual autumn water table observations for each of the forested sites is available as Appendix 5a. Appendix 5b provides an example of the water-mass-balance calculation process.

The following presentation of the initial results for each site includes some commentary on the site observations, particularly where related to the land use change to plantation forest and the management of those forests.

5.3.1 Site MON016

The graph of the calculated net annual water-mass-balance (green), expressed as a depth to the water table, and the actual autumn observed depth to the water table below ground level (blue), in **Figure 5.7**, show a close correlation at MON016 during the grassland land use in the pre-forest period.

Intensive forest development commenced in the 2000-01 period when about 2250 ha of hardwood forest was established at the study site. Most of the 1000 ha forest balance making up the current estate at this site, was planted during the following six years.

A steep downward trend of the water table commences in 2003, generally coinciding with canopy closure of the early plantings and the commencement of extraction by the closed canopy forests, which is considered to commence in the fourth year after planting, according to the forest water accounting model. It is noted that the 2002 annual rainfall was below average, while the 2003 rainfall was above the mean, for both the annual and May-October periods. Rainfall in 2008 was also significantly below the mean for the annual and May-October periods. The steep downward trend in both curves begins to moderate in 2007, a year of about average rainfall following a dry 2006. During the following eight-year period, while there is still a strong correlation in the steep downward trend between the observed outcome and the calculated outcome, a differential rate in the trends is beginning to emerge, with the actual observed groundwater level response not being as pronounced as that predicted by the water-mass-balance calculations.

It is also observed that the direction of annual variations in the calculated net annual water-mass-balance account is generally consistent with the directional moves in the observed water levels. This is observed both in the pre-forest grassland period and during the period of significant water level decline in the plantation forest land use period.

In general, while the statistical analysis returns a coefficient of determination R^2 value of 0.95 during the forested period in **Figure 5.8**, when comparing the calculated net annual water-mass-balance against the changes in the depth to the water table, the accumulative hydrological impacts of plantation forests on the groundwater resource seem to be overstated by the model at this site.

There is water table recovery in the 2003-04 period and this coincides with two years being significantly wetter than the average and following a sequence of three years of about average rainfall. It should also be recognised that the first planted plantations had just reached canopy closure, where recharge is considered to cease and groundwater extraction by the hardwood plantations is commencing.

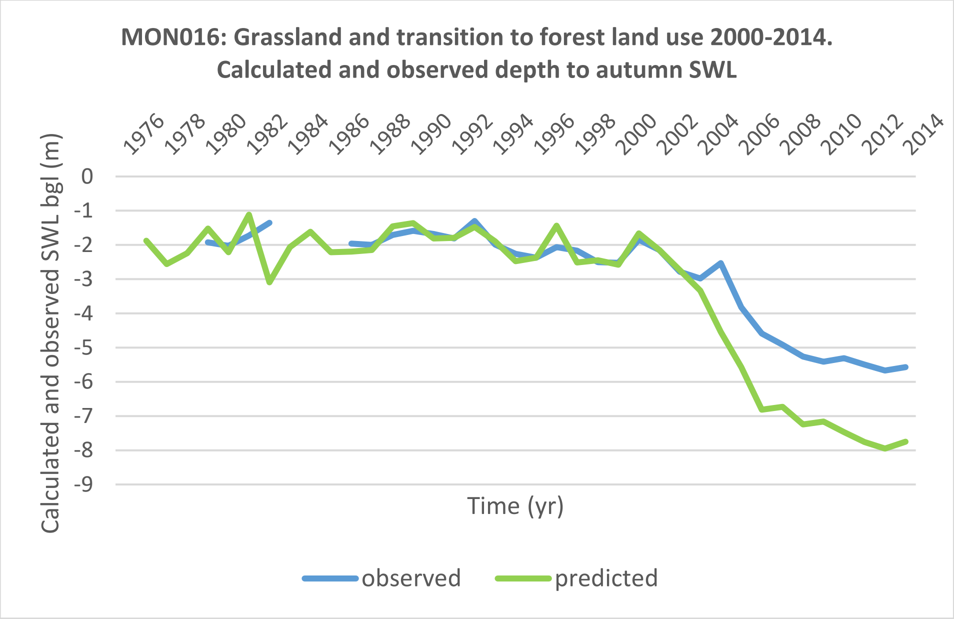
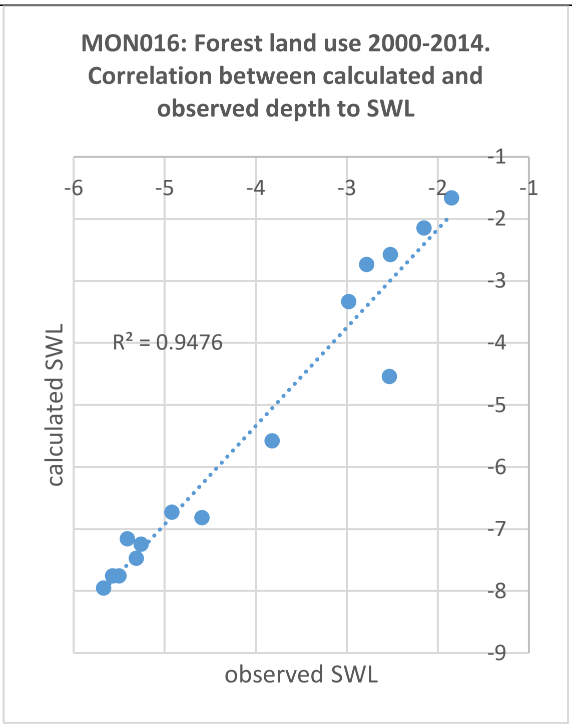


Figure 5.7: Correlation of water account against changes in depth to the water table at MON016



MON016

Afforestation commenced in 2000.

RMSE calculations are from 2000 to 2014.

RMSE = 0.536 m

(15 observations)

Figure 5.8: MON016 statistical analysis

5.3.2 Site SHT012

The graph of the calculated net annual water-mass-balance (green), expressed as a depth to the water table and the actual observed autumn depths to the water table below ground level (blue) at SHT012, in **Figure 5.9**, show a close correlation during the pre-forest grassland period.

Intensive forest development commenced in 1997 and peaked in 2001 with 1611 ha of hardwood being planted. At December 2014, this study site had 2928 ha of hardwood plantations and 623 ha of softwood plantations, with most of the softwood plantation forest being planted in the 2000-03 period. The last significant planting of hardwood was in 2007.

A steep downward trend of the water table commences in 2003, coinciding with groundwater extraction by the large area of early plantings. Coincidently, this also aligns with a drier than average year in 2002, but this is followed by a wetter year in 2003 with the rainfall in the May-October period exceeding the period mean by 17 per cent. The declining trend begins to moderate in 2007. During the following eight-year period, the downward trend of the calculated net annual water-mass-balance continues but at a reduced rate, while the water table exhibits a rise in about 2010. The water table continues to gradually rise until 2013 then it again commences a decline.

The observed rising groundwater trend in 2010, correlates with the re-emergence of water flows in the Bakers Range Drain which passes within about 50 m of the SHT012 monitoring well. Records indicate drain flows also occurred in 2013. Groundwater recharge from any drain discharge has not been considered in the net annual water-mass-balance calculation, but the presence of water in the drain appears to be impacting on the groundwater level at this site. This is discussed later in this thesis.

Rainfall in 2010 was significantly above the mean and this was accompanied by very wet summer months of December and January (2011). The year 2013 also had rainfall significantly above the mean. In **Figure 5.10**, with the drain impact period in the net water-mass-balance calculations being unaccounted for, the data analysis returns a coefficient of determination R^2 value of 0.91 during the forested period.

Other than for 2010-11, the direction of the net annual mass-water-balance account generally correlates with the directional moves in the observed water levels. This is observed both in the pre-forest period and during the period of significant water level decline. During the pre-forest period, when the water table was in the range of 1.5 m below ground level, due to the level proximity of drain floor with the elevated water table, it is considered some unaccounted groundwater discharge may have become drain base flow.

It is generally accepted that depending of the soil profile, solar evaporation of soil and ground water can occur where the table water is at depths of about 2 m, and less, below ground level (Shah *et al* 2007). This may also be a further factor to be considered in an annual water-mass-balance calculation, where shallow water tables are in the vicinity of 2 m below ground level for significant time periods.

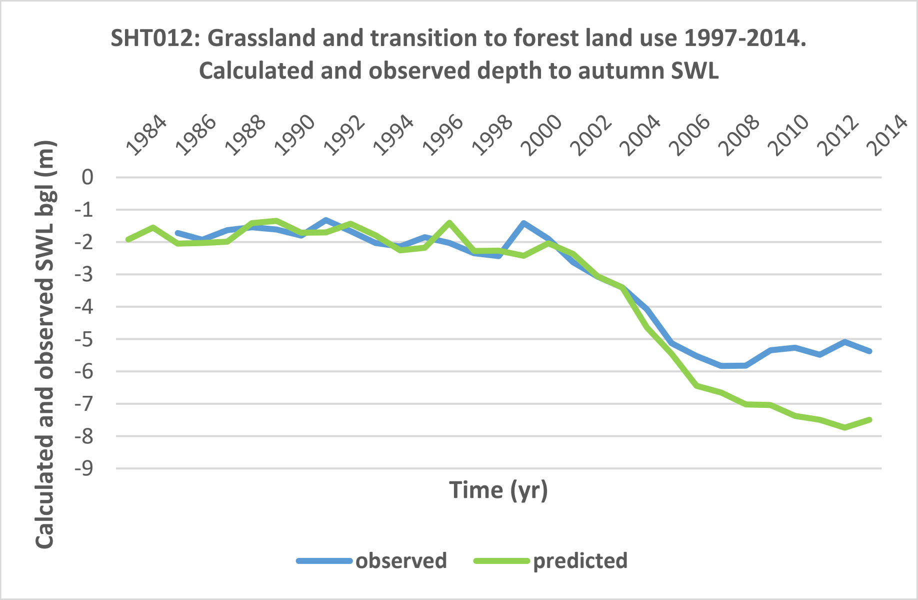
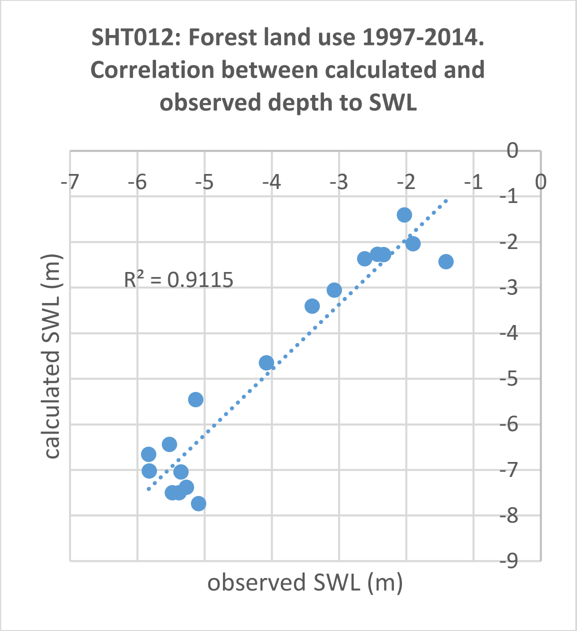


Figure 5.9: Correlation of water account against changes in depth to the water table at SHT012



SHT012

Large scale afforestation commenced in 1997.

RMSE calculations are from 1997 to 2014.

RMSE = 0.308 m

(18 observations)

Figure 5.10: SHT012 statistical analysis

5.3.3 Site SHT014

The graph of the calculated depth to the water table, derived from the net annual water-mass-balance (green), and the actual autumn observed depths to the water table below ground level (blue) at SHT014, in **Figure 5.11**, show a close correlation during the pre-forest grassland period and the period of forest land use.

This is the least intensively forested Wattle Range study site with 1813 ha of hardwood and 353 ha of softwood plantations. Industrial scale forest development commenced in 1999 with about 100 ha of hardwood forest and a further 724 ha in the following year. This was followed by gradual plantings up to, and including, another 980 ha of hardwood plantation in 2008. The softwood plantation development commenced with about 200 ha in the 2000-01 period and the balance of about 150 ha in the 2009 to 2011 period. A downward trend of the water table commences in 2001, with a close correlation maintained between the calculated net annual water-mass-balance and the actual observed groundwater level.

Except for 1982 and 1983, the direction of annual variations in the water-mass-balance correlate closely with the directional moves in the observed water levels. The rainfall record indicates that 1982 was a very dry year followed by a year of higher than average rainfall in 1983. While the water-mass-balance calculations include a rainfall variability factor, it appears as if the water-mass-balance calculations may overstate both circumstances at this site. The statistical analysis of site SHT014 returns a coefficient of determination R^2 value of 0.94 in **Figure 5.12**.

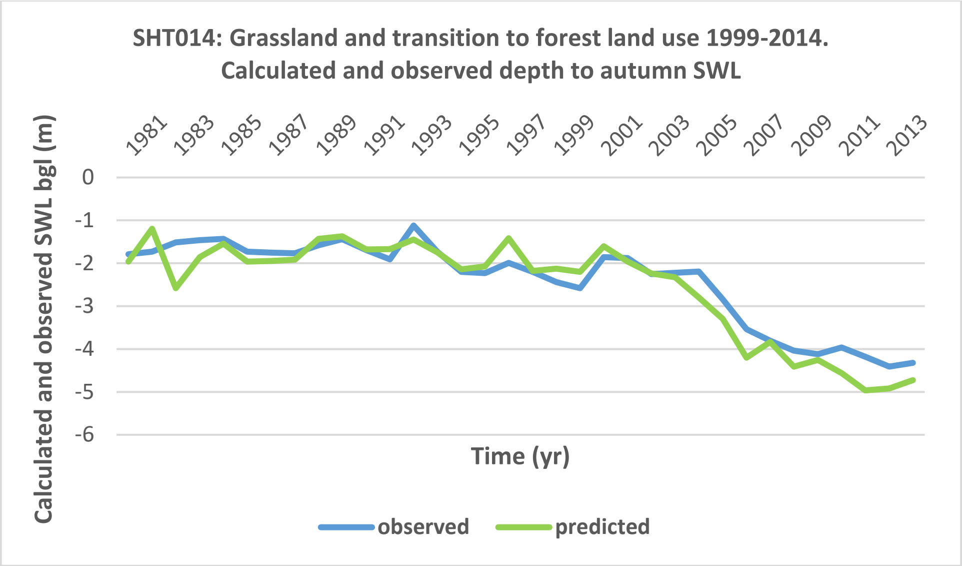
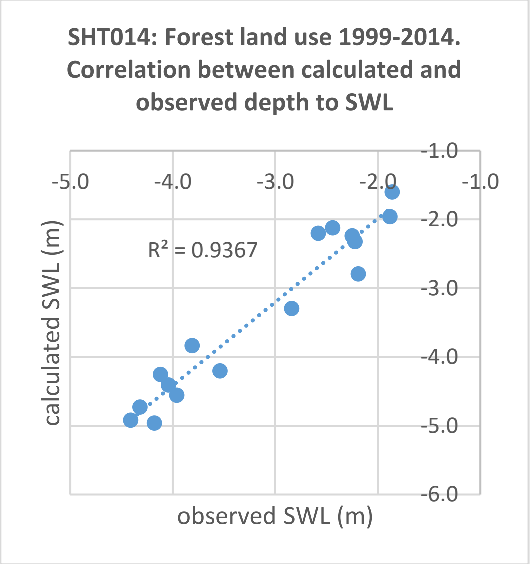


Figure 5.11: Correlation of water account against changes in depth to the water table at SHT014



SHT014

Large scale afforestation commenced in 1999.

RMSE calculations are from 1999 to 2014.

RMSE = 0.106 m

(16 observations)

Figure 5.12: SHT014: statistical analysis

5.3.4 Site NAN009

In order to test for the extinction depth for groundwater extraction by plantation forests, three different approaches are applied for analysis at the Nangwarry sites, where there is a significant decline in the water-table, and to levels generally considered by the local water allocation plan as not supporting groundwater extraction by plantation forests. The three propositions are:

a) There is no extraction by plantations

b) All forests extract groundwater, regardless of the depth of the water table

c) Extraction ceases where the water table falls below 10 metres at June 1990.

In the following graphs for the NAN009 site, a comparison of the calculated net annual water-mass-balance (green), expressed as a depth to the water table and the observed autumn depth to the water table below ground level (blue) is applied to all three propositions. As with the Wattle Range sites, the recharge rate adopted for the calculations is that specified in the regional water allocation plan, with adjustments to reflect rainfall variability in the May-October period of each year.

Due to the strong indication of a direct hydraulic connection between the unconfined aquifer and the underlying confined aquifer at nearby locations (SKM 2012), some alternative approaches to accounting for recharge will follow in the Discussion chapter of this thesis. The storage coefficient applied in the following results is the accepted and previously referred to default value of 0.1.

Due to limitations in the available forest estate data, there is no indication of the age structure of the plantation estate that was destroyed by fire in February 1983. As a result of the large-scale destruction at the time and the necessary re-ordering of government priorities during this period, there is also no groundwater level data for the autumn of 1983. The statistical analysis is undertaken for the period post the 1983 fire, when reforestation had commenced, providing a known forest age and area structure. Continuous groundwater level data is also available in this period.

For the site NAN009, **Figure 5.13** displays the case for proposition (a), that there is, no extraction at the site because the water table was deeper that 6 metres at June 2004. This is the current policy position for the forests at this site. **Figure 5.14** provides the statistical analysis for this proposition with a coefficient of determination R^2 value of 0.51.

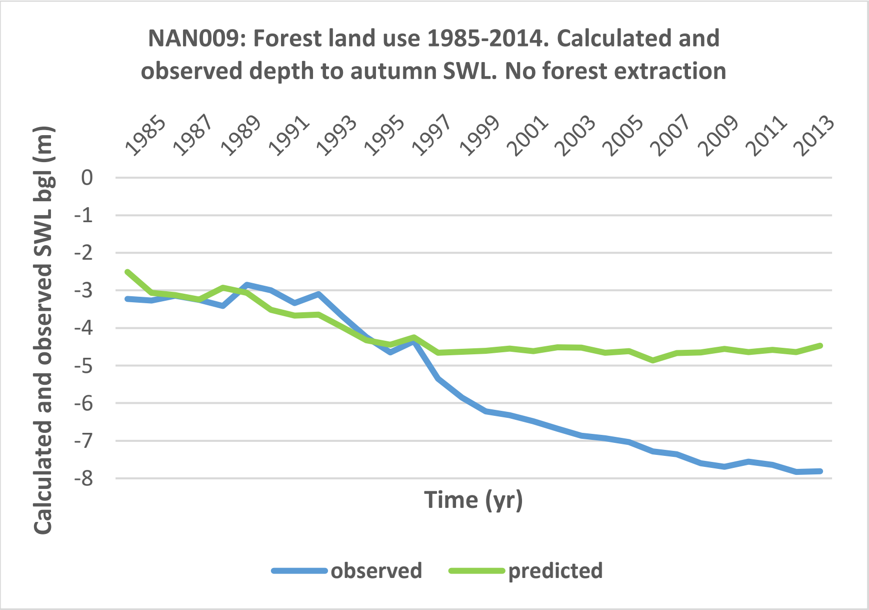
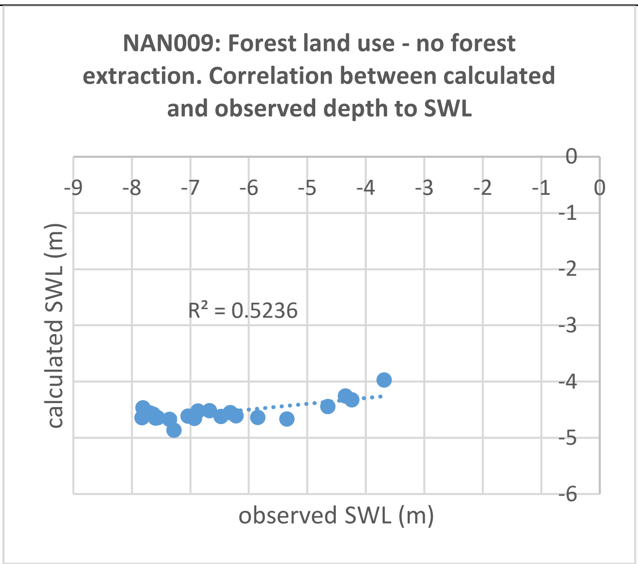


Figure 5.13: Correlation of water account against changes in depth to the water table at NAN009 – no extraction by plantation forest



NAN009 – no extraction test

Statistics are presented for the period after which extraction is considered to commence.

RMSE calculations are from 1990 to 2014.

RMSE = 0.408 m

(25 observations)

Figure 5.14: NAN009: statistical analysis – no groundwater extraction by plantation forest

While there is clear deviation between the two plotted curves after 1996, in the period from 1985 to 1996 there is close visual alignment, this is also the period when the forest water model advises that there is no significant extraction by the replanted plantation forests.

The **Figure 5.15** presents observations for proposition (b); that all plantations extract groundwater, regardless of the depth to the water table during the plantation forest life cycle, while **Figure 5.16** presents a statistical analysis for this proposition with a coefficient of determination R^2 value of 0.75.

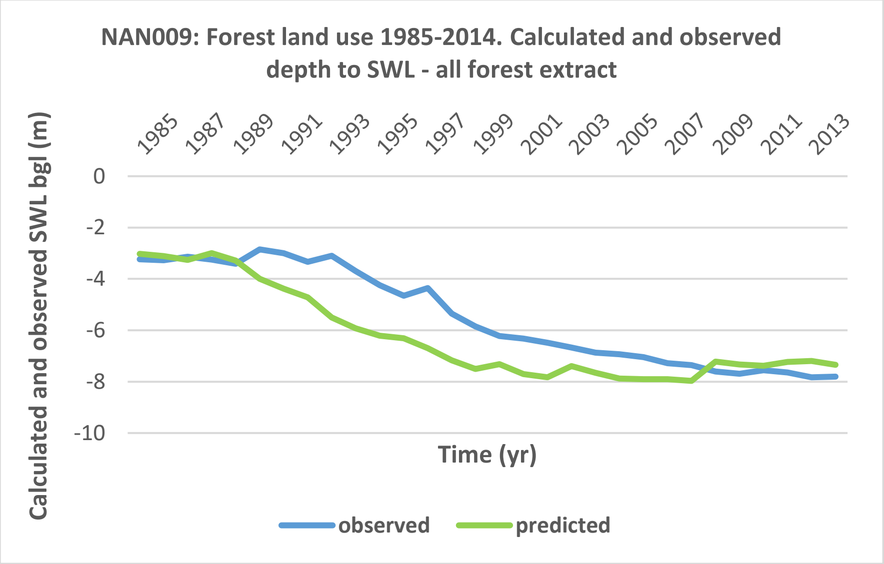
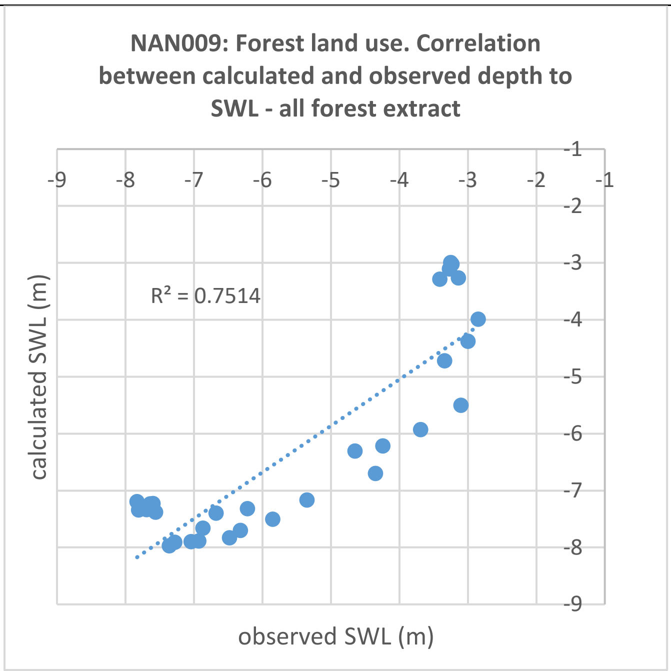


Figure 5.15: Correlation of water account against changes in depth to the water table at NAN009 –all plantation forest extract groundwater



NAN009 – all forest extract test

Statistics are presented for the period after which extraction is considered to commence.

RMSE calculations are from 1990 to 2014.

RMSE = 0.264 m

(25 observations

Figure 5.16: NAN009: statistical analysis – all plantation forest extract groundwater

Proposition (c), that is, extraction ceases when the water table at June 1990 exceeds a depth of 10 metres below ground level, is presented in **Figure 5.17**, and **Figure 5.18** is the statistical analysis outcome for the case with a coefficient of determination R^2 value of 0.87.

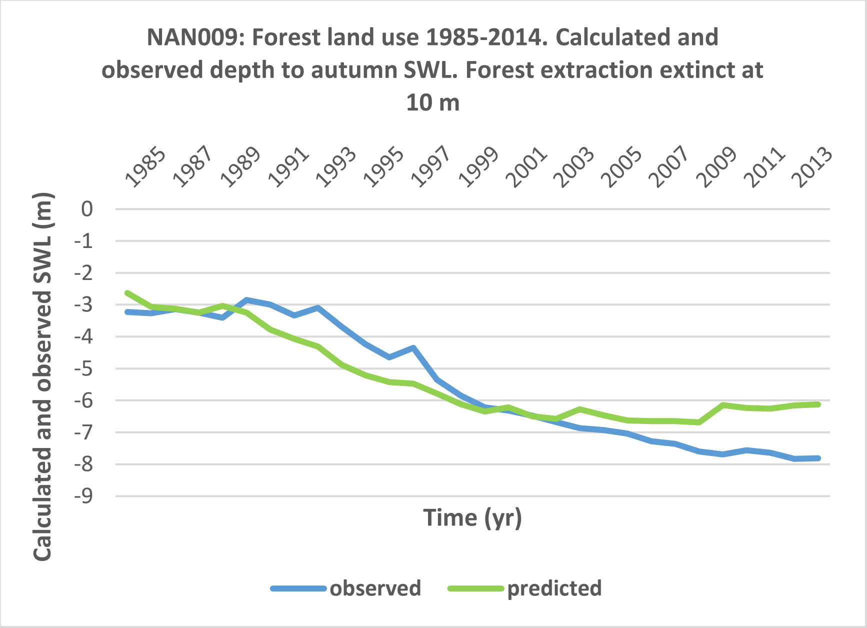
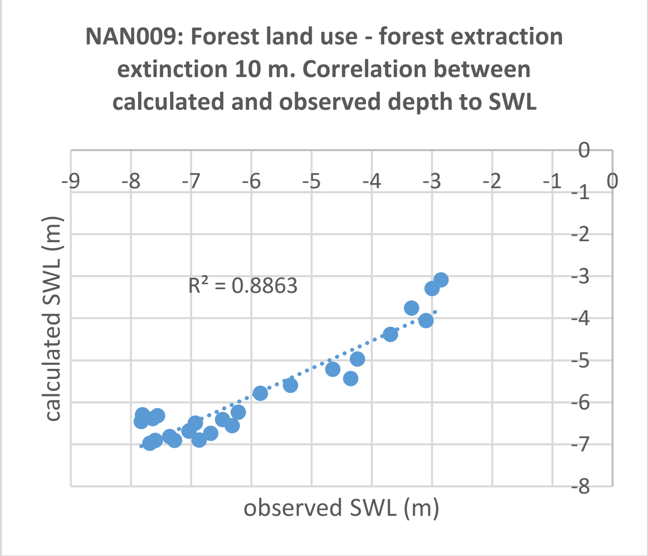


Figure 5.17: Correlation of water account against changes in depth to the water table at NAN009 –plantation forest groundwater extraction ceases at SWL of 10 m

The year 1990 for determining groundwater level reference for extraction was adopted because of the availability of groundwater level contouring information for the period and 1990 offered a relatively stable water table level during the reforestation of most forest compartments following the 1983 fire.



NAN009 –forest extraction extinct at 10 m test

Statistics are presented for the period after which extraction is considered to commence.

RMSE calculations are from 1990 to 2014.

RMSE = 0.185 m

(25 observations

Figure 5.18: NAN009: statistical analysis – forest groundwater extraction ceases at 10 m

5.3.5 Site NAN012

The following graphs for the NAN012 site are for the calculated net annual water-mass-balance (green), expressed as a depth of groundwater, and the observed autumn depth to the water table below ground level (blue), are presented for the same three propositions as applied to NAN009. As in the case of the NAN009 site, the management area recharge rate adopted for the calculations is that in the regional water allocation plan, with adjustments to reflect rainfall variability in the May-October period of each year. The storage coefficient applied at NAN012 for the three propositions is the default value of 0.1. As with the NAN009 case, some alternative approaches to recharge will follow in the discussion chapter of this thesis.

Similar to NAN009, due to the form of the available forest estate data, there is no indication of the age structure of the plantation estate destroyed by fire in February 1983. Similarly, there is no groundwater level data for the autumn of 1983. Consequently, statistical analysis is only under taken for the period post the 1983 fire, where there is continuous groundwater level data and the forest structure is known.

For the site NAN012, **Figure 5.19** plots the case for proposition (a), that there is no extraction at the site because the water table was deeper than 6 metres at June 2004. This is the current policy position for the forest at this site. The **Figure 5.20** provides the statistical analysis for this proposition with a coefficient of determination R^2 value of 0.46.

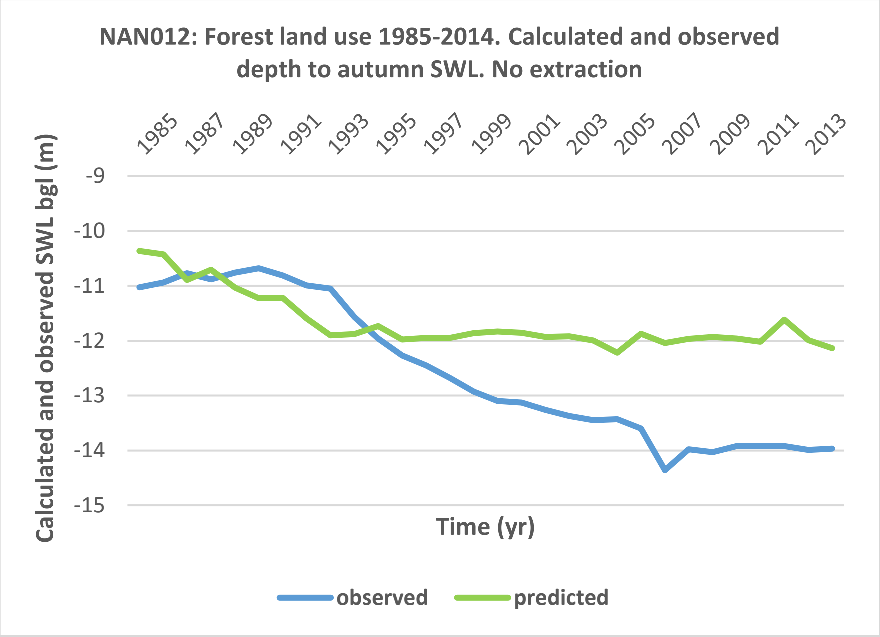


Figure 5.19: Correlation of water account against changes in depth to the water table at NAN012 – no extraction by plantation forest

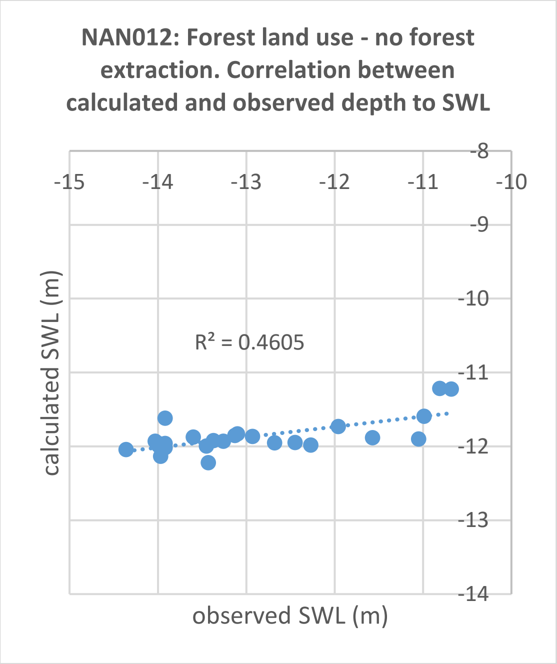
	**NAN012 – no extraction test** Statistics are presented for the period after which extraction is considered to commence. RMSE calculations are from 1990 to 2014. RMSE = 0.287 m (25 observations)

Figure 5.20: NAN012: statistical analysis – no groundwater extraction by plantation forest

The **Figure 5.21** presents observations for proposition (b), that all plantations extract groundwater, regardless of the depth to the water table during the plantation forest life cycle, while **Figure 5.22** provides the statistical analysis with a R^2 value of 0.90.

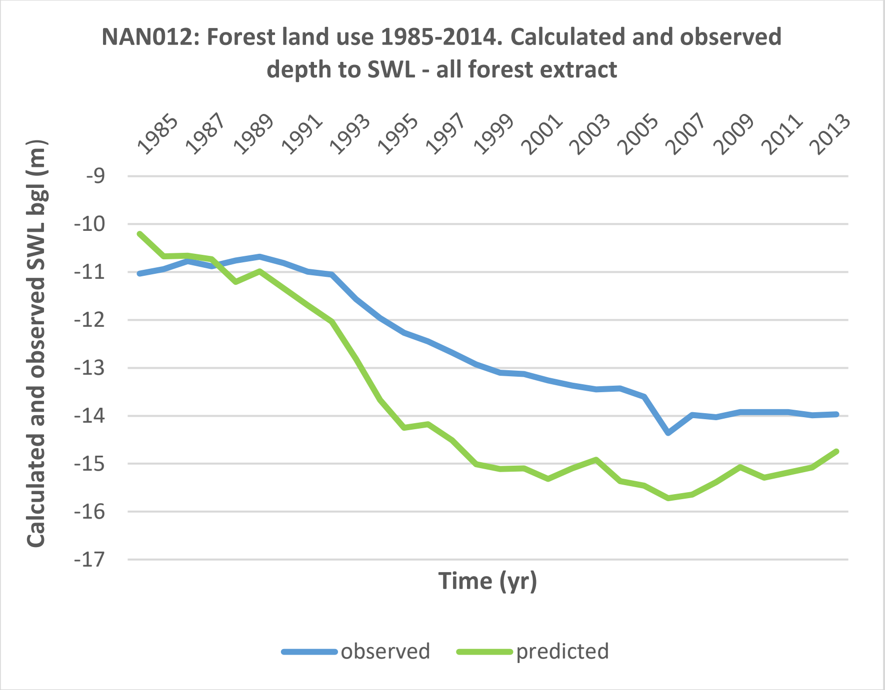
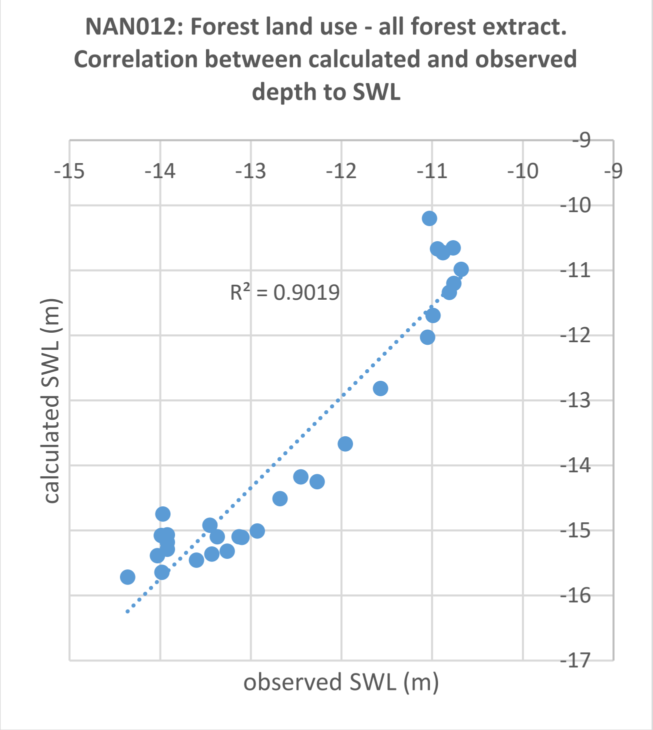


Figure 5.21: Correlation of water account against changes in depth to the water table at NAN012 – all plantation forest extract groundwater



NAN012 – all forest extract test

Statistics are presented for the period after which extraction is considered to commence.

RMSE calculations are from 1990 to 2014.

RMSE = 0.306 m

(25 observations

Figure 5.22: NAN012: statistical analysis – all plantation forest extract groundwater

Proposition (c), that is, extraction ceases when the water table at June 1990 exceeds a depth of 10 metres below ground level, is presented in **Figure 5.23** and **Figure 5.24** is the statistical analysis for the case with a R^2 value of 0.90. As outlined in the comment on site NAN009, the year 1990 was adopted for the 10 metres extraction threshold because of the availability of groundwater level contouring data at this date and 1990 offered a relatively stable water table level during the reforestation following the 1983 fire.

Similar to the NAN009 no extraction condition, it is also noted at NAN012 for the no extraction scenario (Figure 5.19) there is close visual proximity between the two plotted curves in the period from 1985 to 1995, the period when the forest water model advises that no significant extraction by the replanted plantation forests would be occurring.

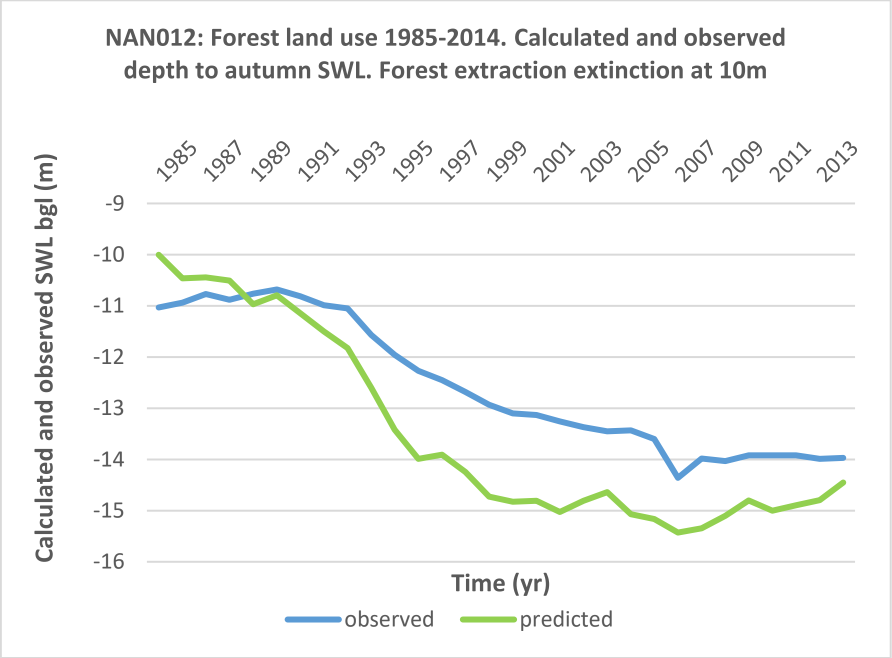
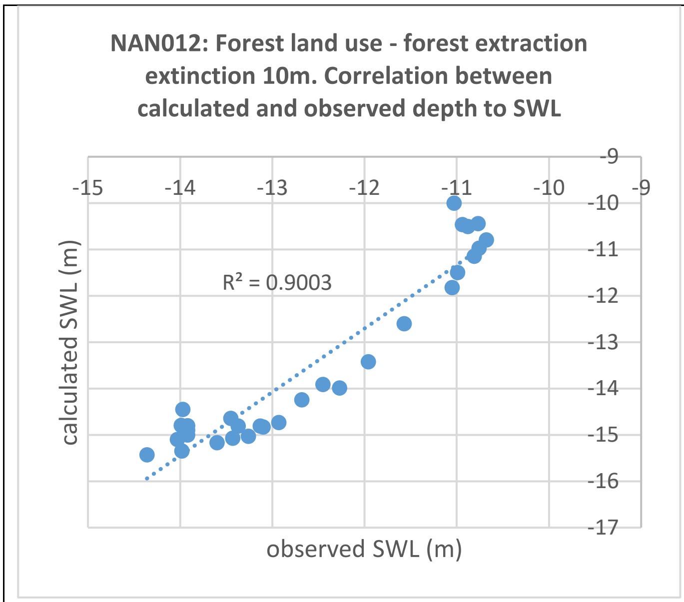


Figure 5.23: Correlation of water account against changes in depth to the water table at NAN012 –plantation forest groundwater extraction ceases at SWL of 10 m



NAN012 –forest extraction extinct at 10 m test

Statistics are presented for the period after which extraction is considered to commence.

RMSE calculations are from 1990 to 2014.

RMSE = 0.254 m

(25 observations

Figure 5.24: NAN012: statistical analysis – plantation forest groundwater extraction ceases at SWL of 10 m

5.4 'Paired' grassland testing and observations

The water-mass-balance analysis at the five 5000 ha forested study sites provides evidence that plantation forests do significantly impact on regional groundwater resources, particularly where the forests overlay shallow water tables and the forests are extracting groundwater. While there is already strong evidence within these results when comparing the pre-forest grassland land use with the groundwater changes that occurred when afforestation commences, it is considered that the same analysis process should be applied to grassland sites in the same geographic areas.

The Wattle Range area is chosen for a grassland land use comparison, using sites FOX004 and MON004. While the Wattle Range forest sites are grassland land use recently converted to plantation forest, the Nangwarry sites have a land use history of long term plantation forest, which is only interrupted by extensive fire damage in 1983. Furthermore, and to be discussed later, there is the likelihood of a connection between the confined and unconfined aquifers at Nangwarry which further disrupts any potential comparison of grassland sites.

The three Wattle Range forest sites all have a similar land use history, with the transition from grassland to plantation forestry as the dominant land use occurring at a similar time; that being in the late 1990s and early 2000s, while the grassland sites of FOX004 and MON004 have always been grassland for the period of available water table level monitoring. The MON016 site is sufficiently removed from the Bakers Range drain to be confident that there is no drain interaction, whereas, the SHT012 site is dissected by the drain and this is believed to influence some of the observed groundwater level changes at the SHT012 monitoring well when water is present in the drain. The SHT012 and the drain context is discussed later in this chapter in section 5.9.

Other than for the upper reach of Drain M, there is no official record of water presence in these drains over time. Water flows in Drain M provide no indications as to local collections of excess surface water as Drain M is the conductor of surplus surface water from Bool and Hacks Lagoons to the coast, rather than being a local collector of surface water.

Local knowledge advises in ‘wet’ years there is often a presence of water in the other drains at the site and on the land around the grassland site of FOX004. This FOX004 area appears to be a historical contributor of surface water as most of the drain infrastructure at the site largely originates in the FOX004 study area. The distribution of drains for both the FOX004 and MON004 sites can be viewed in **Figure 5.25**.

The presence of surface water drains, and consequently the likelihood of surface water outflows, does raise a question as to the reliability of building an accurate water-mass-balance account at the grassland selected sites. In the calculation of a water-mass-balance account at each site, no provision is made to account for the outflow of any surface water as no data is available that indicates the quantity or frequency of surface water flows in the local feeder drains.

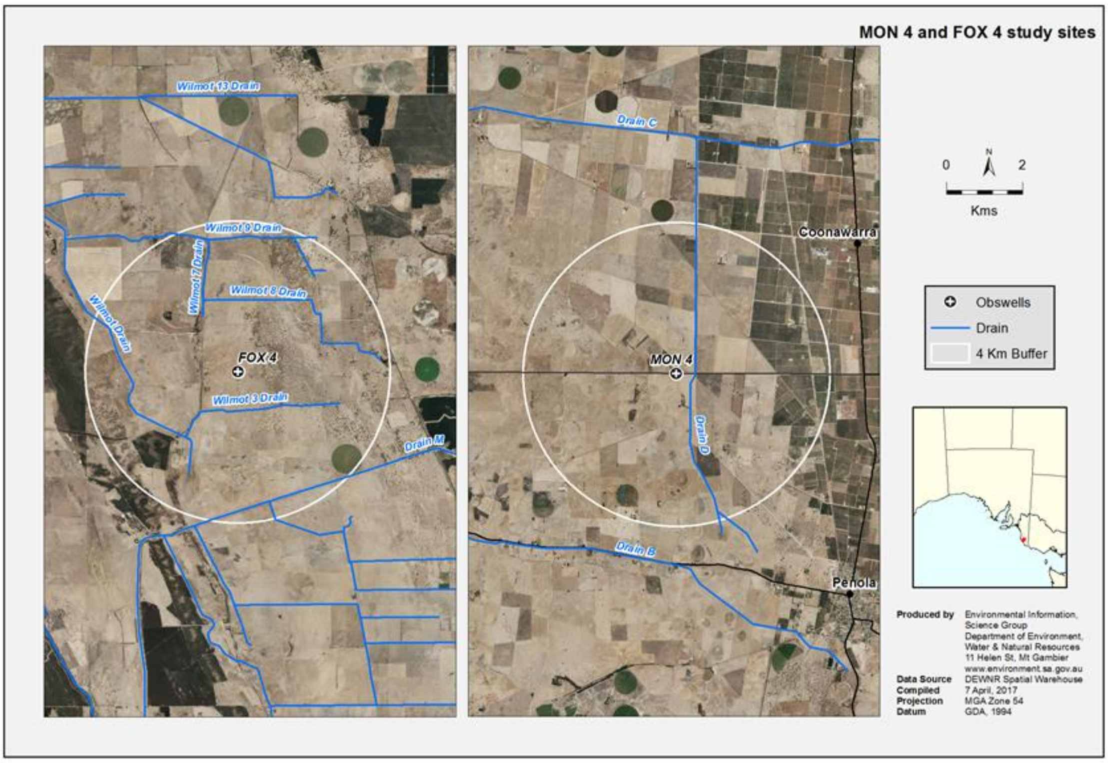


Figure 5.25: Grassland study sites, F0X004 and MON004

The recharge rates applied are those adopted by the regional water allocation plan, that being 180 mm for MON004 and 100 mm for FOX004. In the water-mass-balance calculations, recharge is adjusted for the rainfall occurring in the May-October period of each year, relevant to the mean for that period, as applied to the forested study sites.

The relatively low recharge rate of 100 mm per year, established by Brown *et al* (2006), may indicate a surface water impact being present in the estimation of the mean annual recharge for this management area, where significant shallow water drains exist. Another factor may also be the issue of solar evaporation impacts from shallow water tables (<2 m below ground level) as considered by Shah *et al* (2007). The calculations for FOX004 (presented later in Table 5.4), suggest that the adopted groundwater management area recharge rate may be understated.

At the MON004 site, groundwater use in the vineyards is for supplementary irrigation only and this has been accounted for at an average annual rate of 1.8 ML/ha. Extractions for stock and domestic water is applied as per the methodology at the forested study sites. **Table 5.1** provides a summary of some the grassland site characteristics.

Table 5.1: Grassland study site characteristics

Site ID (obswell identification)	**FOX004**	**MON004**
Area of main land use, grassland	4214 ha	4011 ha
Native vegetation	494 ha	65 ha
Depth to standing water level during study period	1.38 to 2.5 m	2.09 to 3.93 m
Irrigated activity in study area	107 ha pasture	644 ha vineyard 120 ha pasture
Road, rail and drain reserves and other	211 ha	186 ha
Study period	1972-2010	1972-2011
Anomalous characteristics of site requiring consideration	~ 26 km of surface water collecting drains	~8 km of surface water collecting drains
Rainfall data from relevant BOM station	Penola (BOM26025)	Penola (BOM26025
Observation period	1972-2011	1972-2011

The following Figures (5.26 to 5.29) provide the results for each grassland site, in regard to the net annual water-mass-balance calculations, converted to a change in the depth to the water table for comparison with the actual observed autumn groundwater levels. For site FOX004, **Figure 5.26** compares the calculated and observed depth to the water table, while **Figure 5.27** presents the statistical analysis results, expressed in the terms of a coefficient of determination with an R^2 value of 0.39.

Outcomes for the comparative calculations for the grassland site of MON004 are presented in **Figures 5.28** and **5.29** with a coefficient of determination R^2 value of 0.44.

The grassland sites of FOX004 and MON004 have not provided high coefficient of determination values that can be considered comparable to those achieved for the forest land use. There are a number of specific sites issues identified and discussed, that are likely to contribute to the lower values. However, the overall observed water table trends between the calculated and the observed depths to the water table at the grassland sites are aligned, and importantly, there is no significant water table decline at the grassland sites, as observed at the forest sites over the same study period.

In regard to some obvious understatements of a calculated water-mass-balance (and the associated groundwater storage), compared to the observed water table movements, the significant periods of discrepancy are 1982, 1997-99 and 2006. All these years can be considered extremely drier than the norm. The monthly rainfall data relating to these drier periods, and the corresponding mean values, are presented in **Table 5.2**.

From the data in Table 5.2, while there is an overall significant reduction in rainfall, there are months where the rainfall is close to, or above, the mean. In some years, this may be significant in areas with shallow water tables where the recharge response can be rapid. The wetter than average months are identified in the table with green shading while the blue shading identifies the long term mean values. This supports the previously discussed concept that rainfall incidence is likely to be an important factor for actual annual groundwater recharge for very shallow water tables, even where the aggregate annual rainfall may be significantly reduced, compared to the mean value.

Table 5.2: May-October rainfall at Penola (BOM26025) for years of significantly low rainfall

	Monthly observed rainfall at Penola (BOM26025)						Deviation from the mean: mean =1.0	
year	May	Jun	Jul	Aug	Sep	Oct	May-Oct	Annual
mean	60.8	78.1	91.5	90.7	72.0	50.0		
1982	55.6	70.0	44.2	24.8	58.2	21.4	0.62	0.64
1997	52.6	69.4	91.9	78.6	102.1	74.6	0.83	0.82
1998	80.2	73.2	83.8	46.6	41.2	50.4	0.86	0.82
1999	57.0	63.2	155.8	44.6	47.4	24.0	0.81	0.92
2006	61.2	13.4	63.2	28.2	43.6	8.6	0.49	0.67
note: mean values apply to the period of 1971-2015								

In the case of the grassland sites of FOX004 and MON004, in addition to the low annual rainfall issue, there is also likely to be an influence of surface water outflows during wet periods, particularly at FOX004, which is traversed at reasonably frequent intervals with some 26 km of shallow surface water drains. These could have a significant impact in directing rainfall water off the site and consequently reducing the overall potential groundwater diffuse recharge, to that which may occur if drains were not present, or the rainfall occurred with a different intensity, or frequency. This could account for the calculated recharge peaks, based on increased rainfall, not materialising as an observed infield recharge impact at sites where the surface water drains exist.

It can be concluded that the comparison between observations of groundwater levels at sites where grassland is the dominant use, compared to the forested land use sites, plantation forests have a significant impact on groundwater resources, where the water table can be considered to be at a shallow depth (≤ 10 metres), below ground level. This conclusion is also consistent with paired catchment research in surface water catchments that generally conclude that plantation forests do reduce surface water catchment yield, relative to the potential yields of the replaced grassland land uses. Groundwater level monitoring ceased at these sites in 2011.

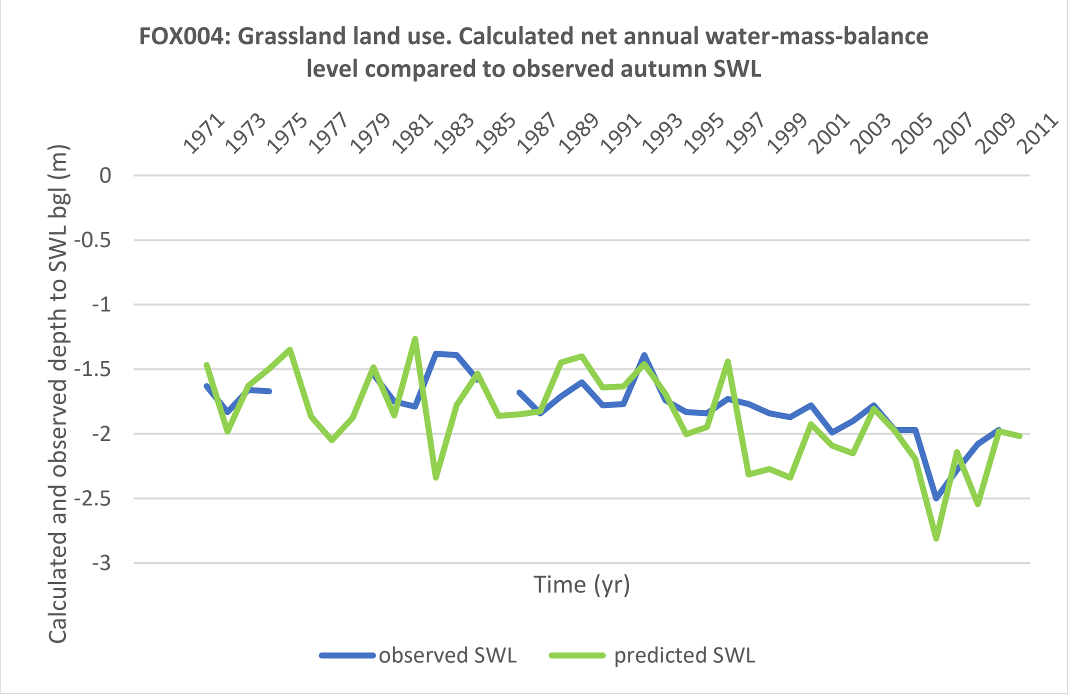


Figure 5.26: FOX004 Grassland site, correlation of water account against depth to water table

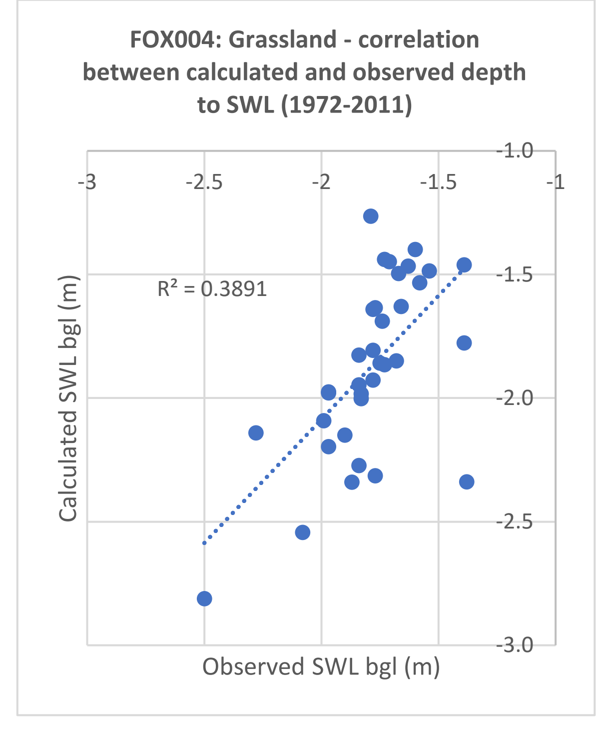


Figure 5.27: FOX004 Grassland site statistical analysis

As a general observation, the trend between the calculated (predicted) depth to the water table (using net water-mass-balance) and observed depths to the water table are reasonably consistent, but the calculated depth exhibits a wider range of variability than the observed.

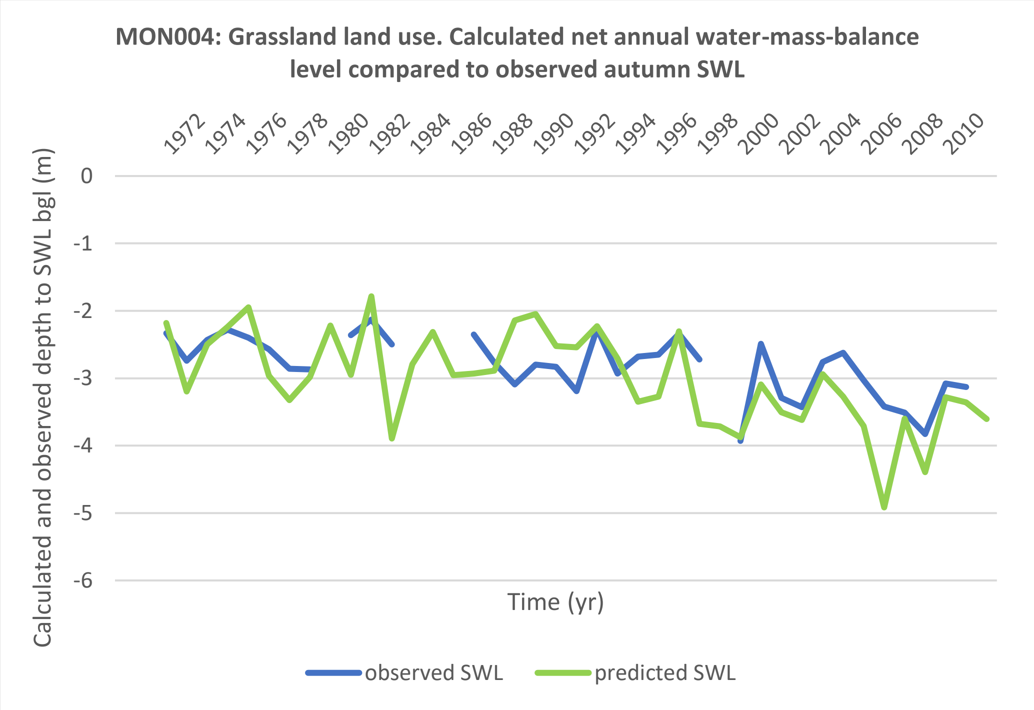


Figure 5.28: MON004 Grassland site, correlation of water account against depth to water table

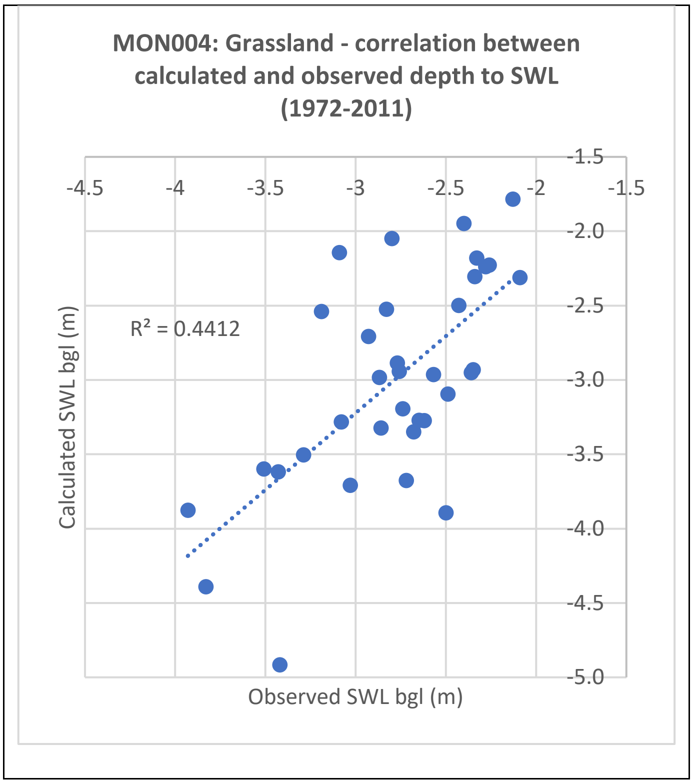


Figure 5.29: MON004 Grassland site statistical analysis

This may be due to the impact of surface water outflows from local rainfall not being accounted for in the water-mass-balance. Similarly, no accounting for any impacts of solar evaporation from surface water and shallow water tables not being included may further exacerbate the difference. Collectively, these factors could result in the actual observed water table variations appearing muted, by comparison to the calculated (predicted) groundwater levels.

5.5 Summary of results

As a generalisation, the net water-mass-balance calculation using the 2006 forest water accounting model components appears to slightly understate the actual recharge that occurs under a plantation forest in the first few years of establishment at the study sites. This appears to be a consistent trend in the Wattle Range and Nangwarry plantations, for both hardwood and softwood plantations.

In respect to the later stages of hardwood forest plantation development at the Wattle Range site MON016, the forest water model appears to overstate the net hydrological impact on the groundwater resource. Other than a model error, several hydrogeological factors could be contributors and these include the storativity of the aquifer (0.1) being understated, and or, the significance of unaccounted groundwater recharge from increased lateral groundwater flow brought about by the groundwater level decline. The impact of aquifer storativity variability from the adopted value of 0.1 on the predicted groundwater level is discussed and demonstrated in section 5.7 for the study sites MON016 for NAN009.

Given the spatial relationship, MON016 could receive additional groundwater lateral flows from the up gradient grasslands due to the creation of the cone of depression, which peaks with an increased head differential of nearly 4 metres. According to Darcy's Law this increased gradient would result in an additional recharge in the water-mass-balance at MON016. This recharge is unaccounted for in the water mass balance calculations and would manifest as a reduction in the observed rate of water level decline at that site. This is discussed further in section 5.10.

The current extraction by softwood plantations appears to require some upwards adjustment to the forest water accounting model. The correlation between the calculated and observed appears to indicate some divergence between the two graphs, suggesting that a nominal annual increment of extraction may require consideration. However, due to the hydraulic connection between the unconfined and confined aquifers not being quantified, it may be necessary to accept a greater degree of variability in correlation as the water table approaches the forest extraction extinction depth in the Nangwarry area.

These points are discussed further in the Discussion chapter when a proposal for revising some parameters in the forest water model is tested.

5.6 Testing of adopted groundwater recharge rates

A significant input to the water-mass-balance calculation is the diffuse recharge component from rainfall. As previously explained, the recharge rates applied are based on the groundwater management area recharge rates set out in the adopted water allocation plan. These values are largely derived by the water table fluctuation method undertaken by Brown *et al* (2006). As part of this current investigation, the water table fluctuation method is applied to all the available water level data at the study site monitoring wells and those wells representing the nearby grassland land use sites. While a rainfall variability factor for the May-October period has been applied in the water-mass-balance calculations, this does not necessarily take account of other rainfall variabilities, such as incidence and sequence of events that may be relevant for annual diffuse recharge.

The water level data are sourced from publicly available data, where the water level observations are generally quarterly, but with some periods occasionally omitted, or limited to a lesser number of observations. Due to the relatively low number of observations in any one year, it is probable that the observations do not necessarily indicate the highest and lowest groundwater levels in that particular year, meaning that the available data may not be accurately indicating the net annual diffuse recharge of the groundwater resource at that particular site in that year. Any inaccuracy is likely to be an understatement of the actual annual groundwater recharge.

Water level observation data for all wells is presented in **Table 5.3**, along with a calculated recharge value for each monitoring well derived from the presented data. This is also compared to the water allocation plan adopted mean management area recharge rate. The table also includes an indication of rainfall variability for each year observed. The rainfall variability is expressed as a variation factor to the mean May-October period rainfall for the 1971 to 2015 period. As an alternative approach, the year rainfall is similarly assessed against the annual mean rainfall for the same 1971 to 2014 period, where the mean rainfall is represented by the value 1.0.

For calculating the annual recharge rate for each site with the water table fluctuation method, a storage coefficient value of 0.1 has been applied. For comparative purposes, the calculations have also been compared to an estimated recharge rate for storage coefficient values of 0.08 and 0.12. They are also compared with rates adopted by the Lower Limestone Coast water allocation plan, which are identified as LLC WAP MARR values in **Table 5.4**.

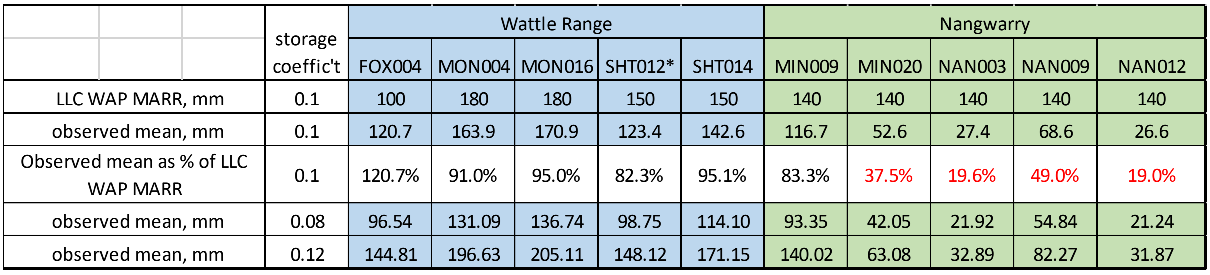
Given the water table fluctuation methodology and the limited data available for assessment of actual annual water table fluctuations, calculations within a range of plus or minus 20 per cent about the adopted value for such a highly variable parameter could be considered acceptable. Values within this range are observed in all the Wattle Range sites and at the MIN009 obswell. It is noted that with the exception of FOX004, all calculations in Table 5.4 are less than the adopted recharge rates in the water allocation plan. This may be contributed to by the low number of observations available within a year, resulting in less than the actual annual maximum water table fluctuation being observed. An understatement of recharge may also be a function of site aquifer storage coefficients being greater that the adopted default value of 0.1.

Annual recharge values for all other Nangwarry sites exhibit a significant understatement, if compared to the adopted value of 140 mm per year. With soil types being generally free draining, the significant understatement, in the order of 50 to 80 per cent, provides further support for the proposition that there is a significant direct hydraulic connection between the unconfined and confined aquifers in this area. This is considered in the Discussion chapter.

Table 5.3: Unconfined aquifer recharge at study sites

	Annual water table fluctuations at observation wells (m)									rainfall variation about the mean	
year	**FOX004**	**MON004**	**MON016**	**SHT012***	**SHT014**	**MIN009**	**MIN020**	**NAN003**	**NAN009**	**NAN012**	**May-Oct**	**annual**
1971	1.7	2.51						0.82			1.21	1.31
1972	0.96	1.2				1.3		0.22			0.86	0.90
1973	1.78	2.44	2.3					0.37			1.10	1.17
1974	1.46	2.12	1.74			3.07		0.2			1.19	1.21
1975		1.8	1.8	1.49		2.96		0.28			1.29	1.14
1976		1.84									0.94	0.99
1977		0.71									0.82	0.94
1978		1.72									0.93	0.90
1979	1.61										1.20	1.08
1980	1.41		2.02			0.83	0.13	0.02			0.94	0.92
1981	1.02	1.66	1.75	1.26	1.75	1.79	1.39	0.8			1.35	1.15
1982	1.25	0.16	0.53	0.22	1.02						0.62	0.64
1983	0.92	1.78	1.15	0.9	1.63	1.58	0.76	0.58	0.94	0.54	1.00	1.17
1984					1.49						1.16	1.16
1985	0.16	0.95	1.26	0.77	0.78	0.65		0.04	0.15	0.07	0.94	0.96
1986					1.24		0.25	0.19	0.58	0.15	0.95	0.99
1987	0.94	1.47	1.43	0.85	1.04	0.96	0.5	0.12	0.41	0.12	0.97	0.85
1988	1.51	2	2.19	1.84	1.84	3.04	0.45	0.42	0.65	0.3	1.22	1.19
1989	1.52	2.92	1.87	1.59	1.76	3.29	1.1	0.08	1.14	0.35	1.26	1.07
1990	1.29	1.91	1.65	1.32	1.27	3.08	0.91	0.54	0.73	0.26	1.09	0.90
1991		2.13	1.86	1.42	1.73	2.83	0.71	0.35	0.48	0.22	1.10	1.06
1992	1.27	2.92	1.79	1.32	1.66	2.6	1.58	0.51	1.09	0.38	1.21	1.31
1993	1.1	1.25	0.73	0.47	0.43	0.44	0.18	0.01			1.06	0.98
1994	1.09	0.47	1.24	0.7	0.85	0.24	0.33	0.03			0.85	0.80
1995	0.99	1.62	1.8	1.35	1.57	1.44	0.45	0.33			0.88	0.93
1996	1.67	1.36	2.44	1.69	1.95	3.24	0.76	0.56			1.23	1.10
1997	1.1	1.08	1.57	1.17	1.18	0.84	0.32	0.15			0.83	0.82
1998	0.8	1.19	1.46	1.21	1.31	0.92	0.44	0.13			0.86	0.82
1999	0.9		1.12	1.27	1.01	0.05	0.29	0.05			0.81	0.92
2000	0.93	3.49	2.56	1.97	2.47	1.18	0.64	0.34			1.09	1.04
2001	1.32	1.71	1.5	0.88	1.26	0.64	0.57	0.23			0.98	1.07
2002	1.42	1.79	1.51	1.04	0.94	0.11	0.3	0.18			0.94	0.86
2003	1.41	3.27	2.42	1.85	1.88	0.75	0.59	0.61			1.17	1.13
2004	1.78	1.75	2.75	1.81	2.17	0.88	0.84	0.5			1.06	1.06
2005	0.91	0.44				0.05	0.2	0.02			0.91	0.86
2006	0.15	0.12					0.28	0			0.49	0.67
2007	1.07	1.11				0.24	0.44	0.09			0.95	1.05
2008	1.37	0.06				0.03	0.14	0.01			0.67	0.78
2009	2.02	1.87				0.39	0.24	0.09			1.06	1.02
2010	1.32	1.63				0.29	0.44	0.36			1.03	1.14
2011	0.88	2.54				0.23	0.39	0.31			0.95	1.18
2012						0.25	0.28	0.18			0.97	0.86
2013						0.39	0.5	0.3			1.39	1.18
2014						0.26	0.42	0.12			0.74	0.78
total	41.03	58.99	44.44	28.39	34.23	40.84	16.82	10.14	6.17	2.39	44.27	44.09
observations	34	36	26	23	24	35	32	37	9	9	44	44
observed mean, mm	**120.7**	**163.9**	**170.9**	**123.4**	**142.6**	**116.7**	**52.6**	**27.4**	**68.6**	**26.6**	1.0	1.0
LLC WAP MARR, mm	**100**	**180**	**180**	**150**	**150**	**140**	**140**	**140**	**140**	**140**		
Observed mean as % of LLC WAP MARR	120.7%	91.0%	95.0%	82.3%	95.1%	83.3%	37.5%	19.6%	49.0%	19.0%	rainfall value 1.0 = mean value	
				note 1				note 2	note 2	note 2		
* MARR:	MARR is the management area recharge rate expressed as ML/ha, being based on a storage coefficient of 0.10											
note 1:	It is recognised that the Bakers Range Drain may reduce the magnitude of elevated groundwater level values											
note 2:	It is recognised that there is an absence of a confining layer just east of this area, suggesting that the unconfined aquifer is providing recharge to the deeper Tertiary Sand Aquifer - This is discussed later in the Discussion chapter.											

Table 5.4: Comparison of calculated recharge rates, WTF and variable storage coefficients



	storage coeffic't	Wattle Range					Nangwarry				
		FOX004	MON004	MON016	SHT012*	SHT014	MIN009	MIN020	NAN003	NAN009	NAN012
LLC WAP MARR, mm	0.1	100	180	180	150	150	140	140	140	140	140
observed mean, mm	0.1	120.7	163.9	170.9	123.4	142.6	116.7	52.6	27.4	68.6	26.6
Observed mean as % of LLC WAP MARR	0.1	120.7%	91.0%	95.0%	82.3%	95.1%	83.3%	37.5%	19.6%	49.0%	19.0%
observed mean, mm	0.08	96.54	131.09	136.74	98.75	114.10	93.35	42.05	21.92	54.84	21.24
observed mean, mm	0.12	144.81	196.63	205.11	148.12	171.15	140.02	63.08	32.89	82.27	31.87

The relevance of the application of May-October rainfall as a variable factor applied to the annual recharge rate is examined in **Figure 5.30 (a)** and **(b)** by comparing the annual rainfall variability about the mean against the observed water table fluctuation for that year. This is repeated by applying the May-October factor. It is observed in the instances tested, that the R^2 statistical analysis is not particularly high (generally in the order to 0.33 to 0.38), and that the May-October approach returns a slightly higher value in all cases except two, where the difference was negligible. It should be noted that all data relates to periods of grassland use. In the case of the forest study sites, observations are limited to the pre-forest period.

The proximity of the May-October rainfall as an overall indicator of annual rainfall is also assessed and this returned an R^2 statistical analysis value of 0.69. This is also presented in Figure 5.30 (b).

Whilst the rainfall relationship with the actual observed water table fluctuations return modest R^2values, the water table fluctuations between MON016 and SHT014 were compared for alignment. This was undertaken for the pre-forest period and where the annual data coincided. This analysis returned a R^2 statistical analysis value of 0.74 and is presented in **Figure 5.31**.

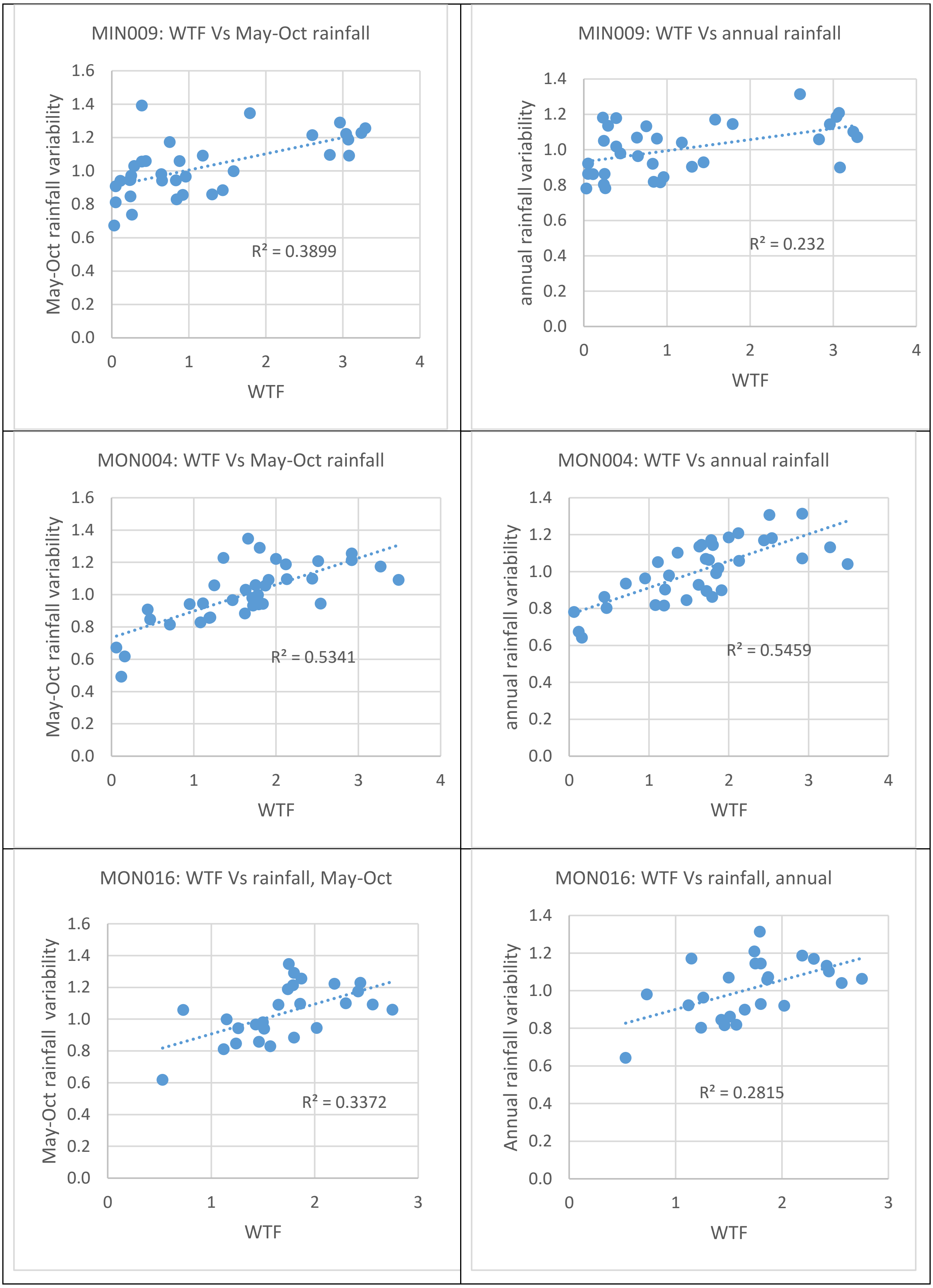


Figure 5.30 (a): Correlation between rainfall and water table fluctuations

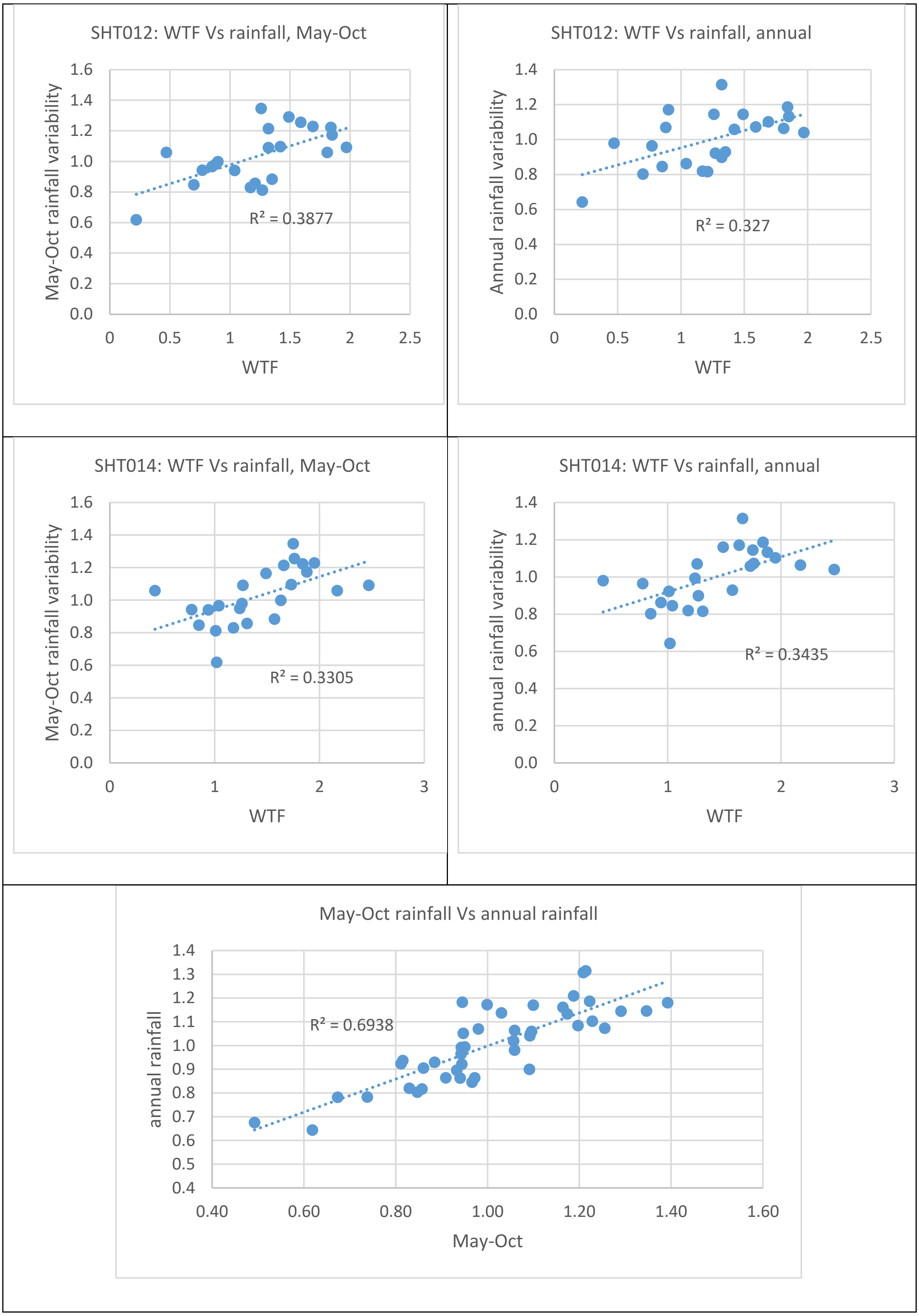


Figure 5.30 (b): Correlation between rainfall and water table fluctuations

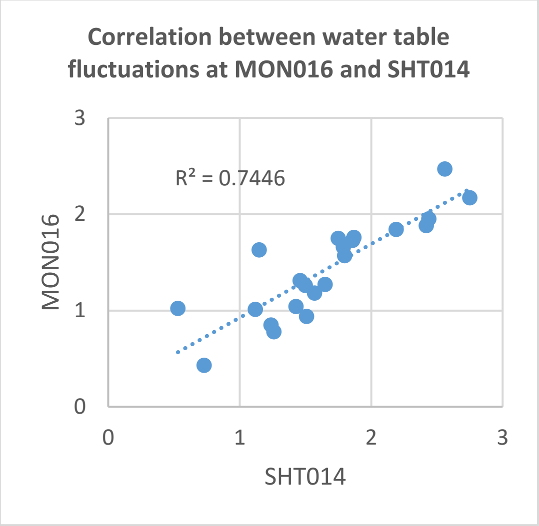


Figure 5.31: Correlation between water table fluctuations at MON016 and SHT014

5.7 Significance of storage coefficients

Other than having relevance as a factor in estimating the diffuse groundwater recharge rate with the water table fluctuation method (Brown *et al* 2006), the storage coefficient is also relevant for the conversion of the net annual water-mass-balance volume to a vertical measure of a change in the net annual groundwater storage.

In Chapter 4, where the study assumptions are discussed (section 4.3.1), it was advised that while there can be significant variation in aquifer storage coefficients, the adopted rate for the initial calculations of the annual net water-mass-balance would be 0.10. This decision is influenced by the earlier conclusions of Dillon *et al* (2000) and Brown *et al* (2006) where they noted, that while storage coefficients can vary significantly within a range from 0.08 to 0.15, earlier research by others, has frequently adopted 0.10 as a safe conservative value for characterising the regional aquifer.

To assess the impact of different storage coefficients, some calculations have been repeated, with the storage coefficient parameter being varied. This has been undertaken for a range of values, but due to the consistency of the outcome only two examples are presented below.

The key observation is, as expected, that when alternative values are compared to the adopted storage coefficient value of 0.1, the coefficient of determination of R^2 in the examples is no different. This observation applies to all examples. However, the application of a different storage coefficient may present a better visual graph fit. This is demonstrated with a 0.15 storage coefficient value at MON016 and 0.13 at NAN009, with both providing a better visual fit of the relevant graphs.

The graphs comparing the calculated and observed depth to the water table are presented in **Figures 5.32** and **5.33** for the sites MON016 and NAN009, respectively. The graphs for the application of a storage coefficient of 0.1 are previously presented in Figures 5.7 and 5.17 for MON016 and NAN009 respectively. The statistical analysis outcomes with the coefficient of determination (R^2) return the same values as applied to the 0.1 storage coefficient application in Figures 5.8 and 5.18.

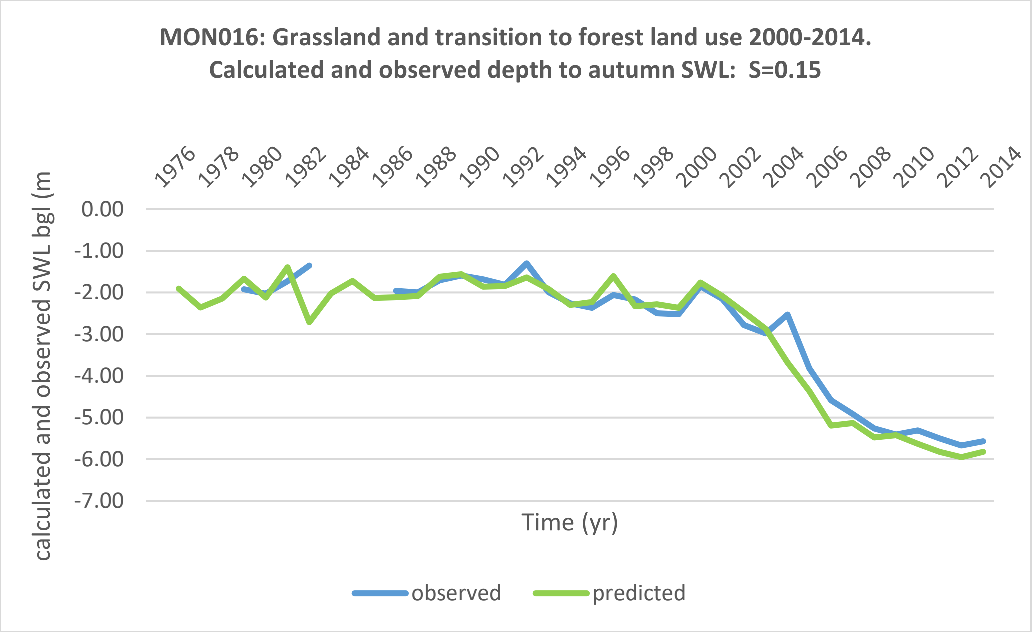


Figure 5.32: Correlation of water account against changes in depth to the water table by applying a storage coefficient of 0.15 at MON016

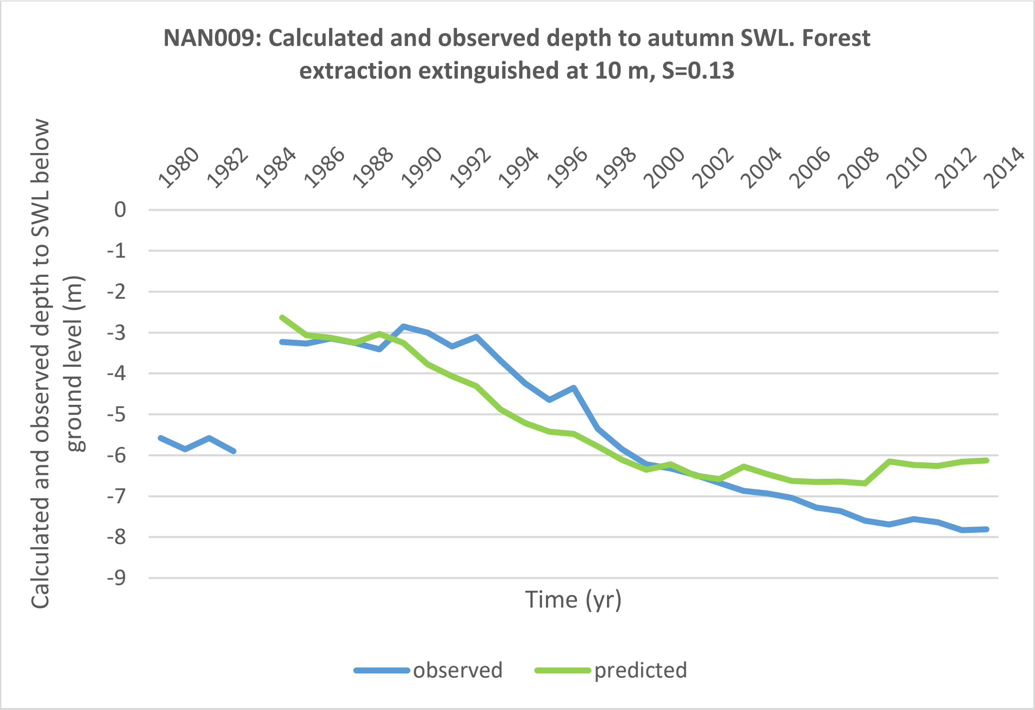


Figure 5.33: Correlation of water account against changes in depth to the water table by applying a storage coefficient of 0.13 at NAN009

5.8 Recharge relationship between unconfined and confined aquifers at Nangwarry

With a growing body of evidence that there is a direct hydraulic connection between the unconfined Tertiary Limestone Aquifer and the Tertiary Confined Sand Aquifer in the Nangwarry area, and the less than anticipated correlation outcome in Section 5.2.2, regarding calculated and observed water table fluctuations, water-mass-balance calculations were repeated for the Nangwarry sites using lower rates of recharge being applied to the unconfined aquifer. This does not imply that a high rate of diffuse groundwater recharge is not occurring, but with a connection between the unconfined and confined aquifers, the resulting net recharge for the unconfined aquifer is possibly occurring at a lower value than that considered by the local water allocation plan.

Hydrogeological and strati-graphical evidence is accumulating that suggests there is a direct hydraulic connection between the unconfined Tertiary Limestone Aquifer and the Tertiary Confined Sand Aquifer in the Nangwarry area. This evidence now includes the results of a drilling and aquifer testing program that was jointly undertaken by the South Australian and Victorian Governments in the border area, just east of the Nangwarry study sites (SKM 2012). Pumping tests reported by SKM (2012), at sites VIC3 and SA2, indicate a ‘highly trans-missive aquitard is apparent’ between the two aquifers. Chemical analysis undertaken by SKM (2012) also indicate the presence of carbon-14 in the confined aquifer, indicating a presence of ‘modern’ water. SKM (2012) concludes that the impact of any hydraulic loading on the lower confined aquifer, from the upper unconfined aquifer, would only contribute a relatively small component in the observed level fluctuations.

In addition, Somarante *et al* (2016) has constructed a conceptual geological cross section through the Nangwarry area. This is presented in Appendix 5c. Key observations related to the Somarante *et al* (2016) figure is a relatively thin Narrawaturk and Mepunga Formations and Dilwyn Clay, either side of observation well NAN042 and almost an absence of the Narrawatuk Formation in the border zone. These three formations contribute to the confining characteristics between the confined and unconfined aquifers.

To be noted in these relatively thin layers is the presence of sand, further reducing the integrity of the confining characteristics, particularly in the Narrawaturk and Mepunga Formations. Somarante *et al* (2016) reports a presence of sand ranging from 15-48 per cent. Furthermore, the displacement between fault lines near to the study sites adds to the probability of a connection between the two aquifers.

The above commentary by others and the comparison of some hydrographs in **Figure 5.34** for wells constructed into the Tertiary Confined Sand Aquifer and others constructed with a Tertiary

Limestone Aquifer production zone, provides indication of a hydraulic connection between the two aquifers.

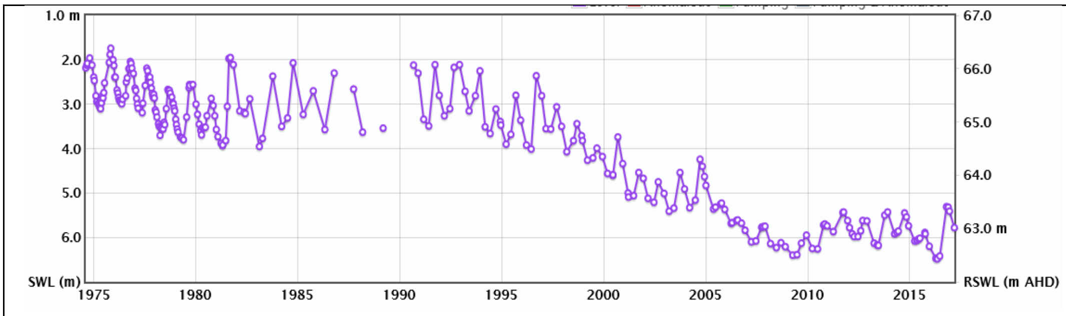
The hydrographs presented in Figure 5.34 include the Nangwarry study site NAN009 (an unconfined obswell) and the confined obswell NAN046, which is located inside the 5000 ha NAN009 study site. The hydrograph for NAN046 is presented as **Figure 5.35**. From the two hydrographs, it can be observed that the potentiometric surface at both sites is very similar. Also, it is observed that over the observation period of NAN046, from 1999 to the current time, the groundwater level has been in a steady decline, totalling about 2.5 metres. The groundwater at NAN009 has incurred a decline of a similar magnitude over the same period, and both exhibit a recharge spike of about 1 metre, at the end of 2016. While specific industry data is not available for 2015 and 2016, it is known that some clear felling of plantation forest has occurred at the Nangwarry sites during this period. Also, 2016 was a year when rainfall was significantly above the mean at the Penola rainfall gauging station (BOM 026025).

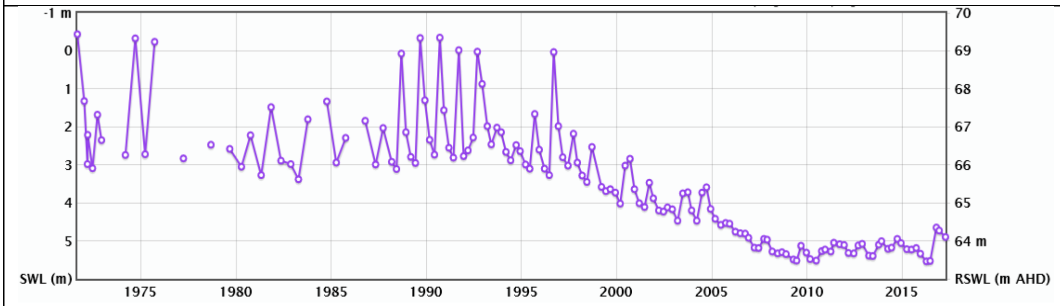
A hydrograph for NAN012 is also included in Figure 5.34. This indicates that the potentiometric surface at this site is lower than both NAN009 and NAN046 by about 6 metres. The decline at NAN012 since 1999 is in the order of about 1.5 metres. Site NAN012 has a similar recharge spike in late 2016, but at a reduced magnitude. These responses at NAN012 are not uncharacteristic of a down gradient observation of water table trends in the same aquifer

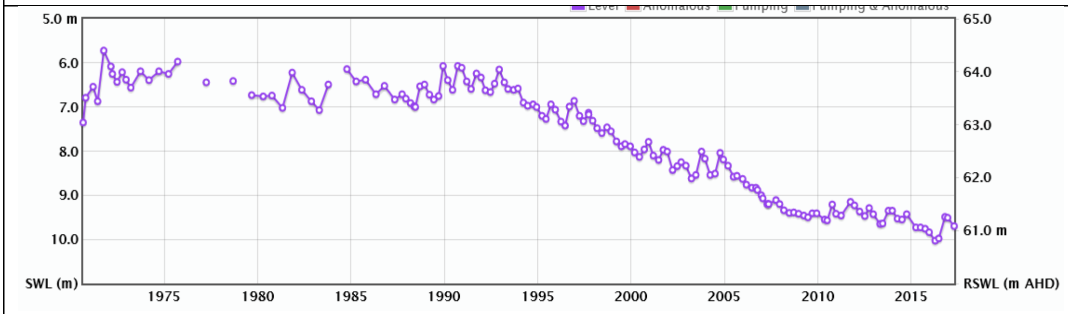
Figure 5.34 also includes the confined obswell MIN018 and the grassland unconfined well MIN009. While there are some data gaps prior to 1990, there are sufficient data to indicate that the trends over 40 years are very similar. During the period since 2007, some groundwater stability can be observed at both with the unconfined aquifer being indicated at a higher level than the confined water level by about 0.5 metres. During the main period of water level decline, the head difference between the two sites was up to about 1.5 metres. In general, from the hydrographs in Figure 5.34, with the exception of NAN012, groundwater levels at all sites in 2015 are approximately 3 metres lower than the levels 40 years earlier.

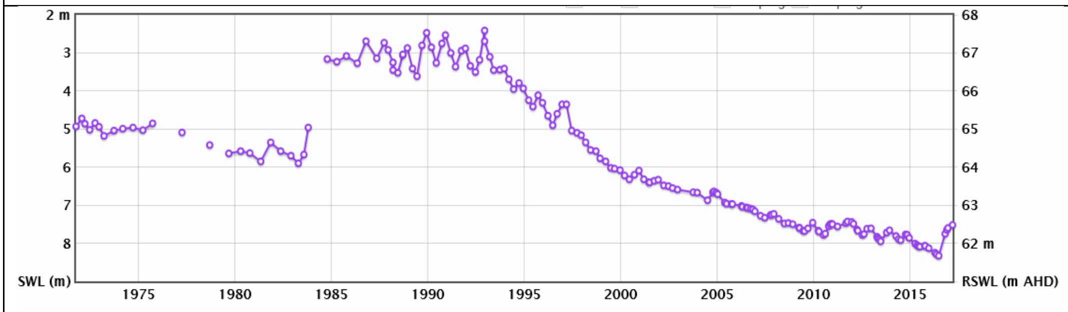
While there are some early data gaps, other than NAN009 and the confined well MIN018, all the other wells seem to exhibit reasonable stability in groundwater levels prior to the fire in 1983. Both NAN009 and MIN018 exhibit a decline of about 1 metre from 1975 to 1984.

While groundwater level observations at NAN012 follow a similar trend to that of NAN009, post fire, there are some erratic observations in the 2006-2007 period, but the water table now appears to be stabilising at about 14 metres below ground level.

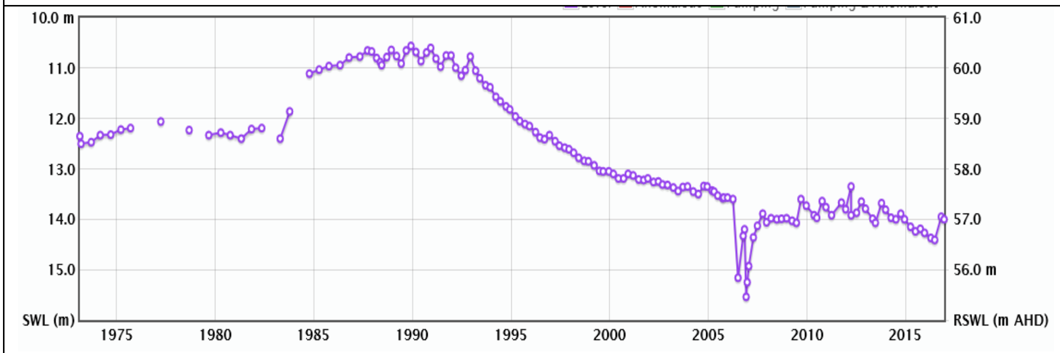
<table>
<tr><td>
</td><td>MIN018
confined

grassland</td></tr>
<tr><td>
</td><td>MIN009
unconfined

grassland
adjacent to
some
forest</td></tr>
<tr><td>
</td><td>NAN003
unconfined

grassland</td></tr>
<tr><td>
</td><td>NAN009

Unconfined

forest</td></tr>
<tr><td>
</td><td>NAN012

Unconfined
forest</td></tr>
</table>

Figure 5.34: Hydrographs for monitoring wells in Nangwarry grassland and forested environments: confined and unconfined

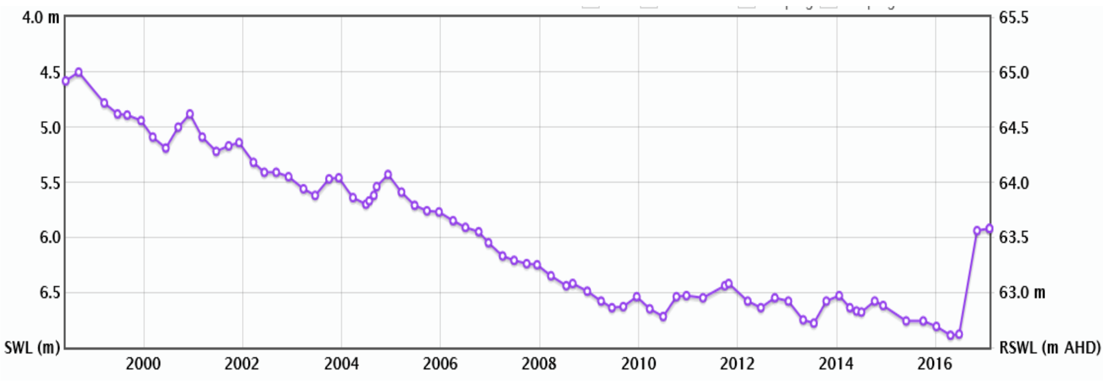


Figure 5.35: Hydrograph of confined monitoring well NAN046

These observations suggest a direct hydraulic connection between the two aquifers in this area and this connection is now at, or close to, a shared common head. In regard to the study site NAN012, while it is in the same general area and the rectified standing water level is generally 6 metres lower, it is considered that any connection between the two aquifers at this site, while subjected to a higher head difference, is possibly less.

A conclusion from this information provides support for the proposition there is a significant transfer of groundwater from the unconfined aquifer to the confined aquifer at the Nangwarry study sites. It is likely that the rate of transfer between the two aquifers will vary, depending on the potentiometric surface differences at the time of transfer.

Although there is evidence of a connection between the two aquifers, the closeness of the rectified standing water level at MIN018 (confined) about 10 km south east of NAN009 and the confined well NAN046, which lies within the NAN009 study site, suggests the water-mass-balance analysis undertaken at the NAN009 site is probably reasonably representative of groundwater behaviour at this site. The form of the connection between the two aquifers and the spatial extent is not fully understood and hence no values representing the connection are introduced into the calculations, but a range of reduced recharge rates were considered and applied to the model. A reduced recharge rate of 70 mm a year is applied in lieu of the adopted rate of 140 mm. This applied to the proposition that extraction by plantation forests is extinguished when the water table is 10 metres below ground level in June 1990, as applied in Figures 5.17 (NAN009) and 5.23 (NAN012).

In considering the evidence of a possible connection between the unconfined and the 'confined' aquifers in the study area, water-mass-balance calculations were repeated for NAN009 and NAN012 with alternative annual recharge rates that could be reflective of a loss of net diffuse recharge from water passing through the unconfined aquifer to the 'confined' aquifer.

Figure 5.36 shows the water-mass-balance results for NAN009, with a 70 mm annual recharge, and the respective statistical analysis outcome is presented in **Figure 5.37**. The process is repeated for the site NAN012 and the results are presented in **Figures 5.38**and **5.39.** The May-October rainfall variant factor is applied in both cases and the storage coefficient of 0.10 is also applied, with other parameters held at the same previous values.

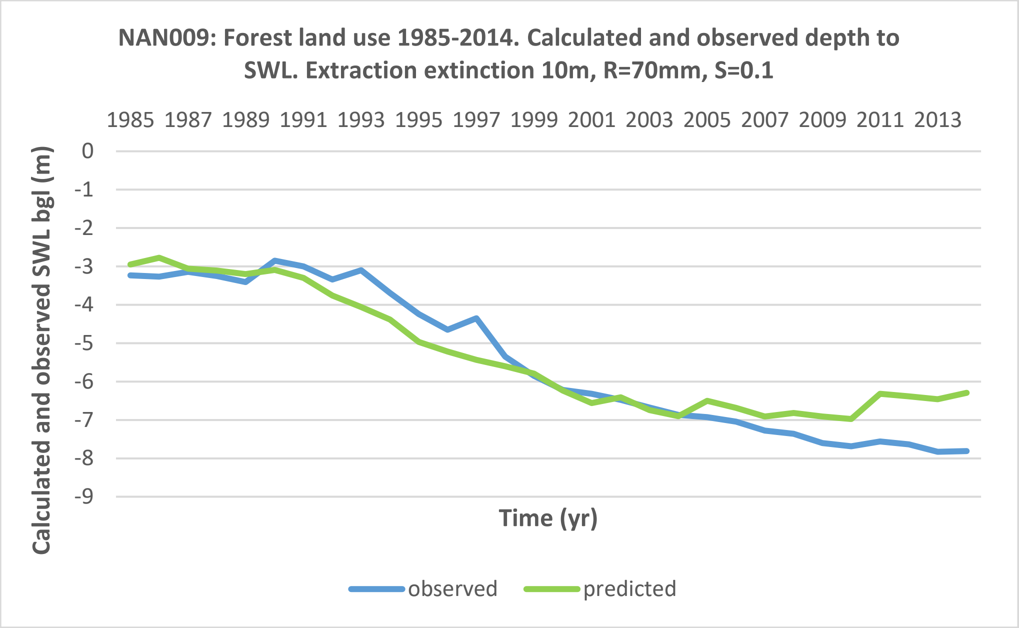
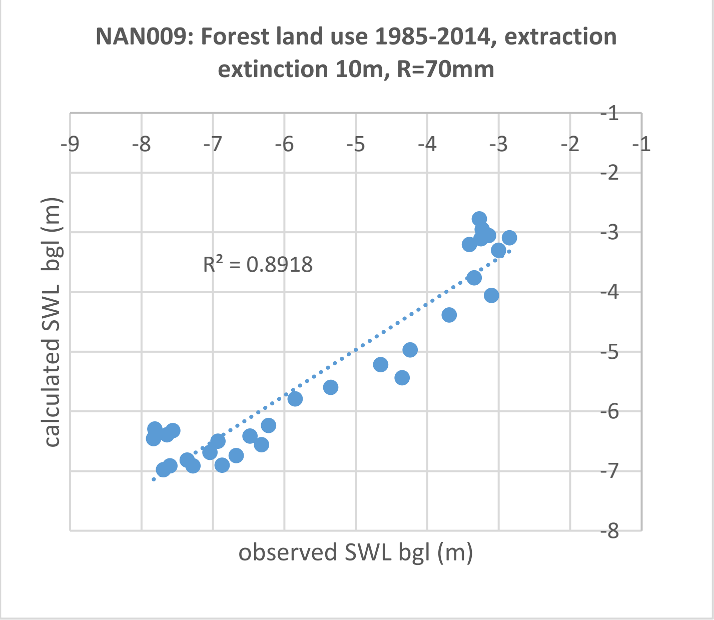


Figure 5.36: NAN009 with an annual recharge rate of 70 mm/year



NAN009: extraction extinguished at 10 m test (70 mm recharge)

RMSE 1985-2014 = 0.122 m, (30 observations)

Note values for the application of 140 mm recharge in Fig 5.17 are

R^2 = 0.886

RMSE = 0.185 m

Figure 5.37: NAN009 statistical analysis for an annual recharge rate of 70 mm/year

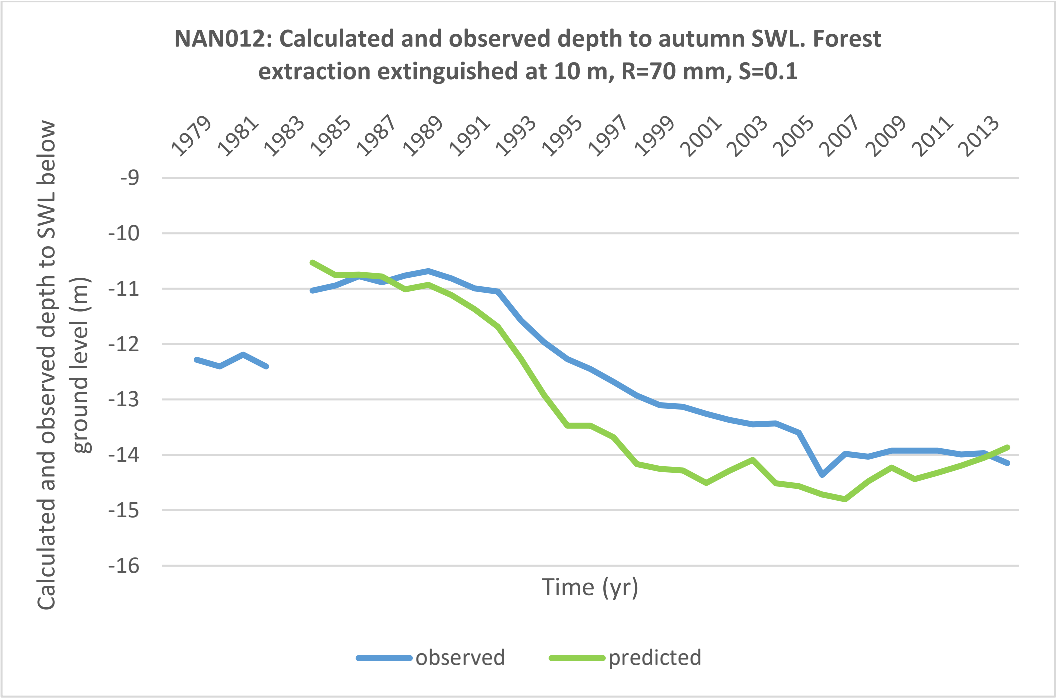
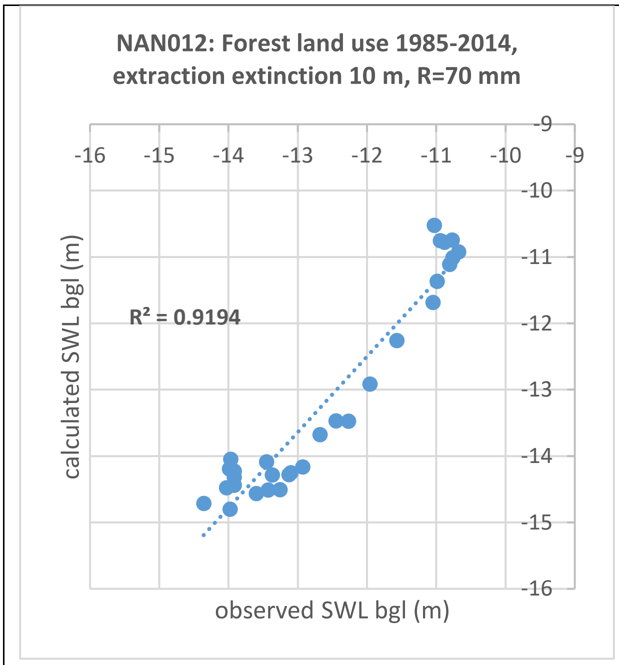


Figure 5.38: NAN012 with an annual recharge rate of 70 mm/year



NAN012: extraction extinguished at 10 m test (70 mm recharge)

RMSE 1985-2014 = 0.136 m

(30 observations)

Note values for the application of 140 mm recharge in Fig 5.23 are

R^2 = 0.900

RMSE = 0.254 m

Figure 5.39: NAN012 statistical analysis for an annual recharge rate of 70 mm/year

The outcome from applying a lower mean annual recharge rate than the value adopted by the water allocation plan, provides a better visual fit of the calculated depth to the water table, as against the observed depth. The statistical analysis of R^2 for NAN009 is slightly improved from 0.88 to 0.89 for the reduced recharge rate and the RMSE presents a substantial improvement from 0.185 m to 0.122 m for the reduced recharge rate of 70 mm compared to the 140 mm applied in Figure 5.18.

In the case of NAN012, the R^2 value exhibits an improvement at 0.92, compared to 0.90 for the adopted rate of 140mm per year (as per Figure 5.23). The RMSE is also improved, reducing from 0.254 m to 0.136 m with a 70mm annual recharge rate.

5.9 Influence of surface water drains on the water-mass-balance

Other than for some minor variations in the rate of water table decline at the Wattle Range forested study sites, the water table trend at MON016 and SHT014 can be regarded as exhibiting a continuing decline in groundwater storage, as indicated by both the observed and calculated depth to the water tables. The Wattle Range exception is the SHT012 site. This has been previously referred to in Section 5.3.2. The hydrograph for the monitoring well SHT012, with all recorded observations, is presented as **Figure 5.40**. This includes additional information to the autumn only depths to the water table presented in Figure 5.9 for comparison with the water-mass-balance calculations.

In Figure 5.40, a rise in the SHT012 water table can be observed in 2010 and this elevation is generally maintained until 2014. As previously advised, this monitoring well is within about 50 metres of the Bakers Range Drain and personal observation reveals a gravel layer near the floor of the drain, which is approximately 1.5 metres below ground level. This would suggest a possible transmissive connection to the upper level of the unconfined aquifer. Consequently, when there is water in the drain, and the groundwater level is below the drain water level, this drain water could then provide an additional source of groundwater recharge to the area adjoining the drain, and therefore, is likely to become visible in the water table responses at SHT012. The characteristics of the water table level variability from 2010 onwards is consistent with seasonal recharge.

Departmental records indicate water was in the Bakers Range Drain during the period commencing in 2010. Furthermore, due to the below average rainfall in the late 1990s and early 2000s, it is understood a number of years have passed without any observable drain capture, or flow.

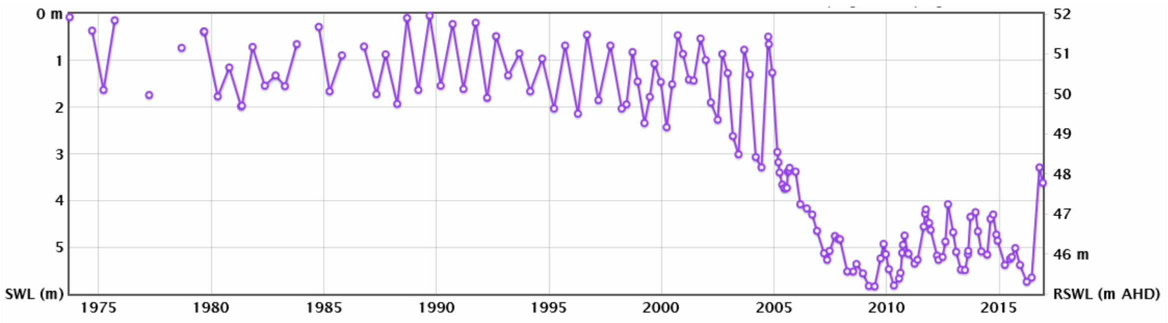


Figure 5.40: Hydrograph for obswell SHT012

This period commencing in 2010 also coincides with higher than average rainfall at Penola (BOM 026025). This can be noted in **Table 5.5**, where the months that are significantly wetter than the mean in this period (2010-2014) are shaded (green) and the period mean values are shaded blue.

Table 5.5: Monthly observed rainfall at Penola (BOM 026025), 2010 to 2014

	Monthly observed rainfall at Penola (BOM26025), 2010 to 2014												Deviation from the mean: mean =1.0		
year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year	May-Oct	annual
mean	28.7	18.8	31.2	44.9	60.8	78.1	91.5	90.7	72.0	50.0	42.8	35.4	645.0		
2010	19.8	35.4	18.0	74.0	52.0	67.8	81.6	126.4	85.4	43.4	32.2	97.0	733.0	1.03	1.14
2011	97.2	49.1	88.3	29.4	72.4	81.6	98.5	93.3	33.2	39.8	46.1	33.2	762.1	0.95	1.18
2012	7.4	2.9	39.9	27.2	45.8	125.8	71.6	108.8	48.6	30.2	27.7	20.9	556.8	0.97	0.86
2013	1.8	25.8	21.8	33.9	55.1	66.6	137.9	157.3	107.3	92.8	31.7	28.7	760.7	1.39	1.18
2014	24.0	18.0	35.8	51.0	62.2	115.5	73.9	36.1	23.3	16.0	19.7	29.4	504.9	0.74	0.78
note: mean values apply to the period of 1971-2015															

In the year 2010, the months of August and September are wetter than average and this is followed by a wet December, which is further followed by a wet opening for 2011, continuing through to March, followed by a wetter than average May to August period. Due to the applied May-October recharge factor methodology, this wet phase outside of the May-October data is not recognised as significant, whereas in fact it is probably instrumental in contributing to additional groundwater recharge and a presence of drain flow of surface water from external catchments. While 2012 is referenced as having below average rainfall, the months of June and August record rainfall significantly above the mean.

The year 2013 is identified by the May-October criteria as being wet and requiring a recharge adjustment by a factor of 1.39. However, if the year is analysed closely, it can be seen that the consecutive months of July to October are significantly wet, with this period exceeding the mean for the July-October sequence, to the extent that the recharge adjustment factor could be of an order of 1.63, if similar criteria is applied to that period.

Due to the proximity of the drain at SHT012, and the height relationship between the drain floor and the recorded water table in the pre-forest period, it is probable that there may have been some groundwater discharge into the drain, muting recharge peaks during this pre-forest period.

A review of data for the Bakers Range Drain indicates that water was present in the drain during the late winter to spring periods from 2010 to 2014. **Table 5.6** is a summary of a presence of water in the drain for the period 2010 to 2014. The presence of drain flow water in 2014 is from water management associated with the ‘reflows’ project. This data is sourced from the regional water resource manager.

The significant rise in the water table at SH012 in 2016 is believed to be contributed to some large-scale forest felling personally observed in the area, but no official forest data confirming the extent of the activity was available at the time of compiling this thesis.

Table 5.6: Days water present in the Bakers Range Drain

Year	Days water present	Year rainfall deviation from the mean (mm)
2010	51	88.0
2011	65	117.1
2012	44	-88.2
2013	91	115.7
2014	50	-140.1

5.10 Influence of lateral groundwater flows

As previously advised, to be consistent with the regional water allocation plan, there is an assumption that inward and outward lateral groundwater flows are considered to be equal (refer to Section 4.3.7). That may be an appropriate approach if the regional groundwater resource is in a general state of equilibrium. However, the reality is that where a cone of depression is formed, there will be increased inflows towards the cone and reduced outward flows into neighboring down gradient areas. The forest water model does not consider the changes in groundwater characteristics and consequently the impact of inward lateral flows exceeding outward lateral flows may results in a net increase in the water mass balance at a specific study site. The appearance of a moderation of water table decline at a forest study site indicates the groundwater resource is approaching a water balance equilibrium, that is, groundwater discharge (extraction) and recharge are approaching an equilibrium, either by increased recharge , decreased discharge, or some combination of both.

The testing of the forest water model does not take into account the changes that occur in lateral groundwater flows and any resulting development of a localised drawdown cone of depression. Changes in the lateral flows is essentially related to the change in the head differential between the impacted site and its neighbouring areas, in accordance with Darcy’s Law. At 1997, prior to the forest land use transition, the groundwater level at MON016 was stable and in the order of 48.5 m (AHD) while the stable groundwater levels at MON004 were at a level in the order 53.2 m (AHD); a differential of 4.7 m (AHD) (refer to Figure 5.2). This was at a time when the groundwater resource was considered to be in equilibrium and inflow and outflows would have been relatively stable and near equal.

By 2011 (when monitoring at MON004 ceased), the groundwater level at MON016 had declined about 3.2 m, whilst MON0004 maintained its earlier level. According to Darcy's Law, this increased gradient would result in increased groundwater lateral flows, at least from an easterly direction from MON004 to MON016 (refer Figure 5.1). This is additional and unaccounted groundwater recharge for the water mass balance at MON016. While unlikely, it also needs to be considered that the emergence of a new groundwater equilibrium, may, in part, be contributed to by a reduction in aggregate groundwater extraction by the overlaying plantation forest. This could occur where plantation forest clearance is occurring, and or, forest extraction is approaching a thresh hold depth at which extraction begins to cease. Both these are unlikely for the MON016 site at that time, because it is known there is no significant clearance occurring in the study period and the water level is relatively shallow, less than 6 metres below ground level.

6 Discussion

6.1 Introduction

As outlined in the beginning of this thesis, an aim of this research is to assess whether the 2006 forest water accounting model, that underpins the Lower Limestone Coast region forest water accounting and management system, adequately accounts for the impacts of plantation forests on groundwater resources in the region, where forests are a significant land use. Until this study, while the forest water model and its deemed output values are agreed between key stakeholders, no attempt had been made to test the model and the accuracy of its output values.

It was also proposed that subject to the outcome of analysis undertaken, knowledge gains may provide avenues to target a refining of the model to improve its output accuracy, and hence increase the confidence in its application, or alternatively, provide advice with respect to its use and limitations.

While the results of the study undertaken have presented a strong endorsement of the 2006 forest water accounting model's suitability for accounting for the hydrological impacts of plantation forests on groundwater resources at the studied sites, new knowledge has also emerged. The following discussion is intended to further explain and discuss these matters, and their significance in the use of the forest water accounting model for accounting for forest hydrological impacts in regional groundwater resource management.

The fact that this analysis is carried out over sites in the order of 5000 ha, and with plantations of mixed ages, a high level of confidence must be placed in the outcome, in respect to applicability at a groundwater management area scale. Many past scientific studies related to plantation forest hydrology are generally at a plot scale, or in the case of paired catchment studies, the areas involved seldom exceed several hundred hectares and are generally restricted in time, and furthermore, the subject plantations do not necessarily represent a mixed aged plantation estate, or are representative of a full forest cycle (which can be in the order of 30 to 40 years for industrial scale softwood plantations). While the resultant data from plot-scale investigations of several hundred square metres can provide strong evidence and indicators, there are inherent risks in predictability when scaling up outcomes to areas at which industrial scale plantation forests occur and regional water resource management operates.

Several key issues to emerge are the depth at which plantation forests cease to extract groundwater (the threshold or extinction depth for forest groundwater extraction) and the possibility of a revision to some of the annual components of the forest water accounting model. While these are technical issues they could have policy implications, whether ignored or introduced. Such implications could lead to a reluctance to adopt the technical advice into operational policy, but if considered to be technically accurate the knowledge should be at least incorporated into ongoing technical assessments, such as groundwater numerical modeling, if related to significant areas of plantation forest impacts.

In this chapter the following matters are discussed:

- Revised annual values in the forest water accounting model
- Threshold or extinction depth for cessation of groundwater extraction by plantations
- Age structure of hardwood plantations and hydrological consequences
- Age structure of softwood plantation and hydrological consequences
- Impacts of plantation forests on groundwater recharge
- Significance of groundwater extractions by plantations
- Appropriateness of annualised forest water accounting

6.2 Revised annual impact rates for plantation forests

It was previously noted, the annual groundwater extraction rates applied to softwood plantation forests in the forest water accounting model, while being based on some scientific observations, also involved negotiation with key stakeholders. The main issue was the hydrological impact of the reduced tree population which is related to the various thinning operations during the rotation life of softwood plantations (Avey and Harvey 2014). Observations by Benyon and Doody (2004) provide scientific outcomes from small plots of closed canopy forests over two and three-year periods, however this information needs to be adapted and extended in a tool to address a softwood plantation life cycle in the order of 35 years. During this 35-year period the plantation tree population would be significantly reduced, possibly over four different occasions. This has resulted in the 2006 forest water accounting model being evolved from some scientific results, biophysical principles, with a significant injection of negotiations with key stakeholders (forest managers, other groundwater users and the water resource manager).

With an awareness of this factor, and an observance that while the correlation between the water-mass-balance accounting calculations and the observed changes in groundwater storage at the Nangwarry sites had improved with modified recharge rates and extraction extinction at 10 m, the outcomes did not quite reach the level of correlation evident at the hardwood plantation study sites at Wattle Range.

An observation of the water-mass-balance results pertaining to the softwood plantations, suggest that the forest water accounting model may underscore the amount of effective diffuse recharge under a newly planted plantation. The intensive reforestation following the 1983 fire at Nangwarry has resulted in a large area of developing plantations, with a compressed age range, providing an opportunity to further consider this impact with time-trend analysis, using existing data for after-the-fact analysis (Zhang *et al* 2010).

Findings by Benyon and Doody (2009), in relation to the testing of groundwater diffuse recharge in the first two years of a second rotation plantation establishment, now provides support for testing an increase in recharge during that period. It is also noted that Benyon and Doody (2009) acknowledge that it is generally considered there is negligible recharge under plantation forests that have reached full canopy closure, supporting the adoption of the principle in the forest water accounting model of no recharge under a closed canopy forest.

The term 'canopy closure' is applied as an advisory term, as an indicator of when recharge ceases under a new plantation forest. In the case of hardwood plantations, it has been generally accepted that this occurs at three years after planting and in the case of softwood, six years after planting (Dillon *et al* 2001).

However, in the case of the softwood plantation industry, whilst the industry is reluctant to discuss productivity at a broad scale, personal comments from some in the plantation forest industry indicate that forest productivity has generally increased across the region in second and third forest rotations. Much of this is attributed to improved management of early weed control and soil fertility. Consequently, there may be a case to be made for canopy closure, or more particularly the cessation of recharge, occurring at a point earlier than the widely accepted six years after planting.

As an acknowledgement of the findings of Benyon and Doody (2009), it is proposed that a revised value for recharge in the year of planting of softwood be tested at 200 per cent of that recharge occurring in a grassland landscape (the mean management area recharge rate), as opposed to the current 120 per cent of the management area recharge rate. As an alternative approach, the cessation of recharge is considered to occur five years after planting, instead of the current six years.

If applied to a plantation in a theoretical management area, where the recharge rate is 150 mm/year (such as the management area of Short), recharge in the year of planting would considered to be 300 mm. As this zone has a mean annual rainfall in the order of 645 mm, this implies evapotranspiration to be in the order of 345 mm; this is also in the range indicated by Benyon and Doody (2009). Consequently, it is also proposed that the diffuse recharge from rainfall occurring in the year of planting a hardwood plantation be considered to be 200 per cent of the management area recharge rate and cessation of recharge is proposed to be two years after planting.

In the proposed revised model (to be referred to as the 2017 model) to be tested, it is intended to adhere to the concept that the reduction in recharge from planting to canopy closure remains linear.

In the current 2006 forest water accounting model, recharge at a rate of 50 per cent of the management area mean rate is considered to occur following each of four thinning operations in softwood plantations. The 50 per cent value is a negotiated figure and has no significant known scientific evidence to support this particular value. As previously advised, the first thinning is significant in reducing the tree population per hectare to provide physical access for harvesting and log hauling. The first thinning can result in about a 40 per cent reduction in tree population and this generally occurs at a relatively immature stage in the plantation life (generally 10 to 16 years after planting).

For the purpose of testing an alternative parameter for recharge, at the time of the first thinning of a softwood plantation, a 25 per cent of the management area recharge rate is proposed to occur in the 2017 forest water accounting model. However, due to subsequent thinning operations occurring at a more mature stage of the plantation, and with a lesser rate of clearance, no further allowances are proposed for recharge in any subsequent thinning events in the 2017 forest water accounting model to be tested.

Table 6.1 summarises the suggested adjustment to annual recharge and extraction impacts of both plantation types. The table also compares the proposed rates with the annual rates currently being applied in the 2006 forest water model. The main differences are the application of the 200 per cent recharge allowance in the year of planting, for both hardwood and softwood plantations. The cessation of recharge is considered to occur one year earlier, which is, two years after planting, as opposed to the current three years for hardwood plantations and for softwood plantations, five years after planting.

Except for the post first thinning phase of softwood plantations, the maximum annual extraction rates remain the same for both forest types. In the case of softwood plantations, the annual rate after the first thinning is at a constant rate and this is explained in **Figure 6.1**. This modified approach results in an increase in the life cycle extraction aggregate of about 10 per cent, a response to the observation in the water-mass-balance analysis in the previous chapter that evapotranspiration in the later years of the plantation rotation may be at a higher rate than provided for in the adopted 2006 forest water model.

Another consideration presented in Table 6.1 is the slightly shorter softwood rotation, from 35 to 32 years at clear felling, which is indicated by the industry data. In the case of hardwood plantations because of the evidence of older aged plantations, the revision provides for the harvesting of hardwood plantations at 15 years after planting.

The application of this proposal does not significantly change the annualised recharge impact of softwood plantations. If the 35-year rotation applies, the annualised rate remains at the current rate of 17 per cent of the management area recharge rate. If the average rotation length is 32-years, the annualised rate becomes 18.9 per cent of the management area recharge rate, noting the accounting cycle includes one year after harvest to allow for clean-up. While not confirmed by the plantation industry, it is believed that a trend may be emerging for clear felling at an earlier age than 35 years, and with less thinning operations during a full rotation.

Table 6.1: Revision of annual recharge rates

Softwood plantation forests				**Hardwood plantation forests**			
rates for suggested revised forest water model: 32 and 35 yr rotation		**rates from 2006 forest water model: 35 yr rotation**		**rates for suggested revised forest water model: 15 year rotation**		**rates from 2006 forest water model: 10 year rotation**	
Recharge		**Recharge**		**Recharge**		**Recharge**	
forest stage	recharge factor*	forest stage	recharge factor*	forest stage	recharge factor*	forest stage	recharge factor*
yr1	2.00	yr1	1.20	yr1	2.00	yr1	1.20
yr2	1.60	yr2	1.00	yr2	1.00	yr2	0.80
yr3	1.20	yr3	0.80	yr3	0.00	yr3	0.40
yr4	0.80	yr4	0.60				
yr5	0.40	yr5	0.40				
yr6	0.00	yr6	0.20				
thin 1	0.25	thin 1	0.5				
		thin 2	0.5				
		thin 3	0.5				
		thin 4	0.5				
aggregate	6.25	**aggregate**	6.20	**aggregate**	3.00	**aggregate**	2.40
annualised-36 yr	**17.4%**	annualised-36 yr	**17.2%**	annualised-16 yr	**18.8%**	annualised-11 yr	**21.8%**
annualised-33 yr	**18.9%**	annualised-33 yr	**18.8%**				
increase on current	**10.0%**			decrease on current	**14.1%**		
Discharge		**Discharge**		**Discharge**		**Discharge**	
forest stage	**ML/ha**	**forest stage**	**ML/ha**	**forest stage**	**ML/ha**	**forest stage**	**ML/ha**
yr7	0.73	yr7	0.73	yr4	0.91	yr4	0.91
yr8	1.46	yr8	1.46	yr5	1.82	yr5	1.82
yr9	2.19	yr9	2.19	yr6	2.73	yr6	2.73
yr10	2.91	yr10	2.91	yr7	3.64	yr7	3.64
yr11	3.64	yr11	3.64				
yr12	2.3	yr12	1				
annual there after until yr 35	2.3	annual there after until yr	variable, refer Table 4.1	annual there after until yr 15	3.64	annual there after until yr	3.64
aggregate	**66.13**	**aggregate**	**59.9**	**aggregate**	**38.22**	**aggregate**	**20.02**
annualised-36 yr	**1.84**	annualised-36 y	**1.66**	annualised-16 yr	**2.39**	annualised-11 y	**1.82**
annualised-33 yr	**2.00**	annualised-33 y	**1.82**				
increase on current	10.40%			increase on current	31.25%		

There is an increase in annualised recharge if the hardwood rotations are conducted on a basis of 10 years from planting to clear felling, however, current practise indicates clear felling at ages significantly older than 10 years. If clear felling is considered to occur 15 years after planting, the annualised recharge rate would be 18.8 percent of the management area recharge rate, compared to the current rate of 22 per cent of the management area recharge rate.

The extraction parameters in the current 2006 forest water accounting model assumes a maximum extraction rate of 3.64 ML/year for both hardwood and softwood planation forests (Harvey 2009). In applying the 2006 forest water accounting model to softwood plantations, this maximum value is achieved progressively from year seven to year 12 after planting. After this point, there was a negotiated outcome, due to the physical reduction in the tree population associated with the thinning regimes practiced by all softwood forest managers (Harvey 2009).

Due to the multiplicity of the forest management scenarios that can be applied, in respect to the number and timing of plantation thinning operations of the tree population, a linear accounting approach is considered more practical. This has been tested against a number of management options using the 2006 forest water accounting model, and it is found that a linear approach does not create any significant deviation from the specifically targeted approach, in terms of the aggregate extraction volumes. This is demonstrated in **Figure 6.1** where five different softwood management variations are compared to constant a linear approach.

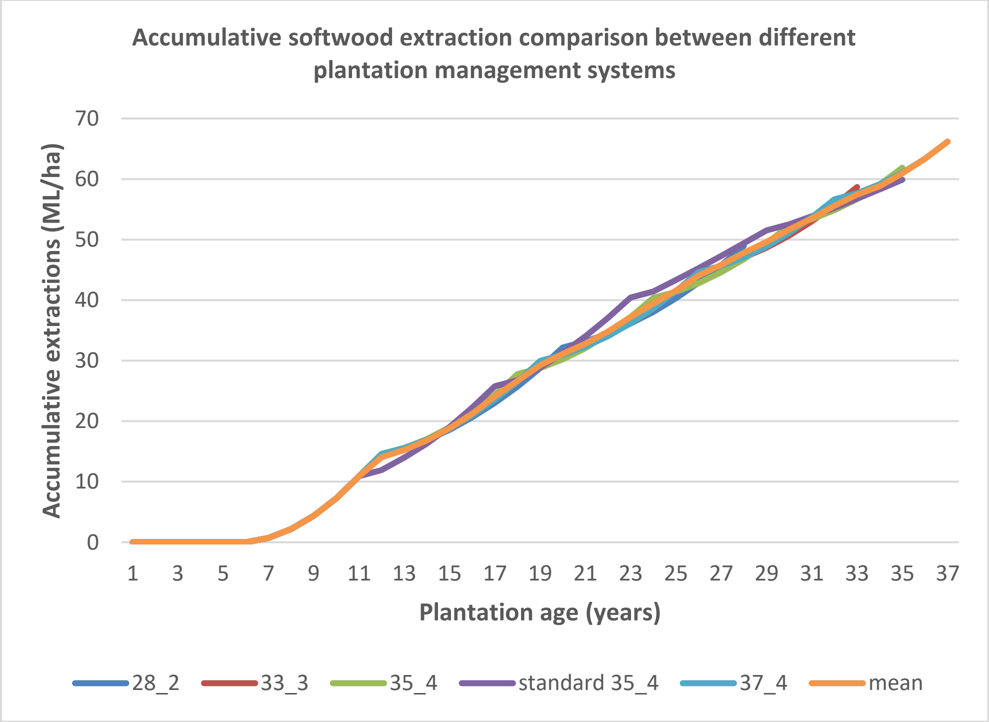


Figure 6.1: Accumulative groundwater extractions for various softwood management scenarios

The legend of Figure 6.1, identifies a 28-year rotation with two thinning events as 28_2. Similarly, this nomenclature format applies to 33_3, 35_4 and 37_4, where the age and number of thinning operations is noted. The orange line represents a linear mean of the accumulative impacts. The main point to note is that there is no significant deviation for any model away from the 'straight line' approach.

For the 35-year age plantation, the aggregate is 61 ML, compared to the 59.9 ML in Table 3.1. For a softwood plantation, under the proposed model revision, the aggregate value at 35 years is increased to 66 ML. On an annualised basis this is equivalent to 1.84 ML/ha/year, compared to the current 2006 forest water accounting model that has an annualised value of 1.66 ML/ha/year.

There is uncertainty associated with the groundwater extraction parameter for softwood plantations and because of the different management approaches, a constant annual extraction rate of 2.3 ML/year will be held across the softwood forest life cycle, following the first thinning. The maximum extraction rate of 3.64 ML/year is still applied and is assumed to be reached 11 years after planting, with the first thinning considered to occur in the following year.

The 2017 forest water accounting model, with the revised parameters for recharge and extraction impacts, is applied to both the NAN009 and NAN012 sites with a 70 mm recharge rate to acknowledge the unconfined aquifer loss to the confined aquifer. The NAN009 outcomes for a 70 mm recharge rate are presented in **Figures 6.2,** with the statistical analysis presented in **Figure 6.3**. The outcomes for NAN012 in **Figure 6.4** for the water-mass-balance outcomes and the statistical analysis presented in **Figure 6.5**. A storage coefficient of 0.10 has been applied in both cases and extraction is considered to become extinct with a 10 metre depth to the water table at 1990.

In the case of NAN009, there is an improvement in RMSE from 0.136 m to 0.122m when compared to the case in Figure 5.36, which is based on 70 mm recharge and 10 metre extraction extinction. However, the R^2 value has declined from 0.89 to 0.85. In the case of NAN012, when Figure 6.4 is compared to the case in Figure 5.38, the R^2 value has improved from 0.92 to 0.95, while the RMSE has degraded from 0.136 m to 0.169 m.

The varied outcomes seem to highlight the extraneous relationship between the confined and unconfined aquifers at the two sites. However, the impact of applying these variations seems to support the notion that the current 2006 forest water accounting model is reasonably robust for its intended purpose.

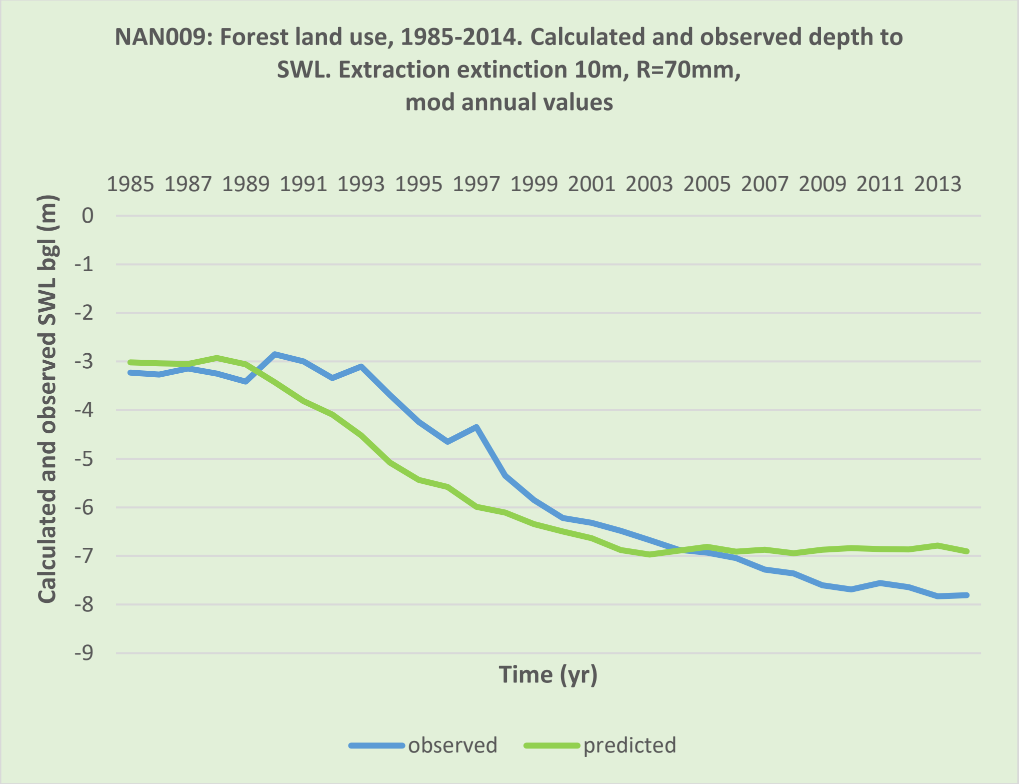
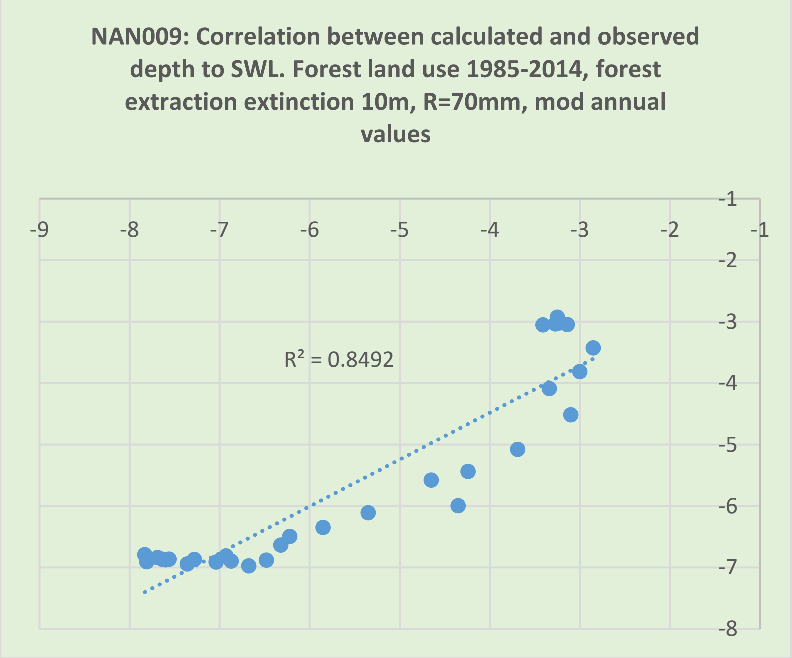


Figure 6.2: NAN009 with a revised annual account of softwood plantation impact (2017 model)



NAN009 (suggested 2017 model): extraction extinguished at 10 m test (70 mm recharge), revised annual rates

RMSE 1985-2014 = 0.136 m, (30 observations)

Note: values for the application of 70 mm recharge in Fig 5.37 are

$R^2 = 0.8918$

RMSE = 0.122 m

Figure 6.3: NAN009 statistical analysis for revised annual softwood plantation impact (2017 model)

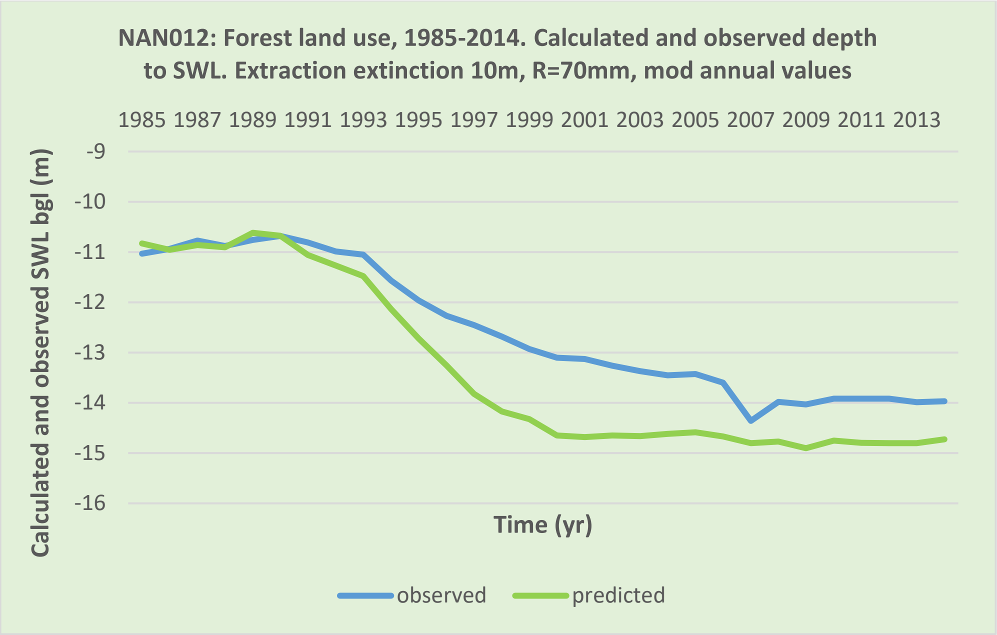


Figure 6.4: NAN012 with a revised annual account of softwood plantation impact (2017 model)

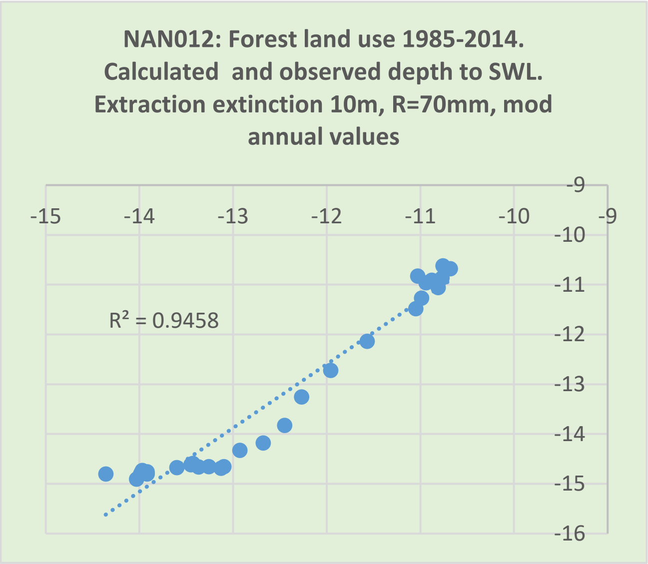
	**NAN012 (suggested 2017 model)**: extraction extinguished at 10 m test (70 mm recharge) RMSE 1985-2014 = 0.169 m (30 observations) Note: values for the application of 70 mm recharge in Fig 5.32 are R^2 = 0.92 RMSE = 0. 136 m

Figure 6.5: NAN012 statistical analysis for revised annual softwood plantation impact (2017 model)

The 2017 forest water accounting model is also tested for the sites MON016 and SHT014 with the revised recharge rate parameter. No change in extraction is incorporated at this time with hardwood plantations as there is little alignment between the actual current harvesting cycles with that proposed by the industry in 2006. The outcomes are presented in **Figures 6.6** and **6.7** for MON016 and **Figures 6.8** and **6.9** for SHT014.

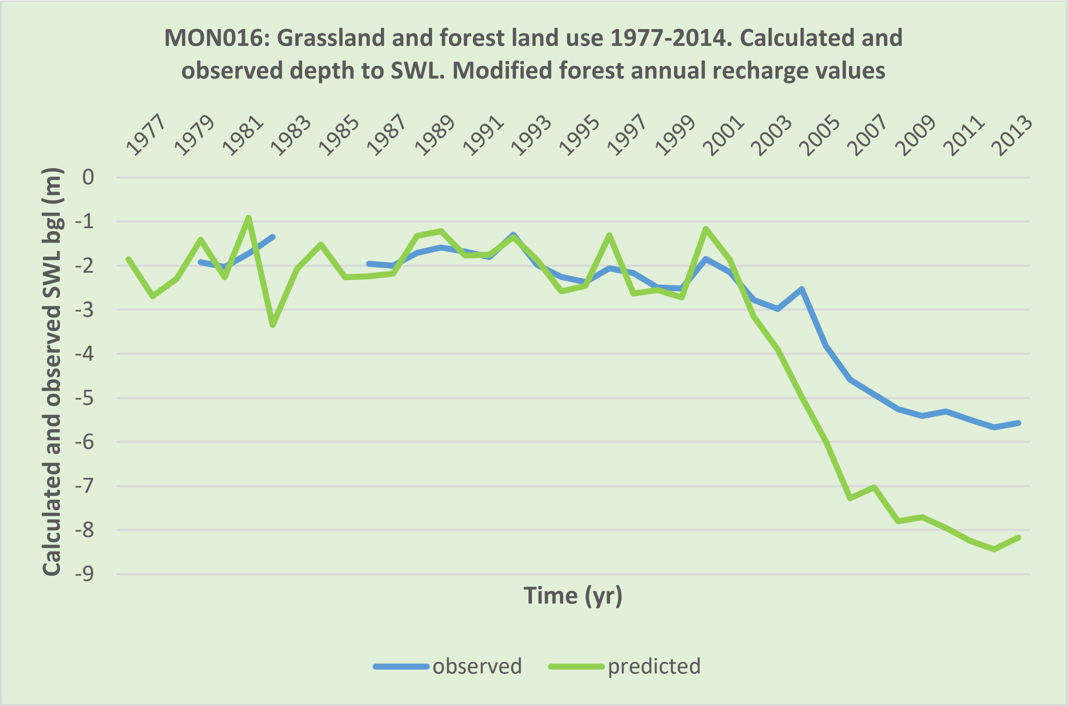
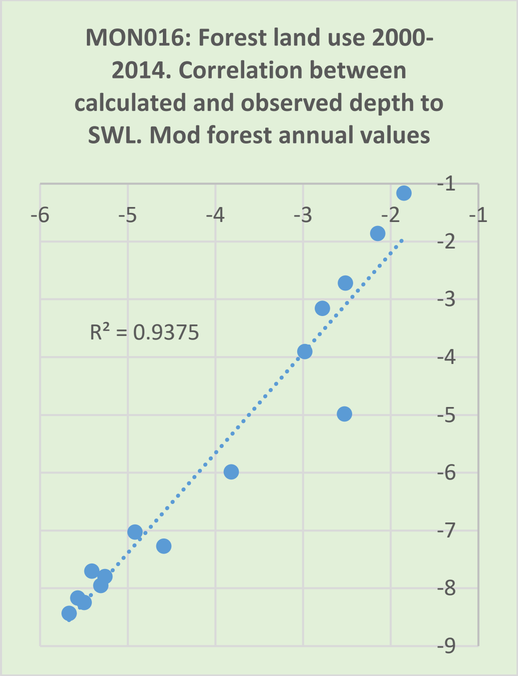


Figure 6.6: MON016 with a revised annual account of hardwood plantation impact (2017 model)



MON016 (suggested 2017 model):

No extraction constraint

RMSE 2000 -2014 (forested period) 0.536 m

(15 observations)

Note: values in Fig 5.8 are

$R^2 = 0.95$

RMSE = 0. 536 m (2000-2014)

Figure 6.7: MON016 statistical analysis for revised annual hardwood plantation impact (2017 model)

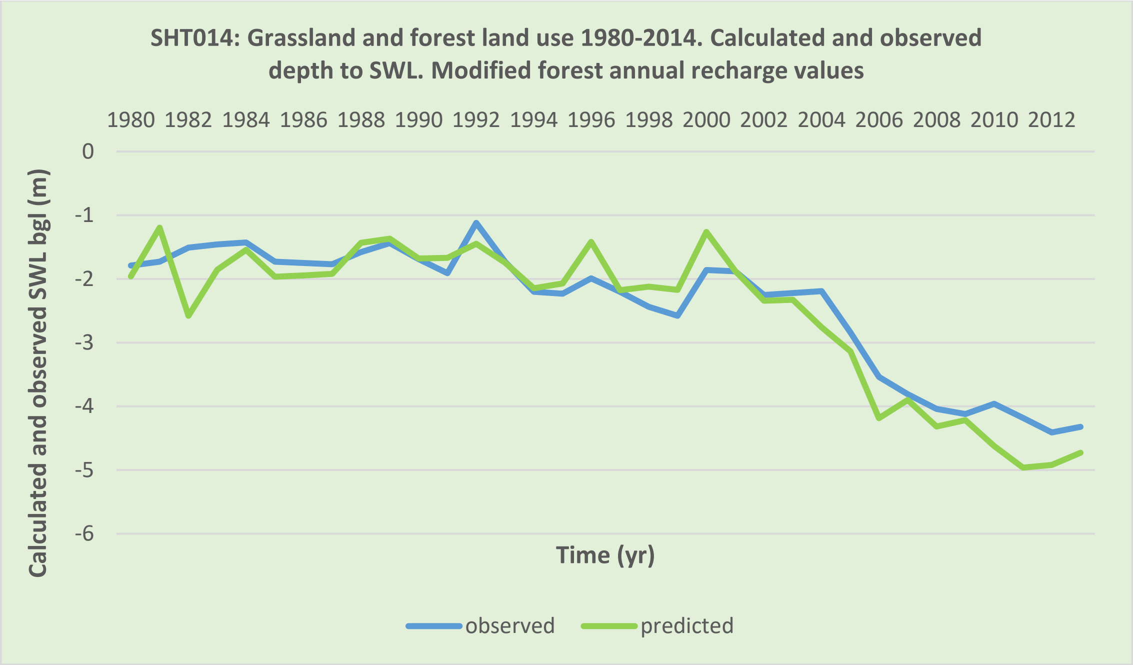


Figure 6.8: SHT014 with a revised annual account of hardwood plantation impact (2017 model)

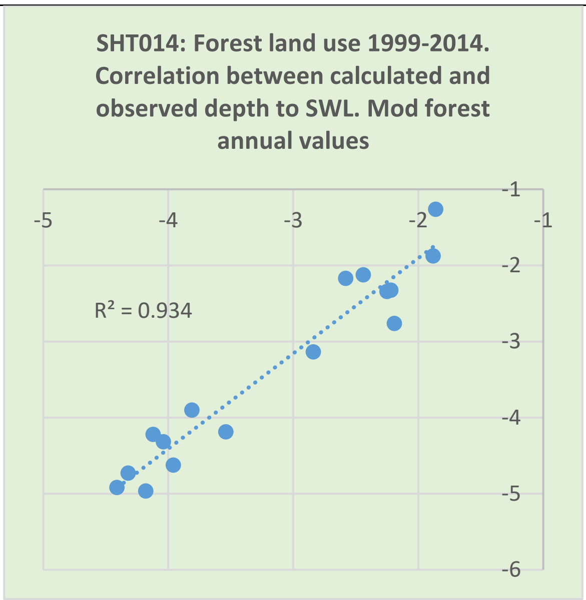
	**SHT014 (suggested 2017 model)**: No extraction constraint RMSE 1999 -2014 (forested period) = 0.114 m (15 observations) Note: values in Fig 5.10 are R^2 = 0.94 RMSE = 0. 106 m (1999-2014)

Figure 6.9: SHT014 statistical analysis for revised annual softwood plantation impact (2017 model)

The impact of increasing the recharge rate for hardwood plantations has caused a small loss in the R^2 correlation values and small increase in the RMSE values during the forest land use period, suggesting that the current annual values in the 2006 forest water accounting model, when applied to hardwood, is relatively robust.

A summary of all statistical analysis is tabled in Appendix 6.

6.3 Threshold depth for groundwater extraction by plantations

Are plantation forests extracting groundwater from deeper water tables? This is a key question for the management of plantation forest impacts on groundwater resources in the Lower Limestone Coast region. While it is now generally accepted that plantation forests can extract groundwater from shallow water tables, the threshold depth at which extraction can be considered to cease, at a management area scale, is not clear. While Benyon and Doody (2004) make the following statement:

> *In the South East of South Australia, eight out of nine research plots where the depth to the water table was less than 6 m used some groundwater at an average of 435 mm year* $^{-1}$*,*

other observations by Benyon *et al* (2006) report the use of groundwater by *Pinus radiata* from depths in the range of 8.5 to 8.9 metres. The work by Benyon and Doody (2004) relates to investigations conducted on a small sample of trees within commercial plantations for a two to three-year period in closed canopy forests. While tree selection took into account soil variability and landscape positions, with a view to presenting results that could be considered to be reflective of trees in a commercial forest, and rigorous statistical methods applied to scale transpiration to plantation evapotranspiration values, the observation period was a relatively short period when compared to the current life cycle of plantation forests.

As an outcome of some of the initial observations, the investigation now being discussed in this thesis is ‘testing’ (at a commercial scale), the proposition that plantation forests extract groundwater from water tables deeper than 6 metres. Other than the quantum of groundwater annually extracted, an important issue for management is a determination of the threshold depth of the water table at which extractions by plantation forests cease (or is extinguished). For management purposes, at a forest compartment scale, or a sub-regional scale, it is important for accounting, policy transparency and confidence, the principles associated with groundwater extraction by plantation forests are robust.

It is considered that having study sites in the order of 5000 ha, and where plantation forests are the most significant land use, a net annual water-mass-balance approach may provide sufficient information to assist in establishing a ‘threshold’ or ‘extinction’ depth at which significant plantation forest groundwater extractions can be considered to cease. While there will likely be some significant variations within plantations due to soil issues and management, the object is for a robust approach that is suitable at a commercial scale.

In addition to the sample of individual tree observances by Benyon and Doody (2004) and Benyon *et al* (2006), the Nangwarry study sites provide a situation where the extinction depth for plantation forest groundwater extraction can be tested at a scale that is relevant for both commercial scale plantation forest management and groundwater management. This is undertaken by applying the water-mass-balance approach and assuming that groundwater extraction by plantation forest is not constrained by depth at locations where the groundwater level is at a depth in excess of the 6 metres below ground level across much of the study sites.

From the water-mass-balance analysis undertaken at the Wattle Range sites, it is concluded that wide spread extraction is occurring where the water table is generally within 6 metres of ground level. This is consistent with the observations by Benyon *et al* (2006). However, observations at both NAN009 and NAN012 (Figure 2.4) indicate a continuing decline in the water table beyond 6 metres below ground level. This indicates ongoing groundwater discharge, and if all aspects of land use and anthropogenic groundwater extractions are considered and accounted for, this discharge could only be from either continuing extraction by plantations, and or, a continuing loss to the confined aquifer, which has been previously discussed in Section 5.8.

It is also noted that the water level decline under the current plantation forest estate is positioning the water table at depths deeper than that observed just prior to the 1983 bushfire when the mixed aged plantation forests occupying the same area were destroyed. The structural difference between the current estate and that existing at the time of the fire, is the current plantation is known to have a relatively compressed age profile. While there is no detail on the forest existing at 1982, it is believed it was more typical of a mixed aged estate with a wide age to area distribution. If this was the situation, this would likely result in forest hydrological impacts prior to 1983, being annually less than what is currently occurring, as there would be areas being clear-felled and replanted, in most years. A mixed aged estate results in some recharge and less than maximum aggregate forest extraction due to the estate containing areas of immature trees which provide some recharge with no extraction, while other areas, while not providing recharge will not have reached maximum extraction activity.

The forest industry data for Nangwarry, as at December 2014, does not indicate any significant areas of harvested and replanted plantations on those areas established after the fire, consequently, the site remains to be occupied by plantations, although having mixed ages, they are generally compressed into a 10-year range, as opposed to a full 30 to 35-year range for an truly mixed age plantation forest estate. Therefore, it is likely that most of the current forested areas would be at, or near, maximum levels of groundwater extraction, compared to what existed prior to the 1983 fire. The hydrographs for both sites indicate a declining water table, beyond that apparent prior to the 1983 fire (refer to Figure 2.4), but it is not clear what share of the declining levels can be attributed to the interaction between the confined and unconfined aquifers in this general area. However, it could be postulated that as NAN012 was showing a relatively stable water table pre-fire, there was some equilibrium or separation between the two aquifers at that site at that time, indicating that the ongoing current decline is largely due to plantation groundwater extraction.

Pre-fire, the NAN009 site was exhibiting an ongoing groundwater level decline and this may be an indication on an ongoing connection with the confined aquifer, as well being subjected to plantation extractions, while the water table at NAN012 was relatively stable (refer to Figure 5.34). The NAN009 and NAN012 calculations with the suggested 2017 forest water accounting model (as per Figures 6.2 and 6.4) present a reasonably stable predicted water table in the later years (since about 2002), indicating there is some degree of accounting stabilisation, albeit strongly negative. While not conclusive, this suggests that the continuing water decline at NAN009 is mainly due to the connection between the two aquifers. The water table stability in the period from 1985 to about 1993 may be a result of the total recharge to the unconfined aquifer being at, or close to, some point of balance with the transfer to the confined aquifer.

In considering the actual estimated depth to the water table below ground level across the 5000 ha study site, the standing water level at NAN012 translates into the water table at about 13 metres, or less, below ground level across a large percentage of the study site area. In 1990, this would have translated into much of the area having a water table about 10 metres, or less, below ground level. This is concluded by aligning data from a digital elevation model with data from an available 1990 regional groundwater contour. This is illustrated in **Figure 6.10**.

Testing a 10 metres extinction hypothesis for the two Nangwarry sites, returns a higher correlation than the 6 metres extraction extinction policy in the water allocation plan. On balance, the application of the water-mass-balance approach, indicates plantation forests are extracting groundwater at Nangwarry from depths in the order of 10 metres, or more, below ground level.

While establishing an artificial extinction depth of 10 metres (or hypothesis) may appear a ‘coarse’ approach, it allows for site variations in respect to geophysical variability in soil characteristics and any ‘tapering’ of groundwater extraction, as the water table level declines towards a point of total extinction of groundwater extraction by plantation forest. This approach is consistent with the approach adopted by Benyon and Doody (2004) in specifying a depth at which extraction occurs, when they included a restrictive ‘hard’ pan layer into their conclusions.

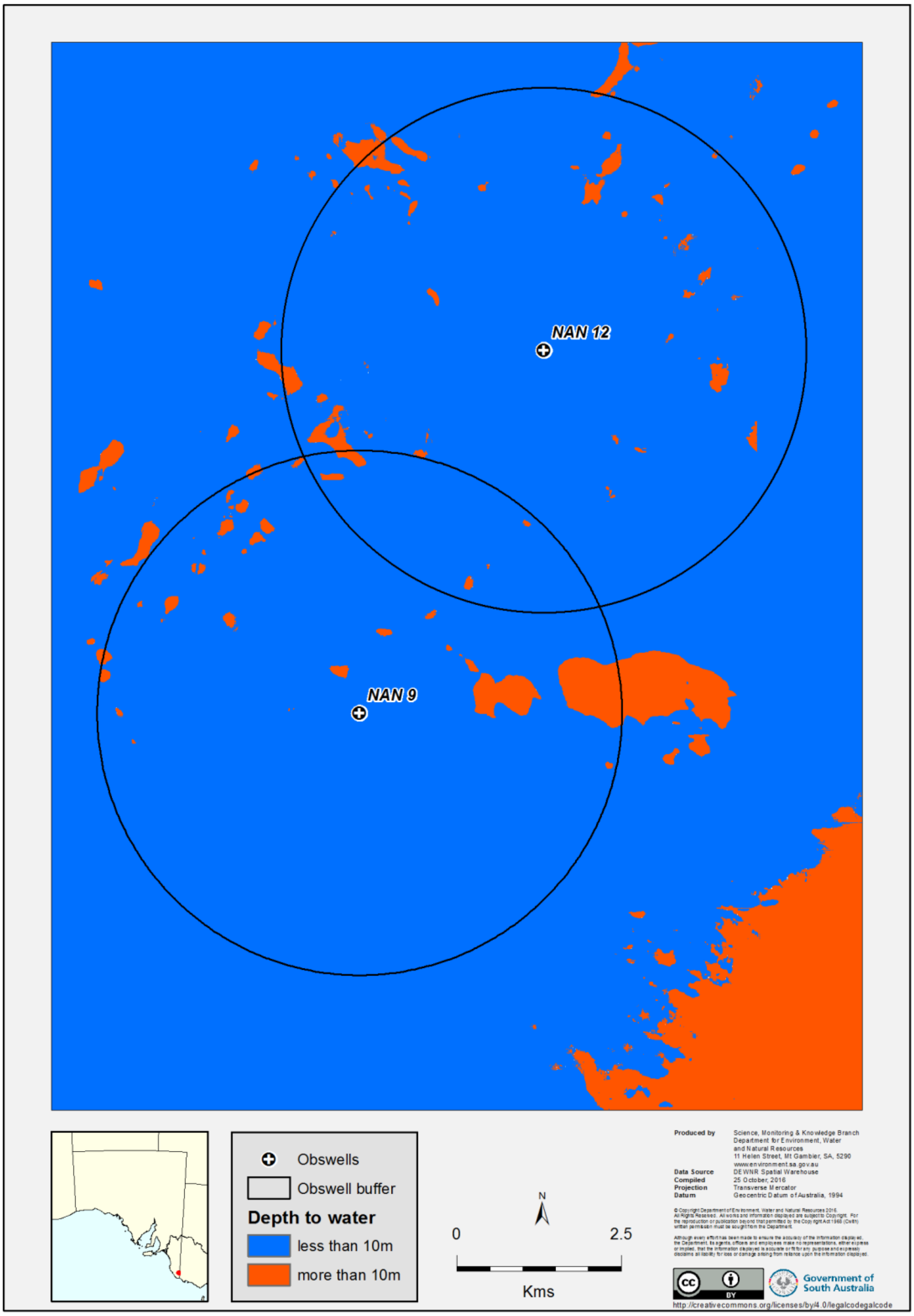


Figure 6.10: Depth to the water table in 1990 at Nangwarry forest sites

6.4 Age structure of hardwood plantations and hydrological consequences

The age structure of the regional hardwood plantation forest estate has been described in Section 2.5 and there is no clear indication from the industry on the future management approach to the age of clear-felling and the subsequent reforestation. Under these circumstances, discussion is confined to the form of the estate at December 2014, and as per the age classes summarised in Table 2.1.

Adopting the principles applied in the 2006 forest water model, the impact on groundwater recharge by extending the hardwood plantation rotation length beyond 10 years is presented in **Table 6.2** for each age class up to 19 years (the oldest age class at December 2014). Discussion in this section is based on 2006 forest water model parameters and the assumptions associated with that model.

From the data presented in Table 6.2, increasing the clear-felling age beyond 10-years results in an aggregate reduction in recharge under the hardwood plantation forest estate to that expected. For a 15-year rotation, the result for the largest age class area (23 per cent of the 2014 estate), is the annualised recharge is reduced to 69 per cent of that budgeted for when the hardwood plantation forest estate was expected to operate a 10-year rotation (as proposed by the industry in 2006).

Table 6.2: Comparison of annualised recharge values for different hardwood forest rotation lengths

Planting to clear fell	Water accounting period	Planting to canopy close	Area recharge rate	Recharge rate at planting time	Recharge pre canopy close	Total recharge for rotation	Annualised recharge under plantation	Recharge as % of 2006 model
yr	yr	yr	mm/yr	% of MARR	mm	mm	% of MARR	% of budget value
10	11	3	100	120	240	240	21.8	100%
11	12	3	100	120	240	240	20.0	92%
12	13	3	100	120	240	240	18.5	85%
13	14	3	100	120	240	240	17.1	79%
14	15	3	100	120	240	240	16.0	73%
15	16	3	100	120	240	240	15.0	69%
16	17	3	100	120	240	240	14.1	65%
17	18	3	100	120	240	240	13.3	61%
18	19	3	100	120	240	240	12.6	58%
19	20	3	100	120	240	240	12.0	55%

The blue shaded row shows calculations for values adopted by the *Water Allocation Plan for the Lower Limestone Coast Water Prescribed Wells Area* (2013) for hardwood plantations. The tan shaded row is the largest single age class in the hardwood plantation estate at December 2014.

In addition to the reduction in annualised recharge, groundwater extraction can be expected to continue at maximum levels in hardwood plantations. The water allocation plan has budgeted for an annualised extraction rate of 1.82 ML/ha/year for an average hardwood plantation rotation length of 10 years and licensed allocations and property rights have been granted on this premise.

Using the same principles and parameters applied in the 2006 groundwater forest model, the extraction calculations for plantations of various ages is presented in **Table 6.3**. The data indicates a 15-year old hardwood plantation extracts a total of 38.22 ML during its life, compared to 20.02 ML for a 10-year rotation plantation. Expressed as an annualised rate, it represents 2.39 ML/ha/year, compared to the budgeted deemed value of 1.82 ML/ha/year; an increase of 31.3 per cent over the budgeted annualised value for a 10-year rotation.

Table 6.3: Comparison of extraction values for different hardwood plantation forest rotations

Hardwood plantation groundwater extraction (ML/ha) aggregate and annualised volume vs rotation period from planting to clear felling: yrs										
Age: years	10	11	12	13	14	15	16	17	18	19
1-3	0	0	0	0	0	0	0	0	0	0
4	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91
5	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82
6	2.73	2.73	2.73	2.73	2.73	2.73	2.73	2.73	2.73	2.73
7	3.64	3.64	3.64	3.64	3.64	3.64	3.64	3.64	3.64	3.64
8	3.64	3.64	3.64	3.64	3.64	3.64	3.64	3.64	3.64	3.64
9	3.64	3.64	3.64	3.64	3.64	3.64	3.64	3.64	3.64	3.64
10	3.64	3.64	3.64	3.64	3.64	3.64	3.64	3.64	3.64	3.64
11		3.64	3.64	3.64	3.64	3.64	3.64	3.64	3.64	3.64
12			3.64	3.64	3.64	3.64	3.64	3.64	3.64	3.64
13				3.64	3.64	3.64	3.64	3.64	3.64	3.64
14					3.64	3.64	3.64	3.64	3.64	3.64
15						3.64	3.64	3.64	3.64	3.64
16							3.64	3.64	3.64	3.64
17								3.64	3.64	3.64
18									3.64	3.64
19										3.64
Total ML/ha at age	20.02	23.66	27.3	30.94	34.58	38.22	41.86	45.5	49.14	52.78
Annualised: ML/ha/yr	**1.82**	1.97	2.10	2.21	2.31	2.39	2.46	2.53	2.59	2.64
% increase extraction above adopted rate		**8.3%**	**15.4%**	**21.4%**	**26.7%**	**31.3%**	**35.3%**	**38.9%**	**42.1%**	**45.0%**

While not appearing to be significantly older than the intended 10-year rotation, it is calculated that on an annualised basis, a 13-year rotation extracts 10.92 ML/ha more during its life than a 10-year rotation, or an additional 21.4 per cent more than the 10-year rotation.

From a holistic groundwater accounting perspective, at a management area scale, the issue relates to the lack of 'pauses' in water demand associated with longer forest rotations and reduced reforestations phases. Coppicing results in a minimal pause in water demands as there is likely to be no recharge gain after felling and groundwater extraction recommences in a shorter period of time after clear felling the first rotation. Overall, the extended rotation life results in reduced recharge across the hardwood plantation estate and a maintenance of continuing extraction by the longer rotations, particularly when incorporated with coppice regeneration for second rotations.

Apart from the increased extraction and reduced recharge, a significant factor is the age bias, due to no consistent program of clear-felling and replanting of the area. If there was no reduction in the total forested area, but there was a uniform distribution of age classes, there is a consistent area providing some recharge and areas of reduced extraction (and no extraction), combining to provide a more uniform hydrological impact across the forest estate. The current forest age structure results in significant peaks in annual hydrological impacts due to the lack of a normally distributed aged hardwood plantation forest estate.

6.5 Age structure of softwood plantation and hydrological consequences

From the age data associated with Figure 2.6, it can be concluded the average age of trees in the regional softwood estate, at the time of clear felling is in the order of 32 to 33 years. In the absence of specific industry data, but based on historic activities, it is estimated that the number of thinning operations undertaken on a forest compartment clear felled at 32 or 33 years of age is likely to be about three times during that life time.

In applying the principles of the 2006 forest water model, a range of forest management strategies have been analysed for assumed groundwater recharge impacts for different thinning regimes for forest compartments clear felled in the 32 to 33-year age category; these are presented in **Table 6.4**. In addition, several extreme alternative possibilities are included to indicate the possible impacts on recharge for any significant deviation from the industry's 2006 advised average age at clear felling of 35 years with four thinning operations. All calculations in Table 6.4 are based on a management area recharge rate of 100 mm/year on grassland and the general principles and parameters applied in the 2006 forest water accounting model.

The softwood industry's characterised average plantation rotation of 35 years, with four thinning operations, is presented in the shaded row in the table. From the annualised recharge under plantation values presented in the last column of the table, it can be seen that many of the recharge values for the different forest management approaches are close to the characterised average forest, with the variability being either side of the adopted deemed recharge value.

Table 6.4: Recharge impacts of various softwood plantation management approaches

Planting to clear fell period	Water accounting period	Thinning operations	Management area recharge rate (MARR)	Recharge rate at planting time	Planting to canopy close	Aggregate recharge pre canopy close	Recharge attributed to thinning	Total recharge for rotation	Annualised recharge under plantation
years	years	number	mm/yr	% of MARR	years	mm	mm	mm	% of MARR
28	29	2	100	120	6	420	100	520	17.9
32	33	3	100	120	6	420	150	570	17.3
32	33	4	100	120	6	420	200	620	18.8
33	34	3	100	120	6	420	150	570	16.8
33	34	4	100	120	6	420	200	620	18.2
35	36	3	100	120	6	420	150	570	15.8
35	**36**	**4**	**100**	**120**	**6**	**420**	**200**	**620**	**17.2**
37	38	3	100	120	6	420	150	570	15.0
37	38	4	100	120	6	420	200	620	16.3
38	39	5	100	120	6	420	250	670	17.2
42	43	5	100	120	6	420	250	670	15.6
Average annualised recharge impact for plantations clear felled between 32 and 33 years of age is									17.8
Average annualised recharge impact for plantations clear felled between 28 and 37 years of age is									17.0

The conclusion from the age analysis of the current softwood plantation estate, as presented in Figure 2.7, is the most of the softwood plantation forest estate is clear felled at an age between 28 and 37 years and if the thinning strategy is consistent with historic trends, the clear-felled plantations are likely to have been thinned up to three to four times. Based on these assumptions, the average annualised recharge under these plantation scenarios is 17.0 per cent of that occurring on the agricultural landscape in the same groundwater management area, compared to the adopted value of 17.2 per cent for a 35-year rotation with four thinning operations. It is also noted that the annualised recharge rate for the suggested 2017 forest water accounting model is of similar order at 17.4 per cent.

This analysis indicates that although the management of softwood forests can vary in respect to the forest thinning regime, if the age at the time of clear felling is in the 28 to 37-year range, there is not a significant variation in annualised recharge impacts within the current softwood plantation forest estate.

As it can be concluded that the current softwood plantation estate practises are similar to the characterised ’average’ softwood plantation forest, it can also be assumed that extraction impacts are reasonably aligned with the 2006 forest water model, as demonstrated by Figure 6.1.

From an administrative perspective, for both the forest manager and the groundwater regulator, it would appear that the principles incorporated into the forest water model, as it applies to softwood plantations is sufficiently robust for the intended purpose, if the parameters applied in the model are relatively representative of the operating environment. If the extraction parameters are adjusted to those proposed in the 2017 revised model, the annualised extraction would be raised from 1.66 ML/ha/year to 1.84 ML/ha/year, an increase of about 11 per cent.

6.6 Impacts of plantation forest on groundwater recharge

While unable to be tested, due to all sites having water tables at depths which are accessible to the plantations, water-mass-balance calculations suggest that if an unconfined aquifer was receiving minimal annual recharge and it was at a depth that made it not accessible for plantation forest extraction, the net water-mass-balance would remain in a positive position. Hence, while the overlying forest would be contributing to the local water-mass-balance, with all other factors being held constant, it would not cause a significant lowering of the water table.

This is demonstrated in **Table 6.5** which summarises a theoretical softwood plantation over a rotation length of 35 years and the harvested compartments are reforested approximately 12 months after harvesting. In this theoretical forest, the annual area of clear fell is 100 ha per year, which would be consistent for the forest estate being managed as a mature industry. From data implicit in the five forested study sites, it is reasonable to speculate that fire breaks and roads account for about 15 per cent of the total area studied where plantation forest occupies about 80 per cent of the area and native vegetation accounts for about 5 per cent which is not considered to provide any recharge. The mean annual rainfall is assumed to occur each year, and for demonstration purposes, a net annual recharge of 100 mm is applied. This example is tested with both the 2006 and 2017 forest water accounting models for softwood plantation forests.

This analysis assumes no other groundwater extractions, for irrigation and other industrial applications. This becomes a broader-scale management issue if groundwater is to be managed to maintain stable water table trends when other anthropogenic discharges are incorporated.

From the analysis undertaken and the results presented in Chapter 5, the water-mass-balance graphs indicate that the annual rainfall trends are visibly reflected in the water table where the main land use is grassland.

Table 6.5: Recharge impacts of a softwood forest if managed as a compliant plantation

Example softwood forest estate land use: recharge impact only							
(management area recharge rate = 100 mm/yr)							
The following describes and accounts for the annual landscape if a 3500 ha softwood plantation is managed as a fully compliant forest with a 35 year rotation cycle from planting to clear felling, resulting in 100 ha of annual clearfell and 100 ha per year of replanting. From data observed at the Nangwarry study sites, this theoretical 3500 ha forest estate would be comprised of 100 ha forest compartments and accompanied by the following listed land use areas:							
land use		area: ha	% of area				
roads and fire breaks		656.25	15%				
natve veg		218.75	5%				
plantation forests		3500	80%				
total area: ha		4375					
annual forest replant		100	2.3%				
rates from suggested revised forest water model				**rates from 2006 forest water model**			
	recharge factor				recharge factor		
grassland	1.00	ML/ha	656.25	grassland	1.00	ML/ha	656.25
forest stage				forest stage			
yr1	2.00	ML/ha	200	yr1	1.20	ML/ha	120
yr2	1.60	ML/ha	160	yr2	1.00	ML/ha	100
yr3	1.20	ML/ha	120	yr3	0.80	ML/ha	80
yr4	0.80	ML/ha	80	yr4	0.60	ML/ha	60
yr5	0.40	ML/ha	40	yr5	0.40	ML/ha	40
yr6	0.00	ML/ha	0	yr6	0.20	ML/ha	20
1 thin yr	0.25	ML/ha	25	yr12,18,24,30	0.5	ML/ha	200
total forest recharge		ML	625	**total forest recharge**		ML	620
total grassland recharge		ML	656.25	**total grassland recharge**		ML	656.25
total recharge on 4375 ha		ML	1281.25	**total recharge on 4375 ha**		ML	1276.25
average recharge per ha		ML/ha	0.293	**average recharge per ha**		ML/ha	0.292

The above data indicates that the water-mass-balance remains in a steady state with a positive balance if the forest is managed in accordance with the ‘mature’ industry approach and there is no forest extraction of groundwater.

While recharge from rainfall is important, the recharge impact is generally muted where there is plantation forest land use overlaying a shallow water table and the plantations are extracting groundwater, as the extraction is a much larger component in the total net water-mass-balance.

6.7 Significance of groundwater extractions by plantations

From the five-study site net annual water-mass-balance calculations, the discharge component, which is significantly influenced by plantation extractions, is the dominant component in the calculation string. Given that there is always a recharge component associated with plantation forest management, whether it is on the firebreaks that accompany a plantation, or in the reforestation phase of a mixed age plantation estate, it is the extraction by plantation forests that significantly drives the discharge or the negative side of a water-mass-balance of a groundwater resource where plantation forest is the predominant land use and the water table is at a shallow depth. This assumes no significant additional extractions by pumping contributing to the discharge side of the water-mass-balance calculation.

The annual extraction volumes applied in the 2006 forest water accounting model (annualised for hardwood and softwood plantations at 1.82 and 1.66 ML/ha year respectively) apply to a region where the mean annual rainfall generally ranges from about 600 to 800 mm. In considering the benefit of plantation forests having access to shallow groundwater for extraction, in addition to the natural rainfall, it could be reasoned that this access to groundwater could be equivalent to similar plantation types being grown in an area where the annual rainfall is of the order of about 1200 mm and there is no access to groundwater.

This reasoning is set out below, using data and assumptions that are relevant to the Lower Limestone Coast region. While the following may not be strictly correct in the field, it is presented to establish some concept of magnitude.

The starting position givens are a land area receiving a mean annual rainfall of 650mm provides about 150mm of groundwater recharge on grassland; both these values are typical of Wattle Range area that is the location of most of the regional hardwood plantation estate. Forest land use at such sites extracts groundwater in the order of up to 364 mm per annum (Harvey 2009), this being the order of peak extractions by hardwood and softwood in the Lower Limestone Coast region.

Assuming a stable typical Mediterranean climate with adequate soil capacity to store water and adopting a principle that about 70 percent of total rainfall can be used by a plantation forest, an additional annual rainfall of 520 mm would be required to offset the 364 mm of annual extraction (364/0.7). For an area where there is no groundwater access, this would then require an annual rainfall of an order of 1170 to 1320 mm per year to provide similar access to total water by a plantation in Lower Limestone Coast region that has access to groundwater. While the processes and outcomes are dependent on-site factors, it could be generalised that the extraction of groundwater by plantation forests in the Lower Limestone Coast region provides a similar hydrological benefit to that available to plantations receiving nearly twice the annual rainfall (but without access to groundwater) of the Lower Limestone Coast.

6.8 Appropriateness of annualised accounting

As forest water licensed allocations are a transferable property right, there is a need to have reporting and compliance processes parallel with accounting transparency. The current annualised forest water accounting was developed to meet such criteria (Avey and Harvey 2014).

Annualised accounting of plantation forest hydrological impacts was incorporated into in the regional groundwater management program as a way to minimise annual reporting and compliance demands. It was based on the principle that the plantation forest estate would be managed generally in accordance with a characterised ’average’ plantation forest by a ‘mature’ industry. This has occurred within the softwood plantation estate, but not for the hardwood estate in the Lower Limestone Coast region.

The analysis undertaken in this study, over about 25 000 ha, through the net annual water-mass-balance accounting approach, has demonstrated that the annual components of the forest water accounting model align reasonably well with actual hydrological impacts of plantation forests in the field. For annualised accounting to provide an appropriate scoring system of what is actually occurring in the wider landscape (at a groundwater management area scale), the regional plantation forest estate needs to be managed in line with the characterised ’average‘ forest incorporated in the forest water accounting model. This is more important where the plantations overlay shallow water tables and extraction is occurring, resulting in a significant impact on the local water-mass-balance, as demonstrated earlier in this thesis.

The forest water accounting model can be adapted to different forest management systems, but the integrity of the forest water accounting system is dependent on whether the actual forest management occurring in the forest estate is consistent with the forest management proposed and incorporated into the forest water accounting model parameters. Too much deviation of the actual forest estate management from that proposed could be considered a potential compliance matter.

In the case of the softwood plantations, it has been demonstrated in Section 6.5, that the model has a reasonable degree of flexibility with respect to departure from the 2006 characterised average forest management. For the hardwood industry, the actual departure from the 2006 characterised average forest management regime is significant and as a consequence, hydrological impacts are significantly greater than intended. However, as demonstrated by the softwood industry, adherence does lead to a simple accounting and management system through the annualised accounting that minimises reporting and compliance burdens on both the forest managers and the water resource manager.

The disparity between the two accounting systems, between the two forest types is illustrated in **Figures 6.11** and **6.12** where the annualised accounting is compared with annual accounting at the softwood site of NAN012 and the hardwood site of MON016. In the case of the softwood site, the ‘over’ accounting in the early stages of annualised plantation accounting is balanced by the under-statement (and general convergence) in the later stage of the plantation. In the case of the hardwood example, the disparity continues to widen as the plantation ages, this being attributed to the age profile with an extended rotation length in the hardwood plantations.

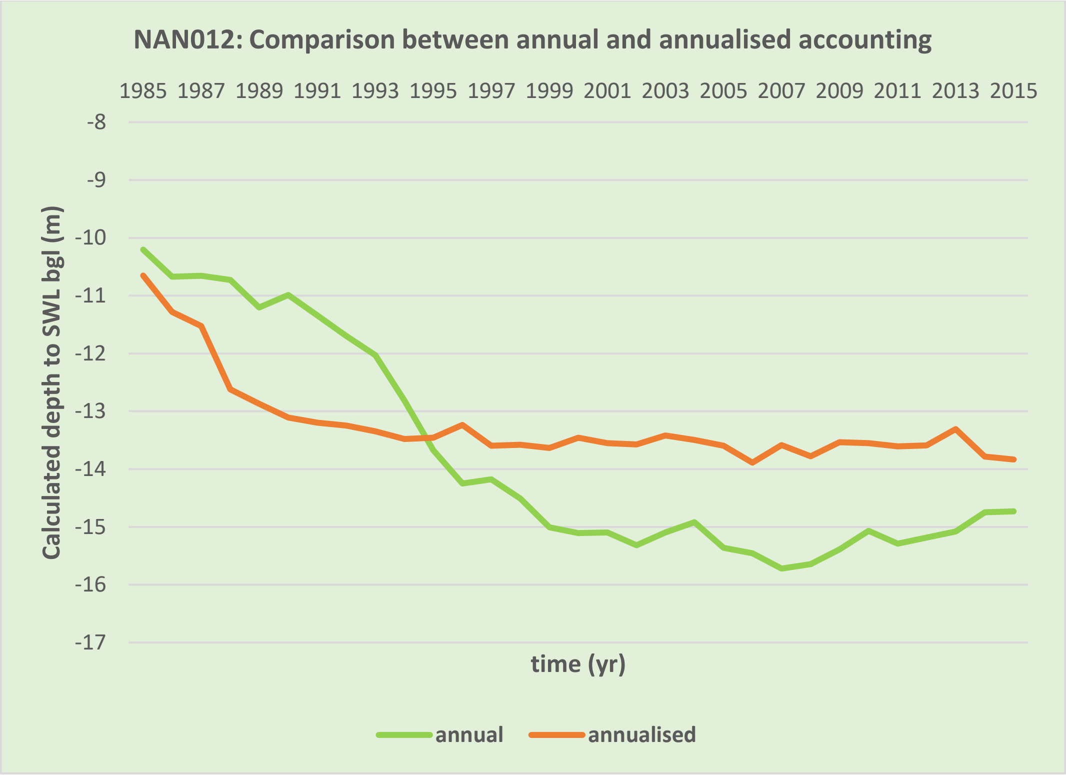


Figure 6.11: NAN012 a comparison between annual and annualised accounting of forest land use

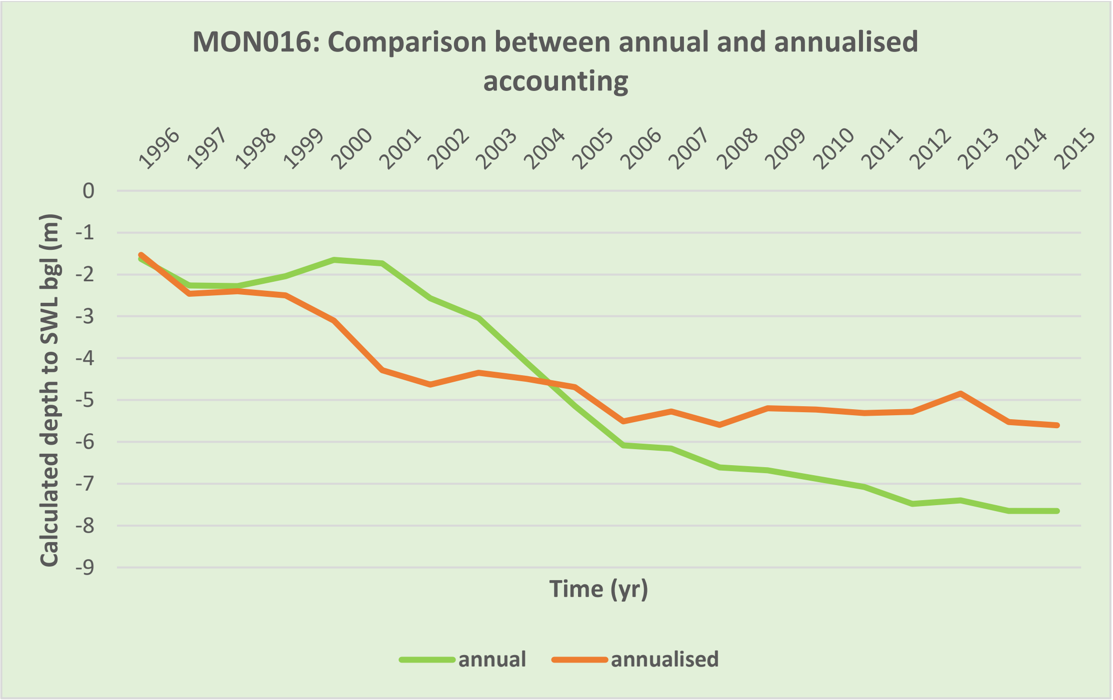


Figure 6.12: MON016 a comparison between annual and annualised accounting of forest land use

7 Summary and conclusions

This thesis has attempted to test or validate the 2006 forest water accounting model that has been incorporated into the 2013 Water Allocation Plan for the Lower Limestone Coast Prescribed Wells Area. The 2006 forest water accounting model is based on biophysical principles with support from research observations and finalised with a degree of negotiation with the plantation forest managers and other key stakeholders. Without any testing, the model output has determined the granting of licensed forest allocations, totalling about 308 GL, to account for the hydrological impacts of the plantation forest estate existing at the time of proclamation.

The scale at which the model is intended to account for plantation forest impacts on groundwater recharge, and groundwater extraction where the plantations overlay shallow water tables, is at a groundwater management area scale. It is also intended to operate in a forest management environment in which there is a recognised industry 'average' forest, but with some scope for variation in management around the average forest, with respect to clear felling age, and thinning regime in the case of softwood plantations.

The notion of adopting annualised accounting for plantation forests has a number of administrative benefits. The relative accuracy is dependent on the plantation forest estate being managed in reasonable alignment with the characterised average plantation management system incorporated into the forest water accounting model and the model incorporating appropriate parameters.

This thesis has applied a time-trend analysis to a relatively large area, where plantation forests are a predominant land use, using existing data for after-the-fact analysis (Zhang *et al* 2010). From this broad scale analysis, the 2006 forest water accounting model would appear to be relatively robust in accommodating natural variability within the hydrogeological settings in which it is intended to operate.

From the investigation conducted over 25 000 ha, and the subsequent analysis, it is clear that plantation forests have a significant net impact on the local shallow groundwater resource (where SWL ≤ 10 m). At all of the studied 5000 ha forested sites, the plantation forest land use has resulted in a drawdown in the order of 2 to 4 metres over a 30 to 40-year period, whereas, the grassland sites in the same areas, other than reflecting some seasonal rainfall impacts, have maintained relatively steady groundwater levels over the same period. The timing of the decline in the water tables at the forested sites aligns the change in land use from grassland to plantation forest land use and the growth development of those forests.

In the case of the Wattle Range forested study sites, there is close visual alignment between the projected depth to the water table and the observed depth to the water table. The directional trends are consistent, albeit the rate, or the trajectory of the trends may not be necessarily mirrored between the calculated and observed depth to groundwater. Some of the differences may be the result of a difference in storage coefficients, as discussed in Section 5.7. While there is some visual difference in the trend rates, the statistical analysis of correlation is generally high, with coefficient of determination R^2 values being generally in the range of low to mid 0.90s.

A significant finding in applying the water-mass-balance analysis approach at a 5000 ha scale, is softwood plantation forests, can extract groundwater from depths in the order of 10 metres below ground level. While the current policy is that plantation forests only extract groundwater where the water table is 6 metres, or less, at June 2004, this 10-metre extraction depth finding should be considered in groundwater technical investigations and groundwater modelling to minimise the risk of compromised technical findings and advice.

The interaction between the confined and unconfined aquifers has interfered with the softwood water-mass-balance calculations at the Nangwarry sites, but while this has occurred, the model has still demonstrated a high level of accuracy in predicting the hydrological impacts of the studied plantation forests.

Coppicing of the harvested compartments was not intended by the hardwood plantation forest industry as the method by which to establish the next forest rotation, but there is emerging evidence that coppicing is currently the preferred approach to introducing a second forest rotation. The reason is not clear, it may be for compliance reasons, or related to the existing terms and conditions for the many land leases in place for this forest sector, rather than for practical forestry management reasons. In addition, the rotation length is significantly longer that the 10-year rotation proposed by the industry.

While the current model is found to be relatively robust, improved predictability values could be achieved with a small increase in the annual recharge values leading up to canopy closure of softwood plantations and a small increase in extraction rates for softwood plantations during the later stages of the forest rotation.

Improved visual alignment between the predicted and observed changes in groundwater storage could be improved for some sites by varying the storage coefficient away from the 0.1 value adopted by the regional water allocation plan.

While the amount of rainfall is a significant factor in contributing to diffuse groundwater recharge, the outcome of analysing the relationship between annual rainfall and rainfall in the May-October period has returned R^2 values in the order of 0.35. This would suggest that other factors associated with rainfall and the observation of water table fluctuations are likely to be interacting. An apparent weakness may be the lack of sufficient data for determining the upper and lower water table levels in any one year. Associated with this is likely to be the sequence and form of rainfall events.

Any revision of the forest water accounting model, or the description of the 'average' characterised forest management of the forest life cycle should be done collaboratively between the water and forest managers to ensure that the forest life cycle being modelled, adequately reflects the general range of forest management activities in the field.

As a result of conducting a series of water-mass-balance studies over extensively forested areas, with the results presented and discussed in this thesis, the 2006 forest water accounting model can be considered fit for its intended purpose, that being for the accounting of the hydrological impacts of plantation forest on groundwater resources in the lower South East of South Australia.

New knowledge could help refine the existing forest water model. However, whilst the current model appears to be robust, increased transparency and confidence should be prerequisites for incorporating any changes. The areas in which improved knowledge could be of significance is the threshold depth at which groundwater extraction by plantation forests ceases. In addition, if coppicing is to be a significant management approach in hardwood forest management, testing the extraction characteristics of coppiced plantations compared to replanted forests may be an important point of knowledge. In the case of softwoods, improved clarity about extraction characteristics as the plantation ages and undergoes thinning may provide for some refinement in the forest water accounting.

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9 Appendices

(To aid relationship with the main text, appendices are prefaced by chapter number)

Appendix 2a

Sample of mean rainfall at BOM sites across the Limestone Coast region

Location	BOM station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Mount Gambier	26021													
	long term mean (1942)	27.2	25.6	35.3	54.9	70.8	84.4	99.6	95.8	71.9	61.3	46.5	38.4	**710.9**
Tantanoola	26027													
	long term mean(1950)	27.9	22.3	36.6	58.3	81.5	103.3	119.0	112.3	79.1	56.7	47.0	40.6	**784.2**
Lake Leake	26014													
	long term mean (1892)	30.0	27.6	38.5	65.7	89.1	105.7	118.7	113.3	87.1	67.3	46.9	42.7	**833.9**
Kalangadoo	26009													
	long term mean (1915)	28.7	26.2	33.8	55.3	76.0	90.6	105.2	100.0	78.3	61.4	46.8	37.7	**741.8**
Penola	26025													
	long term mean (1861)	26.6	22.1	30.7	47.2	68.4	82.2	88.3	87	70.8	56.5	40.6	35.4	**657.2**

Rainfall history at Penola BOM26025

Appendix 4a

Penola Monthly rainfall data 1970 - 2015 BOM station 26025					Red month data indicates some missing data. Mean data applied.									Rainfall variation factor about a period mean: period mean =1.0	
year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**	May-Oct period	annual period
1970	29.7	2.0	38.2	68.0	65.6	74.6	109.6	157.7	42.3	22.6	70.6	51.5	**732.4**	1.07	1.14
1971	10.7	6.2	31.5	121.5	91.8	112.5	51.4	119.5	77.4	83.0	73.8	63.7	**843.0**	1.21	1.31
1972	69.5	28.2	1.4	68.3	33.4	61.6	125.8	101.2	31.6	27.6	33.3	1.1	**583.0**	0.86	0.90
1973	28.2	50.9	55.9	64.0	72.0	100.3	64.0	87.4	111.7	51.9	24.2	43.7	**754.2**	1.10	1.17
1974	38.0	37.6	32.8	90.2	38.6	46.0	157.2	77.8	111.4	95.4	29.6	25.0	**779.6**	1.19	1.21
1975	13.6	4.2	56.2	15.0	101.4	39.2	154.6	69.6	77.8	129.4	52.0	25.0	**738.0**	1.29	1.14
1976	10.4	57.8	9.6	34.6	36.8	73.8	37.8	96.4	113.4	59.8	40.0	69.2	**639.6**	0.94	0.99
1977	39.0	23.0	35.2	11.2	96.8	100.6	64.2	44.8	20.6	34.4	125.6	8.2	**603.6**	0.82	0.94
1978	12.4	14.8	11.6	38.8	49.2	44.2	131.8	83.8	58.0	46.4	65.6	20.8	**577.4**	0.93	0.90
1979	14.6	27.0	7.8	37.0	63.4	61.2	76.4	108.6	137.4	83.6	62.6	19.6	**699.2**	1.20	1.08
1980	17.0	2.4	6.6	100.6	53.8	79.4	96.6	61.8	74.6	52.2	30.8	18.0	**593.8**	0.94	0.92
1981	41.4	1.6	36.8	14.2	60.4	114.0	147.6	183.4	34.6	56.8	41.6	6.2	**738.6**	1.35	1.15
1982	23.0	8.2	41.4	53.6	55.6	70.0	44.2	24.8	58.2	21.4	9.2	5.0	**414.6**	0.62	0.64
1983	22.4	0.0	121.4	70.8	76.0	68.8	92.8	88.8	95.0	21.4	78.8	19.2	**755.4**	1.00	1.17
1984	29.4	3.0	60.4	28.4	39.2	62.8	132.0	144.8	111.2	26.0	84.6	26.4	**748.2**	1.16	1.16
1985	9.8	4.6	27.8	32.8	81.6	62.6	75.0	101.4	32.4	64.6	55.4	73.6	**621.6**	0.94	0.96
1986	12.8	1.6	3.2	72.4	49.8	35.4	110.2	68.2	60.0	97.6	14.6	115.0	**640.8**	0.95	0.99
1987	6.2	18.6	17.0	14.8	145.4	77.0	83.2	44.8	21.8	56.0	22.8	37.6	**545.2**	0.97	0.85
1988	52.2	29.2	44.0	18.6	96.2	107.8	102.2	83.8	93.8	58.0	45.4	33.8	**765.0**	1.22	1.19
1989	20.8	8.0	16.8	55.6	69.2	113.6	124.8	119.4	59.3	70.1	11.6	22.4	**691.6**	1.26	1.07
1990	5.6	9.2	8.6	14.8	15.6	94.2	129.4	130.2	75.8	38.4	34.6	23.6	**580.0**	1.09	0.90
1991	67.6	0.0	27.6	46.0	5.2	156.8	70.6	158.0	86.8	8.4	45.4	10.6	**683.0**	1.10	1.06
1992	5.8	11.8	37.0	102.2	54.1	65.9	99.4	121.8	115.0	81.8	87.8	65.0	**847.6**	1.21	1.31
1993	38.6	28.0	13.6	4.6	52.6	69.4	91.9	78.6	102.1	74.6	16.0	62.0	**632.0**	1.06	0.98
1994	37.4	20.4	0.4	14.0	80.2	73.2	83.8	46.6	41.2	50.4	51.8	18.4	**517.8**	0.85	0.80
1995	50.2	16.8	15.8	88.8	57.0	63.2	155.8	44.6	47.4	24.0	16.0	19.8	**599.4**	0.88	0.93
1996	59.4	15.4	21.4	34.6	2.4	140.4	108.4	137.0	111.0	45.2	9.6	26.2	**711.0**	1.23	1.10
1997	31.4	12.8	19.2	12.4	105.4	26.6	35.4	66.0	107.0	27.3	79.4	5.6	**528.5**	0.83	0.82
1998	20.3	16.0	10.6	67.6	34.4	83.8	89.0	43.2	78.0	51.4	16.4	15.6	**526.3**	0.86	0.82
1999	5.8	26.0	53.8	6.8	85.4	81.7	38.6	54.2	70.8	29.0	54.4	88.4	**594.9**	0.81	0.92
2000	5.2	27.2	13.2	68.2	86.4	68.6	88.2	54.4	120.0	66.4	60.0	13.4	**671.2**	1.09	1.04
2001	8.2	23.8	85.6	38.0	41.8	73.2	28.6	126.8	83.0	81.0	57.4	42.4	**689.8**	0.98	1.07
2002	17.8	11.8	8.6	18.4	43.0	55.2	137.5	52.3	75.6	53.2	41.6	41.4	**556.4**	0.94	0.86
2003	33.6	36.6	62.8	34.2	26.8	184.6	79.4	112.8	61.0	55.6	22.4	20.6	**730.4**	1.17	1.13
2004	20.2	29.8	58.2	29.4	69.2	112.2	88.2	139.0	43.2	17.6	46.6	32.4	**686.0**	1.06	1.06
2005	17.0	37.1	8.6	20.8	17.2	88.6	41.0	97.5	58.2	100.4	26.6	43.8	**556.8**	0.91	0.86
2006	25.4	65.0	24.0	69.6	61.2	13.4	63.2	28.2	43.6	8.6	12.0	20.9	**435.1**	0.49	0.67
2007	100.0	0.0	22.6	24.0	132.8	33.2	81.4	58.6	70.8	43.0	82.8	28.8	**678.0**	0.95	1.05
2008	8.0	14.2	18.4	42.2	44.2	36.8	73.4	77.8	58.4	**8.0**	16.4	106.3	**504.1**	0.67	0.78
2009	1.4	0.0	38.8	69.8	15.2	60.4	121.4	114.6	103.6	53.1	41.8	37.0	**657.1**	1.06	1.02
2010	19.8	35.4	18.0	74.0	52.0	67.8	81.6	126.4	85.4	43.4	32.2	97.0	**733.0**	1.03	1.14
2011	97.2	49.1	88.3	29.4	72.4	81.6	98.5	93.3	33.2	39.8	46.1	33.2	**762.1**	0.95	1.18
2012	7.4	2.9	39.9	27.2	45.8	125.8	71.6	108.8	48.6	30.2	27.7	20.9	**556.8**	0.97	0.86
2013	1.8	25.8	21.8	33.9	55.1	66.6	137.9	157.3	107.3	92.8	31.7	28.7	**760.7**	1.39	1.18
2014	24.0	18.0	35.8	51.0	62.2	115.5	73.9	36.1	23.3	16.0	19.7	29.4	**504.9**	0.74	0.78
2015	110.8	1.7	28.7	34.8	103.1	47.5	61.7	40.8	40.1	1.5	18.5	13.2	**502.4**	0.67	0.78
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**		
mean	**28.7**	**18.8**	**31.2**	**44.9**	**60.8**	**78.1**	**91.5**	**90.7**	**72.0**	**50.0**	**42.8**	**35.4**	**645.0**	**443.1**	**May-Oct**
	3-4 consecutive wet months					**332.4 Jun-Sep**					dry months during May-Oct< 60% of mean				
	wet months: >100 mm					**260.3 Jun-Aug**					wet non seasonal months				
							254.3 Jul-Sep				May-Oct period				

Appendix 4b

Livestock and domestic estimations:

Livestock

Livestock carrying capacity potential is determined by mean annual rainfall. The following formulae provides a robust approach to estimating dry sheep equivalent (dse) carrying capacity. 0.75* (ann. Rainfall-250)/25 = 0.75*(655-250)/25 = 12.15 dse

A dse is estimated to require 6 litres of water a day.

Equates to 0.02187 ML per hectare of pasture/year

Domestic water

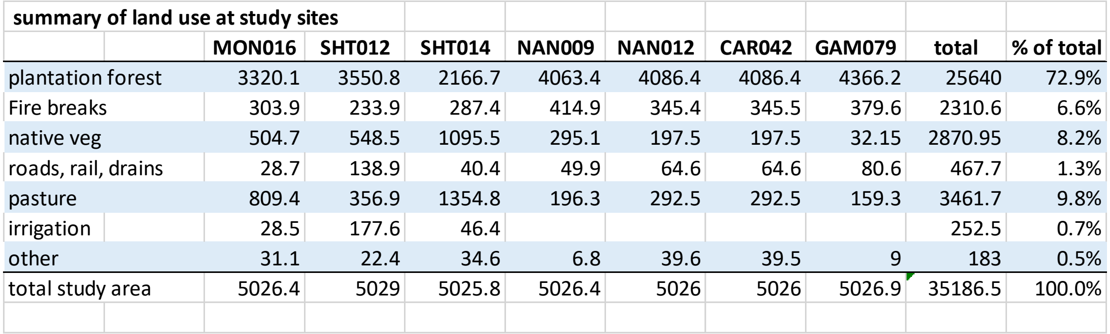
Water resource policy permits a housing living to irrigate up to 0.4 ha. At an irrigation equivalent of 7 ML/ha, this approximates 2.8 ML

Estimates water needs for a domestic house unit is based on about 0.25 ML/year

Total domestic water per dwelling unit is 3.05 ML/year

Appendix 4c

Summary of land use at 5 Lower Limestone Coast study sites



summary of land use at study sites

	MON016	**SHT012**	**SHT014**	**NAN009**	**NAN012**	**CAR042**	**GAM079**	**total**	**% of total**
plantation forest	3320.1	3550.8	2166.7	4063.4	4086.4	4086.4	4366.2	25640	72.9%
Fire breaks	303.9	233.9	287.4	414.9	345.4	345.5	379.6	2310.6	6.6%
native veg	504.7	548.5	1095.5	295.1	197.5	197.5	32.15	2870.95	8.2%
roads, rail, drains	28.7	138.9	40.4	49.9	64.6	64.6	80.6	467.7	1.3%
pasture	809.4	356.9	1354.8	196.3	292.5	292.5	159.3	3461.7	9.8%
irrigation	28.5	177.6	46.4					252.5	0.7%
other	31.1	22.4	34.6	6.8	39.6	39.5	9	183	0.5%
total study area	5026.4	5029	5025.8	5026.4	5026	5026	5026.9	35186.5	100.0%

Appendix 5a

Calculated water-mass-balance values, converted to a depth to the standing water level and autumn water table observations for the forested sites

W-M-B = net annual water-mass-balance as groundwater storage. All values are metres. Alignment value is adjustment to W-M-B to align with calculated (or predicted) standing water level SWL.

	MON016			MON016- mod values			SHT012			SHT014			SHT014- mod values		
	obs SWL	W-M-B	calc SWL	obs SWL	W-M-B	calc SWL	obs SWL	W-M-B	calc SWL	obs SWL	W-M-B	calc SWL	obs SWL	W-M-B	calc SWL
alignment			-4.65			5.31			-3.64			-3.59			3.59
year	observed		predicted	observed		predicted	observed		predicted	observed		predicted	observed		predicted
1976															
1977	-1.99	2.77	-1.88	-1.99	3.45	-1.85									
1978		2.09	-2.56		2.61	-2.69									
1979		2.41	-2.24		3.00	-2.30									
1980	-1.92	3.13	-1.52	-1.92	3.89	-1.41									
1981	-2.03	2.44	-2.21	-2.03	3.04	-2.26				-1.79	1.63	-1.96	-1.79	1.63	-1.96
1982	-1.73	3.53	-1.12	-1.73	4.39	-0.91				-1.73	2.39	-1.20	-1.73	2.39	-1.20
1983	-1.35	1.56	-3.09	-1.35	1.95	-3.35				-1.51	1.01	-2.58	-1.51	1.01	-2.58
1984		2.59	-2.06		3.22	-2.08	-1.66	1.72	-1.92	-1.46	1.73	-1.86	-1.46	1.73	-1.86
1985	-1.86	3.04	-1.61	-1.86	3.78	-1.52		2.09	-1.55	-1.43	2.05	-1.54	-1.43	2.05	-1.54
1986		2.44	-2.21		3.03	-2.27	-1.72	1.59	-2.05	-1.73	1.63	-1.96	-1.73	1.63	-1.96
1987	-1.96	2.46	-2.19	-1.96	3.06	-2.24	-1.93	1.61	-2.03	-1.75	1.64	-1.95	-1.75	1.64	-1.95
1988	-2.00	2.50	-2.15	-2.00	3.11	-2.19	-1.63	1.65	-1.99	-1.77	1.67	-1.92	-1.77	1.67	-1.92
1989	-1.71	3.20	-1.45	-1.71	3.97	-1.33	-1.54	2.22	-1.42	-1.58	2.16	-1.43	-1.58	2.16	-1.43
1990	-1.59	3.29	-1.36	-1.59	4.08	-1.22	-1.61	2.30	-1.34	-1.44	2.22	-1.37	-1.44	2.22	-1.37
1991	-1.68	2.84	-1.81	-1.68	3.53	-1.77	-1.80	1.93	-1.71	-1.69	1.91	-1.68	-1.69	1.91	-1.68
1992	-1.81	2.85	-1.80	-1.81	3.55	-1.75	-1.32	1.94	-1.70	-1.91	1.92	-1.67	-1.91	1.92	-1.67
1993	-1.30	3.17	-1.48	-1.30	3.94	-1.36	-1.66	2.20	-1.44	-1.12	2.14	-1.45	-1.12	2.14	-1.45
1994	-1.99	2.75	-1.90	-1.99	3.42	-1.88	-2.03	1.85	-1.79	-1.73	1.85	-1.74	-1.73	1.85	-1.74
1995	-2.26	2.18	-2.47	-2.26	2.71	-2.59	-2.14	1.38	-2.26	-2.20	1.45	-2.14	-2.20	1.45	-2.14
1996	-2.37	2.28	-2.37	-2.37	2.84	-2.46	-1.85	1.46	-2.18	-2.23	1.52	-2.07	-2.23	1.52	-2.07
1997	-2.06	3.21	-1.44	-2.06	3.99	-1.31	-2.03	2.24	-1.40	-1.99	2.17	-1.42	-1.99	2.17	-1.42
1998	-2.17	2.13	-2.52	-2.17	2.67	-2.63	-2.34	1.36	-2.28	-2.20	1.41	-2.18	-2.20	1.41	-2.18
1999	-2.50	2.20	-2.45	-2.50	2.74	-2.56	-2.43	1.37	-2.27	-2.44	1.47	-2.12	-2.44	1.47	-2.12
2000	-2.52	2.07	-2.58	-2.52	2.58	-2.72	-1.41	1.21	-2.43	-2.58	1.39	-2.20	-2.58	1.42	-2.17
2001	-1.85	2.99	-1.66	-1.85	4.13	-1.17	-1.90	1.60	-2.04	-1.86	1.98	-1.61	-1.86	2.33	-1.26
2002	-2.15	2.50	-2.15	-2.15	3.44	-1.86	-2.62	1.27	-2.37	-1.88	1.63	-1.96	-1.88	1.72	-1.87
2003	-2.78	1.91	-2.74	-2.78	2.14	-3.16	-3.07	0.58	-3.06	-2.25	1.35	-2.24	-2.25	1.25	-2.34
2004	-2.98	1.32	-3.33	-2.98	1.39	-3.91	-3.40	0.24	-3.40	-2.22	1.27	-2.32	-2.22	1.26	-2.33
2005	-2.53	0.11	-4.54	-2.53	0.32	-4.98	-4.08	-1.01	-4.65	-2.19	0.80	-2.79	-2.19	0.83	-2.76
2006	-3.82	-0.93	-5.58	-3.82	-0.69	-5.99	-5.13	-1.81	-5.45	-2.84	0.29	-3.30	-2.84	0.45	-3.14
2007	-4.59	-2.17	-6.82	-4.59	-1.98	-7.28	-5.52	-2.80	-6.44	-3.54	-0.61	-4.20	-3.54	-0.60	-4.19
2008	-4.92	-2.08	-6.73	-4.92	-1.73	-7.03	-5.83	-3.02	-6.66	-3.81	-0.25	-3.84	-3.81	-0.31	-3.90
2009	-5.26	-2.59	-7.24	-5.26	-2.50	-7.80	-5.82	-3.38	-7.02	-4.04	-0.82	-4.41	-4.04	-0.73	-4.32
2010	-5.41	-2.51	-7.16	-5.41	-2.41	-7.71	-5.35	-3.40	-7.04	-4.12	-0.66	-4.25	-4.12	-0.63	-4.22
2011	-5.31	-2.82	-7.47	-5.31	-2.66	-7.96	-5.27	-3.74	-7.38	-3.96	-0.97	-4.56	-3.96	-1.03	-4.62
2012	-5.50	-3.11	-7.76	-5.50	-2.95	-8.25	-5.48	-3.86	-7.50	-4.18	-1.37	-4.96	-4.18	-1.37	-4.96
2013	-5.67	-3.30	-7.95	-5.67	-3.14	-8.44	-5.09	-4.10	-7.74	-4.41	-1.33	-4.92	-4.41	-1.33	-4.92
2014	-5.57	-3.10	-7.75	-5.57	-2.87	-8.17	-5.38	-3.86	-7.50	-4.32	-1.14	-4.73	-4.32	-1.14	-4.73

Appendix 5a (continued)

	NAN009 - no extract			NAN009 - extract			NAN009 ≤10 m 140mm			NAN009 ≤10 m 70mm			NAN009, 10 m, mod valu		
	obs SWL	W-M-B	calc SWL	obs SWL	W-M-B	calc SWL	obs SWL	W-M-B	calc SWL	obs SWL	W-M-B	calc SWL	obs SWL	W-M-B	calc SWL
alignment			-5.07			-5.02						-4.05			-4.19
year	observed		predicted	observed		predicted	observed		predicted	observed		predicted	observed		predicted
1976															
1977															
1978															
1979															
1980															
1981															
1982															
1983															
1984															
1985	-3.23	2.56	-2.51	-3.23	2.56	-3.02	-3.23	1.97	-2.63	-3.23	1.00	-2.95	-3.23	1.17	-3.02
1986	-3.27	2.01	-3.06	-3.27	2.00	-3.11	-3.27	1.54	-3.06	-3.27	0.94	-2.77	-3.27	1.15	-3.04
1987	-3.14	1.94	-3.13	-3.14	1.91	-3.26	-3.14	1.47	-3.13	-3.14	0.85	-3.05	-3.14	1.14	-3.05
1988	-3.25	1.83	-3.24	-3.25	1.76	-3.00	-3.25	1.36	-3.24	-3.25	0.96	-3.11	-3.25	1.26	-2.93
1989	-3.41	2.15	-2.92	-3.41	2.02	-3.28	-3.41	1.56	-3.04	-3.41	0.75	-3.20	-3.41	1.13	-3.05
1990	-2.85	2.01	-3.06	-2.85	1.74	-3.99	-2.85	1.35	-3.25	-2.85	0.29	-3.09	-2.85	0.75	-3.43
1991	-3.00	1.55	-3.52	-3.00	1.03	-4.38	-3.00	0.82	-3.78	-3.00	-0.01	-3.30	-3.00	0.34	-3.81
1992	-3.34	1.40	-3.67	-3.34	0.64	-4.72	-3.34	0.54	-4.06	-3.34	-0.34	-3.76	-3.34	0.05	-4.09
1993	-3.10	1.42	-3.65	-3.10	0.30	-5.50	-3.10	0.29	-4.31	-3.10	-0.92	-4.06	-3.10	-0.41	-4.52
1994	-3.69	1.10	-3.97	-3.69	-0.48	-5.93	-3.69	-0.28	-4.88	-3.69	-1.17	-4.39	-3.69	-1.00	-5.08
1995	-4.24	0.75	-4.32	-4.24	-0.91	-6.22	-4.24	-0.61	-5.21	-4.24	-1.38	-4.97	-4.24	-1.37	-5.43
1996	-4.65	0.63	-4.44	-4.65	-1.20	-6.30	-4.65	-0.82	-5.42	-4.65	-1.55	-5.22	-4.65	-1.53	-5.58
1997	-4.35	0.82	-4.25	-4.35	-1.28	-6.70	-4.35	-0.88	-5.48	-4.35	-1.74	-5.43	-4.35	-1.96	-5.99
1998	-5.35	0.41	-4.66	-5.35	-1.68	-7.17	-5.35	-1.18	-5.78	-5.35	-2.19	-5.60	-5.35	-2.07	-6.11
1999	-5.85	0.43	-4.64	-5.85	-2.15	-7.50	-5.85	-1.51	-6.11	-5.85	-2.51	-5.79	-5.85	-2.33	-6.35
2000	-6.22	0.46	-4.61	-6.22	-2.48	-7.32	-6.22	-1.75	-6.35	-6.22	-2.36	-6.24	-6.22	-2.50	-6.49
2001	-6.32	0.52	-4.55	-6.32	-2.30	-7.70	-6.32	-1.62	-6.22	-6.32	-2.69	-6.56	-6.32	-2.64	-6.63
2002	-6.48	0.45	-4.62	-6.48	-2.68	-7.83	-6.48	-1.89	-6.49	-6.48	-2.85	-6.41	-6.48	-2.90	-6.88
2003	-6.68	0.56	-4.51	-6.68	-2.81	-7.40	-6.68	-1.98	-6.58	-6.68	-2.45	-6.74	-6.68	-3.01	-6.97
2004	-6.87	0.55	-4.52	-6.87	-2.38	-7.66	-6.87	-1.67	-6.27	-6.87	-2.63	-6.90	-6.87	-2.92	-6.89
2005	-6.93	0.42	-4.65	-6.93	-2.64	-7.88	-6.93	-1.87	-6.47	-6.93	-2.86	-6.50	-6.93	-2.83	-6.81
2006	-7.04	0.46	-4.61	-7.04	-2.86	-7.90	-7.04	-2.02	-6.62	-7.04	-2.77	-6.68	-7.04	-2.93	-6.91
2007	-7.28	0.21	-4.86	-7.28	-2.88	-7.91	-7.28	-2.05	-6.65	-7.28	-2.86	-6.91	-7.28	-2.89	-6.87
2008	-7.36	0.40	-4.67	-7.36	-2.89	-7.97	-7.36	-2.05	-6.65	-7.36	-2.93	-6.82	-7.36	-2.97	-6.94
2009	-7.60	0.42	-4.65	-7.60	-2.95	-7.23	-7.60	-2.09	-6.69	-7.60	-2.27	-6.91	-7.60	-2.90	-6.87
2010	-7.69	0.51	-4.56	-7.69	-2.21	-7.34	-7.69	-1.55	-6.15	-7.69	-2.34	-6.98	-7.69	-2.86	-6.84
2011	-7.56	0.43	-4.64	-7.56	-2.32	-7.38	-7.56	-1.63	-6.23	-7.56	-2.41	-6.32	-7.56	-2.88	-6.86
2012	-7.64	0.49	-4.58	-7.64	-2.36	-7.23	-7.64	-1.66	-6.26	-7.64	-2.24	-6.39	-7.64	-2.89	-6.86
2013	-7.83	0.43	-4.64	-7.83	-2.21	-7.20	-7.83	-1.56	-6.16	-7.83	-2.28	-6.46	-7.83	-2.81	-6.79
2014	-7.81	0.60	-4.47	-7.81	-2.18	-7.34	-7.81	-1.52	-6.12	-7.81	-2.34	-6.29	-7.81	-2.93	-6.91

Appendix 5a (continued)

	NAN012-no extract			NAN012 - extract			NAN012 ≤10 m 140 mm			NAN012, 10m, mod value		
	obs SWL	W-M-B	calc SWL	obs SWL	W-M-B	calc SWL	obs SWL	W-M-B	calc SWL	obs SWL	W-M-B	calc SWL
alignment			-12.43			-12.71			-12.49			12.09
year	observed		predicted	observed		predicted	observed		predicted	observed		predicted
1976												
1977												
1978												
1979												
1980												
1981												
1982												
1983												
1984												
1985	-11.03	2.07	-10.36	-11.03	2.50	-10.20	-11.03	2.49	-10.00	-11.03	1.26	-10.83
1986	-10.94	2.00	-10.43	-10.94	2.03	-10.67	-10.94	2.03	-10.46	-10.94	1.13	-10.96
1987	-10.77	1.54	-10.89	-10.77	2.04	-10.66	-10.77	2.05	-10.44	-10.77	1.23	-10.86
1988	-10.88	1.72	-10.71	-10.88	1.97	-10.73	-10.88	1.98	-10.51	-10.88	1.18	-10.91
1989	-10.76	1.40	-11.03	-10.76	1.50	-11.20	-10.76	1.52	-10.97	-10.76	1.47	-10.62
1990	-10.68	1.21	-11.22	-10.68	1.71	-10.99	-10.68	1.70	-10.79	-10.68	1.42	-10.67
1991	-10.81	1.21	-11.22	-10.81	1.36	-11.34	-10.81	1.34	-11.15	-10.81	1.03	-11.06
1992	-10.99	0.84	-11.59	-10.99	1.00	-11.70	-10.99	0.99	-11.50	-10.99	0.82	-11.27
1993	-11.05	0.53	-11.90	-11.05	0.67	-12.03	-11.05	0.67	-11.82	-11.05	0.61	-11.48
1994	-11.57	0.55	-11.88	-11.57	-0.12	-12.82	-11.57	-0.11	-12.60	-11.57	-0.05	-12.14
1995	-11.96	0.70	-11.73	-11.96	-0.97	-13.67	-11.96	-0.93	-13.42	-11.96	-0.63	-12.72
1996	-12.27	0.45	-11.98	-12.27	-1.55	-14.25	-12.27	-1.50	-13.99	-12.27	-1.17	-13.26
1997	-12.45	0.48	-11.95	-12.45	-1.48	-14.18	-12.45	-1.42	-13.91	-12.45	-1.73	-13.82
1998	-12.68	0.48	-11.95	-12.68	-1.81	-14.51	-12.68	-1.75	-14.24	-12.68	-2.09	-14.18
1999	-12.93	0.57	-11.86	-12.93	-2.31	-15.01	-12.93	-2.24	-14.73	-12.93	-2.23	-14.32
2000	-13.10	0.60	-11.83	-13.10	-2.41	-15.11	-13.10	-2.34	-14.83	-13.10	-2.56	-14.65
2001	-13.13	0.58	-11.85	-13.13	-2.40	-15.10	-13.13	-2.32	-14.81	-13.13	-2.59	-14.68
2002	-13.26	0.50	-11.93	-13.26	-2.62	-15.32	-13.26	-2.54	-15.03	-13.26	-2.56	-14.65
2003	-13.37	0.51	-11.92	-13.37	-2.40	-15.10	-13.37	-2.32	-14.81	-13.37	-2.57	-14.66
2004	-13.45	0.44	-11.99	-13.45	-2.22	-14.92	-13.45	-2.15	-14.64	-13.45	-2.53	-14.62
2005	-13.43	0.21	-12.22	-13.43	-2.66	-15.36	-13.43	-2.58	-15.07	-13.43	-2.50	-14.59
2006	-13.60	0.56	-11.87	-13.60	-2.76	-15.46	-13.60	-2.68	-15.17	-13.60	-2.58	-14.67
2007	-14.36	0.38	-12.05	-14.36	-3.02	-15.72	-14.36	-2.94	-15.43	-14.36	-2.71	-14.80
2008	-13.98	0.47	-11.96	-13.98	-2.95	-15.65	-13.98	-2.86	-15.35	-13.98	-2.68	-14.77
2009	-14.03	0.50	-11.93	-14.03	-2.69	-15.39	-14.03	-2.61	-15.10	-14.03	-2.81	-14.90
2010	-13.92	0.47	-11.96	-13.92	-2.37	-15.07	-13.92	-2.31	-14.80	-13.92	-2.66	-14.75
2011	-13.92	0.41	-12.02	-13.92	-2.59	-15.29	-13.92	-2.51	-15.00	-13.92	-2.70	-14.79
2012	-13.92	0.81	-11.62	-13.92	-2.48	-15.18	-13.92	-2.41	-14.90	-13.92	-2.71	-14.80
2013	-13.99	0.44	-11.99	-13.99	-2.38	-15.08	-13.99	-2.31	-14.80	-13.99	-2.71	-14.80
2014	-13.97	0.29	-12.14	-13.97	-2.05	-14.75	-13.97	-1.96	-14.45	-13.97	-2.64	-14.73

Appendix 5b

Sample of calculations sheet for Hardwood site MON016

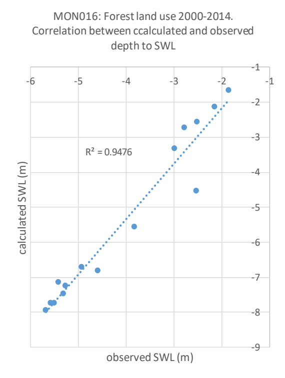
Notes related to worksheet presented as Appendix 5b. To calculate the alignment factor to express the net annual water-mass-balance as predicted standing water level, the difference between a mean value of the W-M-B and the observed SWL is calculated and added to all W-M-B values. In the case of MON016, the period applied is 1987 to 2000. In the worksheet, this data range has been designated by a black line border around the data.
Recharge variability factor. A factor derived from rainfall variability about the mean value is applied to the adopted recharge rate. As an example a 15% rainfall increase above the mean rainfall in the May-Oct period is applied as a multiplier of 1.15

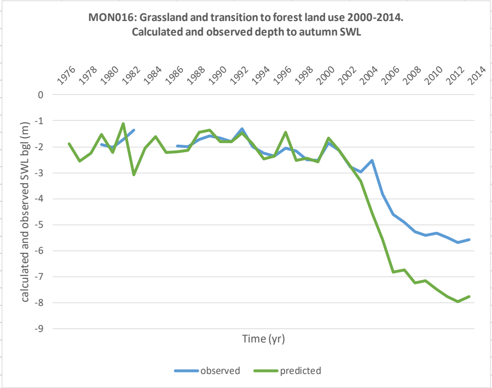
Plantation forest hydrological impacts at MON016

Appendix 5b

Data from GIS				
Land use MON016	at 2015		hardwood	ha
irrigation	28.5		1997	27.6
fire breaks	303.9		1998	
pasture	809.4		1999	
roads	28.7		2000	1234.7
native veg	504.7		2001	1028.0
other	31.1		2002	304.2
	1706.3		2003	18.0
			2004	
hardwood plantation	3320.1	66.1%	2005	
			2006	355.6
total	**5026.4**		2007	314.3
			2008	37.6
Fire Break	303.9		2009	
Native Vegetation	496.7		2010	
Other	31.1		2011	
Pasture	809.4		2012	
Pivot	28.5		2013	
			2014	
Private Road	**2.7**			
Public Road	**26.0**		**total**	**3320.1**
Wetland	8.0			

DSE carry capacity per ha	12.15
l/day/DSE	6
ML/ha/yr	0.0266085
annual (SAW estimate)/unit: ML	0.25
0.4 ha irrigaton	2.8
total domestic	3.05


MON016: Forest land use 2000-2014. Correlation between ccalculated and observed depth to SWL


MON016: Grassland and transition to forest land use 2000-2014. Calculated and observed depth to autumn SWL

Recharge calculations

		age		19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
Hardwood land use		plant year		**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
		ha			27.6			1234.7	1028.0	304.2	18.0			355.6	314.3	37.6						
MARR	ML/ha	1.8		1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80
recharge factor for rainfall variability				1.23	0.83	0.86	0.81	1.09	0.98	0.94	1.17	1.06	0.91	0.49	0.95	0.67	1.06	1.03	0.95	0.97	1.39	0.74
forest annual impact factor from accounting models																						
	yr 1	1.2	ML/ha	2.7	1.8	1.9	1.8	2.4	2.1	2.0	2.5	2.3	2.0	1.1	2.0	1.5	2.3	2.2	2.0	2.1	3.0	1.6
	yr 2	0.8	ML/ha	1.77	1.19	1.23	1.17	1.57	1.41	1.35	1.69	1.53	1.31	0.71	1.36	0.97	1.52	1.48	1.36	1.40	2.00	1.06
	yr 3	0.4	ML/ha	0.88	0.60	0.62	0.58	0.79	0.71	0.68	0.85	0.76	0.65	0.35	0.68	0.49	0.76	0.74	0.68	0.70	1.00	0.53
calculated annual impact of existing forest																						
	1		ML/ha		49.54	0.00	0.00	2912.91	2176.70	618.05	45.70	0.00	0.00	378.17	643.08	54.69	0.00	0.00	0.00	0.00	0.00	0.00
	2		ML/ha			34.11	0.00	0.00	1742.93	1392.34	514.25	27.49	0.00	0.00	485.04	304.95	57.18	0.00	0.00	0.00	0.00	0.00
	3		ML/ha				16.15	0.00	0.00	836.16	868.88	232.02	11.80	0.00	0.00	172.50	239.13	27.88	0.00	0.00	0.00	0.00
aggregate annual hardwood recharge			ML	0.00	49.54	34.11	16.15	2912.91	3919.63	2846.55	1428.83	259.51	11.80	378.17	1128.12	532.14	296.31	27.88	0.00	0.00	0.00	0.00
annualised recharge accounting					0.22 (f) MARR																	
			0.22	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
accrued forest area			ha	0.00	27.6	27.6	27.6	1262.4	2290.4	2594.6	2612.7	2612.7	2612.7	2968.2	3282.5	3320.1	3320.1	3320.1	3320.1	3320.1	3320.1	3320.1
			ML	0.00	10.94	10.94	10.94	499.90	907.00	1027.47	1034.61	1034.61	1034.61	1175.42	1299.87	1314.75	1314.75	1314.75	1314.75	1314.75	1314.75	1314.75
Extraction calculations																						
forest annual extraction impact values from accounting model			ML/ha																			
	yr 4	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91
	yr 5	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82
	yr 6	2.73	2.73	2.73	2.73	2.73	2.73	2.73	2.73	2.73	2.73	2.73	2.73	2.73	2.73	2.73	2.73	2.73	2.73	2.73	2.73	2.73
	yr 7+	3.64	3.64	3.64	3.64	3.64	3.64	3.64	3.64	3.64	3.64	3.64	3.64	3.64	3.64	3.64	3.64	3.64	3.64	3.64	3.64	3.64
calculated annual impact of existing forest																						
	4							25.15	0.0	0.0	1123.6	935.5	276.8	16.4	0.0	0.0	323.6	286.0	34.2	0.0	0.0	0.0
	5								50.3	0.0	0.0	2247.2	1871.0	553.7	32.8	0.0	0.0	647.1	572.0	68.4	0.0	0.0
	6									75.5	0.0	0.0	3370.9	2806.5	830.5	49.2	0.0	0.0	970.7	858.0	102.6	0.0
	7										100.6	0.0	0.0	4494.5	3742.0	1107.4	65.6	0.0	0.0	1294.3	1144.0	136.8
	8											100.6	0.0	0.0	4494.5	3742.0	1107.4	65.6	0.0	0.0	1294.3	1144.0
	9												100.6	0.0	0.0	4494.5	3742.0	1107.4	65.6	0.0	0.0	1294.3
	10													100.6	0.0	0.0	4494.5	3742.0	1107.4	65.6	0.0	0.0
	11														100.6	0.0	0.0	4494.5	3742.0	1107.4	65.6	0.0
	12															100.6	0.0	0.0	4494.5	3742.0	1107.4	65.6
	13																100.6	0.0	0.0	4494.5	3742.0	1107.4
	14																	100.6	0.0	0.0	4494.5	3742.0
	15																		100.6	0.0	0.0	4494.5
	16																			100.6	0.0	0.0
	17																				100.6	0.0
	18																					100.6
aggregate hardwood annual extraction: ML								**25.15**	**50.3**	**75.5**	**1224.2**	**3283.3**	**5619.3**	**7971.7**	**9200.4**	**9493.7**	**9833.6**	**10443.2**	**11087.0**	**11730.7**	**12050.9**	**12085.1**
annualised extraction accounting			ML/ha	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82
			ML	0.0	50.3	50.3	50.3	2297.5	4168.5	4722.2	4755.0	4755.0	4755.0	5402.2	5974.2	6042.5	6042.5	6042.5	6042.5	6042.5	6042.5	6042.5

recharge: all sources			(from GIS)		**1976**	**1977**	**1978**	**1979**	**1980**	**1981**	**1982**	**1983**	**1984**	**1985**	**1986**	**1987**	**1988**	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**
roads and other: ha			59.78		59.8	59.8	59.8	59.8	59.8	59.8	59.8	59.8	59.8	59.8	59.8	59.8	59.8	59.8	59.8	59.8	59.8	59.8	59.8	59.8
pasture and fire breaks: ha			1141.83		1141.8	1141.8	1141.8	1141.8	1141.8	1141.8	1141.8	1141.8	1141.8	1141.8	1141.8	1141.8	1141.8	1141.8	1141.8	1141.8	1141.8	1141.8	1141.8	1141.8
pasture converted to forest; ha			3320.08		3320.1	3320.1	3320.1	3320.1	3320.1	3320.1	3320.1	3320.1	3320.1	3320.1	3320.1	3320.1	3320.1	3320.1	3320.1	3320.1	3320.1	3320.1	3320.1	3320.1
max total recharge area: ha			4521.69		4521.7	4521.7	4521.7	4521.7	4521.7	4521.7	4521.7	4521.7	4521.7	4521.7	4521.7	4521.7	4521.7	4521.7	4521.7	4521.7	4521.7	4521.7	4521.7	4521.7
recharge area at MARR					4521.7	4521.7	4521.7	4521.7	4521.7	4521.7	4521.7	4521.7	4521.7	4521.7	4521.7	4521.7	4521.7	4521.7	4521.7	4521.7	4521.7	4521.7	4521.7	4521.7
MARR	ML/ha		1.8		1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
season recharge factor for rainfall variability				May-Oct variability	1.07	0.82	0.93	1.20	0.94	1.35	0.62	1.00	1.16	0.94	0.95	0.97	1.22	1.26	1.09	1.10	1.21	1.06	0.85	0.88
total non forest recharge: ML					8676.3	6637.6	7592.7	9745.2	7684.5	10961.1	5036.1	8132.7	9477.1	7669.8	7735.9	7864.5	9950.9	10219.1	8882.0	8922.4	9881.1	8617.5	6894.8	7199.6
total annual forest recharge: ML					0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
estimated recharge from drains: ML					0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total recharge, all land use: ML					**8676.3**	**6637.6**	**7592.7**	**9745.2**	**7684.5**	**10961.1**	**5036.1**	**8132.7**	**9477.1**	**7669.8**	**7735.9**	**7864.5**	**9950.9**	**10219.1**	**8882.0**	**8922.4**	**9881.1**	**8617.5**	**6894.8**	**7199.6**
discharge: all sources ML/yr																								
			adopted rates																					
livestock	ML per ha pasture		0.027		118.7	118.7	118.7	118.7	118.7	118.7	118.7	118.7	118.7	118.7	118.7	118.7	118.7	118.7	118.7	118.7	118.7	118.7	118.7	118.7
domestic units	estimated	5	15.25		15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3
irrigation: ML	reported data to be included	8	28.49		227.9	227.9	227.9	227.9	227.9	227.9	227.9	227.9	227.9	227.9	227.9	227.9	227.9	227.9	227.9	227.9	227.9	227.9	227.9	227.9
forest extraction: ML																								
Total discharge, all land uses: ML					361.9	361.9	361.9	361.9	361.9	361.9	361.9	361.9	361.9	361.9	361.9	361.9	361.9	361.9	361.9	361.9	361.9	361.9	361.9	361.9
MON016 annual mass balance			ML		8314.4	6275.7	7230.8	9383.3	7322.6	10599.2	4674.2	7770.7	9115.2	7307.9	7374.0	7502.6	9589.0	9857.2	8520.1	8560.5	9519.2	8255.6	6532.9	6837.7
		(1300=0.13)	1500=0.15																					
calculated annual water account/1000		(1100) =0.11	1000=.1		8.31	6.28	7.23	9.38	7.32	10.60	4.67	7.77	9.12	7.31	7.37	7.50	9.59	9.86	8.52	8.56	9.52	8.26	6.53	6.84
above *1/3	MON016 annual mass balance, standardised: metres SWL				**2.77**	**2.09**	**2.41**	**3.13**	**2.44**	**3.53**	**1.56**	**2.59**	**3.04**	**2.44**	**2.46**	**2.50**	**3.20**	**3.29**	**2.84**	**2.85**	**3.17**	**2.75**	**2.18**	**2.28**

recharge: all sources	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
roads and other: ha	59.8	59.8	59.8	59.8	59.8	59.8	59.8	59.8	59.8	59.8	59.8	59.8	59.8	59.8	59.8	59.8	59.8	59.8	59.8
pasture and fire breaks: ha	1141.8	1141.8	1141.8	1141.8	1141.8	1141.8	1141.8	1141.8	1141.8	1141.8	1141.8	1141.8	1141.8	1141.8	1141.8	1141.8	1141.8	1141.8	1141.8
pasture converted to forest; ha	3320.1	3292.4	3292.4	3292.4	2057.7	1029.7	725.4	707.4	707.4	707.4	351.9	37.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
max total recharge area: ha	4521.7	4494.1	4494.1	4494.1	3259.3	2231.3	1927.1	1909.0	1909.0	1909.0	1553.5	1239.2	1201.6	1201.6	1201.6	1201.6	1201.6	1201.6	1201.6
recharge area at MARR	4521.7	4494.1	4494.1	4494.1	3259.3	2231.3	1927.1	1909.0	1909.0	1909.0	1553.5	1239.2	1201.6	1201.6	1201.6	1201.6	1201.6	1201.6	1201.6
MARR	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
season recharge factor for rainfall variability	1.23	0.83	0.86	0.81	1.09	0.98	0.94	1.17	1.06	0.91	0.49	0.95	0.67	1.06	1.03	0.95	0.97	1.39	0.74
total non forest recharge: ML	9998.7	6712.1	6932.9	6566.0	6407.6	3937.0	3262.5	4033.7	3639.8	3124.2	1376.8	2113.0	1457.4	2285.7	2228.6	2044.1	2102.6	3011.4	1596.0
total annual forest recharge: ML	0.0	49.5	34.1	16.2	2912.9	3919.6	2846.6	1428.8	259.5	11.8	378.2	1128.1	532.1	296.3	27.9	0.0	0.0	0.0	0.0
estimated recharge from drains: ML	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total recharge, all land use: ML	**9998.7**	**6761.6**	**6967.0**	**6582.2**	**9320.5**	**7856.7**	**6109.0**	**5462.6**	**3899.3**	**3136.0**	**1755.0**	**3241.1**	**1989.5**	**2582.0**	**2256.4**	**2044.1**	**2102.6**	**3011.4**	**1596.0**
discharge: all sources ML/yr																			
livestock	118.7	118.0	118.0	118.0	85.1	57.8	49.7	49.2	49.2	49.2	39.7	31.4	30.4	30.4	30.4	30.4	30.4	30.4	30.4
domestic units	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3
irrigation: ML	227.9	227.9	227.9	227.9	227.9	227.9	227.9	227.9	227.9	227.9	227.9	227.9	227.9	227.9	227.9	227.9	227.9	227.9	227.9
forest extraction: ML	0.0	0.0	0.0	0.0	25.2	50.3	75.5	1224.2	3283.3	5619.3	7971.7	9200.4	9493.7	9833.6	10443.2	11087.0	11730.7	12050.9	12085.1
Total discharge, all land uses: ML	361.9	361.2	361.2	361.2	353.5	351.3	368.3	1516.6	3575.7	5911.7	8254.6	9475.0	9767.2	10107.2	10716.8	11360.5	12004.3	12324.5	12358.7
MON016 annual mass balance	9636.8	6400.4	6605.9	6221.0	8967.0	7505.4	5740.7	3946.0	323.6	-2775.7	-6499.6	-6233.8	-7777.7	-7525.2	-8460.3	-9316.5	-9901.6	-9313.0	-10762.6
calculated annual water account/1000	9.64	6.40	6.61	6.22	8.97	7.51	5.74	3.95	0.32	-2.78	-6.50	-6.23	-7.78	-7.53	-8.46	-9.32	-9.90	-9.31	-10.76
above *1/3 MON016 annual mass balance, standardised: metres SWL	**3.21**	**2.13**	**2.20**	**2.07**	**2.99**	**2.50**	**1.91**	**1.32**	**0.11**	**-0.93**	**-2.17**	**-2.08**	**-2.59**	**-2.51**	**-2.82**	**-3.11**	**-3.30**	**-3.10**	**-3.59**

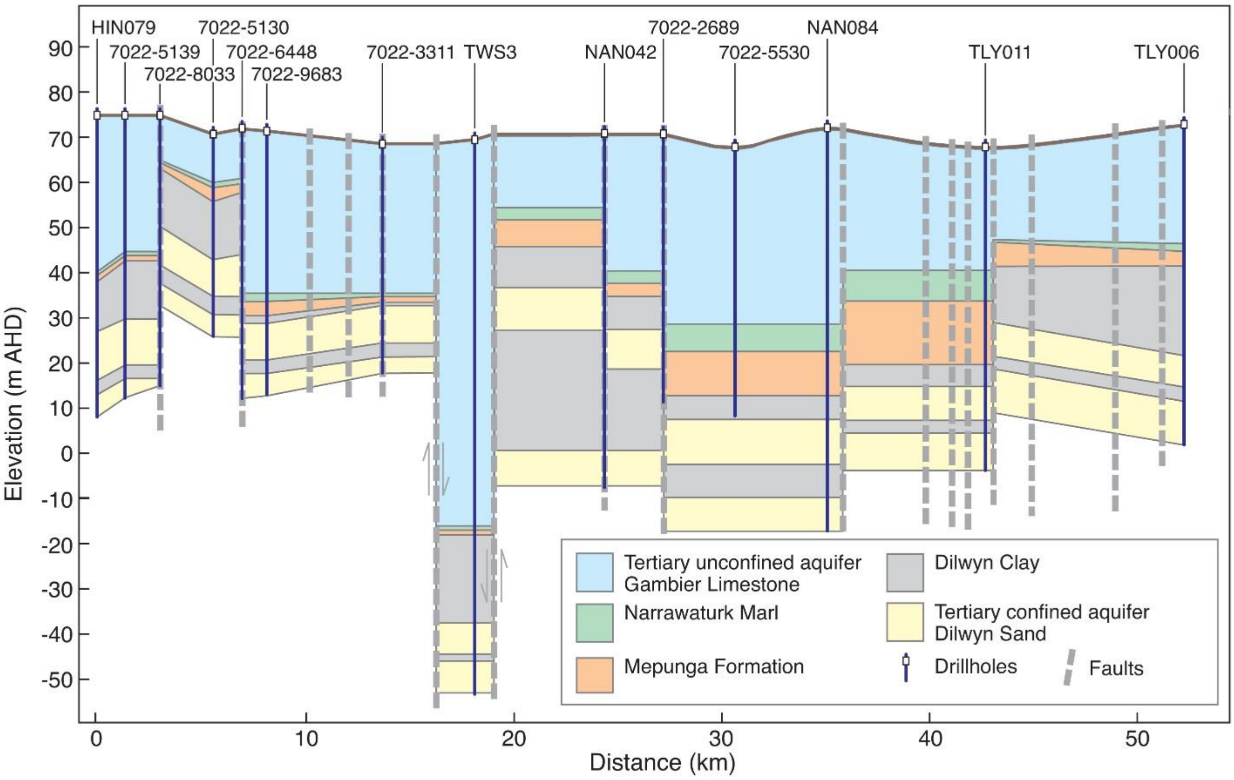
					year	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
mean 1987-99	SWL	-1.954		SWL	observed		-1.99			-1.92	-2.03	-1.73	-1.35		-1.86		-1.96	-2.00	-1.71	-1.59	-1.68	-1.81	-1.30	-1.99	-2.26
	W-M-B	2.697		water mass balance			2.77	2.09	2.41	3.13	2.44	3.53	1.56	2.59	3.04	2.44	2.46	2.50	3.20	3.29	2.84	2.85	3.17	2.75	2.18
adjustment value		-4.651	-4.65	SWL	predicted		-1.88	-2.56	-2.24	-1.52	-2.21	-1.12	-3.09	-2.06	-1.61	-2.21	-2.19	-2.15	-1.45	-1.36	-1.81	-1.80	-1.48	-1.90	-2.47

year	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
SWL observed	-2.37	-2.06	-2.17	-2.50	-2.52	-1.85	-2.15	-2.78	-2.98	-2.53	-3.82	-4.59	-4.92	-5.26	-5.41	-5.31	-5.50	-5.67	-5.57
water mass balance	2.28	3.21	2.13	2.20	2.07	2.99	2.50	1.91	1.32	0.11	-0.93	-2.17	-2.08	-2.59	-2.51	-2.82	-3.11	-3.30	-3.10
SWL predicted	**-2.37**	**-1.44**	**-2.52**	**-2.45**	**-2.58**	**-1.66**	**-2.15**	**-2.74**	**-3.33**	**-4.54**	**-5.58**	**-6.82**	**-6.73**	**-7.24**	**-7.16**	**-7.47**	**-7.76**	**-7.95**	**-7.75**

Appendix 5c

Conceptual geological cross section through the Nangwarry area:

From: Somarante *et al* (2016)



Appendix 6a

Summary of statistical results

Study site	model version	variable parameter	R sq	RMSE (m)	Graph Fig.	Statistic Fig.	observed forest period
MON016	2006		0.95	0.536	5.7	5.8	2000-2014
	2006	storage coef=0.15			5.32		2000-2014
	2017		0.94	0.536	6.6	6.7	2000-2014
SHT012	2006		0.91	0.308	5.9	5.10	1997-2014
SHT014	2006		0.94	0.106	5.11	5.12	1999-2014
	2017		0.93	0.114	6.8	6.9	1999-2014
NAN009	2006	no extraction	0.52	0.408	5.13	5.14	1990-2014
	2006	unrestricted extraction	0.75	0.264	5.15	5.16	1990-2014
	2006	10 m extraction	0.89	0.185	5.17	5.18	1990-2014
	2006	storage coef=0.13			5.33		1990-2014
	2006	10 m, 70 mm	0.89	0.122	5.36	5.37	1985-2014
	2017	10 m, 70 mm	0.85	0.136	6.2	6.3	1985-2014
NAN012	2006	no extraction	0.46	0.287	5.19	5.20	1990-2014
	2006	unrestricted extraction	0.90	0.306	5.21	5.22	1990-2014
	2006	10 m extraction	0.90	0.254	5.23	5.24	1990-2014
	2006	10 m, 70 mm	0.92	0.136	5.38	5.39	1990-2014
	2017	10 m, 70 mm	0.95	0.169	6.4	6.5	1990-2014

10 Glossary and abbreviations

This Glossary is based on the terminology adopted and applied by the Department of Environment, Water and Natural Resources in its technical reports and water allocation plans.

Accounted, accounting or **accountable** — means the process of recording the impact of the plantation forest in the water budget for a management area, or catchment. It does not intend to imply any assignment of responsibility

Act (the) — in this document, refers to the Natural Resources Management (SA) Act 2004, which supercedes the Water Resources (SA) Act 1997

Aquiclude — In hydrologic terms, a formation that contains water but cannot transmit it rapidly enough to furnish a significant supply to a well or spring

Aquifer — An underground layer of rock or sediment that holds water and allows water to percolate through

Aquifer, confined — Aquifer in which the upper surface is impervious (see 'confining layer') and the water is held at greater than atmospheric pressure; water in a penetrating well will rise above the surface of the aquifer

Aquifer test — A hydrological test performed on a well, aimed to increase the understanding of the aquifer properties, including any interference between wells, and to more accurately estimate the sustainable use of the water resources available for development from the well

Aquifer, unconfined — Aquifer in which the upper surface has free connection to the ground surface and the water surface is at atmospheric pressure

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

BoM — Bureau of Meteorology, Australia

Bore — See 'well'

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

Catchment Water Management Board — statutory body established under the Act whose prime function is to implement a catchment water management plan for its area. These Boards have since been succeeded by the Natural Resources Management Board

Commercial forest — the term used in development plans (under the Development Act 1993) for commercial or industrial scale plantation forest land-use. Some members of the plantation forest industry prefer the term 'industrial scale'. Also refer Plantation forest

Coppicing — the term applied to allowing another eucalyptus plantation tree crop to establish after the clear felling of the original plantation forest. Regrowth occurs from the cut stump of the clear felled trees. While coppicing obviates the need to replant new seedlings, it requires a change to forest management practices due to the numerous new shoots (and potential stems) from the parent stump. There are differing views about the cost effectiveness of the aggregate plantation outcomes, but it is an accepted alternative management strategy to single harvest plantings.

Catchment — That area of land determined by topographic features within which rainfall will contribute to runoff at a particular point

Cone of depression — An inverted cone-shaped space within an aquifer caused by a rate of groundwater extraction that exceeds the rate of recharge; continuing extraction of water can extend the area and may affect the viability of adjacent wells, due to declining water levels or water quality

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

Conjunctive use — The utilisation of more than one source of water to satisfy a single demand

CSIRO — Commonwealth Scientific and Industrial Research Organisation

CSIRO — Commonwealth Scientific and Industrial Research Organisation

CWMB — Catchment Water Management Board

Domestic purpose — The taking of water for ordinary household purposes; includes the watering of land in conjunction with a dwelling not exceeding 0.4 hectares

Dryland salinity — The process whereby salts stored below the surface of the ground are brought close to the surface by the rising watertable. The accumulation of salt degrades the upper soil profile, with impacts on agriculture, infrastructure and the environment.

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

EC — Electrical conductivity; 1 EC unit = 1 micro-Siemen per centimetre (µS/cm) measured at 25°C; commonly used as a measure of water salinity as it is quicker and easier than measurement by TDS

Ephemeral streams or wetlands — Those streams or wetlands that usually contain water only on an occasional basis after rainfall events. Many arid zone streams and wetlands are ephemeral.

Erosion — Natural breakdown and movement of soil and rock by water, wind or ice; the process may be accelerated by human activities

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

Filtration — Numerous methods of filtering a water sample or supply to remove suspended sediment and the larger animal and plant life

Geological features — Include geological monuments, landscape amenity and the substrate of land systems and ecosystems

Geomorphic — Related to the physical properties of the rock, soil and water in and around a stream

Geomorphology — The scientific study of the landforms on the Earth's surface and of the processes that have fashioned them

GIS — Geographic Information System; computer software linking geographic data (for example land parcels) to textual data (soil type, land value, ownership). It allows for a range of features, from simple map production to complex data analysis

GL — gigalitre (1,000,000,000 litres)

Groundwater — Water occurring naturally below ground level or water pumped, diverted and released into a well for storage underground; see also 'underground water'

Groundwater Data — Interactive map and search tool for viewing information about South Australia's wells with access to well details including, graphs showing water salinity and water level. It provides a variety of search methods, including filtering the results. [*waterconnect.sa.gov.au/Systems/GD/]*

Groundwater management area — a zone described in a water allocation plan for a prescribed wells area in the South East. Many are the cadastral Hundred

ha — hectares

Hardwood plantation forest — for the purpose of South East management, this term refers to Tasmanian blue gum (*Eucalyptus globulus*) plantations grown expressly for wood chip production. South East stakeholders consider this forest type has a planting to harvest period of ten years and second rotation plantations are established with new seedling stock. It is noted that the life cycle can be up to 12 years, but ten years is a weighted mean value recommended by the plantation industry in 2006

Hydraulic conductivity (K) — A measure of the ease of flow through aquifer material: high K indicates low resistance, or high flow conditions; measured in metres per day

Hydrogeology — The study of groundwater, which includes its occurrence, recharge and discharge processes, and the properties of aquifers; see also 'hydrology'

Hydrography — The discipline related to the measurement and recording of parameters associated with the hydrological cycle, both historic and real time

Hydrology — The study of the characteristics, occurrence, movement and utilisation of water on and below the Earth's surface and within its atmosphere; see also 'hydrogeology'

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

Interception — term used in the *Intergovernmental Agreement on a National Water Initiativ*e (NWI), paragraphs 55-57. This is interpreted as meaning any interruption to the natural water cycle, resulting in a diversion of natural water movement, or a reduction in the consumptive pool by a particular activity. In this document the use of the term interception refers to the impact of plantation forest in:

- reducing surface water catchment yield
- reducing groundwater recharge, and
- extraction of groundwater from shallow water tables

Intensive farming — A method of keeping animals in the course of carrying on the business of primary production in which the animals are confined to a small space or area and are usually fed by hand or mechanical means

Irrigation — Watering land by any means for the purpose of growing plants

Irrigation season — The period in which major irrigation diversions occur, usually starting in August–September and ending in April–May

Land capability — the ability of the land to accept a type and intensity of use without sustaining long-term damage

Leaching — Removal of material in solution such as minerals, nutrients and salts through soil

Licence — A licence to take water in accordance with the Act; see also 'water licence'

Licensee — A person who holds a water licence

Licence system — would record plantation forest impacts as offsets through the water allocation system. Under a licensed allocation system a transferable property right is assigned to the plantation owner/manager/landowner for the deemed impact on the water resource

Local water management plan — A plan prepared by a council and adopted by the Minister in accordance with the Act

m AHD — Defines elevation in metres (m) according to the Australian Height Datum (AHD)

MAR — Managed aquifer recharge (MAR) is a process where water is intentionally placed and stored in an aquifer for later human use, or to benefit the environment.

MARR — Management area recharge rate

m — metres

ML — megalitres, (1,000,000 litres)

Metadata — Information that describes the content, quality, condition, and other characteristics of data, maintained by the Federal Geographic Data Committee

Model — a conceptual or mathematical means of understanding elements of the real world that allows for predictions of outcomes given certain conditions. Examples include estimating storm run-off, assessing the impacts of dams or predicting ecological response to environmental change

Monitoring — (1) The repeated measurement of parameters to assess the current status and changes over time of the parameters measured (2) Periodic or continuous surveillance or testing to determine the level of compliance with statutory requirements and/or pollutant levels in various media or in humans, animals, and other living things

Natural recharge — The infiltration of water into an aquifer from the surface (rainfall, streamflow, irrigation etc). See also recharge area, artificial recharge

Natural resources — Soil, water resources, geological features and landscapes, native vegetation, native animals and other native organisms, ecosystems

NRM — Natural Resources Management; all activities that involve the use or development of natural resources and/or that impact on the state and condition of natural resources, whether positively or negatively

NHT — Natural Heritage Trust

Non-point-source pollution — A contributory factor to water pollution that cannot be traced to a specific location, for example, pollution that results from water runoff from urban areas, construction sites, agricultural and silvicultural operations, etc

NWC — National Water Commission

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

Pasture — Grassland used for the production of grazing animals such as sheep and cattle

Penetrating well — See ‘fully-penetrating well’

Percentile — A way of describing sets of data by ranking the dataset and establishing the value for each percentage of the total number of data records. The 90th percentile of the distribution is the value such that 90% of the observations fall at or below it.

Perennial streams — Permanently inundated surface stream courses. Surface water flows throughout the year except in years of infrequent drought.

Permeability — A measure of the ease with which water flows through an aquifer or aquitard, measured in m^2/d

Piezometer — A narrow tube, pipe or well; used for measuring moisture in soil, water levels in an aquifer, or pressure head in a tank, pipeline, etc.

Plantation forest — for the purpose of this document, the term is used to describe a commercial plantation forest activity carried out at an industrial scale by companies, or private individuals, recognised as commercial forest operators. It excludes small-scale commercial forest integrated into a farming operation

Plantation forest area — for management purposes, the area of plantation forest considered to be relevant for water resource management is the area of the plantation compartment. It is based on the ‘stump to stump’ measurement of the outer boundary. It may include minor access tracks, but excludes firebreaks and easements for electricity transmission lines and protective buffers around native vegetation and wetlands. It is the area that a forest owner/manager reports for fire information surveys and considers to be the productive forest area

Pluviometer — An automated rain gauge consisting of an instrument to measure the quantity of precipitation over a set period of time

Pollution, diffuse source — Pollution from sources such as an eroding paddock, urban or suburban lands and forests; spread out, and often not easily identified or managed

Pollution, point source — Pollution discharged through a pipe or some other discrete source from municipal water treatment plants, factories, confined animal feedlots, or combined sewers

Population — (1) For the purposes of natural resources planning, the set of individuals of the same species that occurs within the natural resource of interest. (2) An aggregate of interbreeding individuals of a biological species within a specified location

Porosity — The ratio of an unconsolidated material that contains pores or voids, commonly expressed as a volume

Potable water — Water suitable for human consumption such as drinking or cooking water

Potentiometric head — The potentiometric head or surface is the level to which water rises in a well due to water pressure in the aquifer, measured in metres (m); also known as piezometric surface

Precautionary principle — Where there are threats of serious or irreversible environmental damage, lack of full scientific certainty should not be used as a reason for postponing measures to prevent environmental degradation

Prescribed area, surface water — Part of the state declared to be a surface water prescribed area under the Act

Prescribed water resource — A water resource declared by the Governor to be prescribed under the Act, and includes underground water to which access is obtained by prescribed wells. Prescription of a water resource requires that future management of the resource be regulated via a licensing system.

Prescribed well — A well declared to be a prescribed well under the Act

Production well — The pumped well in an aquifer test, as opposed to observation wells; a wide-hole well, fully developed and screened for water supply, drilled on the basis of previous exploration wells

Property right — A right of ownership or some other right to property, whether real property or personal property

Proponent — The person or persons (who may be a body corporate) seeking approval to take water from prescribed water

PWA — Prescribed Wells Area

PWRA — Prescribed Water Resources Area

R^2 — is a statistic that will give some information about the 'goodness of fit' of a model. The R2 coefficient of determination is a statistical measure of how well the regression line approximates the real data points. An R^2 of 1 indicates the regression line perfectly fits the data

RMSE — root mean squared error

Ramsar Convention — This is an international treaty on wetlands titled *The Convention on Wetlands of International Importance Especially as Waterfowl Habitat*. It is administered by the International Union for Conservation of Nature and Natural Resources. It was signed in the town of Ramsar, Iran in 1971, hence its common name. The convention includes a list of wetlands of international importance and protocols regarding the management of these wetlands. Australia became a signatory in 1974.

Recharge area — the area of land from which water from the surface (rainfall, streamflow, irrigation, etc.) infiltrates into an aquifer

Runoff — Something which runs off, as rain which flows off from the land in streams.

RSWL — (m AHD) Reduced Standing Water Level (metres AHD) is the elevation of the water level in a well relative to the Australian Height Datum (AHD). The elevation of the water level is calculated by subtracting the Depth to Water (DTW) from the reference elevation. A negative value indicates that the water level is below mean sea level.

Ref Elev (m AHD) — Reference Elevation (metres AHD) is the elevation of the reference point of a well relative to the Australian Height Datum (AHD).

SA Geodata — A collection of linked databases storing geological and hydrogeological data, which the public can access through the offices of PIRSA. Custodianship of data related to minerals and petroleum, and groundwater, is vested in PIRSA and DEWNR, respectively. DEWNR should be contacted for database extracts related to groundwater

Salinity — The concentration of dissolved salts in water or soil, expressed in terms of concentration (mg/L) or electrical conductivity (EC)

Significant (or significance) — term used in the NWI (paragraphs 55-57) When the aggregated impact of plantation forests represents a noteworthy portion of the total water budget in the relevant water allocation plan and has considerable impact, the impacts are considered significant

Silviculture — dealing with the development and care of forests

Softwood plantation forest — for the purpose of South East water resource management, this description refers to pine plantations (mostly *Pinus radiata*) grown mainly for sawlog production. South East stakeholders consider this forest type has a planting to harvest period of 35 years, with four plantation thinning operations prior to clear felling. The life cycle is generally between 25 and 50 years, but 35 years is a weighted mean value recommended by the plantation industry in 2006

Soil water content (Θ) — The ratio of pores in soil that are filled with water; commonly expressed as a volume (L^3 / L^3)

SOP — Standard operating procedure

Specific storage (S_s) — Specific storativity; the amount of stored water realised from a unit volume of aquifer per unit decline in head; measured in m^{-1}

Specific yield (S_y) — The volume ratio of water that drains by gravity, to that of total volume of the porous medium. It is dimensionless

State Water Plan — Policy document prepared by the Minister that sets the strategic direction for water resource management in the State and policies for achieving the objects of the *Natural Resources Management (SA) Act 2004*

Stock use — The taking of water to provide drinking water for stock other than stock subject to intensive farming (as defined by the Act)

(S) — Storativity; storage coefficient; the volume of groundwater released or taken into storage per unit plan area of aquifer per unit change of head; it is dimensionless

Stormwater — Runoff in an urban area

Sub-catchment — The area of land determined by topographical features within which rainfall will contribute to runoff at a particular point

Surface water — (a) water flowing over land (except in a watercourse), (i) after having fallen as rain or hail or having precipitated in any another manner, (ii) or after rising to the surface naturally from underground; (b) water of the kind referred to in paragraph (a) that has been collected in a dam or reservoir

Surface Water Data — Interactive map showing data relating to the historical perspective of the surface water resources located throughout South Australia [waterconnect.sa.gov.au/Systems/SWD/]

Sustainability — The ability of an ecosystem to maintain ecological processes and functions, biological diversity, and productivity over time

Surface water — (a) water flowing over land (except in a watercourse), (i) after having fallen as rain or hail or having precipitated in any another manner, (ii) or after rising to the surface naturally from underground; (b) water of the kind referred to in paragraph (a) that has been collected in a dam or reservoir

Sustainability — the ability of an ecosystem to maintain ecological processes and functions, biological diversity, and productivity over time

SWL — Standing Water Level (metres) is the distance from the ground surface to the water surface in the well

Tertiary aquifer — a term used to describe a water-bearing rock formation deposited in the Tertiary geological period (1–70 million years ago)

Threshold area — a term used in the NWI. 26 It is the sum of the existing plantation forest estate plus any allowance for plantation expansion for which the impact on groundwater recharge has been accounted for within the water budget

In the case of the lower South East, threshold tables were developed by summing the forest estate, as at 2002, and approximately 59 000 ha of expansion potential. Within the threshold area, the impacts of the plantation forest on groundwater recharge are fully accounted for within the relevant groundwater management areas

It should be noted that no allowance has been made for the impacts of direct extraction of groundwater by plantation forest within water budget of the threshold areas that were developed on 2002 data and implemented in 2004

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

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

Tertiary aquifer — A term used to describe a water-bearing rock formation deposited in the Tertiary geological period (1–70 million years ago)

Timelag — broadly refers to the an interval of time between two related phenomena (such as cause and its effect); more specifically for the Mallee it refers to the period of time between water passing the root zone and recharging the regional watertable

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[26] NWI paragraph 57

To take water — From a water resource includes (a) to take water by pumping or siphoning the water; (b) to stop, impede or divert the flow of water over land (whether in a watercourse or not) for the purpose of collecting the water; (c) to divert the flow of water from the watercourse; (d) to release water from a lake; (e) to permit water to flow under natural pressure from a well; (f) to permit stock to drink from a watercourse, a natural or artificial lake, a dam or reservoir

Transfer — A transfer of a licence (including its water allocation) to another person, or the whole or part of the water allocation of a licence to another licensee or the Minister under Part 5, Division 3, s. 38 of the Act, the transfer may be absolute or for a limited period

Transmissivity (T) — A parameter indicating the ease of groundwater flow through a metre width of aquifer section (taken perpendicular to the direction of flow), measured in m^2/d

Tributary — A river or creek that flows into a larger river

Underground water (groundwater) — Water occurring naturally below ground level or water pumped, diverted or released into a well for storage underground

Volumetric allocation — An allocation of water expressed on a water licence as a volume (e.g. kilolitres) to be used over a specified period of time, usually per water use year (as distinct from any other sort of allocation)

Water affecting activities — Activities referred to in Part 4, Division 1, s. 9 of the Act

Water allocation — (1) In respect of a water licence means the quantity of water that the licensee is entitled to take and use pursuant to the licence. (2) In respect of water taken pursuant to an authorisation under s.11 means the maximum quantity of water that can be taken and used pursuant to the authorisation

Water allocation, area based — An allocation of water that entitles the licensee to irrigate a specified area of land for a specified period of time usually per water-use year

WAP — Water Allocation Plan; a plan prepared by a water resources planning committee and adopted by the Minister in accordance with the Act

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

Water column — a section of water extending from the surface of a body of water to its bottom. In the sea or ocean, it is referred to as 'pelagic zone'

Watercourse — A river, creek or other natural watercourse (whether modified or not) and includes: a dam or reservoir that collects water flowing in a watercourse; a lake through which water flows; a channel (but not a channel declared by regulation to be excluded from the this definition) into which the water of a watercourse has been diverted; and part of a watercourse

Water dependent ecosystems — Those parts of the environment, the species composition and natural ecological processes, that are determined by the permanent or temporary presence of flowing or standing water, above or below ground; the in-stream areas of rivers, riparian vegetation, springs, wetlands, floodplains, estuaries and lakes are all water dependent ecosystems

Water licence — A licence granted under the Act entitling the holder to take water from a prescribed watercourse, lake or well or to take surface water from a surface water prescribed area; this grants the licensee a right to take an allocation of water specified on the licence, which may also include conditions on the taking and use of that water; a water licence confers a property right on the holder of the licence and this right is separate from land title

Water plans — The State Water Plan, water allocation plans and local water management plans prepared under Part 7 of the Act

Water resource monitoring — An integrated activity for evaluating the physical, chemical, and biological character of water resources, including (1) surface waters, groundwaters, estuaries, and near-coastal waters; and (2) associated aquatic communities and physical habitats, which include wetlands

Water resource quality — (1) The condition of water or some water-related resource as measured by biological surveys, habitat-quality assessments, chemical-specific analyses of pollutants in water bodies, and toxicity tests. (2) The condition of water or some water-related resource as measured by habitat quality, energy dynamics, chemical quality, hydrological regime, and biotic factors

Water service provider — A person or corporate body that supplies water for domestic, industrial or irrigation purposes or manages wastewater

Watershed — The land area that drains into a stream, river, lake, estuary, or coastal zone

Water-use year — The period between 1 July in any given calendar year and 30 June the following calendar year; also called a licensing year

Well — (1) An opening in the ground excavated for the purpose of obtaining access to underground water. (2) An opening in the ground excavated for some other purpose but that gives access to underground water. (3) A natural opening in the ground that gives access to underground water

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