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## Hydrology of Lakes Nunijup, Poorrarecup and Carabundup

Salinity and Land Use Impacts Series

REPORT NO. SLUI 26  
JUNE 2009



# Hydrology of Lakes Nunijup, Poorrarecup and Carabundup

by

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Department of Water

Salinity and Land Use Impacts Series

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Lake Poorrarecup by Kevin Hopkinson

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## Summary

The earliest signs of emerging salinity in the Upper Kent catchment were noticed in major freshwater lakes such as Poorrarecup and Nunijup which became saline in the late 1960s. The three large lakes of this study retain surface water runoff from the catchment. Their median salinities are respectively 8000, 10 600 and 15 000 mg/L TDS. Anecdotal evidence is that Lakes Poorrarecup and Carabundup have not dried up or overflowed in the last 20 years while Lake Nunijup overflowed briefly in 1982 but there is no inflow data for these lakes.

Good management of the upper catchment is the key to reducing salinity in the Kent River which is a potential water resource for the south coast region but currently non-potable. Its catchment was designated as a Water Resource Recovery Catchment (WRRC) under the State Salinity Strategy (State Salinity Council 2000). After 66% of the upper catchment was cleared of native vegetation between the 1940s and the 1970s, the annual flow-weighted mean stream salinity increased from 250 to 2890 mg/L TDS. The large scale of intervention that will be required for the river to meet the 500 mg/L target by 2030 is reported in the salinity situation statement for this catchment. This statement required a better understanding of the lakes which are the subjects of this report.

The LUCICAT model was used to achieve the objectives of this study: to simulate streamflow and salinity generation processes, understand the salt and water balance of the three lakes, and assess the impacts of tree planting on lake water level and salinity on Lake Nunijup.

The model successfully represented the daily stream flow generation processes of the catchment, and generated inflow and salinity series for the lakes which were used to calibrate the Lake model, in which observed and predicted values matched well.

In the average-flow year of 1990, the spatial distribution of runoff ranged from 3 to 120 mm; and the salt load ranged from 10 to 4.9 tonnes per hectare (t/ha).

Based on catchment and lake water balance, the annual inflow (1973–2001) to Lake Nunijup was 0.72 GL, of which about 70% evaporated and 26% seeped through the lakebed. Average annual salt input to Lake Nunijup was 2080 t, 88% of which seeped through the lakebed.

The average annual inflow and salt load to Lake Poorrarecup (1973–2001) were 2.65 GL and 5300 t respectively. About 78% of the lake water evaporated and 98% of the salt seeped into the groundwater.

The average annual inflow (1973–2001) to Lake Carabundup was 1.9 GL, 84% of which evaporated. Its average annual salt load was 5275 t, 98% of which seeped through the lakebed.

If 25% of the cleared area of the Lake Nunijup catchment was planted to trees, the modelling indicated that the median lake salinity would reduce from 8000 to 3600 mg/L TDS. If 50% of the cleared area was planted to trees, the lake median salinity would be 5300 mg/L TDS with the lake drying out at times.

# 1 Introduction

## 1.1 Purpose and scope

The Kent River catchment is one of five Water Resource Recovery Catchments in the south-west of Western Australia. Following observations of increasing water and land salinisation, legislation was imposed in the catchment in 1978 to control further clearing of native vegetation for agriculture and minimise future salinity increases in the river water. At that time it was recognised that the potential for development of the Kent River as a water supply source was a long-term priority and, given how much clearing had occurred in the upper part of the catchment, salinity was likely to keep rising faster than in the other cleared controlled catchments.

Salt stored in the unsaturated zone of the soil profile was mobilised by increased groundwater recharge and rising watertables following clearing, and eventually discharged into streams (Wood 1924) which became saline (Schofield et al. 1989; Schofield & Ruprecht 1989; Ruprecht & Schofield 1991). How much stream salinity rises depends on annual rainfall and the extent and location of clearing (Schofield & Ruprecht 1989).

As a part of the Kent River recovery process, the then Department of Environment undertook two major studies: *Salinity Situation Statement: Kent River* and this one, on the hydrology of three major lakes.

While the *Salinity Situation Statement: Kent River* (De Silva et al. 2007) looked at the management of the whole upper catchment in terms of stream salinity, this study concentrates on the hydrology, salt and water balance of just three lakes.

The objectives of this study were to:

- simulate the streamflow and salinity generation processes
- understand the salt and water balance of three lakes
- assess the impacts of tree planting on the water level and salinity of Lake Nunijup.

## 1.2 Upper Kent catchment

The *Salinity Situation Statement: Kent River* shows that mean annual salinity at the Styx Junction (Lower Kent) gauging station is still rising but the rate of rise has fallen from 43 (1983–90) to 12 mg/L TDS/yr (1991–98). Salinity at Rocky Glen is also still rising, much more slowly: the rate of rise falling from 81 (1983–90) to 14 mg/L TDS/yr (1991–98). These significant rate changes are attributed to the groundwater system reaching a new equilibrium after clearing, a decline in annual rainfall and extensive bluegum plantations established on a significant proportion of the cleared areas in the 1990s. The key to lowering salinity in the Kent River is to manage the Upper Kent catchment.

## 1.3 Kent lakes

The earliest signs of emerging salinity in the catchment were seen in the salinisation of major lakes of the upper catchment. Freshwater lakes such as Poorrarecup and Nunijup became saline in the late 1960s. The three large lakes in the upper catchment — Nunijup, Poorrarecup and Carabundup — are the natural disposal points for discharge from the catchment and their salinities may have risen as a result of forest clearing and lower rainfall,

possibly caused by climate change. The lakes are important assets not only as water resources but also as parts of wetlands that protect the biodiversity of the catchment. As the lakes and their immediate surroundings provide precious habitat for many native species of fauna and flora, it is important to protect the buffer zones from salinisation. The local community also uses these lakes for recreation.

The results are important in understanding the role of lakes and how much salt and water are stored in the lakes or exported to the main channel of the Kent River. The management options proposed in the *Salinity Situation Statement: Kent River* are based on the lake salt and water balances reported here.

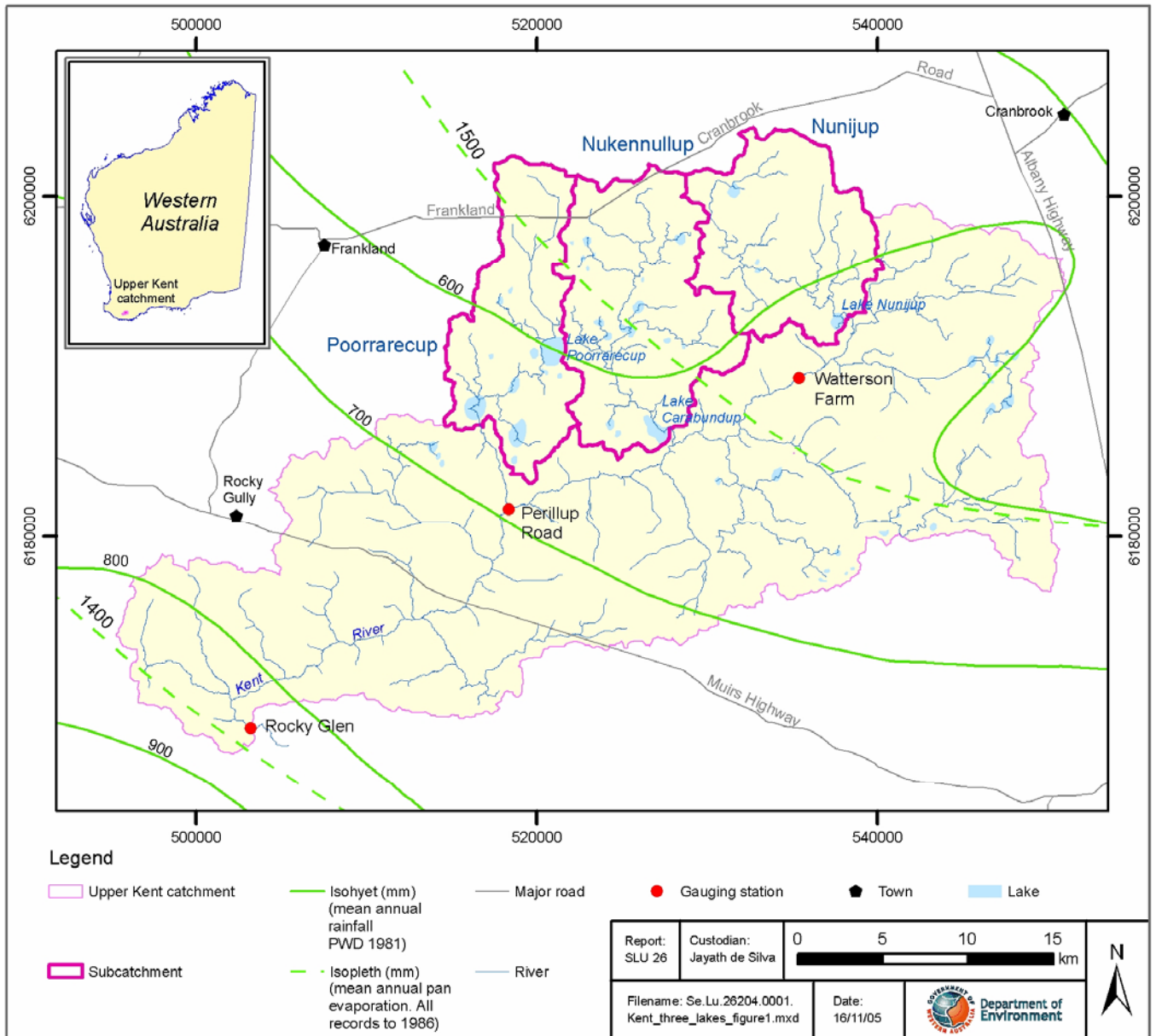
## 1.4 Methodology

An objective of this study was a basic understanding of the salt and water balances of these three lakes. The catchment hydrology model (LUCICAT) simulated the streamflow and salinity generation processes of the catchment and created a long-term inflow series to these lakes which was used with a simple spreadsheet-type lake model (Peck 2000) to understand the salt and water balances. The LUCICAT and Lake models were used to evaluate the effects of tree-planting options on the water level and salinity of Lake Nunijup.

## 2 Catchment description

### 2.1 Location and climate

The Upper Kent catchment (the upper catchment), with an area of 1092 km<sup>2</sup>, is in the south-west of Western Australia and lies in the shires of Cranbrook and Plantagenet (Fig. 1).



**Figure 1** Location of the Upper Kent catchment and the three lakes

The climate is generally described as Mediterranean-like with hot dry summers and cool wet winters. From the inland divide to the coast, mean annual rainfall varies fairly evenly from 550 to 1200 mm, mean annual evaporation ranges between 1500 and 1200 mm and mean summer maximum temperatures vary from 27 to 24 °C.

## 2.2 Physiography and drainage

The upper catchment (Fig. 1) falls completely within the broad physiographic unit of the Darling Plateau that can be further divided into ancient and rejuvenated landscapes. Elevation within the catchment ranges from 180 m AHD near the Rocky Glen gauging station to 400 m AHD (Geekabee Hill) in the upper catchment.

The ancient-landscape part of the upper catchment is characterised by undulating landforms, broad flats and lakes. The undulating landforms extend from the central zone of broad flats and lakes up to the catchment divides and mainly have lateritic soils. The central broad flats, with less than 3 degrees slope, have a number of major lakes such as Nunijup, Poorrarecup and Carabundup. Being so flat, the ancient landscape has weakly-developed drainage. Most of the lakes, including Nunijup, Poorrarecup and Carabundup, form an internal drainage area that occupies 30% of the upper catchment. There have been few observations of overflow from this area into the river even after large-scale clearing has increased surface water runoff.

The rejuvenated landscape in the south-west of the upper catchment has a well-developed dendritic drainage pattern with V-shaped valleys. The soils are generally lateritic, with the exception of podzols and the loamy red earths.

The broad Tertiary alluvial flats that occupy the central part of the upper catchment mark the palaeodrainage system of the Darling Plateau. Geological processes associated with the separation of Australia from Antarctica, including the sagging of the earth's crust, interrupted and ended this pronounced northward- and westward-flowing drainage by the Eocene (Smith 1997), about 43 million years ago. In the Late Tertiary (about 38 million years ago), the sediments associated with the palaeodrainage system were uplifted to their present height of more than 300 m AHD. This uplift also initiated the present day southward drainage of the western south coast region, including the Kent River. This relatively short drainage pattern was rejuvenated by southward tilting (possibly in the Oligocene) which formed the Ravensthorpe Ramp (Smith 1997).

## 2.3 Soils and landforms

The Kent River catchment area varies from gently undulating upland plateau in the north to swampy coastal plain in the south before the river discharges via the Irwin Inlet to the Southern Ocean. The northern part of the catchment consists mainly of low gravelly ridges that separate broad and shallow valleys that contain many swamps and lakes, particularly in the central portion of the upper half of the catchment. The soils of the area, especially in the upper catchment, are mostly yellow podzolic with lateritic duricrusts and gravels on ridges with leached sands occurring in depressions overlaying pallid zone clays. Red loams derived from weathered granite and yellow podzolic soils become dominant in the central and lower parts of the catchment.

## 2.4 Vegetation and land use

The native vegetation consists of karri (*Eucalyptus diversicolor*) forest on the hilly, higher rainfall areas inland from the coastal strip grading to predominantly jarrah forest (*E. marginata*) of medium to low density in the central, intermediate rainfall portion of the catchment. Mixed jarrah, wandoo, and swamp yate open woodland can be found further north as rainfall decreases. Broad swampy drainage lines carry paperbark (*Melaleuca spp.*), banksia (*Banksia spp.*) woodlands and sedge swamps while sandy flats have a low-density

mix of jarrah, marri (*E. calophylla*), wandoo (*E. wandoo*) and swamp yate (*E. occidentalis*). Much of the forest structure in the upper central and upper portions of the catchment has been disturbed by timber felling or removed for agricultural development.

Although the history of settlement and development by Europeans is relatively short, the impacts on the environment have been considerable. The use of forest resources expanded rapidly between the 1880s and 1920s to cater for local and export timber demand but the main impacts were on areas close to the coast where supply was plentiful and transport cheaper.

The greatest impacts of the broadacre clearing of land were in the upper half of the catchment where less than 10% of the area had been cleared by 1946, 46% by 1965 and 66% by 1978, when, with the emerging realisation of the relationship between clearing and secondary salinity, clearing controls were placed on the Kent Recovery catchment. By this time, 40% of the total catchment area had been cleared.

The clearing control legislation limited clearing in the catchment under licence to a further 4800 ha, predominantly in the lower salinity-risk areas. Some 6700 ha of predominantly 'bush' areas in the upper part of the catchment were acquired by the then Water Authority as a result of compensation provisions in the legislation and most of this cleared land was 'sold' to nearby landowners, mostly as part of a compensation provision and in an effort to retain farm viability. The remaining 33 000 ha is private land, protected from outright clearing but at great risk of degradation from the impacts of grazing, waterlogging and salinity. Some areas have been replanted with both commercial and non-commercial tree species, depending on the capability, or state of degradation, of the land involved.

## 3 Hydrogeology

### 3.1 Hydrogeological setting

The three lakes — Nunijup, Poorrarecup and Carabundup — are located within the Albany–Fraser Hydrogeological Province and on major lineaments identified by magnetic intensity surveys. The Boyup Brook Fault runs close to Poorrarecup and Carabundup whereas Lake Nunijup is on the Tenterden Fault.

The lakes are mainly within the Quaternary (Q) and Tertiary (T) or Cainozoic (Cza) sedimentary formations (Fig. 2). Under these lakes, the sedimentary profile may extend into weathered and fractured bedrock at around 30 m depth. The sedimentary profile may comprise clay, lignite, sand and gravel. Some of the lakes are also associated with Eocene or Miocene Palaeochannel Sediments. These three lakes are bounded by lunettes formed during periods of arid climate by wind that reworked the sediments of the lake floors.

Groundwater in areas close to these lakes is very shallow — from 0.5–3 m below ground level (m bgl) with up to a metre variation seasonally. In some situations, the lakes are considered to be a ‘window’ to the groundwater.

The salinity range of groundwater under these lakes is 10 000–15 000 mg/L TDS, which is much less than under lakes like Lake Toolibin where groundwater salinity exceeds 35 000 mg/L. This difference in salinity can be attributed to differences in rainfall: the Kent lakes are in the intermediate rainfall zone whereas Lake Toolibin is within the low rainfall zone.

### 3.2 Lake-groundwater flow regimes

Based on the groundwater flow regimes in and around them, the lakes can be classified into three main groups: flow-through, discharge and recharge (Fig. 3). Flow-through lakes have capture zones on their upgradient side and release zones on their downgradient side (Fig. 3). Groundwater discharges in the capture zone and lake water recharges the groundwater aquifer in the release zone.

According to Townley et al. (1993), some lakes on the Swan Coastal plain move between recharge and flow-through regimes or between flow-through and discharge regimes without necessarily fluctuating all the way between recharge and discharge regimes. Monitoring of the lake water and groundwater indicates that Lake Nunijup fluctuates all the way from recharge and flow-through to discharge regimes.

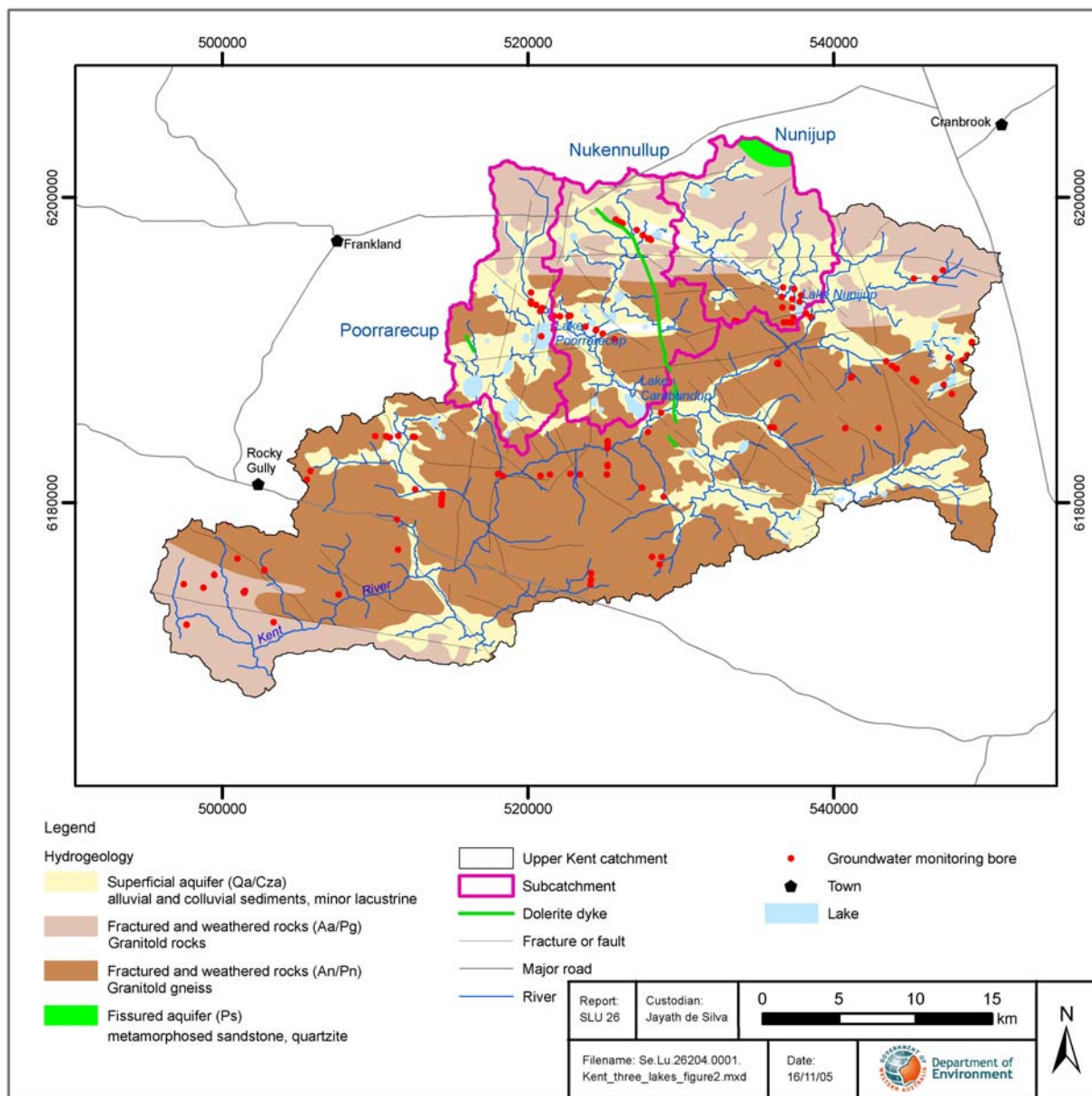


Figure 2 Hydrogeological setting

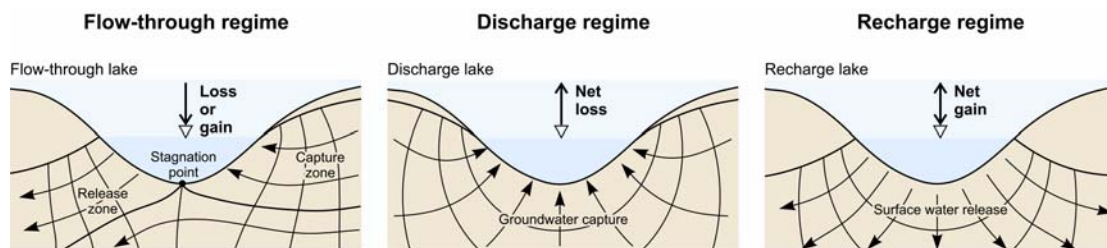


Figure 3 Flow-through, discharge and recharge regimes of lakes (after Born et al. 1979)



### 3.3 Case study – Hydrogeology of Lake Nunijup

The area around the lake is mainly underlain by weathered basement rocks (Pg and Pn), Cainozoic surficial sediments (Cza) and Tertiary palaeochannel sediments (Tpw) (Fig. 2). Lake Nunijup is on a broad flat of Cainozoic sediments (Cza) and Palaeochannel sediments (Tpw). The profile of Cainozoic sediments, which are widespread in the Lake Nunijup area, consists mainly of clay with ironstone gravels and an indurated ferricrete layer within the top 3 m. The salinity of groundwater within this aquifer varies significantly, from 1800 mg/L at NU 6 to 15 000 mg/L at NU 3. Figure A1.1 in Appendix 1 shows the locations of the groundwater monitoring bores on an aerial photograph taken in 1999, and Figure A1.2 shows the hydrogeology.

Bores NU 8, 9 and 12 were drilled into the paleochannel sediments. The general profile of these sediments is of about 7 m of clay overlying fine- to coarse-grained sand with an indurated ferricrete layer within the top 2–3 m. The palaeochannel sediments aquifer is confined by a layer of clay in NU 8 and 9 but, in NU 12 near the lake, this aquifer is unconfined and the depth to palaeochannel sand is less than 3 m. Groundwater salinity varies from 6500 to 14 000 mg/L although during drilling a relatively fresh water layer, with salinity about 1800 mg/L, was observed above the saline groundwater.

The weathered bedrock aquifer (Pn) bounds the western edge of Lake Nunijup. Bores NU 4 and 5 are drilled into this aquifer. The profile consists of ironstone gravelly clay, ferricrete and grey kaolinitic clay that grades into saprolitic grit (fragments of moderately weathered basement rock). The groundwater salinity ranges from 8000 to 13 900 mg/L. A transect across the valley through bores NU 7, 6 and 5 would show a significant decrease in salinity towards the lakes. Groundwater salinity also decreases significantly in the downgradient side of Lake Nunijup compared to background groundwater salinity values, possibly because less saline lake water is recharging groundwater (Fig. A1.3).

#### 3.3.1 Groundwater monitoring

Groundwater is generally shallow; < 3 m below ground level (Fig. 4). NU 9, drilled into a palaeochannel, has the shallowest water, with the water level about 0.3 m below ground level in October 2001 but about 1 m below ground level in March 2002 after evapotranspiration during summer. NU 5, in weathered bedrock, has the deepest water level and fluctuated between 2.1 m and 2.6 m below ground level during winter and summer.

Figure 5 shows the interactions between groundwater and lake water levels. Following winter rainfall, the lake level stabilises above the groundwater levels indicating that lake water may be recharging the underlying groundwater. However, during summer, lake levels appear to fall below groundwater levels (NU 2) which would enable groundwater to discharge through the lakebed. Long-term monitoring of groundwater and lake water is required to find the level of lake water that initiates groundwater discharge into the lakebed.

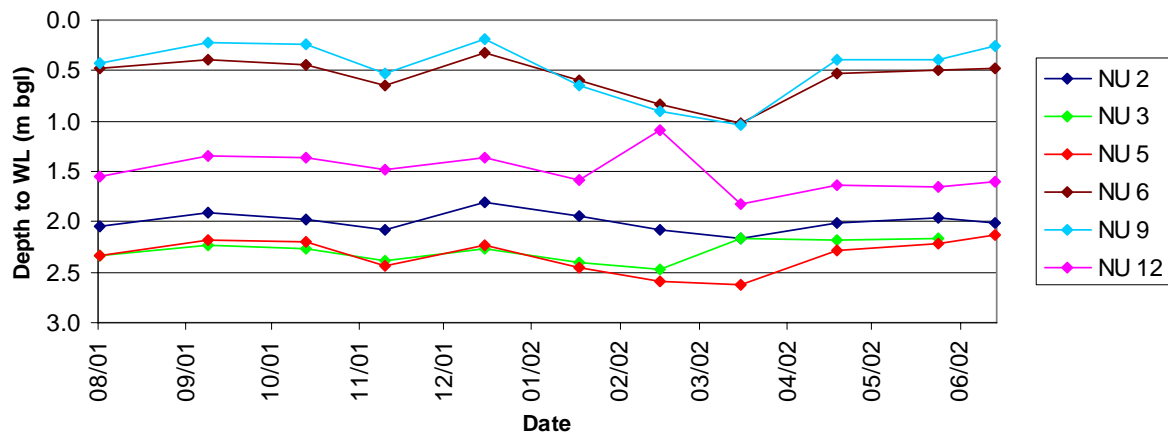


Figure 4 Groundwater levels in monitoring bores from August 2001 to June 2002

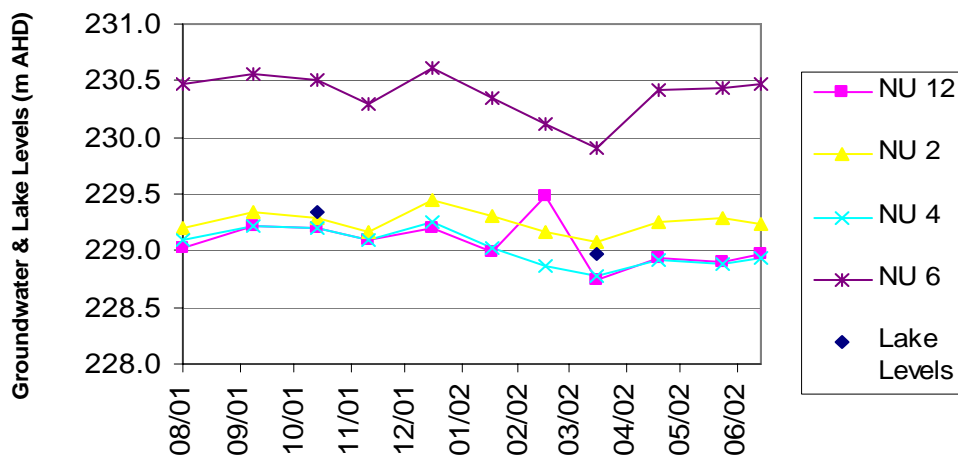


Figure 5 Groundwater and lake levels near Lake Nunijup

### 3.3.2 Groundwater flow

Groundwater contours and flow lines were constructed using groundwater level measurements for December 2001 (Fig. A1.4) and March 2002 (Fig. A1.5). Two major groundwater flow systems were identified: through the Surficial and Palaeochannel Sediments (Flow 1) and through basement rocks (Flow 2). Groundwater flow across NU 9 to NU 3 represents Flow 1 with a hydraulic gradient of 0.001 across Nunijup Lake. Flow 2 is generally from west to east towards the broad flat. The gradient of Flow 2 is about 0.01, and steeper than that of Flow 1.

Groundwater flow near the lake showed considerable seasonal variation during December 2001 to March 2002. Groundwater flow in December (Fig. A1.4) suggested that groundwater flows through the underlying sediments of the lake system in response to winter recharge to the groundwater system from May to September. However, when lake levels drop due to evaporation from the lake surface from January to March, groundwater may start discharging into the lake as demonstrated by the flow lines in March (Fig. A1.5).

### 3.4 Lake and groundwater interactions

Four main types of lake water and groundwater interaction can occur in Nunijup Lake, depending on factors such as inflow to the lake, evapotranspiration losses from the lake and from groundwater, and recharge to groundwater.

- Interaction # 1: Lake level > groundwater level and groundwater level > lake bottom

In this scenario, the lake level rises as surface water flows into the lake after winter and spring rainfall. The lake water recharges the groundwater system (net gain) through the lakebed and the lake loses salt into the groundwater system. This results in increasing groundwater seepage areas downstream and the lake also overflows. During this period, lake remains as a recharge lake (Fig. 3).

- Interaction # 2: Lake level = groundwater level and groundwater level > lake bottom

This scenario may exist in January and February when the high evapotranspiration rate makes water loss from the lake faster than loss from the shallow groundwater. The lake changes from a recharge to a flow-through lake (gain or loss to groundwater). Figure A1.4, based on December groundwater levels, shows groundwater-contour pattern around the lake for a flow-through regime.

- Interaction # 3: Lake level < groundwater level and groundwater level > lake bottom

With further reductions in lake level due to evapotranspiration losses during March and April, the flow regime changes from flow-through to discharge (Fig. 3). Groundwater discharges into the lake (net loss) and the salt load in the lake increases. The rise of groundwater levels in the areas adjacent to the lake will be controlled in this scenario as significant volumes of groundwater discharged into the lake then evaporate. Figure A1.5, based on March groundwater levels, shows the groundwater flow pattern around the lake for this interaction.

- Interaction # 4: Lake level > groundwater level and groundwater level < lake bottom

This scenario may not eventuate under current land use practices in the Nunijup catchment as groundwater levels have risen significantly in relation to the lake bottom since clearing. Groundwater levels need to be lowered by 3 m to achieve this level of minimum interaction between the lake and groundwater. It may not be possible to maintain current lake levels under this scenario but this interaction can be considered as posing the minimum salinisation risk to the catchment and lake.

The groundwater–lake interactions of Lake Nunijup are discussed in detail using a FLOWTHRU model (Appendix 2) and show that the groundwater flow regime changes from time to time in response to stress conditions.

Because there has been a history of groundwater–lake interaction studies at Lake Toolibin (in the Wheatbelt of Western Australia), its hydrogeological characteristics are compared with those of Lake Nunijup (Table 1). The groundwater flow regimes are quite different: the groundwater–lake interaction of Lake Toolibin is limited by the presence of a thick lacustrine plastic-clay layer (De Silva 1999) while Lake Nunijup is likely to be partly filled by groundwater.

**Table 1 Comparison of Lakes Toolibin (Wheatbelt) and Nunijup (Kent)**

<b>Characteristic</b>	<b>Lake Toolibin</b>	<b>Lake Nunijup</b>
Mean annual rainfall	400 mm	500 mm
Mean annual evaporation	1900 mm	1500 mm
Lake floor	10 m thick plastic clay	Sand, gravel
Aquifer	Confined	Unconfined or watertable
Groundwater pressure/level	0.2 m above lake floor (potentiometric head)	Same as ground level to 1 m below ground level
Groundwater salinity	35 000 mg/L TDS	10 000 mg/L TDS
Lake salinity (median)		8000 mg/L TDS (fresh before 1970)
Lake level	Dry most of the time	Not dry since 1983
Groundwater–lake interaction (winter)	No interaction	Flow-through
Groundwater–lake interaction (summer)	No interaction	Discharge
Impact of groundwater discharge on salt balance (lake)	No contribution	Salt loss — winter Salt gain — summer
Impact of groundwater discharge on salt balance (soil, shallow sediments)	Salt accumulation in soil and sediments	

## 4 Salinity and flow characteristics

### 4.1 Hydrology

The Kent River (Fig. 6) has two distinct features: the lower reaches have a younger, rejuvenated drainage system that flows in a southerly direction (Lower Kent), while the upper reaches have a more stagnant weakly-developed drainage system (Upper Kent) that flows in a westerly direction.

The upper Kent River, especially in its northern reaches, has several lakes and swamps that fall within broad flats landform (Fig. 6). About 30% of the upper catchment drains into these lakes that include Nunijup, Carabundup, Nukennullup, Poorrarecup, Wambalup and Katherine. Some, such as Nunijup, Poorrarecup and Carabundup, can overflow into the Kent River, but do so only in peak flood events (Lake Nunijup last overflowed in 1982). Collins and Fowlie (1981) noted that, although these lakes filled well in the winter of 1978, they made no apparent contribution to the flow and salinity of the Kent River. Most of these lakes are bounded by lunettes formed during past periods of arid climate by wind that reworked the sediments of the lake floors.

Three main stations gauge flow on the Upper Kent River: Rocky Glen which has operated since the late 1970s and Perillup Road and Watterson Farm that have operated since 2000. The Lower Kent River is gauged by the Styx Junction gauging station, at the confluence of the Styx and Kent rivers, with flow and salinity records from 1956 (Styx Junction is also a potential dam site for a water supply reservoir). Fortnightly grab samples are taken throughout winter from 20 sample sites operating in the catchment since 2000.

The definition of drainage lines was determined using the Digital Elevation Model (DEM) prepared by the then Department of Land Administration, now Department of Land Information for the Land Monitor Project. In areas where drainage lines were not strongly developed by the topography, and mapping of streams was available from topographic maps, drainage was constrained to following mapped streams.

### 4.2 Runoff and salt load

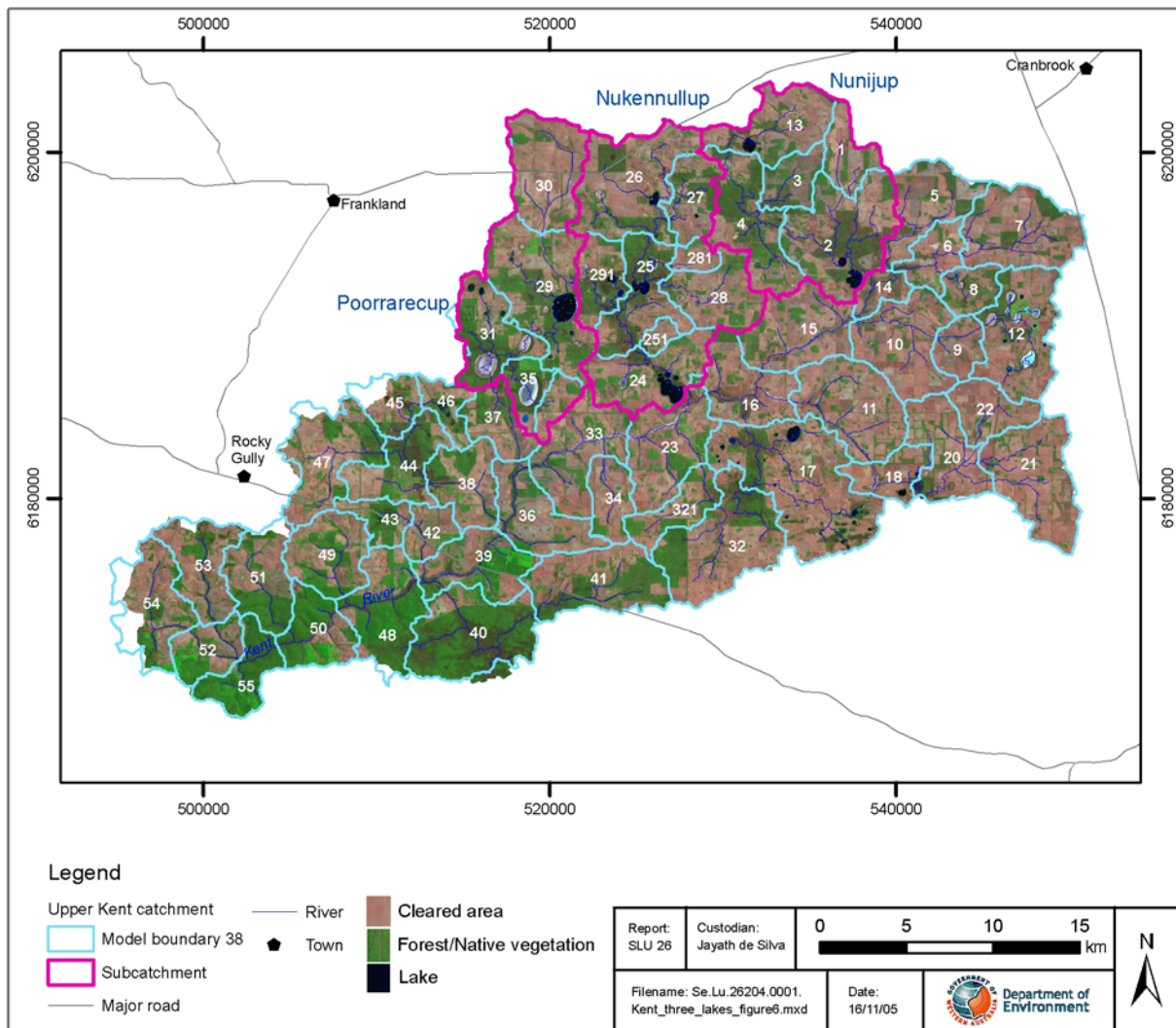
The mean annual runoff (1979–2001) at Rocky Glen was 25 mm but annual runoff varies widely year by year depending on rainfall. The highest and the lowest annual runoffs were observed in 1988 and 2001. Mean annual salt discharge at Rocky Glen was 754 kg/ha and the annual salinity range was 600 to 6500 mg/L TDS.

Most of the streams above Rocky Glen flow during winter. When the rainy season starts in May/June, most of the streams start flowing with very high salinity (more than 10 000 mg/L) due to the flushing of salts stored in the stream zone during the summer months. The lowest daily salinity is generally observed during July–August when the catchment generates most of the runoff. By November, nearly all the streams stop flowing.

LUCICAT is a distributed conceptual catchment hydrology model used to successfully represent the daily flow and salinity generation process of the Upper Kent (see Appendices 3, 4 and 5 for details of modelling and calibration).

### 4.3 Distribution of runoff, salt and salinity

LUCICAT predicted the distribution of annual runoff, salt load and salinity for a representative year (Figs 7, 8 & 9). The distribution of runoff generally reflects the distribution of rainfall (Fig. 6), land use cover, and, to a lesser extent, catchment characteristics. The highest runoff, in excess of 100 mm/year, was from the western wetter part of the catchment, while the yield from the eastern drier part of the catchment was less than 10 mm/year (Fig. 7).



**Figure 6 Stream network, subcatchments, lakes and land use of the upper catchment**

The generation of salt load was particularly dependent upon the proportion of the catchment area cleared and annual rainfall (Fig. 8). Salt loads between 2350 and 4910 kg/ha were predicted from the more extensively cleared western, high-rainfall subcatchments. The salt yield from the eastern drier part of the catchment ranged from 380 to 10 kg/ha (Fig. 8).

The salinity of the runoff generated across the catchment was very variable (Fig. 9), ranging from 270 to 5930 mg/L TDS. Higher salinities were generally associated with lower rainfall and a relatively larger proportion of cleared area.

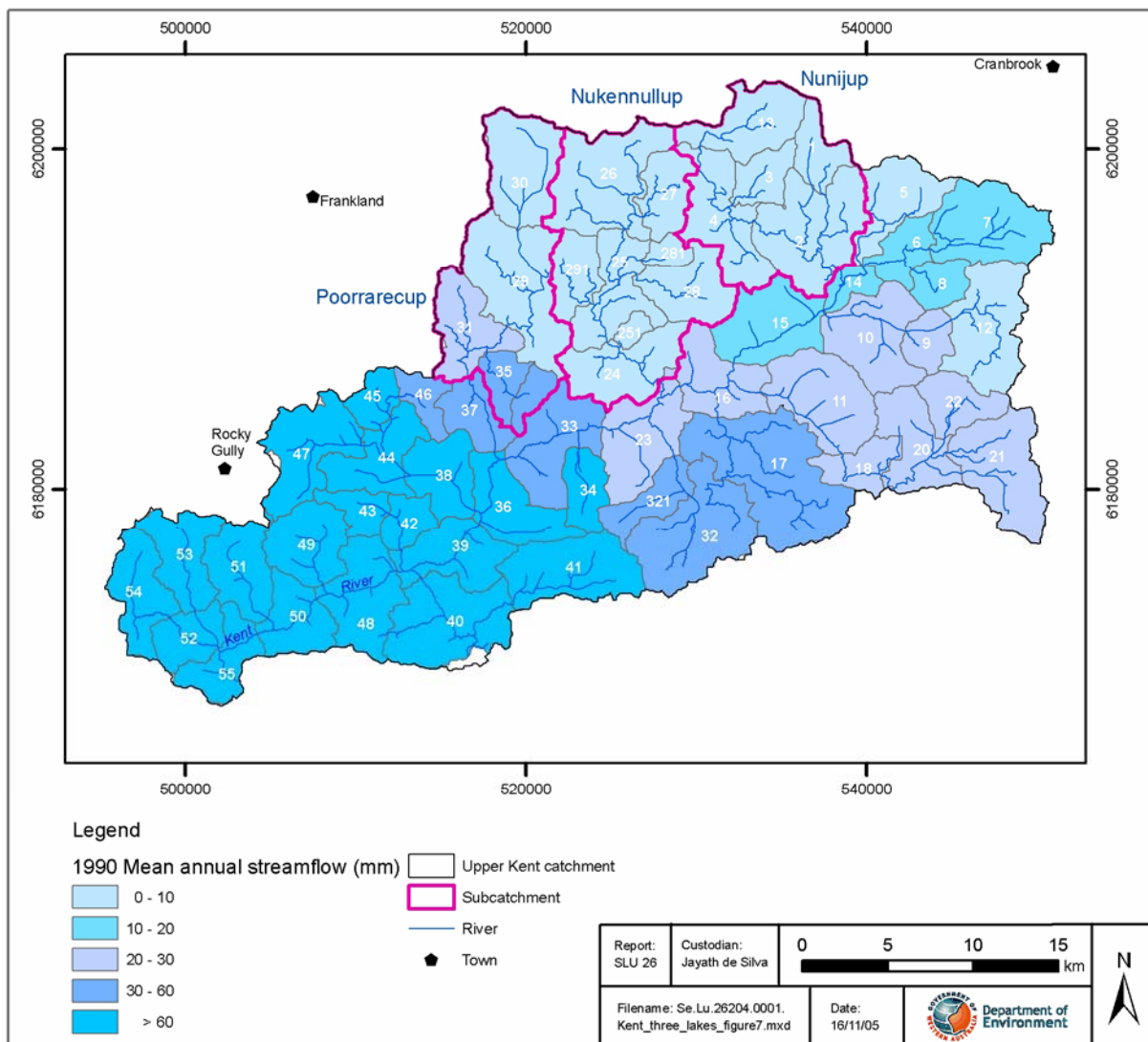


Figure 7 1990 distribution of runoff from the subcatchments

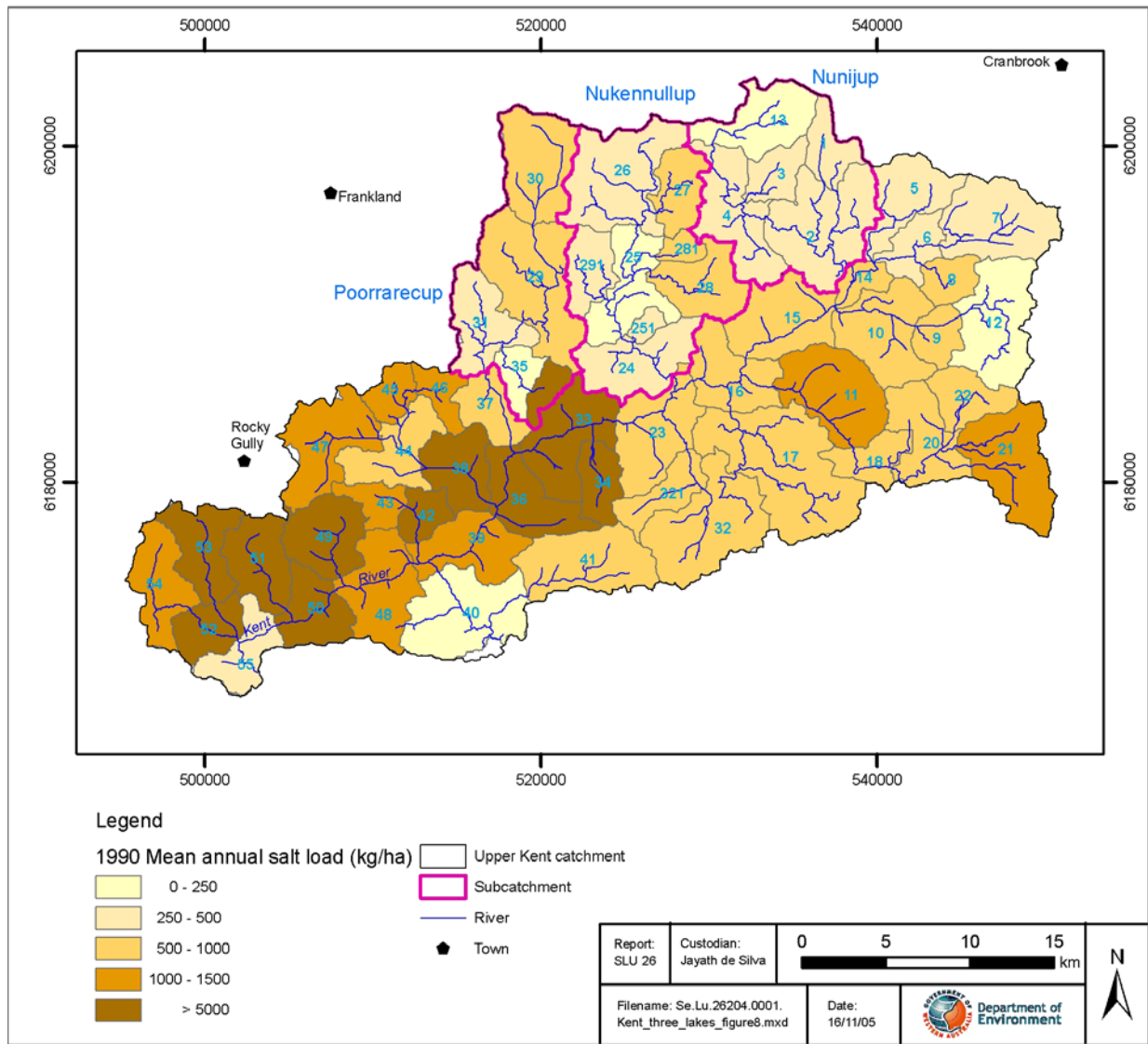


Figure 8 1990 distribution of salt yield of the subcatchments



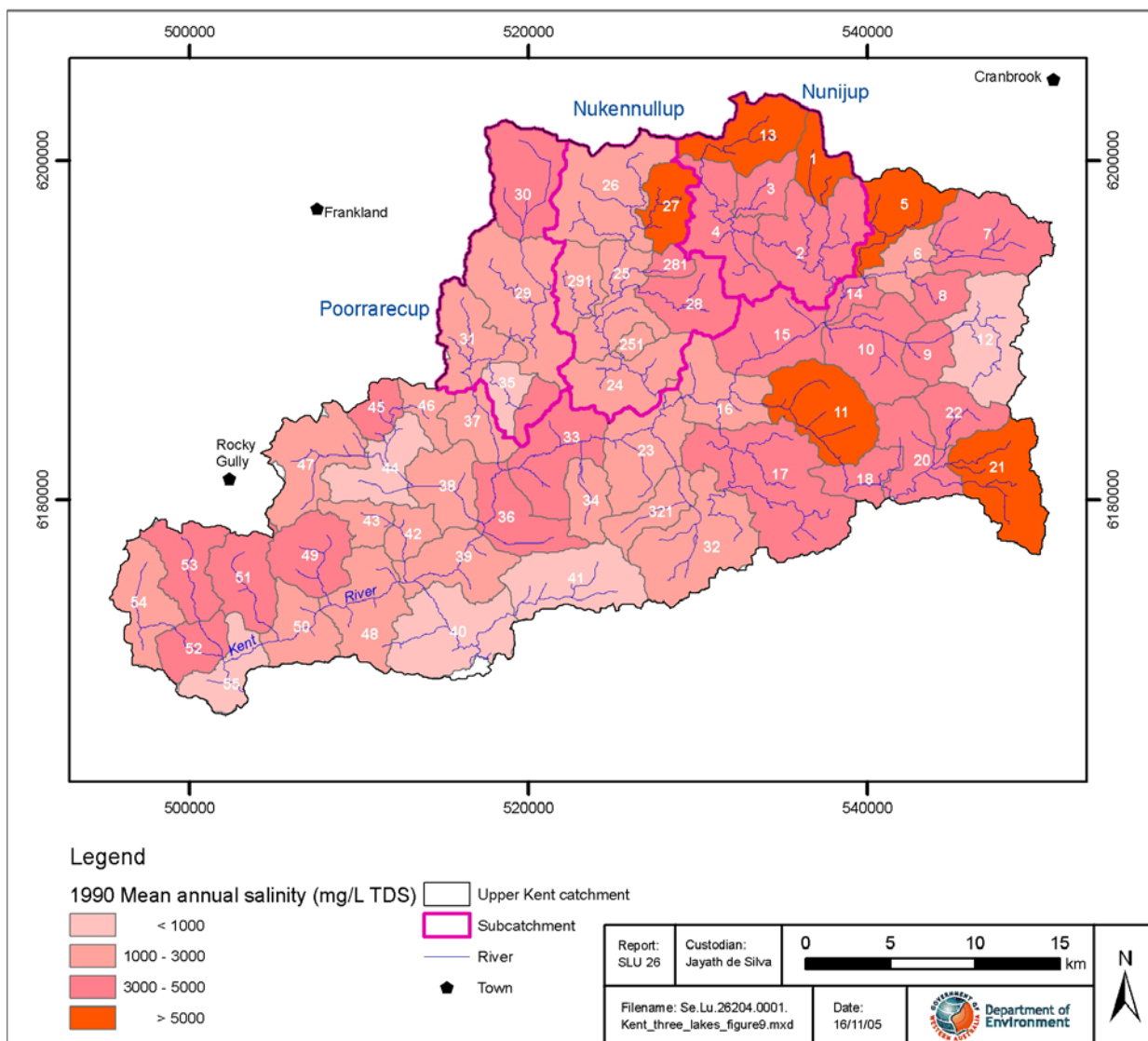


Figure 9 1990 distribution of stream salinity of the subcatchments

## 5 Salt and water balance of the lakes

### 5.1 Surface water inflow to the lakes

Inflows were estimated from application of the LUCICAT model. Annual median inflow to the Nunijup Lake was the lowest, at 0.67 gegalitres (GL), significantly lower than the lake volume at the overflow level (Table 2). Median inflows to Lakes Carabundup and Poorrarecup are 1.55 GL and 1.98 GL respectively.

**Table 2 Modelled lake inflow and overflow characteristics**

Lake	Annual inflow (GL)			Volume at overflow (GL)
	10 <sup>th</sup> percentile	Median	90 <sup>th</sup> percentile	
Nunijup	0.14	0.67	1.46	2.32
Carabundup	0.79	1.55	3.54	5.17
Poorrarecup	1.05	1.98	3.52	4.98

### 5.2 Lake Nunijup

Lake Nunijup is in the north-eastern corner of the upper catchment. This lake and wetland are accessible via Stockyard Road that connects to Albany Highway near Tenterden. When it reaches its overflow depth of 3.9 m, the lake has an area of 0.79 km<sup>2</sup> and can hold 2.32 GL. Its catchment has an area of 100 km<sup>2</sup> (Fig. 10). The average rainfall at the Cranbrook meteorological station (10537), about 15 km north-east of the lake, is 508 mm. Mean annual pan evaporation for the area is about 1500 mm.

Elevation within the catchment ranges from 230 m AHD near the lake to 400 m AHD near Geekabee Hill. The lake is bounded by a 5 m-high lunette on the southern side of the lake and its outflow point is on the eastern side of the lake. Other surface water bodies in this catchment include Little Nunijup Lake and Murdellup Lagoon.

Extensive Quaternary and Tertiary sediments that form an aquifer with shallow groundwater levels occupy 38 km<sup>2</sup> or 38% of the subcatchment. All the lakes and swamps are in this area. Weathered basement rocks, mainly granites and gneisses, underlie the rest of the subcatchment in an undulating landscape. Rocks of Stirling Range Formation form Geekabee Hill near the north-eastern corner of the catchment.

In this lake's catchment, clearing native vegetation started in 1860, by 1965, 39% of the area had been cleared and in 1978, when clearing control legislation was enacted, 59% of the catchment had been cleared. Clearing caused the salinisation of Lake Nunijup and the surrounding wetland. This lake had been an important source of the area's stock quality water, especially during droughts, but now salinity and waterlogging are the main land management issues in this catchment.

The salinity of the lake has been increasing steadily since 1988. Its salinity ranges from about 1000 mg/L in 1988 to about 11 000 mg/L in 2001 but was recorded at 61 000 mg/L in 1984. The median salinity for the lake is 7750 mg/L.

Shire of Cranbrook records show that lake water quality fluctuated between 3400 and 4500 mg/L from 1974 to 1975. Surface water sampling in 1973 by the Department of Agriculture indicated that the river salinity was between 560 and 3260 mg/L. Yate Flat, north of Lake Nunijup, recorded the highest salinity levels.

According to local farmers, in 1963 the lake water was fresh (< 500 mg/L) and used for drinking. By 1976, water had deteriorated to stock quality and was used for lawn irrigation (Andrew Maughan, personal communication).

During the winter of 1978, all three lakes filled but did not appear to contribute to flow and salinity in the Kent River. Lake Nunijup showed evidence of being sustained by shallow groundwater. The lake salinity varied between 5000 in August 1978 and 10 000 mg/L in February 1979 (Collins & Fowlie 1981).

Records on the overflow history of the lakes are rare. The last overflow from the lake was in January–February 1982, following a 180-mm rainfall event (local landholder Mr Bruce Parson's observation). Hydrological monitoring from 2000 to 2002 at Koonje Road (Sth) and Koonje Road (Nth) (Fig. 10) indicated that annual inflow and salt load for this period were 326 ML and 1335 t respectively. The flow-weighted annual salinity range is 2200–4600 mg/L.

Examination of aerial photographs taken in 1965 and 1999 shows that the perimeters of most lakes in the catchment, including Lake Nunijup, expanded during this period indicating that, following clearing, lake levels rose significantly between 1965 and 1999.

### 5.2.1 Lake levels and salinity

The inflow and salt load predicted by LUCICAT were used to calibrate the Lake model, starting from January 1973. Outflow channel characteristics (width, slope and roughness) were estimated from field observation and calibration.

The water levels predicted by the Lake model match observed levels reasonably well, except for the periods 1981–84 and 1988–91 (Fig. 11a) when some of the early recorded data seem to be of poor quality. The inflow series predicted by the catchment model is considered to reasonably represent the catchment contributing to the Lake Nunijup.

During the period 1973–2001, the average annual inflow was 0.72 GL and average annual rainfall on the water surface of the lake was 0.035 GL. About 70% of the total input evaporated, 26% seeped through the base of the lake to the deep aquifer systems, and the rest was stored in the lake (Appendix 6).

The predicted salinity of the lake generally followed the observations, except for a significant underprediction in 1981–84 (Fig. 11b). The median salinity was in the order of 8000 mg/L TDS. (The predicted salinity of the lake was fixed to a maximum of 50 000 mg/L.) The annual average salt input to the lake, including the salt from rainfall, was 2080 t (Appendix 6). Most of the salt (88%) was lost due to net leakage through the lakebed and little is being stored in the lake.

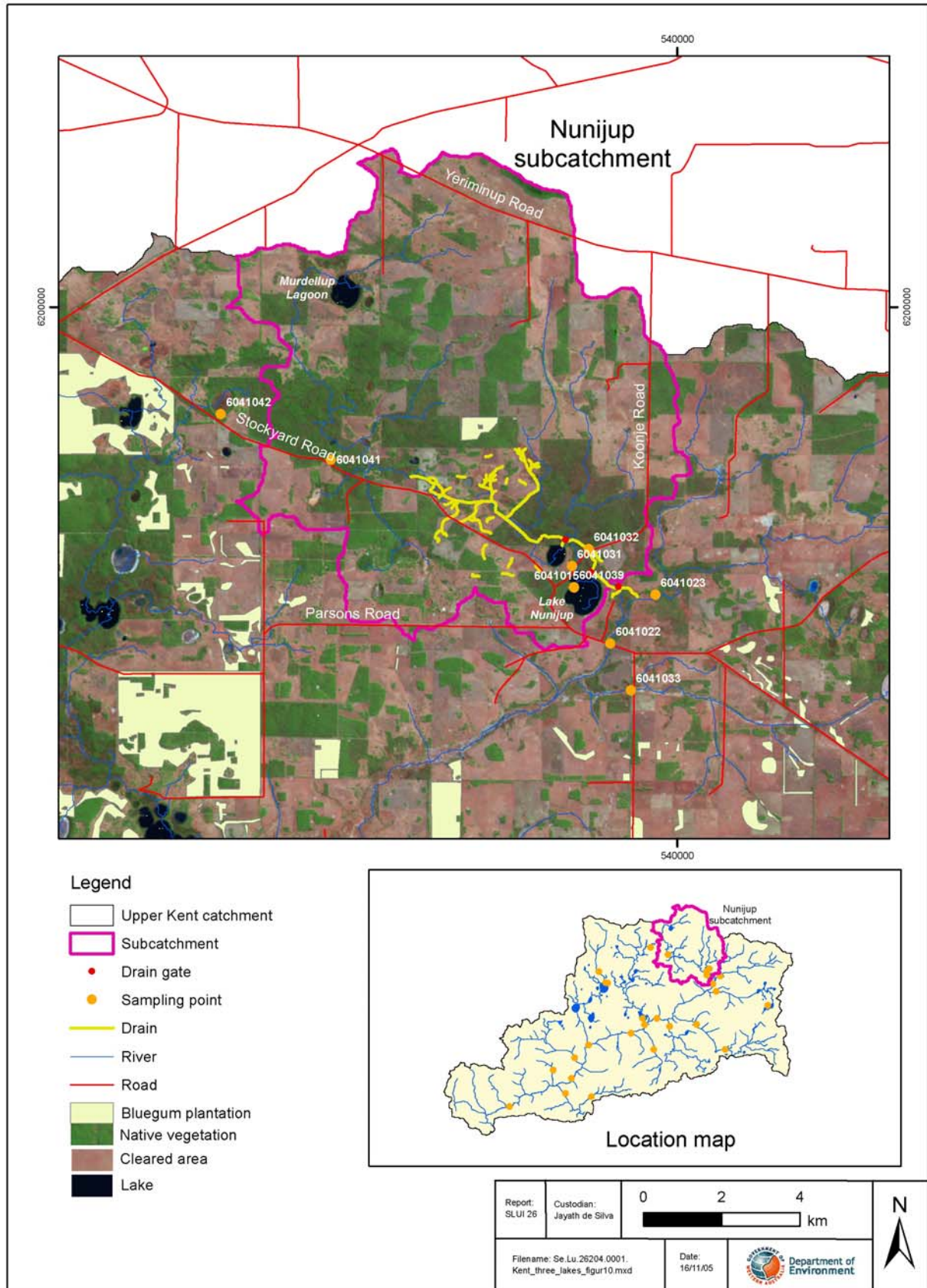
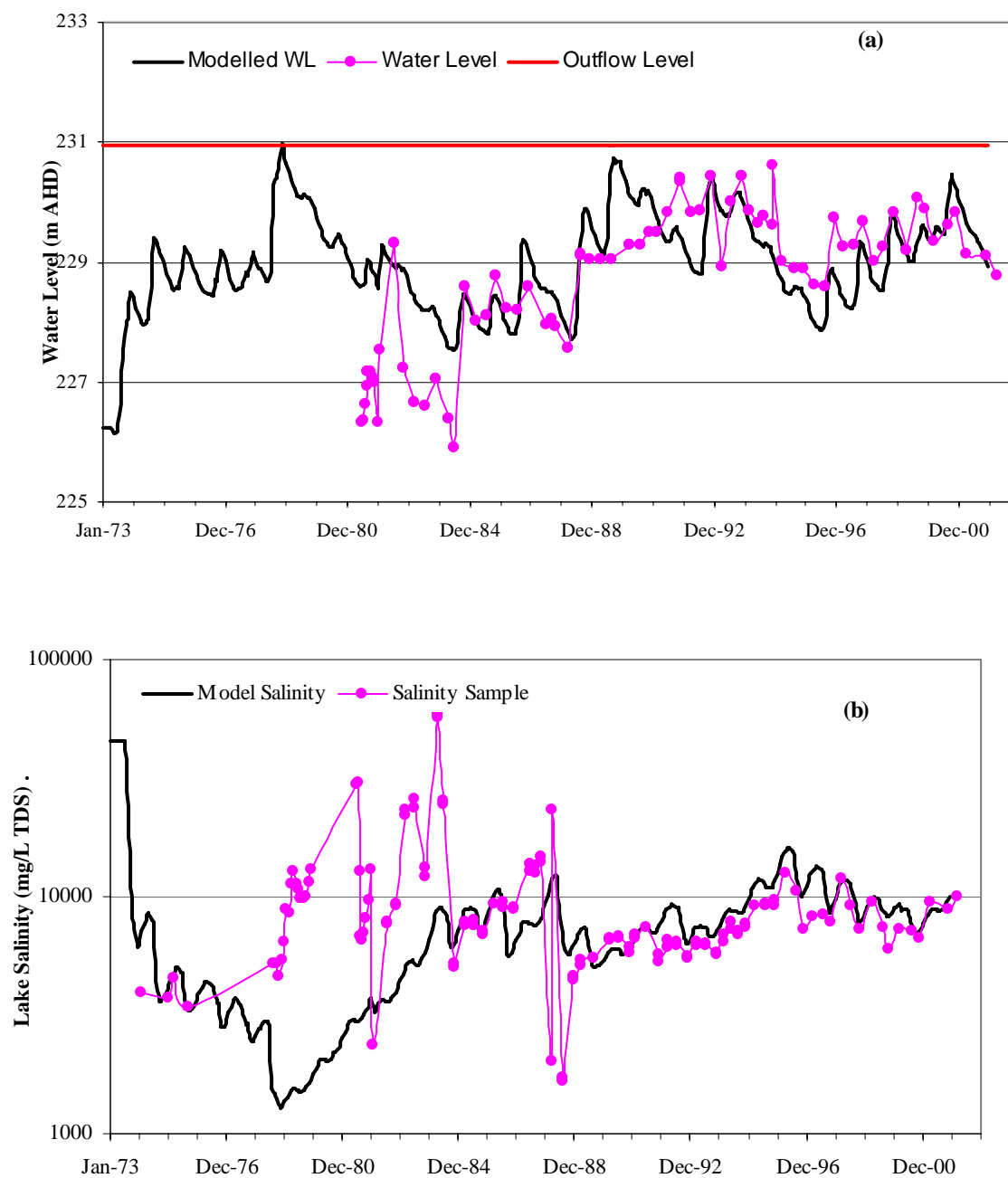


Figure 10 Hydrology of Lake Nunijup



**Figure 11 Observed and modelled (a) water level and (b) salinity of Lake Nunijup**

### 5.3 Lake Carabundup

Lake Carabundup is in the Nukennullup subcatchment. In a hydrological study carried out in 1978, Collins and Fowle (1981) categorised this lake as typically ephemeral or seasonal. It has an area of 1.85 km<sup>2</sup>, can hold 5.17 GL at the overflow level and will have a maximum water depth of 4 m at full capacity. The catchment draining to the lake has an area of 127 km<sup>2</sup>. This catchment has other lakes, including Nukennullup, Stockyard and Mineral (Fig. 12). These lakes have a surface area of about 300 ha.

Elevation within this subcatchment varies from 215 m AHD near Lake Carabundup to 285 m AHD. Within the broad flat landscape that contains most of the lakes, elevation only changes from 215 to 240 m AHD. Lake Carabundup is bounded by a 5–10 m high lunette. The outlet point is near the lower north-eastern side but there are no records of outflow and the lake has probably not overflowed during the past 30 years. In its rare overflow events, it overflows directly into the Kent River.

Extensive Quaternary and Tertiary Sediments that form an aquifer with shallow groundwater occupy 54 km<sup>2</sup> or 42% of the subcatchment: all the lakes and swamps are within this area of sediments. Weathered basement rocks, mainly granites and gneisses, underlie the rest of the subcatchment in an undulating landscape.

Most of the clearing in the catchment occurred after 1946. Between 1965 and 1978 the extent of clearing increased from 43% to 63%. By 2002, as a result of extensive commercial plantations of Tasmanian bluegums, the cleared area had decreased to 38%.

Seasonal variation in lake salinity was observed in 1978 and 1979: from about 10 000 mg/L in August 1978 to the salinity of seawater (35 000 mg/L) as evaporation during summer dropped the lake level. This pattern was repeated in 1979 (Collins & Fowlie 1981). Since 1990, this seasonal or ephemeral nature has probably changed and lake salinity and levels are more stable probably due to increased runoff after clearing and lake levels sustained by the discharge of shallow groundwater. The lake can now be considered as a perennial saline lake with a median salinity (1981–99) of 18 600 mg/L TDS.

Examination of aerial photographs taken in 1965 and 1999 shows the effects of extensive bluegum plantations on surface water inflow to the lakes. By 1999, some of the small lakes in the catchment had dried up while the water level of Lake Carabundup had dropped slightly compared to 1965.

### 5.3.1 Lake levels and salinity

Lake water level and salinity data were collected during the period 1981–2001. The water level data for 1981–88 is of poor quality. Records and anecdotal evidence indicate that no overflow during 1973–2001 (Fig. 13a). The Lake model successfully simulated water levels for 1988 onward (Fig. 13a). During 1973–2001, the average annual inflow and rainfall on the lake surface totalled 1.9 GL. Average evaporation and seepage were 1.5 GL (84%) and 0.35 GL (18%) per year respectively (Appendix 6).

The median salinity of Lake Carabundup was 15 000 mg/L TDS and generally higher than that of Nunijup (Fig. 13b). The Lake model successfully predicted its salinity, except for under prediction during 1979–86. The average annual salt input, including salt from rainfall, was 5275 t, of which 98% seeped into the groundwater system (Appendix 6).



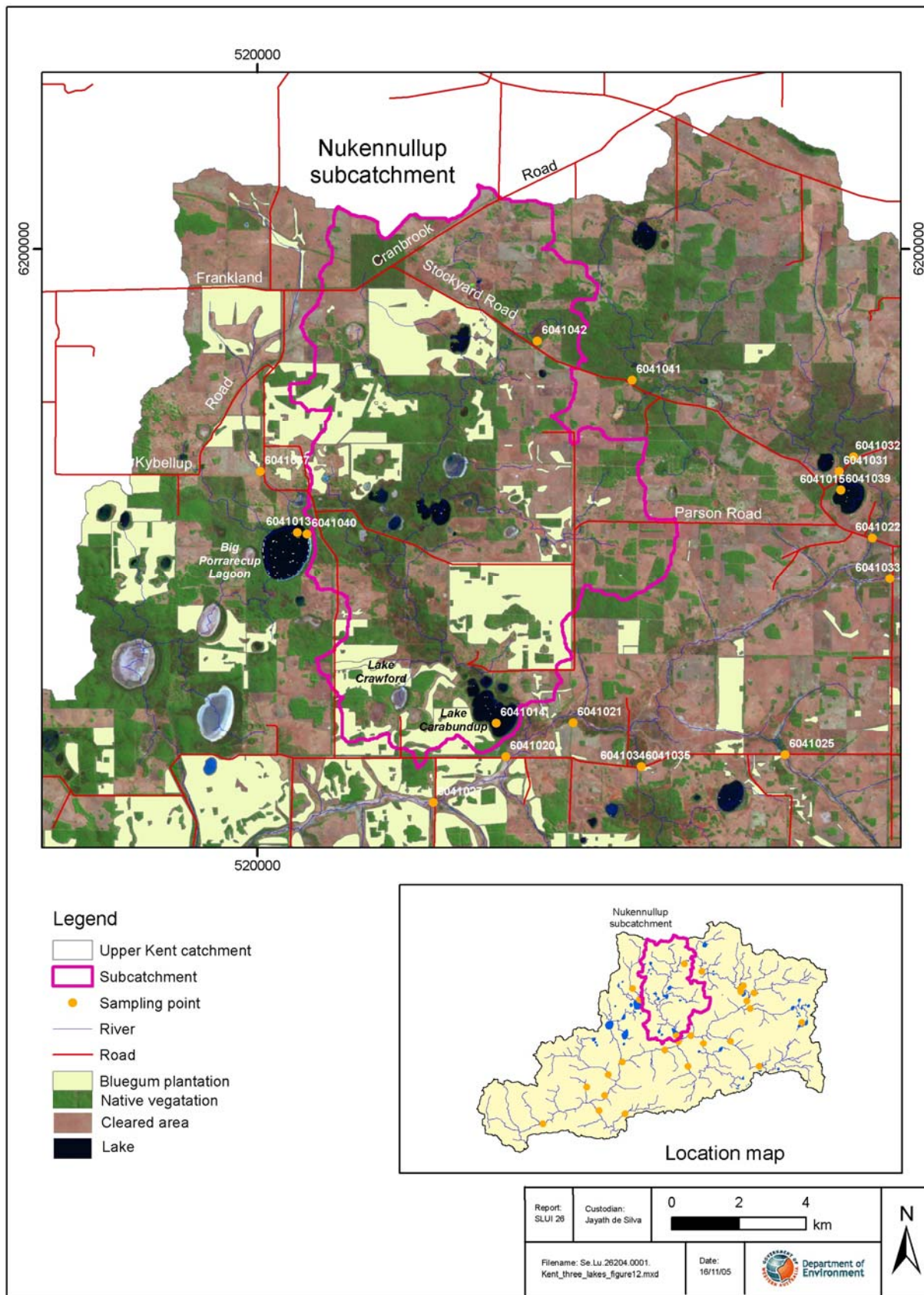
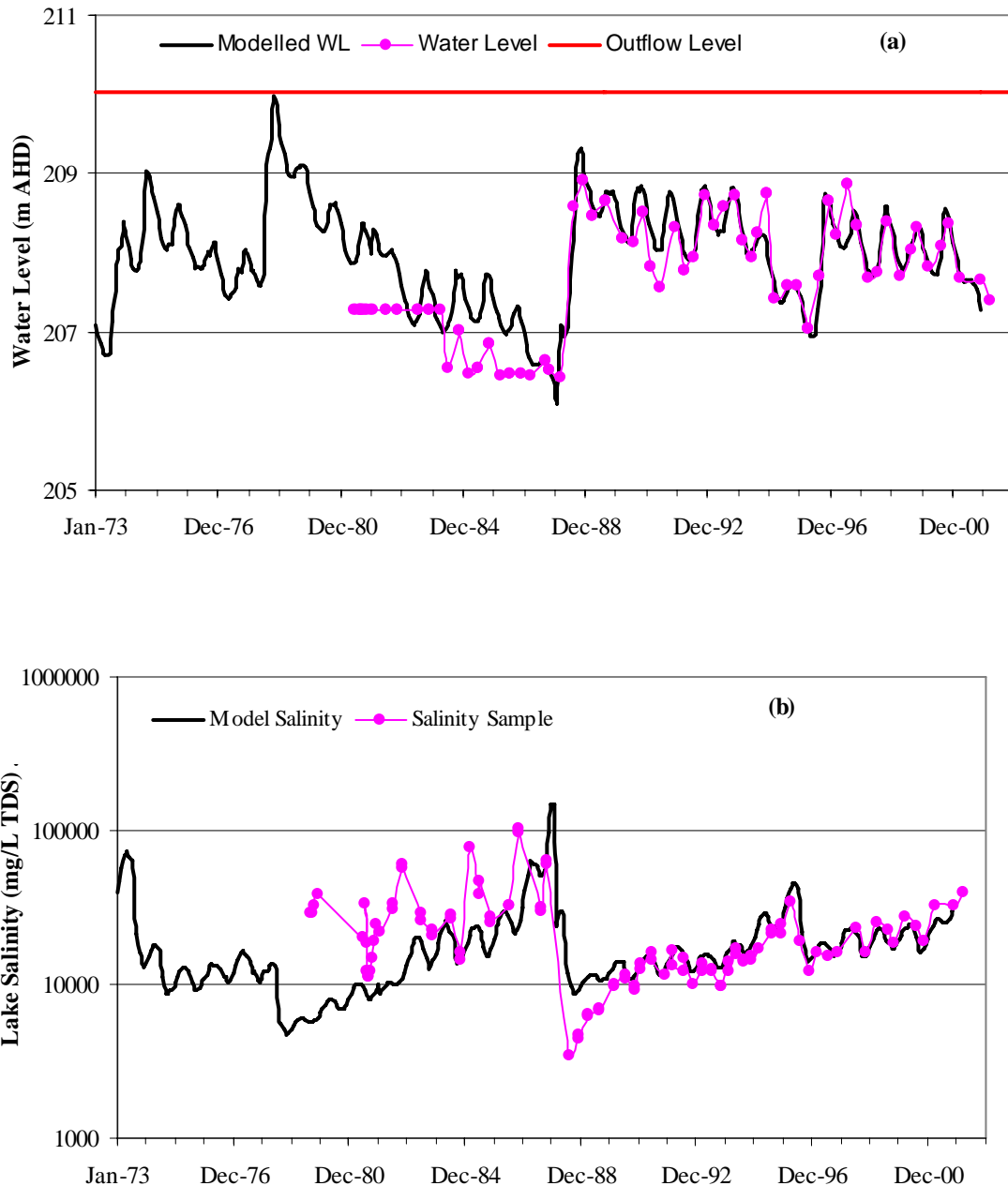


Figure 12 Hydrology of Lake Carabundup



**Figure 13** Observed and predicted (a) water level and (b) salinity of Lake Carabundup

## 5.4 Lake Poorrarecup (Big Poorrarecup Lagoon)

This lake, in the northern part of the upper catchment close to the watershed between the Kent and Frankland rivers, has an area of 1.99 km<sup>2</sup> and can hold 4.98 GL at its outflow level when the lake is about 3 m deep. It is one of the biggest lakes in the upper catchment and showed evidence of being sustained by shallow groundwater (Collins & Fowlie 1981). Median salinity (1981–99) is 9200 mg/L TDS. The Poorrarecup subcatchment has an area of 94 km<sup>2</sup>, but only 59 km<sup>2</sup> drains into the lake (Fig. 14). The rest drains into a number of seasonal lakes and swamps downstream of Lake Poorrarecup with a total area of 3.8 km<sup>2</sup>.

Elevation within this subcatchment ranges between 220 and 310 m AHD with all the lakes within a broad flat between 220 and 225 m AHD and Lake Poorrarecup at 225 m AHD. The



lake is bounded by a 4–5 m high lunette. There are no records of outflow and the lake has probably not overflowed during the past 30 years although the southern outlet point is not clearly defined and the lake may overflow into a seasonal lake system downstream.

Extensive Quaternary and Tertiary Sediments that form an aquifer with shallow groundwater occupy 47 km<sup>2</sup> or 50% of the subcatchment. All the lakes and swamps are within this area of sediments. Weathered basement rocks, mainly granites and gneisses, underlie the rest of the subcatchment in an undulating landscape.

Clearing began before 1946, mainly in areas draining to the lake. By then, 14% of the subcatchment was cleared of native vegetation. Clearing increased significantly between 1950 and 1955 and, by 1965, 46% of the subcatchment had been cleared, mainly areas draining to the lake. Since 1965, other areas of the subcatchment were cleared as well. When clearing controls were enacted in 1978, 63% of the subcatchment had been cleared. With extensive commercial bluegum plantations established, only 36% of this catchment is now cleared.

Aerial photographs taken in 1965 and 1999 show the effects of the plantations on surface water inflow. By 1999, some of the small lakes in the catchment had dried up while lake levels had dropped significantly compared with 1965. The reduced inflow is the opposite of what is happening in the Lake Nunijup catchment where there has been little revegetation since 1996.

#### 5.4.1 Lake levels and salinity

Water level and salinity data are available for the same period as for the other lakes. Lake Poorrarecup did not overflow during 1973–2001. Lake level data collected during 1981–88 are questionable (Fig. 15a). The predicted and observed lake levels for 1988–99 are well matched. From 1999 onwards, the predicted water levels were slightly lower than observed levels (Fig. 15a). During 1973–2001, average annual inflow and rainfall to the lake was 2.6 GL. Average annual evaporation and net seepage to groundwater from the lake were 2.1 GL (78%) and 0.5 GL (18%) respectively (Appendix 6).

Lakes Poorrarecup and Nunijup have similar salinities (Fig. 15b). The median salinity of Lake Poorrarecup is 10 600 mg/L and ranged between 3000 and 70 000 mg/L TDS. The Lake model successfully predicted the lake salinity, except for some extreme values, until 1999, then under predicted it (Fig. 15b). During 1973–2001, average annual salt input, including the salt from rainfall, was 5300 t, of which 98% seeped into the aquifer (Appendix 6).

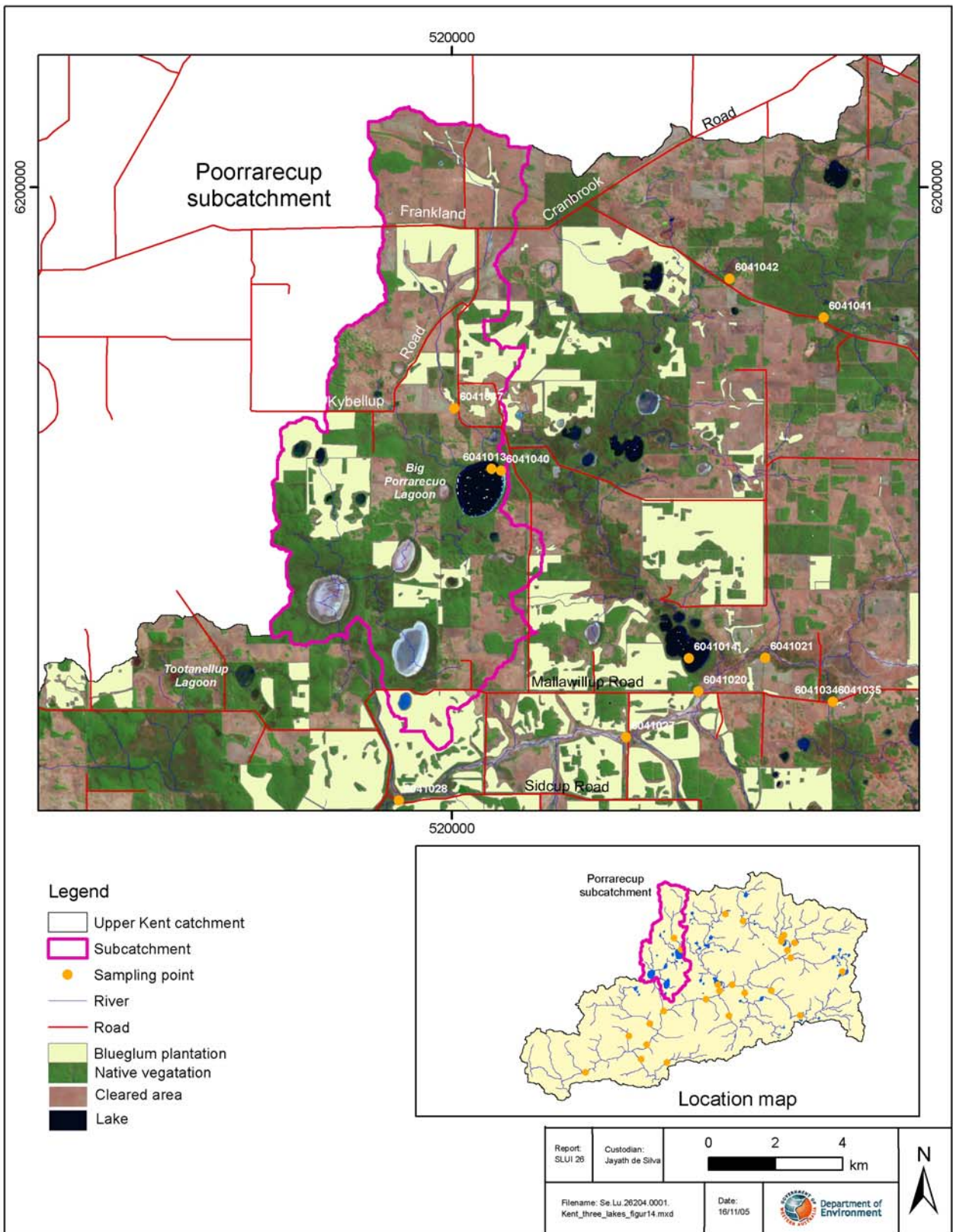


Figure 14 Hydrology of Lake Poorrarecup (fix blueglum, vegetation, Poorrarecup

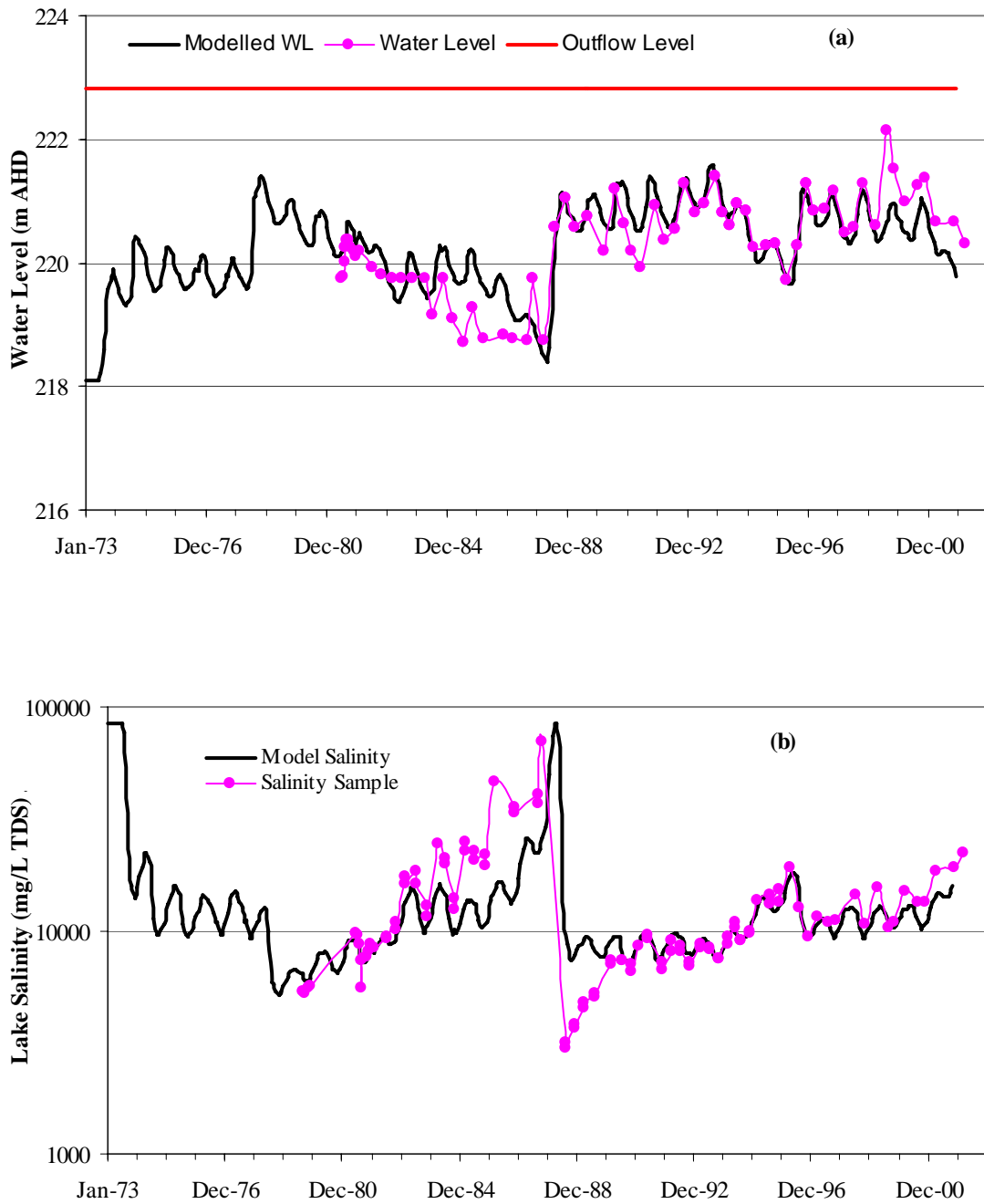


Figure 15 Observed and predicted (a) water level and (b) salinity of Lake Poorrarecup

## 6 Management options

The lakes should be managed to:

- minimise salinisation and waterlogging in the surroundings and the subcatchments
- protect habitat for native flora and fauna
- understand relative contributions to the Kent River flow and salt load
- improve water resource potential of the lakes (e.g. Lake Nunijup)
- improve recreational values (e.g. Lake Poorrarecup).

After reasonable calibrations of both the Lake and LUCICAT models, catchment management scenarios, using daily rainfall and pan evaporation data generated for the period 1973–2001, were incorporated. Only the catchment area of the Nunijup Lake was modelled. The management scenarios for Lake Nunijup are:

- 1 *'Do nothing different'*: This scenario shows that the inflow series will be similar to the one predicted for 1985–2001. The Lake model shows that the long-term steady-state median salinity and water level of the lake will not be significantly different from present values (8200 mg/L TDS). Annual inflow is 8.2 mm and salt load is 2080 t.
- 2 *Planting trees on 50% of the cleared area*: The mean annual inflow and salinity will fall to 3.2 mm and 890 mg/L TDS respectively and inflow salt load will only be 285 t, which is less than the annual mass of salt in rainfall (500 t). The low-inflow salt load indicates that groundwater has stopped discharging. The median lake salinity will fall to 5300 mg/L TDS. With significantly reduced inflow the lake will dry out some of the time.
- 3 *Planting trees on 25% of the cleared area*: The mean annual inflow and salinity would go down to 5.4 mm and 1750 mg/L TDS respectively. The inflow salt load would be 945 t. Because there would be more water in the lake, its median salinity would be 3600 mg/L TDS, less than half the salinity expected for the 50% planted option.

## 7 Conclusions

### 7.1 The catchment

The Upper Kent catchment covers an area of 1092 km<sup>2</sup>. The annual runoff for the period 1979–2001 ranged from 7 to 78 mm and averaged 25 mm. Following clearing of 66% of its area, the average annual salinity and salt load from the catchment increased to 3065 mg/L TDS and 771 kg/ha respectively.

The LUCICAT model was successfully calibrated to match the distribution of the runoff and salt load, and to generate daily streamflow and salinity series. Annual runoff and salt loads are strongly related to the annual rainfall and the proportion of cleared areas. In 1990, a typical average-flow year, the distribution of runoff ranged from 3 to 120 mm; and the salt load ranged from 10 to 4910 kg/ha.

### 7.2 The lakes

Lake Nunijup has a capacity of 2.32 GL at the overflow depth of 4.4 m. During 1973–2001 it had no predicted overflow, an average annual input of 0.76 GL of which 70% evaporated and the rest seeped through the lakebed. Its median salinity was in the order of 8000 mg/L TDS. Average annual salt input was 2080 t. About 88% of the salt seeped through the lakebed and the rest is being stored in the lake.

Lake Carabundup has a capacity of 5.2 GL m. During 1973–2001 it did not overflow, its average annual inflow plus rainfall on the lake totalled 1.9 GL, and average annual evaporation and seepage from the lake were 1.5 GL and 0.35 GL respectively. Its median salinity (15 000 mg/L TDS) was much higher than the other two lakes. Average annual salt input was 5275 t of which 98% seeped into the groundwater.

Lake Poorrarecup has a capacity 4.98 GL. During 1973–2001, it did not overflow, its average annual inflow and rainfall on the lake totalled 2.6 GL, its average annual evaporation and net seepage were 2.1 GL and 0.5 GL respectively. Its median salinity was 10 600 mg/L TDS with a range 3000 mg/L to 70 000 mg/L TDS. Its average annual salt input was 5300 t, of which 98% seeped into the aquifer.

### 7.3 Groundwater-lake interaction

There is a lot of interaction between these lakes and groundwater, mainly due to the presence of unconfined permeable aquifers with shallow watertables. Groundwater flow regimes can change from flow-through in winter, when the lakes can lose or gain salt, to discharge in summer when the lakes can only gain salt.

## 8 Recommendations

Use latest streamflow data generated in the *Salinity Situation Statement: Kent River* as the input to the Lake Model for the three lakes.

Extend the management-options approach to the other subcatchments (Poorrarecup and Carabundup).

Continue monitoring groundwater, lake levels and sample sites.

Document future overflows of the lakes.

Document land-use changes like plantations and harvesting.

Update this report at least every five years with the latest salinity and flow information.

## References

- Bari, MA & Boyd, DW 1992, Water and salt balance of a partially reforested catchment in the south-west of Western Australia, Water Authority, WS 107, 82p.
- Bari, MA & Boyd, DW 1993, *Effects of parkland clearing on groundwater level and salinity*, Water Authority, Western Australia (unpublished).
- Bari, MA & Croton, JC 2000, 'Predicting the impacts of land use changes on streamflow and salinity by a fully distributed catchment model' in: *Hydro 2000, Third International Hydrology and Water resources Symposium*, Institution of Engineers, Australia.
- Bartle, GA, Williamson, DR, Salama, RB & Watson, GD 2000, *A field study of groundwater in the Upper Kent Catchment in south-west of Western Australia*, CSIRO Land and Water Technical Report 4/00.
- Born, SM, Smith, SA & Stephenson, DA 1979, Hydrogeology of glacial-terrain lakes, with management and planning applications, *Journal of Hydrogeology*, vol. 43, pp. 7–43.
- Collins, PDK & Fowlie, WG 1981, *Denmark and Kent River Basins Water Resources Survey*, Water Resources Branch, Public Works Department of WA.
- De Silva, J 1999, *Toolibin Catchment Airborne Geophysics*, Bore Completion Report, HR 126, Water and Rivers Commission, Western Australia.
- De Silva, J 2001, *Lake Nunijup Hydrogeological Investigations*, Bore Completion Report, HR 200, Water and Rivers Commission, Western Australia.
- Dean, JD & Snyder, WM 1977, 'Temporally and areally distributed rainfall', *Journal of Irrigation and Drainage Engineering*, ASCE, vol. 123(IR2), pp. 221–229.
- Dixon, RNM, Mauger, GW & Rogers, A 1998, *Trees on farms to reduce salinity in the clearing control catchments, Volume 3: Kent Catchment*, Water and Rivers Commission Report WRT 20, Western Australia.
- Hingston, FJ & Gailitis, V 1976, 'The geographic variation of salt precipitated over Western Australia' *Australian Journal of Soil Research*, vol. 14, pp. 319–335.
- Johnston, CD 1987, 'Distribution of environmental chloride in relation to sub-surface hydrology', *Journal of Hydrology*, vol. 94, pp. 67–88.
- Johnston, CD, Hurle, DH, Hudson, DR & Height, MI 1983, *Water movement through preferred paths in lateritic profiles of the Darling Plateau, Western Australia*. Tech. paper No.1, CSIRO Division Groundwater Research, Perth.
- Johnson, CD, McArthur, WM & Peck, AJ 1987, *Distribution of Soluble Salts in Soils of the Manjimup Woodchip Licence Area, Western Australia*, CSIRO Land Resources Management Technical Paper No. 5, 29p.
- Luke, GJ, Burke, KL & O'Brien, TM 1988, *Evaporation data for Western Australia*, Western Australian Department of Agriculture, Division of Resource Management Technical Report No. 65, 29p.
- McFarlane, D, Ryder, A, Tipping, P & Ferdowsian, R 1994, *Groundwater trends in the Upper Kent River Catchment*, Department of Agriculture, Albany, Western Australia (unpublished).

- Peck, AJ 2000, 'Salt lake hydrology: potential impact of drainage schemes', in: *Hydro 2000, Third International Hydrology and Water Resources Symposium*, Institution of Engineers Australia.
- Ruprecht, JK & Schofield, NJ 1989, 'Analysis of streamflow generation following deforestation in the south-west of Western Australia', *Journal of Hydrology*, vol. 105, pp. 1–17.
- Schofield, NJ & Ruprecht, JK 1989, 'Regional analysis of stream salinisation in southwest Western Australia', *Journal of Hydrology*, vol. 112, pp. 19–39.
- Schofield, NJ, Loh, IC, Scott, PR, Bartle, JR, Ritson, P, Bell, RW, Borg, H, Anson, B & Moore, R 1989, *Vegetation strategies to reduce stream salinities of water resource catchments in south-west Western Australia*, Water Authority of Western Australia. Report No. WS 33, 82p.
- Sharma, ML, Barron, RJW & Fernie, MS 1987, in 'Areal distribution of infiltration parameters and some soil physical properties in lateritic catchments', in A.J Peck & DR Williamson, (eds), *Hydrology and salinity in the Collie River Basin, Western Australia. Journal of Hydrology*, vol. 94, pp. 109–127.
- Sivapalan, M, Ruprecht, JK & Viney, NR 1996a, 'Water and salt balance modelling to predict the effect of land use changed in forested catchments, 1. Small catchment water balance model', *Hydrological Processes*, vol. 10, pp. 393–411.
- Sivapalan, M, Ruprecht, JK & Viney, NR 1996b, 'Water and salt balance modelling to predict the effect of land use changed in forested catchments, 1. Small catchment water balance model', *Hydrological Processes*, vol. 10, pp. 393–411.
- Sivapalan, M, Viney, NR & Ruprecht, JK 1996c, 'Water and salt balance modelling to predict the effect of land use changed in forested catchments, 3. The large catchment model', *Hydrological Processes*, vol. 10, pp. 429–446.
- State Salinity Council 2000, *Natural resource management in Western Australia — the salinity strategy*, Government of Western Australia, 72p.
- Stokes, RA, Stone, R & Loh, IC 1980, *Summary of soil salt storage characteristics in the Northern Darling Range*, Water Resources Section, Public Works Department of WA, Report No. 4.
- Townley, LR & Barr, AD 2001, *FLOW THRU*, [www.townley.com.au/flowthru](http://www.townley.com.au/flowthru)
- Townley, LR, Turner, JV, Barr, AD, Trefry, MG, Wright, KD, Gailitis, V, Harris CJ & Johnson, CD 1993, *Wetlands of Swan Coastal Plain*, Water Authority, Western Australia.



# Appendix 1– Hydrogeology

## Bore construction

As a part of hydrogeological investigations, 12 groundwater monitoring bores were installed around Lake Nunijup in April 2001 (Fig. A1.1). Construction and lithological details of these bores can be found in the bore completion report (De Silva 2001). Summaries of bore details are included in Table A1.1. All the bores were surveyed and groundwater levels and salinity have been monitored monthly since August 2001.

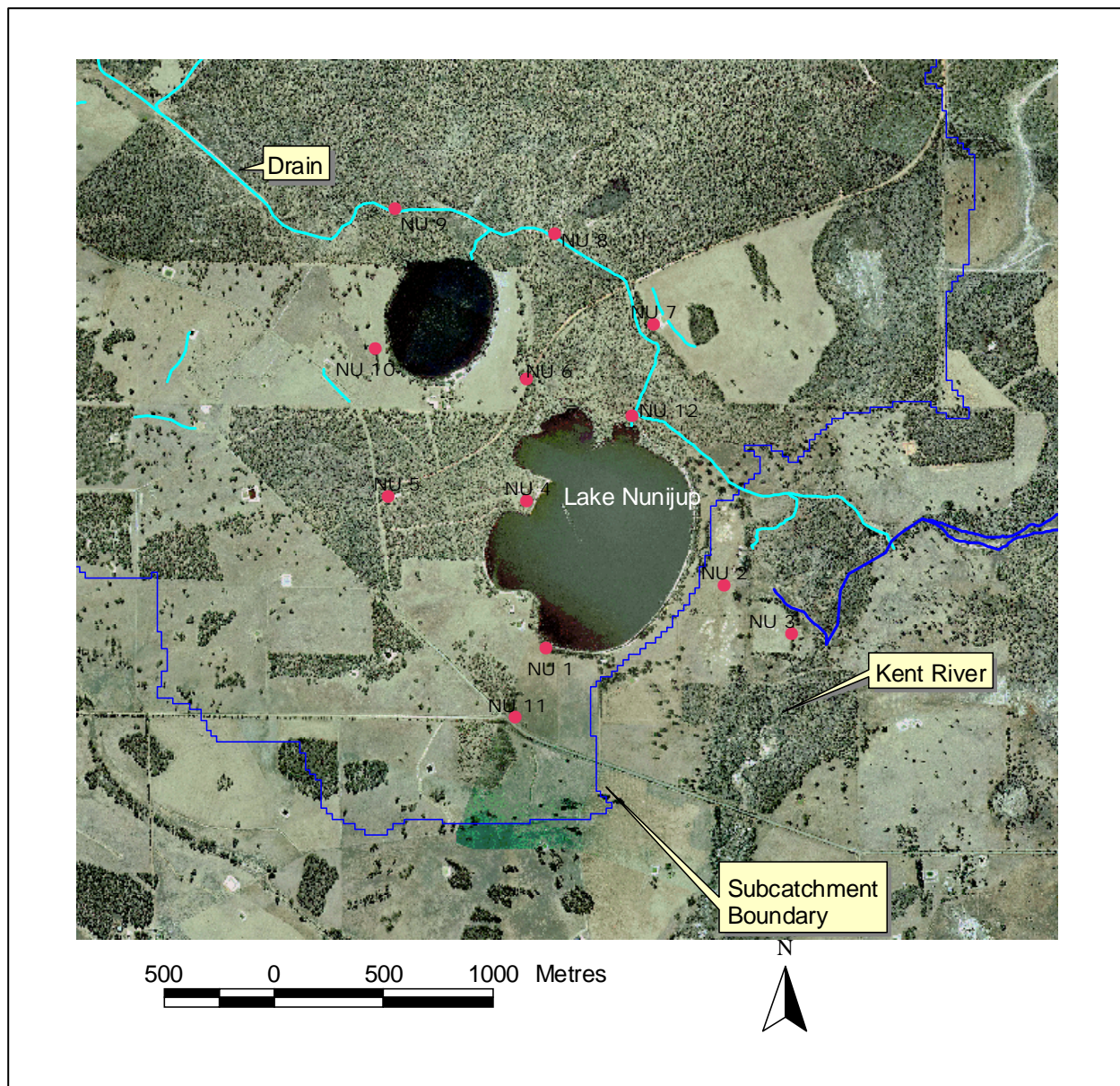
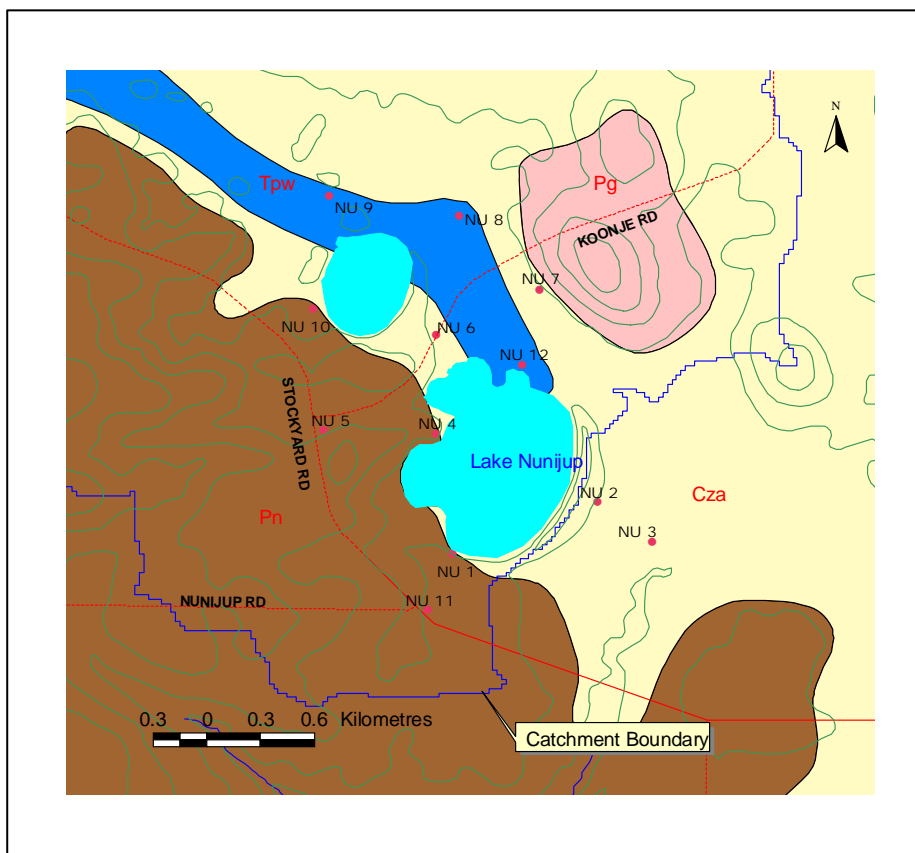


Figure A1.1 Locations of groundwater monitoring bores around Lake Nunijup

**Table A1.1 Summary of groundwater monitoring bores**

Bore ID	Northing	Easting	Drilled depth (m)	Salinity (mg/L TDS)	Water level (m bgl)	Aquifer
NU 1	537386	6192122	10	4125	3.25	Sediments (Q)
NU 2	538196	6192408	18.3	5950	2.1	Sediments (Q)
NU 3	538503	6192190	10	15000	2.3	Sediments (Q)
NU 4	537297	6192794	10	13900	4.6	Weathered bedrock (Pn)
NU 5	536663	6192811	10	8000	2.3	Weathered bedrock (Pn)
NU 6	537296	6193342	10	1800	0.5	Sediments (Q)
NU 7	537873	6193597	15	18370	2.1	Sediments (Q)
NU 8	537426	6194005	15	10000	0.88	Werillup Formation (Tpw)
NU 9	536697	6194120	15	6500	0.6	Werillup Formation (Tpw)
NU 10	536607	6193484	10	13500	0.95	Sediments (Q)
NU 11	537246	6191805	10	11300	1.1	Sediments (Q)
NU 12	537775	6193176	15	14000	1.4	Werillup Formation (Q)

**Hydrogeological setting**



Cza – Cainozoic sediments Tpw – Werillup Formation Pg – Proterozoic granites Pn – Proterozoic gneisses

**Figure A1.2 Hydrogeology of Lake Nunijup**



### Groundwater salinity

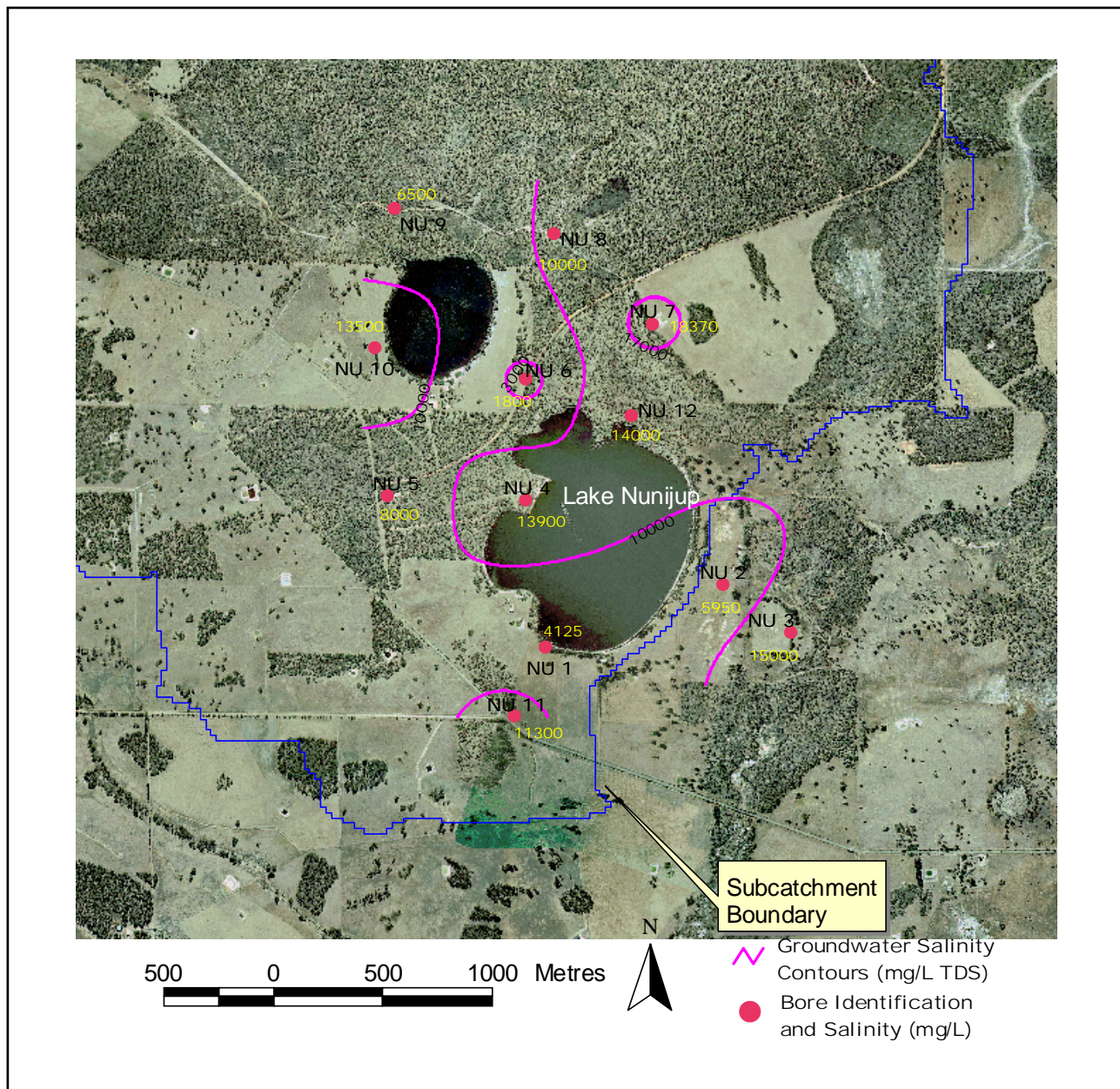
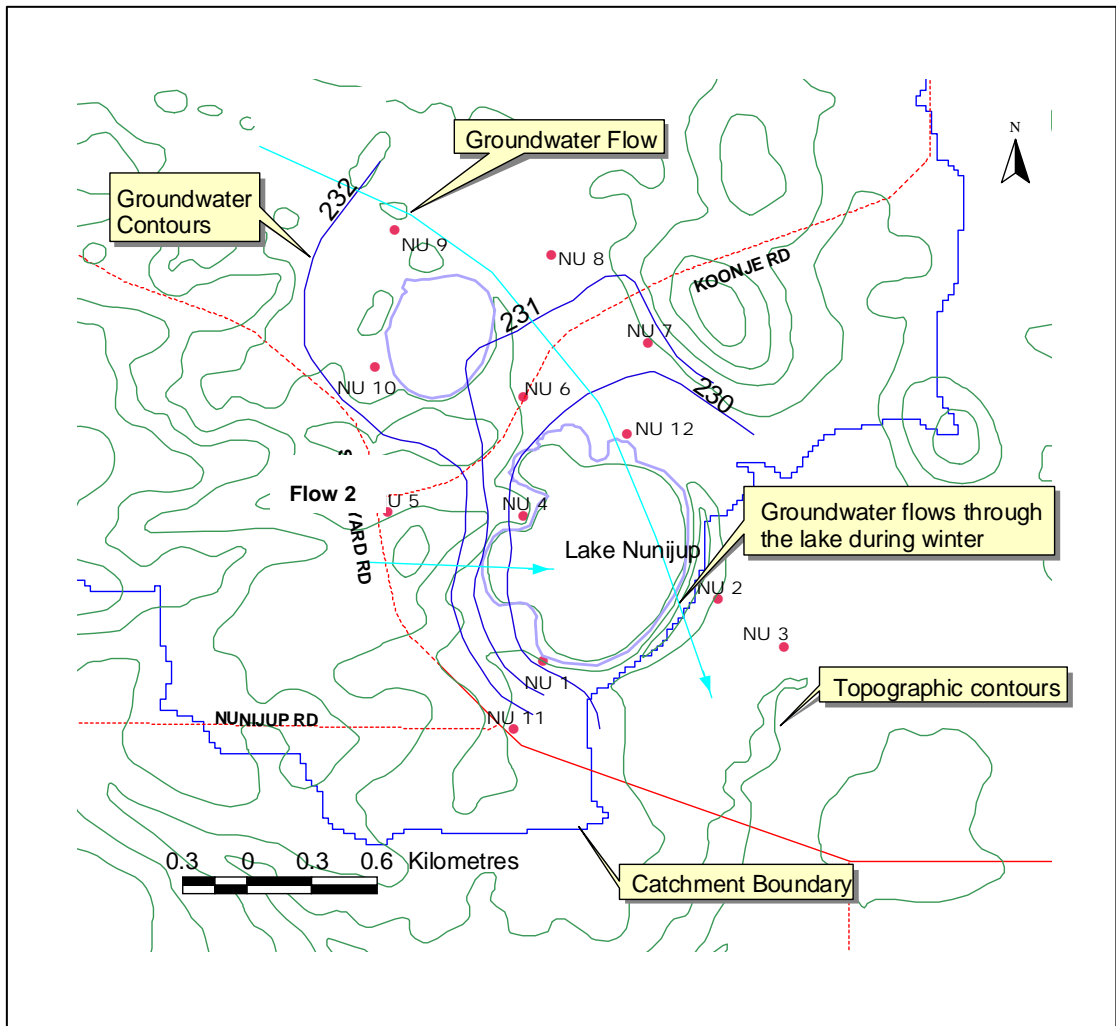
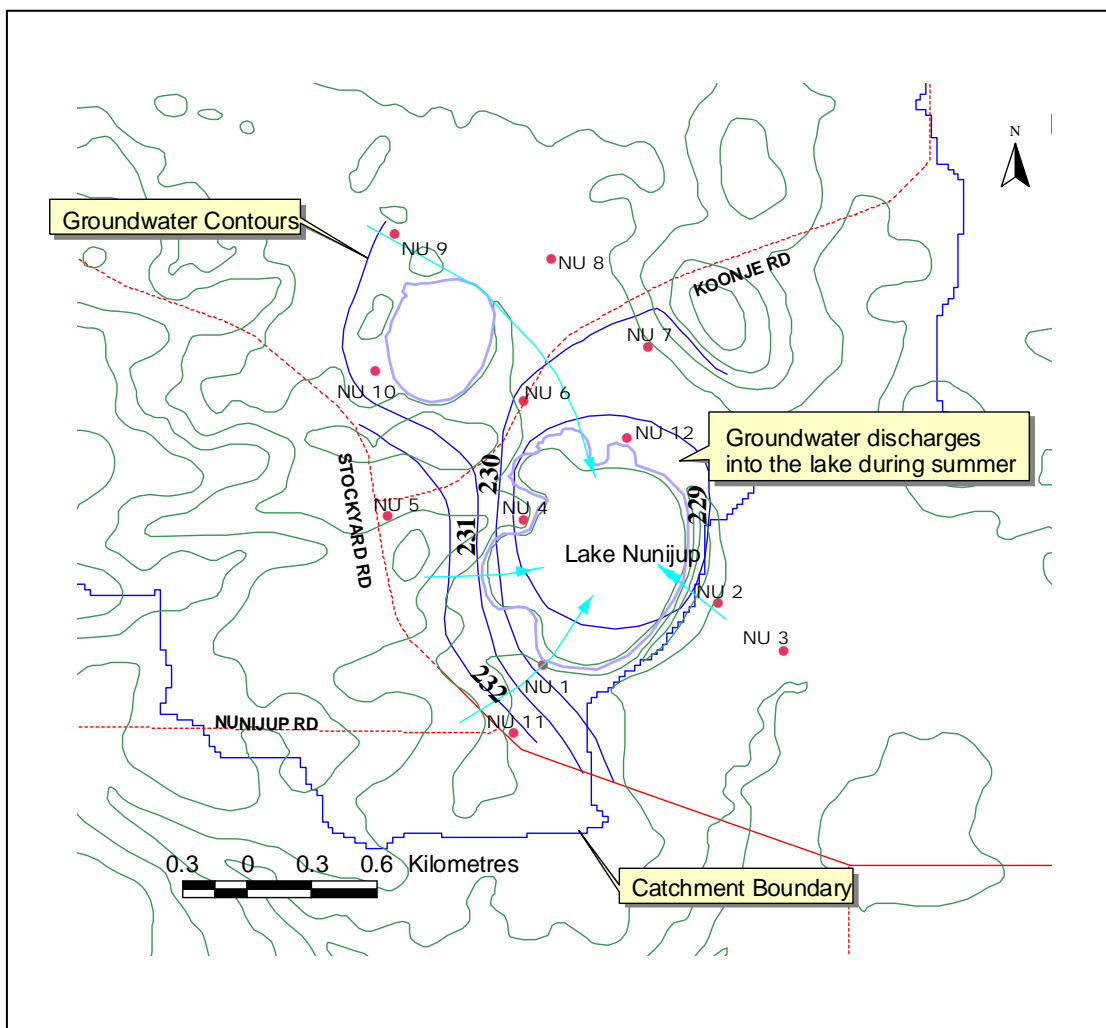


Figure A1.3 Salinity of groundwater near Lake Nunijup

### Groundwater flow



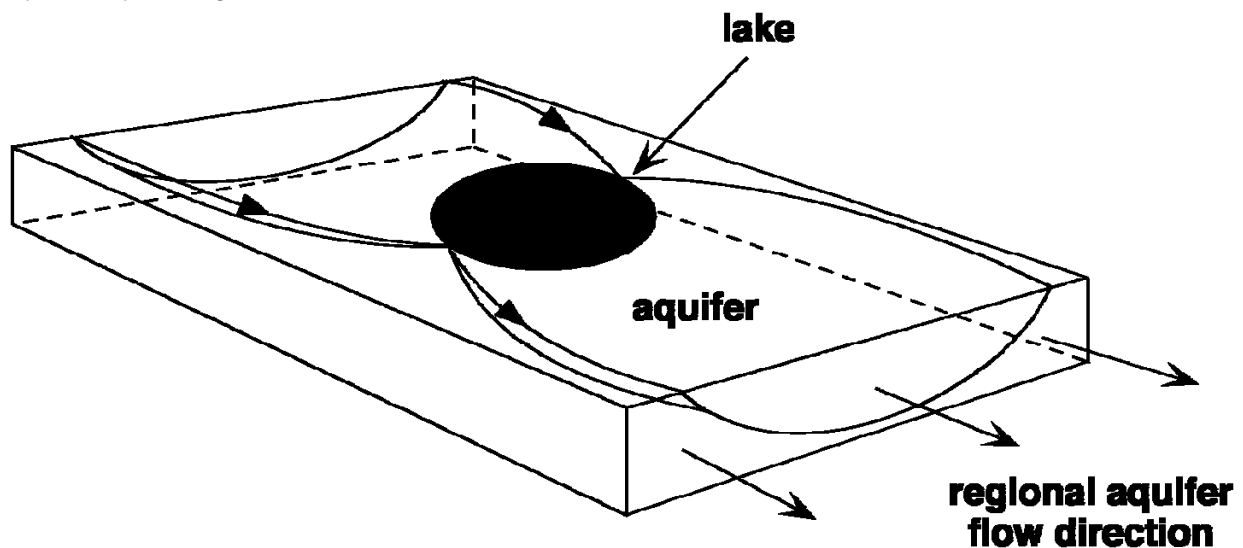
**Figure A1.4 Groundwater flow following winter recharge  
(based on water level measurements — 28/12/2001)**



**Figure A1.5 Groundwater flow following evapotranspiration over summer (based on water level measurements — 28/03/2002)**

## Appendix 2 – Application of the FLOWTHRU groundwater model

FLOWTHRU (Townley & Barr 2001) displays groundwater flow patterns in an aquifer near a surface water body. It is based on groundwater flow patterns in a two-dimensional vertical section through a shallow surface water body. The vertical section needs to be aligned with the direction of regional groundwater flow and the water body is long in the direction perpendicular to that section. FLOWTHRU can also be applied to three-dimensional flow near flow-through lakes (Fig. A2.1). All the flow patterns identified by FLOWTHRU can also occur on the plane of symmetry through a circular lake.



**Figure A2.1 Three-dimensional flow near a circular flow-through lake (after Townley 1983)**

The geometry of the vertical section through the lake is shown in Figure A2.2. The length of the lake in  $x$  direction is  $2a$ . Aquifer thickness is  $B$  and  $L$  is the length of the capture and release zones. The lateral hydraulic conductivity is  $K_x$  and vertical hydraulic conductivity is  $K_z$ .

The boundary conditions for a model of vertical section through a shallow lake are shown in Figure A2.3.  $U_+$  is inflow and  $U_-$  is outflow.  $U_+$  is the product of  $K_x$  and the groundwater gradient of upstream side of the lake. Similarly  $U_-$  is the product of  $K_x$  and groundwater gradient of downstream side of the lake.  $R$  is recharge to the aquifer.  $Q$  is the net flux from the water body to the aquifer for the vertical section.  $Q$ , net flux, is defined as rate of flow volume per unit cross-section normal to the direction of flow. All three flow types,  $U_+$ ,  $U_-$  and  $Q$  can be positive or negative, with the positive direction defined in the figure.

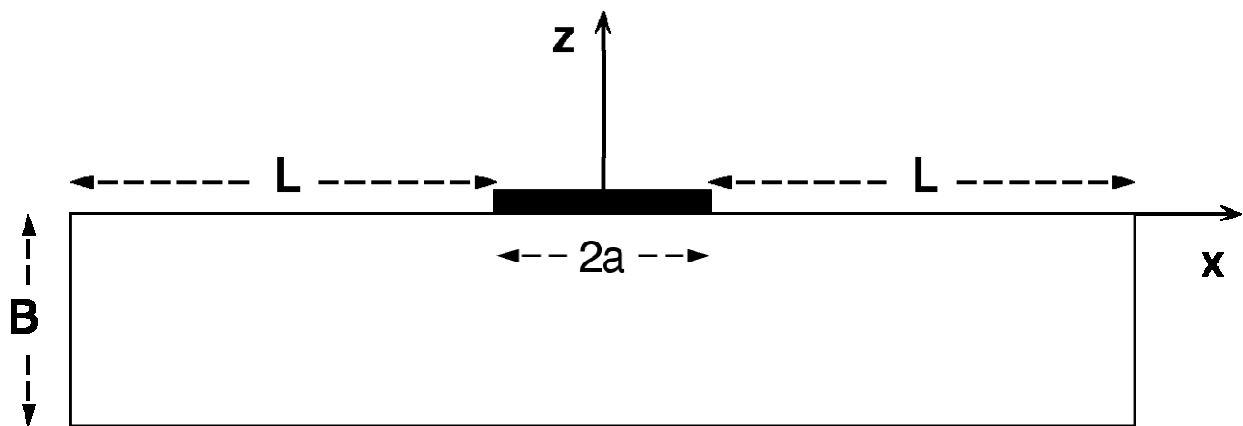


Figure A2.2 Idealised geometry for a model of a vertical section through a shallow lake (after Townley 1983)

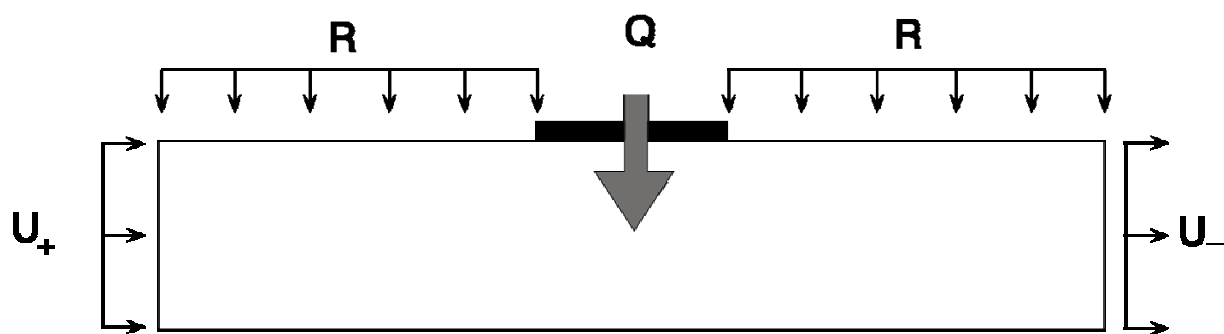
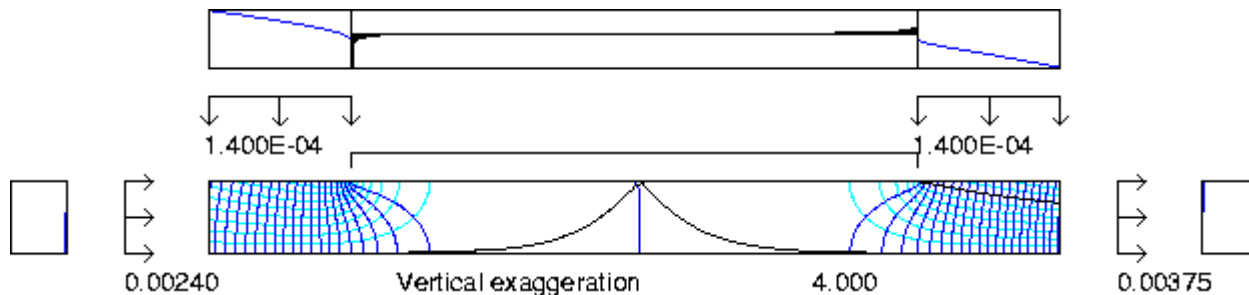


Figure A2.3 Boundary conditions for a model of vertical section through a shallow lake (after Townley 1983)

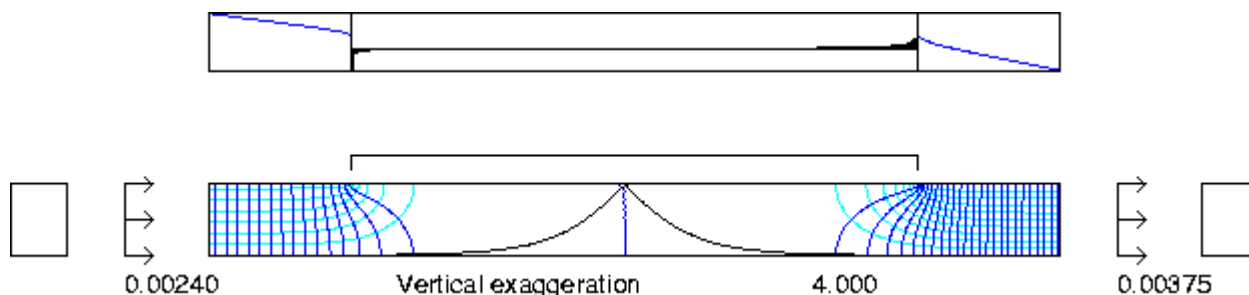
The FLOWTHRU model was applied to Lake Nunijup to evaluate how seasonal variations in groundwater level, recharge and evapotranspiration rates affect its water and salt balance. Results of groundwater monitoring for 2001–02 were used to calculate  $U_+$  (inflow) and  $U_-$  (outflow). Lateral hydraulic conductivity ( $K_x$ ) of 1.5 m/day and a recharge rate of 50 mm/year were used for modelling. Aquifer thickness is assumed to be 25 m. Five different modelling scenarios (Cases 1 to 5) were used to analyse lake and groundwater interactions. The results and the parameters used are given in Table A2.1.

Case 1 (Fig. A2.4) and Case 2 (Fig. A2.5) represent lake–groundwater interactions during or after a groundwater recharge event with special reference to late 2001 when groundwater levels had actually been monitored. In Case 1, a recharge rate of 50 mm/year was applied. Groundwater is flowing through the lake and in the process groundwater is discharging into the lake on the upgradient side and lake water is seeping out on the downgradient side (Fig. A2.4). In Case 1, groundwater discharge > seepage from lake, resulting in a net groundwater discharge into the lake (Table A2.1). When there is no recharge (Case 2), groundwater discharge < seepage from the lake and there is a net seepage of lake water into groundwater. The groundwater flow regime changes from FT2 to FT1.



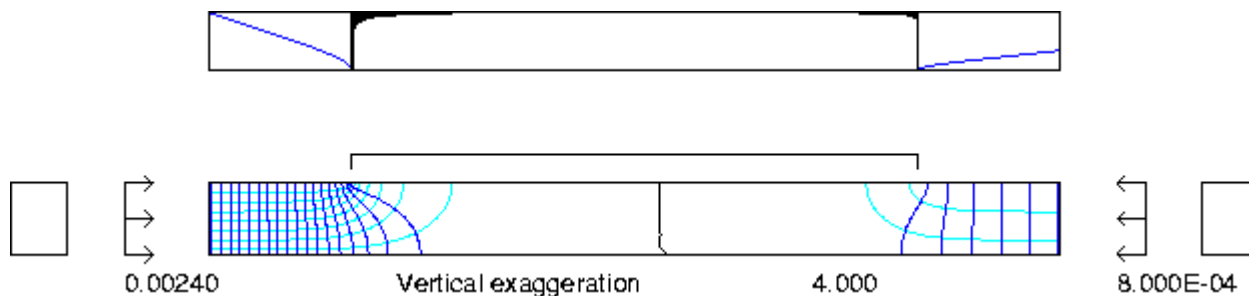


**Figure A2.4 Case 1: Groundwater flow pattern in December 2001**

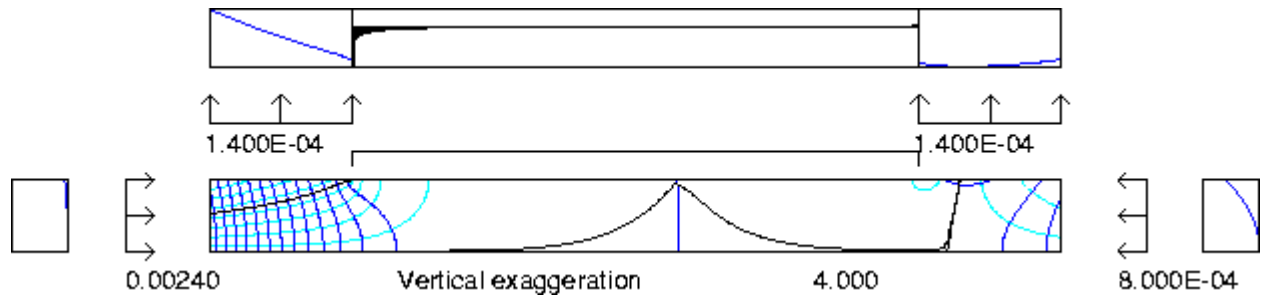


**Figure A2.5 Case 2: Groundwater flow pattern in December 2001 assuming no recharge to groundwater**

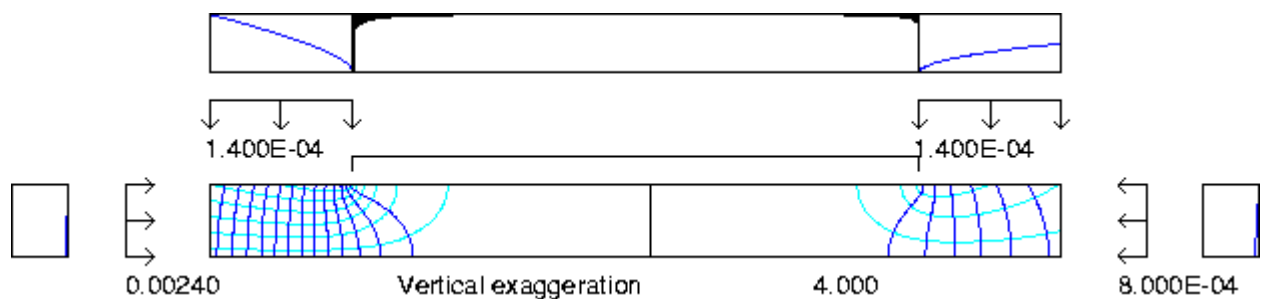
In Case 3, 4 and 5 (Figs A2.6, A2.7 & A2.8), the groundwater gradients of March 2002 are used. So, these represent groundwater flow patterns during summer. In Case 3, no evapotranspiration loss is assumed. In Case 4, the evapotranspiration loss from groundwater is 50 mm/year. In Case 5, a net recharge rate of 50 mm/year is used. In all three cases, groundwater discharges into the lake. The rate of discharge into the lake increases with increasing recharge to groundwater.



**Figure A2.6 Case 3: Groundwater flow pattern in March 2002 assuming no evapotranspiration loss from groundwater**



**Figure A2.7 Case 4: Groundwater flow pattern in March 2002 assuming evapotranspiration loss from groundwater**



**Figure A2.8 Case 5: Groundwater flow pattern in March 2002 assuming a net groundwater recharge**

**Table A2.1 Results of FLOWTHRU modelling for Cases 1 to 5**

Case	U+ (m/d)	U- (m/d)	Kx (m/d)	Kz (m/d)	R (m/d)	L (m)	Q (m <sup>2</sup> /d)*	Flow regime
1	0.0024	0.00375	1.5	0.094	0.00014	200	-0.0223	FT2
2	0.0024	0.00375	1.5	0.094	0	200	0.0337	FT1
3	0.0024	-0.0008	1.5	0.094	0	200	-0.08	D8
4	0.0024	-0.0008	1.5	0.094	-0.00014	200	-0.0240	FT7
5	0.0024	-0.0008	1.5	0.094	0.00014	200	-0.136	D8

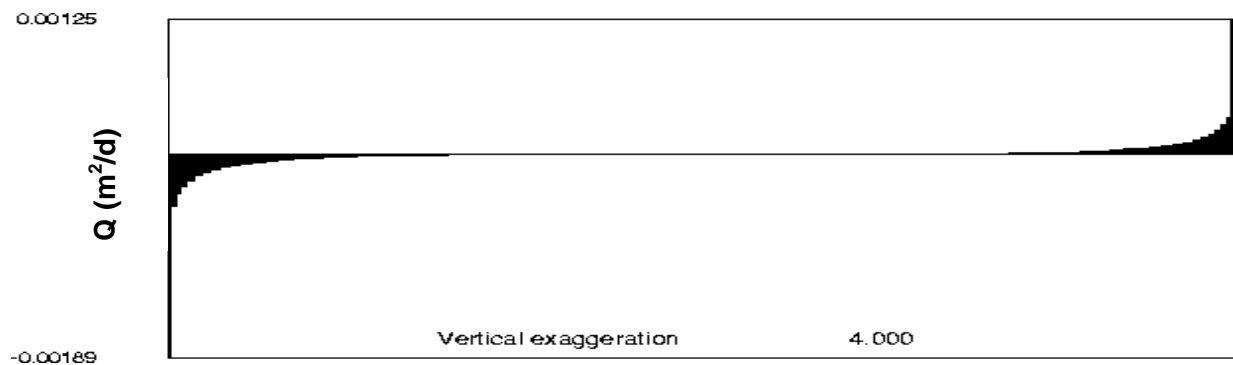
\* Negative Q (net flux) values indicates groundwater discharging into lake

By increasing the stresses, such as in Case 4, on the groundwater system, for example, by a high evapotranspiration rate, pumping or deep drainage, groundwater discharge into the lake can be reduced. Similarly, increased recharge to groundwater (Case 5) increases groundwater discharge into lake. From a management point of view, it will be better to use recharge reduction strategies.

When there is no net recharge (Case 2) and groundwater is flowing through (FT1) the lake, lake water tends to seep into the lakebed. This is the only case where lake water seeps into the groundwater system. In all the other flow regimes, FT2, D8 and FT 7, groundwater discharges into the lake. The volume of groundwater discharge directly relates to the vertical groundwater recharge.

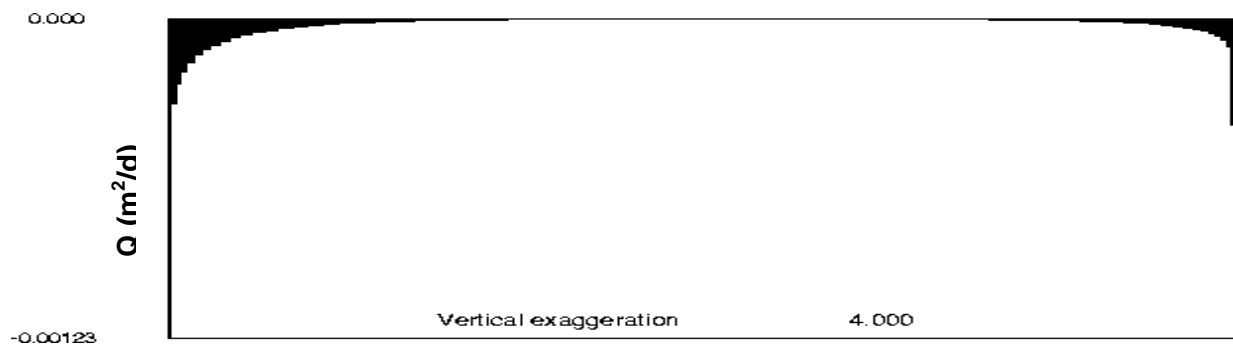
### Seepage and discharge distribution

Groundwater discharge and seepage from the lake in Case 1 are illustrated in Figure A2.9 and are mostly restricted to the upstream and downstream edges of the lake.



**Figure A2.9 Case 1: Seepage and discharge distribution for flow-through regime**

The groundwater discharge pattern for Case 3 is shown in Figure A2.10. There is groundwater discharge at both edges of lake but more at the upgradient side of the lake.



**Figure A2.10 Case 3: Distribution of groundwater discharge into the lake**

Figures A2.9 and A2.10 show that, whatever the flow regime, groundwater is discharging at the upgradient side of the lake and that, at the downgradient side (southern side of the lake), depending on the flow regime, the movement of water may change from seepage of lake water to groundwater discharge. In a particular year, seepage from the lake is the dominant process.

## Capture and release zones

Research by Townley et al. (1983) has led to a knowledge of the most important factors which affect groundwater flow patterns near surface water bodies, particularly lakes and wetlands. They show that for a flow-through lake the ratio of the length of a water body ( $2a$ ) to the thickness of an aquifer ( $B$ ) i.e.  $2a/B$  is one of the most important factors. The depth of the capture zone depends mostly on  $2a/B$  for isotropic aquifers. When  $2a/B$  is about 1, the capture zone is less than half the thickness of the aquifer. When  $2a/B$  is 7 or more, the capture zone extends to the base of the aquifer. The width of the capture zone of a large circular lake is roughly twice the diameter of the lake for a shallow aquifer (where  $2a/B > 8$ ), or 1.5 times the diameter for a deep aquifer ( $2a/B < 8$ ).

For Lake Nunijup,  $2a/B$  is about 32 so the capture zone extends to the base of the Tertiary sediments aquifer. Laterally, the capture zone extends about 200 m from the northern side of lake towards NU 6 in north-west direction passing Koonjie Road. The release zone extends 200 m from the southern side of Lake Nunijup. NU 2 is located within this release zone.

## Appendix 3 – Lake and LUCICAT models

The Lake Model is conceptualized as a simple bucket, with salt and water always well mixed. That means when the lake overflows, the salinity of the outflow is identical to the salinity of the lake. It is a simple spreadsheet-type volumetric salt and water balance model. The time-step is monthly, but it can be run on a daily or yearly basis. The volume of water in the lake at a given time is always known. From the lake water volume, the water level and surface area are calculated from a look-up table of depth–surface area–volume relationship. A simple representation of the Lake model is shown in Figure A3.1. Gains and losses of water from the lake are:

- inflow
- rainfall on the lake surface
- evaporation from the lake surface
- streamflow from the lake
- seepage from the lake bottom.

The salt balance component is very similar to the water balance component of the model but has an additional component of salt exchange on the soil surface during the contraction/expansion of the lake water surface. When the lake contracts, the model leaves on the dry lakebed some salt that dissolves again when lake expands (given as a parameter). Bari (2004) details the numerical representation of the model.

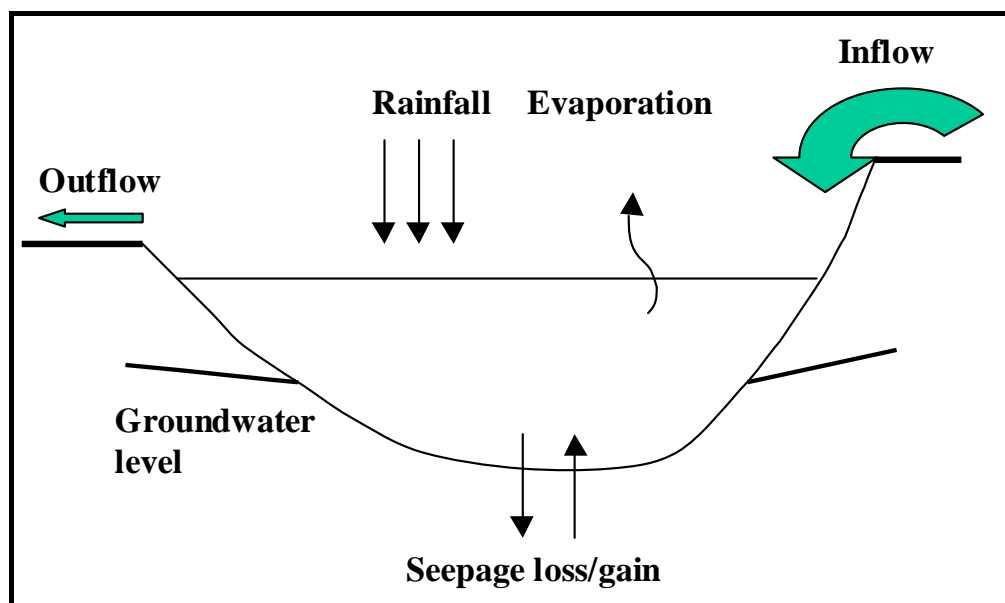


Figure A3.1 Conceptual representation of the lake model

### The LUCICAT model

This is a distributed conceptual catchment hydrology model. A large catchment is divided into subcatchments and the fundamental model is applied to each subcatchment. Division is generally according to the location of the hydrometric measuring stations, land use history and

catchment morphology. The subcatchments are then arranged sequentially, defining the order in which the computations are to be carried out.

In the fundamental model, the catchment is represented by the 'open book' approach (Fig. A3.2). The model consists of three main components: (i) a two-layer unsaturated soil module (upper and lower zone unsaturated store), (ii) a saturated subsurface groundwater module, and (iii) a transient stream zone module. The upper zone unsaturated store is represented by a VIC-type model (Wood et al. 1992; Zhao & Liu 1995), a simple probability distribution function of the soil moisture capacity. The transient stream zone store represents the groundwater-induced 'saturated areas' along the streamline. The flow chart of the different components is shown in Fig. A3.2.

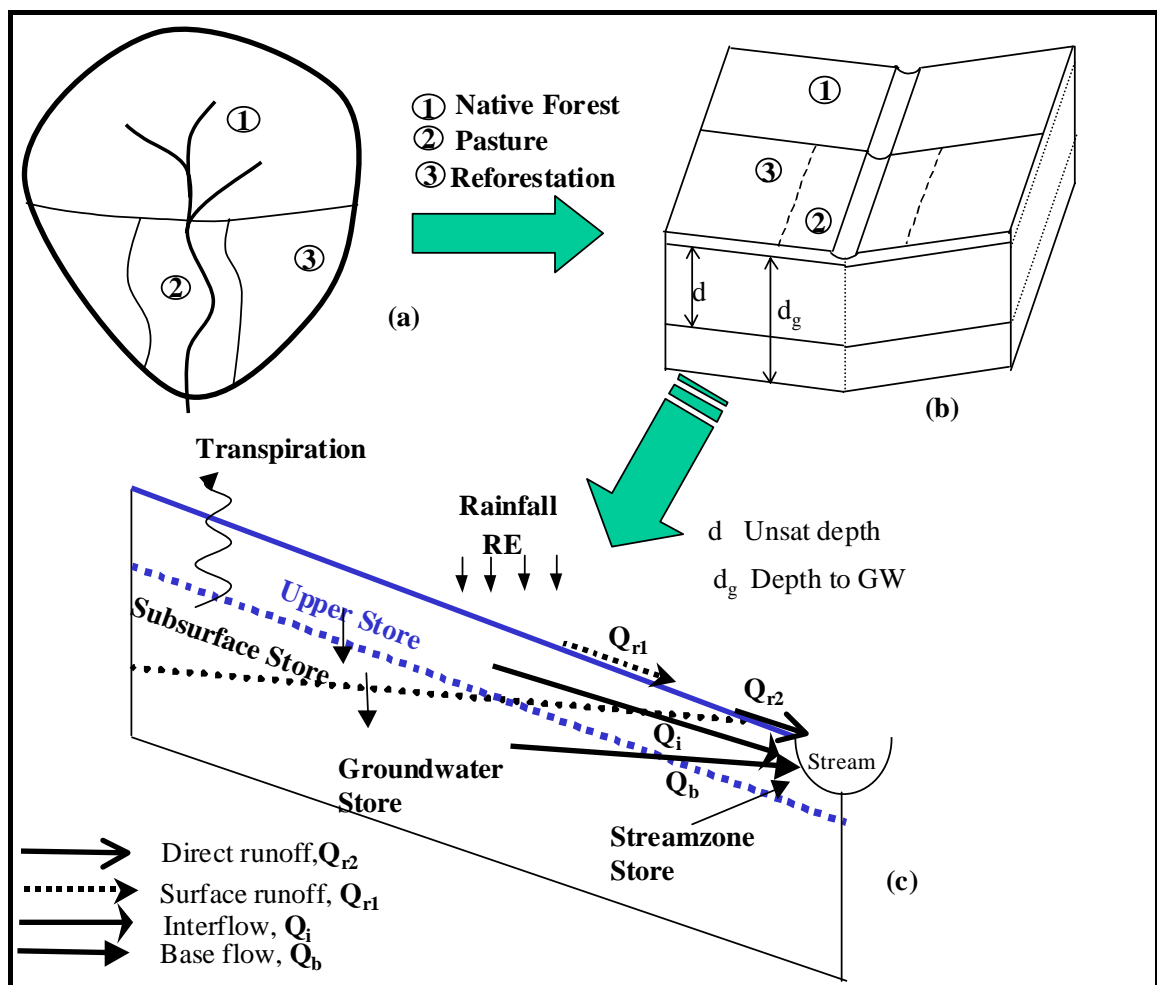


Figure A3.2 Schematic of (a) a subcatchment, (b) the 'open book' representation, (c) the hydrological processes (after Bari et al. 2001)

## Hydrological processes of the fundamental model

Interception, transpiration by plants and evaporation from soil constitute evapotranspiration. Some of the salt from rainfall is intercepted on plant leaves but is washed onto the soil surface later. Transpiration is a function of the Leaf Area Index, relative root volume in the upper and lower stores, moisture content and the potential energy. The transpiration module is described in detail by Bari et al. (2003).

Surface runoff is generated by the process of saturation excess only, as infiltration excess overland flow is a rare event in Western Australia (Sharma et al. 1987). If part of the stream zone is saturated by the presence of a permanent groundwater system, surface runoff ( $Q_{r,2}$ ) is also generated from those areas. Interflow ( $Q_i$ ), the contribution from the intermittent shallow groundwater, is a function of the catchment-wide average lateral conductivity of the A-horizon, and the water content of the Wet Store. Percolation ( $I$ ) is the amount of vertical water flow from the A horizon to the deep unsaturated soil profile. Most of the percolated water is used and transpired used by the deep-rooted trees.

Baseflow ( $Q_b$ ) is defined as the contribution of the permanent groundwater to streamflow.

There is no baseflow unless the groundwater system connects to the stream bed. It is a function of the catchment-average lateral conductivity of the aquifer, groundwater gradient and stream length.

### Flow routing

Once runoff is generated from a particular subcatchment (Fig. A3.3), it is transferred downstream by a simplified hydraulic routing scheme. There is no surface routing component in the model. The water and salt generated from each of the subcatchments reach the stream channel without any time lag and then flow downstream based on open channel hydraulics. Evaporation from the stream channel and loss to groundwater is allowed.

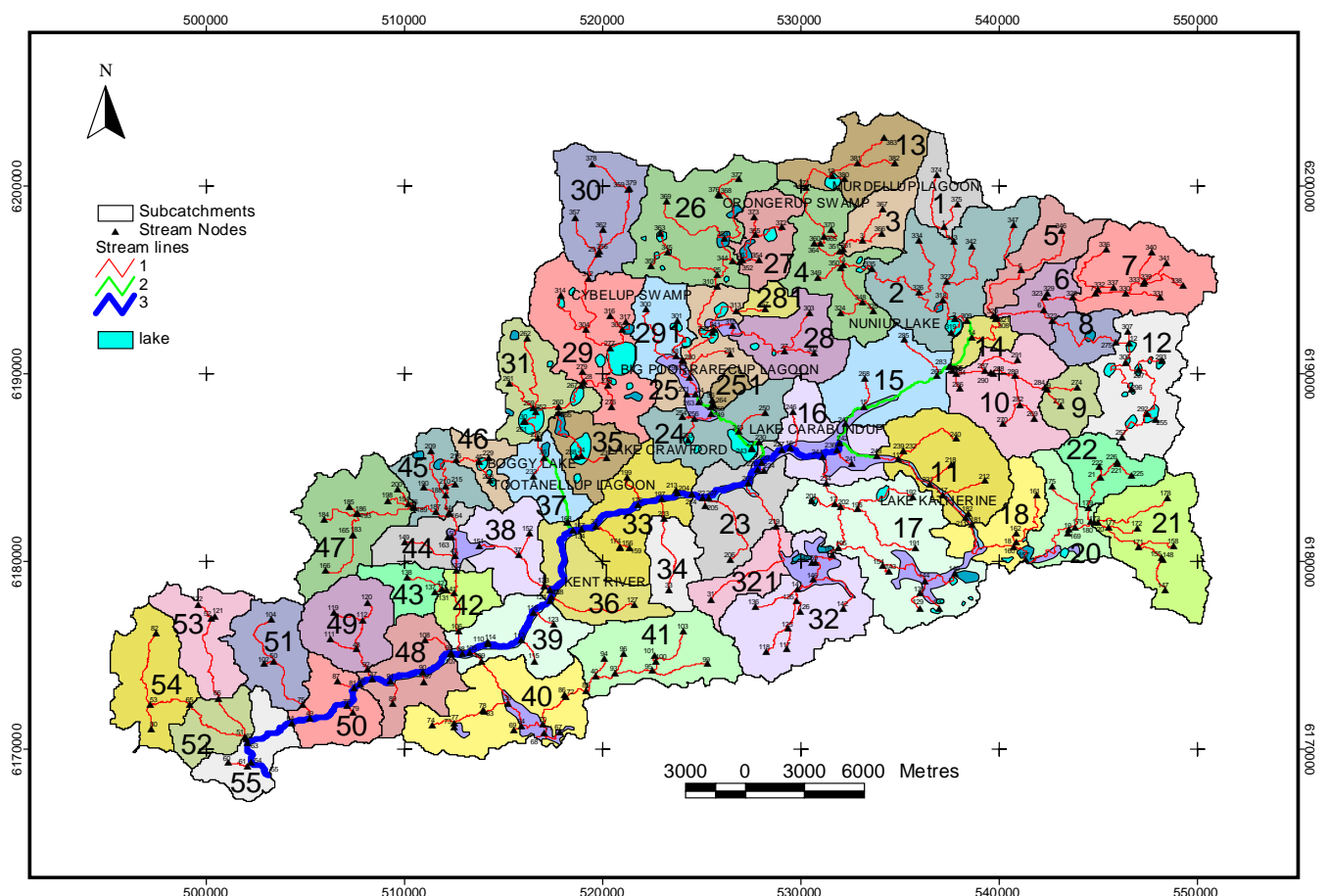


Figure A3.2 Subcatchments, nodes and channel network of the Upper Kent catchment

## Appendix 4 – LUCICAT model set-up

### Rainfall and saltfall

The Kent Recovery catchment has a good coverage of rainfall records. The Bureau of Meteorology started recording daily rainfall from about the 1900s. The Department of Water also operates some pluviometers but, in most cases, monitoring only started in the early 1970s. Twenty-two pluviometers, located within and around the catchment, were selected for creating long-term (1910–2000) daily rainfall series for each subcatchment. The calculation of the daily rainfall series at the centroid of each subcatchment was based on its distance from the nearest three pluviometers (Dean & Snyder 1977). The long-term (1910–2000) average annual rainfall of the upper catchment ranged from 830 mm in the west to 550 mm in the east (Fig. 6).

A limited amount of salt fall data was available for the catchment. The salt concentration of rainfall at the centroid of each subcatchment was estimated from the average annual rainfall to salt concentration relationship as described by Hingston and Gailitis (1976). The estimated salt concentration was cross-checked against observed data where available. The salt concentration of rainfall ranged from 10–6.5 mg/L TDS across the catchment.

### Pan evaporation

As no pan evaporation data have been recorded within the upper catchment, annual pan evaporation data at the centroid of each of the subcatchments were adopted from Luke et al. (1988) and ranged from 1395 mm to 1510 mm. The annual data were then converted to daily data using a simple harmonic function. The maximum daily pan evaporation (more than 12 mm) is generally recorded in December and the minimum (in the order of 1.5 mm) generally in July.

The pan evaporation from each lake surface was taken as the value at the centroid of the respective subcatchment.

### Streamflow and salinity records

Continuous streamflow recording at the catchment's two major gauging stations, Rocky Glen and Styx Junction, began in 1979 and 1956 respectively. Until the 1970s, when continuous conductivity recorders were installed, salinity samples were collected manually. In 1999, two more gauging stations with continuous conductivity recorders (Perillup Road and Watterson Farm) were installed (Fig. 6). Salinity samples were also collected from around the catchment when the water resources survey was undertaken (Collins & Fowlie 1981). At present, salinity samples are being collected from 11 locations around the upper catchment.

### Salt storage

A number of studies have been undertaken in Western Australia to understand local and regional distribution and accumulation of salt. A strong correlation of increasing soil salt storage with decreasing rainfall has been well established for the south-west (Johnston et al. 1980; Stokes et al. 1980; Tsykin & Slessar, 1985). In the 1970s, some measurements were undertaken in the upper catchment to understand the vertical and areal distribution of soil salt storage (Bari & Boyd 1992). In the 1990s, many samples were taken as a part of the regional groundwater study (Bartle et al. 2000). The salt storage of the highly conductive topsoil (generally 2–3 m thick) is very low all over the catchment, and generally in the order of 0.35 kg/m<sup>3</sup>. Most of the salt is stored in the unsaturated soil profile. The groundwater salinity



and long-term average rainfall of the sites were found to be well correlated. There is also a reasonably strong relationship between the groundwater salinity and the salt storage (Fig. A4.1). Based on these two relationships the salt content of each subcatchment was calculated. The average salt storage ranges from 2.2 kg/m<sup>3</sup> in the western high-rainfall areas to 4.6 kg/m<sup>3</sup> in the low-rainfall areas of the upper catchment.

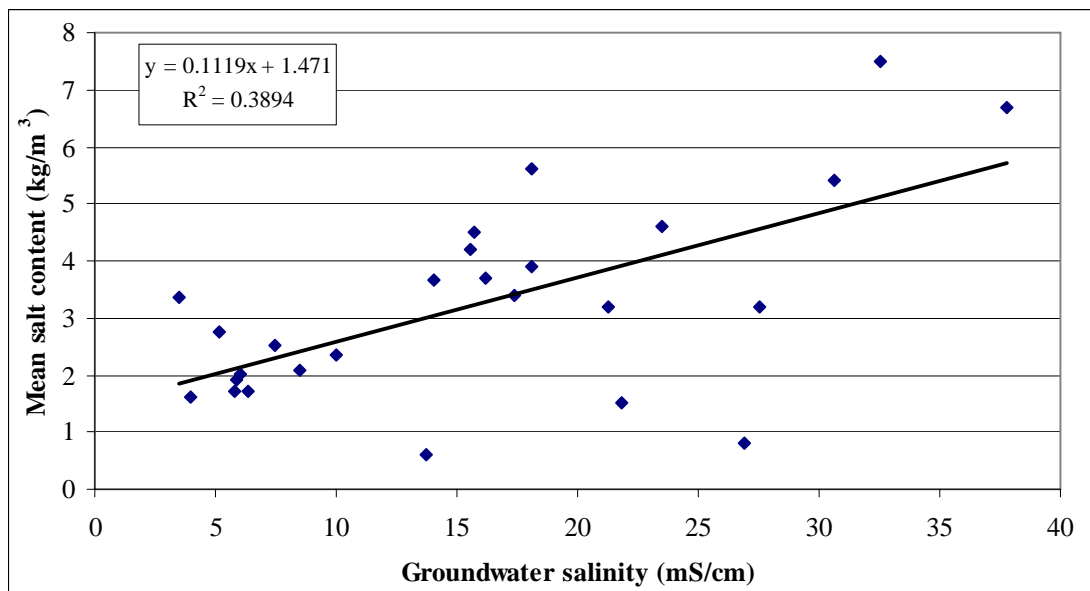


Figure A4.1 Relationship between mean soil salt content and groundwater salinity

## Land-use history

The land-use history of the upper catchment is not well documented. When clearing control legislation was enacted in 1978, 68% of the catchment area had been cleared for agricultural development (Fig. 6). The proportion of the cleared area of each subcatchment was adopted from Dixon et al. (1998). As the progress of clearing is not known, a single clearing trend, as recorded by Collins and Fowlie (1981) was used for all subcatchments. The land use history for each subcatchment for the whole period of simulation (1968–2001) was consolidated as a 'land use history' file. If part of a subcatchment was cleared, a concept of land use fractions was used to reflect the changes. Since the mid-1990s, private companies have planted bluegums on a significant proportion of the cleared areas in the high rainfall portion of the catchment. These changes are yet to be incorporated into the model.

## Groundwater system

In the High Rainfall Zone, groundwater in the south-west of Western Australia is well-connected to the stream channel, whereas in the Low Rainfall Zone it lies about 15-20 m below the stream channel. An initial groundwater level was developed for each of the forested subcatchments based on records and regional trends. Estimation of the initial groundwater level beneath the cleared areas was difficult though there were some studies of groundwater level trends particularly in the cleared areas of the upper catchment (Bari & Boyd 1993; McFarlane et al. 1994; Bartle et al. 2000) and experimental evidence elsewhere in the south-west showing the rate of change in groundwater level following land use changes (Bari 1998; Mauger et al. 2001). Based on those data and land use history, initial groundwater levels beneath the cleared areas were estimated and incorporated into the model.

## Subcatchment attributes

The upper catchment was divided into 58 subcatchments ranging in area from 2.8 to 48 km<sup>2</sup> (Fig. 6). The average subcatchment elevation, stream length, average surface slope, soil type and total profile thickness were determined from digital data through the use of Geographic Information System.

### Lake characteristics

Lake depth–volume–surface area information for all three lakes is available from the DoW south-coast region, Albany (Table A4.1).

The characteristics of the outflow channel, the bed slope, roughness and depth-width are required in the Lake Model. At present no data available, but the best-estimated data has been incorporated into the model. No data is available on lake-bed conductance or the underlying aquifer properties.

**Table A4.1 Lake characteristics**

Lake	Overflow depth (m)	Surface area (km <sup>2</sup> )	Volume (GL)	Median salinity (mg/L TDS)
Nunijup	3.9	0.79	2.32	7 750
Carabundup	4.0	1.85	5.17	15 000
Poorrarecup	3.0	1.99	4.98	10 600

## Initial conditions

The inflow and salt load, predicted by the LUCICAT model, were used to calibrate the Lake model, starting from January 1973. At the beginning of calibration, the Lake Model parameters for all three lakes were kept similar to the application of the model to Lake Toolibin and Lake Dumbleyung (Bari & Ruprecht 2003; Bari 2004). Initial water volumes in all three lakes were assumed to be 1 GL.

## Appendix 5 – LUCICAT model calibration

The principal objective in applying this model was to represent the salinity generation process of the upper catchment on a daily time-step. The model was applied for the period 1968–2001. The stream nodes, channel network and other subcatchment attributes are shown in Fig. A3.3.

LUCICAT needs minimal calibration (Bari et al. 2003). Most of the parameters remain ‘fixed’ once calibrated in a catchment, with exception of 7 physically meaningful parameters which, at times, vary between catchments. The range of parameter values and their ranking in terms of sensitivity are shown in Table A5.1. The most sensitive parameter ( $ia$ ), the relationship between the catchment-wide lateral conductivity of the topsoil and moisture content, ranged from 2.15 to 3.15 (Table A5.1). The second most sensitive parameter was the vertical conductivity of the upper layer ( $pa$ ), which controls the percolation to the deep unsaturated profile and ranged between 15.29 and 27.185 mm per day for other applications (Bari et al. 2003). The other ‘variable’ parameters are the topsoil depth ( $d_{um}$ ) and its spatial distribution of water-holding capacity ( $a, b$ ), and the average lateral conductivity ( $K_{ll}$ ) of the aquifer (Table A5.1).

**Table A5.1** The ‘variable’ parameter set for the upper catchment

Parameter	Range	Sensitivity ranking	Most likely value	Collie River catchment	Upper catchment
$a$	0.256–0.56	3	0.256	0.2	0.15
$b$	0.123–0.625	6	0.256	0.2	0.15
$d$	1900–2500	4	2500	1600–2500	1550–1950
$ia$	2.15–3.15	1	2.3	2.5	2.15
$K_{vu}$	15.29–27.185	2	27.185	27.185	27.185
$K_{ll}$	400–1500	5	500	300	1 800
$C_u$	0.0042–0.0263	7	0.0163	0.0063	0.0063

This model was successfully applied to the Collie River catchment (Bari et al. 2003) and, at first, the identical parameter set was adopted for the whole upper catchment (Table A5.1), without any calibration. The observed and predicted annual streamflows at the Rocky Glen gauging station were comparable but predictions of the annual salinities and salt loads were poor for all subcatchments where there had been significant land use changes, mainly due to the poor representation of the salt storage in the stream zone.

The next step was to adjust some of the parameters to match predicted and observed daily streamflows. The thickness of the topsoil is a sensitive parameter and the literature reveals that it is not uniform across the catchment (Mauger et al. 2001; Bari et al. 2003). After the adjustment, the mean topsoil depth ( $d$ ) over the catchment ranged from 1550–1950 mm (Table A5.1). Adjustment of some of the other four sensitive parameters ( $a, b, ia, pa$ ) to match predicted and observed daily flows followed. The ‘final’ values of these parameters are not significantly different from the initial adopted values (Table A5.1).

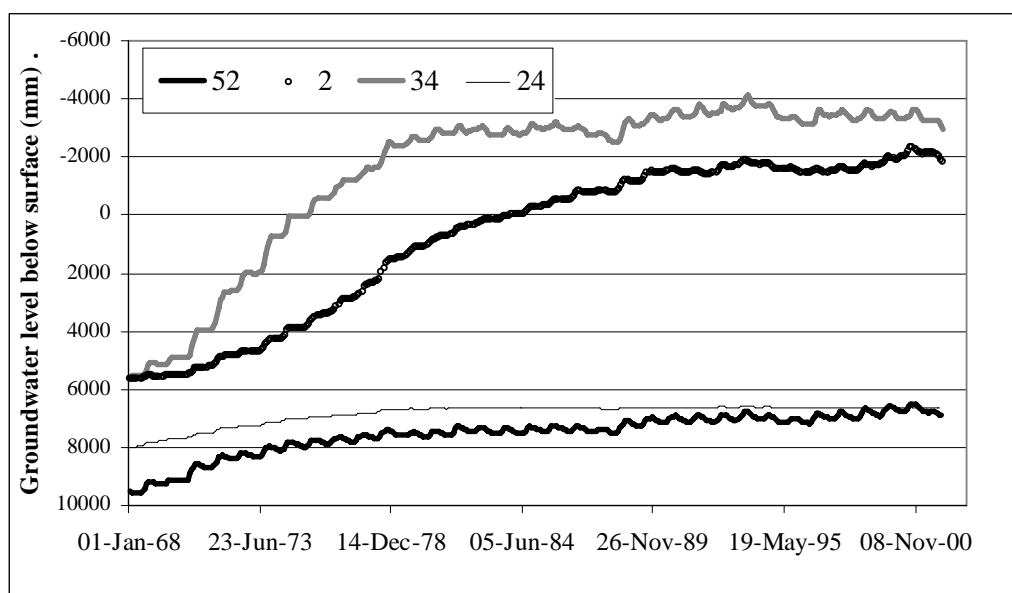
Calibration of the daily stream salinity and salt load followed. As the initial salt storage value of the stream zone could not be estimated from observed data, the model was run a few times and

the final values of the stream zone salt store used as the initial values for subsequent runs. At this stage, the lateral hydraulic conductivity of the deep aquifer ( $K_{ll}$ ) and the other parameter ( $C_{ll}$ ), which controls the stability of the salts stored in the topsoil, were also adjusted to obtain the most satisfactory matchings of the observed and predicted flow, salinity, salt load and groundwater trend. The 'final' parameter set is given in Table A5.1.

The following sections describe the different components of the modelling results.

## Groundwater system

Groundwater beneath native forest in the south-west of Western Australia has either been stable over the last 30 years or, in some areas, has shown a slight downward trend — attributed to the lower than long-term average (1900–70) annual mean rainfall (Schofield & Ruprecht 1989). LUCICAT, representing the groundwater level trends beneath the forested and cleared subcatchments within the upper catchment (Fig. 35), shows that the groundwater levels beneath forested portions of subcatchments 24 and 52 remained practically stable during the whole period of simulation (Fig. A5.1).



**Figure A5.1 Trends of the conceptual groundwater system in selected subcatchments**

After the clearing controls of the 1970s, groundwater levels under cleared areas of all the Recovery Catchments kept rising until a new stability was achieved by the mid 1990s (Bari 1998; Mauger 2001). Rising groundwater was also observed in the upper catchment, particularly in the cleared areas (Bari & Boyd 1993; McFarlane et al. 1994; Bartle et al. 2000; De Silva 2003). The modelled groundwater level stabilised by the late 1990s (Fig. A5.1). For example, the groundwater level had already reached the stream bed in subcatchment 34 where there was no significant reforestation. The trends of the conceptual groundwater levels beneath other subcatchments were very similar to the ones presented in Figure A5.1.

## Annual streamflow, salinity and load

For the whole simulation period, observed and predicted annual streamflows showed good agreement (Fig. A5.2a). The model slightly under-predicted the highest flow on record (1988), generally predicted the low-flow years quite well and overall obtained a very high correlation coefficient ( $R^2 = 0.92$ ). The observed and predicted total streamflows were 579 mm and 625 mm respectively, resulting in an overprediction of only 7%.

For the whole period of study, the modelled and observed annual flow-weighted salinities and salt loads matched reasonably (Figs A5.2b & c). The predicted salinity for 1987 was 5915 mg/L when one of the highest stream salinities (5830 mg/L TDS) was observed. The model slightly overpredicted the annual load some years between 1979 and 1987. During the period 1979–2001, total observed and predicted salt discharges from the catchment were 17 345 kg/ha and 17 480 kg/ha respectively, representing a 1% overprediction (Fig. A5.2b).

## Monthly flow and salt load

The relationships between observed and predicted monthly streamflow and salt load for Rocky Glen gauging station are shown in Figure A5.3. A constrained linear relationship between the monthly observed and modelled streamflow gives a correlation coefficient ( $R^2$ ) of 0.91 (Fig. A5.3a). Similar monthly relationships were also obtained by Sivapalan et al. (1996) when they applied the LASCAM model at Wights and Salmon catchments. The model overpredicts some low flows, particularly those less than 5 mm/month (Figure A5.3a).

Similarly, a satisfactory relationship ( $R^2=0.92$ ) between the observed and predicted monthly salt load was observed (Fig. A5.3b). Monthly salt loads ranged from 0 to 425 kg/ha. The model mostly overpredicted salt loads during low-flow periods (Fig. A5.3b).

## Daily streamflow, salinity and load

Daily simulated and observed streamflow hydrographs matched reasonably well most years. The trend, magnitude and duration of observed and simulated daily flow, salinity and salt loads of 1987 and 1990 are typical for all other years.

In the average-flow year of 1990, the spatial average rainfall of the upper catchment was 620 mm. Daily streamflow was dominated by baseflow component during October to May (Fig. A5.4b). Daily stream salinity was from 5000 to 6000 mg/L TDS. The model predicted the flow generation processes very well, but the predicted daily salinity was, at times, less than that observed (Fig. A5.4b). Daily observed stream salinity rose to 10 000 mg/L TDS during April–June, when the upper part of the catchment began to flow and salts left on the soil surface by evaporated groundwater were flushed into streams. The model slightly underpredicted the daily salinity (Fig. A5.4b), but matched the observed salt load (Fig. A5.4c). The model also slightly underpredicted the maximum daily (peak) flow of the year. The predicted and observed maximum flows were 2.84 mm and 2.75 mm respectively (Fig. A5.4a). The modelled and observed salinities were reasonably similar. The model also slightly overpredicted some of the peak salt loads (Fig. A5.4c).

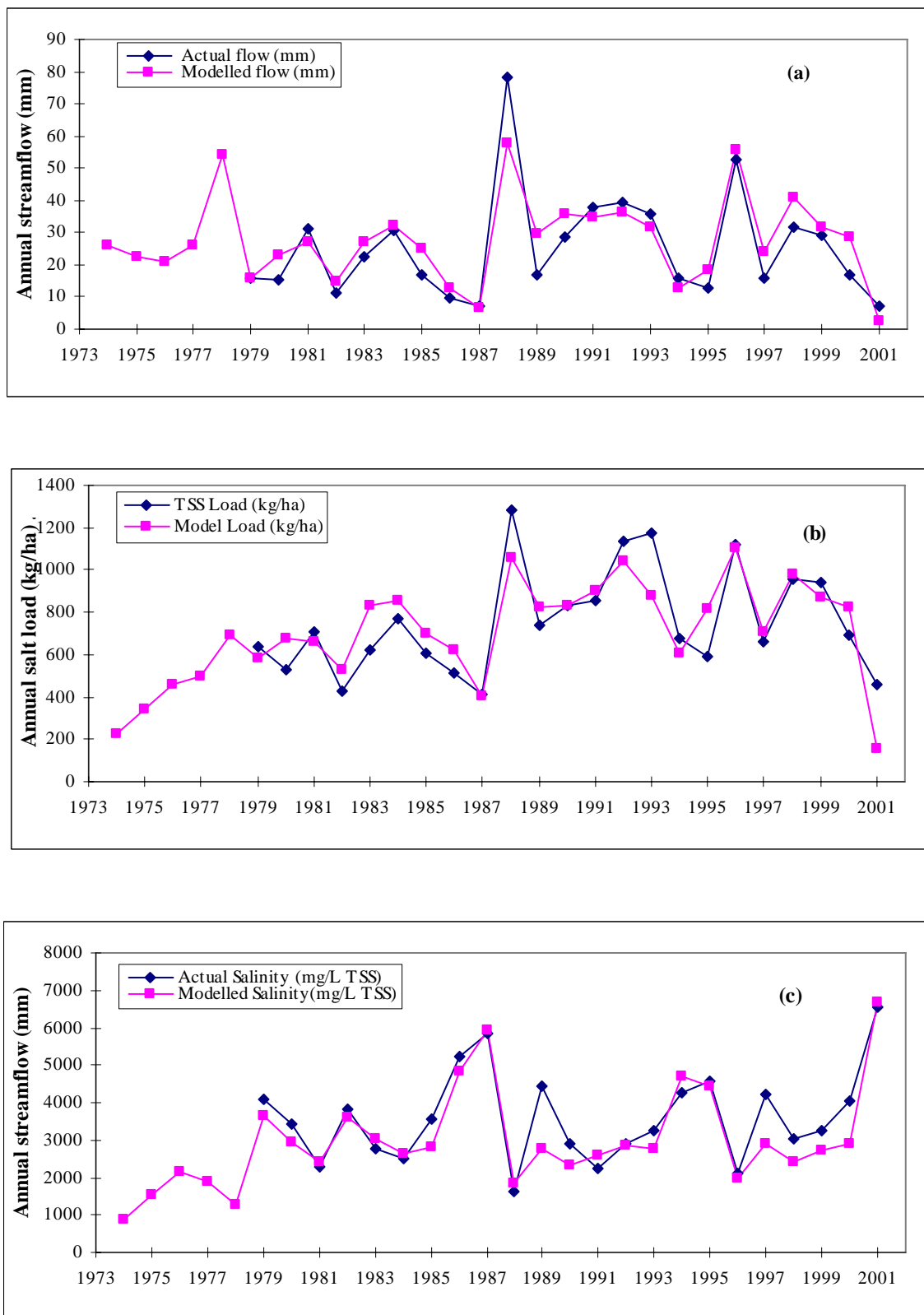
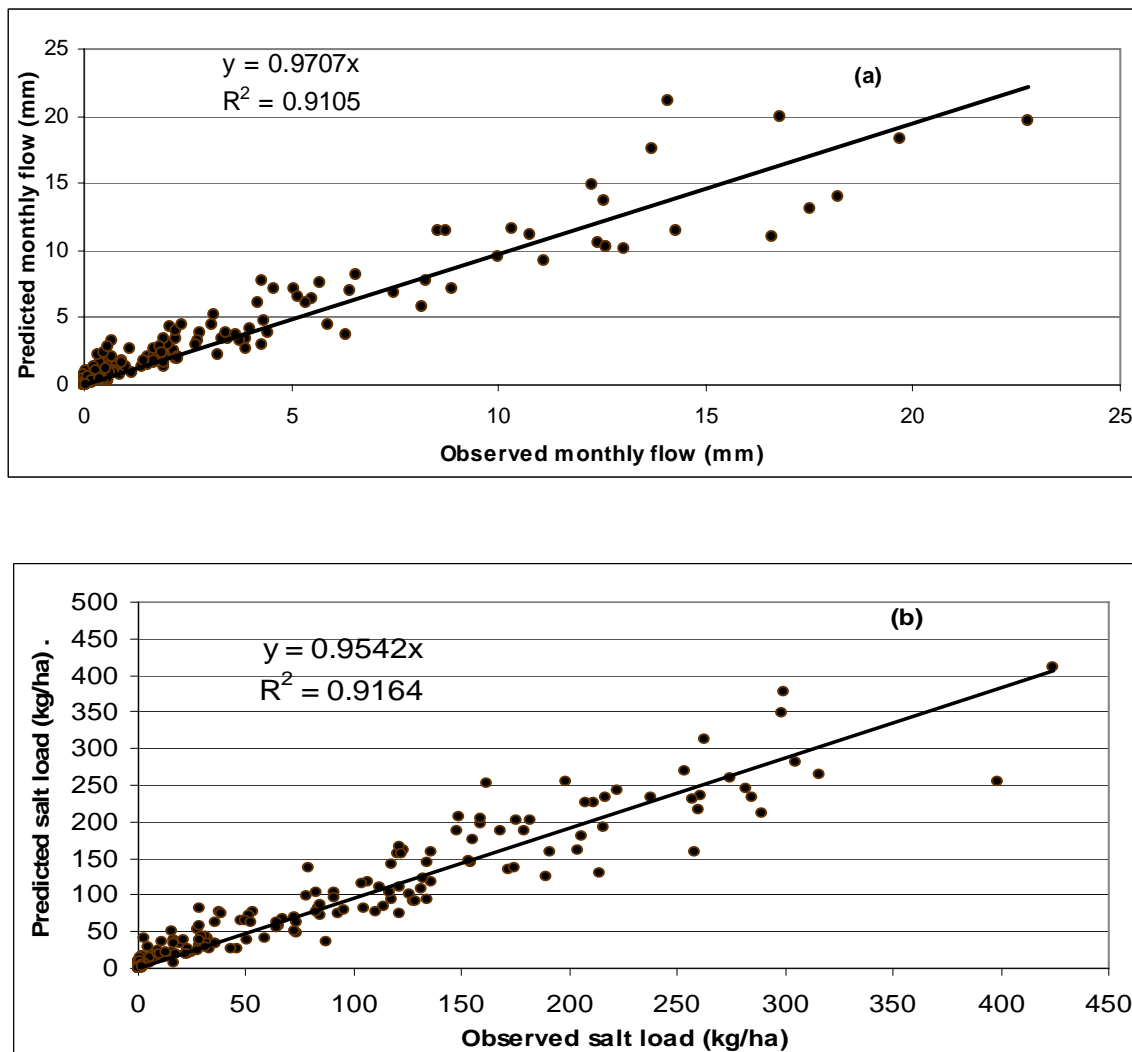


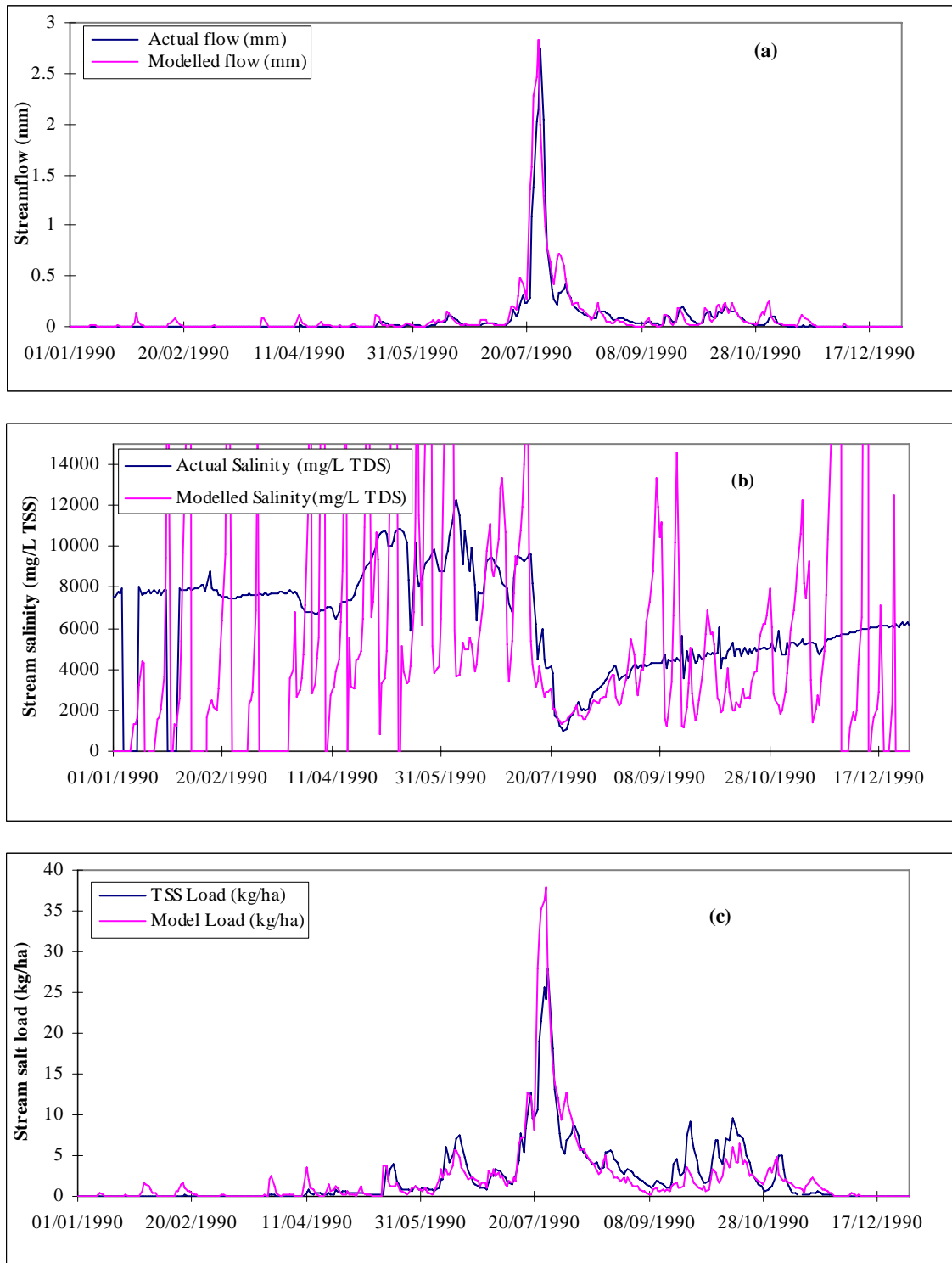
Figure A5.2 Annual modelled and observed (a) streamflow at (b) salinity, and (c) salt load at Rocky Glen



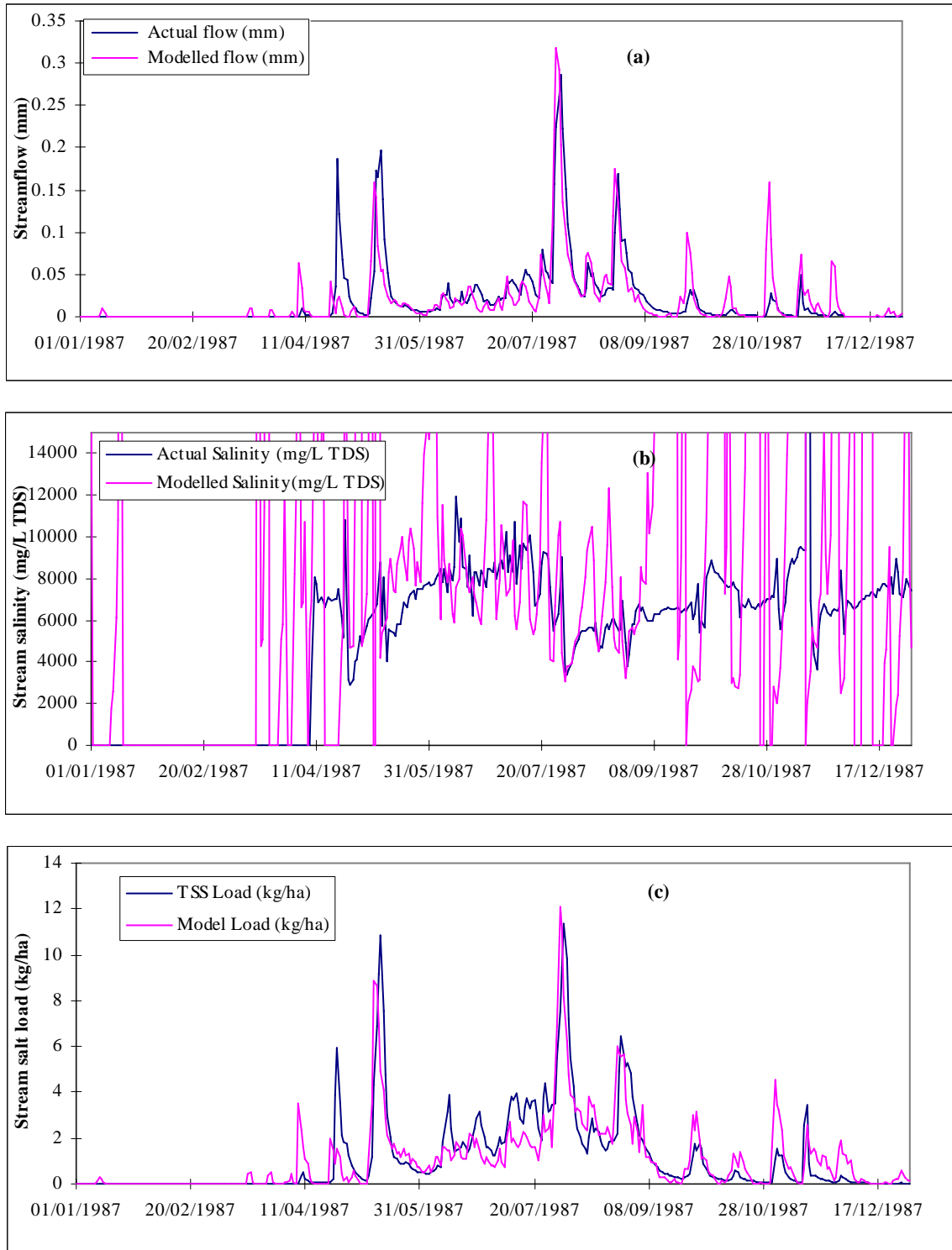
**Figure A5.3 Relationship between monthly modelled and observed (a) streamflow and (b) salt load at Rocky Glen**

The year 1987 was one of the driest during the period 1979–2001 (Fig. A5.2a). There was no streamflow recorded at the Rocky Glen gauging station during the dry months January to April (Fig. A5.5a). When streamflow started in April, daily predicted flow was slightly lower and daily predicted salinity was much higher than observed. During the high-rainfall months (July to October), the model simulated interflow and baseflow well, but overpredicted some of the peak flow components (Fig. A5.5a). During October to December, the simulated daily stream salinity was slightly higher than the observed values (Fig. A5.5b). The observed and simulated stream salt loads were similar, except for a few peaks, which were overpredicted by the model (Fig. A5.5c).





**Figure A5.4 Daily modelled and observed (a) streamflow (b) salinity and (c) salt load at Rocky Glen (1990)**



**Figure A5.5 Daily modelled and observed (a) streamflow (b) salinity, and (c) salt load at Rocky Glen (1987)**

# Appendix 6 – Salt and water balance components of the lakes

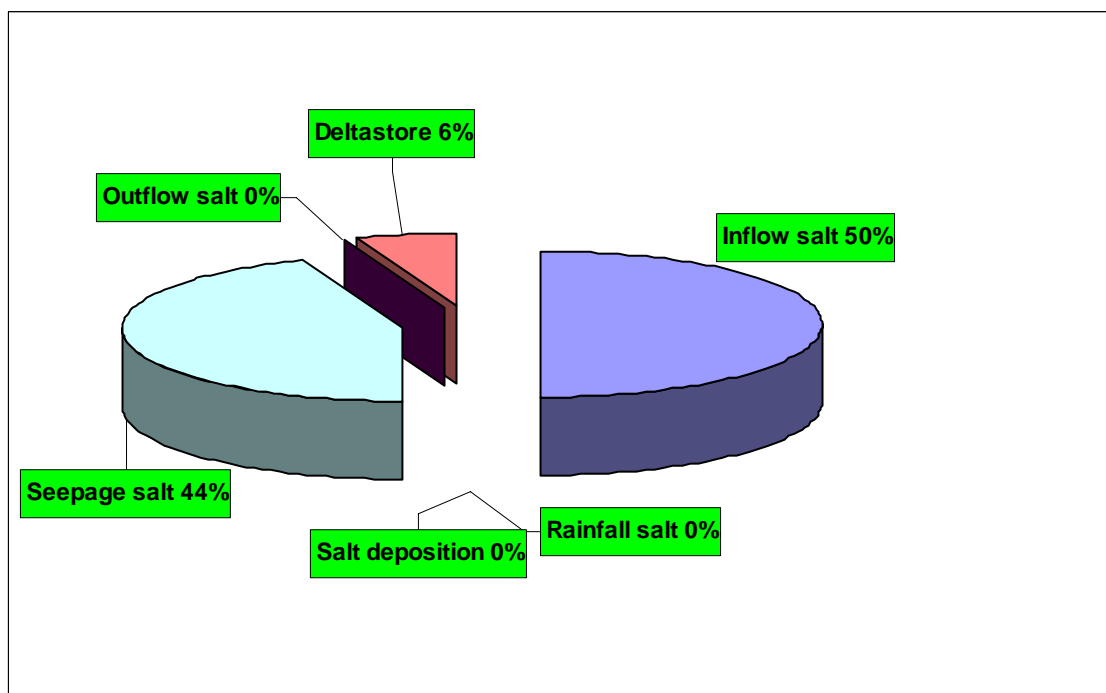
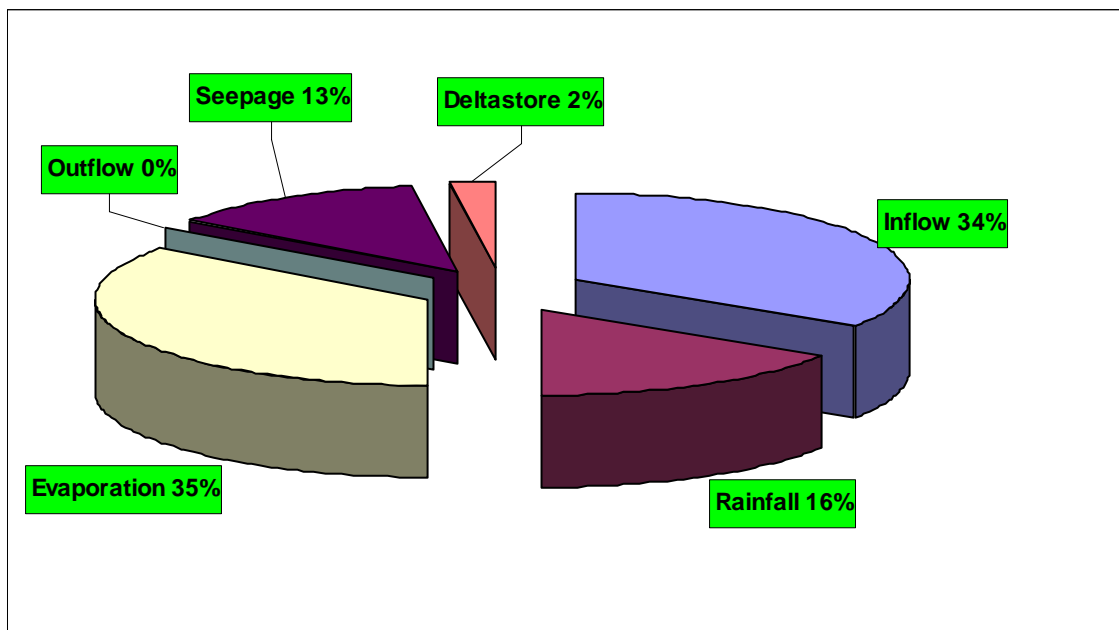


Figure A6.1 Salt and water balance components of Lake Nunijup

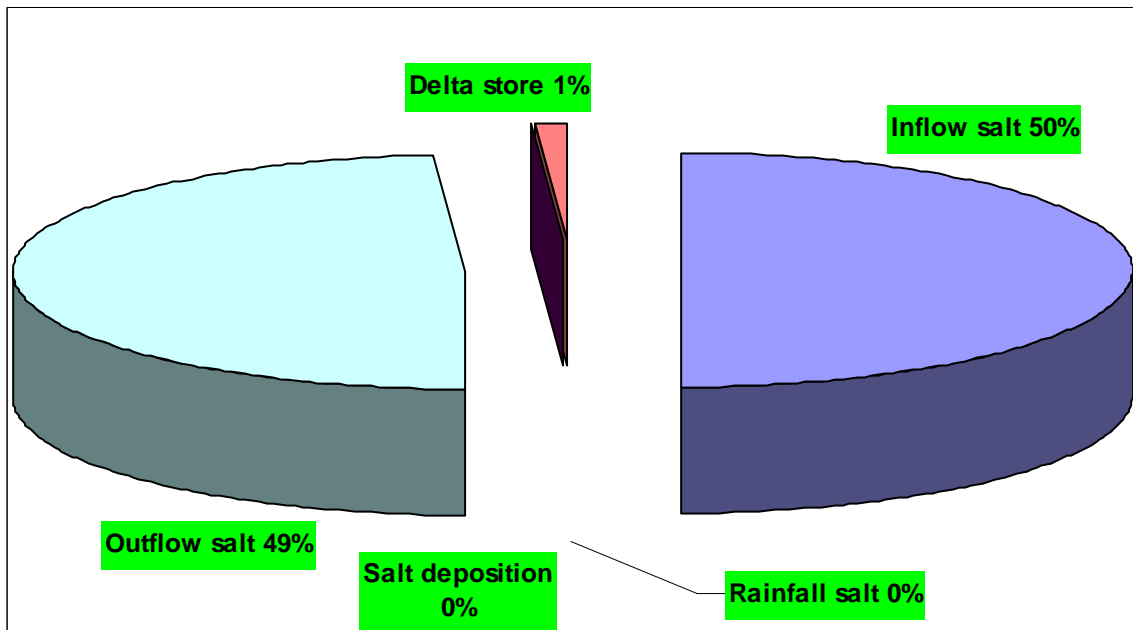
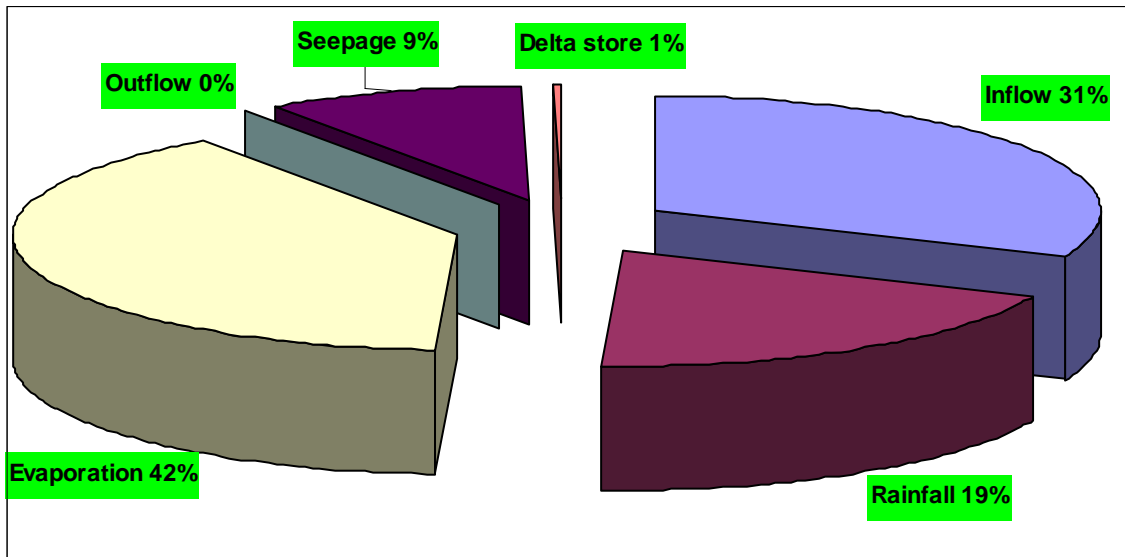


Figure A6.2 Salt and water balance components of Lake Carabundup

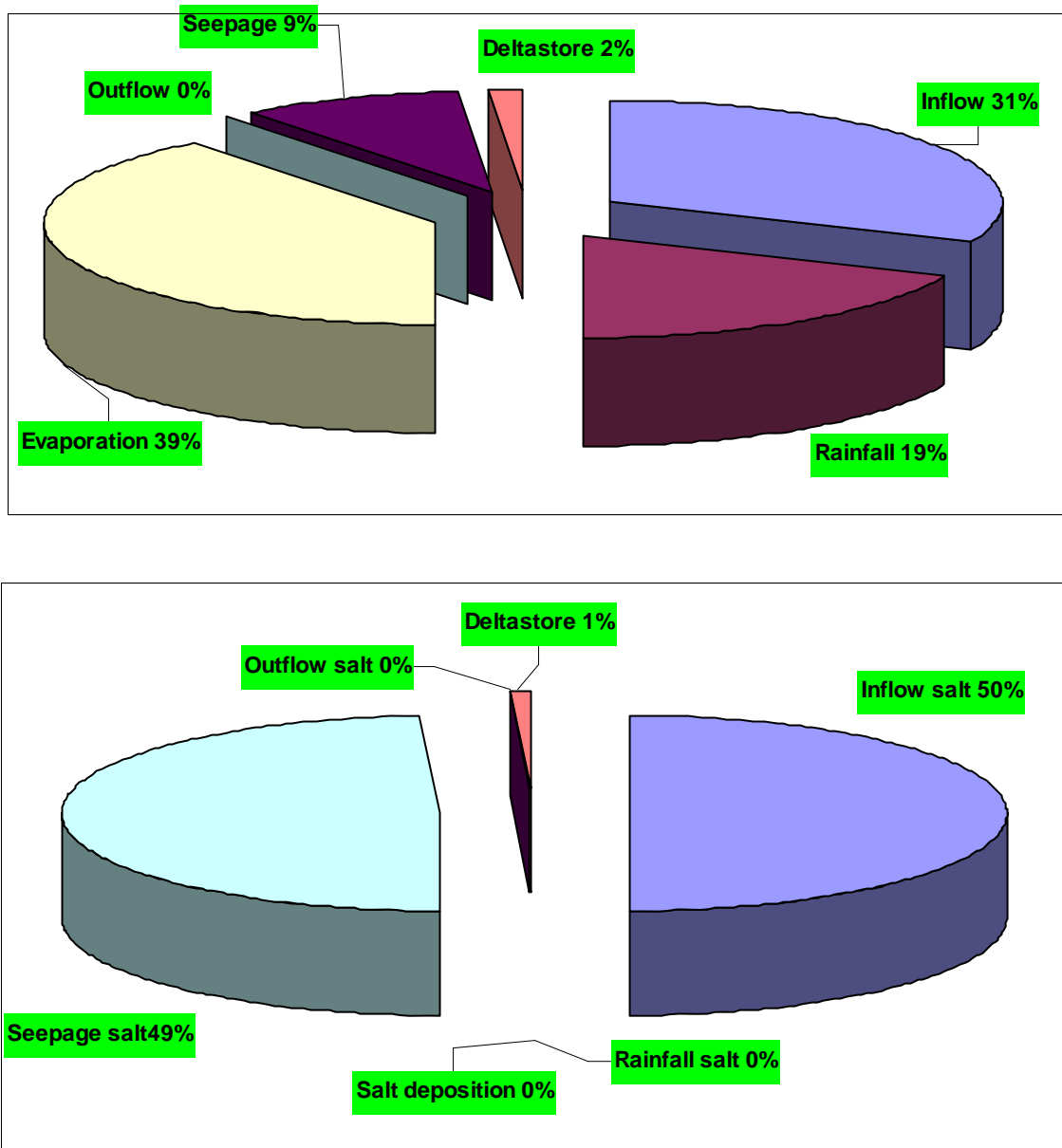


Figure A6.3 Salt and water balance components of Lake Poorrarecup



