Department of Water
Government of Western Australia

Salinity Situation Statement
Kent River

REPORT No. WRT 33
MAY 2007

Water Resource Technical Series

SALINITY SITUATION STATEMENT
KENT RIVER

by

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Water Resource Management Division
Department of Water

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Cover photograph:
The Kent River downstream from near Break Road, in the Lower Kent
by Nikolaus Callow, University of Western Australia

Preface

The Kent River catchment was declared a clearing control catchment in 1978 to help arrest the rise in salinity.

Under the *Salinity Strategy* (State Salinity Council 2000) the Water and Rivers Commission (now the Department of Water) was designated as the lead agency for coordinating efforts to lower salinity in five key Water Resource Recovery Catchments (Kent, Denmark, Warren, Collie and Helena) to ensure the availability of sufficient drinking quality water to meet public needs into the future.

In the Kent, Denmark, Warren and Collie Water Resource Recovery Catchments, the Department works in partnership with local community Catchment Recovery Teams to assess salinity risk, and to plan salinity management options and their implementation.

An important component of the Department's salinity program is to assess the current salinity situation of the targeted rivers, evaluate options available and prepare and implement recovery plans to recover stream salinity to drinking water levels. Salinity Situation Statements for the Collie, Denmark and Warren rivers were published in 2001, 2004 and 2005 respectively. The statement for the Helena catchment is in press as is the evaluation of options for the Denmark River and a salinity recovery plan for the Collie River.

Disclaimer

The maps and results of analyses presented in this report are products of the Department of Water, Water Resource Management Division, Salinity and Water Resource Recovery Branch. Although the Department of Water has made all reasonable efforts to ensure the accuracy of these data, the Department accepts no responsibility for any inaccuracies and persons relying on these data do so at their own risk.

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Summary

Water in the Kent River was once fresh (salinity below 500 mg/L TDS) but by the 1960s the salinity exceeded 500 mg/L TDS and is currently 1480 mg/L TDS and predicted to go down to 950 mg/L (marginal quality) without further land-use changes in the catchment. This report analyses where and why the river water became so saline, describes the current salinity situation and highlights the scale of intervention required to reduce its salinity.

The *State Salinity Action Plan* identified the Kent River as a Water Resource Recovery Catchment and set a water quality target of potable water (500 mg/L TDS) by 2030. The Kent–Denmark Recovery Team was formed to recover the water quality. The team is an active partnership between the community of the Kent and Denmark River catchments and key government agencies led by the Department of Water.

The Kent River Water Resource Recovery Catchment (referred to as the Kent River catchment in this report) is defined as the area from the headwaters of the Kent River to the Styx Junction gauging station. The upper catchment comprises the area from the river's headwaters to the Rocky Glen gauging station and the lower catchment is the area between the Rocky Glen and Styx Junction gauging stations.

Extensive land clearing between 1950 and 1970 contributed to a rapid rise in the salinity of the Kent River. In 1978, when clearing control legislation was enacted to control rising salinity, 66% of the upper catchment had been cleared. By 2002, the rapid growth of Tasmanian bluegum plantations established since 1995 had decreased the cleared area of the upper catchment to 46%.

The catchment has experienced an 11% reduction in rainfall since the early 1970s. The recent annual average rainfall (from 1990 to 2002) for the upper catchment is 590 mm.

The Kent–Denmark Recovery Team with the then Department of Environment proposed the management options to be modelled. Two catchment hydrology models—MAGIC and LUCICAT— were used to model the upper catchment. Their conceptual results indicate the extensive intervention needed to reach the target: 60% (302 km^2) of the cleared land replanted with trees or diversion of water at Rocky Glen. Options that come close to reaching the target are groundwater pumping, and shallow-rooted perennials on 65% (327 km^2) of the cleared land. The social, economic and environmental implications of these options will be evaluated in the next stage of the recovery process.

The recommendations of this report relate to quantifying and testing the assumptions used in the modelling and to maintaining existing monitoring to allow the catchment modelling to be updated. The Department will work closely with the Kent–Denmark Recovery Team to form partnerships with regional groups, research institutions, industry groups and all levels of government to establish, coordinate and guide the investigations.

Key findings of the current salinity situation of the Kent River are:

- The mean annual (1990–2002) salinities of the upper Kent River (Rocky Glen) and the Kent River (Styx Junction) are 3180 mg/L TDS and 1480 mg/L respectively.
- The mean annual salinity of the Kent River (Styx Junction) is still rising but the rate of rise has fallen from 43 (1983–90) to 12 mg/L/yr (1991–98). The mean annual salinity of the upper Kent River (Rocky

Glen) is also still rising but the rate has fallen from 81 (1983–90) to 14 mg/L TDS/yr (1991–98). This large slowing of the rate can be attributed to extensive bluegum plantations established in the upper catchment, clearing controls and climate change.

- About 30% of the upper catchment has a shallow watertable (within 2 m of surface). Water levels in about 70% of groundwater monitoring bores are steady or falling. Groundwater levels near bluegum plantations have fallen up to 5 m.
- The MAGIC steady-state model estimates that about 153 km^2 (14%) of the upper catchment area is at risk of salinisation.
- The upper catchment contributed about 84% of the salt load in 39% of the streamflow to the 73 GL of streamflow and 108 kt salt load of the Kent River at Styx Junction during the period 1990–2002. The catchments draining to Perillup Road and Watterson Farm contributed 41% and 15% of the salt load and 11% and 4% of the flow respectively.
- Lakes Nunijup, Carabundup and Poorrarecup form internally draining lake systems. About 321 km^2 of the area in the Nunijup, Nukennullup and Poorrarecup management units that drain into these lakes have contributed no streamflow or salt load to the main channel of the Kent River since 1973, apart from one overflow of Lake Nunijup in 1982 following a summer thunderstorm.

Some projected results relating to catchment management are:

- When the Kent River catchment (at the Styx Junction gauging station) reaches a new hydrological equilibrium in response to existing land use (28% cleared area), mean annual stream salinity is predicted to be 950 mg/L TDS.
- Planting commercial trees (bluegums, pines and sawlogs) on the 147 km^2 of suitable land could reduce the salinity to 650 mg/L TDS.
- Planting all of the existing cleared area (503 km^2) with trees, irrespective of land suitability, will reduce mean annual salinity to 330 mg/L TDS.
- To reach the potable quality target of 500 mg/L TDS would require replanting trees on 309 km^2 of the cleared land in addition to those planted by 2002.
- Planting deep-rooted perennial pastures at high leaf density on the 147 km^2 of suitable area will reduce salinity to 765 mg/L TDS. Shallow-rooted perennial pastures at high density on the 332 km^2 of suitable land could lower stream salinity to 550 mg/L TDS.
- Pumping groundwater (3.6 GL a year from 650 bores) reduces salinity to 560 mg/L TDS.
- The full diversion of saline water by building a dam near the Rocky Glen gauging station would reduce salinity to 350 mg/L TDS. Diversion of 59% of the saline flow would achieve the target 500 mg/L TDS.
- Shallow and deep drains do not reduce stream salinity.
- A variety of combined management options could be derived from the tree, perennial pasture and engineering options modelled.

Recommendations

- Assess the suitability of commercial tree plantations. Issues to be addressed include encouraging new rotations after harvesting and maintenance of soil fertility.

- Investigate the practicality and design requirements of groundwater pumping in the upper catchment based on current trials at Maxon Farm in the Collie Recovery Catchment.
- Estimate the recharge responses below shallow-rooted and deep-rooted perennial pasture.
- Maintain a database of information on harvesting bluegum plantations. Ascertain the long-term suitability of existing commercial plantations on land assessed as having ‘low suitability’ for trees.
- Evaluate the possible effects of climate change on the management options and the time taken to reach hydrological equilibrium.
- Continue monitoring streamflow and salinity at the four mainstream gauging stations to confirm the current trends in salinity and also to evaluate on-ground works in the catchment.
- Continue the groundwater monitoring program and expand it to accommodate perennial pasture sites.

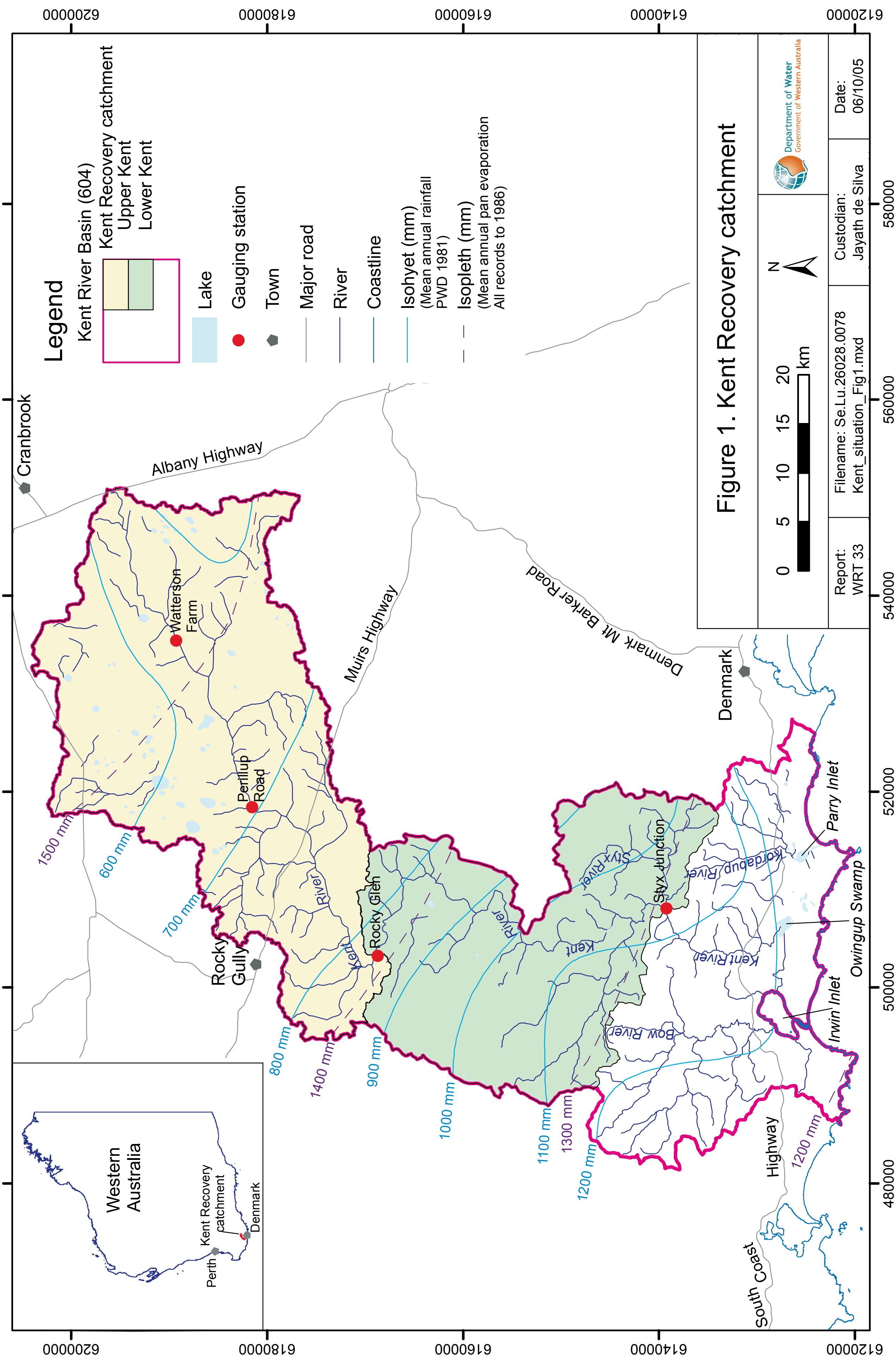

Figure 1. Kent River catchment

1. Introduction

1.1 Purpose and scope

The Kent River (Fig. 1) was originally identified as a potential water resource because of its proximity to South Coast towns and the Great Southern Agricultural Region. The Kent River catchment (more precisely called the Kent River Water Resource Recovery Catchment) is one of the five Water Resource Recovery Catchments designated in the State's *Salinity Action Plan* (Government of Western Australia 1996). This catchment comprises the area from the headwaters of the Kent River to the Styx Junction gauging station, with the upper catchment from the Rocky Glen gauging station to the headwaters of the Kent River and the lower catchment from Rocky Glen to Styx Junction.

As the elevated salinity has been an obstacle for the Kent River to be considered as a water resource for the South Coast towns, lowering river salinity has been an important land and water management issue for the last 30 years. The current target for this river is 500 mg/L TDS at Styx Junction near the potential dam site for a water supply reservoir.

The purpose of this study is to analyse where and why the river water became brackish, state the current salinity, flow and salt load and propose conceptual management options to achieve the salinity target. Other water quality issues are beyond the scope of this study and report.

1.2 Objectives

The objectives of this study and report are to:

- assess and report the current salinity situation of the catchment with respect to land-use changes, groundwater and surface water
- model the hydrology of the catchment to estimate future salinity
- propose management options and their likely effects on stream salinity and water yield.

1.3 Catchment history

1.3.1 Early history

The earliest records of European exploration of the area date back to December 1829 when Surgeon Lieutenant Dr Thomas Braidwood Wilson traversed parts of the catchment. Mokare, an Aboriginal guide from Frederickstown (now Albany), John Kent, Officer in Charge of the Commissariat, Private Gough of the 39th Regiment and two convicts accompanied him (Glover 1979; Conochie 1989). Two days after leaving Frederickstown, Wilson reached a large hill he named Mt Barker after a Captain Barker in Frederickstown. From Mt Barker, Wilson and his party travelled northwards through the Kendenup valleys towards Tenterden before turning westward. It is likely that he travelled down the southern side of the Kent River valley as he found and examined Mortigallup, naming the Kent River (after John Kent) and Lock Katherine (now Lake Katherine) en route to Rocky Gully where he camped at the end of day 5 (Glover 1979). Continuing southwards along the Kent River he left the catchment, passing through swamps and streams before striking and naming Mt Lindesay and the Denmark River.

Wilson and his party were followed in the 1830s by early pioneers seeking 'sheep walks and cattle runs'. Most development occurred along the Hay River — the route of Wilson's exploration to the hinterland.

The Muir family took up 'Forest Hill' in 1851 and from there the family explored the areas to the west taking up land for pastoralism and their homesteads spread as far west as Lake Muir. Their early cart and cattle tracks form the line for the present-day Muirs Highway. The shepherding of sheep on extensive runs was the predominant land use during the 1860s and 1870s. These early pioneers also drove their cattle to the coastal sand dunes (including the Deep River Sand Hills) for a change of diet each summer, forming cattle pads through the lower catchment of the Kent River. Cattle pads traversed the forested country from the inland stations to the coastal hills around Irwin Inlet as the Muirs seasonally drove cattle from their many stations, the Hassells from Kendenup, Moriartys from Poorrarecup and the ration track from Yerriminup (Warburtons). This seasonal droving continued until the late 1930s.

The Land Selection Act 1898 was designed to assist those with little capital to establish themselves on land with a number of easy payment plans including Conditional Purchase, Auction or Freehold Homestead Farms (Glover 1979). The Government was encouraging those from the gold rushes (1895–1904) to stay and settle in WA. The pattern of settlement was changing from extensive pastoral leases and free Crown Land runs for cattle to established families purchasing the better parcels of their leaseholds as freehold. This closer settlement led to the fencing of property boundaries and in turn smaller paddocks.

Although the Perillup area had been grazed as free Crown Land and leasehold since the 1870s, it was not until 1910 that the area was first selected by William Crane who took up 6000 acres.

> Since the early 1850's the area beyond the Hay River to the west and north 'had been used for pastoral runs, shepherds travelling their sheep from well to well, sunk and slabbed by the Government or the shepherds themselves. These were placed 5 or 6 miles apart along the route to Lake Muir (Manjimup) and served the travelling public as camping sites as well as resting places for stock (Glover 1979).

By 1914, FE Hitchins had also taken up land:

> In 1908 the map of the area (Forest Hill to Rocky Gully and beyond) showed completely blank space from Forest Hill west over the Frankland River and south to the coast and north several miles. Neither house nor fence, nor an acre cleared for over 40 miles along the road'. 'The open bushland ran small mobs of horses and cattle owned by various people, chiefly Muir's and Moriarty's…These mobs ranged over wide areas living off the young feed on patches of land burned the previous year' (Glover 1979)

There was a similar pattern of development in the upper (Cranbrook) end of the catchment by the Bunker and Beech families, around this time (Maxine 1994).

Western Australia's population grew by around 98 000 between 1901 and 1911 under the influence of the *Land Selection Act*, assisted immigration schemes and the Coolgardie and Kalgoorlie gold rushes. The Plantagenet area attracted its share of these new settlers seeking land and this demand lead to closer settlement (Glover 1979).

1.3.2 World War I

War Service Land Settlement Scheme

Following World War I, a Discharged Soldiers' Land Settlement Board, the Industries Assistance Board and The Agricultural Bank assisted the returned servicemen to settle on the land. By 1922, repatriation had settled most of those who wanted to be settled and the country was forgetting about the war (Glover 1979).

In 1920, 'there were still many big cattle leases held around Poorrarecup, Cambellup and Kwornicup, and large herds were driven to the coast each year' (Maxine 1994)

With increased settlement after World War I, the timber industry boomed, and locally many small new mills were set up. As a result, the uncleared forests along the Blackwood Road (Muirs Highway) were searched for trees suitable for felling.

The 1930s Depression put many in the area under financial pressure and significantly slowed the expansion of agriculture. To generate employment and stimulate the economy, the Mitchell Government established camps in the south west of WA and set unemployed men to work building roads and clearing and preparing survey blocks for future farms' (Glover 1979). Rocky Gully was named after a natural rock crossing on the original Blackwood Road (the 'Old Road') that was used until 1932 when the 'Sustenance Workers' from the Frankland River camp cleared and formed the road from the Kent River to the Frankland River in 1932 (Beech 1978). By that time, the road from Mt Barker to the Kent River had been cleared. In 1931, Rocky Gully had been surveyed into 250-acre blocks and, in the winter of 1932, the government sent unemployed men down to clear a portion of each block. In the autumn of 1933, clover seed was planted on some of the cleared areas. The Sustenance Workers left after the 1934 state election when the state government changed.

The mid 1930s saw increasing mechanisation of farms in the area. Fencing and the greater crop-growing areas created the need for more sophisticated agricultural implements than those in use at the time.

Settlers grazed the cleared areas for a short time but the many difficulties of running stock in the area led to Rocky Gully being abandoned until about 1949 when the bulldozers moved in. Established settlers continued to graze the area until the end of WW II.

Although farming conditions gradually improved with expanding markets and better prices for farm produce, it took until after the WW II for the industry to fully rebound from the Depression.

1.3.3 World War II

The introduction of the bulldozer and the soldier settlement schemes resulted in an increase in land clearing. This, with necessity for export commodities, led to unlimited expansion at a rate probably never envisaged (Pope 1994).

After World War II, another government-sponsored soldier resettlement scheme brought more returned soldiers to settle Rocky Gully, Perillup and Frankland. 'Government bulldozers cleared areas on the surveyed blocks and put down dams. Potential new farmers were employed on contract work preparing all locations ready for possession. By 1952 the Rocky Gully–Perillup Settlement was well under way.' (Glover 1979).

New and improved methods of farming, including subclover pasture and the addition of trace elements, now meant that poorer land left undeveloped could be brought under agricultural production. These developments, combined with world food shortages and the strong economic growth of Australia's trading partners, resulted in a similar pattern of rapid development in the upper parts of the catchment as bulldozers cleared large areas for new farms. On War Service blocks in the Frankland area bulldozers went to work clearing 50 000 acres at Bokerup, Riversdale and Kybellup (Maxine 1994).

Wool production continued as the principal farm enterprise until the 1990s when the Reserve Price Scheme for wool sales was abandoned (Burdass et al. 1998). Prime lamb and beef cattle production fluctuated over the years in response to market forces. Cropping, once limited to hay and grain production for stock feed, steadily increased as new plant varieties and farming methods became available. Declining rainfall resulting in more favorable growth conditions has also probably been a factor in the success of cropping in the area.

1.4 Salinity and government action

Extensive land clearing between 1950 and 1970 contributed to a rapid rise in stream salinity. Rising salinity in the upper catchment had contributed significant amounts of salt to the Kent River and associated watercourses, lakes and swampy wetlands and this had increased the salinity of the Kent River especially within its upper reaches. Formerly fresh water lakes such as Lakes Poorrarecup and Nunijup had become saline in 1967 and 1970 respectively (Maxine 1994).

In 1978 the *Country Areas Water Supply Act 1947* was amended to introduce a licensing system to control clearing of native vegetation in the Kent catchment.

In 1990, the CSIRO Division of Water Resources in collaboration with four Western Australian state agencies, and supported by the Kent Land Conservation District Committee, established a coordinated and integrated research program for the rehabilitation of the Kent River as a potable water resource. The program included six projects examining catchment characterization, hydrology and hydrogeology, vegetation options, socioeconomic analysis, remediation strategies and the implementation of appropriate management (Salama et al. 1997).

National Dryland Salinity Research, Development and Extension Program selected the Kent catchment as a focus catchment in 1993 (LWRRDC 1994). With the establishment of the National Dryland Salinity Program, a four-year study (1994–98) was sponsored into salinity management. The Kent Steering Committee was formed in 1994, with the responsibility for overseeing 'the development and implementation of catchment management plans integrating salinity management with other resource issues, and ensuring that program activities carried out in the catchment meet the needs of communities and objectives outlined in the plans'. The development of the Integrated Catchment Management (ICM) Plan for the Upper Kent Catchment was one of several outcomes of this program (Burdass et al. 1998).

The Water and Rivers Commission (now the Department of Water) was made the lead agency to implement the *Salinity Action Plan* target of potable water supply by 2030 (Government of Western Australia 1996). The Kent–Denmark Recovery Team was formed in 1998 following the Denmark and Kent River catchments being designated 'Recovery Catchments' in the *Salinity Action Plan*.

1.5 Recovery approach

The Department has adopted a targeted investment approach to recovery (Fig. 2).

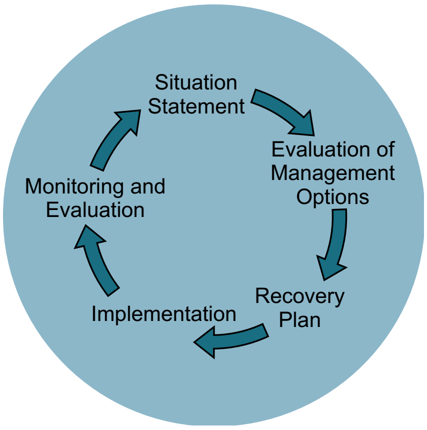

Figure 2. The recovery approach

- The *Salinity Situation Statement* (the study and this report) identifies the current and predicted salinity levels, and describes and evaluates the hydrological impacts of a suite of conceptual management options for the catchment.
- In the step, *Evaluation of Management Options*, water quality objectives are defined and, in consultation with key stakeholders, scenarios to meet these objectives are evaluated considering social, economic and environment aspects.
- The *Recovery Plan* identifies the major components of the options selected for implementation, develops an implementation strategy and identifies funding sources.

- The *Implementation* stage will coordinate on-ground planning and implementation.
- In the *Monitoring and Evaluation* stage, monitoring the main river and subcatchments will be used to review the salinity situation.

1.6 The Kent–Denmark Recovery Team

In September 1998 the Water and Rivers Commission established a local Recovery Team that encourages full stakeholder involvement and fosters partnerships between state government agencies, NRM groups, local government, industry, research institutions, local community groups and catchment landholders to achieve the water quality target.

This Recovery Team is an active partnership between the community of the Kent and Denmark River catchments and key government agencies led by the Department of Water. The Recovery Team's role is to bring parties together at the local level and implement the *Salinity Strategy's* (State Salinity Council 2000) purpose of 'recovering' salinity to potable levels in both rivers.

The Recovery Team has strong community representation — it is chaired by a local landholder and its nine landholder members all actively farm in the catchment and are held in high regard by their community. The local governments of Plantagenet and Cranbrook are represented by council members residing in the catchments. The rest of the team comprises representatives from the state's major natural resource management government agencies, including the Departments of Water, Agriculture and Food, and Environment and Conservation (Appendix 1, Table A1.1).

The Recovery Team has built on the foundation of earlier efforts to provide frameworks for natural resource management at catchment level. From 1988 to 1992, the Department of Agriculture coordinated the preparation of an Integrated Catchment Management (ICM) Plan for the Upper Denmark catchment landholders (Ferdowsian & Greenham 1992). The plan was prepared in collaboration with the Department of Conservation and Land Management and the Water Authority (a predecessor of the Water and Rivers Commission) and funding from the National Soil Conservation Program. The ICM Plan mapped the landforms and land management units on cleared areas and defined the extent of salinity and its causative processes. The plan suggested options for managing the salinity problem and constituted a catchment management plan to remediate major land management issues.

Several members of the Kent Steering Committee became members of the new Recovery Team. The foundation ICM Plans were developed for the Upper Denmark and Upper Kent catchments and the experience and knowledge in developing such plans brought by these Team members have contributed significantly to the successful implementation program coordinated by the Kent–Denmark Recovery Team.

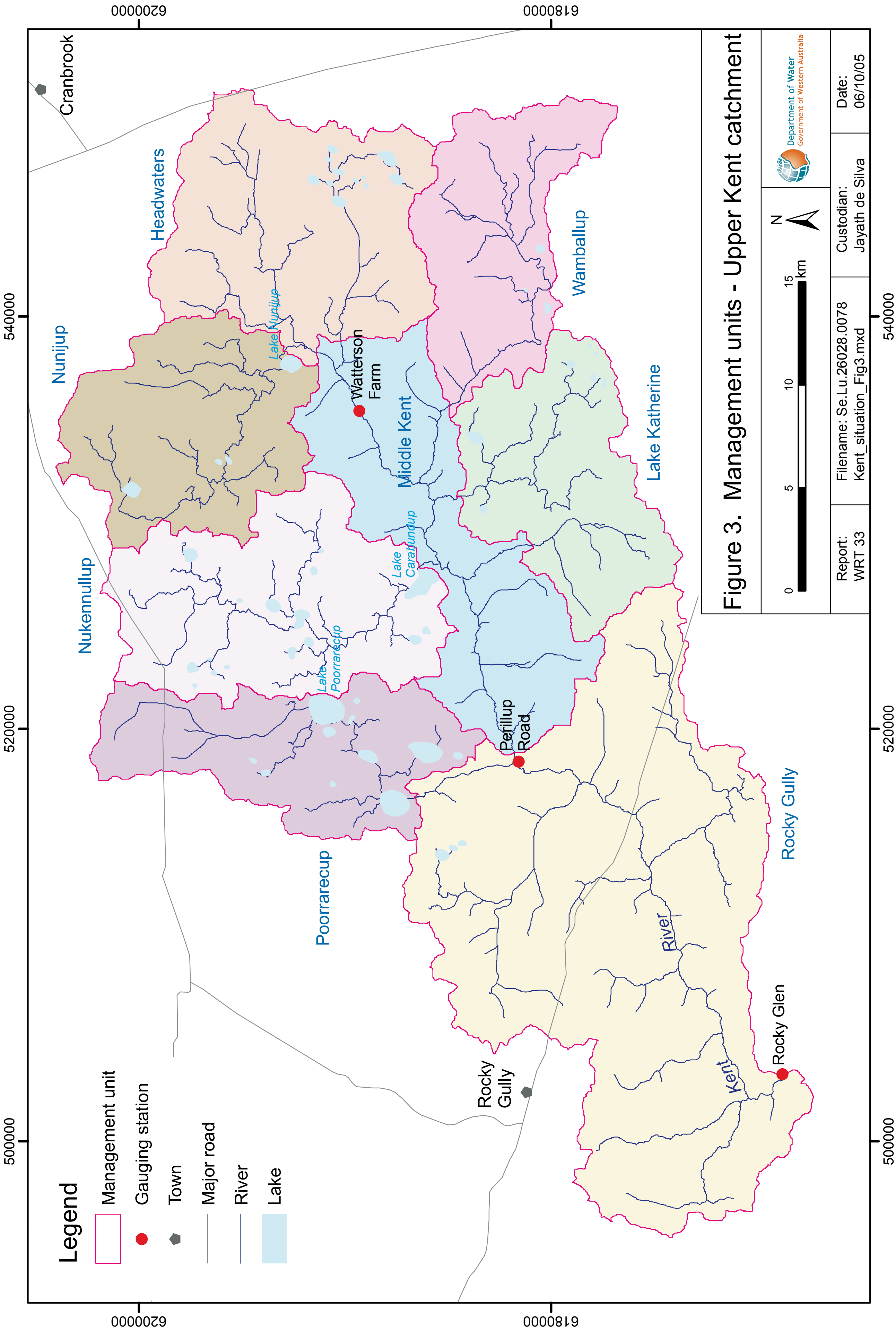

Figure 3. Management units

2 Catchment characteristics

2.1 Location

The Kent River catchment is located in the south-west of Western Australia within the Australian Water Resources Council River Basin 604 (Fig. 1). The Kent River flows westward from headwaters in the north-east near the Albany Highway at Tenterden. It changes its flow direction to southerly near Rocky Gully. The Styx River joins the Kent River before it discharges into Owingup Swamp and then into the Southern Ocean through the Irwin Inlet. The Kent River Water Resource Recovery Catchment has an area of 2170 km^2 with 1092 km^2 in the upper catchment (Upper Kent), from the Rocky Glen gauging station (S604001) to the headwaters, and 751 km^2 in the lower catchment (Lower Kent), from Rocky Glen to the Styx Junction gauging station (S604053). Two more rivers drain the lower part of Kent River Basin that extends from Styx Junction to the coast: the Bow and Kordabup which drain into Irwin Inlet and Parry Inlet respectively.

2.2 Management units

The upper catchment is divided into eight management units (MUs) to reflect the changes in hydrology and land use (Fig. 3). Three of these — Nunijup, Poorrarecup, and Nukennullup — drain into lakes and can be considered as internally draining.

2.3 Shires and cadastre

The upper catchment falls within the Shires of Cranbrook and Plantagenet. The Rocky Gully, Lake Katherine, Middle Kent and Wamballup MUs are administered by the Shire of Plantagenet and Headwaters, Nunijup, Nukennullup and Poorrarecup by the Shire of Cranbrook (Fig. A2.1).

2.4 Climate

The Kent River catchment has a climate characterised by cool, wet winters and warm to hot, dry summers. Average annual rainfall decreases inland from 1200 mm in the south to 500 mm in the north. Most of the rainfall comes from fronts associated with low-pressure systems from the south-west between May and October.

Average annual pan evaporation ranges from 1200 mm near the coast to 1500 mm in the north-east of the catchment (Fig. 1). The summer maximum average temperature ranges from 27 ºC inland to 24 ºC near the coast while the winter maximum range is 15–16 ºC.

The long-term mean annual rainfall (1910–2001) for the upper catchment is 661 mm while the annual average rainfall for the period 1975–2001 is 592 mm — an 11% reduction in rainfall since the early 1970s (Fig. 4).

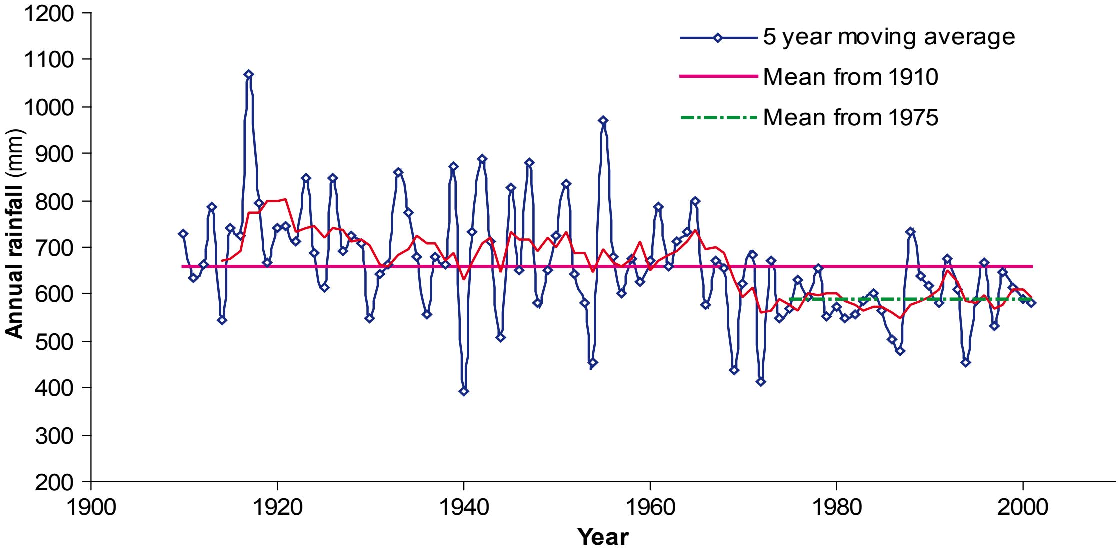

Figure 4. Annual catchment aggregate rainfall for the upper catchment (1910–2001)

2.5 Physiography and drainage

The Kent River catchment falls within a broad physiographic feature, the Ravensthorpe Ramp—the common name for the southward-sloping part of the Darling Plateau (Cope 1975). The hinge line, called the Jarrahwood Axis, about 120 km from the coast, marks the northern limits of the Ravensthorpe Ramp (Fig. 5) which has a gradual southerly slope from around 300 m elevation near the southern edge of the Darling Plateau to sea level. The rivers draining to the south coast, including the Kent, are relatively short and incised into the tilted surface of this ramp.

The Upper Kent part of the river can be further divided into ancient and rejuvenated landscapes. A second hinge line identified by Ferdowsian and Greenham (1992) possibly separates these two landscapes. The formation of the second hinge line disrupted the westerly flow of Eocene Rivers and altered their courses.

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 broad flats in the central part of the catchment, with less than three degrees slope, have a number of major lakes such as Nunijup, Carabundup and Poorrarecup and their soil types include podsolic and solodic soils. The flat or nearly flat ancient landscape has a weakly developed drainage pattern while the rejuvenated landscape in the south-west of the upper catchment has a well-developed dendritic drainage pattern with V-shaped valleys and generally lateritic soils, with the exception of the podzols and the loamy red earths. The lower catchment falls completely within the rejuvenated landscape of the Ravensthorpe Ramp and its physiography is characterised by a pattern of ridges: hills of granitic rocks alternating with broad swampy corridors that have a west-north-west orientation.

The elevation ranges from 45 m AHD near the Styx Junction gauging station and 180 m AHD near the Rocky Glen gauging station to 400 m AHD (Geekabee Hill) in the upper catchment.

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 breakup of Australia and 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 (mya). In the Late Tertiary (about 38 mya), the sediments associated with the palaeodrainage system were uplifted to the present height of

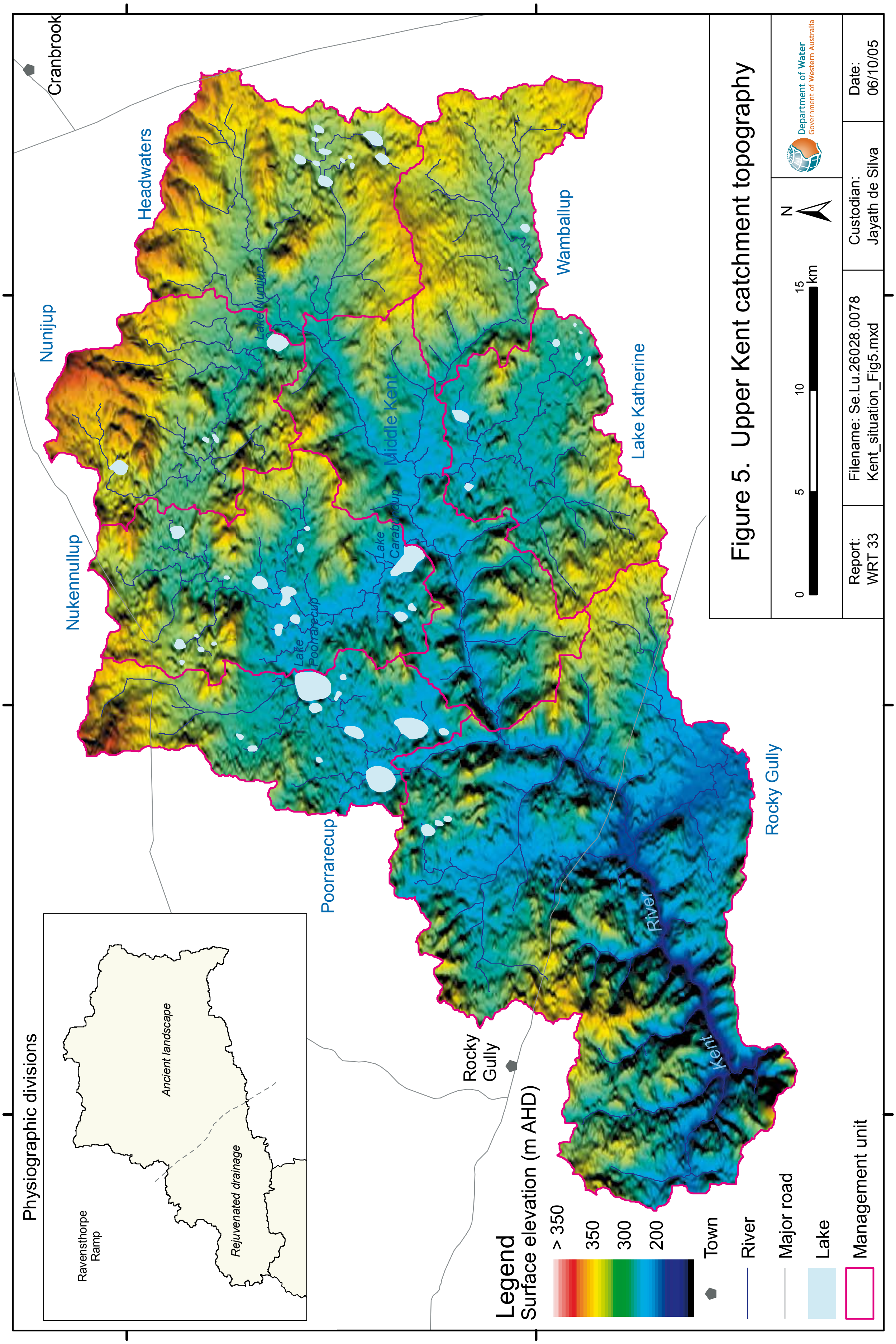

Figure 5. Upper Kent catchment topography

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).

2.6 Geology and structure

Basement rocks of the upper catchment belong to two major lithological and structural units. The northern part is within the Archaean Yilgarn Craton whereas the southern part is within the Proterozoic Albany–Fraser Orogeny. The Archaean and Proterozoic bedrock comprises mixed gneissic and metamorphic rocks and granitoid rocks. The east-west trending Manjimup Fault separates these two units. Alluvial and shallow marine sediments belonging to the (Tertiary) Bremer Basin infilled the depressions within these basement rocks. Depth to fresh basement rocks varies from 10 m to more than 30 m and is greater in areas of Tertiary sediments and the basement rocks are dissected by regional faults and lineaments. An interpretation of geology and structure based on the magnetic intensity image (Fig. A2.2) is given in Figure 6.

2.7 Hydrogeology

Groundwater occurs in the following four major aquifers within the hydrogeological provinces:

- Surficial sediments (Qa\Cza)
- Werillup Formation (Palaeochannel sediments)
- Stirling Range Formation (Ps)
- Weathered bedrocks (Ag\Pg and An\Pn)

Pallinup Siltstone acts as an aquitard to the Palaeochannel sediments aquifer. Smith (1997) described the regional groundwater flow characteristics of these aquifers and aquitard. The following section describes the flow and salinity characteristics that are specific to the catchment. Their distribution of these aquifers is shown in Figure 6.

Surficial sediments (Qa\Cza)

These Quaternary sediments which mainly occur in the broad flat landscape of the upper catchment are predominantly of alluvial origin, although some have colluvial or lacustrine origin. Their profiles consist of clay, ferricrete and sand.

They overlie Tertiary sediments such as Pallinup Siltstone and Werillup Formation or the weathered profiles of basement rocks. The aquifer formed by these sediments is mainly unconfined.

Werillup Formation

The Werillup Formation also occurs in the broad flat landscape of the upper catchment, especially where there are lakes and swamps, and consists of fine to coarse-grained sand, clay, carbonaceous clay or lignite. These sediments represent the palaeochannel deposits of Tertiary Eocene age. They form a semi-confined to confined aquifer depending on the thickness and hydraulic conductivity of the confining layer. Groundwater entering this aquifer from adjacent weathered bedrocks may discharge vertically into surficial sediments. The Pallinup Siltstone overlies this aquifer.

Stirling Range Formation (Ps)

This formation, which occurs in the northern parts of the Nunijup catchment, comprises sandstone, quartzite and shale. The rocks are generally faulted and form a fractured rock aquifer (Smith 1997). The area containing

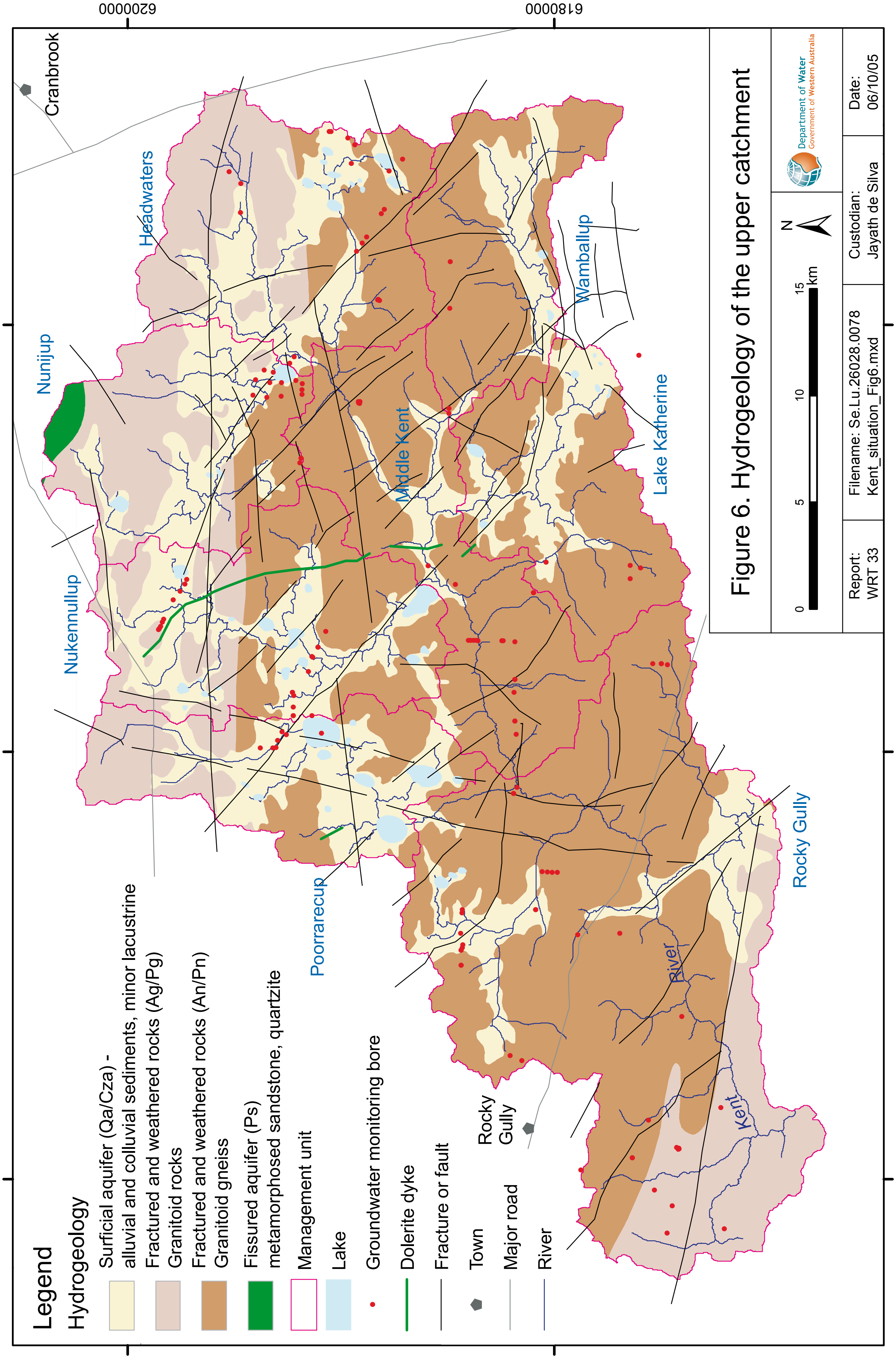

Figure 6. Hydrogeology of the upper catchment

this formation is a recharge area for the Nunijup catchment. This formation's weathered profile is expected to be sandy due to the presence of quartzo-felspathic rocks and its sandy nature may facilitate a high recharge rate.

Weathered bedrock (Ag\Pg and An\Pn)

Weathered profiles of granitoid and gneissic rocks form local aquifers in the upper catchment and generally consist of ferricrete (ironstone), clay and a layer of rock fragments mixed with sand and clay (saprolite grit) from top to bottom respectively. Granitoid rocks have a higher tendency to develop this saprolite grit layer than gneissic rocks due to a higher percentage of quartzo–feldspathic minerals. Groundwater mainly occurs in this saprolite grit layer which is located above the interface between the weathered and fresh rock and has a higher permeability than other layers of the weathered profile. Clays above the saprolite grit may confine this aquifer. Fresh or fractured bedrock marks the lower limit of the weathered rock aquifer.

Potentiometric heads in bores drilled and screened within this weathered rock aquifer range from 0.08 m to 2.95 m below ground level. Potentiometric heads above the natural surface were recorded by a CSIRO groundwater monitoring piezometer, TU5 (Bartle et al. 2000). These results indicate that the weathered rock aquifer can be semi-confined to confined. Groundwater salinity ranges from 6000 mg/L TDS (KNT 15) in the lower parts of the catchment to 23 000 mg/L TDS (KNT 7) in the upper parts of the catchment (Hundi & De Silva 2000). Brackish water used for watering stock can be found in eolian (deposited by wind) profiles.

2.8 Soil–landscape systems

Soil–landscape systems are defined as recurring patterns of soils, landform and vegetation and are useful in defining land suitability criteria for management options. They were mapped in three major surveys carried out by the CSIRO and, more recently, by the Natural Resources Assessment Group at the Department of Agriculture Western Australia:

- South Coast and Hinterland Survey (Churchward et al. 1988)
- Frankland Land Resource Survey (Stuart-Street & Scholz 2004)
- Tambellup and Borden Land Resource Survey (Stuart-Street et al. 2004)

The Kent System which covers about 80% of the upper catchment (Fig. 7; Appendix A2, Table A2.1) is further divided into 5 subsystems and 6 phases (Table A2.2). A subsystem is an area of characteristic landform features containing a defined suite of soils whereas a phase is defined as an area where particular features, such as poorly drained flats, are predominant within the general pattern (Tille 1996). The Camballup subsystem of the Kent soil–landscape system has saline and waterlogged areas.

Most soils in the upper catchment are derived from the laterite profile either exposed by erosion or as colluvial material released by the erosion process and many have ferruginous (ironstone) gravels in the surface horizons (Churchward et al. 1988). Parent material for the soils can be Tertiary sediments and basement rocks such as granites and gneisses.

The soil types may have a uniform texture throughout (sand, deep sand) or change sharply, such as duplex soils where the surface sandy layer changes into loamy or clayey layer. The texture or permeability contrast layer of duplex soils generally occurs within the top 80 cm of the profile and accounts for the tendency of these soils to develop a temporary perched watertable, particularly when they have a shallow sandy surface.

Some duplex soils have acidic to neutral profiles (podzolic) while others are alkaline at depth (solodic). Generally, when soils are affected by salinity through shallow groundwater levels, the profile becomes strongly alkaline with depth. Duplex soils may show the influence of the climate with the more acidic profiles in the wetter parts of the catchment and alkaline profiles where rainfall is lower (Churchward et al. 1988).

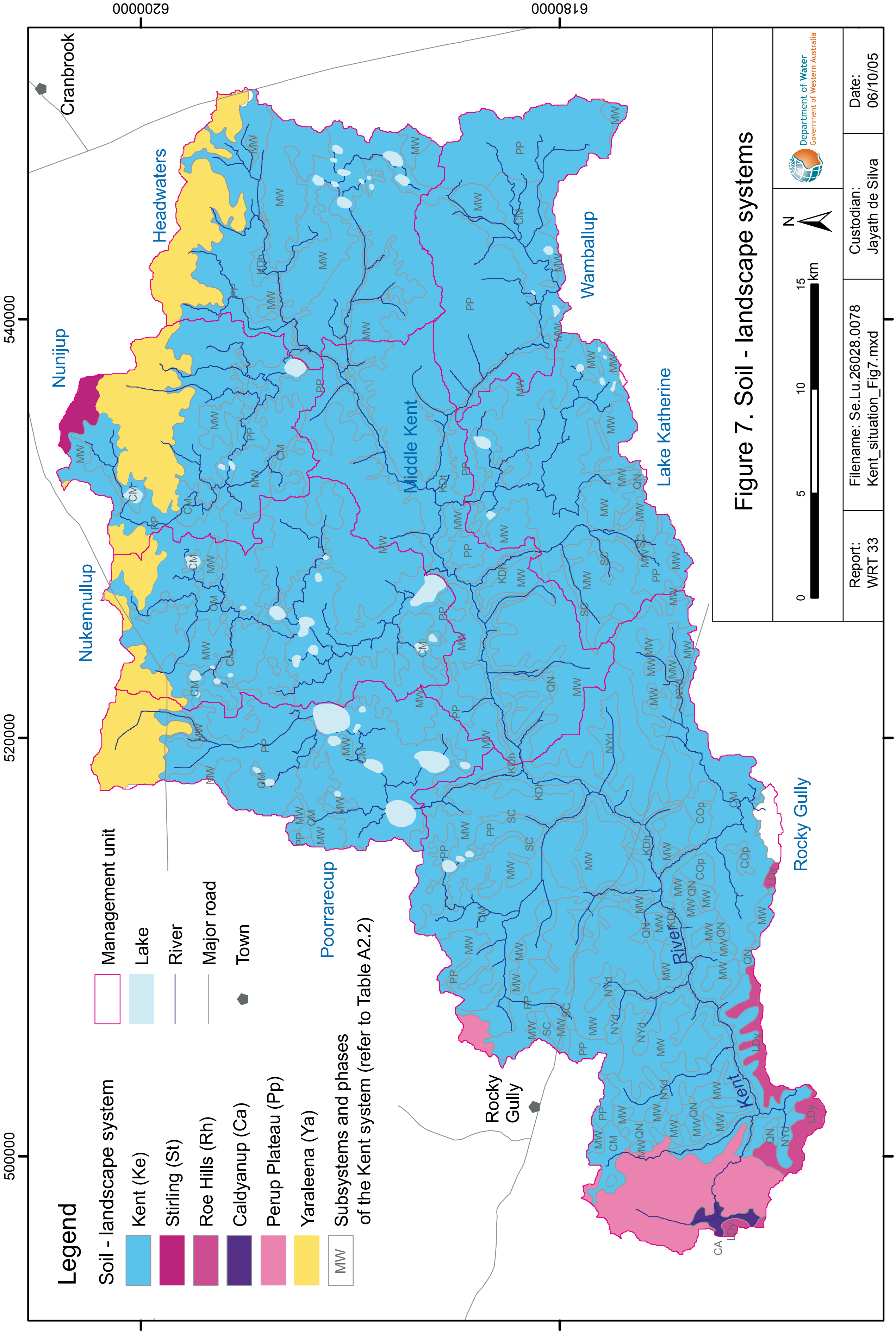

Figure 7. Soil–landscape systems

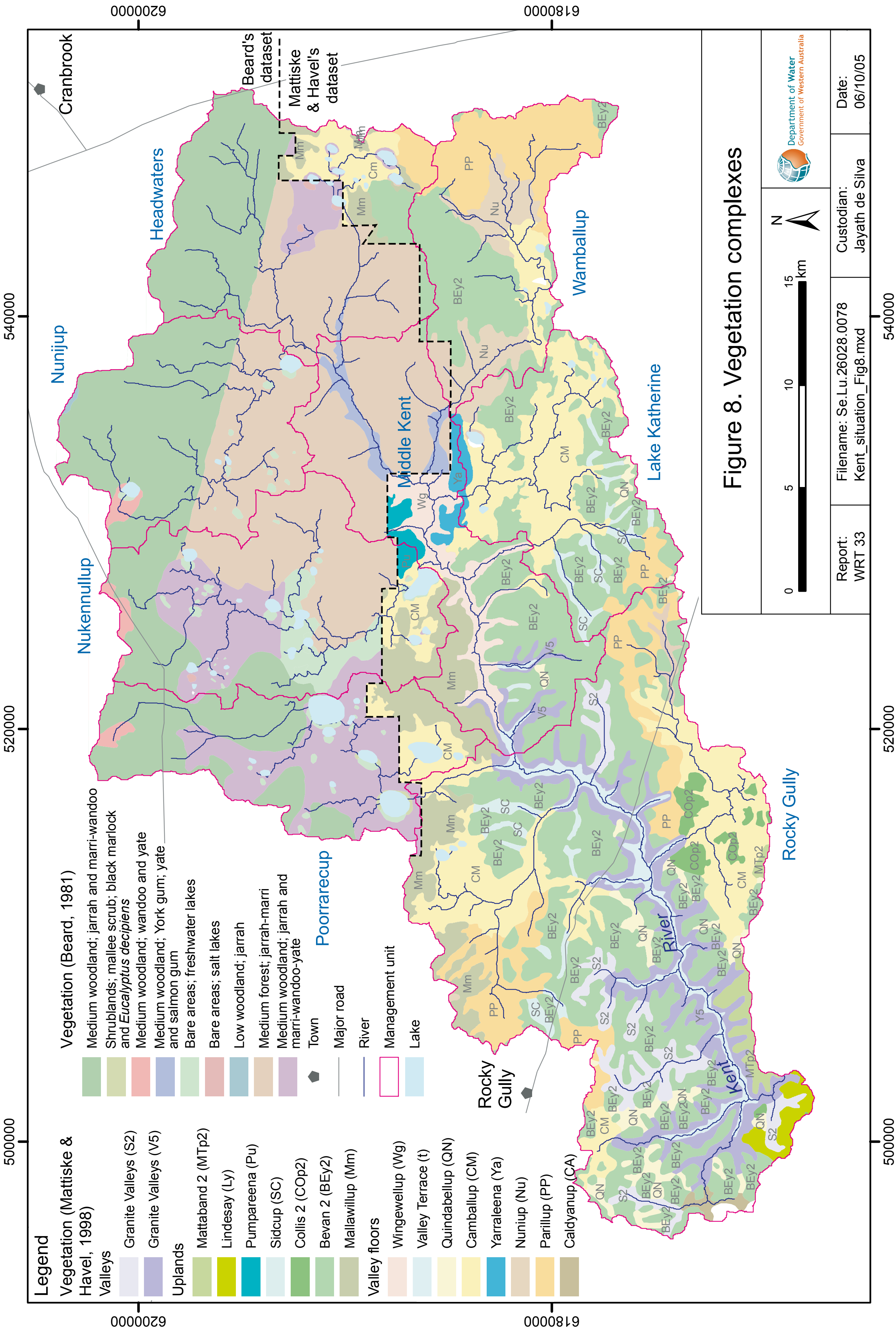

Figure 8. Vegetation complexes

Some soil types generally common in the lower slope areas of lateritic rises and in the broad flats in the upper catchment (Kelly 1995) have a duricrust (indurated iron oxide-rich layer occurring as cemented ironstone gravels) developed within 1 to 1.2 m of the surface.

Kelly (1995) identified a number of land management units (LMU) in the upper catchment, the most common of which is severely 'Waterlogged Footslopes and Flats' (25%), followed by 'Gravel Slopes' (20%), 'Remnant Bush' (20%), 'Saltland' (15%) and 'Streams and Wetlands' (8%). The other minor LMUs include 'Deep Sands', 'Red Soils' and 'Rock Outcrops'. The majority of the good cropping areas of the Kent River catchment fall within the 'Gravel Slopes' LMU that is closely associated with the lateritic low hills and rises or the Mallawillup Subsystem (Fig. 7 & Table A2.2). The areas of 'Red Soils' LMU, mainly found south of Muirs Highway, are also considered as good cropping areas.

Basic soil types can also be interpreted from radiometric geophysical data. Figure A2.3 shows a composite of the elements K (Potassium) = red; Th (Thorium) = green and U (Uranium) = blue. Soils high in all three elements appear as white areas and soils low in all three appear as black. High Th and U signatures are often associated with lateritic soil profiles such as ironstone gravelly soils. Deep leached sands that occur in broad valley floors have a very low radiometric count (black areas). Sandy soils that originated from the weathering of granitic rocks have high K count (red). Further details on application of airborne radiometrics data to map soil types for salinity management can be found in Pracillo et al. (1998) and De Silva (1999).

2.9 Salt storage

Salt storage varies from less than 400 tonnes per hectare (t/ha) in recharge areas to more than 3000 t/ha in groundwater discharge areas with thick clayey profiles (Bari & Boyd 1993; Ferdowsian & Ryder 1997; Bartle et al. 2000). Extensive sampling of the regolith of the Darling Plateau identified five types of salinity profiles (Buselli & Williamson 1994). Further details relating to salt storage in the upper catchment can be found in Knapton (1994) and Salama et al. (1997).

2.10 Vegetation

Beard (1981) describes vegetation associations of the Kent River catchment. The mapping of vegetation complexes by Mattiske and Havel (1998) covered only the southern part of the catchment (Fig. 8). The Kent River catchment mainly falls within the jarrah–marri vegetation association. Low forest jarrah normally predominates with little marri forest. On patches of better soil the vegetation cover improves to jarrah–marri forest.

Remnant vegetation of the 'Gravel Slopes' LMU is predominantly woodland or open forest of jarrah (*Eucalyptus marginata*) and marri (*E. calophylla*), with wandoo (*E. wandoo*) appearing towards the lower slopes of lateritic rises. Flat-topped yate–wandoo can be found in the 'Waterlogged Footslopes and Flats' LMU. Paperbarks and tea-trees can occur close to streams and wetlands. Flooded gums (*Eucalyptus rudis*) surround wetlands. Jarrah–marri woodland with an understorey of banksias occurs in the 'Deep Sands' LMU (Kelly 1995).

3 Land-use changes—clearing and plantations

3.1 Clearing

The clearing of native vegetation in the catchment started in mid 1800s. Interpretation of historical aerial photographs indicates that as late as 1946 only 10% of the catchment had been cleared. Land clearing methods changed rapidly after the World War II (1946) when bulldozers came into use. The extent of cleared land on Western Australian farms doubled in the 20 years 1949–69 (Burvill 1979). This regional trend of land clearing was also reflected in the upper catchment where the area cleared jumped from 10% in 1946 to 46% in 1965 (Fig. 9). In 1946, apart from a few cleared patches, the Rocky Gully MU was still fully forested. Significant areas of the Headwaters and Wamballup MUs were cleared by 1946. The river channel of the Kent River was mainly forested from the Rocky Gully gauging station to Lake Carabundup. Clearing the river valley area started around 1955.

Figure 9. Clearing history of the upper catchment

Table 1. Clearing history of the upper catchment

Management unit	**Clearing** (% of area)			
	1965	**1978**	**2000**	**2002**
Headwaters	53	80	75	74
Wamballup	59	86	81	79
Lake Katherine	31	72	52	42
Middle Kent	61	82	70	54
Rocky Gully	42	52	36	27
Nunijup	39	60	59	59
Nukennullup	43	63	52	38
Poorrarecup	46	63	51	36
Upper Kent	**46**	**66**	**54**	**46**

In 1978 the Western Australian Government introduced clearing control legislation in the Kent River catchment to limit further increases in secondary salinity (caused by human activity). By then, 66% of the upper catchment had been cleared of its natural vegetation for agricultural activities—Appendix 3, Figure A3.1 shows the remnant vegetation in a mosaic aerial photograph taken in 1965. By 2002, only 27% of the Kent River catchment—46% of the upper but only 1% of the lower catchment—was still cleared. The changes in the extent of clearing in the upper catchment over time are shown in Figures 9, 10 and A3.2 and Tables 1 and 2.

3.2 Plantations

The establishment of commercial bluegum plantations in the upper catchment began around 1988, and its rapid growth from 1995 can be seen on Landsat TM scenes from summer 1988 to summer 2002. The area of established plantations jumped from about 1045 ha in 1994 to 18 620 ha in 2002 and decreased the cleared area of the upper catchment to from 66% to 46% (Figs 10 & 11, Table 1). Two or three years after planting, new plantations can generally be identified on summer Landsat TM scenes as very light green patches which darken to green then dark green on subsequent summer Landsat scenes. Figure 11 shows how unevenly the bluegum plantation areas were distributed across the management units in 1988–2002.

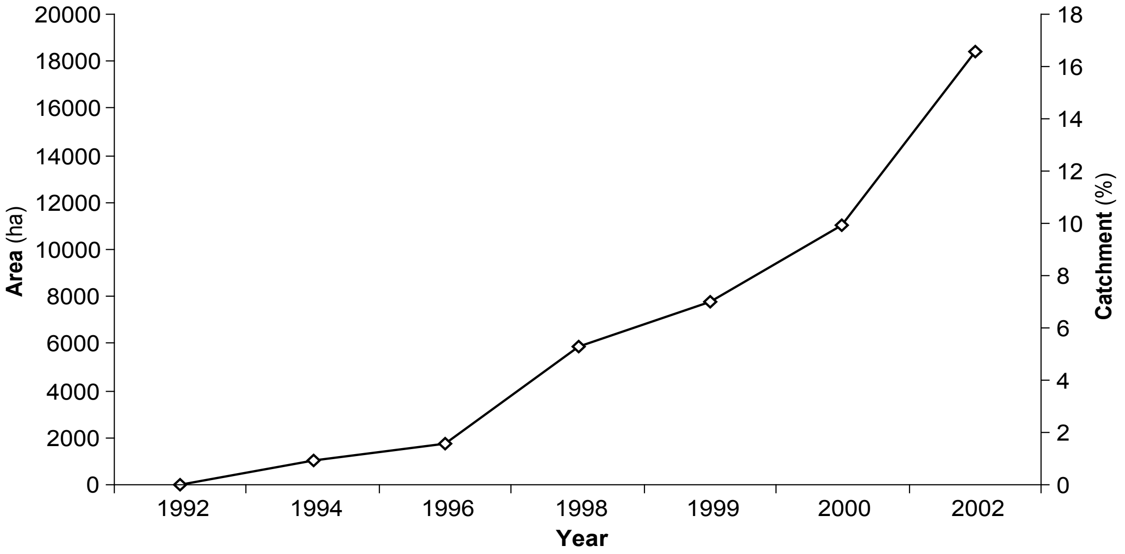

Figure 10. The area of bluegum plantations in the upper catchment

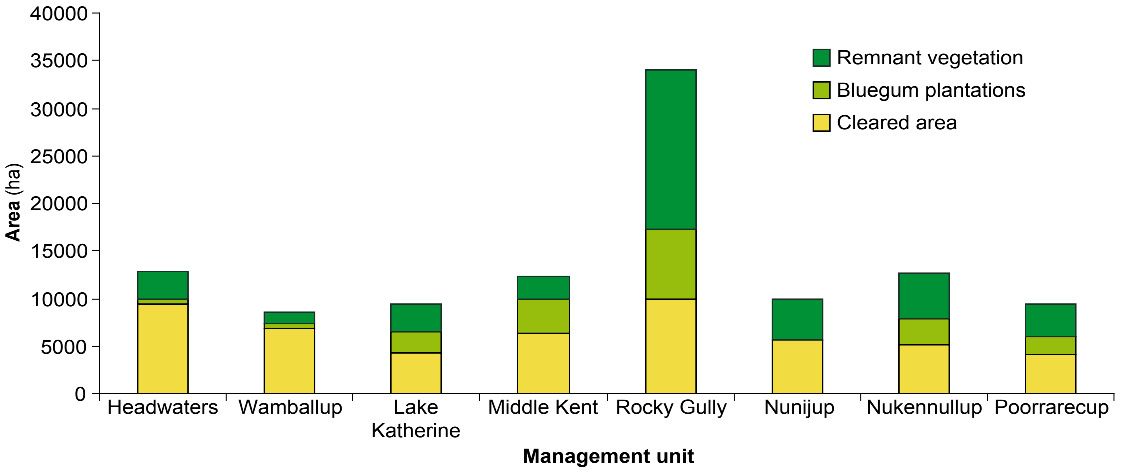

Figure 11. Distribution of bluegum plantations and remnant vegetation in 2002

The Rocky Gully MU, where average annual rainfall exceeds 700 mm and soils and landscape are suitable, has the largest area of plantations (about 7430 ha) while management units such as Nunijup, where average annual rainfall is less than 600 mm and soils are poor/unsuitable (Fig. 11 & Appendix A3, Fig. A3.3) have few or no bluegum plantations.

3.3 Land-use mapping

Table 2 compares land use in the upper and whole Kent catchment in 2002.

Table 2. Summary of land use (2002)

	Clearing (%)	**Plantations** (%)	**Native vegetation** (%)	**Waterbodies** (%)
Upper catchment	46	17	36	1
Kent River catchment	27	10	62	1

Strawbridge (1999) used Landsat TM data, cadastral overlays, aerial photographs and field checking to classify the areas of remnant native vegetation in the upper catchment at risk from grazing by livestock into three classes according to the level of understorey disturbance and found that, in 1998, 21% of the upper catchment had an intact understorey (Appendix 3, Fig. A3.4). The classifications are:

- Native forest (intact understorey) (21%)
- Modified remnant (understorey disturbed principally by livestock grazing) (11%)
- Scattered vegetation (no native understorey and low number of trees) (4%)

4 Salinity and flow characteristics

As outlined in Section 3, the extensive land clearing that occurred between 1950 and 1970 contributed to a rapid rise in the salinity of the Kent River, especially in its upper reaches. The salinity rose from fresh (salinity below 500 mg/L TDS) before the 1960s to 1480 mg/L TDS (1990–2002). Freshwater lakes such as Lakes Poorrarecup and Nunijup became saline in 1967 and 1970 respectively (Maxine 1994). This section discusses how salt and water balance changes brought about by clearing native vegetation affected the surface and groundwater hydrology of the catchment and includes a salinity risk assessment. More details of the dryland salinity problem in Western Australia can be found in Wood (1924), Schofield and Ruprecht (1989), Hatton et al. (2002), Peck and Hatton (2003) and Hatton et al. (2003).

4.1 Streamflow and salinity records

Four main gauging stations and 20 sample sites provided the data for this study (Fig. 12):

- Watterson Farm (Station no. 604003) and Perillup Road (604002) in the upper catchment have complete annual records of continuous streamflow and salinity for the period 2000–02 as they have only been in operation since 2000.
- Rocky Glen (604001), which gauges all streamflow from the upper catchment, has continuous streamflow and salinity records back to 1979 when it began operating.
- Styx Junction (604053), at the confluence of the Styx and Kent rivers, gauges the streamflow from the upper catchment as well as the flows generated between the Rocky Glen and Styx Junction gauging stations; that is, it gauges the Kent River. It has operated since 1956. Between 1956 and 1978, salinity measurements were obtained using a point sampling technique at approximately fortnightly intervals. Since 1978 salinity has been measured continuously. It is considered as a potential dam site.
- The sample sites are all in the upper catchment and, since 2000, have been used for fortnightly grab samples throughout winter.

As the periods of record of the four gauging stations differ greatly and the records are not directly comparable, Table 3 presents the average annual streamflow, salt load, salinity and catchment rainfall for each gauge, averaged over the period of record. The streamflow, salt load and rainfall were simply calculated as averages, while the salinity was calculated by dividing the average salt load by the average streamflow (see Appendix 4 for details). The table shows that average streamflows increase downstream as expected, but that the average salt loads at Rocky Glen and Styx Junction do not. The different lengths of record would affect the average streamflow figures. The yearly variations of salinity, streamflow and salt load for Styx Junction, Rocky Glen and the catchment between them are shown in Figures 13, 14 and 15. The mean annual rainfall across the catchment varies from 515 to 677 mm (Table 3): it is the centroid value of the gauged catchment for the period of record of the gauging station calculated according to the Dean and Snyder (1997) method.

With increasing distance from the coast, annual rainfall and streamflow decrease and average annual stream salinity usually increases — an increase also associated with higher levels of clearing.

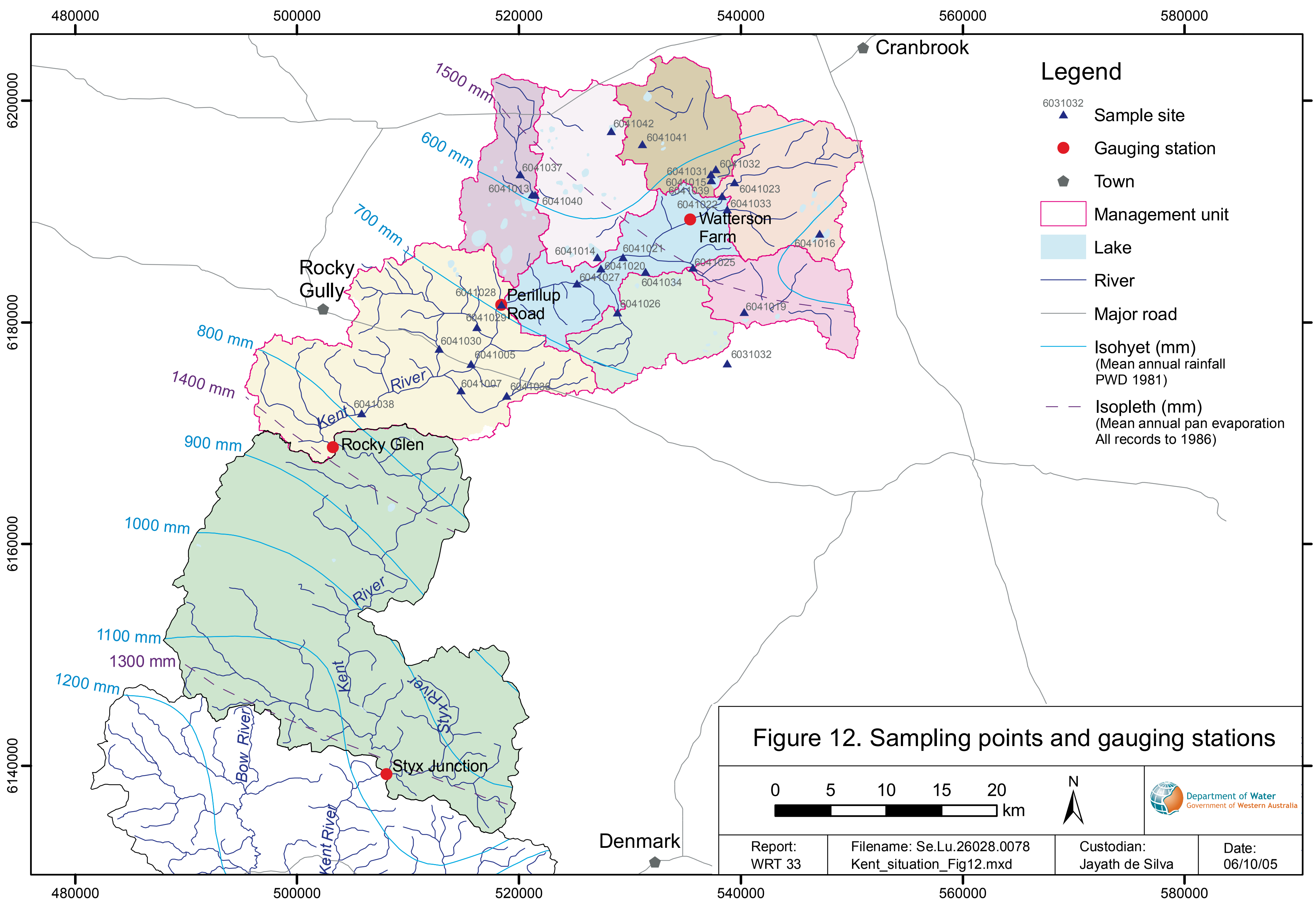

Figure 12. Sampling points and gauging stations

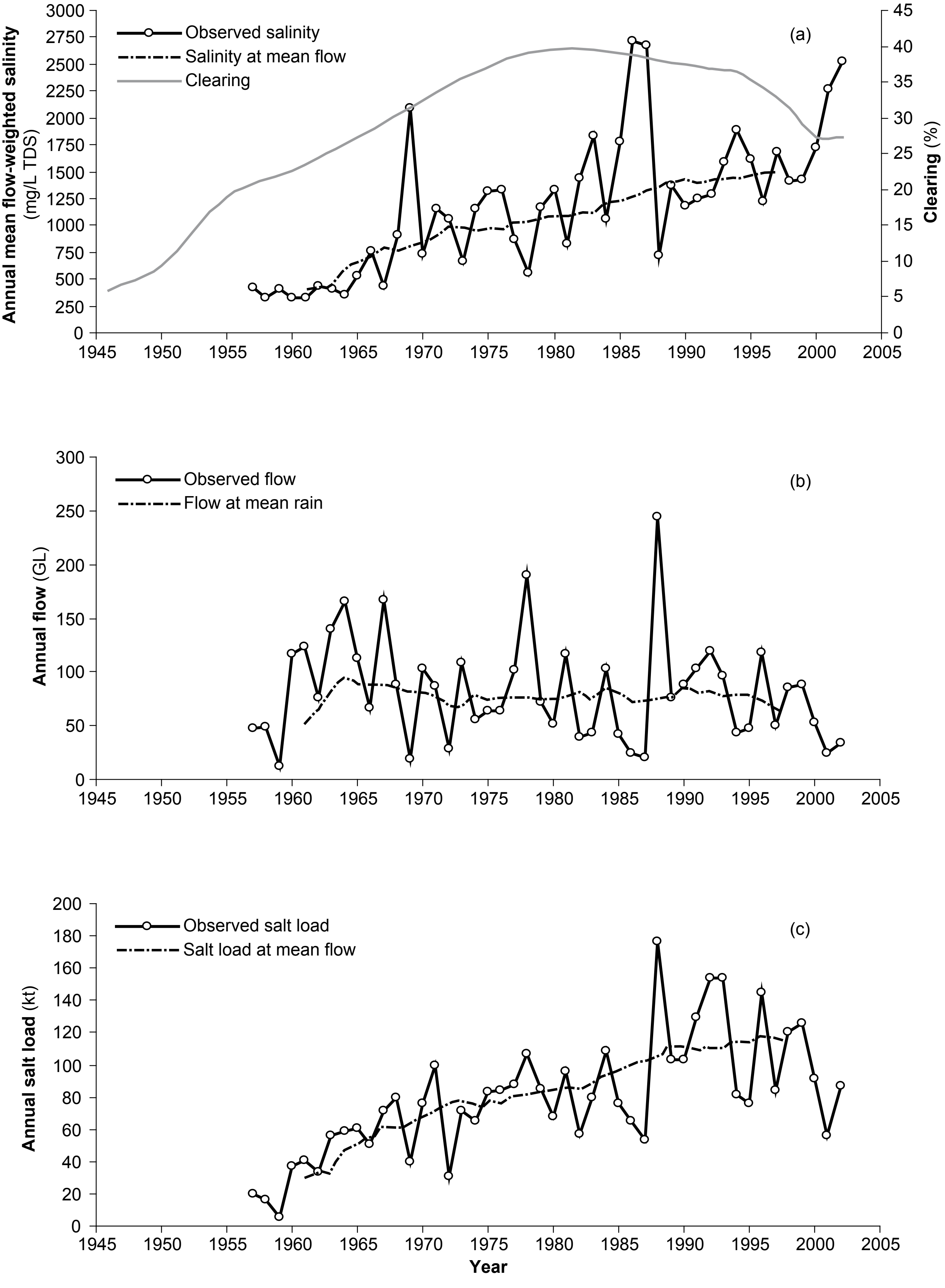

Figure 13. Styx Junction (a) salinity (b) streamflow (c) salt load

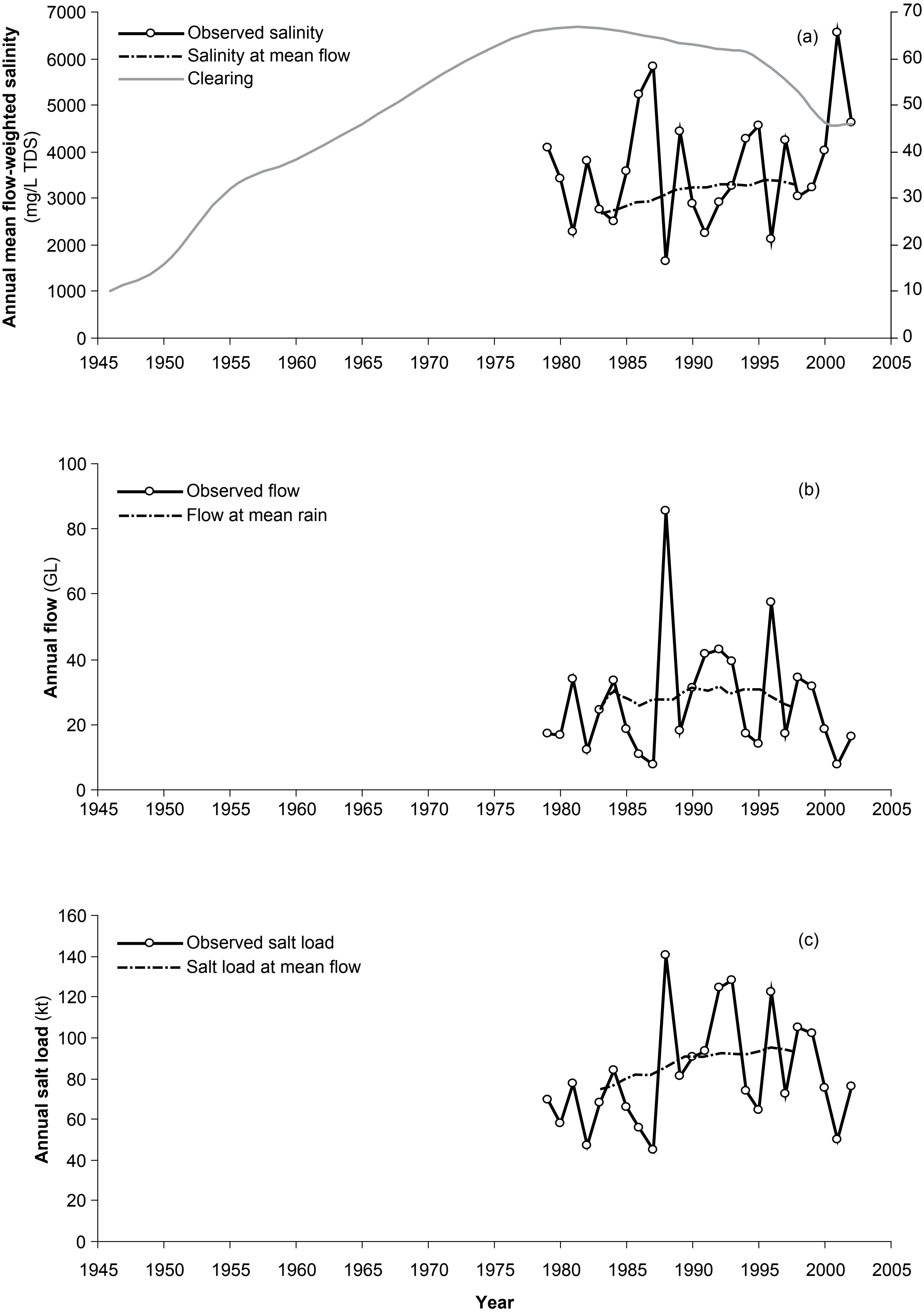

Figure 14. Rocky Glen (a) salinity (b) streamflow (c) salt load

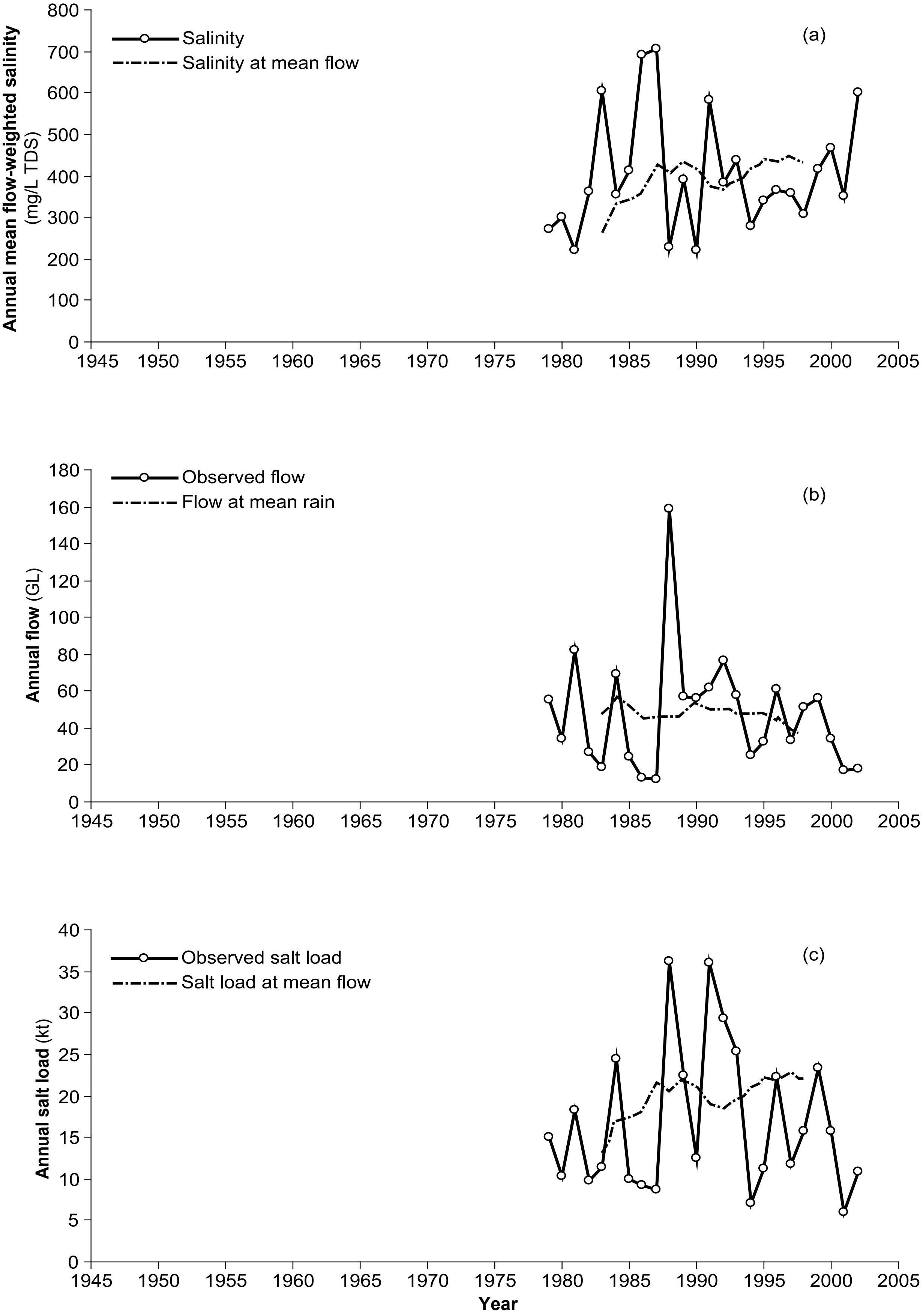

Figure 15. Catchment between Styx Junction and Rocky Glen (a) salinity (b) streamflow (c) salt load

Table 3. Gauged catchment record history

Gauging station	**Station No.**	**Catchment area** (km²)	**Mean annual rainfall** (mm)	**Period of record** [a]	**Mean streamflow** (GL/yr)	**Mean salt load** (kt/yr)	**Mean salinity** (mg/L TDS)
Watterson Farm	604 003	244	515	2000–2002	1.9	14.4	7 600
Perillup Road	604 002	764	541	2000–2002	7.19	36.1	5 025
Rocky Glen	604 001	1 092	583	1979–2002	27.0	82.1	3 037
Styx Junction	604 053	1 843	677	1956–2002	81.9	79.3	968

[a] Mean for the period of record

4.2 Trends in streamflow and salinity

One of the key components of the Salinity Situation Statement documents is an assessment of past, current and predicted catchment streamflow and salinity. This is achieved by analysing data from stream gauging stations.

Only data for the years when both the Rocky Glen and Styx Junction gauging stations were operational (1979–2002) were used for developing the trends between streamflow and salinity, and streamflow and rainfall. Trends can only be reported for the period 1983–98. During this period salinity at both gauging stations was rising but the rate of rise slowed markedly and the trend data are reported in two periods (1983–90 and 1991–98) to capture these changes. Appendix 4 describes the calculations.

Table 4 lists the mean annual data, salinity trends and relative contributions of salt load and streamflow to the Styx Junction gauging station for the upper catchment (Rocky Glen), the lower catchment (between Styx Junction and Rocky Glen) and the Kent River catchment (Styx Junction).

On average, for the period 1990–2002, 28.4 GL (range 7.6–57.4 GL) of water flowed annually through the Rocky Glen gauging station and 73.1 GL (range 24.6–119.2 GL) through Styx Junction.

Table 4. Mean annual (1990–2002) streamflow, salt load, salinity, salinity trends and relative contributions

Catchment	**Mean annual data** (1990–2002)			**Salinity trend** (mg/L TDS/year)		**Relative contribution to Styx Junction** (%)	
	Streamflow (GL)	**Salt load** (kt)	**Salinity** (mg/L TDS)	**1983–90**	**1991–98**	**Streamflow**	**Salt load**
Upper Kent	28.4	90.6	3187	81 (S)	14 (S)	39	84
Lower Kent	44.7	17.5	391	27 (S)	8 (S)	61	16
Kent River	73.1	108	1478	43 (S)	12 (S)	100	100

(S) Statistically significant trend at 95% confidence level

Figures 13–15 show the annual records of streamflow and salt load, and the annual flow-weighted salinity for these three catchments (with trends where applicable). Variations in streamflow over time should mainly occur due to changes in vegetation and rainfall so the trend of salinity at mean rainfall is calculated to remove the effects of high and low rainfall years.

The similar trends of streamflow at mean rainfall across the years — a slight decrease in the 1990s — may reflect the impact of extensive plantations established throughout the upper catchment.

Figures 13a and 14a show the annual flow-weighted salinities for Styx Junction and Rocky Glen calculated from the annual streamflow and salt load figures, as well as the calculated salinity at mean flow. While the salinity of river water has been rising since the early 1960s, the rate of rise at Styx Junction has slowed from

43 mg/L TDS/yr (1983–90) to 12 mg/L TDS/yr (1991–98) and even more at Rocky Glen where the rate of rise has fallen from 81 mg/L TDS/yr (1983–90) to 14 mg/L TDS/yr (1991–98).

Figure 16 and Table 4 show the disproportionate contributions of flow and salt load to Styx Junction: 84% of the salt load from the upper catchment in only 39% of the streamflow while the predominantly forested lower catchment (only 1% of its area cleared) with higher rainfall contributes 61% of the streamflow and 16% of the salt load.

4.3 Lake water and salt balance

The Kent River catchment, especially in its northern areas, has many lakes and swamps within broad flats. About 30% of the upper catchment drains into these lakes which include Nunijup, Carabundup, Nukennullup, Poorrarecup, Wamballup and Katherine. Some, such as Lakes Nunijup, Poorrarecup and Carabundup only overflow into the Kent River in peak flood events. Collins and Fowlie (1981) noted that, although these lakes filled in the winter of 1978, they made no apparent contribution to the flow and salinity of the Kent River. Lake Nunijup last overflowed in 1982 (Bari & De Silva in press). As lake water seeps into groundwater, there is a possibility that groundwater can discharge into the major channel of the Kent River. Most of these lakes are bounded by lunettes that were formed during past periods of arid climate by wind that reworked the sediments of the lake floors.

In 2003, a study, using data for the period 1973–2001, of the salt and water balance of the three major lakes (Nunijup, Carabundup and Poorrarecup) in the Upper Kent drainage system linked a catchment model with a lake model so that long-term inflow and salinity series could be used to predict the monthly lake water levels and salinities (Bari & De Silva in press). As lake water seeps into groundwater, there is a possibility that groundwater can discharge into the main channel of the Kent River. Lake Poorrarecup was reported to be fresh before the extensive development of agriculture in the upper catchment (Bestow 1979; Maxine 1994). The modelled data was analysed for the period 1980–2001 to allow the model to run through a warm-up phase (Table 5).

Table 5. Lake characteristics

Lake	**Depth at overflow level** (m)	**Surface area** (km^2)	**Volume at overflow level** (GL)	**Median salinity** (mg/L TDS)	**Volume as ratio of inflow**
Nunijup	3.9	0.79	2.32	7 750	2.3
Carabundup	4.0	1.85	5.17	15 009	2.95
Poorrarecup	3.0	1.99	4.98	10 600	1.97

The coupled catchment and lake modelling system was run over the period January 1973–December 2001 and Table 6 shows some results, based on annual mean values obtained over the period 1980–2001. The model predicted a mean annual inflow (streamflow plus rainfall on the water surface) of 1.0 GL into Lake Nunijup with the highest mean annual inflow of 2.53 GL into Poorrarecup Lake.

Most of the lake water was lost through evaporation (Table 6) (only Nunijup overflowed during this simulation period) and nearly all the salt leaked through the lake beds (Bari & De Silva in press).

Table 6. Results of the lake modelling

Lake	**Mean inflow including rainfall** (GL)	**Loss by evaporation** (%)	**Loss by seepage** (%)	**Overflow** (%)	**Median salinity** (mg/L TDS)	**Mean annual salt input** (kt)	**Salt load loss by seepage** (%)
Nunijup	1.0	70	26	1	7 750	2.64	88
Carabundup	1.75	81	19	0	15 009	6.64	98
Poorrarecup	2.53	79	19	0	10 600	6.18	98

Source: Bari & De Silva in press

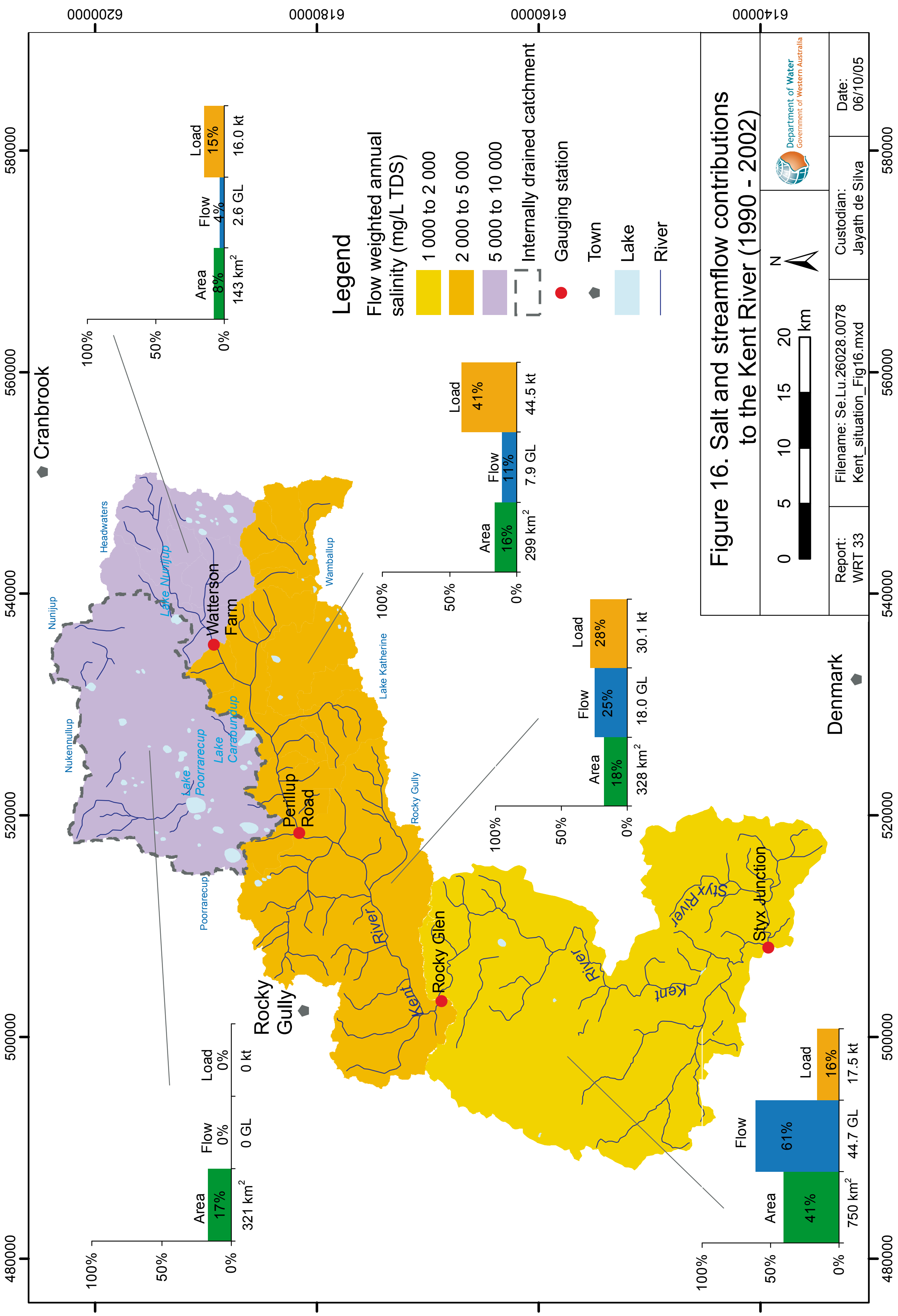

Figure 16. Salt and streamflow contributions to the Kent River (1990–2002)

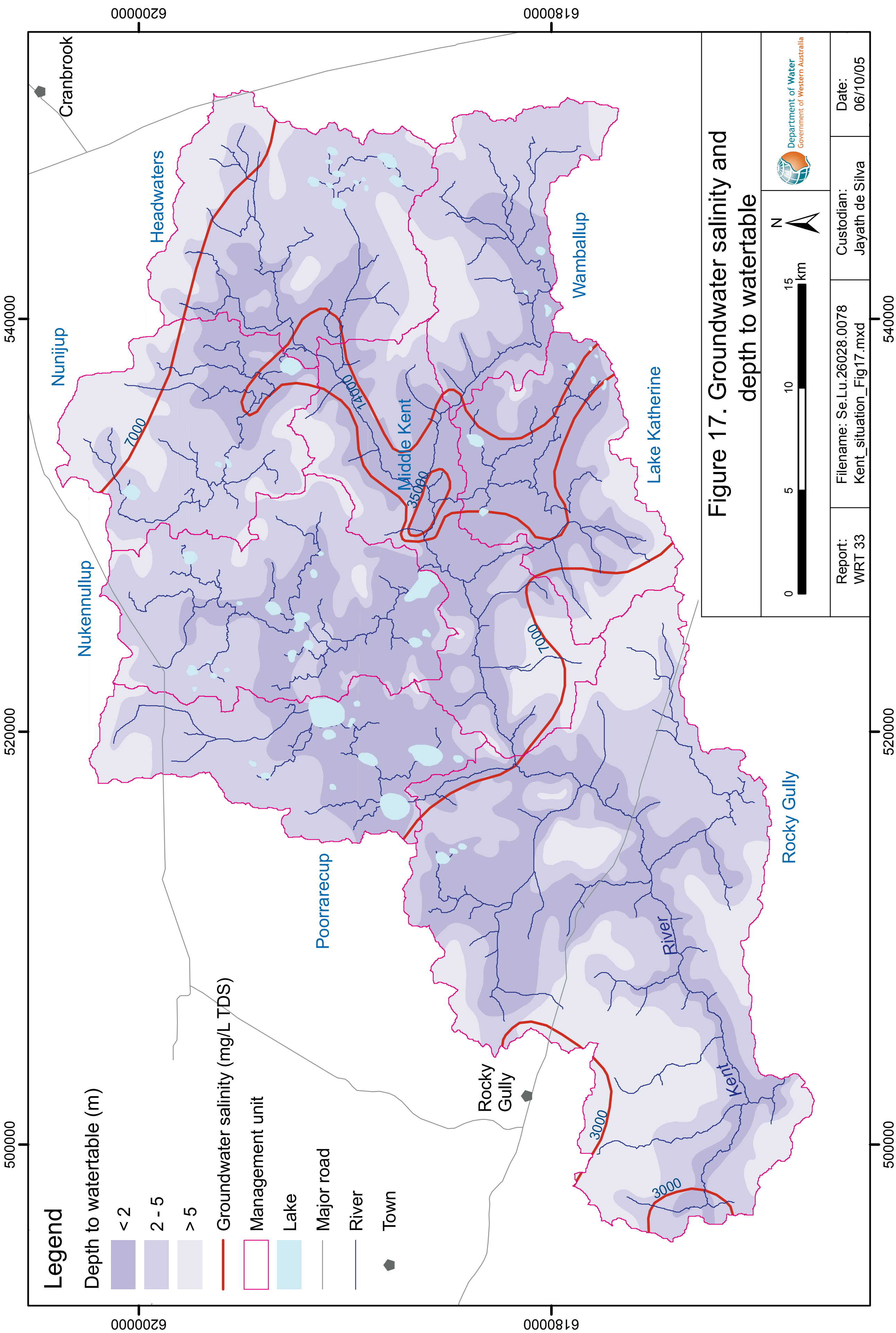

Figure 17. Groundwater salinity and depth to water level

4.4 Groundwater salinity

The distribution of groundwater salinity across the upper catchment was studied using information from about 120 groundwater monitoring and investigation bores drilled between 1980 and 2000 (Fig. 17). The salinity ranges from 3000 mg/L TDS in the area near Rocky Gully to 35 000 mg/L TDS in the centre of the catchment. Groundwater is more saline in the flat low-rainfall (700 mm) areas than in undulating areas with average rainfall of more than 700 mm. In local groundwater flow paths within the weathered rock aquifers, salinity generally increases from upper slope areas to lower slope areas or valleys, with a general trend of salinity increasing with reducing mean annual rainfall (Fig. 18).

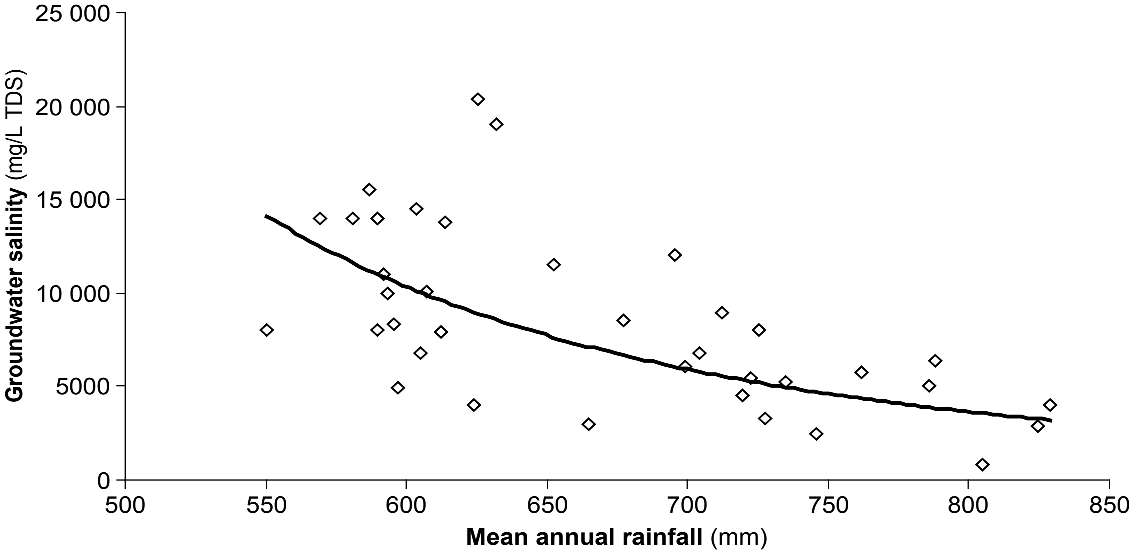

Figure 18. Relationship between groundwater salinity and rainfall

4.5 Groundwater levels (Temporal change)

Three depth-to-water level (WL) classes were identified from the depth-to-groundwater map for the upper catchment (last updated in 2002) produced with measured water level data and the digital elevation model (Fig. 17):

- WL < 2 m (38% of the upper catchment area)—mainly within the flats; has most of the groundwater discharge areas and some areas where bores record potentiometric heads above ground level. These areas are at risk of salinisation.
- WL 2–5 m (42%)—mainly in the flats, the plains and low to mid slope areas of the undulating landform
- WL > 5 m (20%)—within the mid to upper slope areas of the undulating landform and mainly represent the major groundwater recharge areas of the catchment.

Water levels fluctuate seasonally. The watertable in most bores starts falling in November and is deepest in March (due to the high evapotranspiration rate during summer, the absence of recharge, and natural aquifer drainage) though in some bores with watertables deep enough to be unaffected by evaporation the watertable is deepest in April or May. Water levels start rising in May and are shallowest during September in response to recharge from winter–spring rainfall. The rise in water level due to this recharge is greater where water levels are less than 2 m below ground level and decreases with increasing depth to groundwater. The magnitude of rise in water levels after winter–spring rainfall can be directly related to the vertical annual recharge rates of aquifers.

4.6 Groundwater level trends

Groundwater level trends, which are reflections of long-term and short-term land use and climatic changes, have been used to investigate following questions:

- What are the effects of clearing native vegetation on groundwater levels?
- Has groundwater in the catchment reached steady-state equilibrium since clearing controls were imposed in 1978?
- How are groundwater levels responding to bluegum plantations established since 1993?
- What do the trends at the 'parkland clearing' experimental site indicate about this as a useful method of management?

The trends of levels in about 90 upper catchment monitoring bores (Fig. 19) constructed by the Department of Agriculture, CSIRO (Bartle et al. 2000) and the Water and Rivers Commission (Hundi & De Silva 2000) were analysed using the HARTT method (Ferdowsian et al. 2000). This separates the effect of climate variability during the period of measurement from the underlying time trend (Fig. 19 & Appendix 4). Average annual rainfall for 1975–2001, which is 11% less than the long-term rainfall (1910–2001), was used in this analysis.

What are the effects of clearing native vegetation on groundwater levels?

Monitoring (1984–2003) indicated that groundwater levels are rising in about 30% of the bores (with a range of 2 to 45 cm/yr) and either declining or steady in the others. Water levels are rising faster at sites cleared after 1965 than at sites cleared before 1965, perhaps because groundwater levels at the sites of earlier clearing are closer to equilibrium. Groundwater levels are also rising faster in bores with deeper water levels (depth to water more than 10 m) or on upper hill slopes than in bores with shallow groundwater levels or on lower hill slopes or flats.

Has groundwater in the catchment reached steady-state equilibrium since the clearing controls were established in 1978?

A large part of the catchment may have reached steady state or be very close to steady state as groundwater levels in nearly 70% of bores are either declining or steady. For example, groundwater in the Headwaters and Wamballup MUs, where land use has changed little since the 1960s, may have achieved steady state in relation to pre-1978 clearing as most of the trends are downward. The 'Flats' landform that covers about one third of the upper catchment has relatively stable groundwater levels compared with the 'Hill slopes' landform where the trends are still upward.

How are groundwater levels responding to bluegum plantations established since 1993?

Groundwater levels are falling. The monitoring bore, BU8B, at Buswells site in the Middle Kent MU where bluegum plantations were established in 1998 is on a middle hill slope position draining to the Kent River. The groundwater level here has shown two distinct trends: rising at 11 cm/yr before the plantations, but falling at 50 cm/yr after their establishment (Fig. A4.1). This trend reversal demonstrates the effectiveness of the plantations in reducing recharge to groundwater locally. Similar reversals of trends are evident in other sites of bluegum plantations.

What do the groundwater trends of the 'parkland clearing' experimental site indicate?

'Parkland clearing' was a land management experiment where an area of trees was thinned to about 50 stems per hectare. Groundwater levels at the site had two distinct trends (Fig. A4.2): upward at between

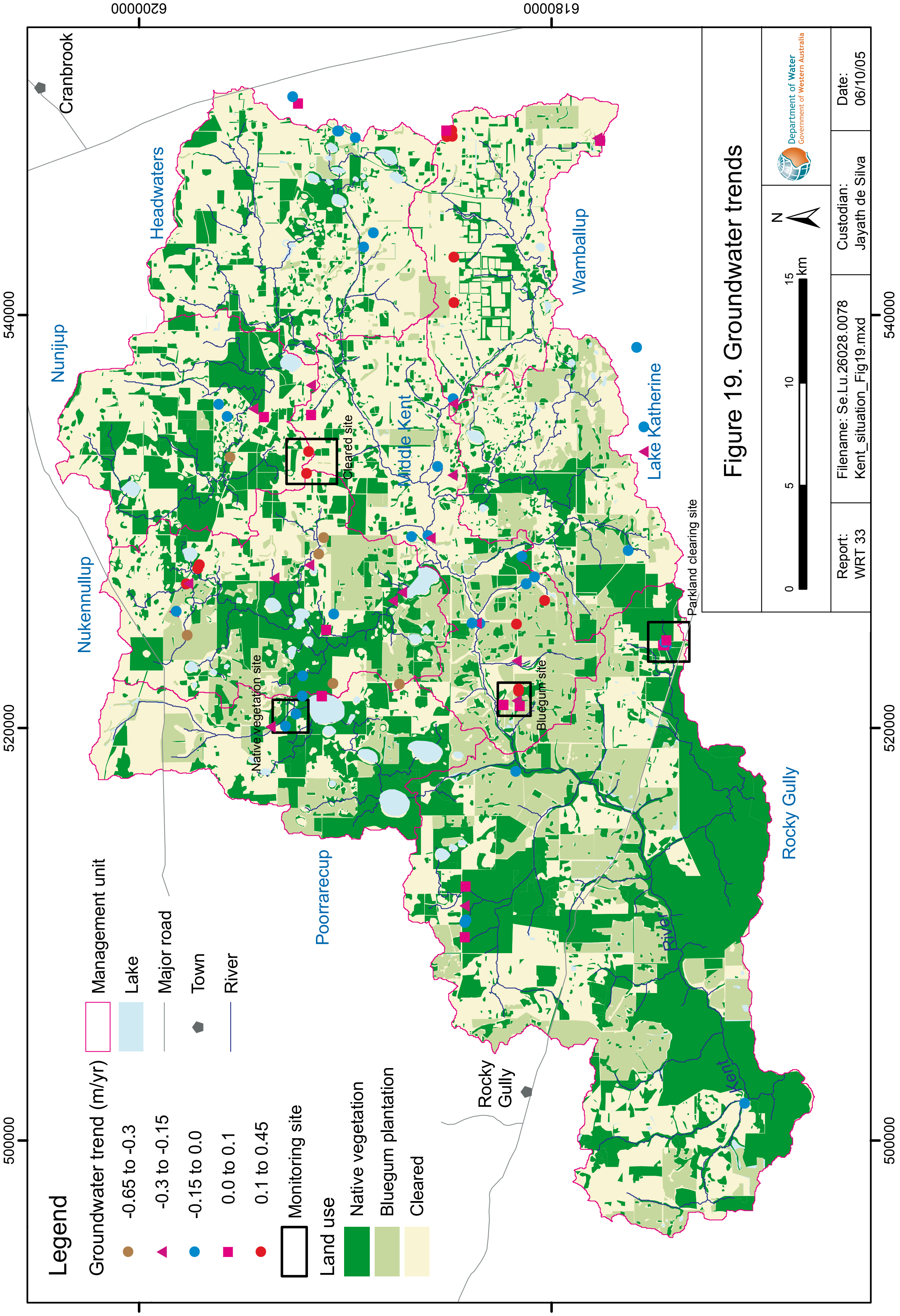

Figure 19. Groundwater trends

4 and 11 cm/yr from 1981 to 1993 but downward at about 3 cm/yr from 1994 to 2002. Groundwater at this site may now have reached steady-state equilibrium. Groundwater in control bores in the adjoining native forest was rising at 2 cm/yr and declining at 1 cm/yr over these periods.

4.7 Areas at risk of dryland salinisation (Spatial change)

Landmonitor mapping (Evans et al. 1995; Allen & Beeston 1999) indicates that about 31% of the upper catchment is at risk of dryland salinisation (Fig. 20). Risk factors include:

- *Depth to water level*—The risk is high in the broad flats and low to moderate in undulating areas where groundwater is less than 2 m from the surface and can evaporate leaving salt on the surface or in soil. The risk decreases as the depth to groundwater increases. Salama et al. (1997) predicted that, in the worst possible scenario, depth to groundwater would be less than 2 m in 65% of the upper catchment area.
- *Salt storage*—The broad flat areas of the upper catchment have a higher risk and a greater potential to mobilise large amounts of salt into groundwater and then into waterways as salt storage in the 'clayey sediments' regolith profiles in lakes and in the broad flats is higher than in the 'weathered rock' regolith profiles in undulating areas where salt storage increases from upper slope to lower slope areas.
- *Groundwater level trends*—The risk is higher where the trends are upward than where there are no trends or falling trends.
- *Groundwater salinity*—The risk is high where groundwater salinity is high and groundwater shallow and both increase as the mean annual rainfall decreases with increasing distance from the coast.

Table A4.2 summarises the above factors for the management units of the upper catchment.

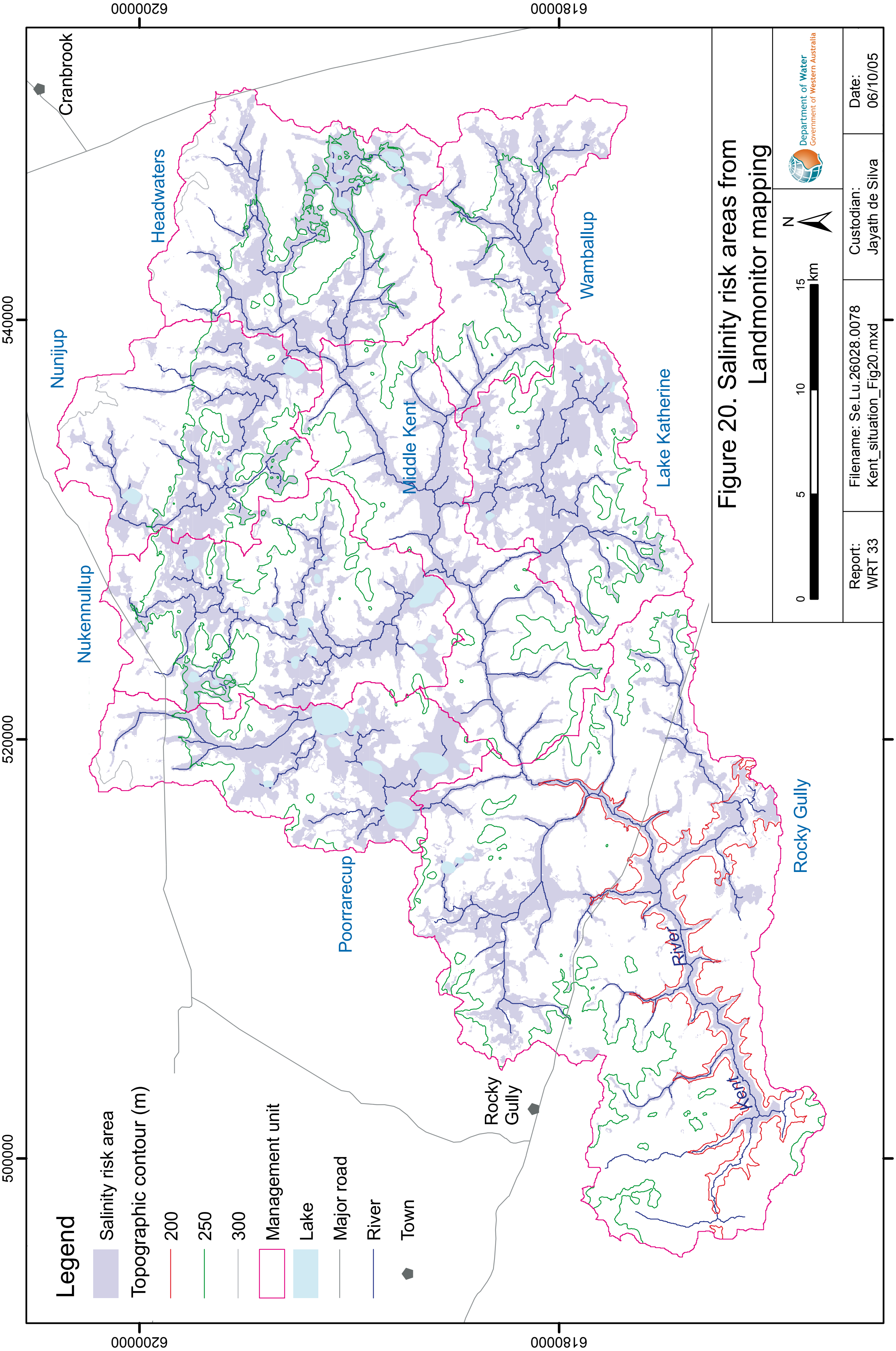

Figure 20. Salinity risk areas from Landmonitor mapping

5 Modelling

Introduction

We used two catchment hydrological models to regenerate the stream salinities measured over the last 30 years at gauging stations and to ‘predict’ stream salinities and other parameters for a range of revegetation and engineering actions suggested by the Recovery Team. These management options or scenarios were applied only to the catchment upstream of the Rocky Glen gauging station. Upstream of Rocky Glen are cleared and pastured areas where changed land use is possible. Downstream of Rocky Glen to Styx Junction the catchment is essentially fully forested.

These models are mathematical tools representing the stream salinity generation processes in the catchment. These processes are affected by long-term changes in land use and long-term climatic changes. Between them these models provide useful information for land managers to assess the effectiveness of various scenarios across the catchment and over time before any actual planting or construction is needed.

The MAGIC model is a steady-state model that assumes the ongoing land use in the catchment for so long that the salinity generation processes are at equilibrium and delivers results as annual outputs. The LUCICAT model is a distributed dynamic conceptual model that can provide daily, monthly and annual flows for particular land uses. Management options are applied to the catchment under the same rainfall conditions and the salinity outputs compared.

For both models the catchment was divided into 61 subcatchments (Fig. 21) to represent the variations of rainfall, land use and soil properties.

This section gives only an overview of the modelling with more details in Appendix 5 on the basic steps: model set up, calibration and verification.

5.1 The MAGIC model

The Microstation and Geographic Information Computation (MAGIC) model is a steady-state model that gives annual outputs for particular long-established land covers. It simulates the steady state of a catchment for an average rainfall year and generally runs on a monthly time-step.

Surface water and groundwater movement within the catchment is represented by the three-layer system of a typical hill slope applicable to the south-west of Western Australia as shown in Figure 22 (Sharma & Williamson 1984). The bottom layer of the three layered catchment has the main aquifer and is overlain by a less permeable layer of sandy clay. A superficial layer of permeable soil over the whole catchment makes up the top layer.

One of the model inputs is rainfall. To allow for interception losses, the rainfall is reduced by 15% before being added to the store of water in the topsoil layer. The topsoil layer is on average 1.6 m thick and very permeable. Plants can draw water for transpiration from this layer until it becomes dry. The rate of transpiration depends on the leaf area coverage, Leaf Area Index (LAI), and rooting depths attributed to the type of vegetation and the pan evaporation rate at the time. Water may be added to the layer by lateral inflow from the topsoil of upstream adjacent cells, or lost by lateral outflow to downstream cells. The rate of lateral flow depends on the slope of the ground, permeability and water content of the topsoil. Water may also be added by upward flow of groundwater, or lost by infiltration from the topsoil layer to layers below. The rates of flow depend on the vertical permeability of the lower layers. Water inputs and outputs are added to the water content of

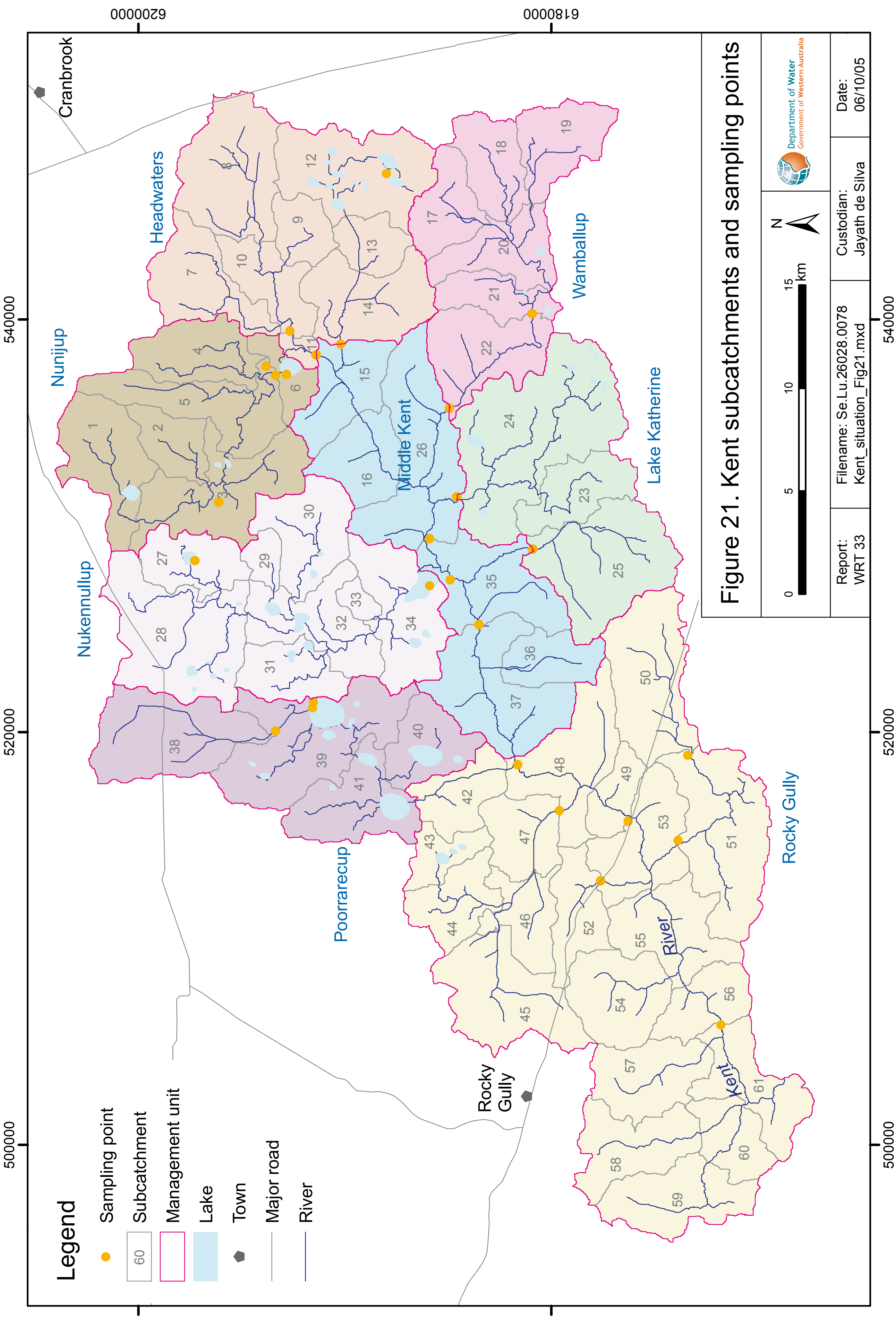

Figure 21. Kent subcatchments and sampling points

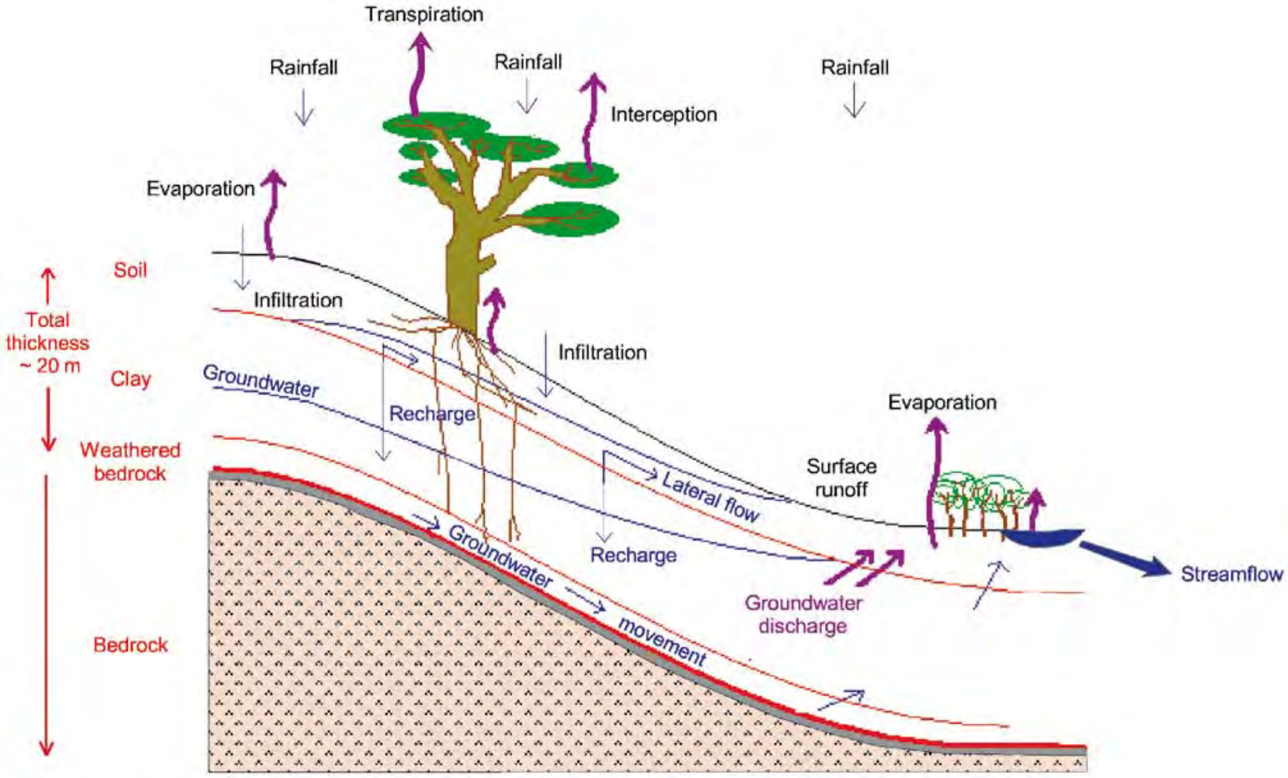

Figure 22. Hill slope processes

the topsoil layer at the start of the month. If the total exceeds the saturation capacity of the layer, the excess is allocated to runoff. Evaporation from soil and lakes, and water held in upland depressions is deducted from the runoff to evaluate the streamflow.

Each subcatchment surface is divided into a grid of 25 m × 25 m cells which were assigned properties (e.g. ground elevation, soil layer thickness, permeability, vegetation type and density) to represent on-ground conditions. The model then generates the water balance for each cell. Figure A5.3 shows a typical representation of a landscape and the flow components by the MAGIC model.

MAGIC was set up, calibrated and verified as detailed in Appendix 5.

5.2 The LUCICAT model

The LUCICAT (Land Use Change Incorporated CATchment) model is a distributed conceptual catchment hydrology model. The catchment is divided into subcatchments to take into account the spatial distribution of catchment attributes. Each of the subcatchments is represented by the 'open book' approach and a fundamental building-block model incorporating catchment attributes like soil depth, rainfall, pan evaporation, land use change, groundwater level and salt storage is applied. (Bari et al. 2003; Bari & Smettem 2003; Bari & Smettem, 2004). The fundamental building-block model consists of (i) an unsaturated soil module (upper and lower zone unsaturated stores), (ii) a saturated groundwater module, and (iii) a stream zone module (Fig. A5.5). The major hydrological processes involved in the model are discussed in Appendix A5.2.

This model needs minimal calibration (Bari & Smettem 2003). All but seven parameters are 'fixed' (Table A5.5). See Appendix A5.2 for details of calibration and verification. As groundwater levels rose following clearing in the 1970s, streamflow and salinity data up to 1990 were used for calibration and data after 1990 used for verification.

5.3 Model calibration

Salinity and flow – spatial distribution

MAGIC's predictions for the streamflow and salinity of the calibration and verification cases are within +7% and –5% of the observed data at Styx Junction (Table 7). In 2000, the observed salt load and streamflow at Perillup Road were 38% and 35% lower than predicted but these differences could be partially attributed to the rating curve of this gauging station.

The results for Styx Junction, where the salinity recovery target is set, were calculated from the Rocky Glen model results by adding annual streamflow and salt load of 51 GL and 18 kt, being the mean of the differences between the gauging station records over the period 1980–95. This assumes that the streamflow and salt-load generating characteristics of the forested catchment are constant with time.

Table 7. Model calibration and verification for the Kent River gauging stations

Management unit		Calibration (maximum clearing)		Verification (Year 2000)	
		Observed	Predicted	Observed	Predicted
Watterson Farm					
	Streamflow (GL)	N/A	2.5	2.7	2.6
	Salt load (kt)	N/A	21	18	21
	Salinity (mg/L TDS)	N/A	8600	6670	7800
Perillup Road					
	Streamflow (GL)	N/A	11	7.4	10.2
	Salt load (kt)	N/A	71	50	67
	Salinity (mg/L TDS)	N/A	6600	6680	6600
Rocky Glen					
	Streamflow (GL)	28	25	18.7	21
	Salt load (kt)	95	88	75	82
	Salinity (mg/L TDS)	3390	3550	4020	3800
Styx Junction					
	Streamflow (GL)	79	75	52.6	55
	Salt load (kt)	117	106	92	98
	Salinity (mg/L TDS)	1490	1400	1750	1800

N/A denotes not applicable or not available

Mapping salt-affected areas

When the model results were compared with observed streamflows and salt loads at major sampling sites Trend analysis showed that the annual salt load at mean streamflow at the Rocky Glen gauging station peaked in 1996 at 95 kt. This salt output was assumed to correspond to the full expression of salinity in response to the last areas cleared. Calibration (with the February 1988 Landsat scene) to produce the mean streamflow for the period 1980–95 and maximum salt load at mean flow gave 180 km^2 (Fig. 23) of shallow watertable, 85 km^2 of which discharged saline groundwater.

Role of lakes

Between 1980 and 1995, small areas of the Headwaters and Rocky Gully management units and the management units Poorrarecup, Nukennullup and Nunijup contributed no streamflow or salt to the Kent River (Fig. 24).

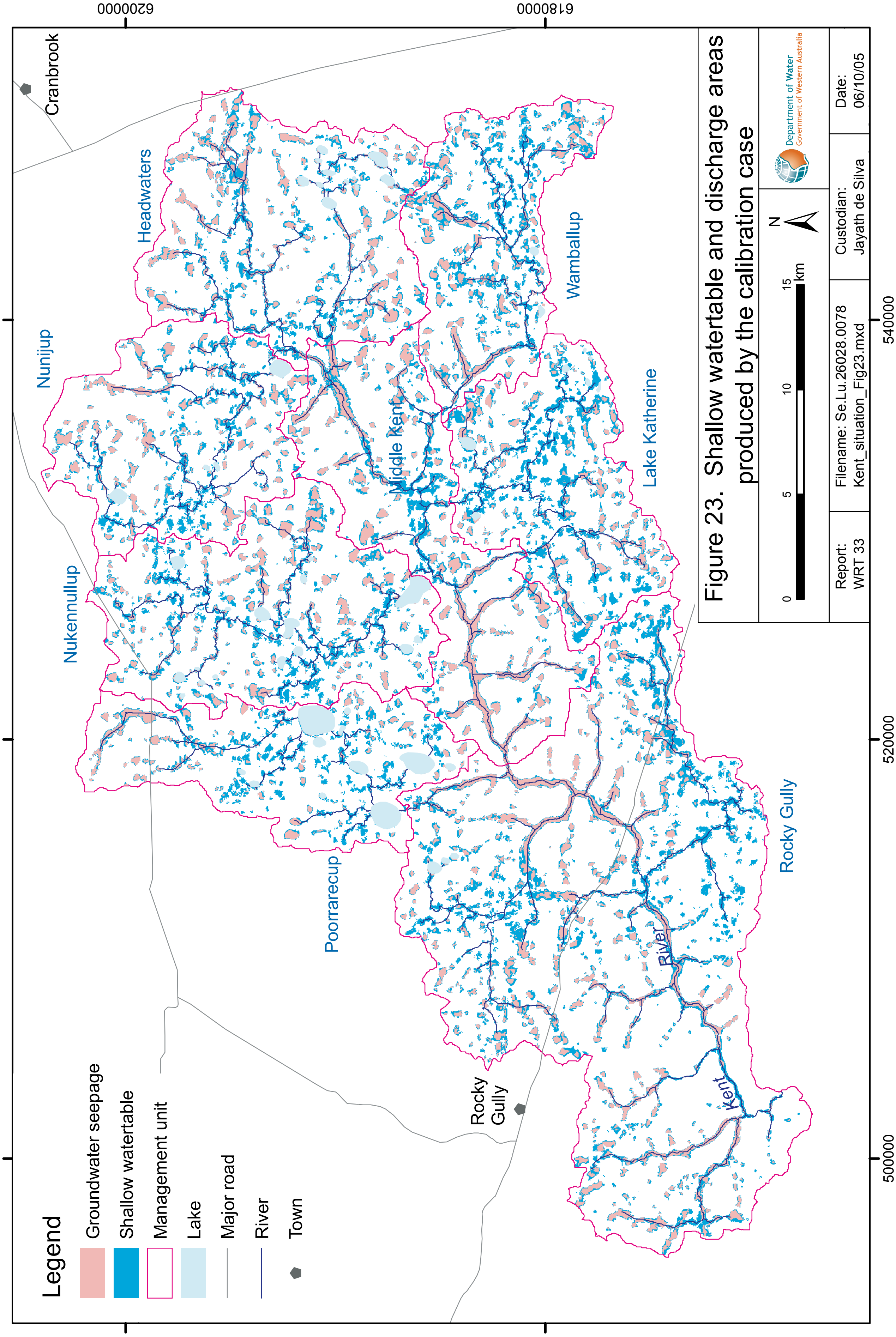

Figure 23. Shallow watertable and discharge areas produced by the calibration case

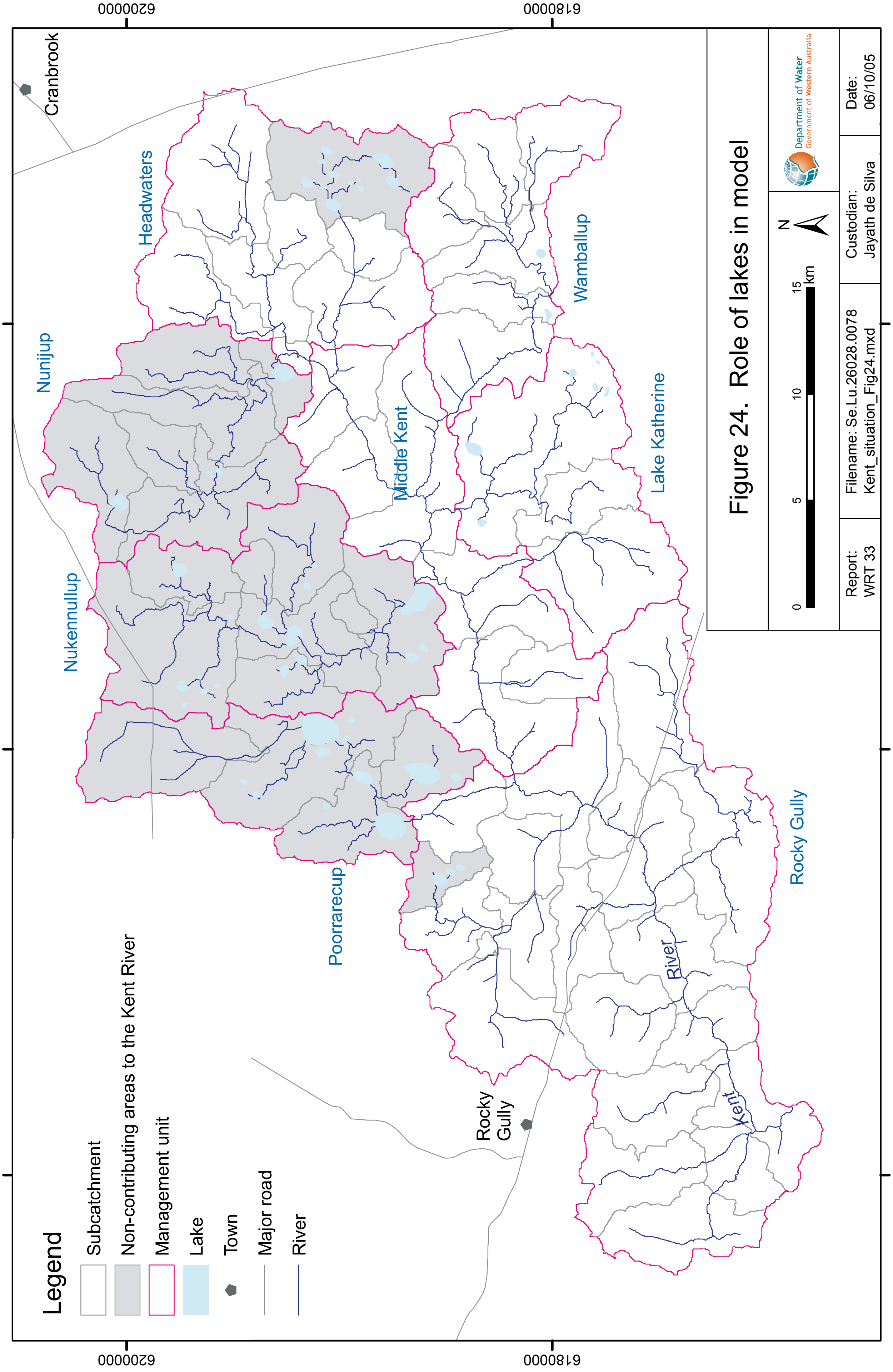

Figure 24. Role of lakes in model

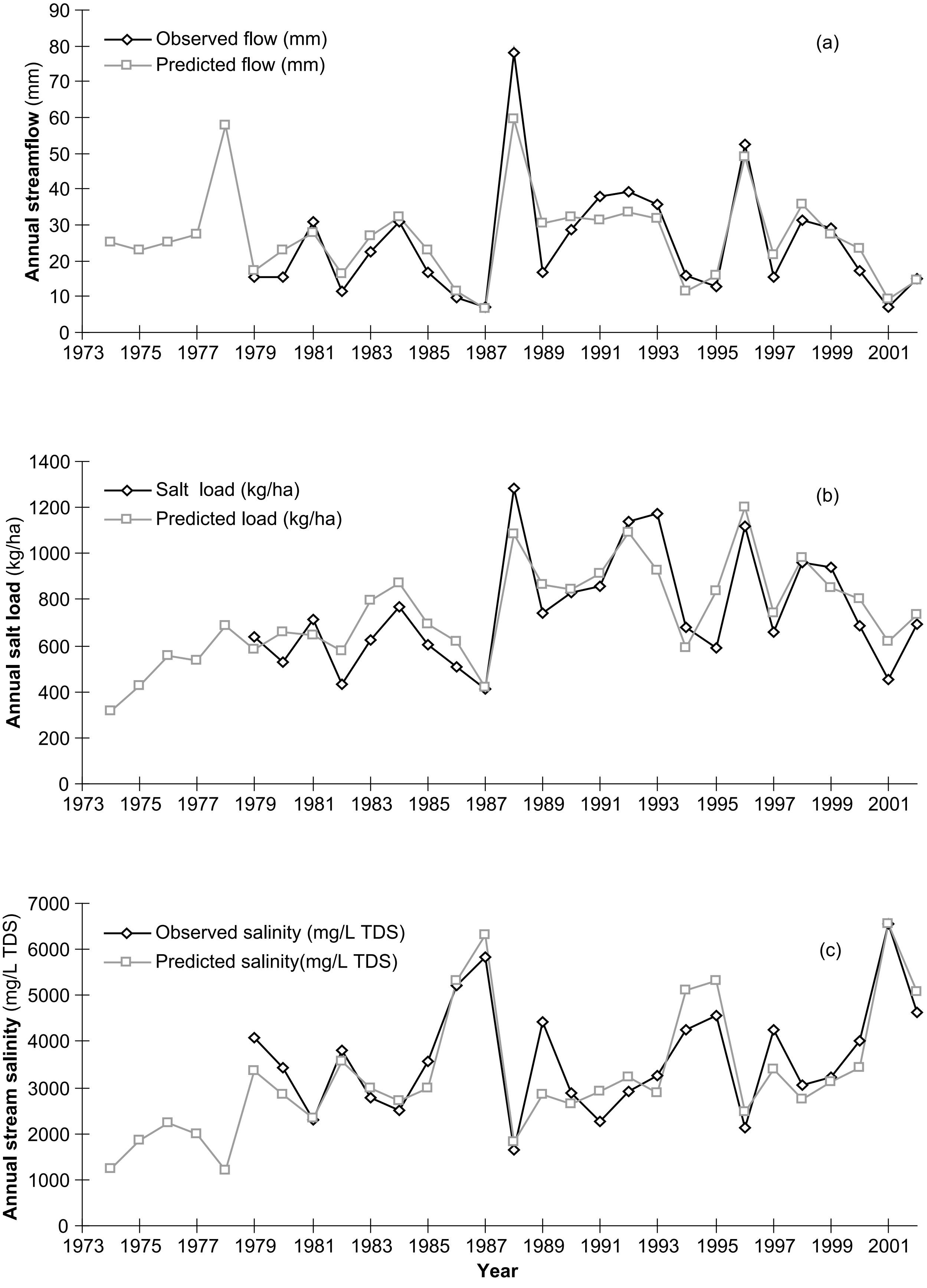

Figure 25. Observed and LUCICAT-predicted annual (a) streamflow (b) salt load and (c) salinity at Rocky Glen

Salinity and flow — temporal changes

The predicted daily streamflow, salinity and salt load hydrographs (1974–2002) for all gauged subcatchments matched very well. The daily streamflows and salt loads were summed for monthly and annual comparisons (Figs 25, A5.7 & A5.8). Daily simulated and observed streamflow hydrographs matched reasonably well in most years. In the average-flow year of 2000, daily streamflow between October and May was dominated by the baseflow component when stream salinity was 5000–6000 mg/L TDS (Fig. A5.9). The model predicted the flow-generation processes during this period very well, but predicted the daily salinities poorly.

The observed and predicted monthly and annual streamflow trends for the whole simulation period agreed well though the model slightly underpredicted the highest annual runoff on record — observed in 1988 (Fig. 25). In the low-flow years, the model generally predicted the annual streamflow and salt load for 1978–2001 well. Overall, the predicted and observed monthly streamflows and salt loads were also well correlated (Fig. A5.8).

During 2000–02, salinity samples and stage heights were collected from around the upper catchment (Fig. 21) and the sampled and LUCICAT-predicted annual streamflows and salt loads correlated well (Fig. 26).

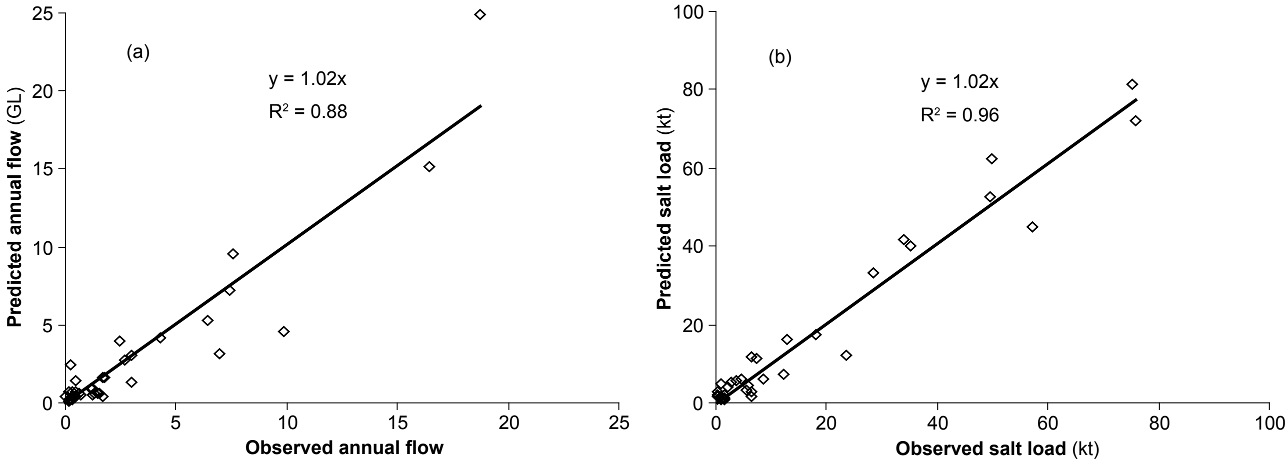

Figure 26. Observed and LUCICAT-predicted (a) streamflow and (b) salt load at major sample sites (2000–2002)

Historical clearing

To understand how the catchment responds to various levels of clearing and compare predictions with stream gauging records, two historical clearing scenarios were run through the model. With the 1946 clearing (9%), salinity at Styx Junction was 355 mg/L TDS (Table A5.10) — which matches the record of the late 1950s (350 mg/L TDS) well (Fig. 13). Studies in the Collie catchment have found that the groundwater system takes approximately 10 years to stabilise after reforestation (Bari & Ruprecht 2003; Bari & Smettem 2004). Model outputs for the 1970s were 860 mg/L TDS and 76.5 GL compared with the observed 955 mg/L TDS and 76 GL.

With the 1965 extent and distribution of clearing, salinity was about 905 mg/L TDS (Table A5.11). Current land use in the Kent catchment and, with the same extent of clearing as in 1965 but different spatial distribution, is predicted to produce a salinity of 950 mg/L TDS. The difference could be due to the differences in distribution of the clearing in 1965 and now, and the difference in clearing histories. These results indicate that LUCICAT predictions are realistic.

5.4 How can these tools be used in catchment management?

As these tools regenerate salinity and flow conditions both spatially and temporally as discussed above, they can be used to generate salinity and flow under ‘base case’ and ‘what if’ scenarios with more confidence.

The base case represents what would be expected at hydrologic equilibrium if there were no further land use changes in the catchment. ‘What if’ scenarios are conceptual management options and include a range of revegetation, perennial and engineering options. They will be discussed in detail in the Section 6.

6 Management options

As shown on Figure 27, without clearing controls and reforestation, the mean salinity of the Kent River could have risen to 1640 mg/L TDS. The salinity is predicted to fall from the current 1480 mg/L TDS to 950 mg/L TDS (marginal quality) without further land-use change in the catchment. The fall can be attributed to the effects of clearing controls, recent bluegum plantations and the 11% reduction in rainfall experienced in the catchment since the mid 1970s. The average inflow to a potential reservoir located at the Styx Junction gauging station would be 75 GL.

Two conceptual options are predicted to meet the target 500 mg/L (the numbers in brackets are salinities at steady state, and yield):

- Planting trees on 60% (309 km^2) of the cleared land (500 mg/L TDS and 66 GL)
- Diverting 100% of the flow at the Rocky Glen gauging station (350 mg/L TDS and 51 GL) and diverting 59% of the flow at Rocky Glen (500 mg/L TDS and 60 GL)

Two options nearly reach the target:

- High density shallow-rooted perennial pastures on 332 km^2 (66%) of the cleared land (550 mg/L TDS and 66 GL)
- Groundwater pumping (560 mg/L TDS and 71 GL). This option would require pumping 3.5 GL using 630 bores at 15 kL/day/bore and require approximately 320 km of pipes within the catchment.

The Base case ('do nothing') and all management option results are averages for the period 1992–2002.

The effects of revegetation and engineering options modelled are summarised in Table 8 and detailed in tables in Appendix 6. Unless otherwise stated, all conceptual results apply at the Styx Junction gauging station. All options, except drains, reduce the possible yield of a future reservoir, but lower stream salinity. All show that large-scale interventions will be required.

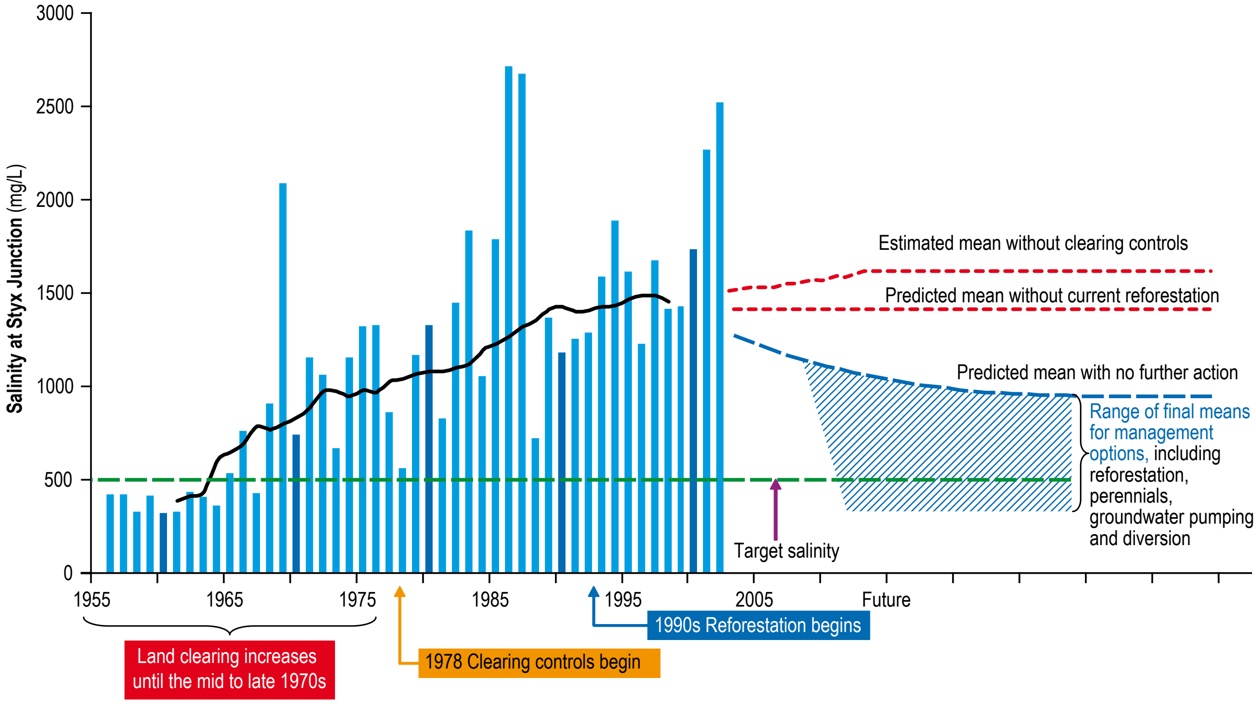

Figure 27. Kent River salinity—past, present and predicted

Table 8. Summary of analysis of management options at Styx Junction

	Management option	**Planted area**[a] (km^2)	**Total cleared area left in Upper Kent** (%)[b]	**Styx Junction**		
				Salinity (mg/L TDS)	**Streamflow** (GL)	**Salt load** (kt)
	Base (do nothing)	0	46	950	75	71
Revegetation	Commercial trees[c]					
	Bluegums only	20	44	910	73	67
	Bluegums and/or pines and sawlogs	147	33	650	71	46
	Non-commercial trees					
	On waterlogged land	150	32	730	68	50
	Enough planting to reach target	309	18	500	66	33
	On all cleared area	503	0	330	62	20
	Perennial pastures[c] deep rooted					
	Low density	147	33	934	72	68
	High density	147	33	766	71	54
	Perennial pastures[c]—shallow rooted					
	Low density	332	16	965	69	66
	High density	332	16	550	66	36
	Perennial pastures—shallow rooted on waterlogged land					
	Low density	150	32	975	72	71
	High density	150	32	900	69	62
Engineering	Groundwater pumping	N/A	46	560	71	40
	Diversion of saline water					
	20% flow; 33% load	N/A		760	70	53
	33% flow; 50% load	N/A		660	67	44
	59% flow; 76% load	N/A		500	60	30
	100% diversion	N/A		350	51	18
	Drains	N/A	46	1010	75	76

[a] All planted trees or perennial pastures replace pastured land in the Upper Kent catchment.
[b] Total cleared area for the Upper Kent is 503 km^2
[c] Land capability maps used to site plantations and perennial pastures

6.1 Base case—'do nothing'

The 'Base' case, which represents the current land use of the catchment at hydrological equilibrium, and assumes that all the bluegum plantations established since 1996 are fully mature produces a salinity of 950 mg/L TDS and a flow of 75 GL (Table A6.19).

The results for the 'Base' case and all management options are averages for the period 1992–2002. All the plantation areas identified in the Landsat 2002 scene were assumed to be fully established and the areas modelled are shown in Figure A5.2. The catchment areas (321 km^2) draining to Lakes Nunijup, Carabundup and Poorrarecup are assumed to contribute no streamflow or salt load to the Kent River (Fig. 24).

6.2 Revegetation options

Three categories of plant-based options were modelled: commercial trees, non-commercial trees and perennial pastures.

Areas of the cleared land suitable for planting commercial trees and perennial pastures were identified from their climatic, landscape and soil requirements by the process described in Appendix A6.1 and incorporated into the catchment model. Figures 28–30 show these 'land capability' maps.

Commercial bluegum plantations in high rainfall areas (> 700 mm/year) on all suitable cleared land (20 km^2) reduce salinity to 910 mg/L TDS (Table A6.21).

A combination of bluegums, sawlogs or pines planted across all of the suitable land (147 km^2) reduce the salinity to 650 mg/L TDS and the flow to 71 GL.

Planting non-commercial trees on 162 km^2 of cleared land in addition to the 147 km^2 of commercial trees (total replanted area 309 km^2) reduces the salinity at Styx Junction to 500 mg/L TDS, leaving 18% (194 km^2) of the land still cleared.

Planting non-commercial trees on areas subject to waterlogging (150 km^2) reduces the salinity to 730 mg/L and the yield to 68 GL (Table A6.7).

Non-commercial trees planted on all the cleared land (503 km^2) reduce salinity to 330 mg/L.

The effects of replanting trees on various proportions of the cleared land can be estimated from the relationships of cleared area to annual streamflow, salt load and salinity at Rocky Glen (for the upper catchment) (Figs A6.3–5). For every square kilometre of cleared area planted, at Rocky Glen, the annual streamflow falls about 0.06 GL, the salt load 0.28 kt and annual salinity about 4 mg/L TDS. These rates of reduction also apply at Styx Junction. This relationship is non-linear so the use of Figure A6.5 to estimate the salinity for an average year from various percentages of cleared area replanted is recommended.

The criteria used to select land suitable for plantations were probably too conservative. Land capability maps (Appendix A6.1) showed that, of the 503 km^2 of the upper catchment currently cleared, 147 km^2 were suitable for commercial trees (Fig. 28), 150 km^2 is subject to waterlogging (Fig. 29) and other 206 km^2 have ‘poor suitability’ for commercial trees due to shallow to medium rooting depth. However, 1946 aerial photographs showed well-established native vegetation in areas classed as ‘poorly suitable’ and the December 2001 Landsat scene showed about 138 km^2 of plantations on land with ‘too little’ rainfall (the average rainfall < 700 mm) and 73 km^2 on land deemed unsuitable due to restricted rooting depth (Table A6.5). It will be interesting to see how these plantations on ‘unsuitable’ land mature and to assess how realistic the land capability maps are.

6.3 Perennial pastures

High-density shallow-rooted perennial pastures planted on more than 300 km^2 produce a salinity of 550 mg/L TDS. All other perennial-pasture scenarios produced salinities well above 700 mg/L.

Deep-rooted perennial pastures on 147 km^2 produce a salinity range 765–935 mg/L TDS and a flow range 71–72 GL, depending on the leaf density. In comparison commercial trees planted on the same land delivered a much lower salinity (650 mg/L TDS) and a similar yield (71 GL). Shallow-rooted perennial pastures planted on this same land (147 km^2) reduce the salinity to a range 785–955 mg/L TDS and the flow to 69–71 GL.

Shallow-rooted perennials planted on 332 km^2 produce salinity ranging from 550 mg/L to 965 mg/L TDS and flows ranging from 66 GL to 69 GL (Table A6.7) depending on the density of leaf area. Low-density shallow-rooted perennial pastures provided less salinity benefit (965 mg/L TDS) than annual pastures with a higher density (950 mg/L TDS).

High-density and low-density perennial pastures were simulated to account for the intensity of grazing, by representing the density as a percentage of the maximum (winter) LAI for annual pasture (which varies across the catchment and is higher in areas of higher rainfall): low and high were set at 50% and 80% respectively of the maximum annual pasture LAI.

The density of leaves is a critical factor when comparing salinity reductions by perennial pastures with reduction by commercial trees. High-density deep-rooted and shallow-rooted perennial pastures provide

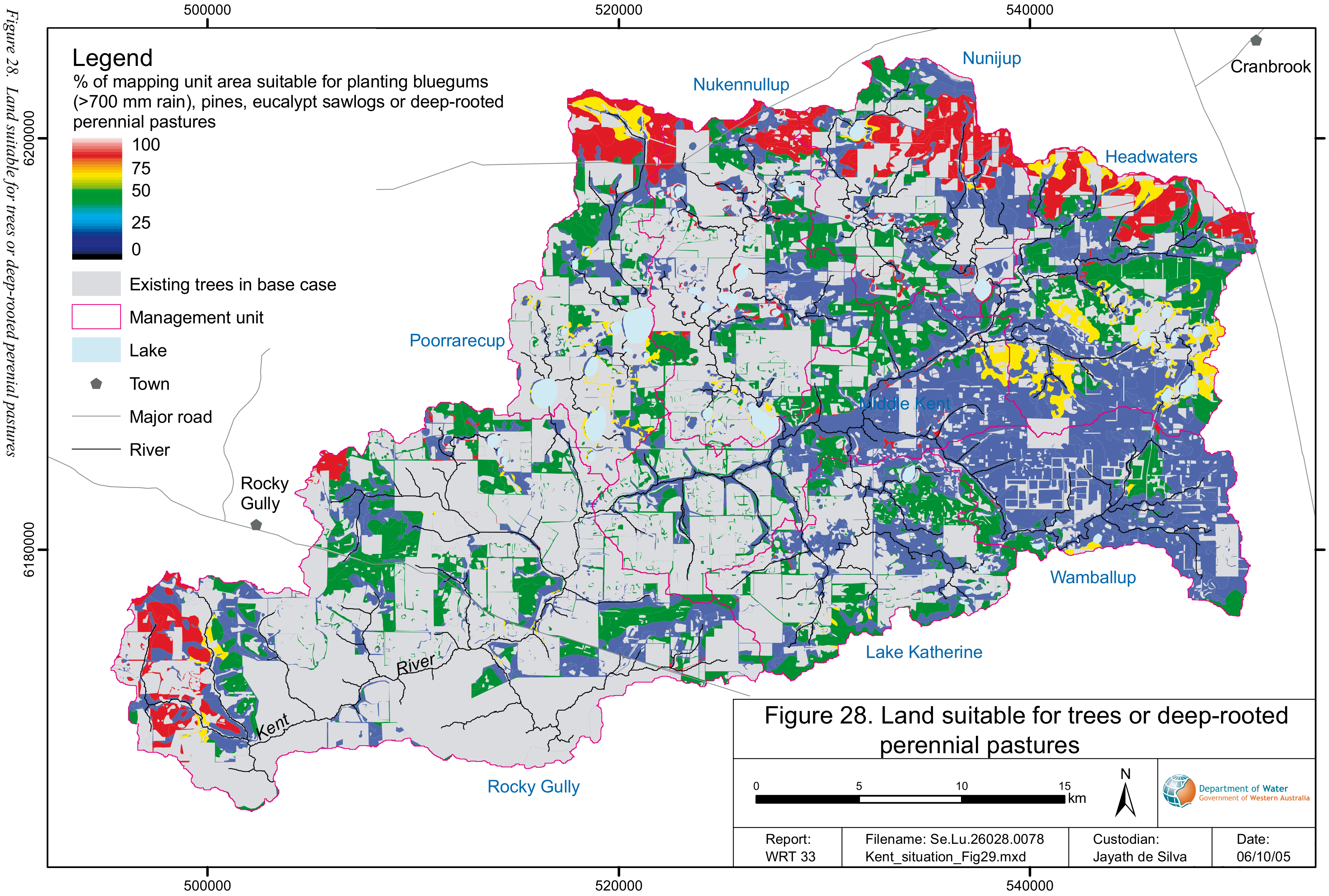

Figure 28. Land suitable for trees or deep-rooted perenial pastures

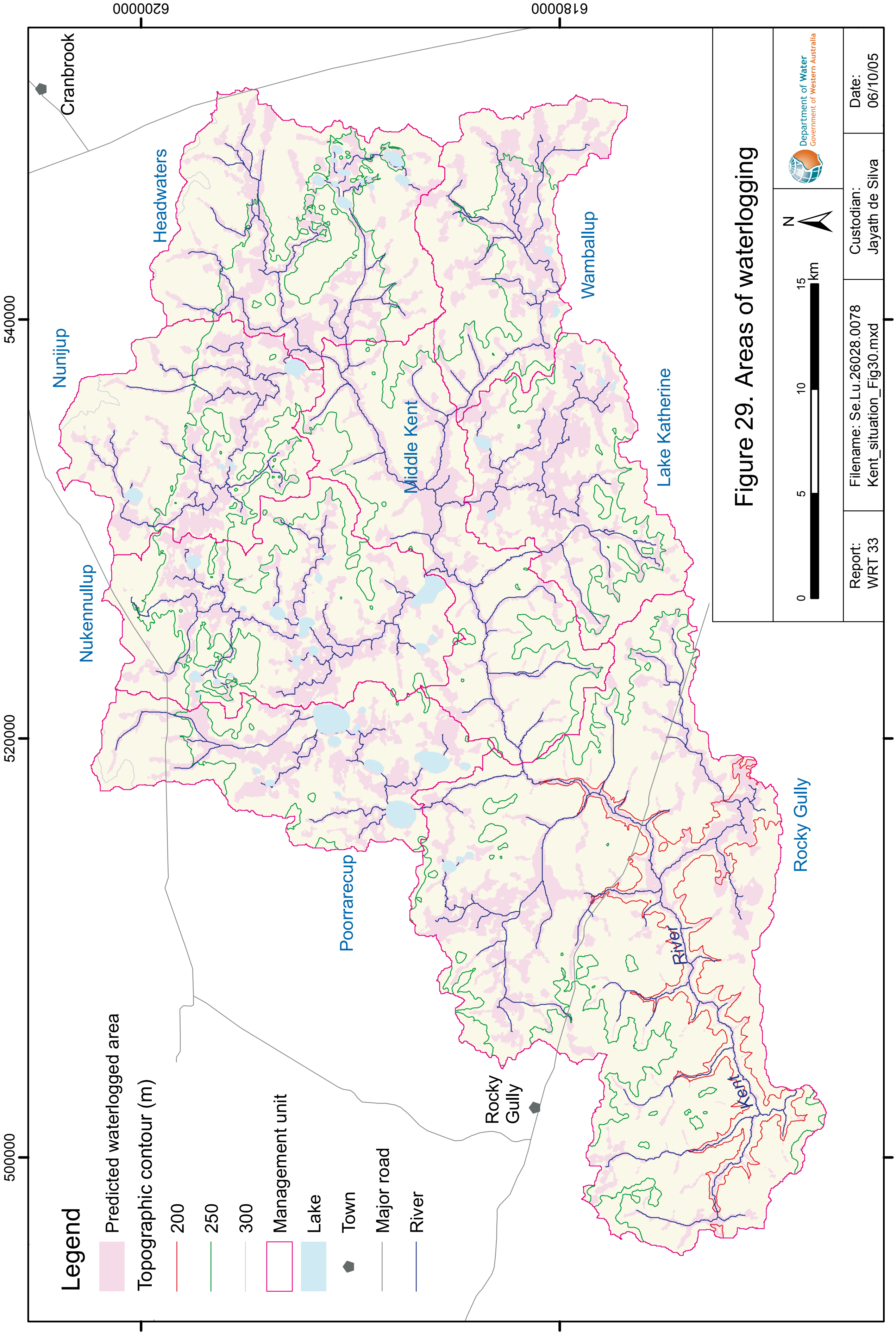

Figure 29. Areas of waterlogging

only 61% and 55% respectively of the reduction by commercial trees. At low density the reductions are minimal.

Shallow-rooted perennial pastures on waterlogged land (150 km^2; Fig. 29) produce a salinity range 900–975 mg/L TDS and a flow range 69–72 GL. If their leaf density is 50% of the LAI of annual pasture in winter they are no better for salinity management than annual pastures.

'No waterlogging' and 'unrestricted rooting depth' were the main land suitability criteria for estimating the areas suitable for the perennial pastures (Fig. 30). See Appendix A6.1. Deep-rooted perennial pastures could be planted on the same 147 km^2 as the commercial trees. An additional 185 km^2—with shallower soil depth—were suitable for shallow-rooted perennials (total of 332 km^2).

6.4 Engineering options

Groundwater pumping and diversion of saline water from the upper catchment could achieve the target. Neither shallow nor deep drains provided a salinity benefit for river water.

6.4.1 Groundwater pumping

A salinity of 560 mg/L TDS could be achieved if 3.56 GL of water is pumped annually using 650 bores (Table A6.17). This would require approximately 208 km of collector pipes and 110 km of transport pipes inside the catchment (Fig. 31) with additional transport pipes needed to carry the discharged groundwater to disposal sites inside or outside the catchment.

The pumps were assumed to collect 50% of the groundwater discharged in the catchment and the streamflow was assumed to decrease by the volume of water pumped. A conceptual layout of collector and transport pipes was designed manually using a map of seepage areas as a guide (Fig. 31). Collector pipes run through most of the major seepage areas generated in the pasture areas of the 'Base' case. Bores, each pumping about 15 kL/day, are about 400 m apart along the collector pipes joined by transport pipes to form a network that drains to three discharge points. Some crude assumptions were made to estimate the effects of groundwater pumping.

The main pipe network finishes collecting discharge at the site of the Rocky Glen gauging station. How best to divert or evaporate the drainage water was not considered in this study. The discharge points should be reviewed to ascertain that a low flow of brackish water would be environmentally acceptable at those locations. Discharge to evaporation ponds within the catchment at sites that could not overflow to the river drainage channels could also be considered.

No bores were placed in the Nunijup, Nukennullup and Poorrarecup management units since the flows and salt loads generated there did not contribute to the main stream of the Kent River. The high transmissivity of palaeochannels in the broad flats and drainage lines should be taken into account if a groundwater pumping network is designed in the future.

6.4.2 Diversion

Diverting 100% of the flow (and salt load) from the Rocky Glen gauging station reduces salinity to 350 mg/L TDS (Appendix 6.5). Diverting 59% reduces salinity to 500 mg/L TDS (Table 8).

Based on records and contour data at the diversion site, the diversion dam would need to be able to hold back 3.6 times the mean annual flow at this point on the river (or 96.5 GL) which would require a wall height of approximately 22.5 m and could inundate 16 km^2 of land when full (Fig. 32 & Table 9). Further information on analysis is in Appendix A6.5.

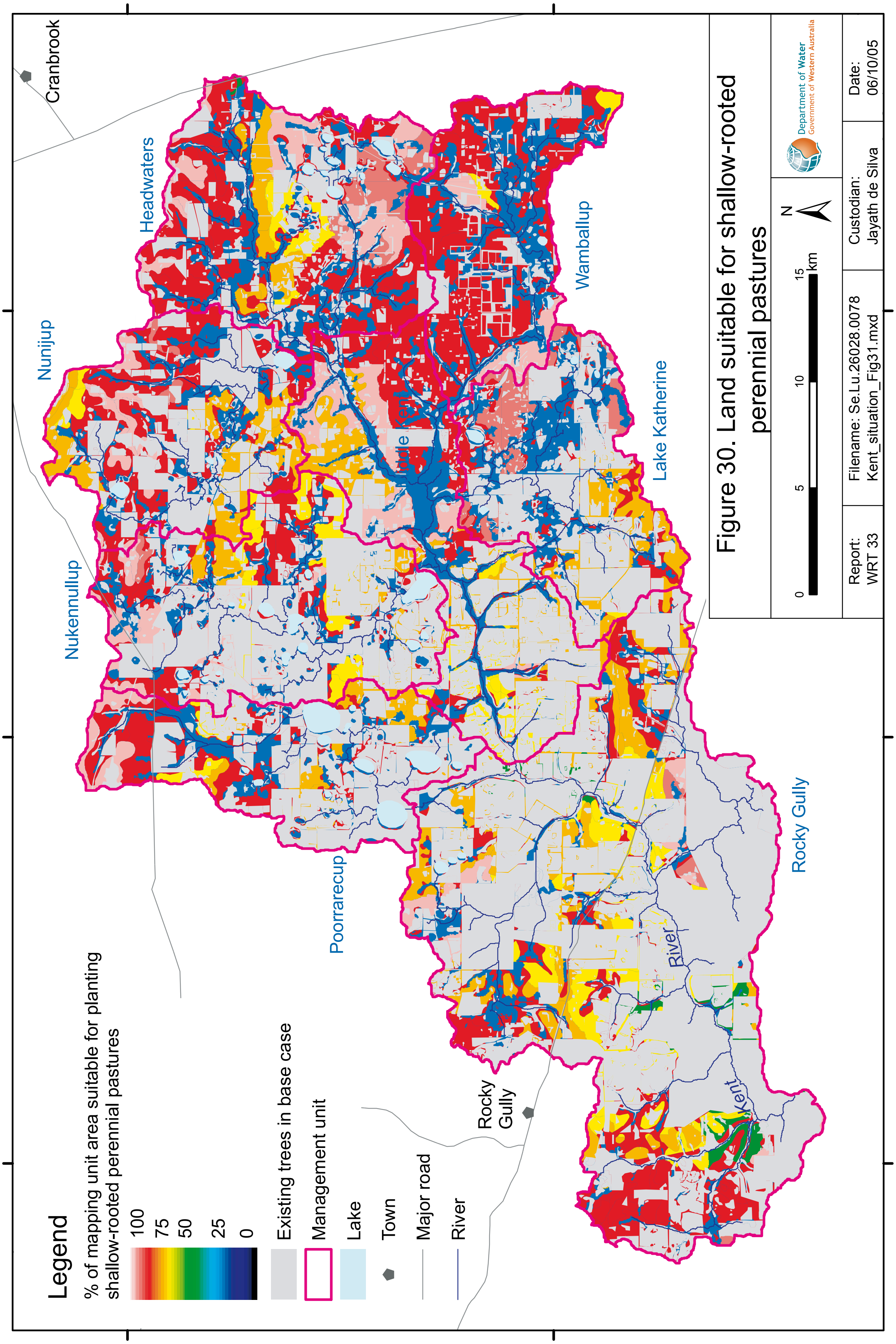

Figure 30. Land suitable for shallow-rooted perennial pastures

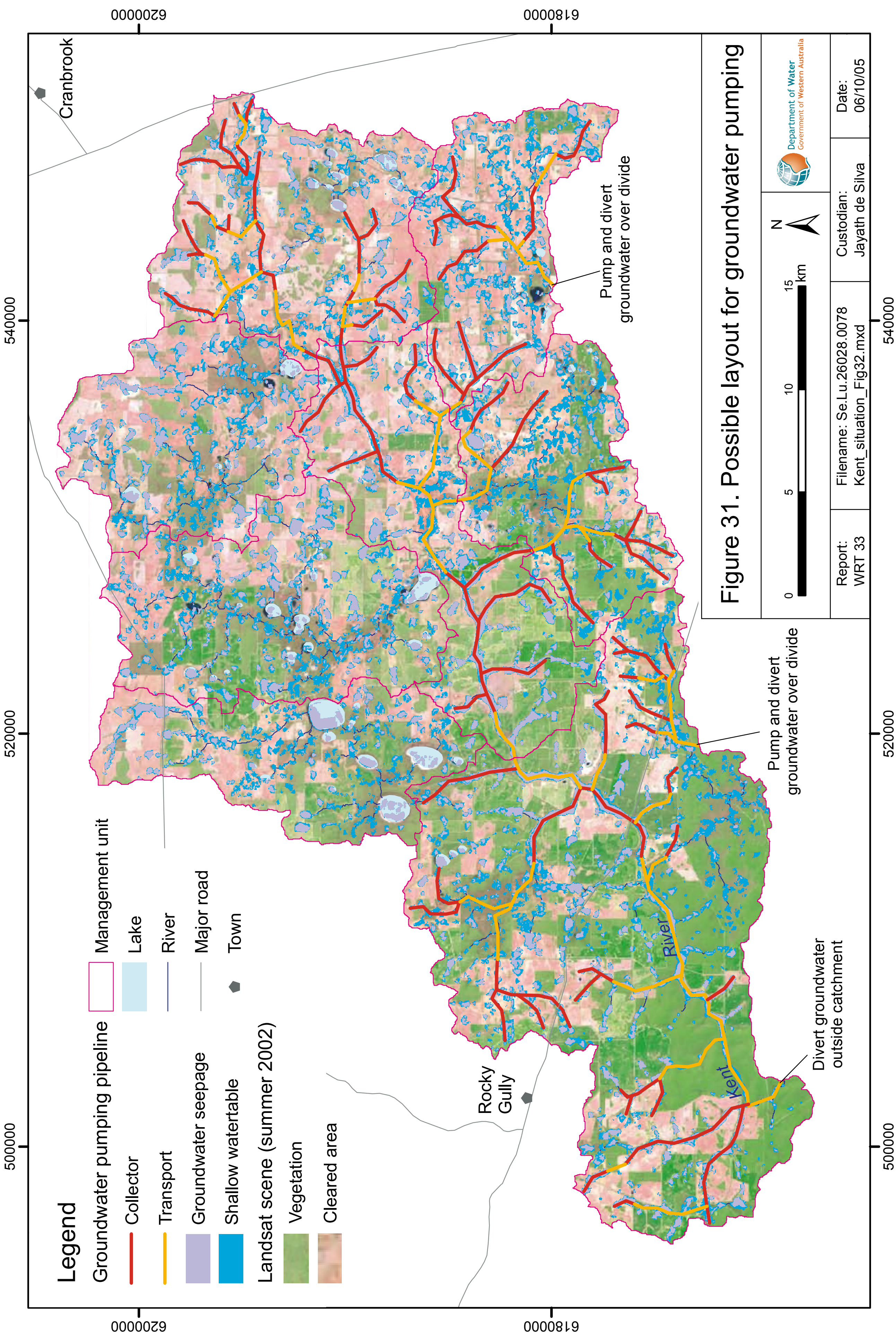

Figure 31. Possible layout for groundwater pumping

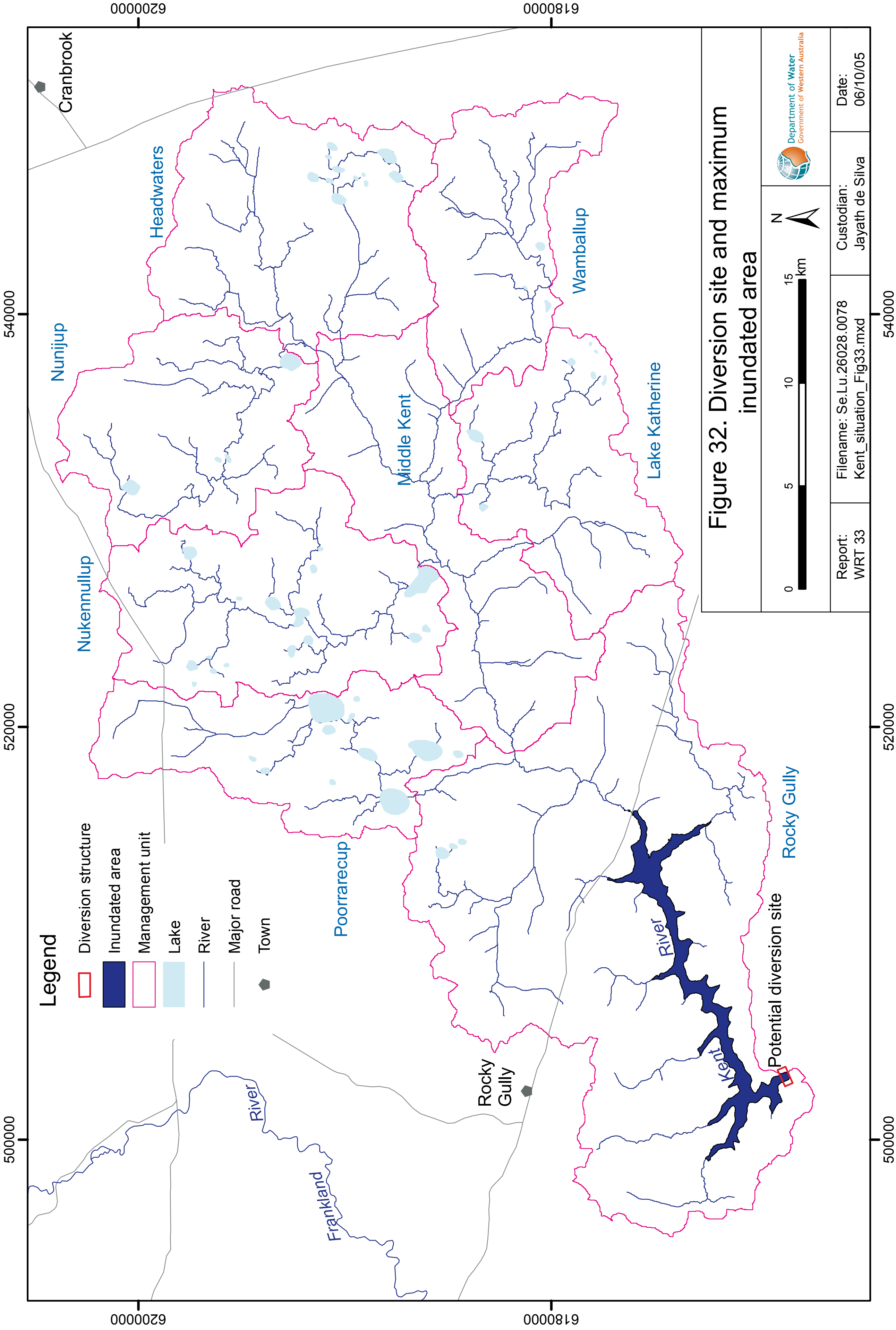

Figure 32. Diversion site and maximum inundated area

Table 9. Diversion site characteristics

Characteristic	**Upper Kent catchment**
Catchment area (km^2)	1090
Mean annual flow (GL)[a]	27.0
Mean annual salt load (kt)[a]	82.1
Diversion storage volume at FSL (GL)[b]	102
Inundated area at FSL (km^2)[c]	16
Dam wall height (m)[d]	22.7

[a] The mean annual flow and load figures are quoted for the entire record at Rocky Glen gauging station.
[b] The final dam storage volume includes 5 GL of dead storage.
[c] Full Supply Level (FSL)
[d] The final dam wall height includes 2 m of freeboard.

Partial streamflow diversions would require smaller diversion structures that are easier to establish and maintain and could be used as combination tools to manage salinity. Diversions of this size would require the use of pipehead dams which work on the principle that only flows equal to or less than the pump capacity are diverted while the rest of the streamflow continues downstream.

The Public Works Department (PWD) explored the possibility of diverting saline water from the Upper Kent as early as 1980 (Public Works Department 1980), located a potential diversion site on the Kent River at Rocky Glen, proposed a route for disposal of the diverted water to the Frankland River, and outlined some limitations in proceeding with such a plan. A recent study that included the cost and size of a lined canal to take water from the Upper Kent catchment to the ocean (Winter 2000) estimated that a 60 km canal would cost about $4.85 million.

6.4.3 Drains

Drains do not lower the salinity of the river water.

Construction of 3340 km of drains is predicted to increase salinity from 950 to 1010 mg/L TDS (Table A6.7). The combined drain discharge would increase the streamflow at Rocky Glen by 1% and the salt load by 5%. The volume of water collected would be, on average, 5.8 kL/km per year from shallow drains and 26 kL/km per year from deep drains. The groundwater discharge collected in the drains would be, on average, 0.88 kL/km per year for shallow drains and 4.2 kL/km per year for deep drains.

In total, 3031 km of shallow drains (1 m deep) and 309 km of deep drains (2 m deep) were simulated. The drain depths were limited to the thickness of the topsoil where this layer was thinner than the required depths.

6.5 Combining options

The effects of combinations of revegetation and engineering options can be estimated using some assumptions. See Appendix A6.6 for more information.

7 Conclusions

The salinity of the Kent River is predicted to reduce from 1480 mg/L TDS to 950 mg/L TDS (marginal quality) with no further land-use changes in the catchment.

The current salinity situation for the Kent River is:

- Mean annual (1990–2002) salinities of the Upper Kent River (Rocky Glen) and the Kent River (Styx Junction) are 3180 mg/L TDS and 1480 mg/L TDS respectively.
- Mean annual salinity of the Kent River (Styx Junction) is still rising but the rate of rise has fallen from 43 mg/L TDS (1983–90) to 12 mg/L TDS (1991–98). The mean annual salinity of the Upper Kent River (Rocky Glen) is also still rising but the rate has fallen from 81 mg/L TDS (1983–90) to 14 mg/L TDS (1991–98). This large slowing of the rate can be attributed to extensive bluegum plantations established in the upper catchment, clearing controls and climate change.
- About 30% of the upper catchment has a shallow watertable (within 2 m of surface). About 70% of groundwater monitoring bores show steady or declining groundwater levels. Groundwater levels near bluegum plantations have fallen as much as 5 m.
- The MAGIC steady-state model estimates that about 153 km^2 of the upper catchment area is at risk of salinisation.
- The upper catchment contributed about 84% of the salt load in 39% of the streamflow to the 73 GL streamflow and 108 kt salt load of the Kent River at Styx Junction during the period 1990–2002. The catchments draining to Perillup Road and Watterson Farm contributed 41% and 15% of the salt load and 11% and 4% of the flow respectively.
- Lakes Nunijup, Carabundup and Poorrarecup form internally draining lake systems. About 321 km^2 of the area in the Nunijup, Nukennullup and Poorrarecup management units that drain into these lakes have contributed no streamflow or salt load to the main channel of the Kent River since 1973, apart from one overflow of Lake Nunijup in 1982 following a summer thunderstorm. Water seeping through the lake beds may discharge as groundwater into the Kent River.

Some of the results relating to catchment management are:

- When the Kent River catchment reaches a new hydrological equilibrium in response to existing land use, mean annual stream salinity is predicted to be 950 mg/L TDS.
- Planting trees (bluegums, pines and sawlogs) on the 147 km^2 of suitable land could reduce the salinity to 650 mg/L TDS.
- Planting all of the existing cleared area (503 km^2) with trees, irrespective of land suitability, will reduce mean annual salinity to 330 mg/L TDS.
- To reach the potable quality target of 500 mg/L TDS would require replanting trees on 309 km^2 of the cleared land in addition to those planted by 2002.
- Planting deep-rooted perennial pastures at high leaf density (i.e. only allowing light grazing) on the 147 km^2 of suitable area will reduce salinity to 765 mg/L TDS. Shallow-rooted perennial pastures at high density on the 332 km^2 of suitable land could lower stream salinity to 550 mg/L TDS.
- Pumping groundwater (3.6 GL a year from 650 bores) reduces salinity to 560 mg/L TDS.

- The full diversion of saline water by building a dam near the Rocky Glen gauging station would reduce salinity to 350 mg/L TDS. Diversion of 59% of the saline flow would achieve the target 500 mg/L TDS.
- Shallow or deep drains do not reduce river salinity.
- A variety of combined management options could be derived from the tree, perennial pasture and engineering options modelled.

8 Recommendations

Management options

- Assess the suitability of commercial tree plantations. Issues to be addressed include encouraging new rotations after harvesting and maintenance of soil fertility.
- Investigate the practicality and design requirements of groundwater pumping in the upper catchment based on current trials at Maxon Farm in the Collie Recovery Catchment.
- Estimate the recharge responses of shallow-rooted and deep-rooted perennial pastures.
- Maintain a database of information of harvesting bluegum plantations. Ascertain the long-term suitability of existing commercial plantations on land assessed as having ‘low suitability’ for trees.
- Evaluate the possible effects of climate change on the management options and the time taken to reach hydrological equilibrium.

Monitoring and evaluation

- Continue monitoring streamflow and salinity at the four mainstream gauging stations to confirm the current trends in salinity and also to evaluate on-ground works in the catchment.
- Continue the groundwater monitoring program and expand to accommodate perennial pasture sites.

Glossary, acronyms and units

Aquifer	A geological formation or group of formations able to receive, store and transmit significant quantities of water
Aquitard	A geological formation of low-permeability that can store groundwater and transmit it slowly from one aquifer to another
Evaporation	The vaporisation of water from a free-water surface above or below ground level, normally measured in millimetres
Evapotranspiration	A collective term for evaporation and transpiration
Gigalitre (GL)	1 000 000 000 litres, 1 million cubic metres or 220 million gallons
Greenness	The percentage of a pixel in a Landsat TM image that has sunlit green leaves
Groundwater level	An imaginary surface representing the total head of groundwater and defined by the level to which water will rise in a piezometer
Hectare (ha)	10 000 square metres or 2.47 acres. 100 ha = 1 square kilometre
Kilolitre (kL)	1000 litres, 1 cubic metre or 220 (approx.) gallons
LAI	Leaf Area Index, which is the ratio of single-sided area of leaves to the area of land occupied by the plants. It is used as a surrogate measure of water use
m AHD	Australian Height Datum. Height in metres above Mean Sea Level +0.026 m at Fremantle
Piezometer	A tube that is inserted in a small diameter bore drilled into an aquifer to monitor water pressure within the aquifer
Recharge	The downwards movement of water that is added to the groundwater system
Regolith	Geological material from fresh rock to the ground surface
Salinity (specific)	The concentration of total dissolved salts in water
Salinity (general)	Term applied to effects on land and in water of the build up of salt in the surface as a result of rising groundwater
TDS (mg/L)	Total dissolved salts expressed as milligrams per litre
Transpiration	Process by which water vapour is lost from the stomata (pores) of leaves

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Appendix 1 Kent–Denmark Recovery Team

The Kent–Denmark Recovery Team formed in September 1998 to oversee the 'recovery' of water quality to potable levels in both rivers.

The Team is a partnership between the community of the Kent and Denmark River catchments and key government agencies and originally comprised 12 landholders actively farming in the catchments. The balance of the Recovery Team is made up of representatives from the major Natural Resource Management agencies, including the Department of Water (formerly the Department of Environment or Water and Rivers Commission), Department of Agriculture and Food (formerly the Department of Agriculture) and the Department of Environment and Conservation (formerly the Department of Conservation and Land Management). The landholders are selected to represent their subcatchments because of their community standing and leadership. The local governments of Plantagenet and Cranbrook are represented by council members residing in the catchments (Table A1.1).

The National Dryland Salinity Program of the Land and Water Resources Research and Development Corporation invested resources in the Kent Catchment to develop techniques to understand landscape salinity over a period of four years from 1995 to 1998. Several members of the Recovery Team were also members of the Steering Team that oversaw the Focus catchment program. The outcomes of that phase were applied in catchments across Australia.

Appointment to the Team was originally by invitation with the endorsement of the Board of the Water and Rivers Commission. The Team still has most of its inaugural members.

Table A1.1 Current members of the Kent–Denmark Recovery Team

Member	Role	Affiliation	Management Area
Lyn Slade	Chairman	Farmer	Wamballup
Brian Bunker	Vice chairman	Farmer	Nukennulup
John Gillam	Member	Farmer	Nunijup
Norm Beech	Member	Farmer	Middle Kent
Ron Watterson	Member	Farmer	Headwaters
Bruce Parsons	Member	Farmer	
		Chairman, Kent River LCDC	
Murray Hall	Member	Farmer	Lake Katherine
Joan Cameron	Member	Farmer	Rocky Gully
		Vice President, Plantagenet Shire	
Dean Trotter	Member	Farmer	Perillup
Michael Jenkins	Member	Farmer	Denbarker
		Member, Wilson Inlet Catchment Committee	
John Blake	Member	Program Manager, Sustainable Rural Development, DAFWA	
Peter Bidwell	Member	District Manager, DEC	
Naomi Arrowsmith	Member	Regional Manager, South Coast, DoW	
Brett Ward	Executive officer	Manager — Western District, DoW	

Other attendees

Depending on the business at hand, others are invited to attend meetings to brief the Team. On several occasions the Team has hosted forums to inform the catchment community of its activities and seek feedback.

As government and community consciousness of the need to more closely manage the land and water quality of Western Australian catchments increased, the Landcare movement of the 1980s and 1990s led to federally-funded catchment and property plans being prepared in the Denmark River catchment in 1992. The Department of Agriculture principally coordinated this activity. Implementation of the plans was seen as the obligation of the landholders although some federal funds were available for soil conservation and protection of native vegetation.

The Water Authority and Department of Conservation and Land Management, who funded experimental plantations and provided funding incentives to landholders to plant bluegums, assisted the establishment of the fledgling bluegum plantation industry in the upper Denmark. This early work quickly led to the establishment, by private investors, of bluegum plantations that led to a significant change in land use in the Upper Denmark catchment and contributed to improved water quality as salinity declined.

Building on the foundations of an earlier strategic planning and development phase as a National Dryland Salinity Program Focus Catchment, the Recovery Team has set about implementing key recommendations of its Integrated Catchment Management Plan.

These recommendations include:

- Develop property plans for all landholders.
- Form of an overarching group to guide the implementation of the ICM.
- Adopt and implement the strategy for the ICM Plan by 2010.
- Develop a communication strategy.
- Prepare subcatchment plans.
- Implement a foreshore protection works program.

The Team has achieved considerable success over the past seven years engaging the wider catchment community to implement on-ground works necessary to manage salinity.

Appendix 2 Catchment characteristics

Table A2.1 Soil–landscape systems of the upper catchment

Symbol	Name	Landform	Soil types	Geology	Vegetation
Ke	Kent System	Undulating lateritic plains with lakes and poorly drained flats	Duplex sandy gravels with semi-wet soil, shallow gravel and grey deep sandy duplex	Tertiary alluvium, colluvium and sand with laterite, and quaternary lake and swamp deposits	Wandoo–yate–flooded gum–jarrah–marri woodland and paperbark heath
Ca	Caldyanup System	Poorly drained flats with scattered rocky rises	Wet and semi-wet soils, loamy gravels and pale and yellow deep sands	Alluvium over granitic rocks	Sedges, mixed heathland, paperbark woodlands and jarrah–marri forest
Pp	Perup Plateau System	Lateritic plateau with broad swampy depressions	Loamy gravels, duplex sandy gravels, loamy gravels and wet soils (sometimes saline)	Deeply weathered mantle over granitic rocks	Jarrah–marri–wandoo forest and woodland
Rh	Roe Hills System	Hilly terrain with rock outcrops	Loamy gravels, duplex sandy gravels, brown deep loamy duplexes and friable red/brown loamy earths	Colluvium over granitic rocks	Jarrah–marri forest and woodland
Ya	Yaraleena System	Undulating low rises	Duplex sandy gravels, shallow and deep sandy duplexes, deep sandy gravels, loamy gravels and gravelly deep sands	Laterite and colluvium over granitic rocks	Jarrah–marri–wandoo woodland
St	Stirling Range System	Hills and mountains with steep rocky peaks separated by plains	Stony soil and duplex sandy gravel with grey deep sandy duplex	Colluvium over sandstone and shale, with laterite and sand	Mallee scrub and heath, with woodland in protected valleys

Table A2.2 Subsystems and phases of the Kent soil–landscape systems

Symbol	Name	Description
KeCM	Camballup subsystem	Swampy plains with some broad drainage lines and salt lakes
KeCMp	Camballup plains phase	Swampy plains with some broad drainage lines and lakes
KeCMw	Cambellup wet phase	Areas of permanent and ephemeral lakes and swamps with lunettes; Semi wet soil with duplex sandy gravel, red deep sands and deep sandy gravel
KeKDh	Kidman valley phase	Upper reaches of the Kent River; granitic basement rock; Shallow gravel with saline wet soil and grey deep sandy duplex
KeKDt	Kidman terrace phase	Broad floor of upper Kent River, usually saline; granitic basement rock; Saline wet soil with duplex sandy gravel soil
KeMW	Mallawillup subsystem	Undulating rises with broad flat swampy depressions; Soils are formed in colluvium and weathered granite; Gravelly soils (bog iron ore) are common
KePP	Perillup plain subsystem	Gently undulating plain with some swamps
KeQN	Quindabellup subsystem	Shallow, elongate sandy depressions and valley divides; Humus podzols and sandy yellow duplex soils; Paperbark woodland
KeCOp	Collis shallow gritty yellow duplex phase	Shallow gritty yellow duplex soils; Jarrah-Bullich woodland
KeNYd	Naypundup downstream phase	Low relief (< 20 m) valleys; Saline in some areas; Soils are formed in weathered colluvium from gneiss
KeNYu	Naypundup upstream valley phase	Low relief (< 20 m) valleys; Saline in some areas; Soils are formed in weathered colluvium from gneiss.
KeSC	Sidcup subsystem	Narrow shallow drainage depressions; Deeply weathered granite; Deep sands, grey shallow sandy duplex

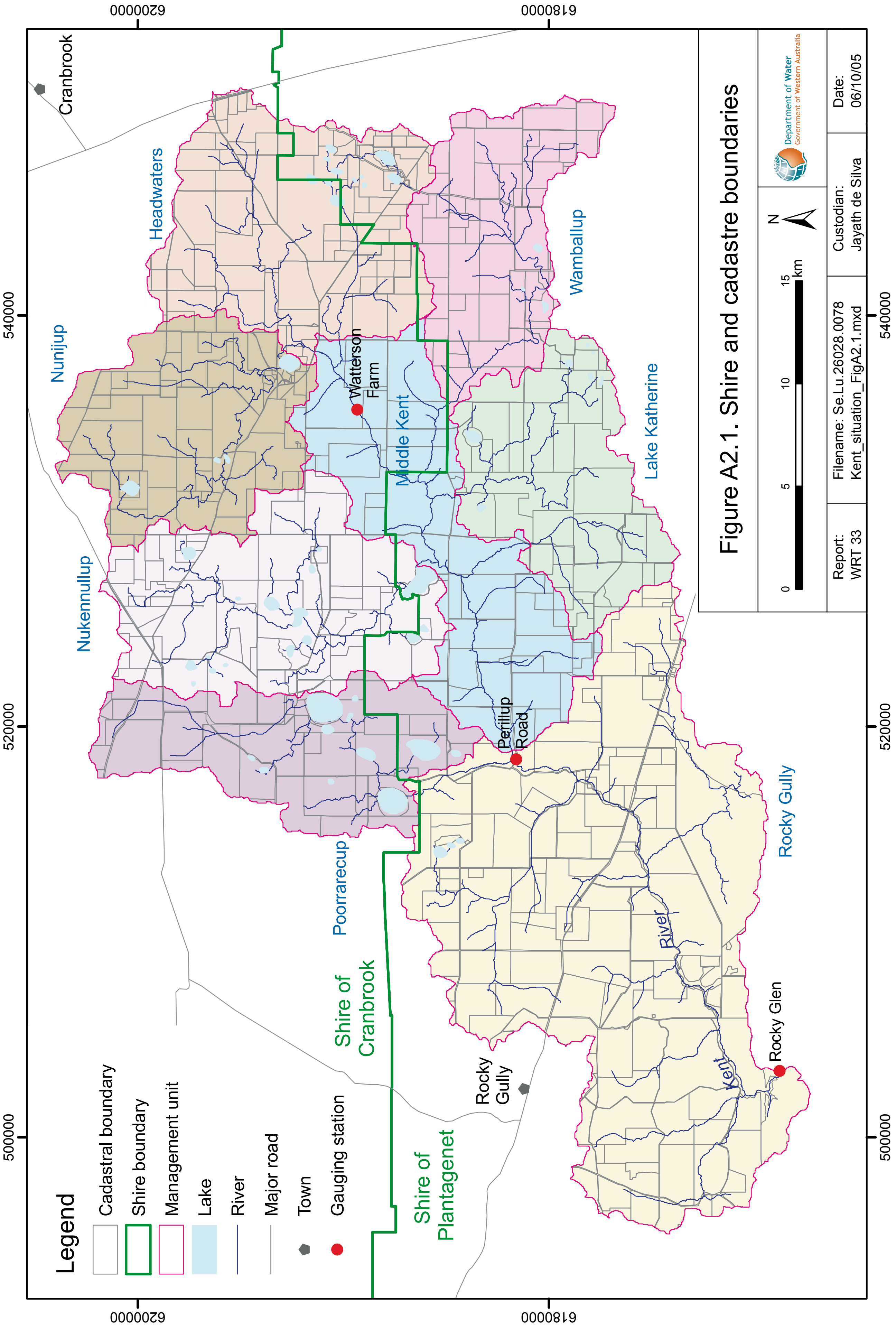


Figure A2.1 Shire and cadastre boundaries

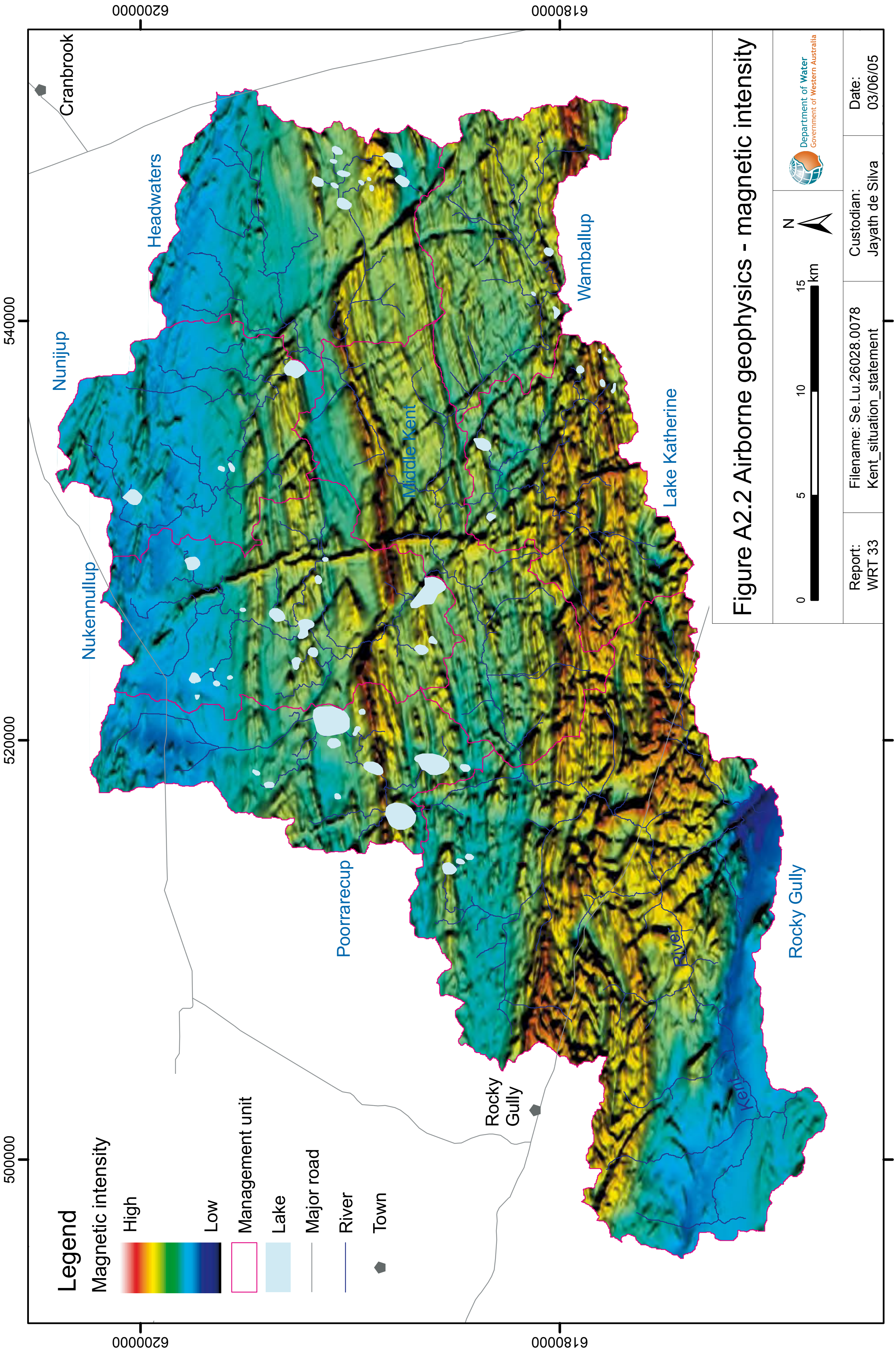


Figure A2.2 Airborne geophysics—magnetic intensity

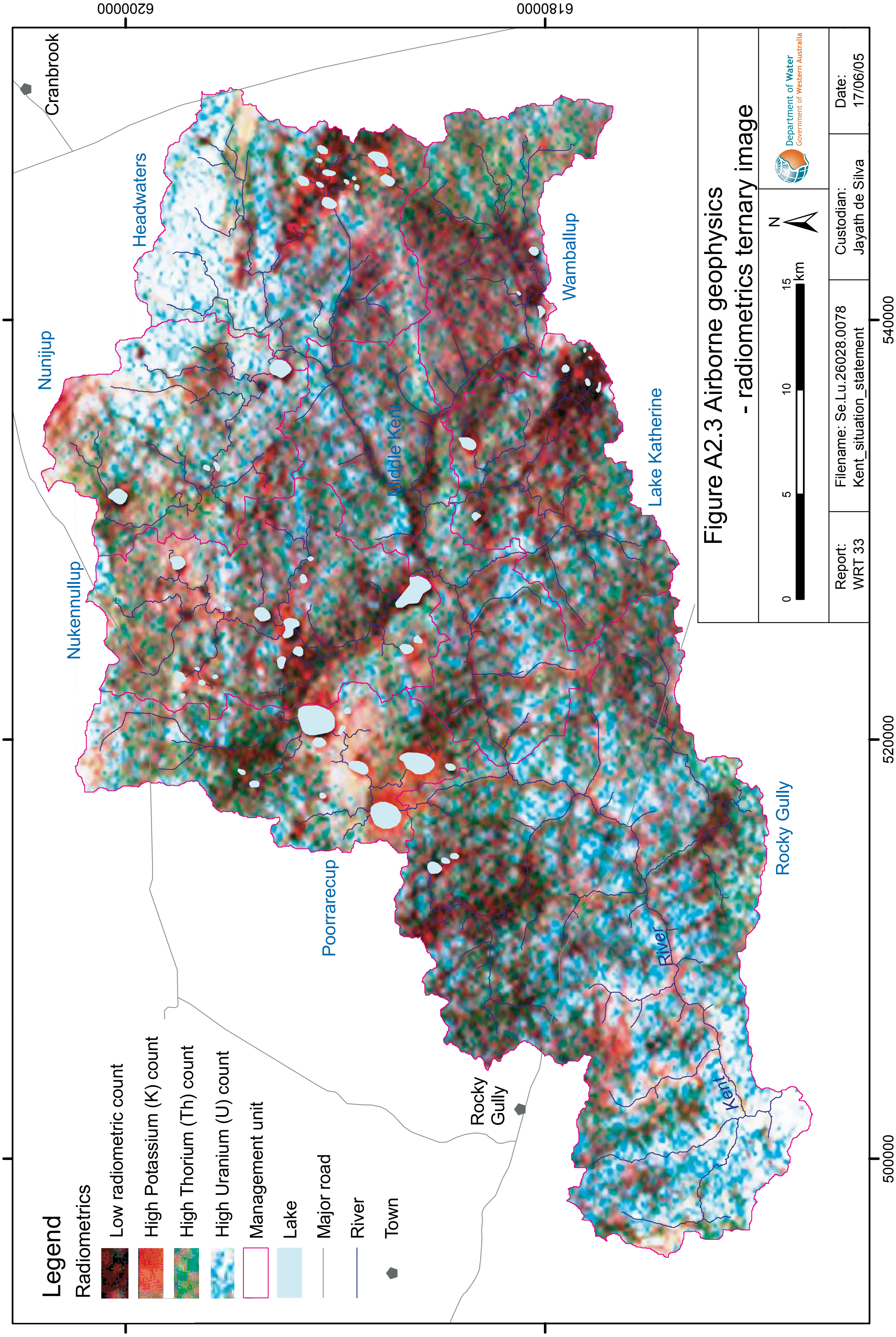


Figure A2.3 Airborne geophysics—radiometrics ternary image

Appendix 3 Land use

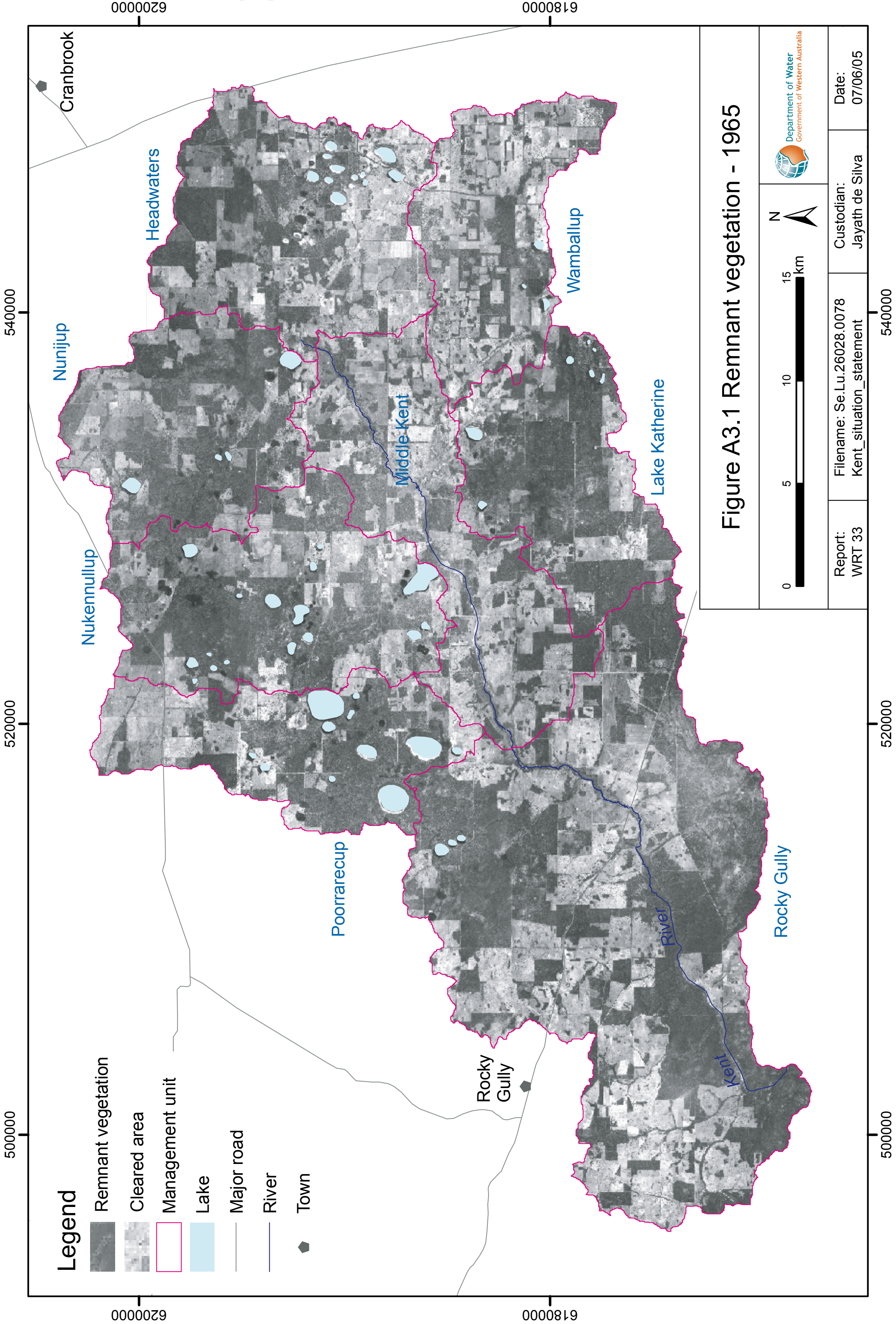


Figure A3.1 Remnant vegetation in 1965

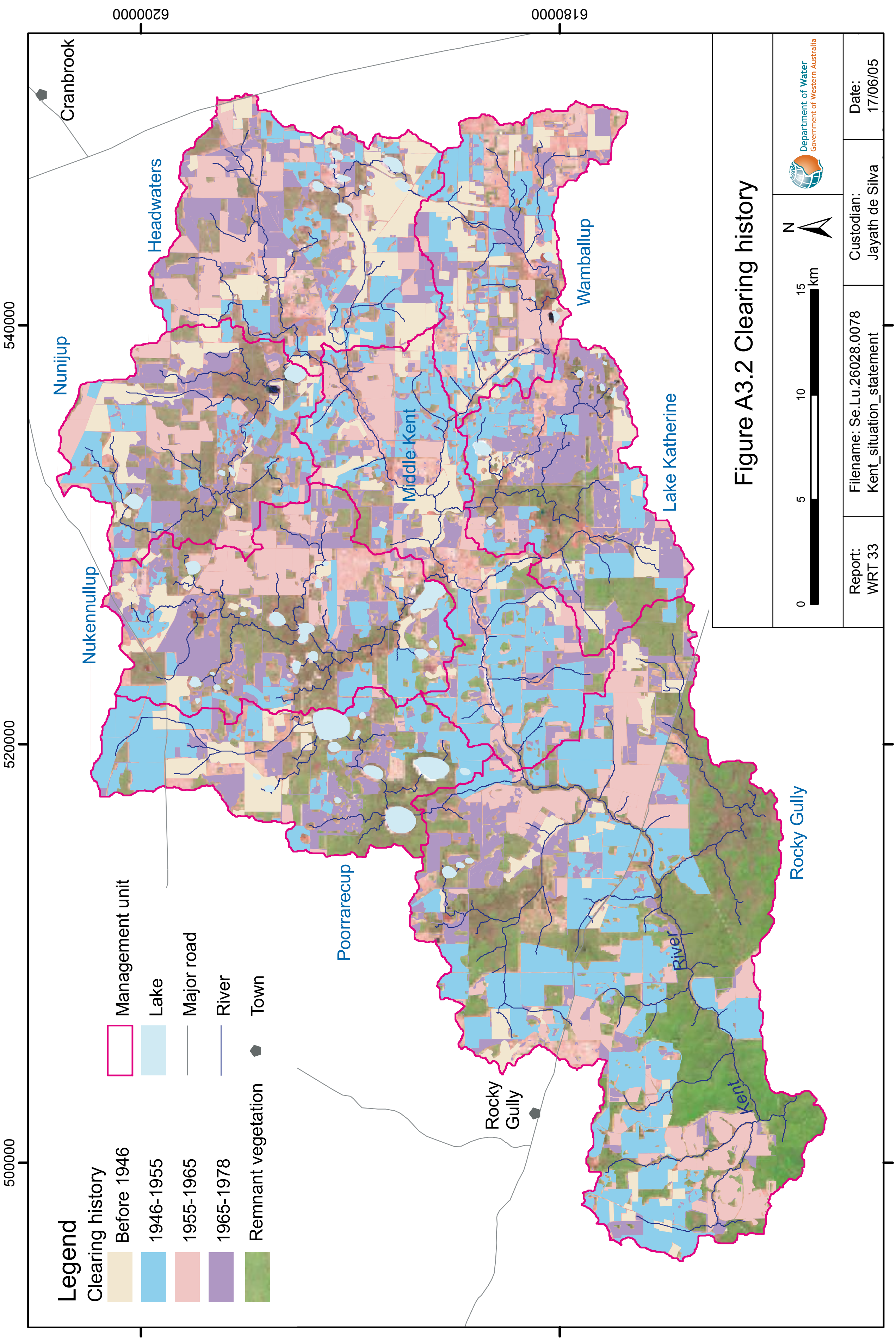


Figure A3.2 Clearing history

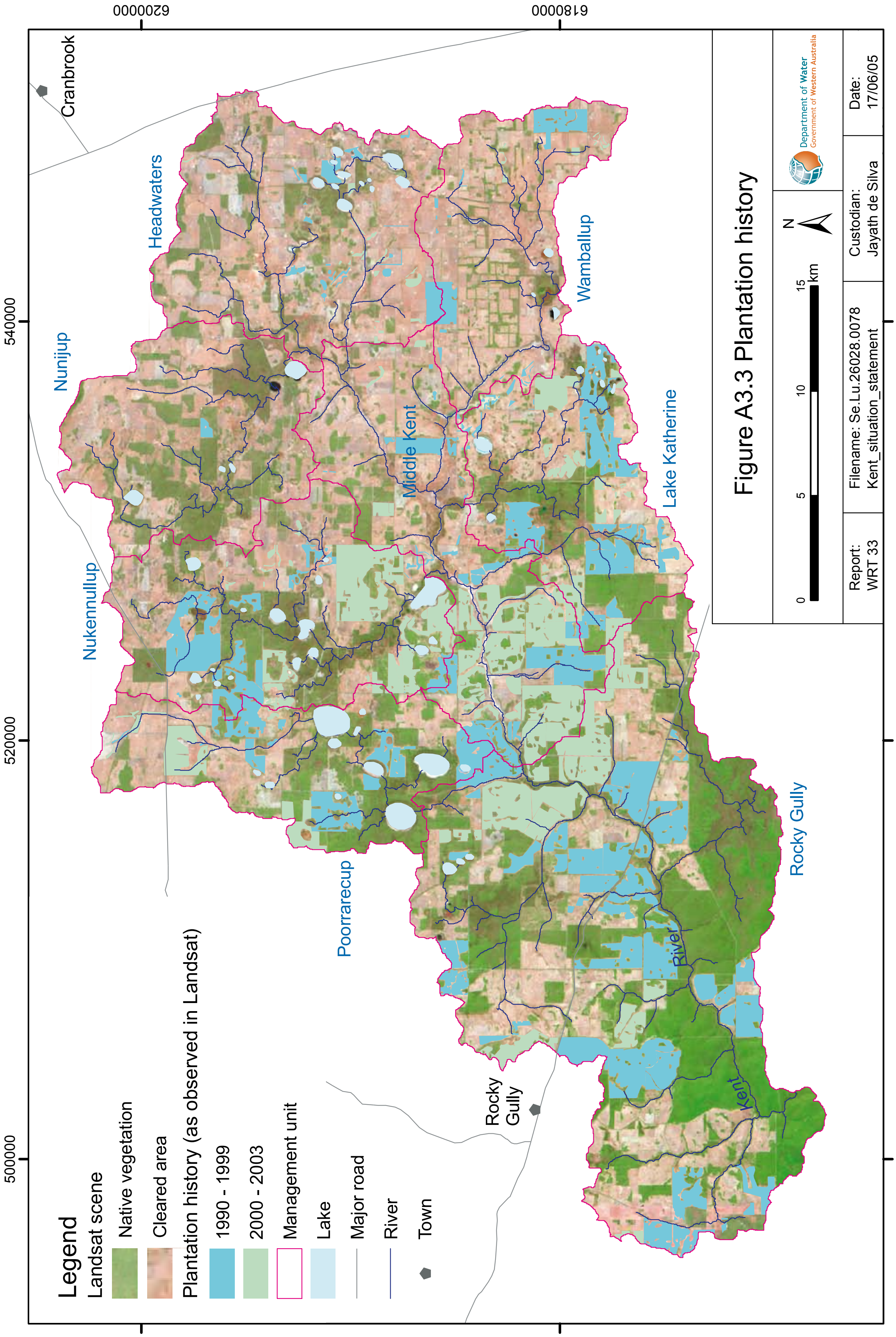


Figure A3.3 Plantation history

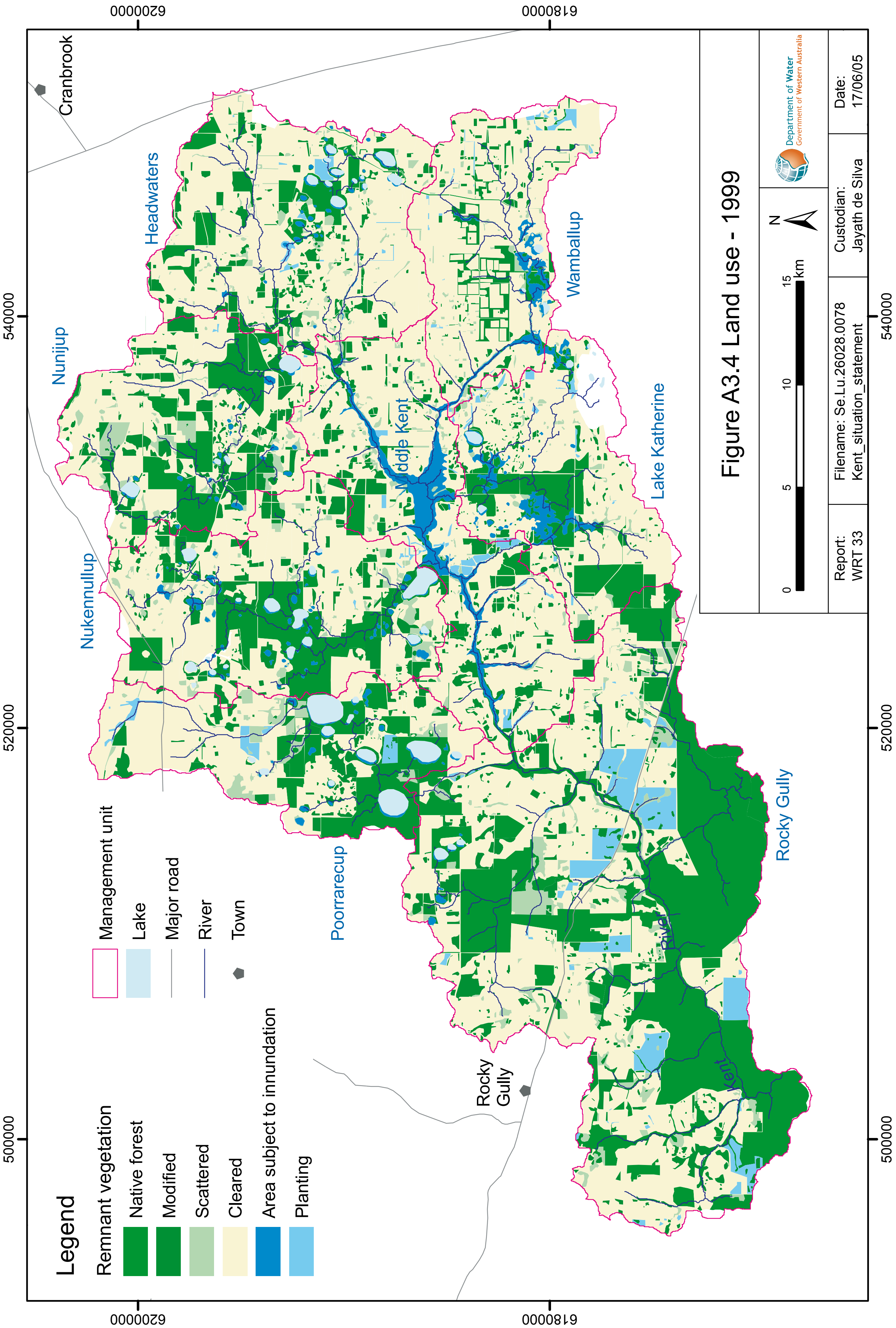


Figure A3.4 Land use — 1999

Appendix 4
Salinity and flow-analysis methodology

Surface water data analysis

The methods detailed below were used when analysing the streamflow, salinity and salt loads of the two gauged subcatchments in the Upper Kent.

The Rocky Glen gauging station has operated since 1979 with continuous streamflow, uncompensated conductivity and water temperature measurements taken at the gauge since this time. (Uncompensated conductivity and water temperature are then used in the calculation of salinity values in mg/L TDS). The Styx Junction gauging station opened in 1956, and has maintained continuous streamflow recording from this time. Continuous uncompensated conductivity and water temperature recording did not begin at the station until 1979. Prior to this, the salinity values at Styx Junction gauge were obtained using a point sampling method for uncompensated conductivity and water temperature at approximately fortnightly intervals. Before calculating trends in annual stream salinity, a daily salinity record for the period 1956 to 1979 at Styx Junction was calculated based on the following method.

Stream salinity is inversely proportional to streamflow; that is, during periods of high streamflow the average stream salinity tends to be low and during low flows the average stream salinity tends to be higher. The relationship between a point salinity sample (S_s) and its associated daily streamflow (F_d) can be described as:

$$S_s = a'F_d^{\,b'} \qquad \textit{(Equation A4.1)}$$

In the above equation the values of the two parameters (*a', b'*) were determined using an interpolation process. Five point samples at a time were used to develop the relationship. As the relationship between the salinity and streamflow changes due to significant changes in land use, the values of these two parameters were different with different sets of interpolations. From Equation A4.1, the daily salinity for the period without continuous record was calculated for the gauging station.

Having obtained these figures, the daily salinity, salt load and streamflow records were then summed to get the annual flow (F), salinity (S) and salt load (L) values for both gauging stations. The annual rainfall (R) for each subcatchment was also calculated.

Next, the annual relationships between: (i) streamflow and salinity, and (ii) streamflow and rainfall for both gauging stations were developed. In the first case, nine years of data were taken at a time and values of the parameters a'' and b'' were determined (Equation A4.2). Similarly, in the streamflow/rainfall case, nine years of data were used each time to determine the values of parameter c and d (Equation A4.3). The values of these parameters also changed with time due to changes in land use of the catchment. The annual relationships can be described as:

$$S = a''F^{b''} \qquad \textit{(Equation A4.2)}$$

$$F = c + dR \qquad \textit{(Equation A4.3)}$$

Based on the parameters of Equation A4.3, values of annual streamflow F_r under mean annual rainfall ($\overline{R}$) conditions for the duration of the trend analyses (1980–95) were determined:

$$F_r = c + d\overline{R} \qquad \textit{(Equation A4.4)}$$

The annual stream salinities (S_f) at mean annual streamflow ($\overline{F}$) were also calculated for the analysis period:

$$S_f = a''\overline{F}^{b''} \qquad \textit{(Equation A4.5)}$$

The annual salt loads at mean flow (L_f) are calculated as:

$$L_f = S_f \overline{F} \qquad \textit{(Equation A4.6)}$$

The annual stream salinity at mean flow (S_f) figures for each gauging station were obtained from Equation A4.5 and then plotted against an annual time-step. As nine years of data were used to calculate each set of parameters, the first date for salinity at mean flow is 1983, five years after the starting year of the analysis. This does not imply that the years 1979 to 1982 are excluded, as the information from these years is used to obtain the a'' and b'' parameters which are then used to calculate the 1983 salinity at mean flow figure.

After inspecting all of the resulting plots of annual salinity at mean flow a linear regression equation was developed for the periods 1983–90 and 1991–98 to quantify the change in the rate of rise in annual salinity levels that were displayed across the gauging stations. The slope of the regression equation is taken as the rate of change in annual stream salinity, and is referred to as the trend.

The trends were then tested to see if they were significant. Using a t-distribution analysis (Watts & Halliwell 1996) the linear regression applied to each trend period was analysed. Taking the correlation coefficient (r) that was obtained from each regression the following equation was used:

$$t = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}} \qquad \textit{(Equation A4.7)}$$

where n is the number of samples. To determine if the trend was significant, the value of t was compared with t at the 95% confidence limit.

The daily contribution from the catchment between the Rocky Glen and Styx Junction gauging stations was not calculated because of the time lag between the gauging stations. It is however possible to calculate the annual flow, annual salinity and annual salt loads from the differences in flow and salt load between Rocky Glen and Styx Junction.

When calculating averages to be used in equations or as part of summary of results, data from the period 1980 to 1995 were used to allow direct comparisons of values at the two stations and allow comparisons with results from the other Salinity Situation Statement documents.

Tables A4.1 Groundwater monitoring trends

WIN Number	**Name**	**Bore depth** (m below ground)	**Monitoring period**	**Ground-water trend** (m/yr)	**Final water level** (m below ground)	**Land use**[a]	**Landscape position**	**Rainfall data used**[b]
Middle Kent management unit								
60418096	CP2	17	93–02	0.19	10.0	C	Hill slope (upper)	L 16
60418027	Buswell 2A	9	84–93	0.02	1.0	C	‘Lowlands’	L 37
60418040	Buswell 8B		84–02 84–98 98–02	0.07 0.11 -0.50	9.8	C/P	Hill slope (middle)	L 37
60418043	Buswell 11B		84–02	0.13	7.5	R&P	Drainage line	L 37
60418044	Buswell 12B		84–02	0.13	7.8	R&P	Drainage line	L 37
60418022	Henderson 4	11	85–02	–0.01	3.9	C/P	Hill slope (lower)	L 35
60418023	Henderson 5	8	85–02	–0.01	3.7	C/P	Hill slope (lower)	L 35
60418024	Henderson 7		85–02	0.12	6.4	C/P	Hill slope (lower)	L 35
60418052	Upper Kent 4A	17	85–88	–0.08	11.7	R	Hill slope (upper)	L 35
60418119	N2	8.4	93–00	0.02	0.8	C	Drainage line	L 15
60418106	K3	9.4	93–00	–0.13	2	C/P	KR flood plain	L 35
60418111	K4	18.9	93–00	–0.28	6.7	C/P	Hill slope (lower)	L 35
60418115	K5	20.4	93–00	–0.07	11.6	C/P	Hill slope (middle)	L 37
60418118	S1	27.0	93–00	–0.01	2.6	R/P	Hill slope (lower)	L 35
60418121	S3	10.0	93–00	0.12	3.5	R/P	Drainage line	L 37
60418123	S5	18.8	93–00	–0.15	5.3	R/P	Hill slope (lower)	L 36
60418124	S6	17.2	93–00	–0.15	5.8	R/P	Hill slope (upper)	L 37
2329-2-SW-0017	KNT01	25	00–03	0	–1.2	C	Tertiary flats	L 26
2329-2-SW-0018	KNT02	33	00–03	–0.22	–1.8	C	Tertiary flats	L 26
2329-2-SW-0019	KNT03	19	00–03	0	–0.8	C	Tertiary flats	L 26
2329-2-SW-0021	KNT05	26	00–03	–0.18	–0.9	C	Tertiary flats	L 35
2329-2-SW-0022	KNT06	20	00–03	–0.12	–6.0	R	Hill slope (upper)	L 26
Rocky Gully management unit								
60419001	MC1/80	12.3	81–02 81–93 94–02	0.00 0.07 –0.02	1.8	PC	Drainage line	BoM
60419002	MC2/80	12	81–02 81–93 94–02	0.04 0.11 –0.03	4.9	PC	Hill slope (lower)	BoM
60419003	MC2A/80	8	81–02 81–93 94–02	0.04 0.10 –0.03	4.8	PC	Hill slope (lower)	BoM
60419004	MC3/80	21	81–02	0.03	5.5	PC	Hill slope (lower)	BoM

[a] C—Clearing, N—Native forest, P—Plantations , PC—Parkland clearing, R—Remnant vegetation,
[b] L—LUCICAT subcatchment, BOM—BoM M009595 using 1975-2002 MRA

Tables A4.1 Groundwater monitoring trends (continued)

WIN Number	Name	Bore depth (m below ground)	Monitoring period	Ground-water trend (m/yr)	Final water level (m below ground)	Land use[a]	Landscape position	Rainfall data used[b]
Rocky Gully management unit (continued)								
60419007	MC4/95	8	95–02	–0.01	4.7	N	Hill slope (lower)	BoM
60419008	MC5/95	23	95–02	0.02	4.9	N	Hill slope (lower)	BoM
60418129	S10	25.1	93–00	–0.11	1.6	R	‘lowlands’	L 48
60418780	RG 1	15.2	93–00	0.01	10.6	C/P	Hill slope (middle)	L 44
60418782	RG 2	14.4	93–00	–0.03	6.5	R	Hill slope (middle)	L 44
60418784	RG 3	19.4	93–00	–0.05	2.0	R	Hill slope (lower)	L 44
60418786	RG 4	6.9	93–00	–0.17	1.3	C	Tertiary flats	L 44
60418787	RG 5	4.3	93–00	0.05	3.0	R	Tertiary flats	L 44
2328-4-NW-0023	KNT24	27	00–03	–0.09	0.4	R	Drainage line	L 60
Nukennullup management unit								
60418122	Tu1	25.6	93–00	-0.06	4.2	R	Tertiary flats	L 31
60418125	Tu2	10.4	93–00	-0.02	2.9	R	Tertiary flats	L 31
60418127	Tu4	18.2	93–00	0.01	0	R/P	Tertiary flats	L 32
60418130	Tu5	13.4	93–00	-0.04	0.1	C/pP	Hill slope (lower)	L 32
60418136	Sy2	37.1	93–00	-0.26	9.0	C/P	low hill in flats	L 28
60418138	Sy3	14.0	93–00	-0.14	5.5	C/P	low hill in flats	L 28
60418140	Sy4	12	93–00	0.20	2.8	R	Tertiary flats	L 27
60418141	Sy5	24.5	93–00	0.27	2.3	R/C	Tertiary flats	L 27
60418143	Sy6	12	93–00	0.12	1.0	R	Tertiary flats	L 27
2329-2-SW-0023	KNT07	33	00–03	-0.26	1.1	C	Tertiary flats	L 34
2329-2-SW-0024	KNT08	24	00–03	-0.18	1.1	R	Tertiary flats	L 34
2329-2-SW-0025	KNT09	25	00–03	-0.19	0.6	C	Drainage line	L 30
2329-2-SW-0026	KNT10	30	00–03	-0.33	1.4	C	Hill slope (lower)	L 30
2329-2-SW-0027	KNT11	33	00–03	-0.32	1	C	Lake	L 30
2329-3-SW-0017	KNT12	30	00–03	-0.65	2.2	R	Tertiary flats	L 31
2329-3-SW-0018	KNT13	10	00–03	-0.51	2.5	R/P	Drainage line	L 34
2329-2-SW-0028	KNT14	15	00–03	-0.16	0.2	C	Hill slope (lower)	L 29
2329-2-NW-0010	KNT16	39	00–03	-0.38	3.2	P	Hill slope (middle)	L 28
2329-2-NW-0011	KNT17	33	00–03	-0.20	2.9	R	Tertiary flats	L 28
Poorrarecup management unit								
60418083	Lake Poorrarecup	14.1	88–02	0.05	11.2	R	Lake-lunette	L 39

[a] C — Clearing, N — Native forest, P — Plantations , PC — Parkland clearing, R — Remnant vegetation,

[b] L — LUCICAT subcatchment, BOM — BoM M009595 using 1975-2002 MRA

Tables A4.1 Groundwater monitoring trends (continued)

WIN Number	**Name**	**Bore depth** (m below ground)	**Monitoring period**	**Ground-water trend** (m/yr)	**Final water level** (m below ground)	**Land use**[a]	**Landscape position**	**Rainfall data used**[b]
Poorrarecup management unit (continued)								
60418178	Lake Poorrarecup		95–02	0.04	10.9	R	Lake-lunette	L 39
60418131	P1	7.6	93–00	–0.03	2.1	R/C	Tertiary flats	L 39
60418132	P2	19.8	93–00	–0.03	1.4	C	Drainage line	L 39
60418134	P3	11.7	93–00	–0.17	3.2	C	Drainage line	L 39
Wamballup management unit								
60418237		17	98–02	–0.07	3	C	Hill slope (lower)	L 19
60418236		10	98–02	0.05	1.1	C	Hill slope (lower)	L 19
60418173		5	98–02	–0.20	2.8	C/P	Hill slope (lower)	L 19
60418174		10	98–02	–0.29	3.1	C/P	Hill slope (lower)	L 19
60418197	MW1	14.8	93–00	0.20	–7.2	C	Hill slope (upper)	L 20
60418198	MW2	12.0	93–00	0.19	-6.6	C	Hill slope (upper)	L 21
60418199	MW4	24.2	93–00	–0.06	–0.7	C	Hill slope (lower)	L 22
60418113	MW5	6.2	93–00	–0.16	–2.5	C	Tertiary flats	L 22
Nunijup management unit								
60418095	CP1	26	93–02	0.04	3.2	C	Hill slope (lower)	L 5
60418117	N1	27.4	93–00	–0.17	3.2	C	Hill slope (lower)	L 6
60418120	N3	27.0	93–00	0.45	19.9	C	Hill slope (upper)	L 3
2329-2-SW-0030	KNT20	10	00–03	–0.36	3.2	R	Tertiary flats	L 3
2329-2-SE-0015	KNT21	33	00–03	–0.20	1.0	C/P.	Tertiary flats	L 5
2329-2-SE-0016	KNT22	27	00–03	0.00	0.1	C	Seepage area	L 5
2329-2-SE-0017	KNT23	25	00–03	0.00	0.0	C	Seepage area	L 5
Headwaters management unit								
60418105	T1	20.8	93–00	–0.10	3.2	C	Low hill	L 12
60418107	T2	24.4	93–00	–0.12	4.86	C	Tertiary flats	L 12
60418108	T3	19.1	93–00	–0.12	4.0	C	Tertiary flats	L 12
60418114	M2	12.9	93–00	–0.11	3.9	C	Hill slope (lower)	L 13
60418116	M3	7.0	93–00	–0.02	0.4	C	Drainage line	L 13
Lake Katherine management unit								
60418133	KW1	24.1	93–00	–0.12	9.6	R	Lake	L 24
60418137	KW3	23.6	93–00	–0.02	10.0	R	Hill slope (middle)	L 24
60418139	KW5	27.6	93–00	–0.19	11.2	R	Hill slope (upper)	L 23
60418142	KW7	9.4	93–00	–0.06	3.3	C/P	Hill slope (lower)	L 25

[a] C—Clearing, N—Native forest, P—Plantations , PC—Parkland clearing, R—Remnant vegetation,
[b] L—LUCICAT subcatchment, BOM—BoM M009595 using 1975-2002 MRA

Table A4.2 Groundwater level trends and salinity

Management unit	**Area** (ha)	**Hydrogeology**			
		Area of shallow groundwater (km^2)	**Groundwater salinity** (mg/L TDS)	**Salt store** (t/ha)	**Water level trends** (cm/yr)
Headwaters	128.1	25	12 000	822	–12 to –2
Wamballup	85.9	21	12 000	786	–16 to +20
Lake Katharine	93.5	16	9 000	666	–19 to –2
Middle Kent	100.9	48	12 000	560	–50 to +19
Rocky Gully	340.0	52	6 000	476	–14 to +10
Nunijup	99.9	16	9 000	820	–17 to +45
Nukennullup	127.3	18	12 000	636	–26 to +27
Poorrarecup	94.4	13	5 000	612	–17 to +5

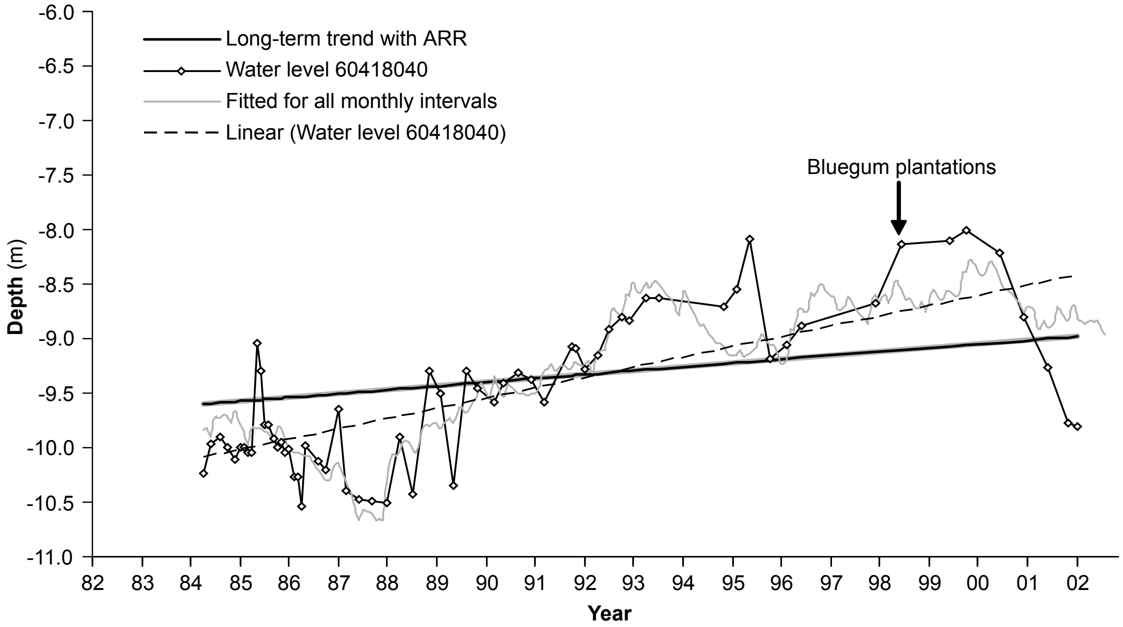


Figure A4.1 Groundwater hydrograph from a bluegum plantation area: water levels with monthly residual rainfall for 60418040 (1975–2002) (0 months delay)

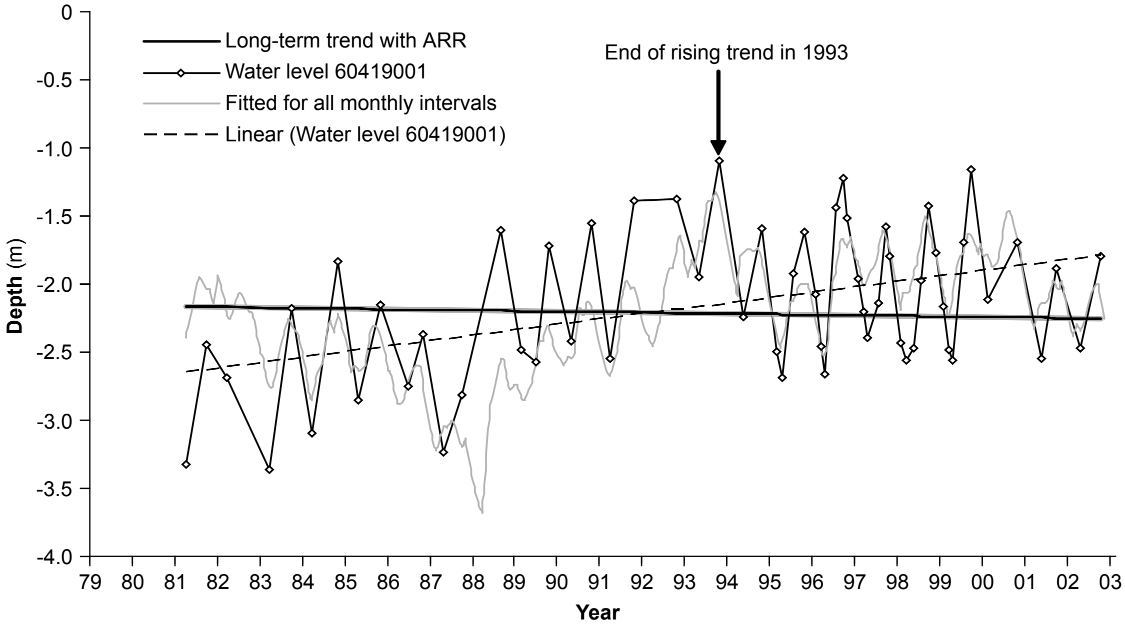


Figure A4.2 Groundwater hydrograph from a parkland clearing site: water levels with cumulative annual residual rainfall for 60419001 (1975–2002) (0 months delay)

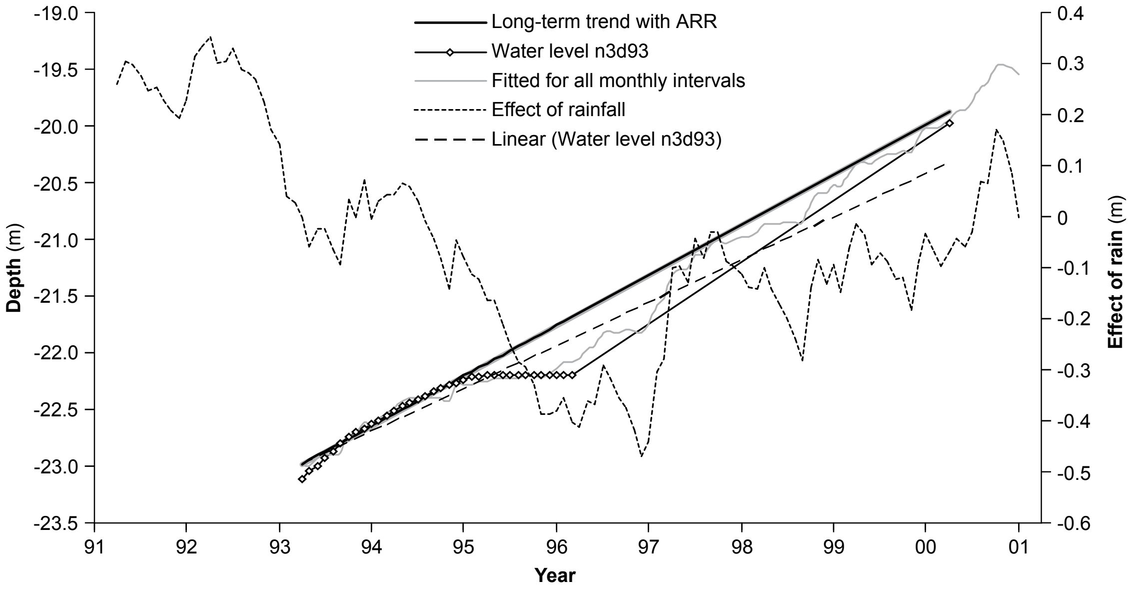


Figure A4.3 Groundwater hydrograph from a cleared site: n3d93 (9 months delay)

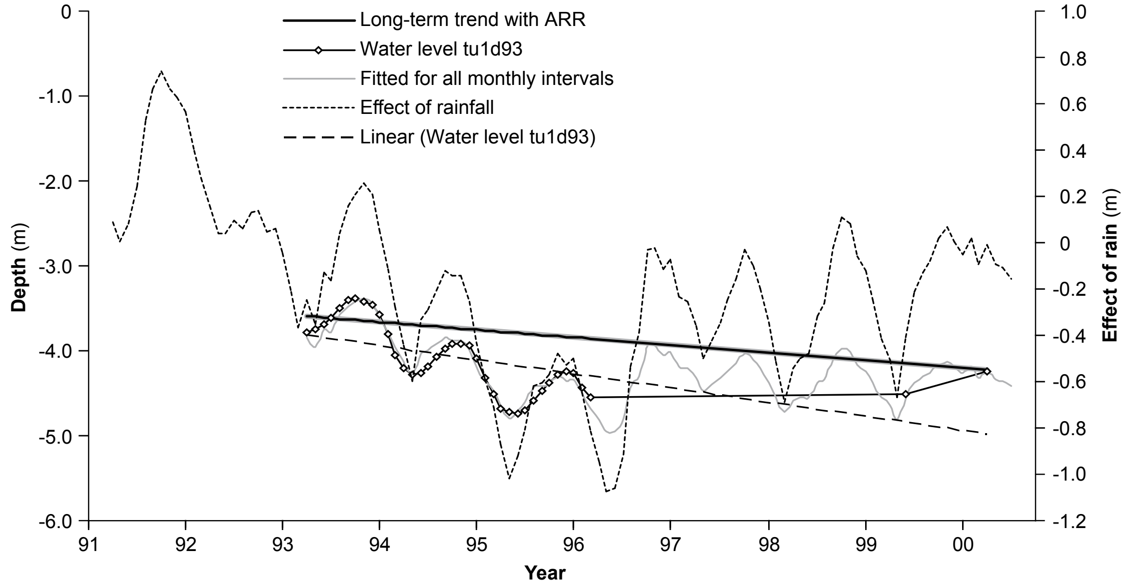


Figure A4.4 Groundwater hydrograph from a remnant vegetation area: tu1d93 (3 months delay)

Appendix 5 Modelling

A5.1 MAGIC model formulation — additional information

A5.1.1 Physical features modelled

Ground surface

The ground surface was represented by the digital elevation model (DEM) prepared in 2002 by DOLA for the Land Monitor Project. Slope, aspect, plan curvature and drainage directions were computed from the DEM. It was necessary to introduce a 1m high embankment across a saddle near 6188600N, 515000E to prevent the outflow from north-western lakes (including Lake Poorrarecup) draining into the Frankland River (Fig. 5). In areas where drainage lines were not strongly defined by the topography, and mapping of streams was available from DOLA topographic maps, drainage was constrained to follow the mapped streams.

Subcatchments

The Department of Environment established sampling points on streams throughout the catchment in 1999 and estimates of annual flow and salinity for the calendar year 2000 were available at 15 of these points. Subcatchment boundaries from previous versions of the model were adjusted so that subcatchment outlets were at the sampling points, allowing modelling reports to correspond with sample point records wherever possible (Fig. 21). Management unit boundaries, where they had followed affected subcatchment boundaries, were changed too. Sixty-one subcatchments in addition to those at sampling points were selected, with sizes in the range 2.3–48.5 km^2 to facilitate computer simulation.

Soil and geological layers

The Upper Kent catchment was represented by three layers: a generally highly permeable surface layer comprising the normal A and B soil horizons, a less permeable middle layer and a more permeable layer above bedrock. The thickness and permeability of the layers at every grid cell in the catchment were determined. More details on the hydrologic properties of these 3 layers can be found in Mauger & Dixon (2003).

The depths of the middle and bottom layers were set from hydrogeological mapping (Smith 1997), with the main subdivision being between areas of Tertiary sediments and areas of in-situ weathering of the granite and gneiss bedrock. Depth to bedrock was interpolated to all grid cells from drilling records and ranged from 10 m to 35 m with an average of 20 m (Fig. A5.1). Because the mapping of depth was not conducive to smooth interpolation, total depths were assigned values of 10 m, 20 m, 30 m or 35 m respectively. In the weathered areas, the bottom layer was assumed to be saprolite (partially weathered rock), with thickness 3 m and lateral permeability 0.8 m/day. The remaining thickness between the surface layer and the saprolite was assigned to the middle layer as sandy clay with lateral permeability 0.1 m/day. In the Tertiary sediment areas, the middle layer was assumed to be a 2 m thick sandy clay with lateral permeability of 0.1 m/day, and the remaining depth to bedrock was assumed to be sand with lateral permeability 0.8 m/day.

Rainfall

A gridded map of average annual rainfall for the period 1980–95 was available from the Bureau of Meteorology (BOM). The grid cells were at 2 km spacing and the spatial distribution of the rainfall took into account rain-shadow effects of the topography. A map gridded at 25 m for modelling was prepared from the BOM map by bi-linear interpolation. The mapped annual average rainfall ranges from 540 mm in the north-east to 880 mm in the south-west.

Two pluviograph stations were also available, the West Tenterden gauge (M009765) near the centre of the catchment, and the Rocky Glen gauge (M509385) at the stream gauging station. The rainfall records were reasonably well correlated with each other, and also to annual streamflow at the Rocky Glen gauging station. Comparison of the 1980–95 annual means at

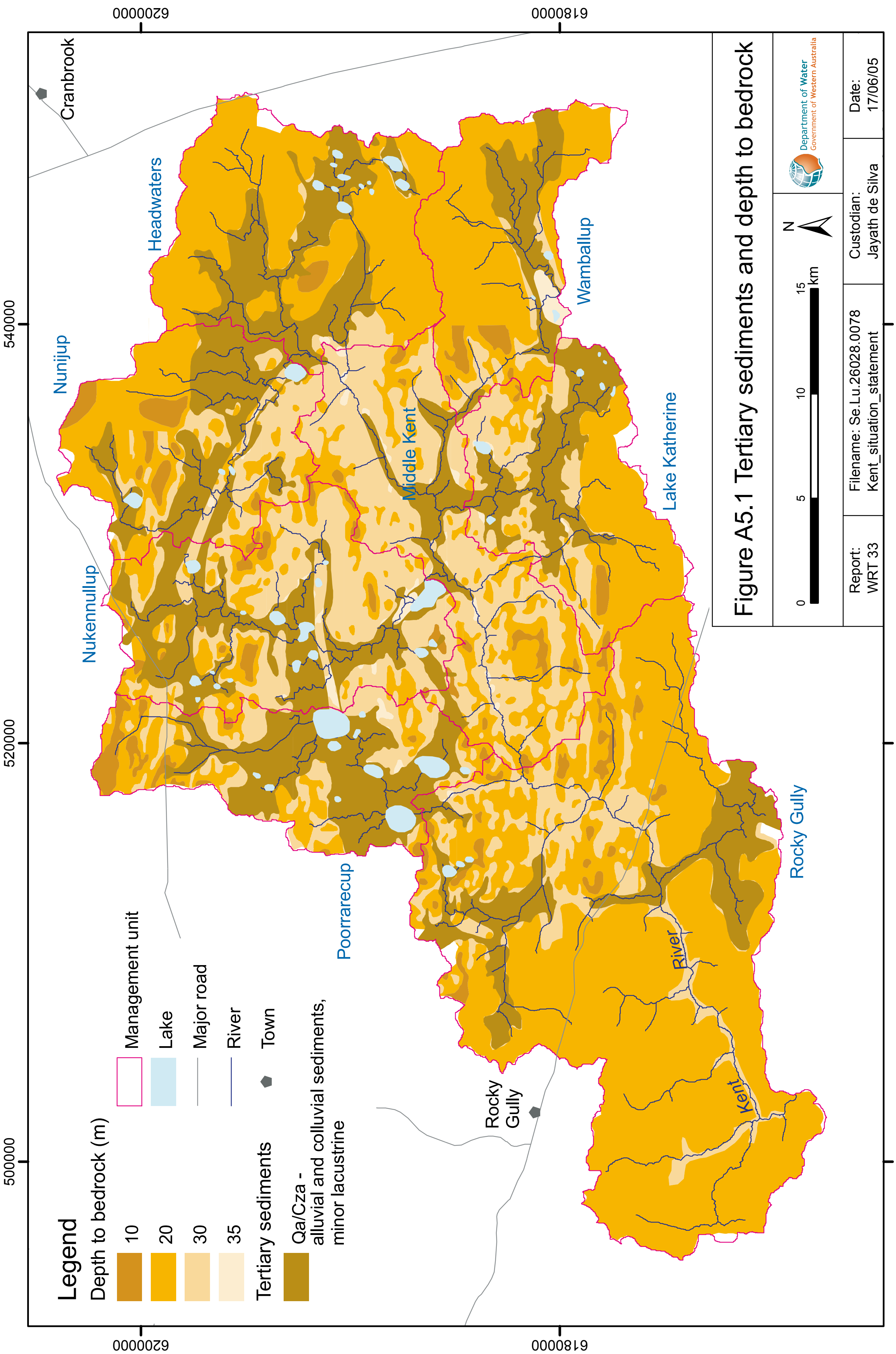


Figure A5.1 Tertiary sediments and depth to bedrock these stations to the values from the gridded BOM map suggested that the BOM values should by multiplied by 0.88. The records also provided estimates of the means by month for the 1980–95 period and actual rainfall for the months following August 1999 that were used in verifying the model. When used in the model, the rainfall is expressed by a multiplier that converts the average annual rain in mm into m^3 over one cell of 625 m^2 after interception losses have been allowed (15% of rain). Table A5.1 shows the multipliers derived from the two rainfall stations.

Table A5.1 Rainfall multipliers used

Month	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug
1980–95	0.053	0.043	0.038	0.015	0.018	0.018	0.019	0.031	0.069	0.072	0.081	0.074
1999	0.084	0.047	0.023	0.024	0.054	0.018	0.054	0.025	0.032	0.068	0.112	0.084
2000	0.035	0.018	0.017	0.004								

Evaporation

A gridded map of annual pan evaporation (Class A Pan with bird guard) was prepared by interpolating the map of isopleths published in Luke et al. (1988). As with rainfall, average means by month were expressed as a multiplier (Table A5.2) to convert annual mm to m^3 over one cell. The averages for the Perth records were used after it was noted that the monthly distributions for all centres in the south -west were essentially the same. The mapped pan evaporation ranges from 1520 mm in the north-east to 1380 mm in the south-west.

Table A5.2 Evaporation multipliers used

Month	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug
Average	0.036	0.054	0.066	0.086	0.091	0.079	0.070	0.041	0.029	0.022	0.023	0.027

Native forest and existing plantations

Native vegetation and pasture cover were derived from Landsat Thematic Mapper TM data supplied by the Land Monitor Project (Allen & Beeston 1999). The Landsat TM data was also used to derive an index called 'greenness' for the tree/plantation areas. The greenness index, which is an indicator of tree density and consequently the rate of water use by trees, is correlated to the leaf area index (LAI).

Using the full sequence of available scenes (1988, 1990, 1992, 1994, 1996, 1998, 1999, 2000 and 2002), the dates when new plantations were well established were determined. Manual digitising based on the 2002 (December 2001) scene provided sharp area boundaries and identified newly-planted areas that would achieve full density in the next year or so.

The 1988 scene, which represented the maximum extent of clearing was used for the calibration case (Section 5.1.2). The February 2000 scene was used to verify the model (Section 5.1.3). The 'Base' case for the management options (Section 6.1) used the greenness index from the February 2000 Landsat scene for the native vegetation with superimposed manually digitised plantations identified from the 2002 Landsat scene. To model them fully-grown, the plantations in the 'Base' case were given the same greenness as the native vegetation. The resulting three stages of tree cover used for MAGIC modelling are shown in Figure A5.2.

Water use by plants

Transpiration rates depend on factors like plant density, root depth, water availability, evaporation rates and plant growth cycles. It is possible to have more than one type of plant in a cell and MAGIC gives first priority of water use to annual pasture, then perennial pasture and finally trees. Water in the surface layer available for transpiration included a 'field capacity' of 32 mm, which is water that cannot participate in lateral flow or infiltration to the middle layer. Also included

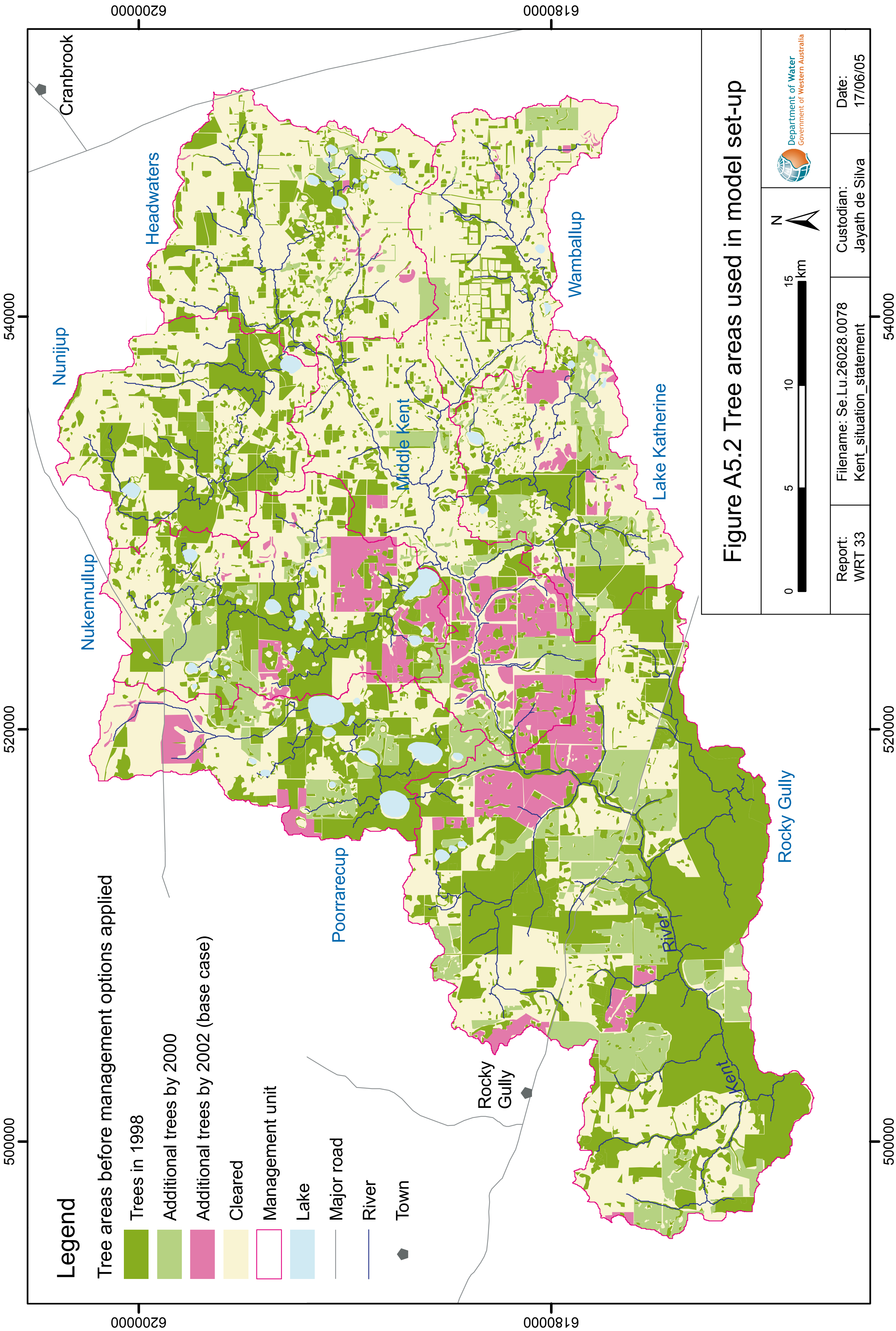


Figure A5.2 Tree areas used in model set-up is water in excess of saturation resulting from the addition of the current month's rainfall after interception and evaporation from soil.

Trees will first attempt to satisfy their demand from water remaining in the surface layer after pasture demands have been met. Any unsatisfied demand is reduced by 60% of its value to account for stress, and drawn from the middle clay layer without regard to depth.

The approach for calculating the annual transpiration by trees and pastures is described in Points 1–3. Points 3–6 describe the assumptions made for LAI definition.

1. Transpiration by trees is proportional to three factors: a) the greenness at a cell (called 'Actual Greenness'), b) the 'Natural Greenness' of undisturbed forest proportional to rainfall, and c) the monthly pan evaporation. Annual transpiration of native forest (AT(F)) is calculated from Equation A5.1:

   $$AT_{(F)} = AG / NG \times NT_{(F)} \qquad \textit{(Equation A5.1)}$$

   where:

   AG = Actual Greenness index describing the plant density and derived from the Landsat TM data.

   NT(F) = Natural Transpiration rate of native forest calculated as the annual rainfall reduced by interception losses (15%) and increased by a factor of 1.4 to compensate for reduced transpiration under drought stress.

   NG = Natural Greenness index describing the density of the natural forest that originally covered the catchment and calculated from Equation A5.2 or A5.3 depending on the Landsat TM scene used.

   $$NG = 0.0844 \times R_{(A)} - 28 \text{ for the 2000 Landsat TM scene} \qquad \textit{(Equation A5.2)}$$

   $$NG = 0.0634 \times R_{(A)} - 22 \text{ for the 1988 Landsat TM scene} \qquad \textit{(Equation A5.3)}$$

   where:

   R(A) = annual rainfall in mm

   Equation A5.2 and A5.3 were obtained by regression of greenness index versus rainfall using undisturbed forest areas in the region.

2. Annual transpiration of annual pasture in the MAGIC model (AT(P)) is set by assuming a growth cycle represented by a coefficient for each month (Table A5.3), which is proportional to a nominated peak LAI.

   The appropriate peak LAI is derived from calibration of the runoff against streamflow. The monthly transpiration (MT(p)) of pasture is defined by Equation A5.4

   $$MT_{(P)} = 0.352 \times EP_{(M)} \times leafarea \qquad \textit{(Equation A5.4)}$$

   where:

   EP(M) = monthly pan evaporation in mm
   Leafarea is the area of leaf surface

   0.352 is the ratio of evaporation from a leaf surface compared to evaporation from a Class A pan. The precise value of the ratio is not critical because leaf area is adjusted in the calibration process.

3. The maximum pasture LAI varies across the catchment based on the following:

   $$LAI_{(\max)} = 0.00247 \times R_{(A)} \qquad \textit{(Equation A5.5)}$$

where:

$R_{(A)}$ = annual rainfall in mm

0.00247 was set during calibration of the Kent model to give a maximum pasture LAI(max) that varies from 1.35 at rainfall 550 mm to 2.0 at rainfall 800 mm. It increases from east to west.

4. The LAI of annual pasture which is set to change monthly to represent its annual growth cycle is zero in summer and peaks in winter (Table A5.3).

Table A5.3 Growth factors for annual pasture

Month	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug
Growth factor	0.8	0.4	0.3	0	0	0	0.2	0.5	1.0	1.0	1.0	1.0

5. MAGIC distinguishes between shallow- and deep-rooted perennial pastures which are both assigned a constant year round LAI (growth factor = 1 for all months) equal to the maximum LAI of annual pasture. The roots of shallow-rooted perennial pastures are confined to the soil layer. While in practice the plants may wither if the soil moisture is depleted, the model assumes that once soil moisture is available they can quickly re-establish.

6. The only difference in water use between shallow and deep-rooted perennials results from the depth of root penetration. The deep-rooted perennials were assumed to have an effective rooting depth of 2 m, which means that, when the soil moisture in the upper layer is depleted, they can draw water from the clay layer if it is available within the nominated depth. Water from the clay layer is used at 60% of the upper layer rate to account for the plant stress of drawing from depth.

Discharge to the shallow layer

The model assumed that any discharge to the shallow top layer had the salinity of the groundwater which was measured from groundwater monitoring as detailed in Section 4.5.

Table A5.4 Average groundwater and rainfall salinity used in MAGIC

Management unit	**Salinity**	
	Groundwater (mg/L TDS)	**Rainfall** (mg/L TDS)
Headwaters	10 100	9.4
Wamballup	8 980	10.0
Lake Katherine	9 000	10.4
Middle Kent	15 460	9.9
Rocky Gully	5 440	10.7
Nunijup	9 000	9.0
Nukennullup	12 920	9.3
Poorrarecup	5 400	9.5
Watterson Farm	10 970	9.7
Perillup Road	10 450	9.8
Rocky Glen	8 890	9.9

A5.1.2 Physical processes modelled

MAGIC is usually used as a steady-state salinity model and assumes that the same land use has been applied to the catchment for many years and the water storages in each soil layer are unchanged from year to year if the catchment receives the same rainfall each year. It is useful to apply different land uses to the same catchment with the same rainfall to see how they influence salinity. Various management options were applied to the upper catchment and compared to a 'Base' case. The catchment is divided into 25 × 25 m gridded cells, each with 3 layers. Earlier applications used two soil layers (Mauger 1996). The water movement modelled for a group of cells is represented in Figure A5.3. Some of the key points on modelling physical process are given in the following section.

1. Time-steps—The model was run in monthly time-steps starting in September and finishing in August. When a catchment is in steady-state, the soil moisture content in every cell at the end of the year would equal their soil moisture content at the start of the year. To approximate this, the model was started with all soil saturated, and then run for three consecutive years with the same average monthly rainfall for the period 1980–95. The annual totals for the third year were reported as the steady-state condition of the catchment. In the verification case, the initial soil moistures were set by running the calibration case (steady-state) first. Then the actual rainfall for the period September 1999 to December 2000 was run with the annual quantities for the year 2000 reported.

2. Interception of rain by leaves and other above ground surfaces was allowed for by reducing rain input by 15%. Infiltration excess was assumed negligible and not calculated.

3. Evaporation from the topsoil layer was assumed to occur within 200 mm of the surface when it was saturated. It was evaporated at 40% of pan evaporation rate, both in the pasture or forest areas. The calibration is sensitive to the depth but not very sensitive to the rates, indicating that the important factor is how much water is available rather than its rate of use. Evaporation from soil accounted for about 8% of the rainfall and varied for each subcatchment.

4. Infiltration to the middle layer—If the surface layer is partially saturated (i.e. moisture exceeds field capacity) and the middle (clay) layer is not saturated, surface layer water can infiltrate into the clay at a relatively high rate (about 1 mm/day). In an undisturbed forest, the rate should be sufficient to add enough water to the clay layer while the surface layer is partially saturated, to satisfy the trees' stressed rate of transpiration over summer when the surface layer is dry. The total is in the order of 100–200 mm per year.

5. Recharge to the bottom layer—Other researchers have noted that the rate of recharge to deep groundwater after clearing is much lower than would be expected if it was only controlled by the saturated permeability of the clay as determined from pump tests. The mechanism for the higher resistance has not been proven, but it must be accounted for in modelling based on physical processes. Thus, when the clay is saturated, the rate at which water leaves the saturated part of the surface layer to recharge groundwater in the bottom layer is limited as if there was a resistance at the top of the clay. The limiting rate is the main determinant of the total recharge to groundwater and is varied in the calibration of the model to result in groundwater discharge that will carry the annual salt load recorded at stream gauging stations. The rate determined by calibration in the Kent River catchment was 27 mm/year.

6. Lateral flow in the bottom layer—Darcy's Law was used to estimate the lateral flow in the bottom layer and some computational rules using the dispersed drainage directions were also used to transfer the water from cell to cell, starting with upstream cells. The ground slope was used for the hydraulic gradient and the lateral transmissivity of the bottom layer and middle layer combined determined the capacity for throughflow. The vertical permeability of the clay layer is used to determine the pressure that must exist in the bottom layer to drive the required discharge rate to the level of the water table in the surface layer, i.e. the bottom of the surface layer plus the depth of saturation.

7. MAGIC model outputs—Cells that have discharge into the surface layer but are where the hydraulic head is below ground are reported as 'shallow watertable area'. Cells where the hydraulic head is above ground are reported as 'discharge area'.

8. Evaporation of runoff—Water in the surface layer in excess of its saturation capacity is classed as runoff. Runoff is subjected to additional evaporation processes before it is classed as streamflow. Maximum evaporation from the ground surface in a month is assumed to be as for a lake, which is 70% of pan evaporation. Evaporation from the soil and pasture transpiration were assumed to be part of the maximum because the water vapour is released at ground level. Transpiration from trees is not because the leaves are well off the ground. On ground with slopes greater than 0.5%, runoff produced in the current month can be evaporated up to the remainder of the maximum for the month. On flatter slopes, runoff produced in previous months can also be evaporated if the maximum is not reached by evaporating the current month's runoff.

9. If the cell is in a designated stream zone and there is unsatisfied transpiration demand (including reduced demand due to stress), this is removed from runoff on the assumption that it is supplied by streamflow arriving from upstream.

10. Runoff across depressions—Some upper parts of catchments have shallow depressions that are not lakes that have been identified by analysing the DEM. The terrain analysis gives the depth of the cell below the overflow level of the depression. This depth is greater than the real depth because the overflow may be a small channel or just lower ground between DEM elevations that are spaced 25 m apart. A depth reduction of 0.2 m has been allowed. The remaining volume of water held in upland depressions is subtracted from runoff generated upstream of them because the depressions must be filled before overflow occurs, and they clearly dry out in a normal season.

11. The model has a special post-processing calculation that 'cascades' water through depressions so that the upstream negative totals do not propagate downstream of the depression that generated them.

12. Lake evaporation—In areas designated as lakes, the full volume of 'lake evaporation' is taken off every month. It may lead to the aggregate streamflow from a subcatchment containing a lake becoming negative, which would indicate that the lake level would fall in an average rainfall year. This negative volume should be included in the catchment total when evaluating the long-term average streamflow because it has to be made up in high rainfall years before the catchment area upstream of the lake contributes to streamflow. However, when comparing the model output with gauged stream records in a year of average rainfall, negative volumes should not be included because the upstream areas make no contribution, not negative.

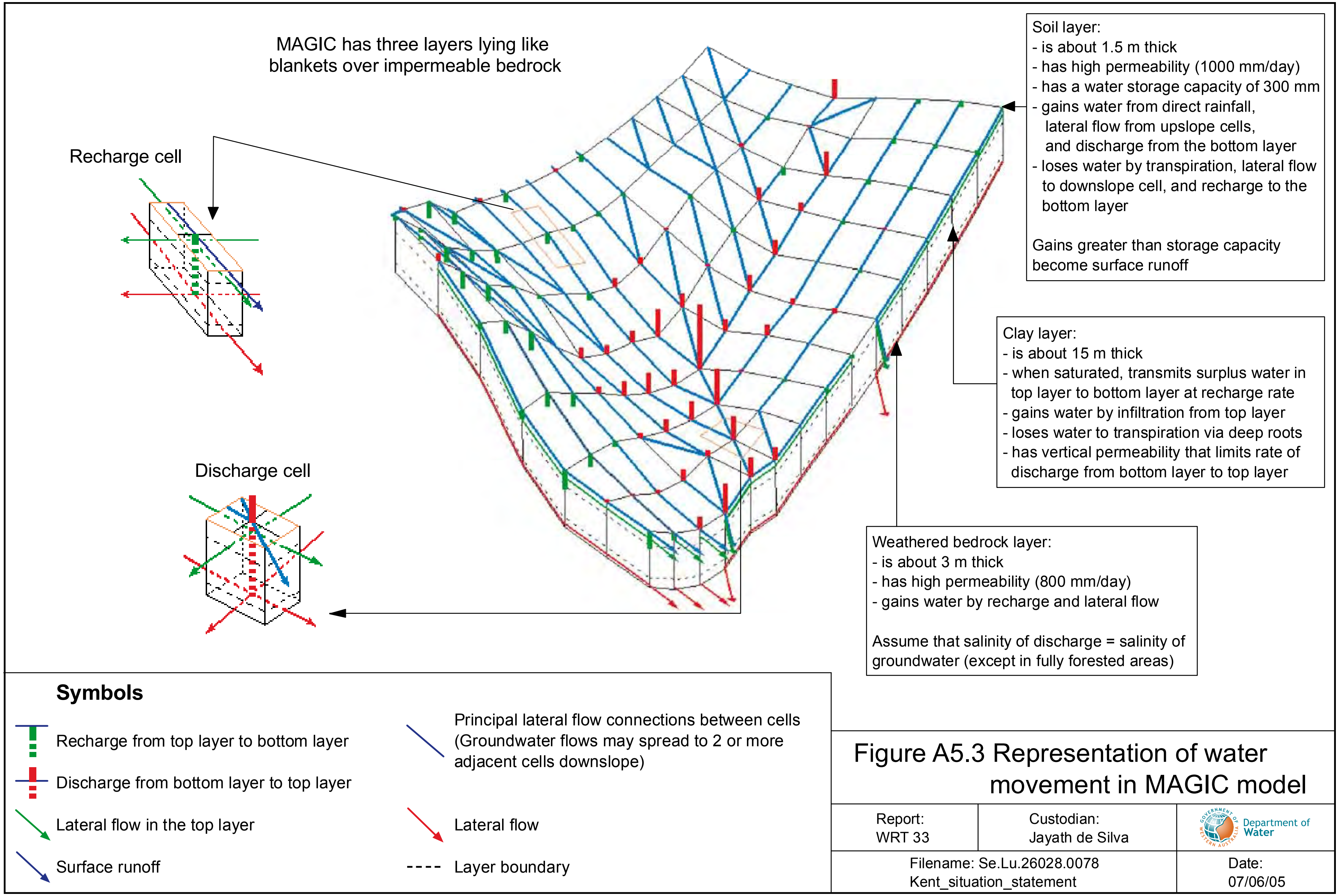
13. The spreadsheet summary of model outputs allows any negative streamflows from subcatchments that terminate in lakes to be either included or excluded in downstream accumulations, according to reporting requirements. When negative streamflows are not accumulated downstream, neither are accumulations of salt loads and deep groundwater discharge. It was decided to exclude the negative streamflows generated from the Poorrarecup and Nukennullup management units since in all cases modelled an average year was applied to the Kent catchment.

14. Lake overflow—After comparing model outputs with records from an actual year, it is sometimes necessary to check whether a major lake overflowed or not. The model might have started with a higher water level than in the actual lake. In this case the model might have predicted the lake would overflow, when in fact it did not. The spreadsheet that summarises model outputs allows the streamflow, salt load and groundwater discharge to be prevented from overflowing if review of the records suggests this is appropriate which was the case for the Nunijup management unit.

Model calibration and verification

The modelling process normally used is based on the description in Mauger (1996) with modifications as described in Mauger et al. (2001). The first three-layer application of MAGIC modelling for this study was by Mauger & Dixon (2003). Descriptions of previous two-layer MAGIC modelling in the upper catchment include Dixon et al. (1998) and JDA Consultant Hydrologists (1998).

The model was calibrated to the hydraulic steady-state condition of the catchment in its maximum cleared state which, since clearing control legislation had been introduced in 1978, was closely represented by the vegetation distribution of the 1988 Landsat scene. The model was then verified by using the 2000 land use and rainfall with the same parameters as in the calibration case.



Soil layer:
- is about 1.5 m thick
- has high permeability (1000 mm/day)
- has a water storage capacity of 300 mm
- gains water from direct rainfall, lateral flow from upslope cells, and discharge from the bottom layer
- loses water by transpiration, lateral flow to downslope cell, and recharge to the bottom layer

Gains greater than storage capacity become surface runoff

Clay layer:
- is about 15 m thick
- when saturated, transmits surplus water in top layer to bottom layer at recharge rate
- gains water by infiltration from top layer
- loses water to transpiration via deep roots
- has vertical permeability that limits rate of discharge from bottom layer to top layer

Weathered bedrock layer:
- is about 3 m thick
- has high permeability (800 mm/day)
- gains water by recharge and lateral flow

Assume that salinity of discharge = salinity of groundwater (except in fully forested areas)

Figure A5.3 Representation of water movement in MAGIC model

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Figure A5.3 Representation of water movement in MAGIC

When the model results were compared with observed streamflows and salt loads at major sampling sites for 2000 (Fig. A5.4), MAGIC was found to have over-estimated the streamflow and salt load at Rocky Glen by 9% and 12% respectively.

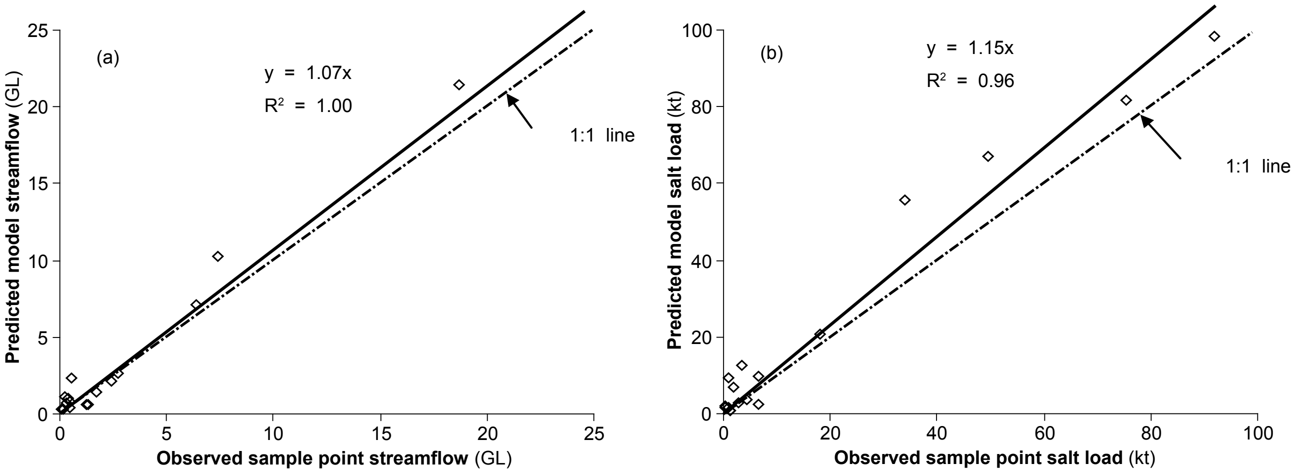


Figure A5.4. Observed and MAGIC-predicted (a) streamflow and (b) salt load at sample sites (2000)

Since 1990, 26% (186 km^2) of the previously cleared area has been replanted with commercial trees (Fig. A5.2), with about 90% of these established after 1996. To verify the model, the vegetation distribution defined by the 1988 Landsat scene was substituted with the 2000 scene and rainfall changed; all other data were unchanged. The model was initially run with the average rainfall (1980–85), repeated three times to establish realistic soil moisture conditions, then run with the actual rainfall of the period September–December 1999 to produce soil moisture conditions appropriate to the start of January 2000, and finally run for the year 2000 with actual monthly rainfall to produce annual streamflow and salt load estimates. The actual streamflow and salt load differences between Styx Junction and Rocky Glen in 2000 were added to the model results for verification.

The results for Styx Junction, where the salinity recovery target is set, were calculated from the Rocky Glen model results by adding annual streamflow and salt load of 51 GL and 18 kt, being the mean of the differences between the gauging station records over the period 1980–95. This assumes that the streamflow and salt-load generating characteristics of the forested catchment are constant with time.

It was difficult to improve the accuracy for the verification case because MAGIC was run with monthly not daily time-steps and because the spatial distribution of rainfall in 2000 was different from that of average years used in the model.

A5.2 The LUCICAT model—additional information

A5.2.1 Hydrological processes

Evapotranspiration comprises three components—interception, transpiration by plants and evaporation from soil. Interception is represented by a canopy store, which is dependent on the Leaf Area Index of the vegetation. The rest of the rainfall reaches the soil surface and either infiltrates or creates runoff. Some of the salt in rainfall is intercepted on the plant leaves but then washed onto the soil surface in subsequent rain events. Transpiration is modelled as a function of the Leaf Area Index, relative root volume in the upper and lower stores, moisture content and the potential energy. Evaporation takes place from upper zone Dry and Wet Stores and Stream Zone Store (where it exists).

Surface runoff generated only by the process of saturation excess is rare in Western Australia as the intensity of rainfall rarely exceeds the infiltration capacity of soils. It is dependent upon the water content of the Wet Store and the variably contributing stream zone saturated areas. If part of the stream zone is saturated by the presence of the permanent groundwater system, direct runoff is also generated.

Interflow is the contribution from the shallow, intermittent groundwater system. If the permanent groundwater system does not discharge to the stream, interflow controls the recession limb of the streamflow hydrograph. Interflow is a function of the catchment-wide average lateral conductivity of the A-horizon, and the water content of the Wet Store.

Percolation is the amount of vertical water flow between the highly conductive A-horizon to the less conductive deep unsaturated soil profile. It is controlled by the catchment-wide vertical conductivity, water content in the Wet Store and the soil moisture deficit in the Subsurface Store. Most of the percolated water is used by the deep-rooted trees for transpiration so very little reaches the groundwater system. Recharge to the Groundwater Store consists of matrix and the preferential flow components.

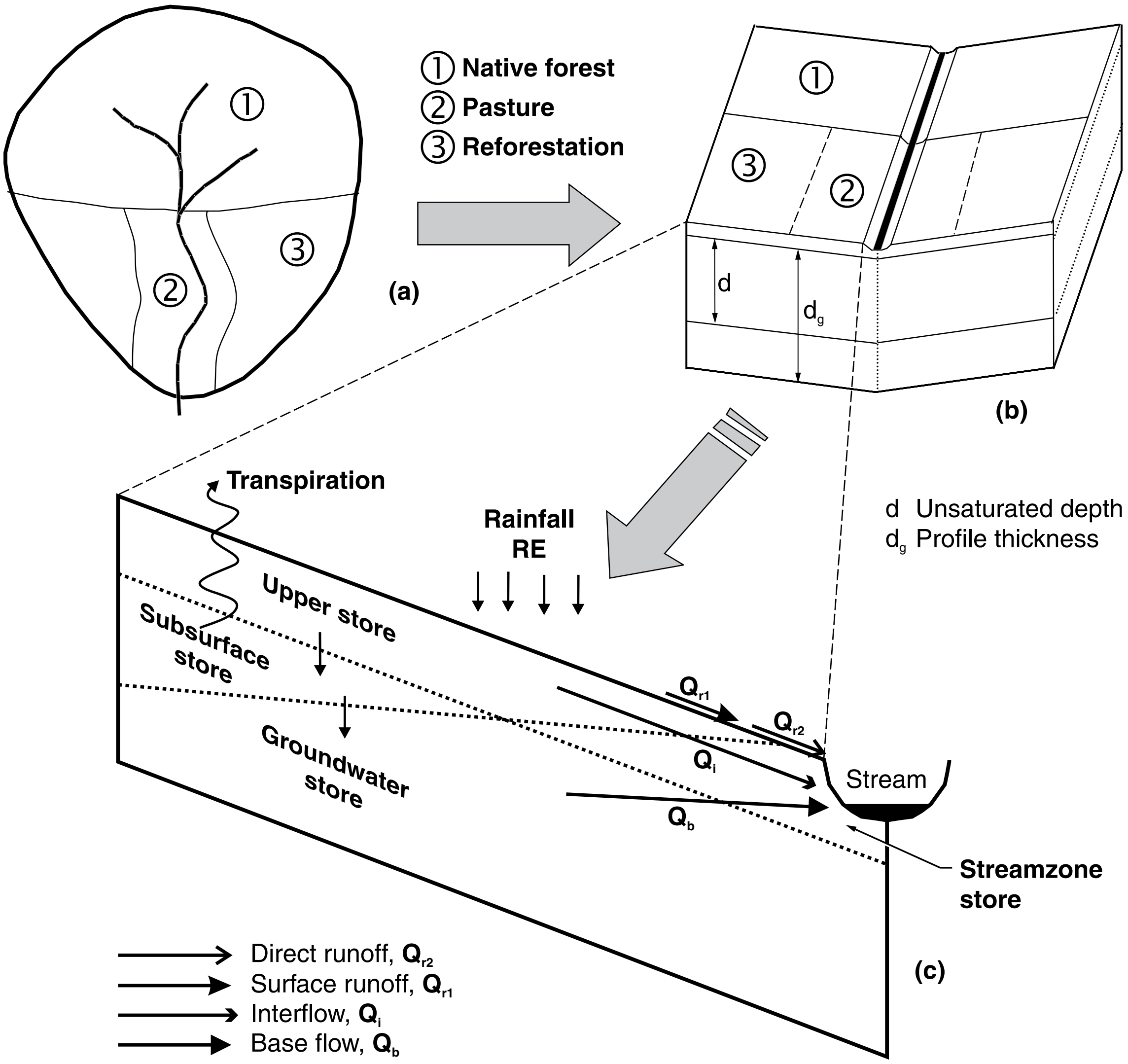


Figure A5.5 Schematic representation of (a) a subcatchment, (b) 'open book' representation, (c) hydrological processes

Baseflow is defined as the contribution of the permanent groundwater system to streamflow. Baseflow is considered to be zero unless the groundwater system connects to the stream bed. It is a function of the catchment-average lateral hydraulic conductivity of the aquifer, slope of the groundwater system, hydraulic head and stream length.

Generated flow from each of the subcatchments is routed downstream based on open channel hydraulics through a detailed channel and stream network. A particular segment of the channel may lose water through evaporation and infiltration if it becomes dry or the groundwater system does not contribute to the stream. The model is capable of reporting streamflow and salinity at any of the nominated channel nodes. All the spatially variable attributes of the catchment are incorporated into the model.

A5.2.2 Data preparation and LUCICAT model set up

Rainfall and salt fall

A total of 22 pluviometers located within and around the catchment was selected for creating long term daily rainfall series for each of the subcatchments. The daily rainfall series for each subcatchment was calculated based on its distance from nearest three pluviometers (Dean & Snyder 1977). The long-term (1910–2000) average annual rainfall for the Upper Kent River ranged from 830 mm in the west to 550 mm in the east. Salt concentration of the rainfall at the centroid of each of the subcatchment was estimated from the average annual rainfall to salt concentration relationship as described by Hingston and Gailitis (1976), and ranged from 10 to 6.5 mg/L TDS.

Pan evaporation

With no pan evaporation data recorded within the Upper Kent catchment, annual pan evaporation data at the centroid of each of the subcatchments was adopted from Luke et al. (1988) and ranged from 1395 mm to 1510 mm.

Salt storage

A strong correlation of increasing soil salt storage with decreasing rainfall is well established for south-west Western Australia (Stokes et al. 1980; Johnston et al. 1987). In the upper catchment, a number of soil salt storage measurements were undertaken in the 1970s to understand the vertical and areal distribution (Johnson et al. 1987; Bari & Boyd 1993) and many samples taken in the 1990s 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, generally in the order of 0.35 kg/m^3. Most of the salt is stored in the unsaturated soil profile. The groundwater salinity and long-term average rainfall of the sites were well correlated. There is also a reasonably strong relationship between the groundwater salinity and the salt storage. Based on these two relationships, salt content of the subcatchments were estimated as 2.2 kg/m^3 in the west to 4.6 kg/m^3 in the eastern part of the upper catchment.

Land-use history

The land use history of each subcatchment for the whole period of simulation (1968–2003) 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.

A5.2.3 LUCICAT model calibration

LUCICAT needs minimal calibration (Bari et al. 2003; Bari & Smettem 2003) as most of the parameters are 'fixed' once calibrated in a catchment with the exception of 7 physically meaningful parameters which may vary between catchments. 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. The second most sensitive parameter was vertical conductivity of the upper layer (K_{uv}), which controls the percolation to the deep unsaturated profile. The vertical conductivity ranged between 15.29 and 27.185 mm/day for other applications (Bari et al. 2003). The other 'variable' parameters are the topsoil depth (*d*) and its spatial distribution of water-holding capacity (c,b), and the average lateral conductivity (K_{ll}) of the aquifer.

Once satisfactory matching of the observed and predicted daily flows was achieved, the next step was to calibrate the daily stream salinity and salt load. It was not possible to estimate the initial salt storage value of the stream zone from observed data. Therefore, the model was run for few times and the final value of the stream zone salt store was taken as the initial values for each of the runs. At this stage the lateral hydraulic conductivity of the deep aquifer (K_{ll}) and the other parameter (C_u) which controls the stability of the salts stored in the topsoil were also adjusted so that most satisfactory matching of the observed and predicted flow, salinity, salt load and groundwater trend were achieved. The 'final' value of each parameter and a comparison of the magnitude of the parameters between the Collie River and Kent River catchments is given in Table A5.5.

Table A5.5 Adopted and final values of the 'variable' parameter set for the Upper Kent catchment

Parameter	Unit	Range	Rank	Most likely	Collie River	Upper Kent
c	-	0.256–0.56	3	0.256	0.2056	0.125
b	-	0.123–0.625	6	0.256	0.2056	0.125
d	(mm)	1900–2500	4	2500	1600–2500	1550–2500
ia	-	2.15–3.15	1	2.3	2.5	2.0
K_{uv}	(mm/day)	15.29–27.185	2	27.185	27.185	27.185
K_{ll}	(mm/day)	400–1500	5	500	300	350
C_u	-	0.0042–0.0263	7	0.0163	0.0063	0.0063

Groundwater system

In the upper catchment, groundwater levels under native forest vary due to local geology and the presence of palaeochannels. Based on records and regional trends, an initial groundwater level was developed for each of the forested subcatchments but estimation of the initial groundwater level beneath the cleared areas was difficult. There were some studies of trends in groundwater level, particularly in the cleared areas of the upper catchment (Bari & Boyd 1993; McFarlane et al. 1994; Bartle et al. 2000; Bari & de Silva 2006). There is experimental evidence from 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. Typical examples of the predicted groundwater levels under native forest, cleared and replanted subcatchments are shown in Figure A5.6.

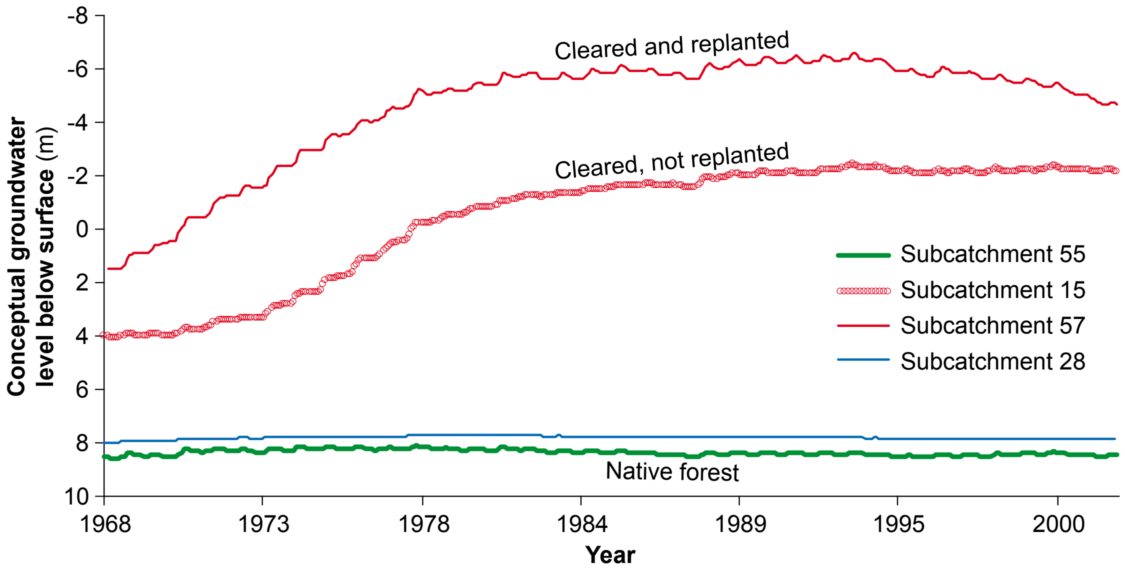


Figure A5.6 LUCICAT-predicted conceptual groundwater level below the stream bed of selected subcatchments

Annual streamflow, salinity and load

Annual observed and predicted streamflow salinity and salt load trends for the whole simulation period showed good agreement. The model slightly underpredicted the highest flow on record, observed in 1988. Annual streamflows for the low-flow years were generally well predicted but the predicted salt loads were higher than observed ones. Overall, LUCICAT successfully predicted annual salinity with a very high R^2 between the observed and predicted salinity (Fig. A5.7).

The LUCICAT-predicted annual streamflow, salinity and salt loads are highly variable over the catchment (Table A5.9). The 1992–2002 mean annual salinity ranged from 9300 mg/L TDS (Nukennullup MU) to 1920 mg/L TDS (Rocky Gully MU).

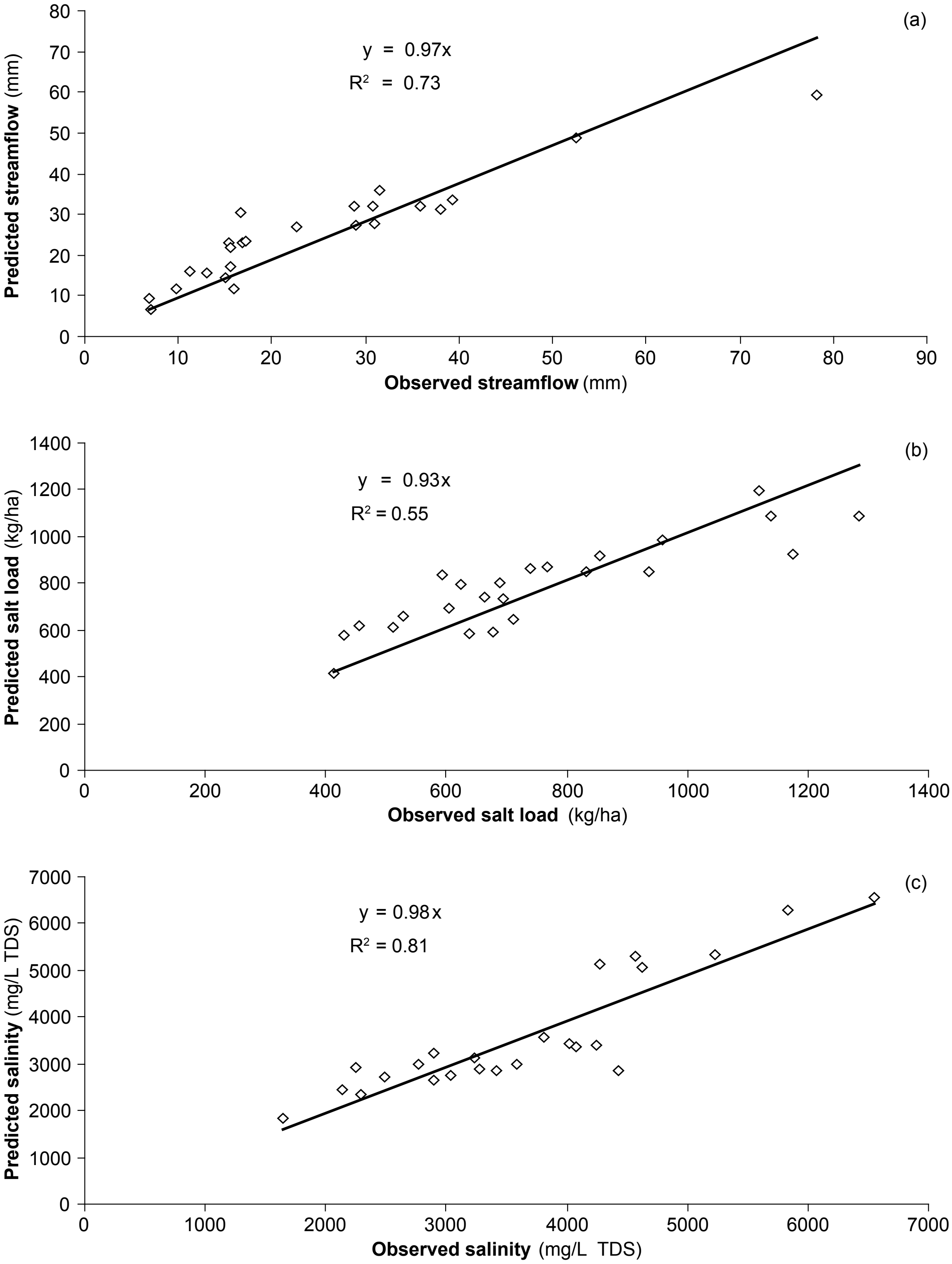


Figure A5.7 LUCICAT-predicted and observed annual (a) streamflow at (b) salinity, and (c) salt load at Rocky Glen

Monthly flow and salt load

A constrained linear relationship between the monthly observed and modelled streamflow gives a R^2 of 0.91 (Fig. A5.8a). The model overpredicts some low flows, particularly those less than 5 mm/month. A satisfactory relationship between the observed and predicted monthly salt load was observed (Fig. A5.8b).

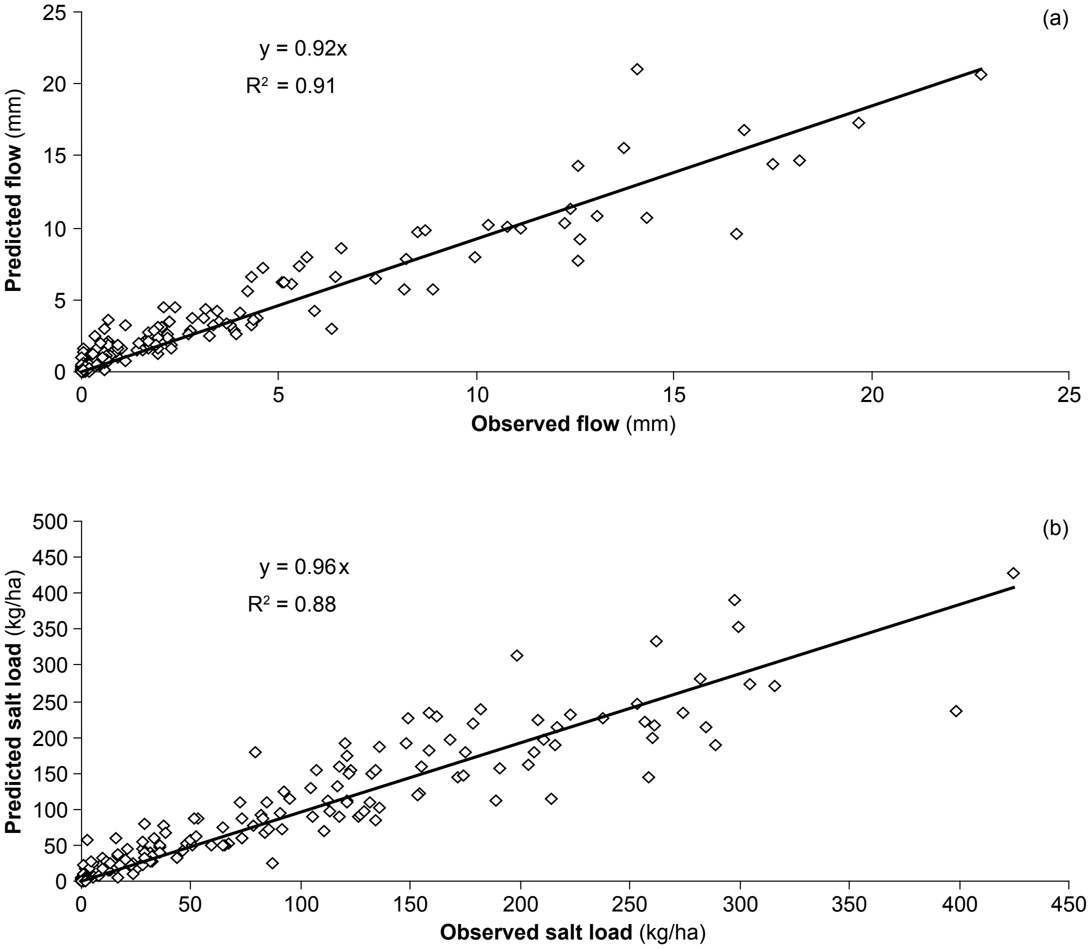


Figure A5.8 Relationship between monthly LUCICAT-predicted and observed (a) streamflow and (b) salt load at Rocky Glen

Daily streamflow salinity and load

For most years, daily simulated and observed streamflow hydrographs matched reasonably well. In the average-flow year of 2000, the spatial average rainfall in the Upper Kent was 590 mm. Daily streamflow was dominated by the baseflow component in October–May (Fig. A5.9a). Daily stream salinity was 5000–6000 mg/L TDS. The model predicted the flow generation processes very well, but the predicted daily salinity was more variable. Daily observed stream salinity increased to 10 000 mg/L TDS in April–June when the upstream part of the catchment began to flow and salt left on the soil surface when groundwater evaporated was flushed into the stream. The model slightly underpredicted the daily salinity, but matched the observed salt load. The model also slightly overpredicted the maximum daily (peak) flow of the year. The predicted and observed maximum runoff was 0.82 mm and 0.7 mm respectively.

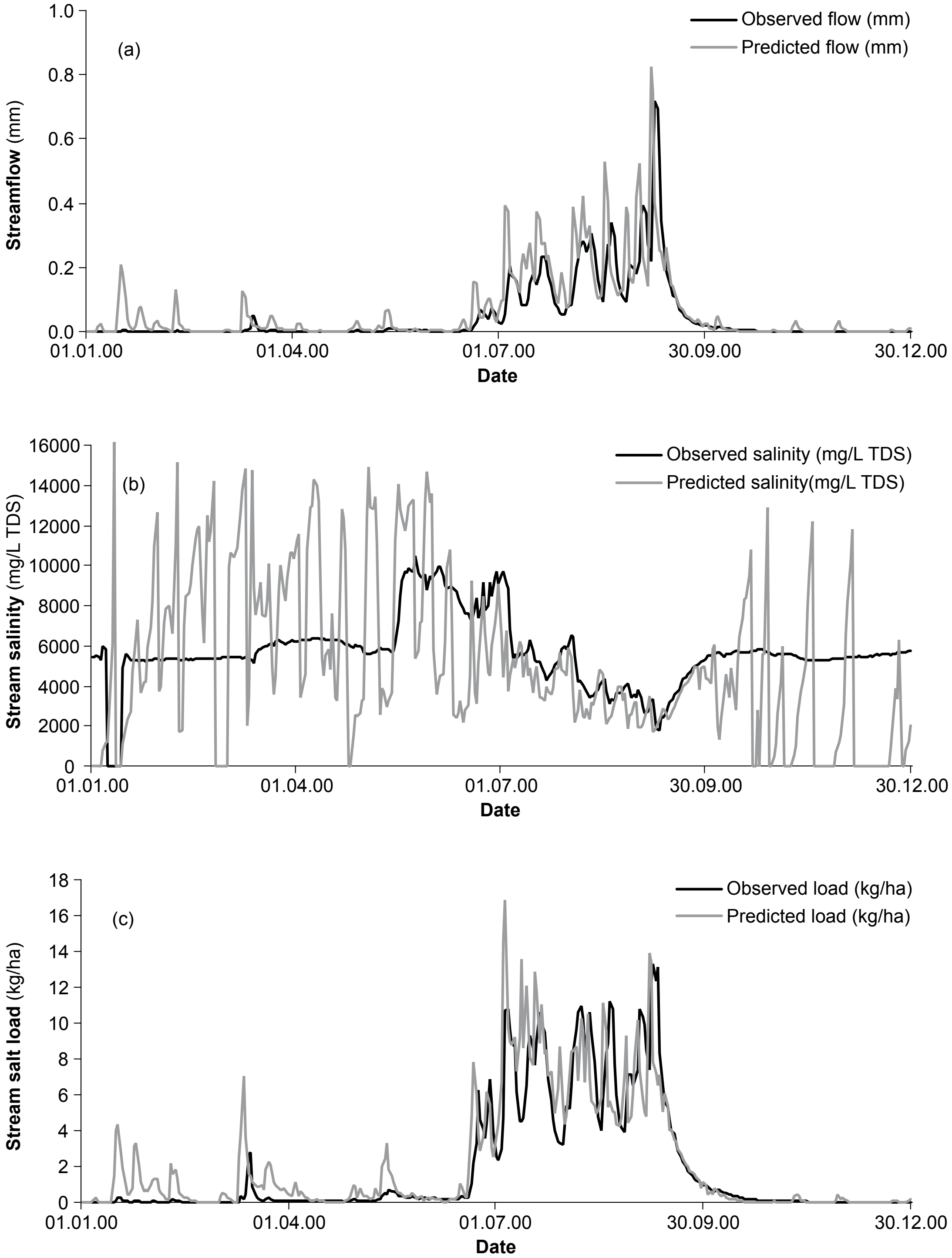


Figure A5.9 Daily observed and LUCICAT-predicted (a) streamflow, (b) salinity and (c) salt load at Rocky Glen for the year 2000

Table A5.6 Calibration case for MAGIC—Maximum clearing with average rainfall year (1980–95)

	Management unit								Gauging station			
						Internally drained[a]						
	Headwaters	**Wamballup**	**Lake Katherine**	**Middle Kent**	**Rocky Gully**	**Nunijup**	**Nukennullup**	**Poorrarecup**	**Watterson Farm**	**Perillup Road**	**Rocky Glen**	**Styx Junction**[b]
Total area (km^2)	128	86	93	123	340	100	127	94	244	764	1092	1843
Total cleared area in 1988 (km^2)	103	73	62	98	172	60	82	60	176	545	710	718
Total cleared in 1988 (%)	80	85	66	80	51	60	64	63	72	71	65	39
Average rainfall (mm/yr) (1980–95)	501	547	574	544	648	489	513	530	497	527	564	736
Streamflow (GL)	2.0	2.3	1.7	4.3	14.6	1.2	1.2	2.2	2.5	10.7	25	75
Runoff (mm)	16	27	18	35	43	12	10	23	10	14	23	41
Salt load (kt)	17	12	10	30	18	10	5	5	21	71	88	106
Stream salinity (mg/L TDS)	8520	5480	6300	6970	1250	8540	3800	2240	8560	6640	3550	1440
Groundwater discharge (GL)	1.6	1.4	1.2	1.9	3.4	1.1	0.3	0.9	1.9	6.3	9	N/A
Groundwater discharge (mm)	13	16	12	16	10	11	3	10	8	8	9	N/A
Shallow watertable (km^2)	24	22	18	27	42	14	18	12	42	136	177	N/A
Shallow watertable[c] (%)	19	25	19	22	12	14	14	13	17	18	16	N/A
Discharge area (km^2)	11	9	7	16	22	6	9	6	21	65	86	N/A
Modelled discharge area[d] (%)	9	10	7	13	7	6	7	7	9	8	8	N/A

[a] The inflow streamflow, salt load, stream salinity and groundwater discharge are for Lakes Nunijup, Carabundup and Poorrarecup.
[b] The catchment between Rocky Glen and Styx Junction is assumed to have 1% clearing in 1988.
[c] Shallow watertable as a % of the total area
[d] Discharge area as a % of the total area

Table A5.7 Verification case for MAGIC —Year 2000 vegetation with 2000 rainfall

	Management unit								Gauging station			
						Internally drained[a]						
	Headwaters	**Wamballup**	**Lake Katherine**	**Middle Kent**	**Rocky Gully**	**Nunijup**	**Nukennullup**	**Poorrarecup**	**Watterson Farm**	**Perillup Road**	**Rocky Glen**	**Styx Junction**[b]
Total area (km^2)	128	86	93	123	340	100	127	94	244	764	1092	1843
Total cleared area in 2000 (km^2)	98	69	47	88	114	59	64	43	170	471	580	N/A
Total cleared in 2000 (%)	76	80	50	72	33	59	50	45	70	62	53	N/A
Rainfall (mm/yr)	492	538	564	535	637	481	504	521	488	518	555	736
Streamflow (GL)	2.1	2.4	1.3	4.1	11.5	1.4	1.4	2.1	2.6	10.2	21	55
Runoff (mm)	17	28	14	33	34	14	11	22	11	13	20	30
Salt load (kt)	17	13	9	28	15	10	5	5	21	67	82	98
Stream salinity (mg/L TDS)	7920	5300	6770	6840	1330	7070	3590	2270	7840	6560	3810	1780
Groundwater discharge (GL)	1.6	1.4	1.0	1.7	2.5	1.1	0.4	0.9	1.8	5.8	8	N/A
Groundwater discharge (mm)	12	16	10	14	7	11	3	9	7	8	8	N/A
Shallow watertable (km^2)	23	22	16	26	49	14	17	12	41	132	180	N/A
Shallow watertable[c] (%)	18	25	18	21	15	14	14	13	17	17	16	N/A
Discharge area (km^2)	11	9	5	15	23	6	8	5	20	60	82	N/A
Modelled discharge area[d] (%)	8	10	6	12	7	6	6	6	8	8	7	N/A

[a] The inflow streamflow, salt load, stream salinity and groundwater discharge are for Lakes Nunijup, Carabundup and Poorrarecup.
[b] The catchment between Rocky Glen and Styx Junction is assumed to have 1% clearing in 1988.
[c] Shallow watertable as a % of the total area
[d] Discharge area as a % of the total area

Table A5.8 MAGIC model— Year 2000 vegetation with average rainfall year (1980–95)

	Management unit								Gauging station			
						Internally drained[a]						
	Headwaters	**Wamballup**	**Lake Katherine**	**Middle Kent**	**Rocky Gully**	**Nunijup**	**Nukennullup**	**Poorrarecup**	**Watterson Farm**	**Perillup Road**	**Rocky Glen**	**Styx Junction**[b]
Total area (km^2)	128	86	93	123	340	100	127	94	244	764	1092	1843
Total cleared area in 1988 (km^2)	98	69	47	88	114	59	64	43	170	471	580	587
Total cleared in 1988 (%)	76	80	50	72	33	59	50	45	70	62	53	32
Average rainfall (mm/yr) (1980–95)	501	547	574	544	648	489	513	530	497	527	564	736
Streamflow (GL)	1.9	2.1	1.1	3.8	10.1	1.2	1.3	2.0	2.3	9.1	19	69
Runoff (mm)	14	25	11	31	30	12	10	21	10	12	17	38
Salt load (kt)	17	13	9	28	15	10	5	5	21	68	82	100
Stream salinity (mg/L TDS)	9110	6000	8530	7440	1520	8580	3780	2480	8950	7440	4350	1440
Groundwater discharge (GL)	1.6	1.4	1.0	1.8	2.5	1.1	0.4	0.9	1.8	5.8	8	N/A
Groundwater discharge (mm)	12	16	10	14	7	11	3	9	7	8	8	N/A
Shallow watertable (km^2)	24	22	17	26	37	14	17	12	42	133	168	N/A
Shallow watertable[c] (%)	18	25	18	21	11	14	14	13	17	17	15	N/A
Discharge area (km^2)	11	9	5	15	17	7	8	5	20	60	77	N/A
Modelled discharge area[d] (%)	9	10	6	12	5	7	6	6	8	8	7	N/A

[a] The inflow streamflow, salt load, stream salinity and groundwater discharge are for Lakes Nunijup, Carabundup and Poorrarecup.

[b] The catchment between Rocky Glen and Styx Junction is assumed to have 1% clearing in 1988.

[c] Shallow watertable as a % of the total area

[d] Discharge area as a % of the total area

Table A5.9 Calibration case for LUCICAT

	Management unit								Gauging station			
	Headwaters	**Wamballup**	**Lake Katherine**	**Middle Kent**	**Rocky Gully**	**Nunijup**	**Nukennullup**	**Poorrarecup**	**Watersons**	**Perillup Road**	**Rocky Glen**	**Styx Junction**[a]
Area (km^2)	128	86	93	123	340	100	127	94	244	764	1092	1843
Cleared area in 1978 (km^2)	102	74	68	101	176	60	80	59	176	551	719	727[a]
Cleared area in 1978 (%)	80	86	72	82	52	60	63	63	72	72	66	39
Cleared area in 2002 (km^2)	95	68	40	66	93	59	49	34	168	412	503	511[a]
Cleared area in 2002 (%)	74	79	42	54	27	59	38	36	69	54	46	28
Means (1992–2002)												
Annual rainfall (mm)	530	545	590	570	670	525	535	545	530	560	590	665
Streamflow (GL)	2.3	1.8	2.0	3.4	17.6	1.0	1.4	0.8	2.6	10.1	27.2	77.7
Runoff (mm)	17.7	21.5	21.8	27.9	51.8	10.1	11.4	8.6	10.6	11.7	24.9	42.2
Salt load (kt)	14.8	11.0	16.7	16.7	33.8	9.2	13.4	2.8	16.5	60.8	93.0	110.7
Mean salinity (mg/L TDS)	6555	5970	8150	4860	1920	9110	9300	3495	6360	6040	3420	1425
Groundwater discharge to stream zone (mm)	8.7	13.8	13.6	14.2	12.1	7.6	8.5	3.2	8.5	10.0	10.0	
Baseflow (mm)	0.9	1.7	2.0	2.1	1.1	0.9	1.3	0.9	1.0	1.6	1.8	
Year 2000												
Annual rainfall (mm)	515	510	575	560	670	590	545	570	550	565	590	665
Streamflow (GL)	2.3	1.5	1.4	2.4	17.9	2.0	1.5	0.8	2.7	8.0	25.6	76.1
Runoff (mm)	18.2	17.8	15.4	19.5	52.6	19.6	11.6	9.0	11.1	9.4	23.5	41.3
Salt load (kt)	15.7	10.3	15.6	15.7	30.5	12.0	14.4	2.8	17.6	58.7	87.8	105.4
Mean salinity (mg/L TDS)	6730	6705	10805	6525	1705	6090	9840	3350	6460	7295	3430	1385
Groundwater discharge to stream zone (mm)	7.9	14.0	13.3	15.7	12.1	8.6	8.2	2.9	9.3	10.0	9.8	
Baseflow (mm)	0.6	1.4	2.0	3.2	1.1	0.9	1.4	0.9	1.0	1.6	1.8	

[a] The catchment between Rocky Glen and Styx Junction is assumed to have 1% clearing in 2002

Table A5.10 1940s forest

	Management unit								Gauging station			
						Internally drained						
	Headwaters	Wamballup	Lake Katherine	Middle Kent	Rocky Gully	Nunijup	Nukennullup	Poorrarecup	Watterson Farm	Perillup Road	Rocky Glen	Styx Junction [c]
Area (km²)	128	86	93	123	340	100	127	94	244	764	1092	1843
Cleared area (km²)	26	16	7.6	14	11	12	6.8	10	38	92	103	111[c]
Cleared area (%)	20	18	8.1	11	3.3	12	5.3	11	16	12	9.4	6.0
Rainfall period at equilibrium [a]												
Annual rainfall (mm)	530	545	590	570	670	525	535	545	530	560	590	665
Streamflow (GL)	0.5	0.4	0.5	0.8	10.4	0.1	0.2	0.2	0.5	2.4	12.6	63.1
Runoff (mm)	3.6	4.8	5.4	6.7	30.5	1.4	1.4	2.6	2.0	2.8	11.5	34.2
Salt load (kt)	0.5	0.6	0.7	0.8	2.1	0.1	0.1	0.06	0.5	2.5	4.6	22.3
Mean salinity (mg/L TDS)	1080	1375	1360	920	205	515	505	250	995	1070	370	355
Groundwater discharge to stream zone (mm)	0.3	0.4	0.5	0.7	0.5	0.0	0.0	0.0	0.1	0.2	0.3	
Baseflow (mm)	0.1	0.1	0.2	1.0	0.3	0.0	0.0	0.0	0.0	0.3	0.3	
Representative year at equilibrium [b]												
Annual rainfall (mm)	515	510	575	560	670	590	545	570	550	565	590	665
Streamflow (GL)	0.6	0.4	0.6	1.0	11.4	0.4	0.3	0.4	0.6	2.8	13.9	64.5
Runoff (mm)	4.4	5.2	6.0	8.2	33.4	4.0	2.1	4.2	2.4	3.3	12.8	35.0
Salt load (kt)	0.5	0.3	0.31	0.5	2.0	0.2	0.1	0.1	0.5	1.6	3.6	21.3
Mean salinity (mg/L TDS)	870	675	550	510	180	445	490	230	810	590	260	330
Groundwater discharge to stream zone (mm)	0.2	0.2	0.2	0.8	0.4	0.0	0.0	0.0	0.1	0.2	0.3	
Baseflow (mm)	0.0	0.1	0.1	0.8	0.2	0.0	0.0	0.0	0.0	0.2	0.2	

[a] Annual mean for the period 1992–2002
[b] Annual rainfall of 2000
[c] The catchment between Rocky Glen and Styx Junction is assumed to have 1% clearing in 2002.

Table A5.11 1965 clearing

	Management unit								Gauging station			
						Internally drained						
	Headwaters	Wamballup	Lake Katherine	Middle Kent	Rocky Gully	Nunijup	Nukennullup	Poorrarecup	Watterson Farm	Perillup Road	Rocky Glen	Styx Junction [c]
Area (km²)	128	86	93	123	340	100	127	94	244	764	1092	1843
Cleared area (km²)	68	50	29	75	144	39	54	43	117	363	504	512[c]
Cleared area (%)	53	59	31	61	42	39	43	46	48	48	46	28
Rainfall period at equilibrium [a]												
Annual rainfall (mm)	530	545	590	570	670	525	535	545	530	560	590	665
Streamflow (GL)	1.1	1.6	1.2	3.3	18.8	0.4	1.1	0.8	1.3	7.6	26.0	76.5
Runoff (mm)	9.0	18.2	12.4	26.9	55.4	4.2	8.7	9.0	5.2	8.9	23.8	41.5
Salt load (kt)	4.3	6.2	3.1	10.8	27.2	0.6	5.4	1.98	4.5	25.2	51.6	69.3
Mean salinity (mg/L TDS)	3715	3975	2640	3280	1445	1495	4865	2340	3570	3305	1985	905
Groundwater discharge to stream zone (mm	3.3	5.4	2.5	6.0	9.2	1.7	3.6	0.1	2.6	4.2	5.4	
Baseflow (mm)	0.5	0.9	0.7	2.1	2.2	0.3	0.7	0.4	0.5	0.9	1.3	
Representative year at equilibrium [b]												
Annual rainfall (mm)	515	510	575	560	670	590	545	570	550	565	590	665
Streamflow (GL)	1.5	1.6	1.4	3.6	20.8	1.1	1.6	1.1	1.6	8.6	28.9	79.4
Runoff (mm)	11.5	18.7	15.0	29.6	61.1	10.9	12.6	11.7	6.5	10.0	26.5	43.1
Salt load (kt)	4.2	6.1	2.67	11.4	26.3	0.7	5.8	2.3	4.4	25.1	50.6	68.3
Mean salinity (mg/L TDS)	2875	3800	1895	3115	1265	615	3640	2050	2770	2910	1755	860
Groundwater discharge to stream zone (mm	3.2	5.3	1.9	6.0	9.6	1.5	3.4	0.0	2.5	4.1	5.4	
Baseflow (mm)	0.4	0.8	0.6	2.1	2.3	0.3	0.7	0.4	0.4	0.9	1.3	

[a] Annual mean for the period 1992–2002
[b] Annual rainfall of 2000
[c] The catchment between Rocky Glen and Styx Junction is assumed to have 1% clearing in 2002.

Appendix 6 Management options

A6.1 Land suitable for tree planting and perennial pastures

Environmental requirements

Environmental requirements for some selected commercial trees and perennial pastures were obtained from the Forest Products Commission (D Guille & G Batty pers. comm.) when preparing the Warren Salinity Situation Statement (Smith et al. 2005). The environmental requirements for commercial trees are listed in Table A6.1.

Table A6.1 Environmental requirements for commercial trees

	Preferred requirements	**Bluegum for pulp (*E. globulus*)**	**Hardwood sawlogs (*E. cladocalyx, E. saligna* and *C. maculata*)**	**Pines (Pinus pinaster)**
Rain-fall	Average rainfall (mm/yr)	> 700	> 550 (in blocks[a]) > 450 (in belts[b])	> 400
Land-scape	Inundation (months)	< 2	< 2	< 1
	Slopes (%)	< 14	< 14	< 14
Soil properties	Unrestricted rooting depth (m)	> 2	> 1.5 (in belts) > 2.0 (in blocks)	> 2.5
	Depth of sandy soil (m)	< 2	< 2	No limit
	Salinity (EM38) (mS/m)	< 50	< 60 (*E. saligna* and *C. maculata*) < 90 (*E. cladocalyx*)	< 60
	Soil pH (pH_{Ca})	4.5 to 8.5	4.5 to 8.5	< 8.5

[a] Blocks are plantings more than three rows wide
[b] Belt plantings 1, 2 or 3 rows wide, alleys with other uses > 20 m

Rainfall

Adequate rainfall is an important requirement for successful growth of commercial trees. Most of the upper catchment has an average annual rainfall of less than 700 mm, which is a major restriction for bluegum plantations that require, on average, more than 700 mm but less of a restriction for planting pines and hardwood sawlogs.

Landscape

Waterlogging is defined as saturation excess water in the root zone accompanied by anaerobic conditions. The excess water inhibits gas exchange with the atmosphere and the soil oxygen is rapidly depleted by biological activities and photosynthesis is impaired. The waterlogged areas were mapped directly based on analysis of the DEM, the criteria being that the land was less than 2.5 m above the stream level where the stream had a catchment area greater than 250 ha, and the slope of the ground was less than 4%. The suitable percentages for land outside waterlogged areas were therefore adjusted on the assumption that none of the suitable area was within the waterlogged area. The adjustments were based on the total areas of each 'soil mapping' unit within a subcatchment. Details of the calculation process are given in Smith et al. (2005).

Soil properties

The soil requirements for the commercial trees are listed in Table A6.1.

Soil groups in Western Australia are classified by criteria that include physical and chemical properties. For the upper catchment, digital soil–landscape mapping (Churchward et al. 1988; Stuart-Street et al. 2004; Stuart-Street & Scholz 2004) was used to identify the soil groups with the required physical and chemical properties to grow the commercial crops. These groups are represented as a percentage of a larger mapped area called a map unit. This type of soil mapping, by the Department of Agriculture, is called proportional mapping and the mapping process is detailed by van Gool and Moore (1999), and Schoknecht (2001). Unrestricted rooting depth and soil texture were the criteria used in this study.

Van Gool and Moore (1999) described the unrestricted rooting depth as 'the depth to a layer that restricts some or most plant roots'. The properties used in defining this depth are listed in Table A6.3. If one or more of these soil properties is within the range of the limiting value then plant growth is restricted. As soil pH and salinity are included as part of the unrestricted rooting depth they have not been considered as individual properties. Waterlogging is also considered as part of the unrestricted rooting depth. However, the predicted waterlogging areas described above were used.

Unrestricted rooting depth has a descriptive code where 'moderate' is 0.3–0.8 m; deep > 0.8 m; and 'very deep' is > 1.5 m (van Gool & Moore 1999). Soil groups with very deep unrestricted rooting depth (> 1.5 m) were considered suitable for commercial trees, deep-rooted and shallow perennial pastures. Shallow-rooted perennial pastures could also grow where the unrestricted rooting depth is moderate to deep (0.5 to 1.5 m).

Soil groups are also classed according to texture. Soil groups with deep sands (sands at depths > 0.8 m) were identified as suitable for pine trees and deep-rooted perennial pastures, but not for *Eucalyptus globulus*; *E. saligna*; *Corymbia maculata*; and *E. cladocalyx*.

Table A6.2 Limiting values for unrestricted rooting depth

Soil property	Non-limiting value	Limiting value
Aluminium toxicity	$pH_{Ca} > 4$	$pH_{Ca} < 4$
Alkalinity	$pH_w < 8.5$	$pH_w > 8.5$
Depth to permanently saturated horizon	Nil, low or very low risk	Very high waterlogging is always limiting. For areas with moderate to high waterlogging, root growth is generally limited to the lower depth of the seasonal watertable or depth to the impermeable layer.
Clayey subsoils	Porous, earthy soils or moderate to strongly pedal subsoils with a granular sub-angular blocky, polyhedral, angular blocky (< 50 mm) structure	Subsoils with a columnar or prismatic (> 100 mm) subsoil. Massive or weakly pedal subsoils that are not porous
Pans and hard layers	Absent	Presence of ferricrete and other cemented pans, saprolite
Gravels	< 60%	> 60%
Surface salinity	EC (1:5) < 50 mS/m	EC (1:5) > 50 mS/m

Land suitability criteria

The outcome was two gridded maps in which the value of each cell was the percentage of area that satisfied the criterion 'non-waterlogged unrestricted rooting depth very deep' and 'non-waterlogged unrestricted rooting depth deep and medium depth' (Table A6.3). Medium and deep unrestricted rooting depth was between 30–150 cm, while very deep unrestricted rooting depth was > 150 cm.

These maps were combined with limits on average rainfall, and that the land was still cleared in 2002, to identify the location and amount of land suitable for additional plantings of bluegums, pines, sawlogs, perennial pastures and deep rooted perennial pastures.

Table A6.3 Land suitability criteria

Land use	Waterlogged	Unrestricted rooting depth percentage criterion	Average annual rainfall
Bluegums	No	Very deep	> 700 mm
Pines (*Pinus pinaster*)		Very deep	> 400 mm
Eucalypt sawlogs		Very deep	Plantations > 550 mm Alleys > 450 mm
Shallow-rooted perennials in depths 50–150 cm	No	Medium and deep	N/A
Shallow-rooted perennials in depths >150 cm	No	Very deep	N/A
Deep-rooted perennials in depths >150 cm	No	Very deep	N/A

The requirements for perennial pastures (e.g. lucerne and kikuyu) were less restrictive than for commercial plantations and lucerne and kikuyu grow successfully on land with gradients less than 14%, and in soils with both an unrestricted rooting depth greater than 50 cm and pH 4.5–8.5.

Land capability results for trees and perennial pastures

Figures 29 and 31 are maps that show the percentages of land suitable for planting commercial trees and perennial pastures. The rainfall isohyets are shown in Figure 12 so that the areas in low rainfall zones can be seen. Table A6.4 lists the existing pasture areas of management units suitable for planting trees and perennial pastures.

Table A6.4 Existing pasture areas suitable for planting trees and perennial pasture

Management unit	Bluegums		Pines and sawlogs		Deep-rooted perennials		Shallow-rooted perennials	
	(km^2)	(%)[a]	(km^2)	(%)[a]	(km^2)	(%)[a]	(km^2)	(%)[a]
Headwaters	0	0	31	32	31	32	65	68
Wamballup	0	0	11	16	11	16	43	63
Lake Katherine	0	0	10	24	9	24	21	54
Middle Kent	0	0	14	21	14	21	40	61
Rocky Gully	20	21	30	32	30	32	68	73
Nunijup	0	0	23	39	23	39	41	71
Nukennullup	0	0	16	34	16	34	32	66
Poorrarecup	0	0	13	38	13	38	21	63
Watterson Farm	0	0	57	34	57	34	116	69
Perillup Road	9	2	117	28	136	33	310	75
Upper Kent	**20**	**4**	**150**	**29**	**147**	**29**	**332**	**66**

[a] Suitable area as a percentage of the 'Base' cleared

Comparison with existing bluegum plantations

The 2002 Landsat scene was used to estimate plantation areas in the upper catchment. The type of plantation was not evident by analysing the scene, but most of them are known to be bluegums. The criteria used in this study to define suitable areas seem too conservative given that 78% of all plantations in the Kent by 2002 were on land with too little rain (average rainfall < 700 mm), while 68% were on land deemed unsuitable due to restricted rooting depth (Table A6.3). According to the land suitability criteria, these plantations may have poor yields or die during long dry periods. Site investigations by bluegum plantation companies might have revealed that this land was suitable. Table A6.5 shows the areas of existing commercial plantations grown in land rated unsuitable due to restricted rooting depth and rainfall.

Table A6.5 Plantations rated according to 'Land capability study'

	Plantations in high rainfall zone (≥ 700 mm)		**Plantations in low rainfall zone (< 700 mm)**	
	Total (km²)	**On 'unsuitable' land** (km²)	**Total** (km²)	**In 'unsuitable' land** (km²)
Headwaters	0	0	5	1
Wamballup	0	0	5	0.7
Lake Katherine	0	0	23	8
Middle Kent	0	0	34	12
Rocky Gully	39	28	25	8
Nunijup	0	0	0.5	0.2
Nukennullup	0	0	28	10
Poorrarecup	0	0	18	6
Watterson Farm	0	0	5	1
Perillup Road	0	0	117	39
Upper Kent	**39**	**28**	**138**	**45**

Note: Commercial plantations as seen in the December 2001 Landsat scene

A6.2 Application of MAGIC model for the management options

Base case

A 'Base' case in which all plantation areas identified in the 2002 Landsat scene were assumed to be fully established was prepared. The 2002 Landsat scene was used to digitise plantation areas into a map and, within the manually digitised plantation areas, any tree greenness less than 80% of the model values of nearby forest was set equal to the model value tree greenness. Where there was plantation the pasture map was set to zero. The base case also used the model's estimate of lake evaporation similar to the calibration case. The model estimated the average annual salinity at Styx Junction to be 1310 mg/L TDS.

Revegetation management options

The land capability maps gridded into 25-m × 25-m cells with values showing the percentage of land suitable to plant either commercial trees or perennials were input into the model and used to simulate most of the vegetation management options.

The effects of partial treatments for each management unit were calculated by the method below. These calculations are in the 'management units' sheet of each MAGIC management option spreadsheet.

1. All catchments were simulated assuming that all pasture areas with any land suitable for the proposed vegetation was 100% planted and included the plantations and native vegetation from the 'Base' case. This simulation was called 'modelling of full areas'.

2. The differences in streamflow and salt load between the ‘Base’ case and the ‘modelling of full areas’ results were calculated — called ‘Base case minus full area modelling’.
3. The above differences was/were multiplied by the percentage of suitable area and divided by the modelled planted area, separately for each management unit, and the revised differences subtracted from the base case results to estimate the maximum effect feasible with that vegetation option — called ‘Base case minus suitable area case’.
4. The effects of partial treatments for each management unit were estimated by multiplying the percentage of partial treatment by the differences calculated in No. 3 above — called ‘% of suitable areas planted’.
5. The sum of salt load and streamflow at Rocky Glen or Upper Kent is calculated by summing only the salt loads and streamflows from the management units Headwaters, Wamballup, Lake Katherine, Middle Kent and Rocky Gully that have positive streamflows. (The ‘internally drained’ non-contributing catchments — Nukennullup, Poorrarecup and Nunijup — were omitted.)

Summary of MAGIC results

The management options modelled using MAGIC are summarised in Table A6.6 and detailed in Appendix A6.7 (Tables A6.8–A6.18).

Table A6.6 Summary of MAGIC results for management options

Management option	**Comments**	**Planted area**[a] (km^2)	**Upper catchment still cleared** (%)	**Styx Junction**		
				Salinity (mg/L TDS)	**Streamflow** (GL)	**Salt load** (kt)
Base	Do nothing	0	46	1310	66	87
Commercial trees [b]	Sited according to land capability					
Bluegums		20	44	1300	65	85
Bluegums and/or pines and sawlogs	Bluegums in suitable areas only	147	33	1090	63	68
Non-commercial trees	Most of the cleared area planted	360	13	480	55	26
	Waterlogged land	150	32	1180	60	71
Perennial pasture [b]						
Deep-rooted [c]	Sited according to land capability	147	33	1190–1320	63–64	74–85
Shallow-rooted [c]	Sited according to land capability	332	16	1050–1380	57–61	60–84
Shallow-rooted perennial pastures	Waterlogged land	150	32	1320–1350	61–64	80–87
Drains	309 km of deep drains and 3031 km of shallow drains	N/A	46	1360	67	91

[a] All planted trees and perennial pastures replace pastured land in the Upper Kent catchment

[b] Land capability maps used to site plantations and perennial pasture

[c] Results given as range because of uncertainties with LAI for perennial pastures

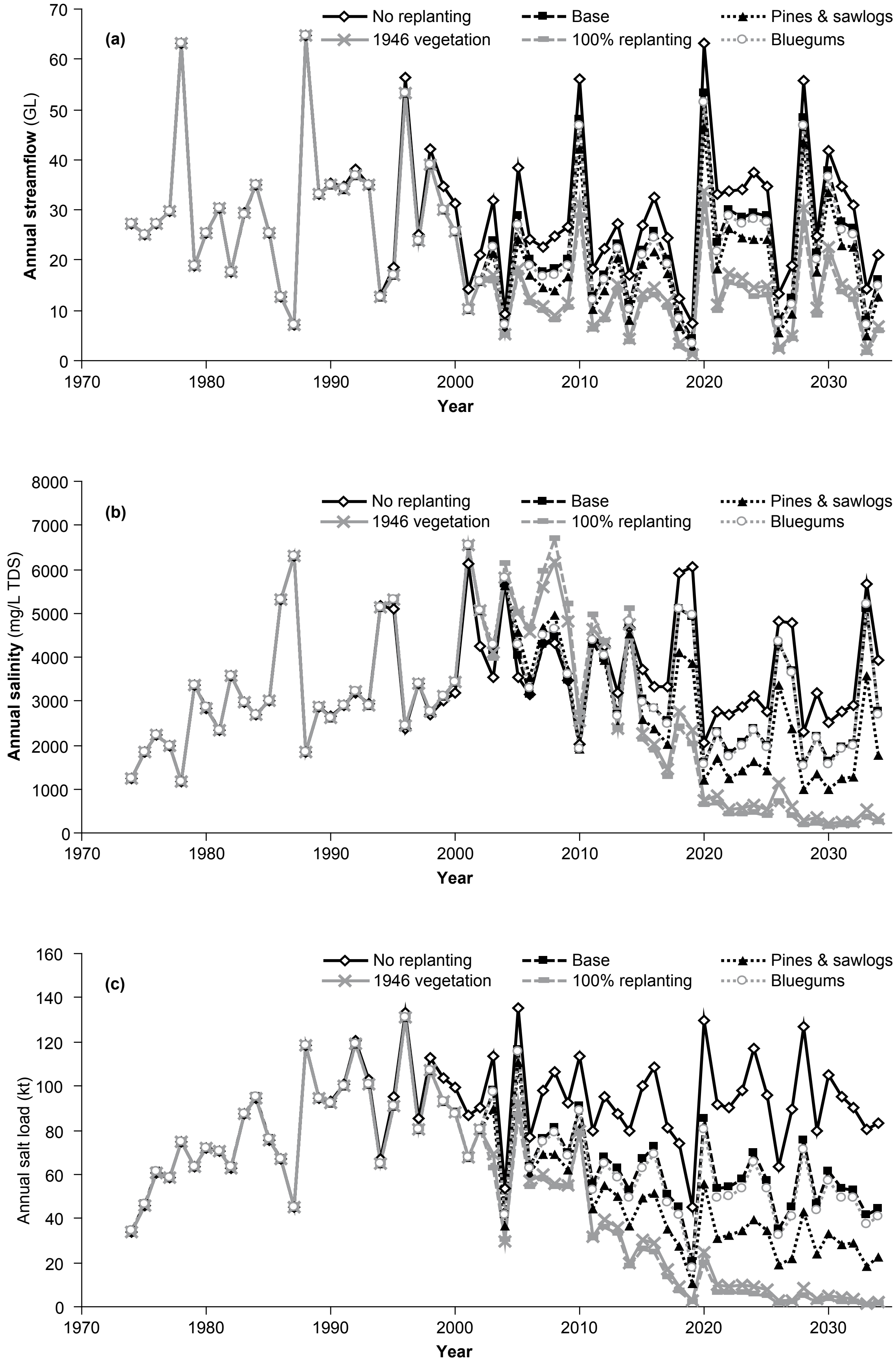


Figure A6.1 LUCICAT-predicted annual (a) streamflow (b) salinity and (c) salt load at Rocky Glen

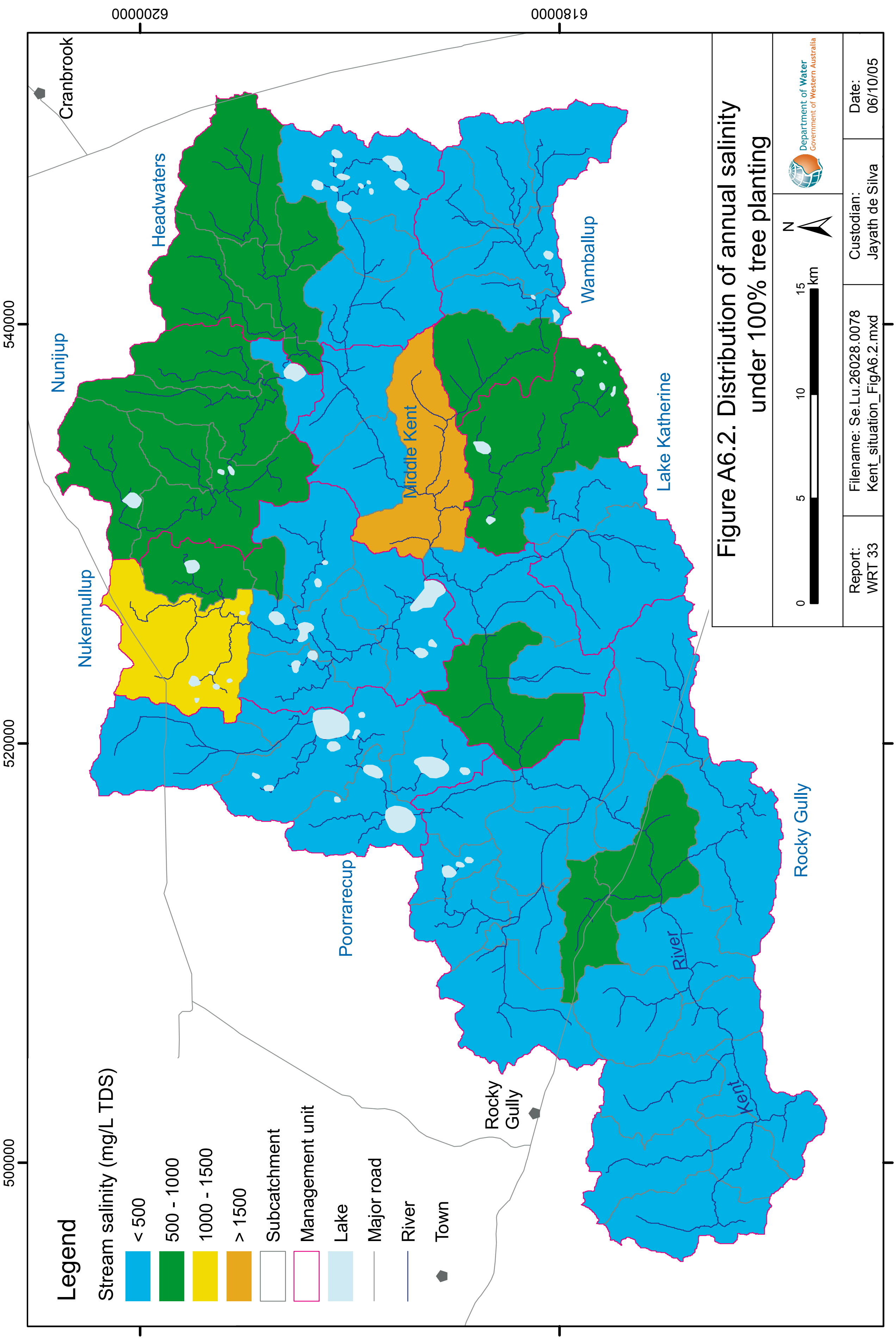


Figure A6.2 Distribution of annual salinity under 100% tree planting

A6.3 Application of LUCICAT for tree options

LUCICAT was applied to evaluate the effects of different catchment management options and scenarios. Daily rainfall and pan evaporation data for 1971–2002 were repeated taking 1971 as 2003. All the management options were implemented on 1 January 2003. Plant rooting depth and Leaf Area Index were increased gradually to represent normal plant growth and reached mature forest level in year 10. The model was run on a daily time-step and the outputs summed to annual for comparison with observations. Figure A6.1 shows the annual values at Rocky Glen for various land use management options. If all the cleared area of the catchment were planted, annual stream salinity at Styx Junction would fall to approximately 250 mg/L TDS by 2025. Therefore mean annual rainfall for the period (2024–34) which corresponds to the annual rainfall of 1992–2002 was taken for comparison with different management options.

Base case

The LUCICAT model was run up to the year 2002, but most of the trees planted in the mid 1990s were still immature. A picture of the catchment at equilibrium with no further action was built by retaining the same subcatchment fractions of pasture and forest, and allowing all recent plantations to grow to maturity. Daily streamflow, particularly the peak flow, and salinity were reduced at equilibrium. Average annual figures were also reduced (Fig. A6.1): salinity down to 2210 mg/L TDS, and flows down by 3 GL to 24 GL at Rocky Glen. Detailed reductions in streamflow and salt load by management units are in Table A6.19.

Bluegums

With only another 2% of the upper catchment deemed suitable for bluegums, this option provides no dramatic salinity reductions: stream salinity at Rocky Glen down by less than 100 mg/L TDS and minimal reduction at Styx Junction. The biggest reduction is in the Rocky Gully management unit which has most of the cleared area suitable for bluegums (Table A6.20).

Bluegums and/or pines and sawlogs

By planting either bluegums, pines or sawlogs on the 151 km^2 of suitable land, at Rocky Glen, mean annual stream salinity falls to 1415 mgL/TDS, streamflow reduces by approximately 4 GL due to the increased evapotranspiration, and average salt load falls dramatically from 53.1 kt to 28.4 kt. At Styx Junction, stream salinity is down to 650 mg/LTDS. Annual stream salinity in the Rocky Gully management unit is predicted to go down to 570 mg/L TDS and the Wamballup management unit to have the highest salinity, 3875 mg/L TDS (Table A6.21).

All the cleared area planted with trees

Replanting 100% of the cleared are area would reduce mean annual stream salinity at Rocky Glen and Styx Junction to 255 and 330 mg/L TDS respectively (Table A6.22). The conceptual groundwater levels below the replanted areas fall greatly over time, with further reductions possible beyond the modelling time frame. The groundwater level beneath native forest was practically stable for the whole simulation period. In terms of within-year variations, the peak flow, recession and flow duration all reduced. The groundwater contribution to the stream zone nearly reaches zero and for all management units mean annual salinity falls below 1000 mg/L TDS (Table A6.22). Figure A6.2 represents the salinity in each subcatchment under 100% tree planting for a typical year in equilibrium (2000 rainfall). The highest salinity (above 500 mg/L TDS) remained in the eastern section of the catchment, where lower rainfall, higher evaporation and low runoff limit flushing of accumulated salts from the stream zone. These areas may need longer to reach their steady-state salinity.

No tree planting after clearing controls

If trees had not been replanted in the upper catchment following clearing controls (1978) then average annual stream salinity at the Rocky Glen gauging station could have reached 3140 mg/L TDS, instead of the observed mean of 2210 mg/L TDS —reduction from the base is 930 mg/L TDS. The corresponding salinity at Styx Junction would have been 1380 mg/L TDS rather than 950 mg/L TDS. Average annual salt load reduction was 40.2 kt at the Rocky Glen gauging station. The average annual streamflow reduction due to tree planting was 5.7 GL. Mean annual stream salinity at the outlet of the different management units would vary significantly, ranging from 1665 mg/L TDS to 9730 mg/L TDS (Table A6.23).

All private land cleared

If all the private land in the Upper Kent catchment had been cleared mean annual stream salinity at Rocky Glen and Styx Junction would probably have reached 3350 mg/L TDS and 1640 mg/L TDS respectively (Table A6.24).

Characteristic curves

Plotting the proportions of the cleared area planted with trees against mean annual runoff, salinity and salt load at equilibrium revealed some interesting facts (Fig. A6.3). Mean annual runoff is predicted to decline systematically to 10 mm if all the cleared areas are planted. Predicted runoff was also compared with records of south-west Western Australian catchments with similar rainfall, evapotranspiration demand and clearing (shown in text box—Fig. A6.3). The observed mean runoff at gauging station 616013 was significantly lower than the predicted runoff at Rocky Glen, probably due to higher pan evaporation and lower rainfall. The observed runoff of gauging station 614196 (80% clearing) was higher than the predicted runoff at Rocky Glen with a similar proportion of clearing.

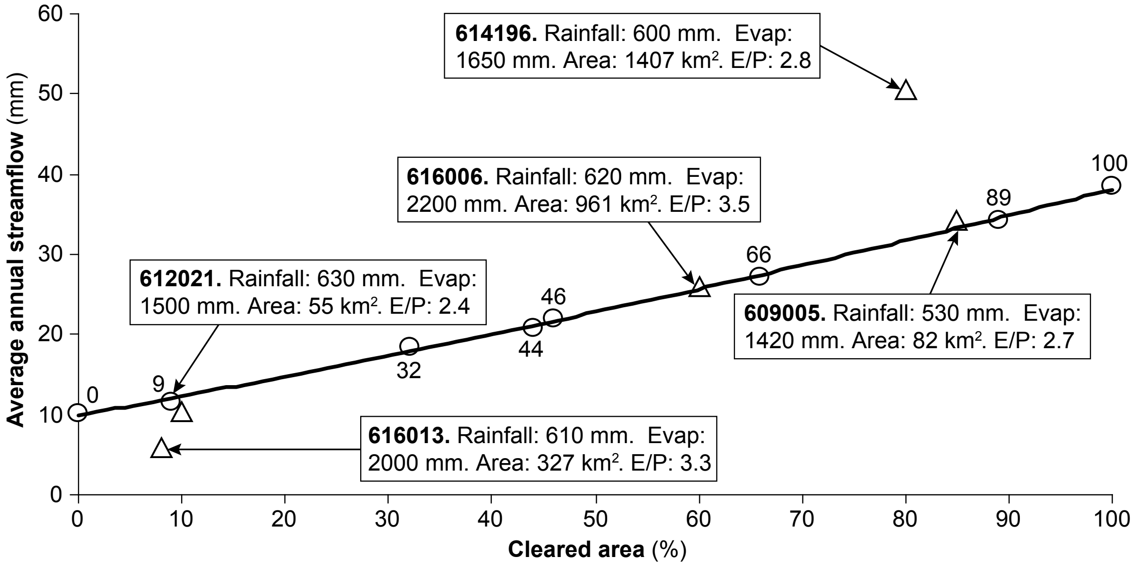


Figure A6.3 LUCICAT-predicted mean annual runoff at Rocky Glen

The relationships between the proportion of the cleared area planted to mean stream salt load and salinity reductions are clearly non-linear (Figs A6.4 & A6.5). The predicted salt load reduction matches with records of similar gauging stations reasonably well but the observed salinities at gauging stations with similar catchment attributes are highly variable. The mean annual salinity at Rocky Glen is predicted to decrease roughly 4 mg/L TDS per square kilometre of cleared area planted. Similar results of 3 mg/L TDS were obtained from the Denmark River catchment when the MAGIC model was applied to predict the effects of management options (Bari et al. 2004).

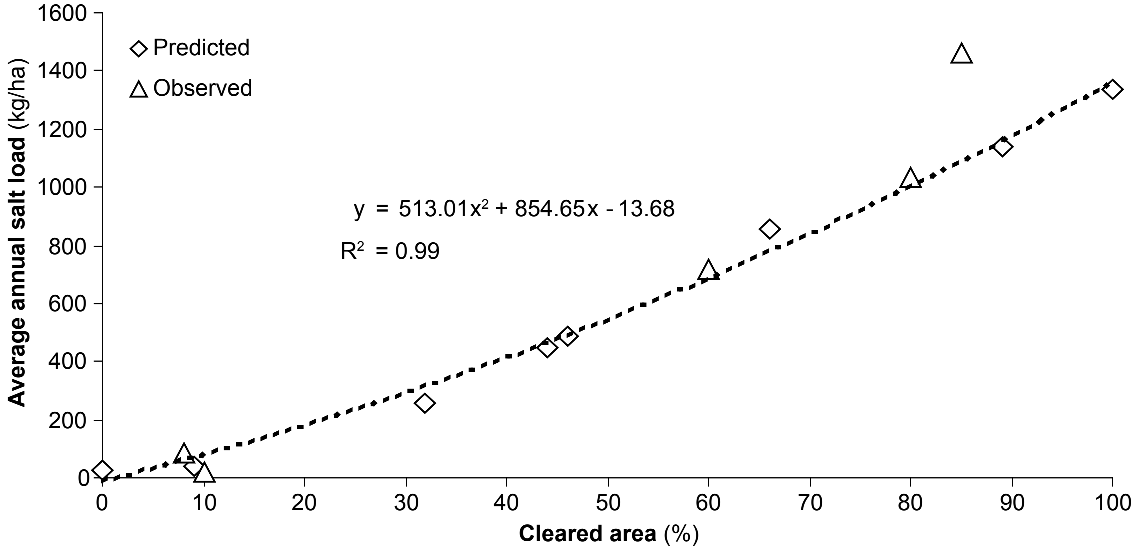


Figure A6.4 LUCICAT-predicted mean annual salt load at Rocky Glen

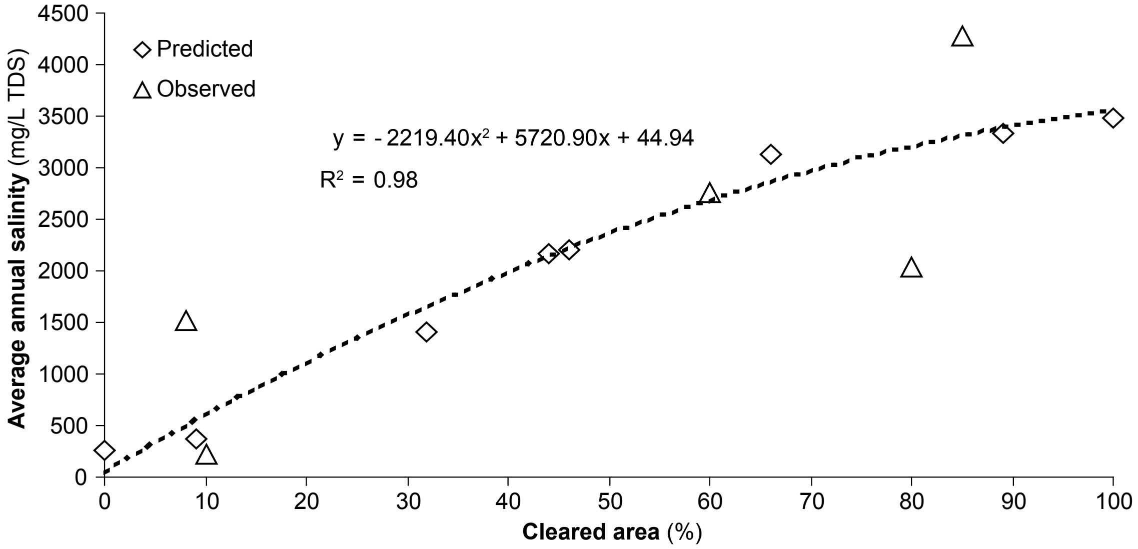


Figure A6.5 LUCICAT-predicted annual salinity at Rocky Glen

A6.4 Comparing MAGIC and LUCICAT models for the tree management options

The two models are fundamentally very different: MAGIC is a steady-state model that assumes the same land use in a catchment for so many years that the salinity processes are at equilibrium while LUCICAT was used to take a snapshot of the catchment with a particular land use for an average year. Management options are applied to the catchment under the same rainfall and the salinity outputs compared.

MAGIC was calibrated first to the catchment under the maximum cleared state using records that represented the catchment in its full expression of salinity. To compare the outputs of the models, the daily rainfall and pan evaporation data for the period 1971–2002 in the LUCICAT model was repeated after 2002, taking 1971 as 2003. All the management options were implemented on 1 January 2003. Plant rooting depth and Leaf Area Index were increased gradually to represent normal plant growth and reached mature forest level in year 10. By the year 2024, the catchment was in equilibrium. The average annual figures for 2024–34 were compared to MAGIC and reported under the heading ‘Rainfall period at equilibrium’ in Tables A6.19–24.

The differences between the models for different areas of trees planted are shown in Figure A6.6. The MAGIC results are for the calibration or ‘maximum cleared’ case (Table A5.6), ‘Base’ case (Table A6.8), bluegums and/or pines and sawlogs’(147 km^2 of extra trees, Table A6.10) and ‘most of the cleared land planted’ (Table A6.12). The LUCICAT results are for calibration or ‘maximum cleared’ case (Table A5.9), the ‘Base’ case (Table A6.19), bluegums and/or pines and sawlogs (147 km^2 of extra trees, Table A6.21) and ‘1940’s forest’ (Table A5.10).

Streamflow

The streamflows generated by MAGIC and LUCICAT were similar for the maximum cleared case and agreed with the records at the Rocky Glen gauging station (data point 1, Fig. A6.6a). The streamflows from MAGIC for all other options were around 8–9 GL lower than the streamflows from LUCICAT (data points 2-4, Fig. 6.6a).

MAGIC used 25 m gridded square cells derived from geographical information to capture the land use of each subcatchment and ‘greenness’ index to estimate transpiration by trees. It is difficult to estimate the ‘greenness’ of the added plantations: if it is too high, not enough streamflow is generated and if it is too low then recharge can occur under the plantation. The greenness of the added plantations varied with rainfall and was calculated to try and match the existing native forest in good condition. This was a bit subjective in catchments that were heavily cleared and left only with scattered paddock trees since there was not much existing native forest with understorey. However, MAGIC could distinguish between native forest in poor condition and healthy native forest. The plantations were made to use as much water as healthy native forest.

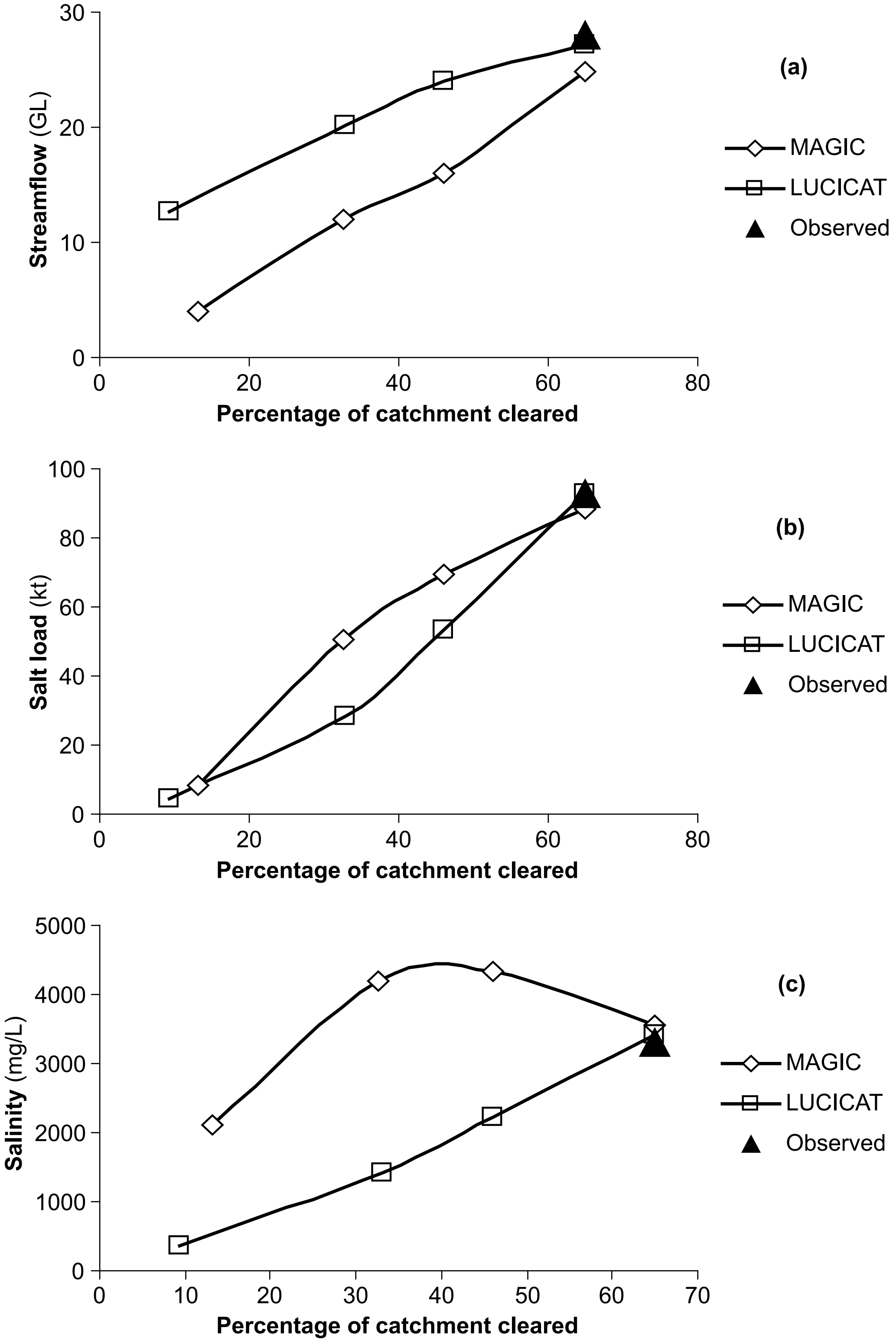
LUCICAT used a simpler method to input land-use information for each subcatchment. The LAI of the plantations was assumed to be equal to that of native forest already in the model. It assumed a constant LAI for the added plantations with a percentage of the catchment under trees. The water use of the trees (native forest or plantations) was adjusted during calibration to match the records.

The ‘characteristic’ curve for predicted mean annual runoff at Rocky Glen (Fig. A6.3) suggests that LUCICAT was better at estimating streamflows than MAGIC, which potentially underestimated streamflow of substantially forested catchments because it had no process for producing infiltration excess which happens when the rainfall intensity exceeds the infiltration capacity of unsaturated areas during intense storms. A version of MAGIC with this process applied has subsequently been developed, applied to a cleared, lower-rainfall catchment and produced several extra millimetres of rainfall per year (Geoff Mauger, pers. comm). The extra runoff would have been small compared to the total annual runoff produced during the maximum cleared case (data point 1 in Fig. A6.6a), but more significant when saturated areas were reduced by large-scale tree planting (data points 2–4 in Fig. A6.6a).

Salt loads

MAGIC produced higher salt loads than LUCICAT (Fig. A6.6b).

In the tree management options modelled by MAGIC, no trees were planted on the stream zones which are unsuitable waterlogged areas. In MAGIC, there was no groundwater discharge under large areas of trees; all of the discharge appeared in the stream zone, where there were few trees. Groundwater discharge into the shallow layer for ‘most of the cleared land planted’ (13% cleared, data point 4) was 1.4 mm. The groundwater discharge to the stream zone and baseflow in LUCICAT for ‘1940s forest’ (9% cleared, data point 5) was 0.3 mm and 0.2 mm respectively. The discharge from MAGIC might have been less if the trees were planted more evenly in the landscape. Even if all up-slope areas are forested, minor clearing along valley floors may produce saline discharge, as shown by historical experience in the Collie catchment. For relatively small cleared areas, the rate of discharge will be very sensitive to the capacity of the deep aquifer to carry groundwater down the valley length, and to the recharge rates. This can lead to relatively large differences in estimates when different calculating methods are used, as is the case between MAGIC and LUCICAT.



Data points

1. Calibration or 'Maximum cleared' case
2. Base case
3. Bluegums and/or pines and sawlogs (147 km^2 of additional commercial trees since 2002)
4. 'Most of the cleared land planted by MAGIC' (360 km^2 of additional trees since 2002)
5. '1940s forest by LUCICAT' (400 km^2 of additional trees since 2002)

Figure A6.6 Comparing tree-based management options at Rocky Glen

Under large areas of native forest and plantations in low rainfall catchments like the Upper Kent, the trees may use so much water that the groundwater aquifer beneath the shallow surface layer is lowered and disconnects from the stream. Groundwater discharge into the stream is then zero. The LUCICAT model assumes this process. For the '1940s forest' case modelled by LUCICAT, (Table A5.10) the baseflow was close to zero for most of the management units. However, under certain geological conditions such as in alluvial and colluvial sediments, groundwater can connect to parts of the streams, even under native forest. LUCICAT does not model these conditions. As alluvial and colluvial sediments are evident in all the management units (Fig. A5.1), LUCICAT might be under-estimating some of the seepage in these areas where cleared areas are upstream of the sediment areas (except for Poorrarecup, Nukennullup and Nunijup where the salt is trapped in these internally drained management units).

Most of the salt load from MAGIC is from groundwater discharge to the stream (baseflow) with a smaller component from salt in the rain (salt fall). The 'discharge into the shallow top layer' output from MAGIC and the 'groundwater discharge to stream zone' output in LUCICAT should be similar because they both represent discharge to the shallow top layer. The 'baseflow' output from LUCICAT is the estimated average annual discharge that reaches the stream. MAGIC does not separate this groundwater flow component from the total streamflow.

In the 'Base' case, MAGIC and LUCICAT both had the groundwater discharge into the shallow layer as 6 mm at Rocky Glen. (Tables A6.7 & A6.20). LUCICAT estimated that the baseflow for the 'Base' case was 1.2 mm. The resulting salt loads were different: 69 kt for MAGIC and 53 kt for LUCICAT. This is partly because the salt load calculated by MAGIC uses all of the groundwater that discharges into the shallow layer, while LUCICAT uses a proportion of this that ends up in the stream.

For the 'bluegums and/or pines and sawlogs' case, the discharge into the shallow layer estimated by MAGIC was 5.0 mm (Table A6.10), while the corresponding discharge into the stream zone estimated by LUCICAT was 2.7 mm (Table A6.21) at Rocky Glen. The baseflow calculated by LUCICAT was 0.7 mm for the same case. This resulted in the MAGIC-salt load at Rocky Glen being 78% higher than the LUCICAT-salt load.

MAGIC assumes that all the groundwater discharged into the shallow layer eventually ends up in the stream over a year. If the evaporation at the surface is too high, the salt in the discharge may stay in the soil for a few months or a few years. If the catchment receives high rainfall when it is already wet (usually in winter), the interflow (lateral flow of water in the top layer) will move the salt in the groundwater discharge to the stream. The lower salt loads produced by LUCICAT are partly due to a time delay where the salt discharged into the shallow topsoil does not all reach the stream in one year. Some of the salt may stay in the soil, close to the surface.

A small component of the differences in salt loads between the models might be due in some part to MAGIC not reaching equilibrium after 3 years. MAGIC was run for 3 years using a repeat of the average monthly rainfall for the period 1980–95 and the land use of the catchment constant for all management options. Option 2 was re-run for the whole upper catchment for 5 years with the top layer not fully saturated initially. The salt load at Rocky Glen was 5% lower than the 3-year case. Starting the top layer unsaturated and running the model longer could improve its convergence to steady-state for more forested catchments. With the Option 2 vegetation applied to the catchment, it took LUCICAT 22 years to stabilise salinity (Fig. A6.1b).

Salinity

The salinity of the stream is inversely proportional to streamflow. MAGIC produced higher stream salinities in the upper catchment than LUCICAT (Fig. A6.6c) because MAGIC always generated lower streamflow and higher salt load than LUCICAT. The average annual salinity characteristic curve in Figure A6.5 suggests that the LUCICAT-estimates of salinity could be more realistic. The predicted salinities were compared satisfactory with records of other catchments in the south-west of Western Australia with similar clearing, rainfall and evapotranspirational demand and the LUCICAT-estimates at Rocky Glen for the tree management options.

As not all of the management options could be modelled using LUCICAT, the perennial-pasture management options, ‘non-commercial trees on waterlogged land’ and ‘drain’ cases modelled by MAGIC were adjusted to match the LUCICAT-base case at Styx Junction.

Adjusting MAGIC results to match LUCICAT’s ‘Base’ case

The MAGIC modelling results were adjusted for LUCICAT by:

1. Making a flow adjustment = ‘LUCICAT base’ streamflow minus the reduction in ‘MAGIC Option’ streamflow from ‘MAGIC base’
2. Making a salt adjustment = ‘LUCICAT base’ salt load minus the reduction in ‘MAGIC Option’ salt load from ‘MAGIC base’ multiplied by 1.31
3. Adjusted salinity was derived from adjusted salt load / adjusted streamflow.

Table A6.7 Adjusting MAGIC management options to LUCICAT base case

Management option	**Streamflow** (GL)	**Salt load** (kt)	**Decrease in streamflow** (GL)	**Adjusted streamflow** (GL)	**Decrease in salt load scaled** (kt)	**Adjusted salt load** (kt)	**MAGIC salinity** (mg/L TDS)	**Adjusted MAGIC salinity** (mg/L TDS)
LUCICAT								
Base	75.0	71.0					949	949
Bluegums and/or pines and sawlogs	70.6	46.0	4.0		24.7		652	652
MAGIC								
Base	66.5	87.0					1308	
Bluegums and/or pines and sawlogs	62.6	68.1	3.9	70.6	18.8	46.0	1089	651
Bluegums	65.3	84.9	1.2	73.3	2.1	68.0	1300	927
Deep-rooted perennial pastures[a]	62.6	74.3	3.8	70.7	12.6	54.2	1187	766
Deep-rooted perennial pastures[b]	64.2	84.5	2.3	72.3	2.4	67.5	1317	934
Shallow-rooted perennial pastures[a]	57.4	60.4	9.1	65.5	26.6	35.8	1052	547
Shallow-rooted perennial pastures[b]	60.8	83.7	5.7	68.9	3.3	66.4	1375	963
Drains	67.4	91.3	–0.9	75.5	–4.4	76.5	1355	1013
Waterlogged trees	60.3	71.0	6.2	68.4	15.9	49.8	1178	729
Waterlogged shallow-rooted perennial pastures[b]	64.3	86.8	2.2	72.4	0.1	70.6	1350	975
Waterlogged shallow-rooted perennial pastures[a]	60.9	80.4	5.6	69.0	6.6	62.1	1319	900

[a] at high density (80% LAI of annual pasture in winter)
[b] at low density (50% LAI of annual pasture in winter)

The above adjustments were justified by calculating the decrease in streamflow and salt load between ‘Bluegums and/or pines and sawlogs’ and the ‘Base’ case for both models at Styx Junction. The streamflow reduction for both models was 4 GL and did not need re-scaling. The salt load reduction was 24.7 kt for LUCICAT and 18.8 kt for MAGIC and was re-scaled by a factor of 24.7/18.8 = 1.31. The same 150 km^2 were suitable for commercial trees, deep-rooted and shallow-rooted perennial pastures, and trees on waterlogged land. Additional land was suitable for shallow-rooted perennials — a total area of 332 km^2. There could be more error in adjusting the MAGIC results for this option.

This method of adjusting the MAGIC management option results was tested on the 'Bluegums'. The adjusted salinity calculated was 927 mg/L TDS which was slightly higher than the LUCICAT modelled result of 910 mg/L TDS.

A6.5 Additional information — Diversion

'Where to divert the water to' is an important issue. As suggested in the PWD report (1980) diversion into the Frankland River is an option and another is disposal to the Southern Ocean. The diverted water could be conveyed to disposal sites via channels or pipelines. This report only aimed to analyse the effectiveness of an in-stream diversion on reducing salinity downstream, rather than fully developing a diversion proposal. Thus, while the final disposal location is a major consideration, it will not be discussed in more detail in this report.

Public Works Department (1980) proposed a diversion site at the Rocky Glen gauging station, which would remove water from the cleared agricultural zones of the catchment. At the time the PWD work was completed, the gauging station had been operating for less than a year. Now, more than 20 years of data have been analysed.

More than 84% of the salt load but only 39% of the flow that reaches Styx Junction goes through Rocky Glen so diversion here should provide dramatic salinity reduction.

A total flow diversion requires that all water reaching the diversion point be prevented from continuing downstream. To maximise efficiency it is assumed that one mean annual flow will be diverted each year but the diversion dam needs to be capable of retaining additional water during high flow years and the accumulation of excess water if several high-flow years occurred in a row.

Total flow diversion

To determine the holding capacity of a total diversion dam, it was assumed that the equivalent of one mean annual flow would be diverted each year. The entire annual record at the gauging station was assessed and, following an iterative summation process, the values for each summation ranked. The maximum volume of water that might need to be contained was calculated from these figures.

The diversion site characteristics, such as size, and dam wall height, were then calculated. The MAGIC system (Mauger 1996) was used to assess digital elevation maps of the diversion site specified in the PWD report (Public Works Department 1980). The limiting height of the dam was determined by analysing the contours in the area surrounding the proposed dam wall location. This limiting height contour became the uppermost boundary for the inundated area. Increments of dam height, area and volume were calculated up to the limiting height. These figures were then compared to the total holding capacity calculated, and a dam wall height and area of maximum inundation determined.

Partial flow diversion

Gauging station records were analysed to calculate the characteristics of a partial flow diversion. The daily streamflow and salt load records were ranked according to the flow values and then accumulated and used to calculate the reverse accumulated salinity concentration. A percentage of flow to be diverted was then determined based on the daily flow and the total accumulated flow, with the calculation adjusted based on the number of daily values used. The load diverted was calculated using a relationship between the daily flow, the corresponding reverse accumulated concentration, and the daily load figure. This was then adjusted based on the number of days used in the calculation.

Figure A6.7 illustrates the relationship between the percentages of flow and load diverted for the Rocky Glen gauging station.

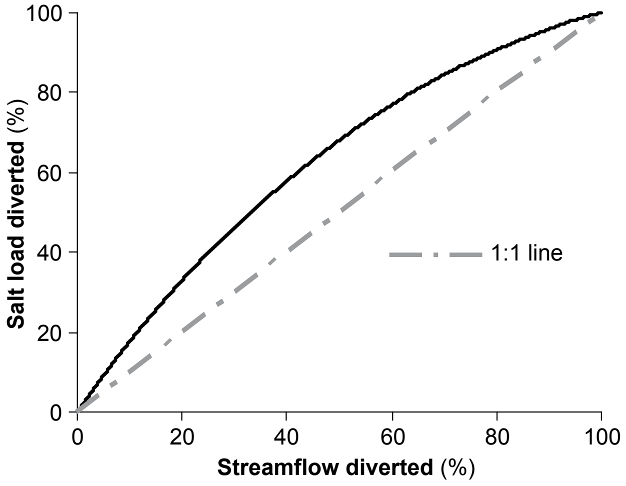


Figure A6.7 Partial diversion calculations for the Rocky Glen gauging station

Diversion site characteristics were not calculated for the partial flow diversions but would require the construction of a small pipehead dam, and would inundate a significantly smaller area than total flow diversion.

Impacts on salinity at Styx Junction

The impacts of total and partial flow diversions at Rocky Glen on the salinity at the Styx Junction outlet were calculated by applying the diverted percentages to the results of the LUCICAT Base case simulation.

A6.6 Additional information — Combination of management options

The impacts of implementing several revegetation management options are calculated assuming that the outputs vary linearly with the area planted.

Combined (‘Option 1’ + ‘Option 2’) streamflow =
‘Option 1’ streamflow + ‘Option 2’ streamflow – ‘Base’ streamflow

Combined (‘Option 1’ + ‘Option 2’) salt load =
‘Option 1’ salt load + ‘Option 2’ salt load – ‘Base’ salt load

Combined (‘Option 1’ + ‘Option 2’) salinity =
Combined (‘Option 1’ + ‘Option 2’) salt load / Combined (‘Option 1’ + ‘Option 2’) streamflow

The combined effects of the groundwater pumping option and revegetation at the same location are calculated by assuming that pumping takes 50% of the groundwater discharge remaining after the application of the other management options. This assumes the two options behave in a linear manner, which is a crude assumption. Similar collector pipe networks would be required, but the bores may be spaced further apart or pumped at lower rates.

A6.7 MAGIC results for management options

Table A6.8 MAGIC Base case— 'do nothing'

In 2002, assumes plantations are fully grown with average rainfall year (1980–95)

	Management unit								Gauging station			
						Internally drained[a]						
	Headwaters	**Wamballup**	**Lake Katherine**	**Middle Kent**	**Rocky Gully**	**Nunijup**	**Nukennullup**	**Poorrarecup**	**Watterson Farm**	**Perillup Road**	**Rocky Glen**	**Styx Junction[b]**
Total area (km²)	128	86	93	123	340	100	127	94	244	764	1092	1843
Total cleared area in 2002 (km²)	95	68	40	66	93	59	49	34	168	412	503	511
Total cleared in 2002 (%)	74	79	42	54	27	59	38	36	69	54	46	28
Average rainfall (mm/yr) (1980–95)	501	547	574	544	648	489	513	530	497	527	564	736
Surface water												
Streamflow (GL)	1.8	2.1	0.8	2.6	8.6	1.2	1.0	1.8	2.2	7.5	16	66
Runoff (mm)	14	24	9	22	25	12	8	19	9	10	15	36
Salt load (kt)	16	12	7	23	12	10	2	4	20	57	69	87
Stream salinity (mg/L TDS)	9020	5560	8260	8510	1420	8850	2480	2010	8870	7670	4340	1310
Groundwater												
Groundwater discharge (GL)	1.5	1.3	0.7	1.2	2.0	1.1	0.2	0.6	1.7	4.8	7	N/A
Groundwater discharge (mm)	12	15	8	10	6	11	1	7	7	6	6	N/A
Shallow watertable (km²)	23	21	15	22	32	14	15	11	42	122	153	N/A
Shallow watertable[c] (%)	18	25	16	18	9	14	11	12	17	16	14	N/A
Discharge area (km²)	11	8	4	11	14	7	6	5	20	52	65	N/A
Modelled discharge area[c] (%)	8	10	5	9	4	7	5	5	8	7	6	N/A

[a] The inflow streamflow, salt load, stream salinity and groundwater discharge are for Lakes Nunijup, Carabundup and Poorrarecup.

[b] The catchment between Rocky Glen and Styx Junction is assumed to have 1% clearing in 1988.

[c] As a % of the total area

Table A6.9 MAGIC—Bluegums only

	Management unit								Gauging station			
						Internally drained[a]						
	Headwaters	**Wamballup**	**Lake Katherine**	**Middle Kent**	**Rocky Gully**	**Nunijup**	**Nukennullup**	**Poorrarecup**	**Watterson Farm**	**Perillup Road**	**Rocky Glen**	**Styx Junction[b]**
Total area (km²)	128	86	93	123	340	100	127	94	244	764	1092	1843
Cleared area after planting the management option (km²)	95	68	40	66	73	59	49	34	168	403	483	491
Total cleared area after planting the management option (%)	74	79	42	54	22	59	38	36	69	53	44	27
Planted area (km²)	0	0	0	0	20	0	0	0	0	0	20	20
Planted area[c] (%)	0	0	0	0	21	0	0	0	0	0	4	4
Surface water												
Streamflow (GL)	1.8	2.1	0.8	2.6	7.4	1.2	1.0	1.8	2.2	7.3	15	65
Runoff (mm)	14	24	9	22	22	12	8	19	9	10	13	35
Salt load (kt)	16	12	7	23	10	10	2	4	20	56	67	85
Stream salinity (mg/L TDS)	9020	5560	8000	8510	1380	8850	2480	2010	8870	7640	4570	1300
Groundwater												
Discharge into shallow top layer (GL)	2.0	1.3	0.7	1.2	1.8	1.2	1.1	0.9	1.7	4.7	7	N/A
Discharge into shallow top layer (mm)	15	15	8	10	5	12	9	9	7	6	6	N/A
Shallow watertable (km²)	23	21	15	22	31	14	15	11	42	121	153	N/A
Shallow watertable[c] (%)	18	25	16	18	9	14	11	12	17	16	14	N/A
Discharge area (km²)	11	8	4	11	12	7	6	5	20	51	65	N/A
Discharge area[c] (%)	8	10	5	9	4	7	5	5	8	7	6	N/A

[a] The inflow streamflow, salt load, stream salinity and groundwater discharge are for Lakes Nunijup, Carabundup and Poorrarecup

[b] The catchment between Rocky Glen and Styx Junction is assumed to have 1% clearing in 1988.

[c] As a % of the total area

Table A6.10 MAGIC—Bluegums and/or pines and sawlogs

	Management unit								Gauging station			
						Internally drained [a]						
	Headwaters	Wamballup	Lake Katherine	Middle Kent	Rocky Gully	Nunijup	Nukennullup	Poorrarecup	Watterson Farm	Perillup Road	Rocky Glen	Styx Junction [b]
Total area (km^2)	128	86	93	123	340	100	127	94	244	764	1092	1843
Cleared area after planting the management option (km^2)	64	57	30	53	63	36	32	21	111	295	356	364
Total cleared area after planting the management option (%)	50	66	32	43	19	36	25	23	46	39	33	20
Planted area (km^2)	31	11	9	14	30	23	16	13	57	57	147	147
Planted area [c] (%)	32	16	24	21	32	39	34	38	34	14	29	29
Surface water												
Streamflow (GL)	1.2	1.7	0.5	2.2	6.5	0.7	0.9	1.6	1.5	5.3	12	63
Runoff (mm)	9	20	5	18	19	7	7	17	6	7	11	34
Salt load (kt)	10	10	5	17	9	6	2	2	12	38	50	68
Stream salinity (mg/L TDS)	8460	5560	10000	7960	1340	8980	2190	1420	8190	7160	4190	1090
Groundwater												
Discharge into shallow top layer (GL)	1.3	1.1	0.5	1.0	1.5	0.8	0.6	0.5	1.0	3.4	5	N/A
Discharge into shallow top layer (mm)	10	12	6	8	4	8	5	6	4	4	5	N/A
Shallow watertable (km^2)	18	19	13	20	27	11	12	9	33	101	153	N/A
Shallow watertable [c] (%)	14	22	14	16	8	11	9	10	13	13	14	N/A
Discharge area (km^2)	7	7	3	9	10	4	5	4	14	38	65	N/A
Discharge area [c] (%)	6	8	4	7	3	4	4	4	6	5	6	N/A

[a] The inflow streamflow, salt load, stream salinity and groundwater discharge are for Lakes Nunijup, Carabundup and Poorrarecup

[b] The catchment between Rocky Glen and Styx Junction is assumed to have 1% clearing in 2002

[c] As a % of the total area

Table A6.11 MAGIC—Non-commercial trees on waterlogged land

	Management unit								Gauging station			
						Internally drained [a]						
	Headwaters	Wamballup	Lake Katherine	Middle Kent	Rocky Gully	Nunijup	Nukennullup	Poorrarecup	Watterson Farm	Perillup Road	Rocky Glen	Styx Junction [b]
Total area (km^2)	128	86	93	123	340	100	127	94	244	764	1092	1843
Cleared area after planting the management option (km^2)	68	43	23	44	75	44	34	22	122	264	353	361
Total cleared area after planting the management option (%)	53	50	24	36	22	44	27	24	50	35	32	20
Planted area (km^2)	27	24	17	22	18	15	14	12	45	148	150	150
Planted area [c] (%)	21	28	18	18	5	15	11	13	19	19	14	8
Surface water												
Streamflow (GL)	0.8	0.8	0.1	1.1	6.9	0.4	0.9	1.6	1.0	2.5	10	60
Runoff (mm)	6	10	1	9	20	4	7	17	4	3	9	33
Salt load (kt)	13	9	1	18	12	5	2	3	17	40	53	71
Stream salinity (mg/L TDS)	17 090	10 650	16 000	16 740	1690	12 300	2310	1880	16 920	16 290	5460	1180
Groundwater												
Discharge into shallow top layer (GL)	1.3	1.1	0.6	1.1	2.0	0.6	0.2	0.5	0.3	3.6	6	N/A
Discharge into shallow top layer (mm)	10	12	6	9	6	6	1	6	1	5	5	N/A
Shallow watertable (km^2)	18	17	11	17	29	3	12	9	34	95	153	N/A
Shallow watertable [c] (%)	14	20	12	14	9	3	9	10	14	12	14	N/A
Discharge area (km^2)	3	2	2	3	8	1	3	3	7	6	65	N/A
Discharge area [c] (%)	3	2	2	2	2	1	2	4	3	2	6	N/A

[a] The inflow streamflow, salt load, stream salinity and groundwater discharge are for Lakes Nunijup, Carabundup and Poorrarecup

[b] The catchment between Rocky Glen and Styx Junction is assumed to have 1% clearing in 2002

[c] As a % of the total area

Table A6.12 MAGIC —Most of the cleared land planted

	Management unit								**Gauging station**			
						Internally drained [a]						
	Headwaters	**Wamballup**	**Lake Katherine**	**Middle Kent**	**Rocky Gully**	**Nunijup**	**Nukennullup**	**Poorrarecup**	**Watterson Farm**	**Perillup Road**	**Rocky Glen**	**Styx Junction** [b]
Total area (km^2)	128	86	93	123	340	100	127	94	244	764	1092	1843
Cleared area after planting the management option (km^2)	23	19	13	19	24	16	16	12	42	120	143	150
Total cleared area after planting the management option (%)	18	22	14	16	7	16	12	13	17	16	13	8
Planted area (km^2)	72	49	26	47	69	43	33	22	126	292	360	360
Planted area [c] (%)	76	72	67	71	74	73	67	64	75	38	33	20
Surface water												
Streamflow (GL)	0.3	0.2	0.1	0.8	2.6	0.1	0.8	1.3	0.4	1.6	4.0	55
Runoff (mm)	2.6	2.7	1.1	6.4	7.5	1.0	6.7	13.6	1.7	2.1	3.7	30
Salt load (kt)	1.2	1.3	0.4	2.4	3.2	1.4	1.3	0.9	1.1	5.4	8.5	26
Stream salinity (mg/L TDS)	3690	5470	4000	3110	1250	12910	1490	720	2650	3370	2120	480
Groundwater												
Discharge into shallow top layer (GL)	0.3	0.3	0.3	0.3	0.6	0.3	0.1	0.2	0.3	1.0	1.5	N/A
Discharge into shallow top layer (mm)	2.3	3.5	2.8	2.5	1.7	2.5	0.8	2.3	1.3	1.3	1.4	N/A
Shallow watertable (km^2)	7.1	6.8	6.1	9.0	13.3	4.2	5.7	5.1	13.0	44.6	57.4	N/A
Shallow watertable [c] (%)	5.6	8.0	6.6	7.3	3.9	4.2	4.5	5.4	5.3	5.8	5.3	N/A
Discharge area (km^2)	1.6	1.1	1.2	2.2	2.8	0.8	1.9	2.3	2.8	11.3	14.0	N/A
Discharge area [c] (%)	1.2	1.3	1.3	1.8	0.8	0.8	1.5	2.4	1.2	1.5	1.3	N/A

[a] The inflow streamflow, salt load, stream salinity and groundwater discharge are for Lakes Nunijup, Carabundup and Poorrarecup

[b] The catchment between Rocky Glen and Styx Junction is assumed to be 1% cleared in 2002

[c] As a % of the total area

Table A6.13 MAGIC—Deep-rooted perennial pastures at high density

	Management unit								**Gauging station**			
						Internally drained [a]						
	Headwaters	**Wamballup**	**Lake Katherine**	**Middle Kent**	**Rocky Gully**	**Nunijup**	**Nukennullup**	**Poorrarecup**	**Watterson Farm**	**Perillup Road**	**Rocky Glen**	**Styx Junction** [b]
Total area (km^2)	128	86	93	123	340	100	127	94	244	764	1092	1843
Cleared area after planting the management option (km^2)	64	57	30	53	63	36	32	21	111	276	356	364
Total cleared area after planting the management option (%)	50	66	32	43	19	36	25	23	46	36	33	20
Planted area (km^2)	31	11	9	14	30	23	16	13	57	136	147	147
Planted area (%) [c]	32	12	10	11	9	23	13	14	23	18	29	8
Surface water												
Streamflow (GL)	1.2	1.7	0.5	2.2	6.5	0.7	0.9	1.6	1.5	5.1	12	63
Runoff (mm)	10	20	5	18	19	7	7	17	6	7	11	34
Salt load (kt)	12	10	6	19	10	7	2	3	15	42	57	74
Stream salinity (mg/L TDS)	9850	5950	11000	8760	1520	10190	2180	1650	9730	8260	4680	1190
Groundwater												
Discharge into shallow top layer (GL)	1.4	1.1	0.6	1.0	1.6	0.8	0.6	0.5	1.0	3.4	6	N/A
Discharge into shallow top layer (mm)	11	13	6	8	5	8	5	6	4	4	5	N/A
Shallow watertable (km^2)	20	20	13	20	29	11	12	10	35	104	153	N/A
Shallow watertable [c] (%)	15	23	14	17	8	11	10	10	14	14	14	N/A
Discharge area (km^2)	8	7	3	9	11	4	5	4	14	38	65	N/A
Discharge area [c] (%)	6	8	4	7	3	4	4	4	6	5	6	N/A

[a] The inflow streamflow, salt load, stream salinity and groundwater discharge are for Lakes Nunijup, Carabundup and Poorrarecup

[b] The catchment between Rocky Glen and Styx Junction is assumed to have 1% clearing in 2002

[c] As a % of the total area

Table A6.14 MAGIC—Deep-rooted perennial pastures at low density

	Management unit								Gauging station			
						Internally drained[a]						
	Headwaters	Wamballup	Lake Katherine	Middle Kent	Rocky Gully	Nunijup	Nukennullup	Poorrarecup	Watterson Farm	Perillup Road	Rocky Glen	Styx Junction[b]
Total area (km^2)	128	86	93	123	340	100	127	94	244	764	1092	1843
Cleared area after planting the management option (km^2)	64	57	30	53	63	36	32	21	111	276	356	364
Total cleared area after planting the management option (%)	50	66	32	43	19	36	25	23	46	36	33	20
Planted area (km^2)	31	11	9	14	30	23	16	13	57	57	147	147
Planted area[c] (%)	32	16	24	21	32	39	34	38	34	14	29	29
Surface water												
Streamflow (GL)	1.5	1.9	0.6	2.4	7.4	0.9	0.9	1.7	1.8	6.0	14	64
Runoff (mm)	11	22	6	19	22	9	7	18	8	8	13	35
Salt load (kt)	15	11	7	22	11	9	2	3	19	55	67	85
Stream salinity (mg/L TDS)	10540	6160	11000	9260	1540	10460	2420	2050	10460	9250	4890	1320
Groundwater												
Discharge into shallow top layer (GL)	1.7	1.2	0.7	1.2	2.0	1.0	0.7	0.7	1.0	4.7	7	N/A
Discharge into shallow top layer (mm)	13	15	8	10	6	10	5	8	4	6	6	N/A
Shallow watertable (km^2)	24	21	15	22	32	14	15	11	42	124	153	N/A
Shallow watertable[c] (%)	19	25	16	18	9	14	12	12	17	16	14	N/A
Discharge area (km^2)	10	8	4	10	13	6	6	4	18	48	65	N/A
Discharge area[c] (%)	8	9	4	8	4	6	4	5	8	6	6	N/A

[a] The inflow streamflow, salt load, stream salinity and groundwater discharge are for Lakes Nunijup, Carabundup and Poorrarecup

[b] The catchment between Rocky Glen and Styx Junction is assumed to have 1% clearing in 2002

[c] As a % of the total area

Table A6.15 MAGIC—Shallow-rooted perennial pastures at high density

	Management unit								Gauging station			
						Internally drained[a]						
	Headwaters	Wamballup	Lake Katherine	Middle Kent	Rocky Gully	Nunijup	Nukennullup	Poorrarecup	Watterson Farm	Perillup Road	Rocky Glen	Styx Junction[b]
Total area (km^2)	128	86	93	123	340	100	127	94	244	764	1092	1843
Cleared area after planting the management option (km^2)	30	25	18	26	25	17	16	13	51	102	171	178
Total cleared area after planting the management option (%)	24	29	20	21	7	17	13	13	21	13	16	10
Planted area (km^2)	65	43	21	40	68	41	32	22	116	116	332	332
Planted area[c] (%)	68	63	54	61	73	71	66	63	69	28	66	65
Surface water												
Streamflow (GL)	0.6	0.7	0.1	1.3	4.1	0.3	0.9	1.4	0.8	2.1	7	57
Runoff (mm)	5	8	1	10	12	3	7	15	3	3	6	31
Salt load (kt)	10	8	1	15	9	5	2	2	13	31	43	60
Stream salinity (mg/L TDS)	15460	11700	15000	11810	2150	17170	2090	1660	15390	14370	6220	1050
Groundwater												
Discharge into shallow top layer (GL)	1.0	0.8	0.5	0.8	1.4	0.6	0.2	0.4	0.2	2.4	4	N/A
Discharge into shallow top layer (mm)	7	10	6	7	4	6	2	4	1	3	4	N/A
Shallow watertable (km^2)	19	18	13	19	28	11	12	9	34	98	153	N/A
Shallow watertable[c] (%)	15	21	14	15	8	11	9	10	14	13	14	N/A
Discharge area (km^2)	5	4	3	6	8	3	4	3	10	25	65	N/A
Discharge area[c] (%)	4	5	3	5	2	3	3	4	4	3	6	N/A

[a] The inflow streamflow, salt load, stream salinity and groundwater discharge are for Lakes Nunijup, Carabundup and Poorrarecup

[b] The catchment between Rocky Glen and Styx Junction is assumed to have 1% clearing in 2002

[c] As a % of the total area

Table A6.16 MAGIC—Shallow-rooted perennial pastures at low density

	Management unit								Gauging station			
						Internally drained [a]						
	Headwaters	Wamballup	Lake Katherine	Middle Kent	Rocky Gully	Nunijup	Nukennullup	Poorrarecup	Watterson Farm	Perillup Road	Rocky Glen	Styx Junction [b]
Total area (km²)	128	86	93	123	340	100	127	94	244	764	1092	1843
Cleared area after planting the management option (km²)	30	25	18	26	25	17	16	13	51	102	171	178
Total cleared area after planting the management option (%)	24	29	20	21	7	17	13	13	21	13	16	10
Planted area (km²)	65	43	21	40	68	41	32	22	116	116	332	332
Planted area [c] (%)	68	63	54	61	73	71	66	63	69	28	66	65
Surface water												
Streamflow (GL)	1.1	1.2	0.3	1.9	5.9	0.6	0.9	1.6	1.4	4.1	10	61
Runoff (mm)	9	13	3	15	17	6	7	17	6	5	9	33
Salt load (kt)	15	11	7	22	12	8	2	3	19	54	66	84
Stream salinity (mg/L TDS)	13450	9620	22000	11550	1970	13320	2450	2200	13270	13310	6400	1380
Groundwater												
Discharge into shallow top layer (GL)	1.5	1.2	0.7	1.2	1.9	0.9	0.2	0.6	0.3	4.5	6	N/A
Discharge into shallow top layer (mm)	11	14	7	10	6	9	2	7	1	6	6	N/A
Shallow watertable (km²)	24	22	15	23	32	14	15	11	43	125	153	N/A
Shallow watertable [c] (%)	19	26	16	18	9	14	12	12	18	16	14	N/A
Discharge area (km²)	9	7	4	9	11	5	5	4	17	43	65	N/A
Discharge area [c] (%)	7	8	4	8	3	5	4	4	7	6	6	N/A

[a] The inflow streamflow, salt load, stream salinity and groundwater discharge are for Lakes Nunijup, Carabundup and Poorrarecup

[b] The catchment between Rocky Glen and Styx Junction is assumed to have 1% clearing in 1988

[c] As a % of the total area

Table A6.17 MAGIC – Groundwater pumping (15 kL/day/bore)

	Management unit								Gauging station			
						Internally drained [a]						
	Headwaters	Wamballup	Lake Katherine	Middle Kent	Rocky Gully	Nunijup	Nukennullup	Poorrarecup	Watterson Farm	Perillup Road	Rocky Glen	Styx Junction [b]
Pipe network												
Length of collector pipes (km)	38.92	27.79	24.86	41.63	74.43	0	0	0	49.74	138.25	207.63	207.63
Length of transport pipes [c] (km)	16.73	10.55	13.30	15.24	54.16	0	0	0	16.73	56.29	109.98	109.98
Number of bores	118	115	66	114	185	0	0	0	115	438	628	628
Groundwater												
Volume pumped (GL/yr)	0.65	0.63	0.36	0.62	1.01	0	0	0	0.63	0.63	3.44	3.44
Salt in pumped water (kt/yr)	6.5	5.7	3.3	9.6	5.5	0.0	0.0	0.0	6.9	6.9	30.6	30.6
Surface water												
Streamflow (GL)	1.58	1.20	1.27	1.98	14.72	0.99	1.02	0.77	1.93	7.97	20.59	71.12
Salt load (kt)	0.8	3.5	3.3	6.9	7.9	9.5	4.8	1.1	9.3	32.9	22.5	40.1
Mean stream salinity (mg/L TDS)	500	2910	2630	3500	540	9590	4720	1400	4820	4130	1090	560

Assumes 50% of discharge to shallow layers is pumped out. The discharge to shallow layers is from MAGIC.
Uses LUCICAT 'Base' case flow and salt loads.

[a] The inflow streamflow, salt load, stream salinity, and groundwater discharge are for Lakes Nunijup, Carabundup and Poorrarecup

[b] The catchment between Rocky Glen and Styx Junction is assumed to have 1% clearing in 2002

[c] Length of pipes within Upper Kent catchment only

Table A6.18 MAGIC – Deep and shallow drains

	Management unit								Gauging station			
						Internally drained						
	Headwaters	**Wamballup**	**Lake Katherine**	**Middle Kent**	**Rocky Gully**	**Nunijup**	**Nukennullup**	**Poorrarecup**	**Watterson Farm**	**Perillup Road**	**Rocky Glen**	**Styx Junction**[a]
Total area (km^2)	128	86	93	123	340	100	127	94	244	764	1092	1843
Total cleared in area in 2002 (km^2)	95	68	40	66	93	59	49	34	168	412	503	503
Total cleared area in 2002 (%)	74	79	42	54	27	59	38	36	69	54	46	27
Surface water												
Streamflow (GL)	2.0	2.2	0.9	2.8	8.9	1.1	1.0	1.9	2.8	8.1	17	67
Runoff (mm)	16	26	10	23	26	11	8	20	11	11	15	37
Salt load (kt)	17	12	7	24	13	12	3	4	21	62	74	91
Stream salinity (mg/L TDS)	8510	5460	8000	8690	1410	10690	2780	2010	8470	7600	4370	1360
Groundwater												
Discharge (GL)	1.6	1.3	0.8	1.3	2.1	1.3	0.2	0.7	0.2	5.1	7	N/A
Discharge (mm)	13	16	8	11	6	13	1	7	1	7	7	N/A
Shallow watertable (km^2)	21	19	13	20	31	13	13	10	38	110	140	N/A
Shallow watertable[b] (%)	16	22	14	16	9	13	10	11	16	14	13	N/A
Discharge area (km^2)	7	5	3	7	10	5	4	4	14	35	46	N/A
Discharge area[b] (%)	5	6	3	6	3	5	3	4	6	5	4	N/A
Drain statistics												
Length of shallow drains (km)	558	387	229	404	598	345	299	212	985	2448	3031	3031
Length of deep drain (km)	56	47	25	66	39	29	30	18	95	274	309	309
Total water in shallow (GL)	2.0	2.5	1.9	2.3	6.8	1.6	0.3	0.1	2.5	8.7	17.4	17.4
Water in shallow drains (kL/km)	3.6	6.4	8.1	5.6	11.3	4.8	0.9	0.7	2.5	3.6	5.8	5.8
Total water in deep drains (GL)	0.5	0.5	0.7	0.7	2.6	1.1	0.9	1.1	0.5	2.5	8.2	8.2
Water in deep drains (kL/km)	8	12	30	10	67	37	32	61	6	9	26	26
Total discharge in shallow drains (GL)	0.54	0.50	0.31	0.46	0.44	0.37	0.04	0.01	0.61	1.84	2.67	2.67
Discharge in shallow drains (kL/km)	0.97	1.30	1.37	1.14	0.74	1.06	0.14	0.02	0.62	0.75	0.88	0.88
Total discharge in deep drains (GL)	0.35	0.21	0.10	0.29	0.14	0.18	0.03	0.004	0.37	0.96	1.30	1.30

Note: 2-m deep drains were placed on major streams in pasture areas. 1-m deep shallow drains were at 200 m centres in pasture areas.

[a] The catchment between Rocky Glen and Styx Junction is assumed to have 1% clearing in 1988

[b] As a % of the total area

A6.8 LUCICAT results for management options

Table A6.19 LUCICAT— 'Base' case— 'do nothing'

	Management unit								Gauging station			
						Internally drained						
	Headwaters	Wamballup	Lake Katherine	Middle Kent	Rocky Gully	Nunijup	Nukennullup	Poorrarecup	Watterson Farm	Perillup Road	Rocky Glen	Styx Junction [a]
Area (km^2)	128	86	93	123	340	100	127	94	244	764	1092	1843
Cleared area in 1978 (km^2)	102	74	68	101	176	60	80	59	176	551	719	727 [a]
Cleared area in 1978 (%)	80	86	72	82	52	60	63	63	72	72	66	39
Cleared area in 2002 (km^2)	95	68	40	66	93	59	49	34	168	412	503	511 [a]
Cleared area in 2002 (%)	74	79	42	54	27	59	38	36	69	54	46	28
Rainfall period at equilibrium [b]												
Annual rainfall (mm)	530	545	590	570	670	525	535	545	530	560	590	665
Streamflow (GL)	2.2	1.8	1.6	2.6	15.7	1.0	1.0	0.8	2.6	8.6	24.0	74.6
Runoff (mm)	17.4	21.3	17.4	21.2	46.3	9.9	8.1	8.2	10.5	10.0	22.0	40.5
Salt load (kt)	7.3	9.2	6.6	16.6	13.4	9.5	4.8	1.1	16.2	39.8	53.1	70.7
Mean salinity (mg/L TDS)	3300	5000	4045	6355	855	9595	4720	1400	6335	4630	2210	950
Groundwater discharge to stream zone (mm)	8.9	12.6	5.3	11.4	4.5	8.5	2.9	2.0	9.0	6.2	5.7	
Baseflow (mm)	0.9	1.6	1.0	2.3	1.1	1.0	0.6	0.2	1.1	1.3	1.2	
Representative year at equilibrium [c]												
Annual rainfall (mm)	515	510	575	560	670	590	545	570	550	565	590	665
Streamflow (GL)	2.4	1.7	2.0	3.0	17.3	2.0	1.5	1.1	2.8	9.5	26.4	76.9
Runoff (mm)	19.1	19.4	21.0	24.4	50.9	19.5	11.8	11.4	11.6	11.0	24.2	41.7
Salt load (kt)	14.8	8.7	7.0	9.6	13.1	11.6	5.3	1.2	16.5	40.2	53.2	70.8
Mean salinity (mg/L TDS)	6055	5210	3550	3200	755	5920	3555	1110	5820	4250	2015	920
Groundwater discharge to stream zone (mm)	9.3	12.9	5.1	11.6	4.3	8.9	2.8	2.1	9.5	6.3	5.8	
Baseflow (mm)	0.8	1.4	1.0	2.4	1.4	1.0	0.6	0.2	1.1	1.2	1.2	

[a] The catchment between Rocky Glen and Styx Junction is assumed to have 1% clearing in 2002

[b] Annual mean for the period 1992–2002

[c] Annual rainfall of 2000

A6.8 LUCICAT results for management options (continued)

Table A6.20 LUCICAT—Bluegums only

	Management unit								Gauging station			
						Internally drained						
	Headwaters	**Wamballup**	**Lake Katherine**	**Middle Kent**	**Rocky Gully**	**Nunijup**	**Nukennullup**	**Poorrarecup**	**Watterson Farm**	**Perillup Road**	**Rocky Glen**	**Styx Junction**[a]
Area (km^2)	128	86	93	123	340	100	127	94	244	764	1092	1843
Cleared area after planting (km^2)	95	68	40	66	73	59	49	34	168	412	483	491[a]
Cleared area after planting (%)	74	79	42	54	22	59	38	36	69	54	44	27
Planted area (km^2)	0	0	0	0	20	0	0	0	0	0	20	20
Planted area (%)	0	0	0	0	5.8	0	0	0	0	0	1.8	1.1
Rainfall period at equilibrium[b]												
Annual rainfall (mm)	530	545	590	570	670	525	535	545	530	560	590	665
Streamflow (GL)	2.2	1.8	1.6	2.6	14.5	1.0	1.0	0.8	2.6	8.6	22.8	73.3
Runoff (mm)	17.4	21.3	17.4	21.2	42.6	9.9	8.1	8.2	10.5	10.0	20.9	39.8
Salt load (kt)	14.7	9.2	6.6	9.2	9.5	9.5	4.8	1.08	16.2	39.8	49.2	66.8
Mean salinity (mg/L TDS)	6595	5000	4045	3540	660	9595	4720	1400	6335	4630	2160	910
Groundwater discharge to stream zone (mm)	2.7	8.8	2.8	3.9	2.3	1.4	0.7	0.3	2.5	2.8	2.7	
Baseflow (mm)	0.4	1.3	0.8	2.1	0.9	0.3	0.2	0.1	0.5	0.8	0.8	
Representative year at equilibrium[c]												
Annual rainfall (mm)	515	510	575	560	670	590	545	570	550	565	590	665
Streamflow (GL)	2.4	1.7	2.0	3.0	15.9	2.0	1.5	1.1	2.8	9.4	25.0	75.6
Runoff (mm)	19.1	19.4	21.0	24.4	46.8	19.5	11.8	11.4	11.6	11.0	22.9	41.0
Salt load (kt)	14.8	8.7	7.0	9.6	9.3	11.6	5.3	1.2	16.5	40.2	49.4	67.1
Mean salinity (mg/L TDS)	6055	5210	3550	3200	585	5920	3555	1110	5820	4255	1975	890
Groundwater discharge to stream zone (mm)	2.6	9.0	2.2	4.2	2.3	1.3	0.6	0.2	2.5	2.8	2.6	
Baseflow (mm)	0.3	1.1	0.7	2.0	0.9	0.3	0.1	0.1	0.5	0.8	0.7	

[a] The catchment between Rocky Glen and Styx Junction is assumed to have 1% clearing in 2002

[b] Annual mean for the period 1992–2002

[c] Annual rainfall of 2000

A6.8 LUCICAT results for management options (continued)

Table A6.21 LUCICAT—Bluegums and/or pines and sawlogs

	Management unit								**Gauging station**			
						Internally drained						
	Headwaters	**Wamballup**	**Lake Katherine**	**Middle Kent**	**Rocky Gully**	**Nunijup**	**Nukennullup**	**Poorrarecup**	**Watterson Farm**	**Perillup Road**	**Rocky Glen**	**Styx Junction**[a]
Area (km^2)	128	86	93	123	340	100	127	94	244	764	1092	1843
Cleared area after planting (km^2)	64	57	30	53	63	36	32	21	111	295	356	364[a]
Cleared area after planting (%)	50	66	32	43	19	36	25	23	46	39	33	20
Planted area (km^2)	31	11	9.5	14	30	23	16	13	57	117	147	147
Planted area (%)	24	12	10	11	8.8	23	13	14	23	15	13	8.0
Rainfall period at equilibrium[b]												
Annual rainfall (mm)	530	545	590	570	670	525	535	545	530	560	590	665
Streamflow (GL)	1.4	1.6	1.2	2.2	13.8	0.5	0.6	0.4	1.7	6.6	20.1	70.6
Runoff (mm)	10.7	19.0	12.4	17.5	40.5	4.9	4.6	4.5	6.8	7.7	18.4	38.3
Salt load (kt)	4.8	6.3	3.2	6.1	7.9	1.4	1.3	0.42	5.7	20.6	28.4	46.0
Mean salinity (mg/L TDS)	3515	3875	2745	2845	570	2805	2155	1010	3390	3120	1410	650
Groundwater discharge to stream zone (mm)	2.7	8.8	2.8	3.9	2.3	1.4	0.7	0.3	2.5	2.8	2.7	
Baseflow (mm)	0.4	1.3	0.8	2.1	0.9	0.3	0.2	0.1	0.5	0.8	0.8	
Representative year at equilibrium[c]												
Annual rainfall (mm)	515	510	575	560	670	590	545	570	550	565	590	665
Streamflow (GL)	1.7	1.6	1.5	2.7	15.1	1.2	0.9	0.6	2.1	7.8	22.6	73.1
Runoff (mm)	13.3	19.1	15.5	21.8	44.5	12.1	7.3	6.5	8.6	9.1	20.7	39.7
Salt load (kt)	4.9	6.2	2.8	6.8	8.0	1.7	1.4	0.5	6.0	20.9	28.8	46.4
Mean salinity (mg/L TDS)	2890	3795	1950	2550	525	1400	1545	790	2830	2680	1275	635
Groundwater discharge to stream zone (mm)	2.6	9.0	2.2	4.2	2.3	1.3	0.6	0.2	2.5	2.8	2.6	
Baseflow (mm)	0.3	1.1	0.7	2.0	0.9	0.3	0.1	0.1	0.5	0.8	0.7	

[a] The catchment between Rocky Glen and Styx Junction is assumed to have 1% clearing in 2002

[b] Annual mean for the period 1992–2002

[c] Annual rainfall of 2000

A6.8 LUCICAT results for management options (continued)

Table A6.22 LUCICAT—All cleared areas planted

	Management unit								Gauging station			
						Internally drained						
	Headwaters	Wamballup	Lake Katherine	Middle Kent	Rocky Gully	Nunijup	Nukennullup	Poorrarecup	Watterson Farm	Perillup Road	Rocky Glen	Styx Junction[a]
Area (km^2)	128	86	93	123	340	100	127	94	244	764	1092	1843
Cleared area (km^2)	0	0	0	0	0	0	0	0	0	0	0	8[a]
Cleared area (%)	0	0	0	0	0	0	0	0	0	0	0	0.4
Rainfall period at equilibrium[b]												
Annual rainfall (mm)	530	545	590	570	670	525	535	545	530	560	590	665
Streamflow (GL)	0.2	0.2	0.3	0.6	9.7	0.1	0.2	0.1	0.2	1.6	11.1	61.6
Runoff (mm)	1.4	2.5	3.6	5.2	28.6	0.8	1.2	1.4	0.8	1.8	10.2	33.4
Salt load (kt)	0.1	0.2	0.2	0.4	1.9	0.1	0.1	0.05	0.1	1.0	2.8	20.5
Mean salinity (mg/L TDS)	595	925	670	615	200	720	525	360	565	620	255	330
Groundwater discharge to stream zone (mm)	0.0	0.1	0.2	0.4	0.4	0.0	0.0	0.0	0.0	0.1	0.2	
Baseflow (mm)	0.0	0.1	0.1	0.6	0.3	0.0	0.0	0.0	0.0	0.1	0.2	
Representative year at equilibrium[c]												
Annual rainfall (mm)	513	507	575	561	671	590	546	567	548	563	588	666
Streamflow (GL)	0.2	0.2	0.3	0.8	10.7	0.2	0.2	0.2	0.2	1.7	12.2	62.8
Runoff (mm)	10.9	11.5	15.8	30.8	210.3	10.8	19.1	17.6	20.6	158.0	505.5	1876.1
Salt load (kt)	0.1	0.1	0.10	0.2	1.8	0.1	0.1	0.1	0.1	0.6	2.3	20.0
Mean salinity (mg/L TDS)	520	390	300	300	170	705	490	355	500	320	190	320
Groundwater discharge to stream zone (mm)	0.0	0.0	0.0	0.2	0.3	0.0	0.0	0.0	0.0	0.0	0.1	
Baseflow (mm)	0.0	0.0	0.0	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.1	

[a] The catchment between Rocky Glen and Styx Junction is assumed to have 1% clearing in 2002

[b] Annual mean for the period 1992–2002

[c] Annual rainfall of 2000

Table A6.23 No tree planting after clearing controls

	Management unit								**Gauging station**			
						Internally drained						
	Headwaters	**Wamballup**	**Lake Katherine**	**Middle Kent**	**Rocky Gully**	**Nunijup**	**Nukennullup**	**Poorrarecup**	**Watterson Farm**	**Perillup Road**	**Rocky Glen**	**Styx Junction**[a]
Area (km²)	128	86	93	123	340	100	127	94	244	764	1092	1843
Cleared area (km²)	102	74	68	101	176	60	80	59	176	551	719	727[a]
Cleared area (%)	80	86	72	82	52	60	63	63	72	72	66	39
Planted area (km²)	0	0	0	0	0	0	0	0	0	0	0	0
Planted area (%)	0	0	0	0	0	0	0	0	0	0	0	0
Rainfall period at equilibrium[b]												
Annual rainfall (mm)	530	545	590	570	670	525	535	545	530	560	590	665
Streamflow (GL)	2.3	1.9	2.4	3.8	19.4	1.0	1.7	1.0	2.6	10.9	29.8	80.3
Runoff (mm)	17.6	22.4	25.3	31.0	57.0	10.0	13.4	10.4	10.6	12.7	27.2	43.6
Salt load (kt)	16.0	11.1	17.6	16.5	32.3	9.7	14.7	3.15	17.5	62.6	93.3	111.0
Mean salinity (mg/L TDS)	7065	5745	7390	4310	1665	9730	8665	3225	6755	5725	3140	1380
Groundwater discharge to stream zone (mm)	10.3	14.8	15.0	7.9	11.6	8.8	9.8	3.8	9.8	11.1	11.1	
Baseflow (mm)	0.9	1.7	1.7	2.1	2.4	1.0	1.3	0.8	1.1	1.6	1.8	
Representative year at equilibrium[c]												
Annual rainfall (mm)	515	510	575	560	670	590	545	570	550	565	590	665
Streamflow (GL)	2.4	1.7	2.3	3.8	20.9	1.9	2.1	1.2	2.8	10.7	31.0	81.6
Runoff (mm)	18.8	19.2	24.0	30.5	61.6	19.4	16.2	12.3	11.4	12.4	28.4	44.2
Salt load (kt)	15.9	10.2	16.99	16.6	30.8	11.8	15.7	3.4	17.6	61.2	90.5	108.1
Mean salinity (mg/L TDS)	6607	6155	7520	4430	1470	6075	7630	2985	6310	5740	2915	1325
Groundwater discharge to stream zone (mm)	10.6	15.1	15.1	8.0	12.0	9.2	9.9	3.8	10.3	11.3	11.3	
Baseflow (mm)	0.9	1.5	1.7	2.1	2.4	1.0	1.3	0.8	1.1	1.5	1.7	

[a] The catchment between Rocky Glen and Styx Junction is assumed to have 1% clearing in 2002

[b] Annual mean for the period 1992–2002

[c] Annual rainfall of 2000

Table A6.24 All private land cleared

	Management unit								Gauging station			
						Internally drained						
	Headwaters	Wamballup	Lake Katherine	Middle Kent	Rocky Gully	Nunijup	Nukennullup	Poorrarecup	Watterson Farm	Perillup Road	Rocky Glen	Styx Junction [a]
Area (km²)	128	86	93	123	340	100	127	94	244	764	1092	1843
Cleared area (km²)	128	85	93	123	251	93	121	79	237	734	973	981 [a]
Cleared area (%)	100	99	100	100	74	93	95	84	97	96	89	53
Planted area (km²)	0	0	0	0	0	0	0	0	0	0	0	0
Planted area (%)	0	0	0	0	0	0	0	0	0	0	0	0
Rainfall period at equilibrium [b]												
Annual rainfall (mm)	530	545	590	570	670	525	535	545	530	560	590	665
Streamflow (GL)	3.2	2.2	3.3	4.5	25.0	1.6	2.7	0.6	3.6	15	38	89
Runoff (mm)	25	26	35	36	73	16	21	6.4	15	17	35	48
Salt load (kt)	21	12	26	21	47	12	19	2.2	23	84	128	146
Mean salinity (mg/L TDS)	6655	5520	7820	4750	1895	7695	7290	3600	6460	5755	3350	1640
Groundwater discharge to stream zone (mm)	12	16	20	8.0	15	10	12	5.5	11	13	13	
Baseflow (mm)	1.1	1.8	2.4	2.5	3.2	1.1	1.7	0.8	1.3	1.9	2.2	
Representative year at equilibrium [c]												
Annual rainfall (mm)	515	510	575	560	670	590	545	570	550	565	590	665
Streamflow (GL)	4.5	2.0	3.1	4.6	27	3.1	3.4	0.7	5.0	16	42	92
Runoff (mm)	36	23	33	38	80	31	26	7.5	20	18	38	50
Salt load (kt)	30	12	25	24	46	16	22	2.5	32	95	138	155
Mean salinity (mg/L TDS)	6730	5940	8015	5135	1705	5330	6600	3500	6550	5960	3315	1685
Groundwater discharge to stream zone (mm)	13	16	20	8.2	16	11	13	5.6	12	14	14	
Baseflow (mm)	1.1	1.6	2.2	2.5	3.3	1.2	1.8	0.9	1.3	1.8	2.2	

[a] The catchment between Rocky Glen and Styx Junction is assumed to have 1% clearing in 2002

[b] Annual mean for the period 1992–2002

[c] Annual rainfall of 2000

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