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IRRIGATION FUTURES

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Current understanding of the water cycle in the Limestone Coast region

Zahra Paydar, Yun Chen, Emmanuel Xevi and Heinz Buettikofer

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CRC for Irrigation Futures

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Executive Summary

The CRC for Irrigation Futures System Harmonisation program provides a framework to improve regional production and environmental outcomes through improved understanding and management of a regions water resource. The framework recognises that water management is linked to the catchments environment and socio-economics and that the water cycle needs to be considered in the whole-of- system context.

This review presents the results of a wide-ranging search for literature relating to the hydrology, and water use including irrigation as well as simple model conceptualization and water balance calculations in the Limestone Coast (South East catchment) in SA, one of the CRC IF's study regions. The aim of the review is to provide a summary of existing information about the current understanding of the hydrological system (the water cycle), the natural resource management issues and estimate of a regional water balance and its components.

The Limestone Coast has some of the most productive land in South Australia. The economy, environment and community are linked to its water resources with groundwater being the main source of water. The irrigation industry is the most significant user of groundwater in the region, though forestry is considered as a large water user with more than 140,000 ha of forest and substantial recharge reduction.There are over 2,300 farms in the region. Approximately 80,000 hectares of land are irrigated with over 2000 licensees. There are clear differences between irrigated crops in the proportion of water used compared to the area grown. Pastures, which account for the bulk of the water used, use a greater proportion of water than area occupied. Vines in contrast, account for a smaller proportion of total water use than area occupied. Water for industry, irrigation, stock and domestic use in the region is primarily sourced from the ground water system, which consists of extensive confined and unconfined aquifers.

Natural Resource Management (NRM) issues in the region include groundwater quality decline due to increasing salinity and nutrient (particularly nitrate) contamination (e.g. due to the application of fertilizer to pasture and crops and leaching of nitrogen- rich wastes), unsustainable groundwater extraction, loss of biodiversity including decline in wetland and riparian vegetation health. Irrigation has contributed to rising groundwater salinity in parts of the region. In some areas under irrigation, salt accessions to the unconfined aquifer are increased by the addition of irrigation water (from groundwater) causing a recycling of salt in the system. This cycle, over a number of years, leads to an increase in groundwater salinity, as has occurred in irrigated areas near Padthaway and Naracoorte.

An intimate link exists between surface water, groundwater and the ecosystems in the region. The regional water balance has been altered over the years due to a variety of factors such as climate, clearing of natural vegetation, planting of low water use crops, irrigation, drainage construction and expansion of plantation forestry. Local variations in

groundwater flow and quality can occur and are largely the result of spatial variability of aquifer recharge or discharge impacts.

The regional water balance analysis indicated a substantial part (~90%) of the water that enters the system is lost through evapotranspiration from vegetation and soils or evaporation from water bodies. Irrigation only contributes to about 4% of this total ET, though it consumes a substantial part of the groundwater extraction in the region. Up to half of the total water being applied for irrigation plus rain on irrigated areas may return to the aquifer as recharge. Plantation forestry is considered as a “water use” activity as it affects the water balance, not only by reducing recharge to the aquifer, but also by direct use of groundwater by trees in shallow groundwater areas. Most of the rainfall, if not evaporated or transpired by vegetation, is recharged to the unconfined aquifer. Around 9% of the total rainfall is recharged to the aquifer and that is the major contribution to this extensive groundwater resource, estimated around 1000 GL as Permissible Annual Volume. Around the southern coast, large quantities of groundwater discharge to short streams or ponds before flowing into the sea (~97 GL). This is supplemented by the surface waters of the coastal lakes and drains (~ 106 GL) presented as soakage on the landscape and springs near to the coast.

Although the regional water balance is useful in giving indications for the relative contribution of different components of the water cycle, it is only a static analysis at the system level and as such it does not show the spatial and temporal variability of these terms. This is an important issue when dealing with the potential expansion of irrigation industry and the impact of different water use activities in the region. It is recommended that:

While, maintaining the current range of primary and secondary industries in the catchment will depend on sustainable land and water management, future intensification of agriculture is likely to be reliant on a continuing or increased availability of water of suitable quality, in localities of suitable climate and soils. Any future hydrological studies should consider spatial variability and the water quality issues to better quantify the dominant processes as affected by land and water use activities.

More accurate estimate of the regional evapotranspiration is required, since it accounts for a significant part of the water balance. Remote sensing techniques are promising in this regard to capture the spatial distribution of ET in the region.

Expansion in irrigated agriculture is likely to present significant new demand for water resources. Within the irrigation industry there is likely to be a further shift towards higher value crops (e.g. vines), increasing the economic value derived from the resources. Groundwater will continue to be the main source of water supply for irrigation. This should be addressed with a multiple objective and constraints analysis in meeting an increasing demand on land and water resources of the region.

The analysis in this report is only the first step towards building a fully dynamic model of the surface and groundwater system in the Limestone Coast. Such a dynamic model is needed for developing a holistic water management regime that allows irrigation, forestry and other groundwater users to continue to prosper within sustainable limits of the resources. The management regime also needs to balance the needs of the environment, with all other water users through protecting both priority ecosystems and water user's rights for a sustainable future.

Contents

List of Tables

List of Figures

1. Introduction

This review presents the results of a wide-ranging search for literature relating to the hydrology, and water use including irrigation as well as simple model conceptualization and water balance calculations in the Limestone Coast (South East catchment) in SA, one of the focus catchments of the System Harmonisation program. The aim of the review is to provide the development of the first component of System Harmonisation by providing a summary of existing information about the current understanding of the hydrological system (the water cycle), the natural resource management issues and an estimate of the regional water balance and its components.

The South East of SA has some of the most productive land in South Australia with 3/4 of the State's (SA) forests and 1/3 of its improved pastures. The economy, environment and community are linked to its water resources with groundwater being the main source of water. The irrigation industry is the most significant user of groundwater in the South East, though plantation forestry is considered as a large water user with more than 140,000 ha of plantations. There are over 2,300 farms in the region. Approximately 80,000 hectares of land are irrigated with over 2000 licensees. Over the last few years, there has been a marked increase in irrigation activity in the region. The majority of this irrigation has been established for dairy enterprises, with improved pastures being the main irrigated crop. One of the unique characteristics of the region is the link between surface water, groundwater and the ecosystems of the region. The nature of these links differs across the region. Groundwater supports a broad range of dependent ecosystems including wetlands, coastal lakes, riparian vegetation, and near coast marine environments. Many of these ecosystems are significant tourist attractions and contribute to the regional economy.

The following is a summary of the review of basic characteristics of the region reported on various studies in the Limestone Coast region.

2. Description of the Area

The South East region of South Australia is 28,120 km^2 and extends from the South Australia–Victoria border in the east, to the coast in the south and west, and to Coonalpyn in the north, covering the south-eastern corner of South Australia (Fig. 1). Mount Gambier is the main regional centre and city in the South East with other major towns being Keith, Naracoorte, Kingston, Robe, Millicent, Penola, Bordertown, Port MacDonnell and Beachport. There are currently four Prescribed Wells Areas (PWA) in the region (Fig. 1) including the Lower Limestone Coast PWA (incoporporating the former Lacepede Kongorong, Comaum-Caroline and Naracoorte Ranges), Padthaway PWA, Tatiara PWA and Tintinara Coonalpyn PWA. The region extends from the southern most part of the South Australia to Coonalpyn and Tintinara in the north, from higher ground along the Victorian border to the Coorong and the sea. The whole catchment extends approximately 280 km from north to south and about 150 km wide.

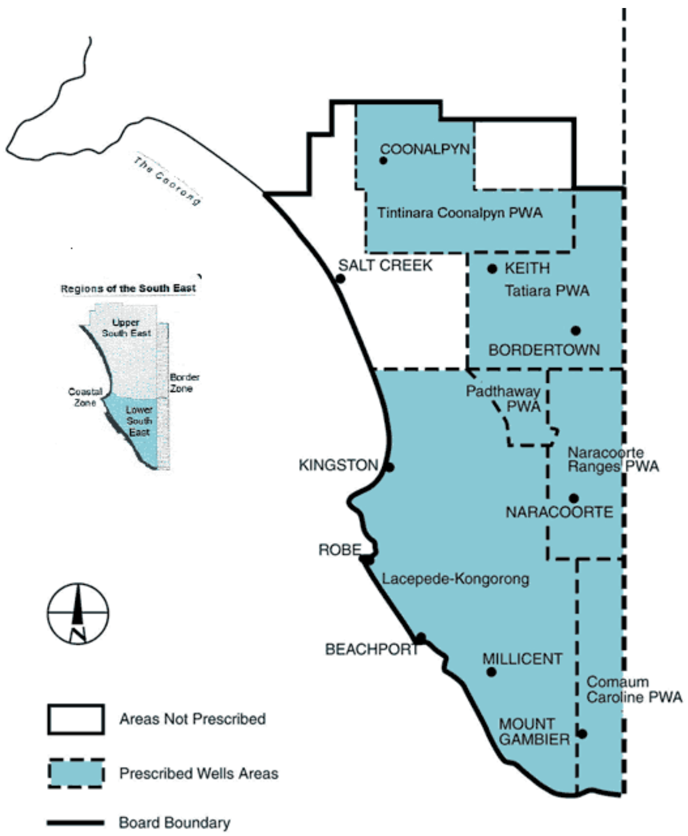

Figure 1 - Location map of the South East Region (Source: SECWMB 2003)

The climate of the region is considered to be essentially Mediterranean, with cool wet winters and mild to hot, dry summers. Annual average rainfall ranges from more than 800 mm in the south to ~450 mm in the north. Much of the region receives an annual rainfall in excess of 500 mm/year (Fig 11). Evaporation is extremely high during the summer months in the South East region. The long term mean potential evaporation rate ranges from 1330 mm/year in the north to around 1000 mm/year in the south (Fig 2).

The South East of SA (or the Limestone Coast) has some of the most productive land that supports a diverse range of industries including sheep (wool, meat), beef and dairy production, cereal cropping, wine grapes, annual horticulture crops and crop and pasture seed production. The economy, environment and community are linked to its water resources with groundwater being the main source of water. There is a heavy social reliance on water resources for drinking water supplies, recreation, and amenity values. Commercial forestry is a significant industry in the region and is based around large-scale plantations and processing of softwoods and hardwoods. Fishing is also an important component of the area's economy, as processing activities and tourism.

Commercial forestry with around 140,000 hectares planted to radiata pine and Tasmanian blue gum plantations provides substantial economic benefits to the region. The establishment of pines in the region commenced in the late 19th century and now supports a thriving industry. Planting of blue gums for wood chip production had a dramatic increase in the late 1990's and early 2000's as a result of prospectus-based planting.

The irrigation industry is the most significant user of groundwater in the South East, though forestry is considered as a large water user and leads to substantial recharge reduction. Timber plantations affect water tables by intercepting rainfall and reducing recharge to the groundwater. Consequently, the depth to the water table is declining in many forested areas. In areas with shallow water table (median depth < 6m) trees use water directly from the groundwater. This reduces the water availability for other groundwater uses in the region including groundwater dependent ecosystem.

There are over 2,300 farms in the region. Approximately 80,000 hectares of land are irrigated (over 2000 licensees). The Lacepede Kongorong PWA has the largest share of irrigated area (31% of the total). Other than several intensive pockets, irrigated crops are dispersed widely across prescribed wells areas (see Figures 2 and 11). The unconfined aquifer is the major source of groundwater used in the South East given that it occurs at a relatively shallow depth and can have yields of up to 300 liters per second. Regulation of the groundwater resources in parts of the South East region has been progressively introduced since the early 1970's to overcome longer-term problems, such as groundwater depletion and groundwater quality deterioration.

NRM issues in the region include water quality decline due to increasing salinity and nutrient contamination (e.g. rise of nitrate concentration in groundwater due to the application of fertilizer to pasture and crops and leaching of nitrogen- rich wastes), unsustainable groundwater extraction, loss of biodiversity including decline in wetland and riparian vegetation health. Irrigation has contributed to rising groundwater salinity in parts of the South East. In some areas under irrigation, salt accessions to the unconfined aquifer are increased by the addition of irrigation water. Groundwater salinity can increase due to evapotranspiration and subsequent recycling process.

2.1. Topography and landscape

The dominant landscape can be described as being an extensive plain transacted by belts of sand dunes and swamps. A series of sand dunes parallel to the coast and between 25-50m high with intervening wide inter-dunal flats (1-10km wide) are the most important topographic features of this region. These flats slope gently down from east to west and from south to north. The plains are prone to winter inundation and host a variety of wetland systems, including the Ramsar listed wetland Bool and Hacks Lagoons.

Two contrasting landscapes exist in the region: the Upper South East with the lower rainfall, originally supporting low mallee and heath with very few surface water features, and the dunal ranges of the Lower South East with forests, woodland, grassland and wetland systems, in the south. The southern part is characterised by limestone geology and volcanic activity resulting in unique surface water features such as the Blue Lake and Crater Lakes. Coastal springs, to the south of Mount Gambier are produced by groundwater discharge. Karstic areas, such as those that exist in the Gambier Limestone of the catchment have a high permeability and contain extensive network of caves, and fissures that allow the free movement of water within the substrate. Karst landscape features including cave systems (including the world heritage listed Naracoorte Caves), sinkholes, and spring lakes are key natural assets of the catchment. In the eastern area of the catchment higher inland plains extend into Victoria. These elevated plains, known as the Naracoorte Ranges, hold a small number of well-defined flow paths that collect surface water from catchments that extend into Victoria. These flow paths lose their natural definition on reaching the relatively flat plains to the west of the range. The surface water gently drains in a westerly direction across the flats until the eastern side of the dunal range obstructs the flow, directing flow north- westwards.

A consequence of the topography of the region is that few well-defined streams exist and most of the region has no natural outlet for surface flow and no permanent streams. However, there are extensive drainage system and wetlands, mainly along the western side of the inter-dunal flats. Surface water flows to the west, across the flats until the eastern side of the dunal range obstructs the flow, directing flow north westwards, approximately at right angles to the groundwater flow direction.

The catchment contains a series of coastal lakes that extend from Port MacDonnell in the South through to the Coroong in the north-west of the catchment. The lakes are situated adjacent to the coast and receive water from a range of sources including local run-off, drainage networks, spring inflow from groundwater and the exchange of waters with the sea. The contribution of each of these sources depends on the seasonal conditions, the position of the lakes in the landscape and their morphology.

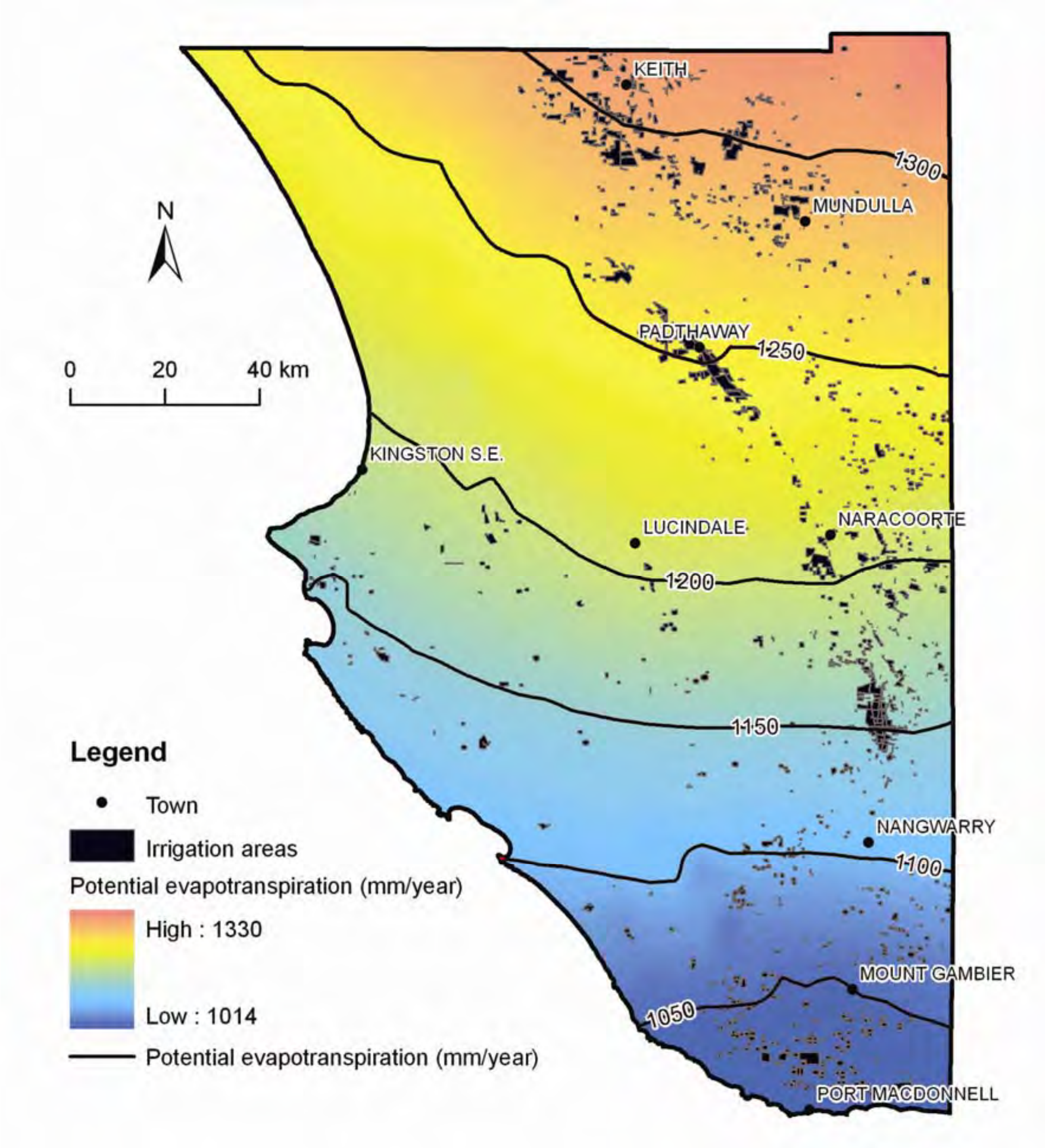

Figure 2 - Long- term potential evapotranspiration in the region with the location of irrigation areas

2.2. Soils and geology

The soils of the region vary significantly across the catchment, ranging from a mix of deep sands in the dunal ranges, to medium and fine textured saline soils in the swamps and loamy clays in the Naracoorte Ranges. The interdunal flats include heavier clays that overlie limestone or sand over clay, while volcanic soils exist around Mount Gambier. Along the coast, soils range from calcareous sand through to small areas of acidic and alkaline peats (SENRCC, 2003). To the north of the catchment the landscape is dominated by dunes and swales of deep sand and sand over clay, while in the Bordertown–Keith area soils are characterised by a combination of loamy sand and some red-brown earths.

Three main geological provinces exist within the catchment: the Otway Basin, the Murray Basin and the Pathway Ridge. The Otway and Murray Basins contain sedimentary strata of similar character, but different gradient (much lower in the upper south east part of the basin), and it is these geological units that contain the main water-bearing resources used throughout the region. The deeper sediments in the basins are referred to as the Dilwyn Formation in the Otway Basin and the Renmark Group in the Murray Basin. There is generally a clay unit at the top of the Dilwyn Formation and Renmark Group sequence, which forms part of the aquitard separating the confined aquifer from the upper unconfined aquifer. Overlying the Dilwyn Formation and Renmark Group, are a number of younger geological units that were deposited under marine and terrestrial environments. These units are generally carbonate rich.

The predominant unit in the Otway basin is the Gambier Limestone which is exposed at the surface in areas south of Mount Gambier and its equivalent is the Murray Group Limestone in the Murray Basin. Extensive dissolution of the limestone has occurred in some areas through the actions of infiltrating water, groundwater flow and historic sea-level fluctuations. Other lithological units occur above the Gambier Limestone in the Otway Basin such as the Padthaway and Bridgewater Formations, which are important hydrogeologically and are associated with the alternating lateral sequence of dune ranges and inter-dunal flats (SENRCC, 2003). The Padthaway Formation occurs exclusively within the inter-dunal corridors and the Bridgewater Formation occurs within the dunal ranges and comprises a spatial mix of unconsolidated calcareous sand and sandstone, with some limestone interbeds.

2.3. Groundwater

The groundwater resource underlying the region encompasses some of the largest groundwater systems in Australia.

There are two regional groundwater systems in the Limestone Coast region – an unconfined aquifer, which is recharged locally, and a deeper, confined aquifer, which is thought to be recharged in parts of the lower South East and western Victoria. Groundwater flow for both the confined and unconfined aquifers originates from the Dundas Plateau, a topographic high located in Victoria. The rate of the groundwater movement varies depending on the hydrogeological properties of the aquifer and the potentiometric gradient. Groundwater tends to move faster within the unconfined aquifer, where secondary porosity (known as karstic features) has often developed.

The groundwater basin is called the Otway Basin and contains a number of different aquifers and aquitards:

- The Tertiary Limestone Aquifer comprising mainly the Gambier Limestone but also consisting of other units in some areas (Padthaway and Bridgewater Formations);
- The Lower Tertiary Aquitard consisting of marl and clay with the aquifer top ranging from 35 m to 300 meters below ground level; and
- The Tertiary Confined Sand Aquifer of the Dilwyn Formation.

The two aquifers are separated by low permeability aquitards, commonly a carbonaceous clay. The aquifers are believed to be hydraulically connected; however, the extent of this connection is poorly understood and is currently being assessed. The upper Unconfined Aquifer is more extensively used than the lower Confined Aquifer.

2.3.1. Tertiary Limestone Aquifer - TLA (unconfined)

The unconfined limestone aquifer is the main source of water for irrigation, stock and domestic and industrial use. The depth to the watertable varies from greater than 20m in the south and north east to less than 2m over much of the central area. The thickness of this aquifer varies regionally with the largest depth of about 300 m occurring in the area south of Mount Gambier. The unconfined aquifer generally has a dual porosity with a primary porosity and secondary fracture porosity resulting from dissolution of the limestone. This secondary porosity forms paths for preferential flow. The karstic nature of the aquifer is reflected in the wide range of reported transmissivities (200 to more than 10,000 m^2/day).

The unconfined aquifer is recharged mainly by diffuse rainfall on the flats and dunal ranges, however local contributions are also important, including seepage from wetlands and swamps, surface water discharge into sinkholes and drainage wells, and irrigation drainage returns. The long-term, mean annual recharge rate varies from a few mm/yr under native vegetation to more than 150mm/yr in areas of high rainfall, permeable soils and annual pastures. Vertical recharge can occur through diffuse sources such as rainfall/irrigation or, in some areas such as Tatiara and Mount Gambier, through point sources such as sinkholes, natural runaway holes and drainage wells. These features enable direct surface-water discharge to the aquifer. Recharge to the unconfined aquifer may also occur through upward leakage of water from the confined aquifer in locations where the head differences and the confining layer material permits flow. Lateral recharge of the aquifer also occurs through lateral groundwater flow which is generally very slow.

Groundwater salinity varies between less than 500 mg/L in the south, 500-1500 in the east and increases to 3000-7000 mg/L in the north and west of the region. In some areas such as Padthaway and Hundred of Stirling, intensive irrigation is increasing groundwater salinity at a high rate (up to 100 mg/L/year) due to recycling of irrigation drainage water and salt. Increasing salinity trends are also evident in some non-irrigation areas, where land clearance by early European settlers has resulted in substantially higher rainfall recharge volumes. This in-turn has remobilised salts stored in the soil profile and unsaturated zone which have subsequently percolated down into the aquifer.

The watertable over some parts of the region has declined over the last 30-40 years because of drier climate and groundwater extraction for irrigation. For example, water levels are falling in the “Hundred of Stirling” area. Watertables were also rising in some parts of the upper South East until recently (at a rate of 5-10cm/year) due to land clearing.

The volume of groundwater that can be sustainably extracted for use on an annual basis is referred to as the Permissible Annual Volume (PAV) which is periodically revised, based on aquifer responses observed through groundwater monitoring and increased technical understanding. The aim of setting the PAV, and for the active management of regional groundwater resources, is that trends in aquifer salinity and water level remain within acceptable bounds.

Most of the groundwater discharge in the South East occurs to the sea. Some occurs via drains, wetlands and streams, but most occurs directly from unidentified springs and seeps. Large coastal discharges from the aquifer occur in the area south of Mount Gambier, at places such as Piccaninnie Ponds and Eight Mile Creek. Local variations in groundwater flow can occur and are largely the result of spatial variability of aquifer recharge or discharge impacts.

2.3.2. Tertiary Confined Sand Aquifer (Dilwyn)

The Tertiary Confined Sand Aquifer (TCSA) occurs within an interbedded sequence of sands, gravel and clays and increases in thickness towards the south of the region, reaching more than 500 m near the coast. At the top of the Dilwyn Formation there is generally a clay unit, which forms part of the aquitard separating the confined and unconfined aquifers. Clay and marl units that occur at the base of the Gambier Limestone and within intermediate units between the Dilwyn Formation and the Gambier Limestone also form part of the aquitard (SENRCC 2003). Following the recent allocation of most of the available groundwater from the Unconfined Aquifer there has been increased interest in the groundwater resource of the confined Aquifer.

The confined aquifer has varying depth with estimated transmissivity ranging from 200 to 1600 m^2/day. Groundwater movement in the TCSA is generally in a westerly or southerly direction towards the sea. There are only a few areas where the confined aquifer is exposed at the surface. Vertical recharge to the confined aquifer is therefore primarily via downward leakage of groundwater from the unconfined aquifer where the head differences between the aquifers and the confining layer permit the flow. This vertical recharge occurs mostly in the eastern part of the study area. In the west and south however, the head gradient is reversed where there is a potential for discharge from the confined aquifer to the unconfined aquifer (Brown et al. 2001). The point where the heads in both aquifers are the same is termed as the “zero head difference”. Figure 3 shows a schematic cross section of the groundwater flow and head differences in the two aquifers where downward leakage occurs in the east while upward leakage is mostly in the west and south of the region.

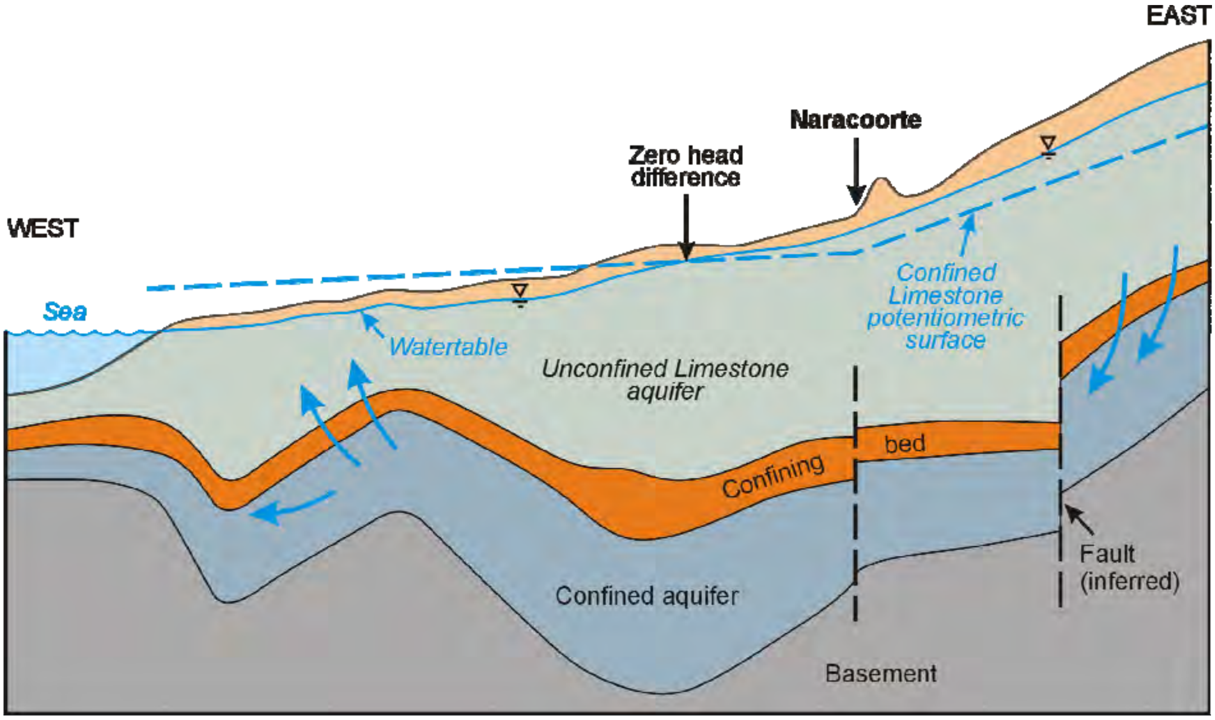

Figure 3 - Schematic presentation of the recharge and discharge processes (Based on: Rammers and Stadter 2002)

Most of the groundwater in the confined aquifer has a low salinity (<700 mg/L TDS), although there are areas where the salinity is >1500 mg/L (Brown et al. 2002). Love et al. (1993, 1994) using modelled groundwater and isotopes studies, inferred that most of the low-salinity groundwater was probably recharged after the last glacial period. During this period, the mean sea level was lower by ~120 m, causing the zero head difference to move ~50 km east of its present position; no vertical recharge could occur in this area at that time as the head in the confined aquifer is higher than the unconfined aquifer west of the zero head difference. At the end of the last glacial period mean sea level rose and the zero head difference moved to its current position thereby allowing vertical recharge to the confined aquifer.

Recharge rates to the confined aquifer are considered to be generally very small (Brown et al. 2001). Most of this recharge occurs in Victoria on the eastern edge of the aquifer, and over limited areas in South Australia, near Nangwarry.

Groundwater from the confined aquifer is utilized mainly by agricultural industry and for municipal water supplies. In the Kingston - Lucindale - Beachport area there is a reliance on the TCSA for supplies for irrigation, stock and domestic requirements and some aquaculture developments. Bore yields range from 20 to 100 liters per second with artesian flows occurring in areas of low elevation. Large-scale extraction of the groundwater for the irrigation in the artesian area accounts for a significant percentage of water used from the aquifer.

2.4. Drainage

Most of the region has no natural outlet for surface water except near the coast where water can enter the Coorong during high flows. Water flows each year when watertable rises to the surface in winter. Surface water in the winter flows in the north-west direction where it is eventually prevented from flowing further by a continuous dune complex.

An extensive drainage system, comprising of more than 2000 kilometres of drains, has been constructed over the years throughout the South East to drain water rapidly from inundated land. The most extensive drainage network exists in the lower South east and has been expanded in the Upper South East. The drainage network runs surface water in an east-west direction interconnecting the southern watercourses and discharging to the coast. In the Upper South East drainage has increased the movement of surface water and intercepted groundwater in a north-westerly direction towards the Coorong.

Construction of regional drainage infrastructure has altered the movement of surface water and has modified the interaction between the surface and groundwaters of the region. Drains have helped in controlling floods, intercepting groundwater and reducing watertable a considerable distance around drains. This has allowed inundated land to be developed as well as to minimise the effects of waterlogging. Another benefit of the drainage infrastructure has been the export of salt from the region and reducing the effect of salinity.

Wetlands and lakes are the final discharge points for drainage water or used for temporary storage of water in some parts of the system. In other areas, drainage prevents wetlands receiving the water they would have before the construction of drains. The typical wetting and drying process usually occurring in those wetlands are altered which has caused a decline and change in biodiversity in some ecosystems.

2.5. Irrigated land use

Pasture is the dominant irrigated crop, particularly in the Lacepede Kongorong area. Pastures make up about 43% of the total irrigated area in the South East and are grown extensively through the region. Grapevines and lucerne grown for seed production are the next most significant crops in the area. The largest areas of vines are in the Coonawarra district and the Padthaway area. The lucerne seed industry is concentrated in the Tatiara prescribed wells area, around Keith. Generally, cropping in the north, and livestock grazing and forestry in the cooler, wetter south are the dominant regional land use (Binks 2000).

Pasture crops grown for seed and potato production are other major irrigated industries. Other crops include cereals, vegetable seeds, oil seed, vegetables, fruit and nuts and fodder crops (Table 1).

The total area of irrigated activity in the region in 2004 was 79,118 ha representing 3.6 per cent of the total land area. The three most significant irrigated crop types by area (i.e. pasture, vines and lucerne) accounted for almost 80 per cent of all irrigated area in the region in 2003/04 (Econsearch, 2005).

There are clear differences between irrigated crops in the proportion of water used compared to the area grown. Pastures and lucerne, which account for the bulk of total water use (> 80%) both use a greater proportion of water than area occupied (>60% of land). Vines in contrast, account for a smaller proportion of total water use (~ 5%) than area occupied (< 20% of land).

Table 1. Land use (irrigated) in the South East (Econsearch, 2005)

Crop type	Area (ha)
Vines	15,164
Vegetables	1,288
Recreation	337
Potatoes	2,462
Pasture/Seed	5,529
Pasture	34,900
Oilseeds	1,867
Lucerne	12,289
Grain Legumes	574
Fruit & Nuts	1,249
Flowers/Shrubs	175
Cereals	1,813
Other	16
Total	79,118

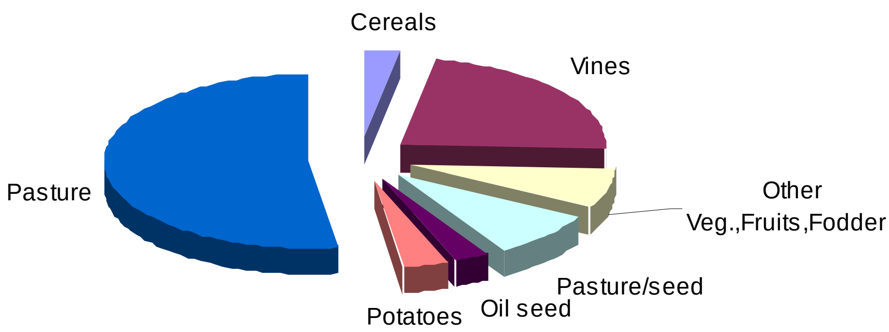

Figure 4 - Area of irrigated activity by crop, South East 2003/04 (Econsearch, 2005)

2.6. Irrigation (on-farm)

Currently, pastures use the bulk of water applied for irrigation in the South East but earn a relatively low income per unit of water than other commodities. Of an estimated total of $234.4 million (farm gate value) generated from irrigation in 1999, vines contributed the bulk with approximately $103 million. Irrigated dairy production earns approximately $28 million, out of $47 million for all pastures (20% of total).

A breakdown of the total area of irrigated activity by method in the South East region in 2003/04 is provided in Figure 5. Flood, centre pivot/lateral move and drip irrigation accounted for 86 per cent of the irrigated area in the South East region in 2003/04 (Econsearch 2005).

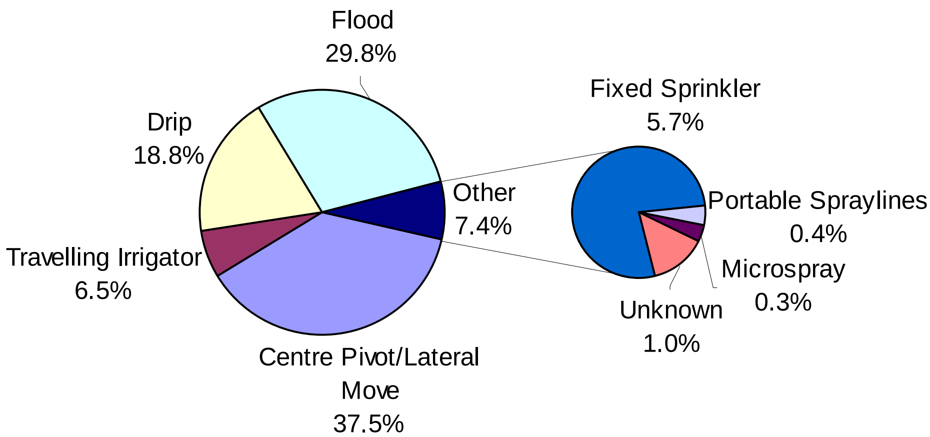

Figure 5 - Area of irrigated activity by method, South East catchment region, 2003/04 (Source: Kelly and McIntyre 2005)

There were some significant changes in irrigation methods across the South East region over the period 1999 to 2004. The shift toward drip and centre pivot irrigation and away from flood and traveling irrigators was notable. In 1999, traveling irrigators were used on 12% of the irrigated area (largely for pasture, pasture/seed and potatoes) which reduced to 6.5% in 2004, while the use of centre pivot increased from 29% to 38% during the same period.

Currently water taking allocations (WTA) are based on the area of crop allowed to be irrigated, with no limitations on the volume of water pumped. As a result a large percentage of irrigators have, until the recent introduction of legislative requirements to install meters, had little understanding of actual volumes pumped or the efficiency of their irrigation systems. In 2002 the Volumetric Conversion Project was initiated to facilitate the process of converting the area based water licenses to volumetric based licenses (Carruthers et al. 2005).

It was estimated that 459,007 ML of groundwater was utilised for irrigated agricultural activity in the South East catchment in 2003/04. The majority of this water (over 95 per cent) was sourced from the unconfined aquifer. Pasture and lucerne accounted for over 80 per cent of all irrigation water utilised in the South East catchment in 2003/04 (Econsearch, 2005).

In terms of on-farm irrigation losses, losses from pivots (evaporation and drift) were estimated in the range of 10 - 30% and losses through flood irrigation distribution systems vary between 1 to 17% (Ross Carruthers, pers. Comm.).

An important issue in irrigation areas is the rising salinity of the root zone and groundwater as has been observed in parts of the South East Prescribed Wells Areas. In areas under irrigation, salt accessions to the unconfined aquifer are increased by the addition of excess irrigation water, which has the potential to flush the soil profile. When the depth to groundwater is relatively shallow, groundwater salinity can increase due to evapotranspiration and subsequent recycling. This cycle, over a number of years, leads to an increase in salinity, as has occurred in irrigated areas near Padthaway and Naracoorte.

2.7. Summary of key NRM issues

In summary, some key issues in the region are:

- Salinity increase due to land clearing in the upper South East (resulting in rising groundwater levels) and irrigation recycling in some irrigation developments.
- Unsustainable groundwater extraction and use in some areas and new developments including land use change. Uncontrolled developments of land use systems that reduce recharge and affect the availability of groundwater in the region (e.g. expansion of plantation forestry).
- The impact of climate on existing and new developments with prediction of an annual decline in rainfall and hence decline in recharge and uncertainty in available water resources.
- Irrigation practice and irrigation efficiency are the key areas for improvements in water resource management of the region.
- Environmental impact of water management - groundwater dependent ecosystem, wetlands vegetation health, and biodiversity (e.g. on-going drainage which reduces wetland habitat and changes the quantity, duration and frequency of flows; blockages caused by weed infestation).
- Groundwater contamination - from point sources (e.g. wastewater disposal to sinkholes and drainage bores) and diffuse sources (e.g. nitrate and pesticides from agricultural areas).

The challenge for the region is to develop an integrated water management regime at the system level that allows a balanced use of water resources taking into account the needs of all groundwater users within sustainable limits. While the irrigation industry and plantation forestry sector will continue to prosper from the water resources, the management regime must consider the needs of the environment and groundwater dependent ecosystem for the sustainable management of regional water resources.

3. Hydrological analysis

The methodology adopted for hydrological analysis was to collate all available data related to the hydrological components of the system including climate, topography, geology, landuse, soils, irrigation and water use; review previous studies in the region and extract relevant information from those studies; construct a 3-D conceptual model of the hydrology of the system including surface and subsurface features based on available data; calculate an average annual water balance of the region including inflows and outflows. These steps are required for better understanding of how the system functions, where the interactions are and for identifying the information and knowledge gaps in our water cycle analysis. The same steps are also required for building a dynamic model of the system. This whole-of-system approach can then be used to identify water availability for extraction in different areas as well as areas for future irrigation expansion considering interdependencies between different zones and constraints in the system as a whole.

3.1. Data collated

To understand the hydrology and water cycle of the system, data have been collected and collated on climate, topography, hydrogeology, land use, and water use of the Limestone Coast region as summarized below:

- Climate- Daily climate data (since 1995) for two stations: Keith and Mt Gambier were obtained from SILO. The data include: max/ min temp, rainfall, Potential reference crop evapotranspiration (FAO56), radiation and max / min RH. Also mean annual climate surfaces, as gridded data, for the region were obtained from CSIRO Climate Data at CSIRO Earth Observation Centre.
- Soils - Soil hydraulic properties (A& B horizons) in GIS. This data includes soil hydraulic conductivity, depth, bulk density, upper and lower limits, water holding capacity, obtained from CSIRO/ASRIS data base covering the region under study.
- Cropping - Land use and crop water use (estimates) for the years– 98/99, 02/03, 03/04 and 04/05; Crop factors (Kc values); Crop calendars.
- Hydrology and water use - Groundwater recharge values estimated by DWLBC for 73 groundwater management areas (in GIS); Groundwater level data obtained from DWLBC staff; Water allocations and estimated use for 2002-2004 (various reports); Water use by forestry for each management zone (2004). Surface flow data (creeks and drains) were obtained from DWLBC's surface flow archive : http://e-nrims.dwlbc.sa.gov.au/swa/map.aspx) and consultation with DWLBC staff.
- Spatial data- Boundary of the catchment; Landuse: 50m resolution (2000)- obtained fromDWLBC; DEM: The National 9 Second DEM grid, 250m resolution was used to accurately represent surface shape, elevation and drainage structure. It was computed from topographic information (at 1:250 000 source scale); Rivers/Streams, Towns, Dams; Landsat7 TM 25m mosaic (2002); Boundary of groundwater provinces; Boundary of groundwater aquifers; Boundary of groundwater basins; Remotely sensed images as Colour composite of Landsat 7 bands 7, 4, 2. The image resolution is 25 metres.

- Hydrogeology – Data on geological formations containing the elevation and depths of the different layers, confined aquifers and bedrock for the region under study obtained from DWLBC.
- In addition, previous studies and reports, web sites with information related to the hydrology of the region were consulted.

3.2. Building a conceptual 3-D model

A three-dimensional (3-D) conceptual model developed in ArcGIS for the Limestone Coast (Chen et al. 2008) is a spatial integration of data layers and can be used to explain the water cycle, surface and subsurface features in this region. Kriging method was used to interpolate representative surfaces for point data. It illustrates the geological formations, hydrological flows, the capacity of the aquifers, and the surface-groundwater interactions.

Figure 6 shows a representation of this 3-D model for the region. Detail description of the 3-D conceptual model can be found in Chen et al. (2008).

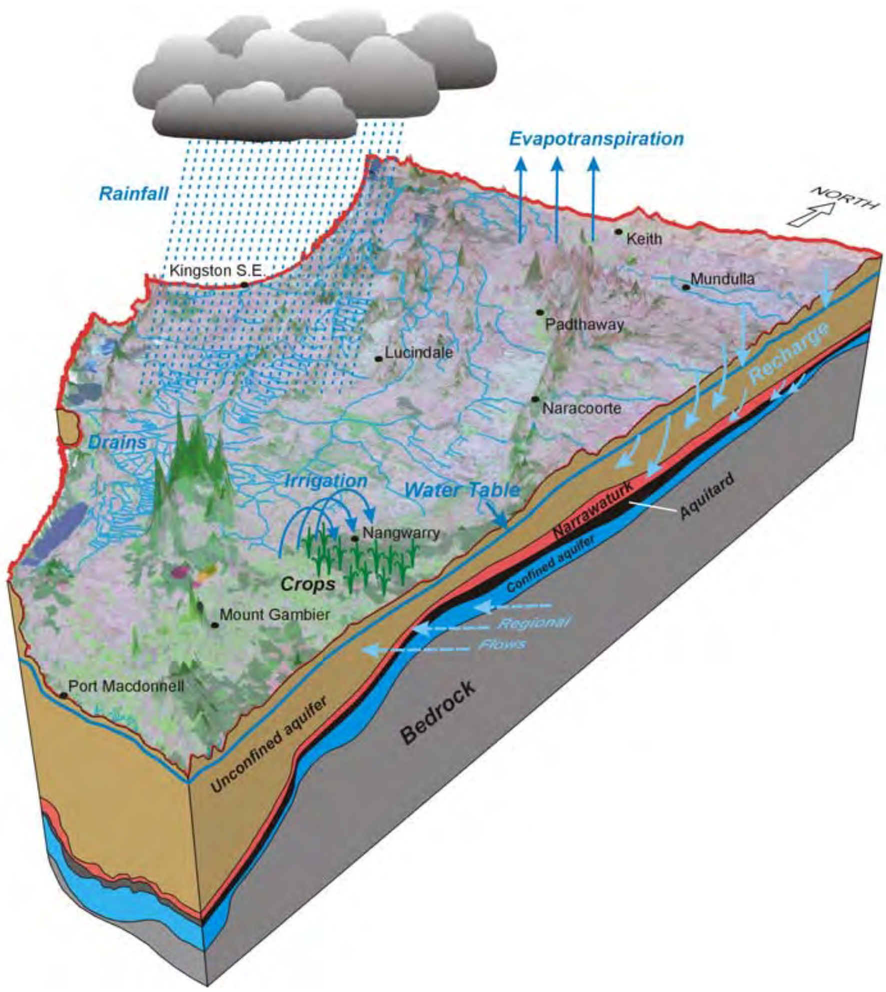

Figure 6 - A 3-D representation of the surface and subsurface features of the Limestone Coast

A 3-D conceptual model is a simplified representation of the essential features of the hydrological system. It has the following advantages compared to common 2-D conceptual models:

3-D representation is one of the best ways to present spatial data for visualization and is very valuable in understanding the system, in particular, its hydro-geological characteristics in the spatial context.

It allows simple and clear visual representation of complex information of natural systems and processes to be easily understood by both technical and non-technical interested parties, especially stakeholders.

It brings together the numerous and diverse relevant data sets providing a data platform and a means for further quantitative analysis both in itself and in dynamic models such as MODFLOW.

The novel approach of 3-D interactive conceptual model for hydrological systems has been used as an excellent tool to improve communications with CRC partnerships and the regional stakeholders. This conceptual model is also a useful tool to build a quantitative framework for analyzing surface and groundwater quantity and quality transformations across a range of regimes and scales.

3.3. Recharge

Groundwater recharge is an important part of the water balance of the area influencing the amount of water available for use. There are different mechanisms of groundwater recharge in this region. Recharge processes to the unconfined aquifer are identified as diffuse infiltration of rainfall or irrigation and point source recharge through sinkholes, drainage wells and runaway holes. In some areas such as Tatiara and Mount Gambier, point source recharge to the aquifer occurs where local surface water run-off is discharged to the aquifer through sinkholes, runaway holes and constructed drainage or stormwater wells. In other areas recharge may occur indirectly through seepage from wetlands and swamps. Recharge may also occur through upward leakage of water from the confined aquifer in locations where the relative head differences and the confining layer permit the upward flow. Groundwater in the unconfined aquifer is mainly recharged locally, whereas the confined aquifer is mainly recharged in western Victoria (Hopton et al. 2001, South East Catchment Water Management Board 2003). Brown et al. (2001) based on hydrochemical, isotopic and hydraulic information, inferred that recharge to the confined aquifer at the Nangwarry and Tarpeena sites is occurring via preferential flow (fractures, faults or sinkholes), rather than via porous media flow through the regional aquitard. Expansion of forestry plantations may significantly impact on vertical recharge to the confined aquifer of these sites. Regional carbon-14 mapping suggested that recharge to the confined aquifer may occur in relatively small, localized areas, possibly controlled by preferential flow (Brown et al. 2001).

The magnitude of average annual vertical recharge varies according to rainfall, the nature of the soil, the depth to the water table, the nature of the vegetation cover and variations in land management practices including irrigation. Recharge is difficult to measure in the field and is often modeled using techniques which can vary from simple relationships with rainfall to process models. There have been some studies on estimation of the groundwater recharge in the region, mostly focusing on the unconfined aquifer recharge (Colville and Holmes, 1972; Allison and Hughes, 1978; Herczeg and Leaney, 1993; Brown et al., 2006). Allison and Hughes (1978) estimated the mean annual recharge in the Lower South East (around Mt Gambier) using natural tracers (chloride and tritium) on different soil types. Good agreement was obtained between the two methods with local recharge varying between 50 and 250mm/year. Total annual recharge for the area of around 162,000ha was estimated to be about 240-250 GL/year.

For the border designated zone (on the east) areas recharge studies included hydrogeological studies (Stadter, 1989) and studies based on hydrochemical techniques (Herczeg and Leaney, 1993). Vertical recharge was assessed by examining the relationship between annual changes in groundwater storage and rainfall. The estimates of recharge varied from 75 to 100 mm per year for some parts of the border areas (Stadter, 1989; De Silva, 1994). The magnitude of diffuse recharge decreases northward where Stadter (1989) gave estimates of 10-40mm/year and Walker et al. (1990) reported 2-12 mm/year.

In a hydro-chemical study by Herczeg and Leaney (1993), investigations were carried out to fingerprint possible sources of recharge (diffuse or point source) by analyzing major ions and stable isotopes for water, deuterium and oxygen 18. Their work showed that vertical recharge is low for most of the study area (border zones) and diffuse recharge was identified as the dominant form of vertical recharge. A diffuse recharge of 4mm per year for clay soils and 30 mm per year for areas with sandy soils (Herczeg and Leaney, 1993) was estimated by this analysis. However, De Silva (1994) showed much higher values of recharge on the border areas based on the hydrographic responses of the unconfined aquifer. Recharge rates varied from 10 to 45 mm per year for clayey soil areas where the thickness of the unsaturated zone exceeds 5m. For sandy areas the range of recharge estimates was from 20 to 60 (and up to 120) mm per year depending on the extent and density of the vegetation cover. It was considered that previous studies using the chloride technique for determining vertical recharge provide conservative results, because little account is made for preferential flow paths whereas the groundwater hydrographic response method (or watertable fluctuation method) provides results which integrate all forms of vertical recharge (De Silva, 1994).

Brown et al. (2006) applied the watertable fluctuation method using the water level observation network for estimating the mean annual recharge rates to almost all (total of 73) groundwater management zones in the Lower South East, Padthaway and Tatiara. For some areas, within the Prescribed Wells Areas, for which this method was not appropriate (groundwater extraction or deep water levels), the recharge rates were estimated based on previous studies and soil and land use type (Brown et al. 2006). The result was a set of revised recharge values for each groundwater management zone. Later, Latcham et al. (2007) revised the recharge estimates for two groundwate management zones at the border (i.e. 2A and 3A zones). Figure 7 shows a map of the region based on the revised estimates of recharge rates to the unconfined aquifer. Effect of forestry on recharge was also considered as a reduction of recharge (recharge debits – approximately 80% of total recharge) in the management areas with forest (see next section). The total available recharge figures, in each zone, were then used to estimate the permissible annual volume for use in management zones.

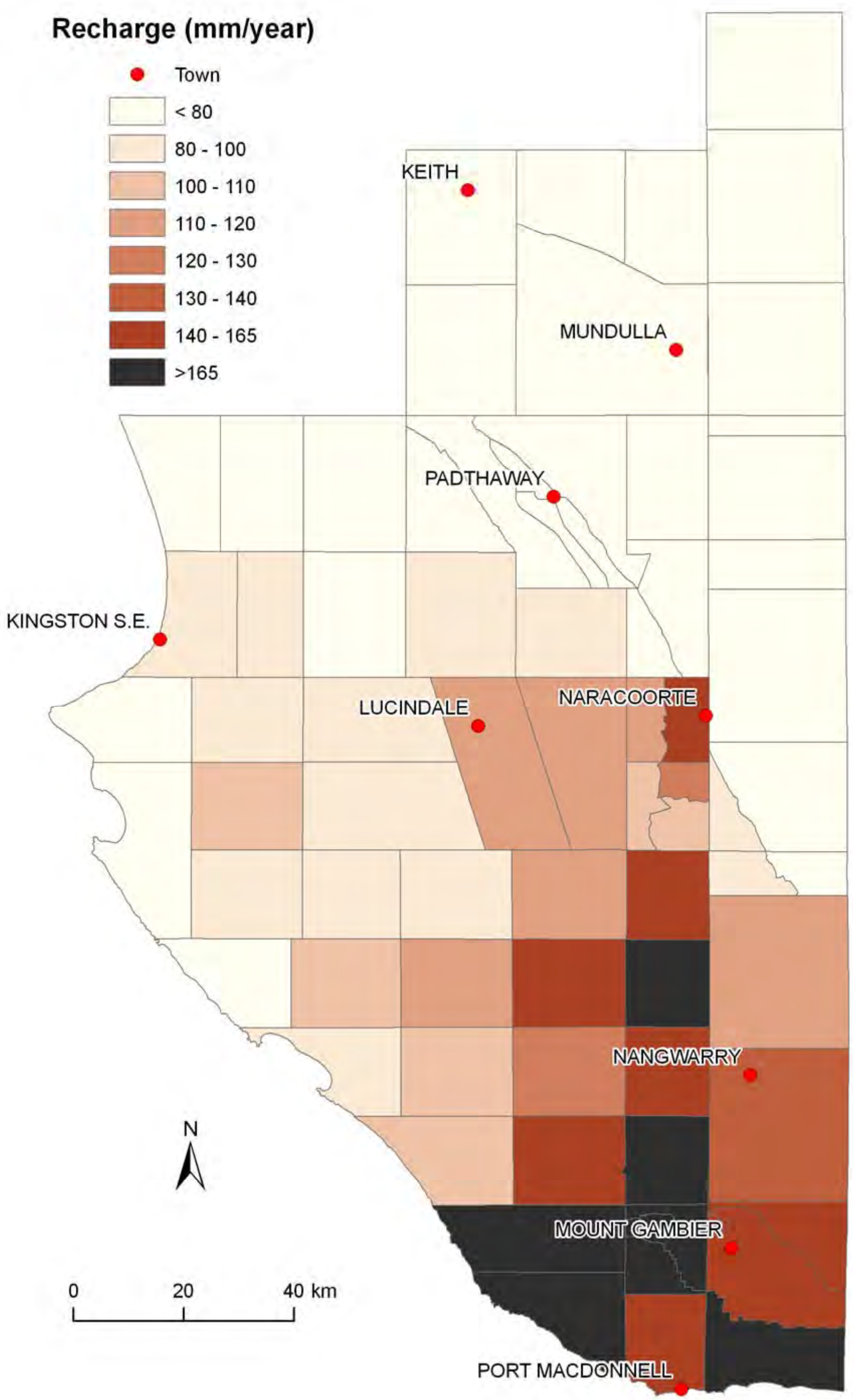

Figure 7 - Recharge estimates of the region (based on Brown et al. 2006 and Latcham et al. 2007)

We have compared the previous recharge estimates with a different approach by estimating the deep drainage values passing beyond the root zone of crops using a 1-dimentional model. The model is called SWAGMAN-GIS which is an integration of a 1-dimentional (1-D) SWAGMAN-Destiny (Khan et al. 2003, Xevi et al. 2008) into a GIS framework. SWAGMAN Destiny is a deterministic crop/soil/environment model that has been extensively modified to integrate tightly into a GIS environment. The generic crop growth model simulates canopy development using intercepted radiant energy and ambient temperature as the major drivers. Growth, and ultimately yield, is modified from a nominated potential by invoking daily stress factors induced by water deficit, aeration stress, salt stress and nitrogen deficit. Partitioning of growth between shoots and roots and the distribution of roots in the layered soil profile is also influenced by the limiting stress factors. Given the climate, soil and crop data, it can simulate the infiltration, drainage, evapotranspiration and crop growth and describe the principle processes that determine the fluxes of water and salt into and through a soil profile during a specified time period. Preliminary runs of SWAGMAN-Destiny in the Limestone Coast on a spatial context using land use, climate and soil distribution in the whole area for the year 1996, resulted in drainage values between 80 to 165 mm/year (Fig. 8).

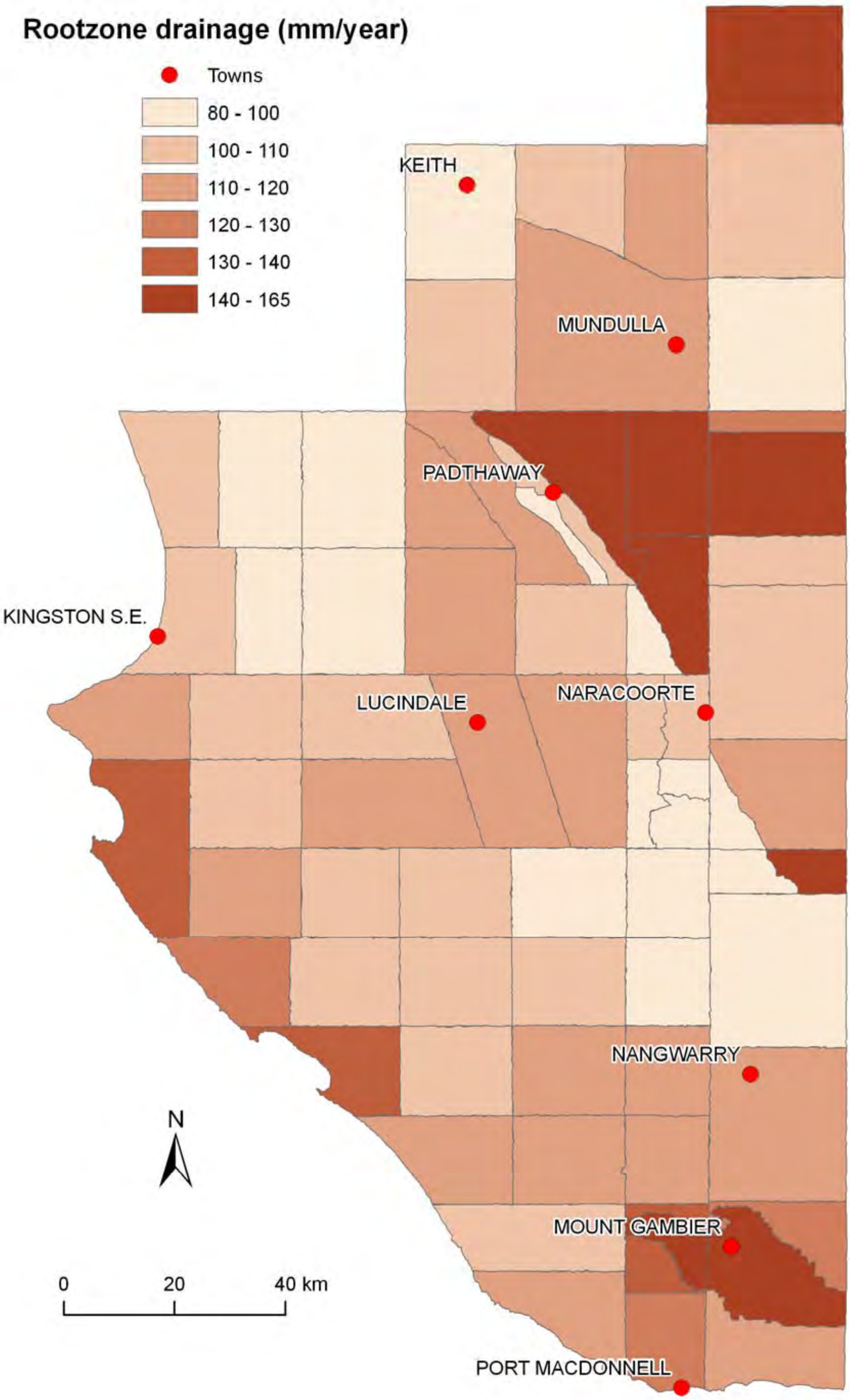

Figure 8 - Spatial estimates of drainage below the root zone in management zones based on 1-D modeling.

These values are somewhat higher than what were estimated previously in the region with most areas showing drainage values around 100mm/ year. The average annual recharge spatially averaged over the region by this approach was 118mm compared to only 51mm based on reported values by Brown et al. (2006). There are a few reasons for this:

- The 1-D model gives estimates of the drainage beyond 1.5 m depth in the soil profile. Although this shows what potentially can be recharge, in some places where the watertable is deep, the drainage amount may not end up in recharging the aquifer and may take some time to reach to the groundwater before being stored in the profile.
- The 1-D model does not consider the lateral flow as it only simulates vertical flow. This can result in high estimates of the recharge where subsurface lateral flow occurs.
- The simulation has been carried out for only one year whereas the reported recharge estimates by Brown et al. (2006) were the averages of at least several years based on available observation well records.
- The 1-D model considers only the porous media flow (through soil matrix), thus ignoring the effect of the preferential flow paths that especially exist in the karstic region in the south. While this will usually result in lower recharge rates than with including the preferential flows, it would also result in compensating all the above causes of over-estimation in 1-D modeling. Thus comparing Figures 7 and 8 for some of the zones in the south, 1-D modeling shows lower values of potential recharge as compared to the recharge values estimated with the water table fluctuations. These are the areas where, because of probable preferential flows, the compensating errors show.

Based on the above considerations and the robustness of the watertable fluctuation method in integrating all processes affecting recharge, especially in shallow watertable areas, it was decided to use the recharge estimate made by Brown et al. (2006) as in Figure 7 for our water balance analysis.

3.4. Effect of forestry

Plantation forestry plays an important role in the regional economy. The area of plantations has grown rapidly in the region over the past years, due mainly to the establishment of new Tasmanian blue gum plantations (*Eucalyptus globulus*) supplying the export woodchip market. In the lower South East region, forestry plantations occupy about 14% of the land area available for agriculture and forestry. In the South East catchment, the forest industry provides about one third of the region's gross product and 25% of the employment, with annual turnover exceeding $1,000 million (Benyon, 2002).

The effects of forestry on the water resources of the region have been considered in two ways: its influence on groundwater recharge and the likelihood of direct access of deep-rooted trees to groundwater. The long-term impacts of plantation forestry on regional water resources, in terms of water use and recharge reduction should be considered over the entire crop cycle incorporating changes through the growth cycle of different forest types (Brown et al. 2006, Benyon and Doody 2004).

Groundwater use of plantations was studied in research plots on sandy soils over watertables of low salinity in the South East on closed canopy plantations (Benyon and Doody, 2004). For the eight study plots which used groundwater, the mean annual groundwater uptake was 435 mm/ year which represented 35% of their total water use, on average. The annual extraction values ranged from 107 to 671 mm/year. These measurements were all made in closed canopy plantations and therefore do not apply to the period before canopy closure when evapotranspiration will be lower (Benyon and Doody, 2004). Site factors influencing water use of the plantations with closed canopies include rainfall, soil depth and depth to groundwater. Brown et al. (2006), based on these results and some simplifying assumptions, estimated the mean annual extraction rates of hardwood (230mm/year) and softwood (260mm/year) plantations from shallow groundwater (< 7meters depth) for the whole forest life cycle.

The forestry impact also includes reduction in recharge to the groundwater (recharge debit). Petheram et al. (1999) showed that at sites receiving 600-800 mm of rain annually, recharge was around 20-160 mm under annual crops (e .g. cereal crops) and 10-60 mm under perennial crops (e.g. lucerne). Of the studies they reviewed, recharge under trees was close to zero in the <600 mm rainfall zone and only about 10 mm for rainfall of around 1000 mm.

Colville and Holmes (1972), based on groundwater level observations, concluded that there may be some recharge under pine plantations in an area east of Nangwarry, equivalent to about half the recharge under grassland . Supporting the original findings of Holmes and Colville (1970a), Allison and Hughes (1972) from studies of naturally occurring tritium in groundwater, concluded that there was virtually no recharge to groundwater under mid-rotation pine plantations southwest of Nangwarry. Results from recent studies indicate that water use by plantations is variable within the region. Plantations with below average productivity have low LAI (Leaf Area Index) and appear to use less water than rainfall and may permit recharge (Benyon 2002). The long-term average interception loss for a closed-canopy of trees generally ranges from around 10% to 35% of rainfall depending on the vegetation type (Wells and Blake 1972; Smith 1974; Langford and O'Shaughnessy 1977; Feller 1981). Recharge is also affected by deep roots of the trees. Benyon and Doody (2004) speculated that average total recharge across the plantation estate in areas with deep watertables will be less than under dryland agriculture; there will still be periods where some recharge under plantations occur. A rise in watertables under pine plantation areas burnt in bushfires in 1983 indicates that recharge equivalent to that under grassland occurred in the period up until canopy closure (Dillon et al. 2002), which is around 20% of the rotation. While Benyon (2002) suggest an average of 80% for the recharge reduction under forestry, Brown et al. (2006) after consultation with the industry and the SA Government, use agreed values of 83% average recharge reduction underneath softwood plantations and 77% reduction underneath hardwood plantations. These figures together with the areas under forestry and direct groundwater use in shallow watertable areas were then used to estimate the available recharge and permissible annual volumes in each groundwater management zone (Brown et al. 2006). Forestry is considered as a “water use” activity in these calculations which significantly uses water and needs to be fully accounted for in the water availability and management.

3.5. Regional water balance analysis

In this section we give a first cut analysis of the water cycle in the region. Although the region is mainly a groundwater dominant system with no perenial surface flow, all surface water entering and leaving the region have been considered in the analysis. The concept of water balance provides a useful tool for better understanding of the water cycle and the relative importance of its components in the whole hydrological scene. Although it is usually calculated for a steady state condition, it is also useful in evaluating a relative response to some major hydrological changes given the processes are well understood or reasonable assumptions can be made. There are many processes occurring at different spatial and temporal scales that affect the overall water balance of a hydrological system. Figure 9 shows a schematic view of some of these processes for the South East region. They include different land use activities (e.g. irrigation, forestry, dryland agriculture, water bodies, towns) with different water needs affecting the total water use as well as ground water recharge occurring from the rainfall and irrigation. Drains play a role in collecting all the surface water as well as being fed by the deeper drains tapping into the groundwater, before flowing out to the sea. At the same time, exchanges between different aquifers take place, but they are not considered here for a regional water balance analysis.

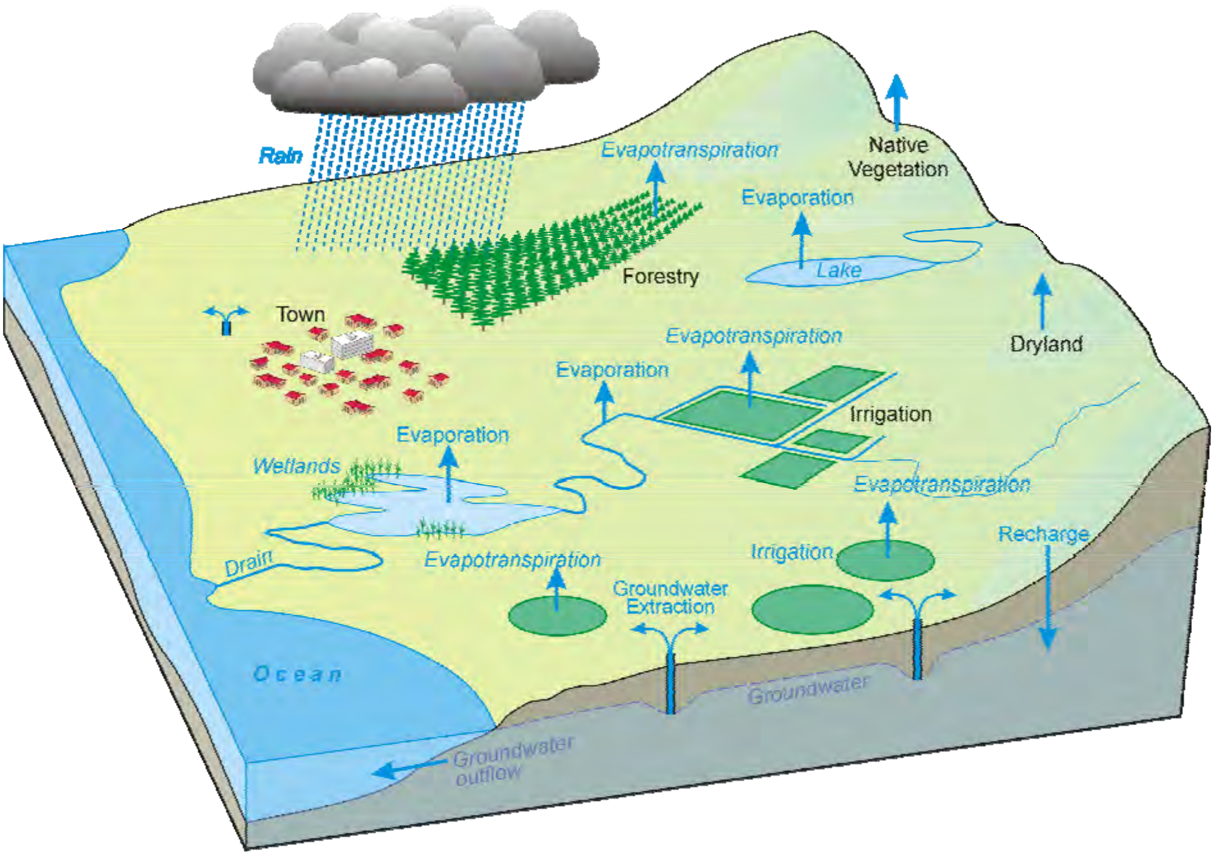

Figure 9 - Schematic representation of the water cycle processes in the South East SA

In a water balance analysis, we need to define the control volume and a time frame for which the calculations are carried out and assumptions are valid. The boundary used for the water balance analysis follows mostly the boundary of the 3-D conceptual model (Figure 6) which were defined the same as the region boundaries in the east (Victoria-South Australia border), south and west (the sea). In the north, the boundary was identified to include areas with available groundwater observation data and include most of the irrigation areas in the catchment and it basically follows the groundwater management zone boundaries north of Keith (Figure 2). These boundaries were used to define boundaries for the water balance calculations. The control volume, for this water balance analysis, consists of the area from the surface to the watertable (the vadose zone) considering all flows occuring between this zone and outside the zone (i.e. fluxes to and from the groundwater, atmosphere, and the sea).

In mathematical terms, a regional water balance can be written as:

$$Inflows - Outflows = \Delta S \quad (1)$$

Where *Inflows* refer to all incoming water to the region and *Outflows* refer to all the outgoing water flowing out of the system. ΔS refers to the change in the region water storage. When averaged over a long period, ΔS can be neglected (assumed zero). A simplified conceptual representation of the hydrological components of the water supply for the region is shown in Figure 10, following our understanding of the hydrological system in the region.

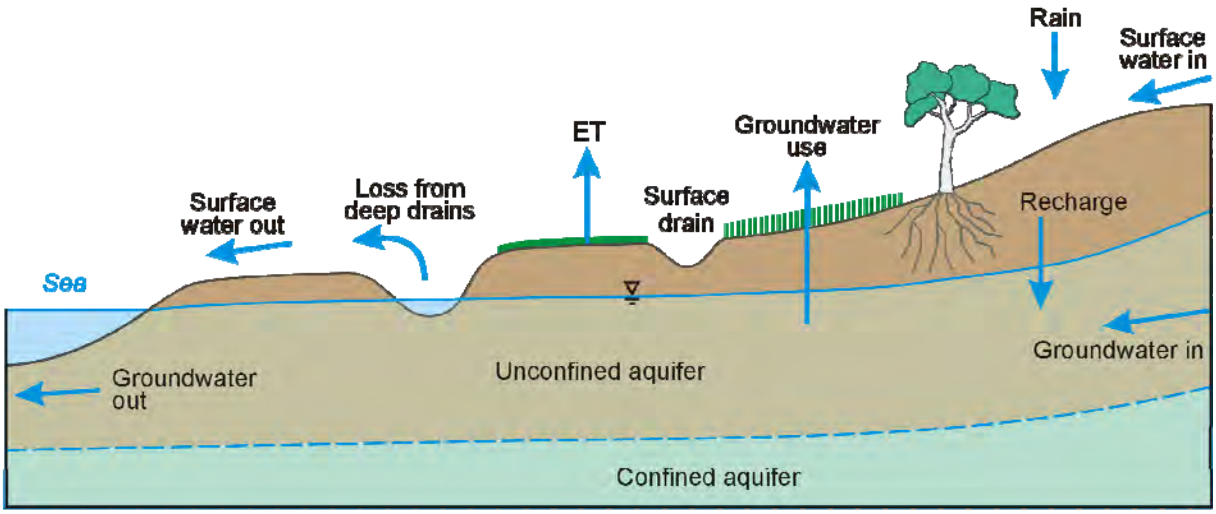

Figure 10 - A simplified conceptual model of the Limestone Coast, South East (SA)

At the regional scale, the main *inflow* is rain which recharges the underground aquifer(s) as a proportion not being used for evapotranspiration (ET) of crops and natural vegetation or intercepted by trees and plants. *Inflows* also include surface and groundwater inflows from the Victorian side into the region. The *Outflows* consist of mainly the ET from different land uses as well as the flow of drains (surface and some groundwater-fed system) and groundwater flow directly out of the region and out to the sea. The intention was to estimate an average water balance for the region within a period covering the years 1995 to 2007. Where data did not exist for some components, assumptions about these average conditions were made (e.g. average land use). The steps followed for estimation of these components are described in this section.

Climate data - Mean annual climate surfaces for 1961-1990, the reference period used by the Bureau of Meteorology, from QDNR (Queensland Department of Natural Resources) Silo daily data (Jeffrey et al. 2001) were used for the analysis. The dataset provides interpolated data for a 5kmx 5km grid across Australia. Areal potential evapotranspiration (ET_0) data calculated from the QDNR gridded data set (daily temperatures and solar radiation) using Priestley-Taylor method (Priestley and Taylor 1972) were used in the analysis. Using these climate surfaces (Figures 11 and 2), the long-term average rainfall for the region was calculated as 600.8 mm and the mean annual potential evapotranspiration as 1193mm.

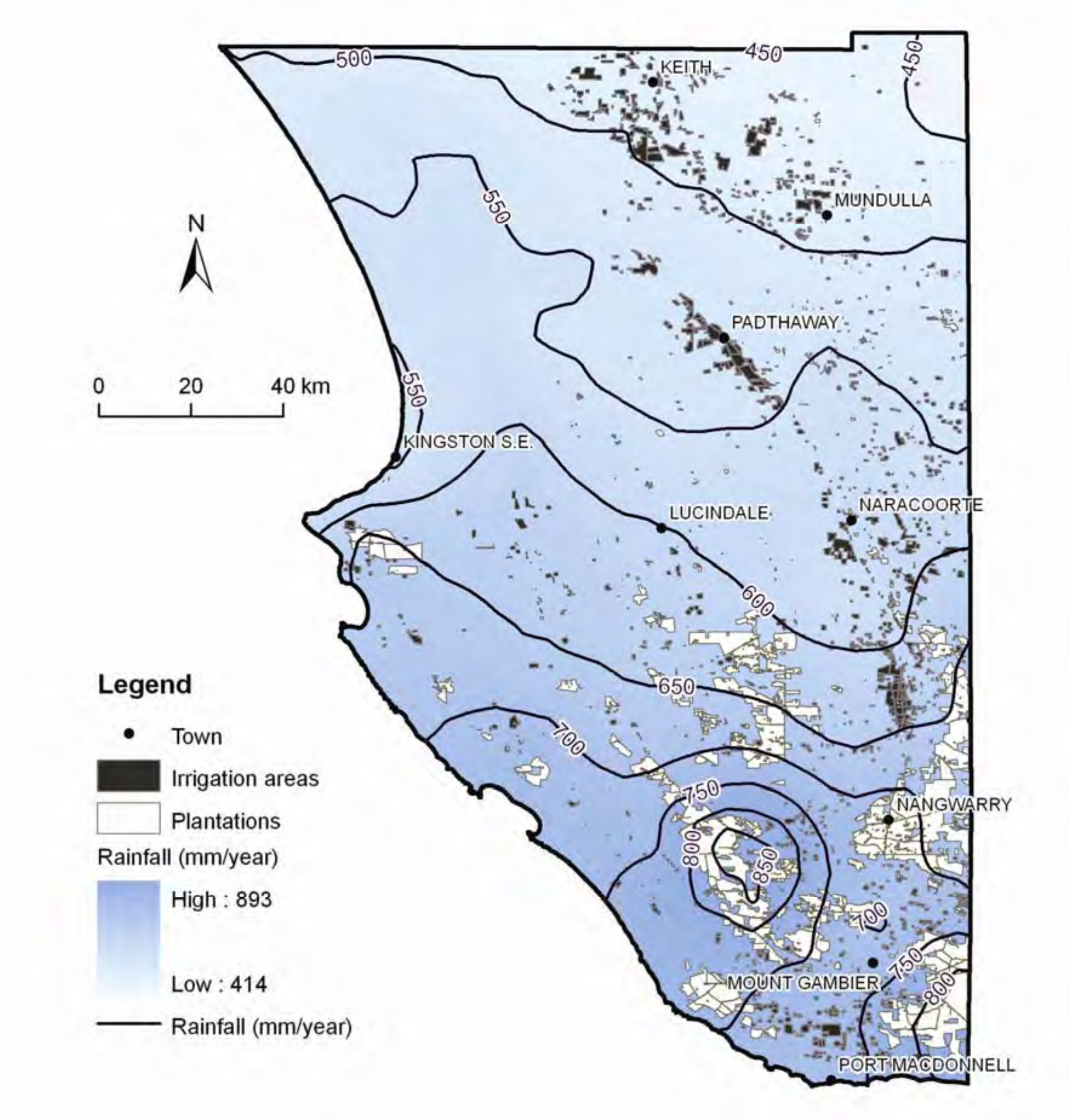

Figure 11 - Long term average (1961-1990) rainfall contours for the study area

A further analysis of the climate data showed close correlation between long term (30years) data and the climate data for the shorter period of 1995-2007 chosen for the water balance analysis. Figure 12 shows this comparison for the rainfall data at Mt Gambier station (Site 026021). Similar analysis on other locations resulted in an average annual rainfall and evaporation values that were close to the long term values (e.g. average annual rainfall after 1995 was 95% of the 30-year averages and average ET_0 was 98% of the 30-year average annual potential evapotranspiration). These figures were used to scale the long term average rainfall and evpotranspiration figures for the whole region to the period of water accounting accordingly.

Surface water inflow - The catchment contains a small number of well defined flow paths that exist primarily as ephemeral creeks. A number of these have their headwaters in Victoria. The Naracoorte and Morambro Creeks are two of the few well-defined streams with significant portions of their contributing catchments in Victoria. The other principal streams are Tatiara Creek, Nalang Creek, Mosquito Creek and

Glenroy Creek. These creeks mostly discharge into swamps and runaway holes. The Mosquito Creek catchment, which flows into Bool Lagoon, generates the largest and most consistent flows of the creeks in the central catchment area, being fed by two tributaries in Victoria. The Glenroy Creek is located east of Coonawarra and is formed by a series of inter-connected swamps with no available flow record.

All the data were obtained from the DWLBC's surface flow archive (website: http://e-nrims.dwlbc.sa.gov.au/swa/map.aspx). The main creeks flowing as surface inflow are Mosquito Creek with a mean annual total flow of 10.8 GL, Naracoorte Creek (2.5 GL), Morambro Creek (2.1 GL), Nalang Creek (~ 1 GL) and Tatiara Creek with 1.2 GL/year giving a total of 17.52 GL surface water inflow to the region.

Surface water outflow - There are two types of drains flowing out to the sea: surface drains and ground water-fed system of drains which are deeper drains collecting groundwater or are fed by springs before they flow out of the region and to the sea. All surface water flow data were obtained from the Department of Water Land and Biodiversity Conservation (DWLBC) for the gauged flows and estimated (in consultation with DWLBC staff) for ungauged flows. Table 2 summarises the surface drainage data for the outflow calculations.

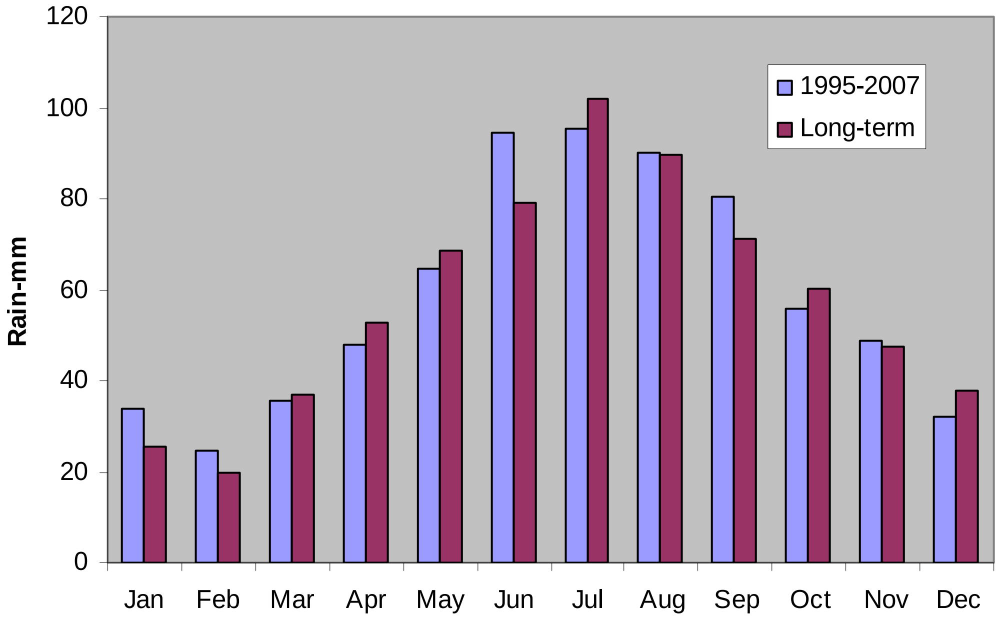

Figure 12 - Comparison of long term (30 year) rainfall with the rainfall in the water accounting period (1995-2007) at Mt Gambier

Table 2. Surface drainage data used in the water balance analysis

station	Description	Period of record	Mean annual flow (ML) (since1995)
Gauged flows			
A2390532	Drain 44 @ 100m U/S Lake Bonney Rd Bdge.	1976- date	3718
A2390513	Reedy Creek - MT. Hope Drain @ 7.2km NE South End	1971- date	14220
A2390505	Drain L @ Boomaroo Park Amtd 7.3 km	1972- date	75376
A2390506	Blackford Drain @ Amtd 4.0km	1971- date	20400
A2390568	Salt Creek outlet @ Salt Creek	2000- date	7805
A2390512	Drain M @ Woakwine Amtd 5.1km	1971- date	28490
A2390523	Stony Creek@ Woakwine Range	1973- date	3025
A2390533	Drain 48 @ 200m U/S Lake Bonney Rd Bdge	1976- date	12665
Ungauged flows			
	Cape Douglas Outlet Drain	N/A	500
	Mt Benson Drain	N/A	2000
	Butchers Gap Drain	N/A	2400
Total surface drainage			106400

Groundwater- fed drainage discharge - There are a number of small but regionally significant coastal streams south of Mount Gambier that are fed by groundwater discharge from the unconfined aquifer. The main spring fed streams that discharge to the sea include Deep Creek, Eight Mile Creek, Cress Creek and Piccaninnie Ponds outlet. Table 3 gives a summary of total volume of flow discharging through these systems annually.

Table 3. Groundwater-fed drainage discharge used in the water balance analysis

station	Description	Period of record	Mean annual flow (ML) (since1995)
239508	Eight Mile Creek	1970- date	52658
239507	Deep Creek	1970- date	22816
239570	Cress Creek	2004- date	4498
239509	Piccaninnie Pond	1970- date	17342
Total gw-fed drainage			97315

Recharge to groundwater - Here we refer to recharge as the volume of water moving vertically through the soil, passing the root zone and adding to the groundwater storage. This definition ignores the possibility of lateral movement of water and away from vertical direction. In the South East region, there are a few different mechanisms controlling groundwater recharge (see section 4.3). These briefly consist of diffuse recharge identified as infiltration of rainfall and irrigation or seepage from wetlands and swamps and point source recharge through sinkholes, drainage wells and runaway holes. We used the mean annual values of recharge calculated by Brown et al. (2006) mostly with the watertable fluctuation method using the water level observation network. These values, ranging from 15 to 200mm/year, are shown in Figure 7 for all groundwater management zones in the region. At the regional scale these annual recharge values were spatially weighted to get the total average annual recharge for our study area. Effect of forestry on recharge was then considered as a forestry recharge debit adjusted by the mean area of forestry in the period of analysis (assumed 110,000 ha in the period 1995-date). These calculations resulted in a mean annual volume of 1110 GL of recharge.

Estimating evapotranspiration (ET) - A significant proportion of the water entering the surface in the region, either as rainfall, groundwater extraction or surface flow, will leave the surface as evapotranspiration from different parts of the catchment and with different rates according to the land use. For estimating average annual ET in the catchment, gridded land use data (50m resolution) for the study area were categorised into 5 classes: irrigated areas, dryland agriculture, plantation forestry, natural vegetation and wetlands/water bodies. The areas under each land use class were then determined in GIS. In the absence of actual ET measurements a different method of ET estimation was used for each class. These are described in this section:

Irrigation areas - For areas under irrigation, ET estimation requires specific crop water use (ET_c) calculations. These were calculated mainly following FAO 56 methodology (Allen et al. 1998) which is based on the relationship between potential reference crop evapotranspiration (ET_0) and a crop factor (Kc) as in equation (2).

$$ET_c = ET_0 * Kc \tag{2}$$

Monthly ET_0 values in mm were obtained from the climate data together with the information reported on land use and crop mixes under irrigation (Binks, 2000, Kelly & McIntyre, 2005, Kelly& Laslett, 2002 and Kelly & Laslett, 2003) to calculate the actual ETc according to equation (2). *Kc* values for different crops were taken from published values (Skewes 2006, Christiansen and Hargreaves 1969, PIRSA Solutions 2000). Estimated values of ET_c were compared with the reported water use for different crops and in some cases adjustments were made (e.g. under-irrigation in vines for better quality of wine). Average annual volume of actual ET from the irrigation areas (in GL) were then calculated from our study area (an average of 65800 ha) as a total of 404 GL/year.

Dryland agriculture - This land use class includes cropping, grazing and some perennial horticulture. For these areas, an estimate of ET was made based on average empirical values suggested by Zhang et al. (2004) based on the work of Fu (1981).

Actual evapotranspiration is calculated in the model using the following equation from Fu (1981):

$$\frac{ET}{P} = 1 + \frac{ET_0}{P} - \left[1 + \left(\frac{ET_0}{P}\right)^w\right]^{\frac{1}{w}} \tag{3}$$

Where:

ET = actual evapotranspiration

ET_o = potential evapotranspiration

P = rainfall

w = a model parameter

Evaporation is determined by water supply (rainfall) in dry environments and energy supply (radiation) in wet environments. A single-parameter hyperbolic function (Equation 3) interpolates between dry (rainfall limited) and wet (energy limited) total evaporation rates. The value of this parameter (w) describes the influence of catchment land characteristics and vegetation on actual evapotranspiration. In a water balance study of over 270 Australian catchments, Zhang et al. (2004) found an average value of 2.55 for w parameter to give good ET prediction (by Fu's model) against the observed data for grass land use. It was argued that the empirical parameter w can represent the integrated effects of catchment characteristics such as vegetation cover, soil properties, and catchment topography on water balance (Zhang et al. 2004). It was postulated that quantification of this parameter according to the cachment characteristics would be difficult. Adopting the average value (2.55) for w parameter in equation (3), the average annual ET from dryland areas was estimated to be 500 mm in the region. This amounts to 7687 GL of water each year.

Plantation forestry - Plantation forestry covers more than 140000 ha of land in the study area and it has been expanding during the last 10 years. An average area for forestry during the water accounting period was estimated as 110,000ha (R. Benyon, per. Comm.) As discussed in previous sections of this report, water use by tree plantations in the region has been studied mostly on shallow groundwater areas and in closed canopy (Benyon 2002 and Benyon and Doody 2004). An average water use of 944 mm/year was reported under these conditions which use ground water directly as a source (Benyon 2004). To consider an overall average water use (ET) by forestry, we need to take into account the relative areas on shallow water table (<6 m depth), the mix of different trees (pine plantation vs. blue gum) and the whole crop cycle water use (i.e. there are periods before canopy closure and after harvest). Based on these factors and previous experience, an average annual ET for the plantation forestry was estimated to be around 740mm/year (R. Benyon, Pres. Comm.). This amounts to an average of 814 GL of water which is used as evpotranspiration each year from the plantation areas.

Natural vegetation - There are large areas of land (more than 250,000ha) under this class of land use including nature conservation, grazing natural vegetation and managed resource protection. Some of the typical native vegetation in the region include Red-gum woodland (*Eucalyptus camaldulensis*), Stringy-bark forests (*E. baxteri, E. arenacaea, E. obliqua*), and grassy woodlands.They are highly variable in terms of vegetation composition, structure and spatial arrangement which are likely to affect their water use. Schulze (2007) used the concept of the crop coefficient, similar to the equation (2), for the natural vegetation in South Africa for estimating water use and fluxes in agrohydrological modelling. Typical values of crop coefficients were assigned to forests, grassland and bushlands in different vegetation classes (Schulze 2007). Although useful for estimating water use in hydrological modelling, the concept of the crop coefficient is mostly used for maximum plant ET (i.e. not a water limited condition). There are indications that as the dryness index defined by the ratio of ET_0 /P increases above 1 (water limited condition), the influence of P (available water) on actual ET increases (Benyon et al. 2005). This is the case in our study area where this ratio is about 2 (1193/600.8) indicating a water limited condition. Here we considered expert opinion on long term average water use of these natural vegetations to be almost the same as the average rainfall for the region (J. Eastham Pers. Comm.). This resulted in a value of 1532 GL as an average annual ET.

Wetlands and water bodies - Wetlands and lakes are the final discharge points for drainage water or used for storage of water. For this class of land use, which includes lakes, reservoir, channels, swamps and wetlands, ET was assumed to be the same as average potential ET.

This resulted in annual ET volumes of 424 GL from wetlands and 347 GL from water bodies. Table 4 summarizes the ET calculations from each land use type.

Table 4. Average annual ET estimates from each land use type

Land use	Area (ha)	Annual ET (GL)
Irrigated land	65,877	404
Plantation forestry	110,000	814
Natural vegetation	268,438	1532
Wetland/marshes	36,306	424
Dryland agriculture	1,536 058	7687
Water bodies	29,720	347
Other areas-residential	45857	
Total-study area	2,092 257	11208

Since large areas of land are under shallow (< 2m) watertable depth, an analysis was done to estimate groundwater contribution to evaporation resulting from capillary upflow. Groundwater contribution from forestry and irrigation areas was already included in estimating total evapotranspiration from these land uses so only dryland agriculture and natural vegetation on shallow watertable areas were considered for this analysis. We looked at a medium soil in the area where the watertable was at 0.5m and at 1 and 2m below the surface. A 1-D simulation with SWAGMAN- Destiny on a fallow land showed an annual maximum of 69mm of upflow from the groundwater when watertable was at 0.5m depth, decreasing to 23 and 0 when watertable dropped to 1 and 2m respectively. Of the total area of about 17000 ha of dryland and natural vegetation on shallow watertable, about 7 GL of capillary upflow can thus be evaporated (~ 6 GL from areas with watertable depth < 0.5m). Overall, the total contribution of upflow to total ET from these land use classes was about 0.13% which is not significant. The contribution of the groundwater to increasing transpiration of crops and natural vegetation in areas with shallow watertable was not considered in this analysis, since the estimation of total ET from these lands are not accurate enough to result in meaningful conclusions. It should be noted that whatever capillary upflow contribution to ET from the groundwater as inflow, it would be considered as outflow from the surface control volume in our analysis, so that it would not affect the water balance calculations.

Considering all components of annual regional water balance comprising all water entering the surface (inflows) and leaving the region (outflows), Table 5 gives a summary of the water balance. The difference (balance) between inflows and outflows is relatively small (21 GL). This is equivalent to only 0.17% water balance error which is surprising given the uncertainties in our estimations. This, without considering uncertainties and some possible compensating errors, is an indication that the system overall is in balance and our estimates roughly describe the physical characteristics of the hydrology of the region (See Fig 13). This does not mean that estimation of each component is without possible errors and hence a range of possible values can be expected. We have not looked at the uncertainties and the ranges of errors in this analysis.

Table 5. Annual regional water balance components

Inflows (GL/year)				Outflows (GL/year)				
Rain	Surface	GW extraction Unconfined	confined	ET	Surface	GW-fed drains	Recharge	Other uses
11942	18	573	30	11208	106	97	1110	20
Total inflows = 12563				Total outflows = 12542				

The results show that a large proportion (90%) of all the water entering the region leaves the surface as evpotranspiration. Of the remaining water, 8.8 % goes to the groundwater as recharge, while less than 2% leaves the region as surface water in drains or creeks. The Permissible Annual Volume of extraction (PAV) from both aquifers is given as a total of 995 GL (reported in various sources) which is in the same range as the estimated annual recharge of 1110 GL.

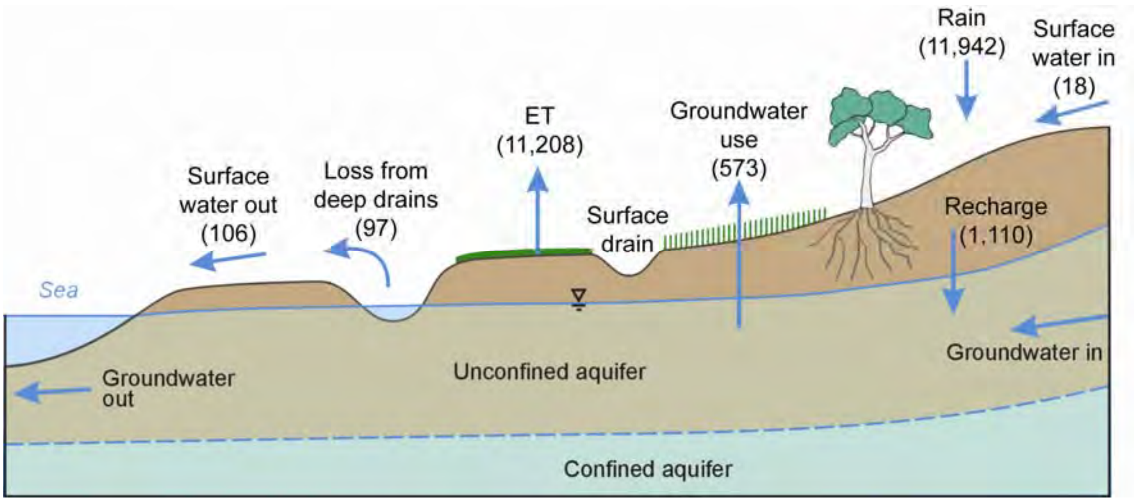

Figure 13 - Average annual regional surface water balance components (GL)

Of the total annual evpotranspiration of 11208 GL from the region, irrigation accounts for only 404 GL or about 3.6% of total ET. Plantation forestry uses 814 GL or about 7% total ET. Not all of this water use comes from the groundwater and in our analysis we have not separated the sources of water use (i.e. rainfall and groundwater). There are some indications from the published data; however, that irrigation use of groundwater might be in the range of 240 GL (based on an average extracted irrigation water of ~400 GL and ~60% net water use (Kelly & McIntyre, 2005, Kelly & Laslett, 2002 and Kelly & Laslett, 2003)) while forestry impact is in the range of 260 GL (based on direct groundwater use of forestry of 150 GL and a recharge reduction of 114 GL (Brown et al. 2006)). Converting these figures to ML of groundwater use (or impact) per hectare of land, irrigation water use is in the range of 3.6 ML/ha (360 mm), whereas forestry on the average has an impact of 2.4 ML/ha (240 mm) on the groundwater. This shows that, on a unit land area basis, irrigation has a higher impact on the groundwater than the forestry.

The average annual volume of water applied for irrigation is 400 GL/yr or 605 mm/yr which, when added to the average rainfall of 570 mm/yr, yields a total of 1175 mm/yr. Based on the first order approximations made in this study, if only 630 mm/yr (404 GL/yr) is evapotranspired from these lands, then the rest (545 mm/yr) is going back to the aquifer. Thus, on average (across all soil, crop and irrigation system types) about half (46%) of the total water applied as rrigation or rain is returned back to the aquifer. This simplified anlysis does however neglect the timing of rainfall, irrigation application, crop water use and fallow periods. In reality, a higher proportion of irrigation water returning to the aquifer will be expected under flood systems and lighter soils and much lower rates under more-efficient systems.

It should be noted that this regional water balance gives an overall picture of the hydrology of the system. It does not consider the year to year variation of the terms for accounting water balance as the conditions will change in a wet year compared to a dry year. It also does not consider the spatial distribution of these components as they are averaged in space and time with rough estimates and assumptions. These should be kept in mind when interpreting the results.

4. Closing comments

This report has summarized the current understanding of the hydrology of the Limestone Coast, South Australia based on a literature review, collation of a considerable amount of data and a simplified model of the water cycle as a first cut regional water balance analysis. At the regional level, it showed that a substantial (~ 90%) part of the water input to the region is consumed through either plant transpiration or evaporation from water bodies, wetlands and soils. Irrigation only contributes to about 4% of this total ET, though it consumes a substantial part of the groundwater extraction in the region. Plantation forestry is considered as a “water use” activity as it affects the water balance, not only by reducing recharge to the aquifer, but also by direct use of groundwater by trees in shallow groundwater areas. Its share of the total regional ET is around 7%. In the south of the region, the flat landscape and porous soils result in little or no surface run off and no major natural surface drainage despite the high rainfall. Most of the rainfall not evaporated or transpired by vegetation is recharged to the unconfined aquifer. Around 9% of the total rainfall is recharged to the aquifer and that is the major contribution to this huge groundwater resource (estimated around 1000 GL as permissible annual volume). Around the southern coast, significant quantities of groundwater discharged to short streams or ponds before flowing into the sea (~97 GL). This groundwater discharge also supplemented the surface waters of the coastal lakes and drains (~ 106 GL) presented as soakage on the landscape and springs near to the coast.

The regional water balance gives an indication of the relative contribution of different components of the water cycle at the steady state and at the system level and as such it does not show the spatial and temporal variability of these terms. This is an important issue when dealing with the potential expansion of irrigation industry and the impact of different water use activities in the region.

Based on our study, the following recommendations are made for future studies related to the hydrology of this region:

- Spatial variability in aquifer recharge and discharge processes and groundwater salinity identifies the importance of spatial analysis with respect to land use change and impact on the hydrology and groundwater management of different parts of the catchment. For example, the higher groundwater salinities found in the north-west of the region are likely to be a result of a combination of lower vertical recharge rates, reduced aquifer flushing, relatively small aquifer thickness, and increased evaporative discharge. Adoption of efficient irrigation practices in areas of intensive irrigation where groundwater salinity levels are increasing is an important consideration for salinity control. This study has not looked into the water quality issues or spatial distribution related to recharge and discharge. Any future hydrological studies should consider this spatial variability and the water quality issues to better quantify the dominant processes.

- More accurate estimate of the regional evapotranspiration is required, since it accounts for a significant part of the water balance. Remote sensing techniques are promising in this regard to capture the spatial distribution of ET in the region.
- Expansion in irrigated agriculture is likely to present the most significant new demand for water resources. Within the irrigation industry there is likely to be a further shift towards higher value crops (e.g. vines), increasing the economic value derived from the resource. Groundwater will continue to be the main source of water supply for irrigation. This should be addressed with a multiple objective and constraints in mind in meeting an increasing demand on land and water resources of the region. It is proposed that a spatial multi-criteria analysis linked to 1-D modeling would be used for analysis of these expansions showing suitable areas in terms of soils, groundwater and water quality issues and the impacts on water balance and crop production.
- The static analysis in this report is only the first step towards building a fully dynamic model of the surface and groundwater for the Limestone Coast. Such a dynamic model is needed for an integrated approach for studying impact of different scenarios (e.g. climate, land use change) on water resource management. The model could make full use of the spatial data in the 3-D conceptual model. The challenge for the region is then to develop a holistic water management regime that allows forestry and other groundwater users to continue to prosper within sustainable limits of the resources. The management regime also needs to balance the needs of the environment, with all other water users for a sustainable future through protecting both water quality and the physical integrity of the water resources (mainly the aquifer system).

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