SALINITY SITUATION STATEMENT

Denmark River

DEPARTMENT OF ENVIRONMENT
WRT 30
2004
WATER RESOURCE TECHNICAL SERIES

Department of Environment

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DENMARK RIVER

by

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Cover photograph: Kompup gauging station [taken by Andrew Maughan]

Acknowledgments

Information on the Denmark River catchment has been produced from a number of special studies and long-term monitoring programs.

The suite of experimental catchments (Pardelup, Barrama and Willmay) to study the impacts of tree planting was set up by the Water Authority in 1988. The cooperation of the landowners of these catchments, respectively the Pardelup Prison Farm, the Clode family at Barrama and the Drage family at Willmay, in allowing the experiments to proceed has been greatly appreciated.

The *Integrated Catchment Management Plan for the Upper Denmark Catchment* began in 1991 as a cooperative project by the WA Department of Agriculture, Department of Conservation and Land Management, the Water Authority, the West Mount Barker LCDC and farmers in the catchment. Mr Ruhi Ferdowsian of the Department of Agriculture, Western Australia was mostly responsible for the detailed investigations of site characteristics and the preparation of farm plans in consultation with the farmers.

Streamflows, groundwater levels, and associated salinity from the experimental sites and also from the main stream gauging stations, were recorded by hydrographers from the Water and Rivers Commission (now Department of Environment) and stored in their water information database (WIN). The data have been further analysed by the Salinity and Land Use Impacts Branch of the Department.

Data preparation and modelling of revegetation management options for the salt-affected areas of the Denmark River catchment used the MAGIC system developed by Geoff Mauger, formerly of the Commission. Alex Rogers of Jim Davies and Associates helped to run the model and prepare spreadsheets of results. General mapping and preparation of area statements used ESRI's GIS program ArcView and its extensions.

Thanks also go to all those who offered comments on the draft version of the report, including: Richard Silberstein, Richard George, and John Ruprecht.

MA Bari
Department of Environment

Disclaimer

Preface

The Denmark River catchment is one of the original clearing control catchments. The Denmark River catchment was declared a clearing control catchment in 1978 to help arrest the rise in salinity.

Under the Salinity Action Plan (Government of Western Australia 1996) the Water and Rivers Commission (now the Department of Environment) was designated as the lead agency for coordinating efforts to lower salinity in five key Water Resource Recovery Catchments to ensure the availability of sufficient drinking quality water to meet public needs into the future. These are the catchments (or the upper parts of the catchments) of the Kent, Denmark, Warren, Collie and Helena rivers.

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. The stream salinity from the Helena catchment is being monitored.

An important component of the Department of Environment's salinity program is to assess the current state of the targeted rivers and evaluate various options available to recover stream salinity to drinking water levels. The Salinity Situation Statement for the Collie River was published in 2001 and the statements for the Warren and Kent catchments are in preparation.

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Summary

The water in the Denmark River was fresh (salinity below 500 mg/L TDS) until the mid-1970s. Intermittently since then, and especially in dry years, it has been too saline for public water supply. This report analyses where and why it became saline, describes its salinity in the intervening 30 years and suggests technically feasible management options to restore the river water to fresh condition.

The Denmark River discharges into the Wilson Inlet at the town of Denmark on the south coast of Western Australia. It is one of the water sources for Denmark (population about 5000). The annual demand for the town is 400 000 kilolitres (kL or 0.4 gigalitres), but the river could provide up to 20 gigalitres (GL) of water for the Albany–Denmark region. Previous studies for water source development identified a dam site near Mt Lindesay. Further studies and consultation processes need to be undertaken before a dam site could be selected.

Extensive clearing of native vegetation from the upper catchment from the 1920s, but primarily in the 1960s and 1970s, resulted in increased salinity and it was forecast that, without intervention, the annual average salinity could have peaked at 1410 milligrams per litre Total Dissolved Solids (mg/L TDS) at the Kompup gauging station in the upper catchment and 700 mg/L in the lower catchment near the Mt Lindesay gauging station. This posed a threat to the Denmark River as a drinking-water supply. Accordingly, the State and Commonwealth governments undertook recovery measures, including reafforestation and land acquisition. The Upper Denmark River Catchment is currently a Water Resource Recovery Catchment under the Salinity Action Plan. In the Salinity Action Plan a salt target was set — to recover the Denmark River to potable water standards (500 mg/L) at Mt Lindesay by 2020.

The Water and Rivers Commission (now the Department of Environment) established the Kent–Denmark Recovery Team, a group of community and government representatives, to help meet its commitments. Computer modelling (with the MAGIC system) used the hydrological records collected within the catchment and from three nearby experimental catchments to assess the current salinity situation and suggest a range of vegetation-based and engineered options which, if implemented, could result in meeting the target river salinity. This report focuses on the status of dryland salinity in the catchment and estimates the effectiveness of selected management options with respect to the salinity target only.

The maps, graphs and tables are intended to give an accessible overview of the information. The data from which they have been produced are all available digitally in Geographic Information Systems, spreadsheets and databases held by the Department of Environment.

The report shows that:

- Annual salinity of the Denmark River peaked at 1520 mg/L TDS at the Mt Lindesay gauging station in 1987. However, since 1991 annual stream salinity has been decreasing by 8 mg/L/yr. This is partly because groundwater level rises following clearing have largely stopped, and, in part, due to the groundwater-lowering effects of plantations established after 1988.
- Further reduction in salinity is expected once all existing and planned plantations have been fully established but not enough to meet the salinity target.
- Modelling indicated technically feasible management options with the potential to reduce the salinity to the target. They include engineering options such as groundwater pumping and saline water diversion, and vegetation options such as tree plantations and lucerne.

- All salinity management works should be in place by 2010 to meet the 2020 target, as the full effects of works are expected to take up to ten years.
- Continuing protection of remnant native vegetation is important because loss of this vegetation (with the loss of its water-use functions) can negate efforts to reduce salinity by other means.
- Most management options require action in the Upper Denmark catchment.
- Stored salt leaching from the upper catchment may be the reason that stream salinity is falling. If so, it is expected to take more than 50 years to fall to the target at the Mt Lindesay gauging station without additional land management changes.

The following are technically feasible options to achieve the salinity target:

- Plant more trees.
- Plant substantial areas to perennial pasture such as lucerne.
- Establish a groundwater pumping scheme.
- Build dams to divert saline water.

The impacts of drainage were also considered. Shallow drainage is expected to have little effect on salinity at Mt Lindesay. Deep drainage would not help meet the target salinity unless the drainage water was collected and transported out of the catchment.

The following are recommendations on the management options presented.

- Associate the economic and social costs and benefits of the various management options with their physical impacts on streamflow, salinity and salt-affected land. Determine the long-term sustainability of commercial plantations. Issues to be addressed include the incentives for private owners to embark on a new rotation after harvesting, maintenance of soil fertility, and the possibility of salt accumulation in the root zone if trees are planted where deep groundwater is discharging.
- Review the practicality of groundwater pumping when the results of the current trial in the Collie River Recovery Catchment are available.
- Investigate the viability of perennial pastures in reducing stream salinity.

The following are recommendations for monitoring and evaluation.

- Update this report at five-year intervals until the salinity target at the Mt Lindesay gauging station is reached.
- Continue monitoring streamflow and salinity at mainstream gauging stations to confirm the recent indications of downwards trends in salinity.
- Re-activate monitoring of the Perillup River to confirm assumptions of salinity and salt load from this catchment.
- Establish a program to ascertain whether leaching of salt from the Upper Denmark catchment will be a significant contributor to reducing the salinity of streamflow.
- Resume monitoring of selected piezometers and stream gauging (flow and salinity) in the Barrama and Pardelup experimental catchments for at least two years to confirm model estimates of the effects of reforestation.
- Review the groundwater monitoring network in the Upper Denmark catchment to ensure that the response of groundwater levels to land use changes can be efficiently monitored.

This report focuses on conceptual salinity reduction options. This was important in order to understand the extent of the land use changes needed to achieve the salinity target. The next steps are to talk to the stakeholders about the options and evaluate the social, economic and environmental implications of each option prior to finalising a salinity recovery plan.

The final step would be to implement this plan and to recover a major river from salinity – a national first!

1 Introduction

1.1 Background

The water in the Denmark River was fresh (salinity below 500 mg/L TDS) until the mid 1970s. Since then, it has usually been too saline for public water supply. This report analyses where and why it became saline, describes its salinity in the intervening thirty years and provides management options to restore the river water to a fresh condition.

Clearing the high water-use forest and other native vegetation for lower water-using vegetation like crops and pastures changed the water balance of the Denmark River catchment. The lower evapotranspiration of pasture and crop areas and the consequent increased infiltration of rainfall to groundwater stores resulted in rising groundwater levels in salinised valley floors and hillsides, and eventually in rising salinity of rivers and streams. This higher salinity precludes use of the river water for public water supplies other than opportunistically during high-rainfall years. Recent plantations (high water-use vegetation) have gone some way to reversing the trend of rising salinity, but additional management is needed to achieve the target of 500 mg/L at the Mt Lindesay gauging station by 2020.

The subject of this report is the Denmark River Water Resource Recovery Catchment (usually referred to as the Denmark River Recovery Catchment) which is the part of the Denmark River catchment upstream of the Mt Lindesay gauging station. The Denmark River Recovery Catchment consists of four areas: three ‘management units’ called Perillup, Kompup and Yate Flat Creek where changes in land use to manage salinity need to occur, and the almost totally (95%) forested area between the Kompup and Mt Lindesay gauging stations which does not contribute to the salinity problems of the river. The area encompassing the management units is also referred to as the Upper Denmark catchment. The locations and relationships between the areas are shown in Figure 1.

1. 2 Objectives

This report deals only with dryland salinity and the resulting salinity of the Denmark River. The objectives of the study and this report were to:

- assess the current salinity situation of the Denmark River Recovery Catchment
- predict what could be expected if no land use changes or engineering works were established
- provide a range of management options and their likely effects on river salinity.

1.3 Brief history of European settlement and land use

Before World War I

Humans had already inhabited the area for thousands of years when, in 1829, Thomas Braidwood Wilson became the first European to explore the region, naming the local river (called ‘Kurrabup’ by the indigenous people) in honour of his friend, English naval surgeon Dr Alexander Denmark. Although the townsite of Denmark was officially gazetted in 1909, there had been a settlement there at least since 1894 when a Millars Brothers timber mill was established on the banks of the river. Timber production was the major land use in the catchment until 1904 when the timber was nearly exhausted. Many people left and those that stayed farmed fruit and vegetables. Until World War I, sales of cheap land assisted immigration from Britain, and people moving from gold mining at Kalgoorlie resulted in a steady stream of people taking up land in the catchment and establishing farms. Most inland farming consisted of pastoralism as clearing the land was difficult and there were problems with local soils and poisonous plants (Conochie 1979).

Group Settlement Scheme

Agriculture was severely interrupted by World War I but received a tremendous boost in the 1920s when the Group Settlement Scheme began. This scheme saw groups of British ex-servicemen work in teams in areas like Scotsdale, Hazelvale, William Bay, Golden Hill and Tingledale to clear tracts of land. These prospective farmers and their families worked in primitive conditions for the right to take part in a ballot for distribution of the cleared farm land. The farms covered about 200 acres and included a standard four-room

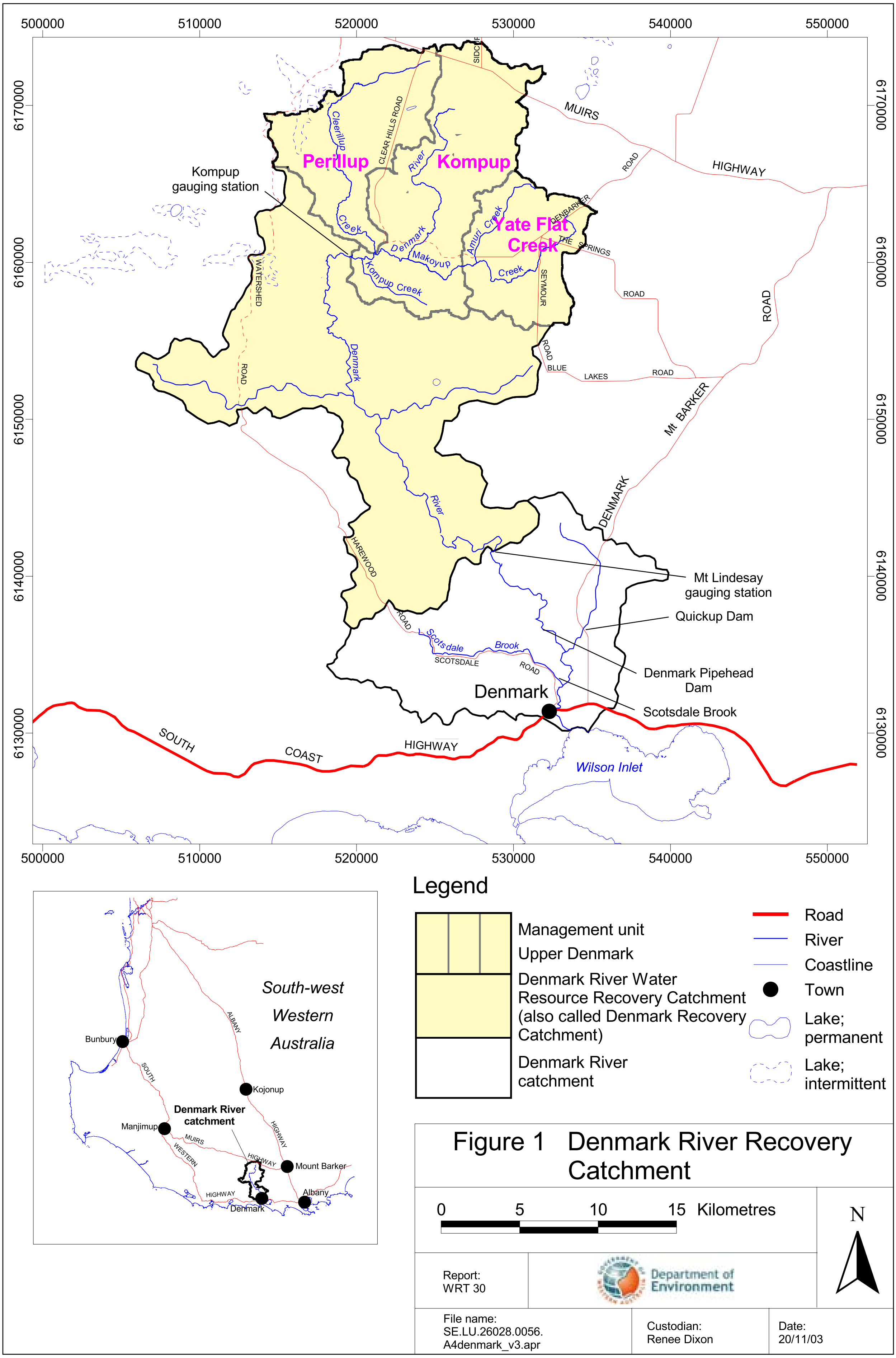


Figure 1 Denmark River Recovery Catchment

house. The farms were established in an attempt to set up a dairy industry in the South West. Again, knowledge of soils was a problem. Pastures grown on cleared karri forest soils resulted in the infamous 'Denmark Wasting Disease'. We now know that it was a deficiency of trace elements, particularly cobalt, which caused livestock mortality (Conochie 1979).

By the late 1920s, it was clear that the scheme was not working and that farms were not economically viable, as the farmers were accruing large personal debts. The fledgling agriculture industry was dealt a further blow by the economic depression of the 1930s. People were forced to walk off their farms. Agriculture in the Denmark River catchment was still at a low ebb at the outbreak of World War II, but the war at least provided regular markets and fixed commodity prices.

War Service Land Settlement Scheme
After World War II came the introduction of the War Service Land Settlement Scheme. This scheme involved the government repatriating ex-servicemen onto subsidised farms. Although similar in concept to the Group Settlement Scheme of the 1920s, this scheme was considered economically and socially successful. Considerable land was opened up around Rocky Gully (Kent River catchment), Denbarker and Narrikup. By 1950 the area of land alienated in the Denmark River catchment was about 250 km^2, and by 1965 nearly 300 km^2. This indicates that much of the land had been partially developed (alienated) by 1950 but not cleared. The advent and availability of better machinery meant that clearing became much easier and thus increased markedly from approximately 125 km^2 in 1950 to around 225 km^2 in the mid to late 1970s.

The 1950s also saw the timber industry increase again with the post-war building boom. Whittakers established a large mill near the river mouth. The mill produced large amounts of timber till it closed in 1974.

Water supplies and salinity
The Denmark River was first dammed in 1960–1, when a concrete pipehead dam was constructed 5 km north of the town of Denmark. The dam with a 420 ML (0.4 GL) capacity was constructed as a water supply for the town (Ruprecht et al. 1985).

As recognition of the salinity problem grew in 1961, government legislated to control the release of Crown land. By the late 1960s, clearing had caused a significant increase in the salinity of water supplied from the main stream of the Denmark River. Then, in 1978, Clearing Control legislation to control the clearing of native forest (Country Areas Water Supply Act, 1947, Part IIA) was applied to the catchment to limit the maximum salinity. The small storage capacity of the Pipehead Dam exacerbated the effects of salinity increase for the town supply. Low salinity winter water could not be stored to dilute the high salinity summer flow for summer supply. For some years, water was drawn from Scotsdale Brook (shown in Fig. 1) to dilute the water from the Pipehead Dam when salinity was high. However, without a storage dam, supply from Scotsdale Brook could not be relied on in droughts. In 1990, the Quickup Dam (Fig. 1) replaced the Pipehead Dam as the water supply source for Denmark. The Quickup River had a suitable site for a storage dam and its catchment is fully forested (Collins & Fowlie 1981).

After clearing, land in the Upper Denmark catchment was used mostly for pasture and cropping. The principal livestock was sheep for wool. In recent years, some of the cleared land has been converted to plantations of Tasmanian Bluegum (*Eucalyptus globulus*) for woodchips. These plantations will be harvested when about ten years old. At this time the landowner will decide whether to grow another plantation on the land or revert to pasture (Conochie 1979).

1.4 The Kent–Denmark Recovery Team

The Denmark River catchment was designated as one of the five Water Resource Recovery Catchments in the Salinity Action Plan (Government of Western Australia 1996). (The others are the Collie, Warren, Kent, and Helena river catchments). The Water and Rivers Commission (now the Department of Environment) was the lead agency in these catchments for implementing the Salinity Action Plan. To achieve the aims in the Denmark River Recovery Catchment with full involvement of stakeholders, the Water and Rivers Commission established a Recovery Team in 1998.

The Kent–Denmark Recovery Team is an active partnership between the community of the Kent and Denmark river catchments and key government agencies lead by the Department of Environment.

The role of the Recovery Team is to bring parties together at the local level and implement the state salinity program's purpose of 'recovering' water quality to potable levels in both rivers. As a subcommittee of the Board of the Water and Rivers Commission, the Team is a non-statutory, non-incorporated decision-making group.

The 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, while the rest of the team comprises representatives from the state's major natural resource management government agencies, including Department of Environment, Department of Agriculture and the Department of Conservation and Land Management (CALM) (see Appendix 1 for current and past Recovery Team members).

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 the Water Corporation) 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 in the catchment.

In the neighbouring Upper Kent catchment, the National Dryland Salinity Program sponsored a four-year study (1994–98) into salinity management. The Kent Steering Committee, formed in 1994, was responsible 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 ICM Plan for the Upper Kent Catchment was one of several outcomes of this program, which contributed to work in the Upper Denmark catchment (Burdass et al. 1998).

The Kent–Denmark Recovery Team was formed when the Denmark and Kent river catchments were designated 'Recovery Catchments' in the State's 1996 Salinity Action Plan. Several members of the Kent Steering Committee became members of the new Recovery Team. The foundation ICM Plans developed for the Upper Denmark and Upper Kent catchments and 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. The early bluegum plantings sponsored by the Water Authority, for instance, were the forerunners of the substantial bluegum plantation industry plantings in the Upper Denmark catchment that are helping to redress the hydrological imbalance underlying salinity in this catchment. Similarly, the property plans developed for Upper Denmark landholders pre-1996 and the ICM Plan of 1992 continue to guide the implementation of works to manage salinity.

2 Catchment characteristics

This section presents catchment characteristics relevant to management planning. More detailed information, particularly on the prevalence of the characteristics within each management unit, is presented in Appendix 2. Most data have been confined to the three management units (Perillup, Kompup and Yate Flat Creek) of the Upper Denmark catchment, where they are relevant to managing the cleared land.

2.1 Location

The Denmark River discharges into Wilson Inlet at the town of Denmark on the south coast of Western Australia (Fig. 1). There are three reference points relating to streamflow and salinity along the Denmark River: the mouth of the river, the Mt Lindesay gauging station, and the Kompup gauging station. These are shown on Figure 1.

To the mouth of the Denmark River, the catchment has an area of 704 km^2. Future development as a water source is likely to collect water from near the Mt Lindesay gauging station, where the catchment area is 525 km^2. Salinity targets for potable supply are assumed to refer to the stream water quality at the Mt Lindesay gauging station.

2.2 Shires and cadastre

Figure 2 shows shire boundaries, roads and lot boundaries for the Upper Denmark catchment. All of the Upper Denmark catchment and 95 km^2 downstream of the Upper Denmark catchment are located within the Shire of Plantagenet. The rest of the Denmark River catchment lies within the Shire of Denmark. Road and cadastral information was supplied by the Department of Land Administration (DOLA).

2.3 Climate

The Denmark River catchment experiences a Mediterranean-type climate of mild wet winters and hot dry summers. The average annual rainfall is about 700 mm. The mean average rainfall varies from 1200 to 700 mm at Upper Denmark. Most falls between May and October. Since the 1970s, average annual rainfall has been decreasing (Moulds & Bari 1995). Mean annual pan evaporation ranges from 1250 to 1430 mm.

2.4 Geology and physiography of the catchment

The landscape of the Upper Denmark catchment has developed by weathering of the Proterozoic granitoid, gneissic and metamorphic rocks of the Albany–Fraser Orogen. Except for occasional outcrops, these rocks are completely weathered to depths of 10–20 m, resulting in sandy clays with lateritisation at or near the surface (Smith 1997). Clearing this landscape for agriculture has resulted in the development of dryland salinity and increased river salinity.

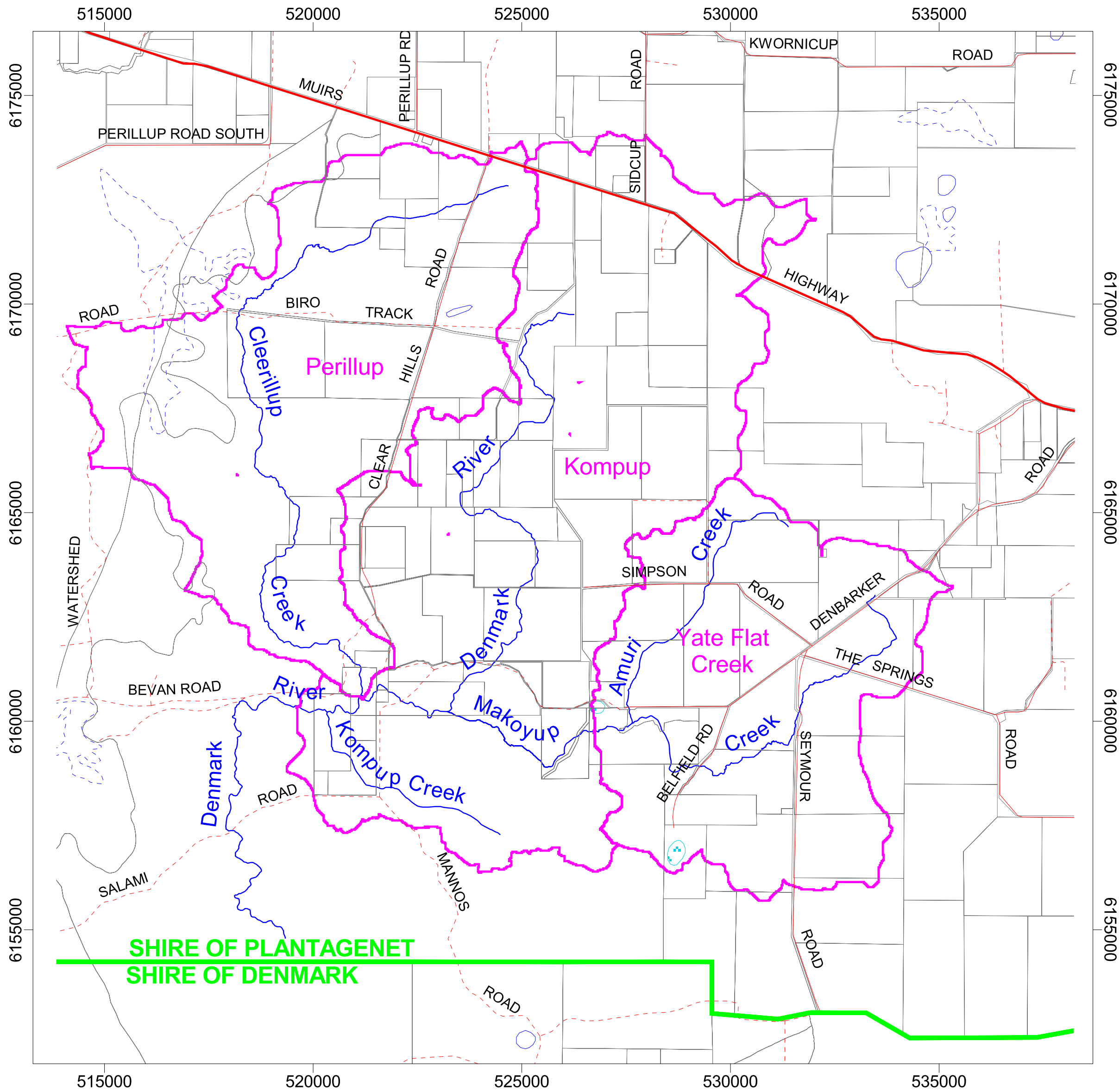
Description – from Ferdowsian and Greenham, (1992)

The Upper Denmark catchment lies within the Albany–Fraser Orogen, a tectonic unit bordering the southern margin of the Yilgarn Craton. The catchment lies predominantly within the Nornalup Complex of the Albany–Fraser Orogen, with the northerly precincts extending onto the Biranup Complex.

An active period of widespread lateritization occurred in the Oligocene and/or Miocene. Over a large part of the catchment the weathering profile was capped by a massive pisolitic laterite between 2 and 4 m thick. Lateritization and erosion are probably still continuing.

A hinge line formed the northern catchment boundary and disrupted the southerly flow of rivers and has altered their course since the Eocene. Rounded quartz pebbles and cobbles on some locations are probably deposits of these rivers. Boulders of ferruginized sandstone and lake sediments have been found high in the catchment, which confirms that this area was uplifted and tilted since the Miocene.

The Denmark River is a rejuvenated river that, through active headward erosion and river capture, has dissected a series of east–west benches (with ancillary swampy flats), and formed new landform patterns. These swampy flats are probably remnants of ancient river courses that flowed westwards.



Legend

- Main road
- Minor sealed road
- Unsealed road
- Lot boundary
- Shire boundary
- Lake; permanent
- Lake; intermittent
- Swamp
- Management unit boundary
- River

Figure 2 Shires and cadastre for Upper Denmark catchment

0 2 4 6 8 Kilometres

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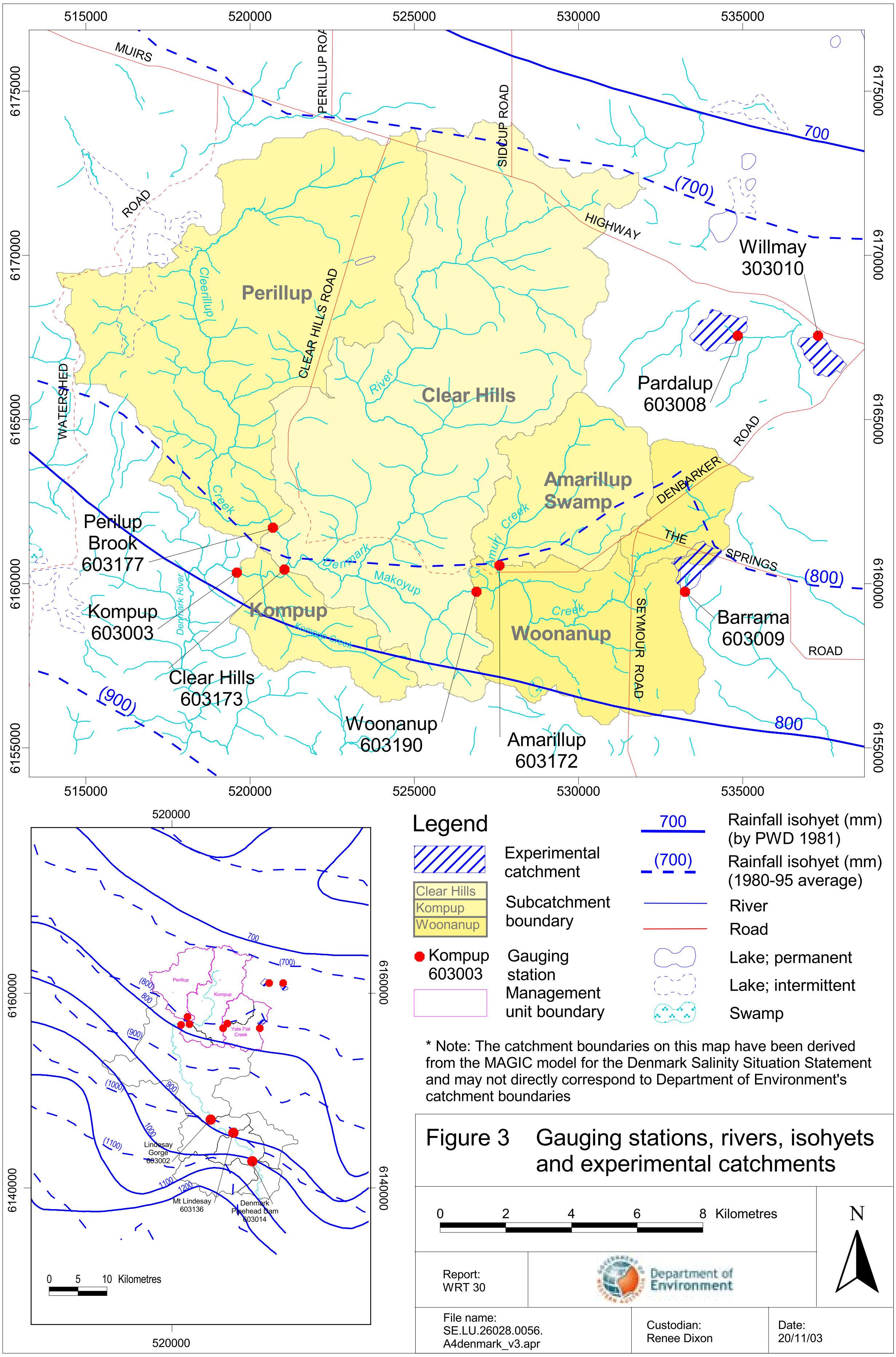

Figure 3 Gauging stations, rivers, isohyets and experimental catchments

Numerous shear zones occur throughout the study area. The shear zones have affected the drainage pattern of the study area as most of the creeks follow the shear zones. These zones act as conduits or barriers to groundwater movement.

Landform patterns

The Upper Denmark catchment can be divided into three areas:

- the upper catchment with broad swampy flats and poor drainage
- the mid catchment with defined shallow creek lines
- the lower catchment with incised valleys in granitic areas.

2.5 Soil–landscape systems

The Upper Denmark catchment has been mapped as comprising three soil and landscape systems.

A 'system' comprises an area with a recurring pattern of soils, landforms and vegetation. A 'subsystem' comprises an area of characteristic landform features containing a defined suite of soils. A 'phase' is an area where particular features, such as poorly drained flats, are predominant within the general pattern (Tille 1996). See Appendix 2 for information about the source of this mapping.

Table 1 describes the landforms, geology, soil types and vegetation components of each system. About 70% of the catchment is categorised as Kent system. The area of each soil–landscape system by management unit is shown in Appendix 2 Table A2.1. The systems are further divided into 16 subsystems. These are mapped on Figure 4 and the descriptions are provided in Appendix 2 Tables A2.2 and A2.3.

The soil thickness varies from 1.1 to 1.8 m and the permeability varies from 31 mm/hour to 62 mm/hour (Table A2.2). About half the catchment falls into just two subsystems — Mallawillup and Camballup. About 27% of the Upper Denmark catchment is classed as Mallawillup subsystem (MW) of the Kent system and is described as 'undulating rises with broad flat swampy depressions. Soils are formed in colluvium and weathered granite. Gravelly soils (bog iron ore) are common'. The soil thickness is about 1.6 m and the permeability is 20 mm/hour. About 16% of the catchment is classed as Camballup subsystem (CM) of the Kent system and is described as having soil thickness of 1.15 m and a permeability of 28 mm/hour and 'swampy plains with some broad drainage lines and salt lakes'.

The pre-European vegetation complexes are listed in Appendix 2 supported by Figure A2.1 and Table A2.4. The correlation of these vegetation complexes with soils and slope is shown in Section 2.7 Topography and Appendix 2.

Table 1. Soil–landscape system names and descriptions

System	*Landform*	*Geology*	*Soil types*	*Vegetation*
Kent (Ke)	Undulating lateritic plains with lakes and poorly drained flats	Tertiary alluvium, colluvium and sand with laterite, and quaternary lake and swamp deposits	Duplex sandy gravels with semi-wet soil, shallow gravel and grey deep sandy duplex	Wandoo–yate–flooded gum–jarrah–marri woodland and paperbark heath
Roe Hills (Rh)	Hilly terrain with rock outcrops	Colluvium over granitic rocks	Loamy gravels, duplex sandy gravels, brown deep loamy duplexes and friable red/brown loamy earths	Jarrah–marri forest and woodland
Wilgarup Valleys (Wv)	Major valleys	Colluvium over granitic rocks	Loamy gravels, friable red/brown loamy earths, duplex sandy gravels, stony soils and semi-wet soils	Marri–jarrah-wandoo forest and woodland

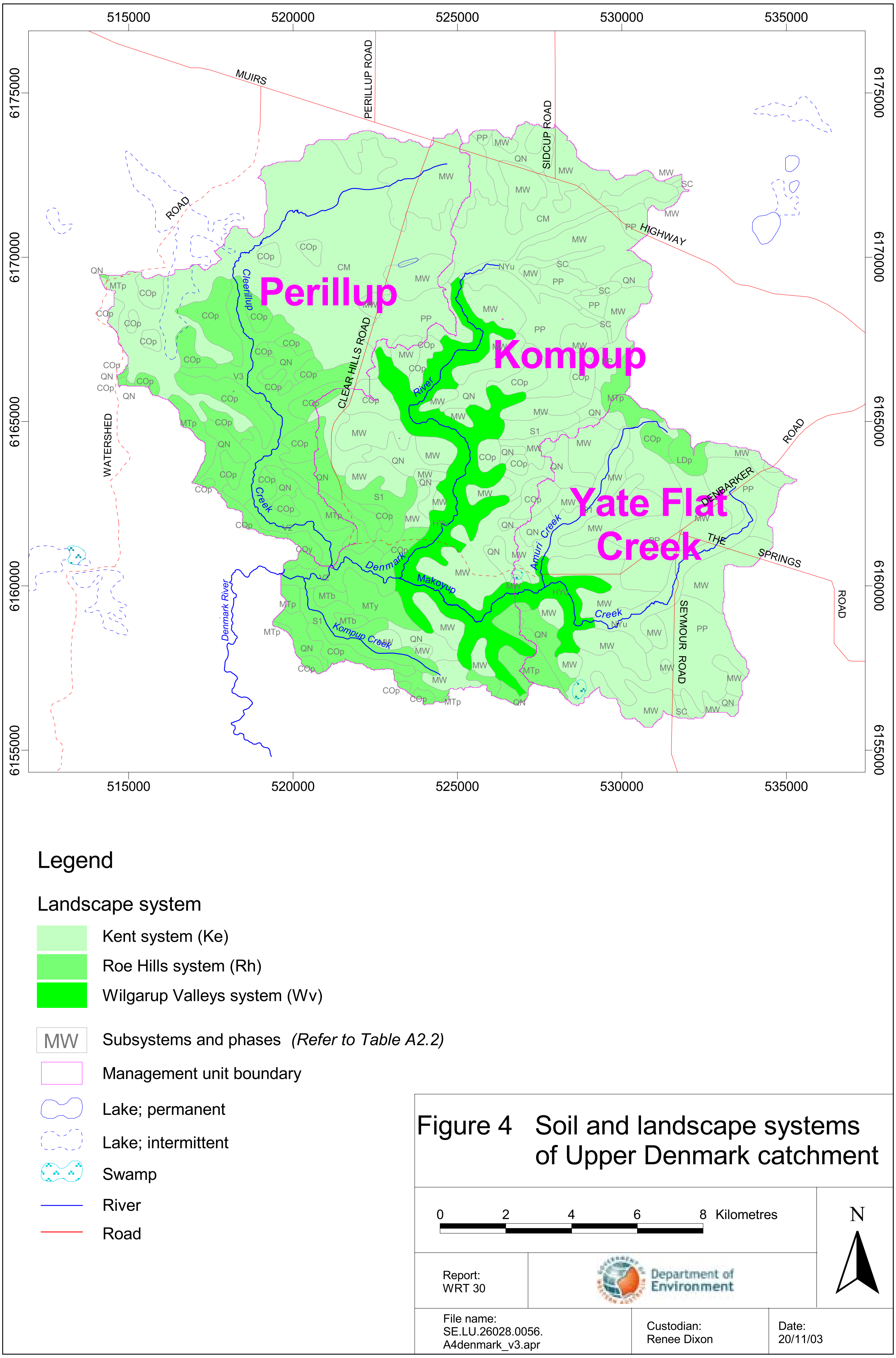

Figure 4 Soil and landscape systems of Upper Denmark catchment

2.6 Hydrogeology

Geology and geomorphology influence the occurrence and movement of groundwater and hence the susceptibility of the land and waterbodies to salinisation.

Groundwater occurs in the weathered and fractured bedrock aquifers of Proterozoic metamorphic rocks including granites and gneisses (Fig. 5). The catchment falls completely within the Albany–Fraser Orogen Hydrogeological Province. Groundwater is held in unconfined- to semi-confined aquifers and receives vertical recharge from rainfall. Groundwater flow is local (moving from hills and hill slopes) and discharges into drainage lines. In shallow water level areas in the lower parts of the catchment, groundwater also discharges through evaporation, leaving salt in soils. Groundwater movement from the upper to the lower catchment is an important part of the salt leaching process in the catchment.

Groundwater salinity is in the range of 1000 to 3000 mg/L Total Dissolved Solids (TDS). Groundwater in the lower parts of the catchments is within two metres of the natural surface and, in places, the potentiometric heads stand above ground surface.

The prevalence of the hydrogeological units within the management units is listed in Appendix 2 Table A2.5.

The hydrogeological data shown in Figure 5 are reported in Smith (1997) and the Department of Environment is the custodian for the digital data.

2.7 Topography

Topography, as shown by the digital elevation model (DEM), is a very useful tool for visualising the catchment as well as being necessary for modelling.

The digital elevation model (DEM) was extracted from the DEM prepared by DOLA for the Land Monitor Project, which had cell centres on a 10 m grid and a quoted vertical accuracy of 1.5–2 m.

Figure 6 is an enhanced view of the DEM used for hydrological modelling of the catchment. Data points are available at 25 m centres on the ground. Other datasets generated from the DEM with values at 25 m centres are slope, aspect, plan curvature of the ground, and drainage linkages. When the data are considered as a two-dimensional array of ‘cells’, the drainage linkage in any particular cell identifies which adjacent cell or cells would receive water running off the surface of that cell in accordance with its aspect and plan curvature. The drainage linkage allows a computer to accumulate the values of other features over the complete catchment area upstream of each cell; it also facilitates the automatic generation of catchment boundaries.

Contours can be prepared at whatever interval local planning requires, recognising that accuracy will be relatively low.

The elevation of the Upper Denmark catchment varies from about 100 to greater than 250 m AHD (Fig. 6).

2.8 Vegetation information from Landsat

Information on the vegetation complexes that existed before European settlement and clearing is provided in Appendix 2 *Pre-European vegetation complexes* and Table A2.4.

Vegetation changes caused by clearing and establishing plantations are well shown by Landsat TM scenes recorded between December and March. These images indicate the status of vegetation in summer and are good for tracking land use changes involving clearing and planting. These scenes are an important tool in modelling the catchment.

Two scenes are shown in this section. Figure 7 shows the first available high resolution Landsat photo. This summer 1988 scene predated the start of tree farming and best represents the state of the catchment that produced the peak river salinity. Figure 8 shows the latest Landsat scene used in this study, the December 2001 scene. The reduction in the extent of cleared land and its substitution by plantations is clearly visible.

Section 4 describes how data from these scenes are used in the hydrological modelling to estimate the density of trees in forested areas and to identify areas of pasture and crops. This information is then used to estimate the quantities of water transpired by the different forms of vegetation.

Figures A2.2 to 2.5 in Appendix 2 show Landsat TM scenes of Summer 1995, 1998, 1999 and 2000.

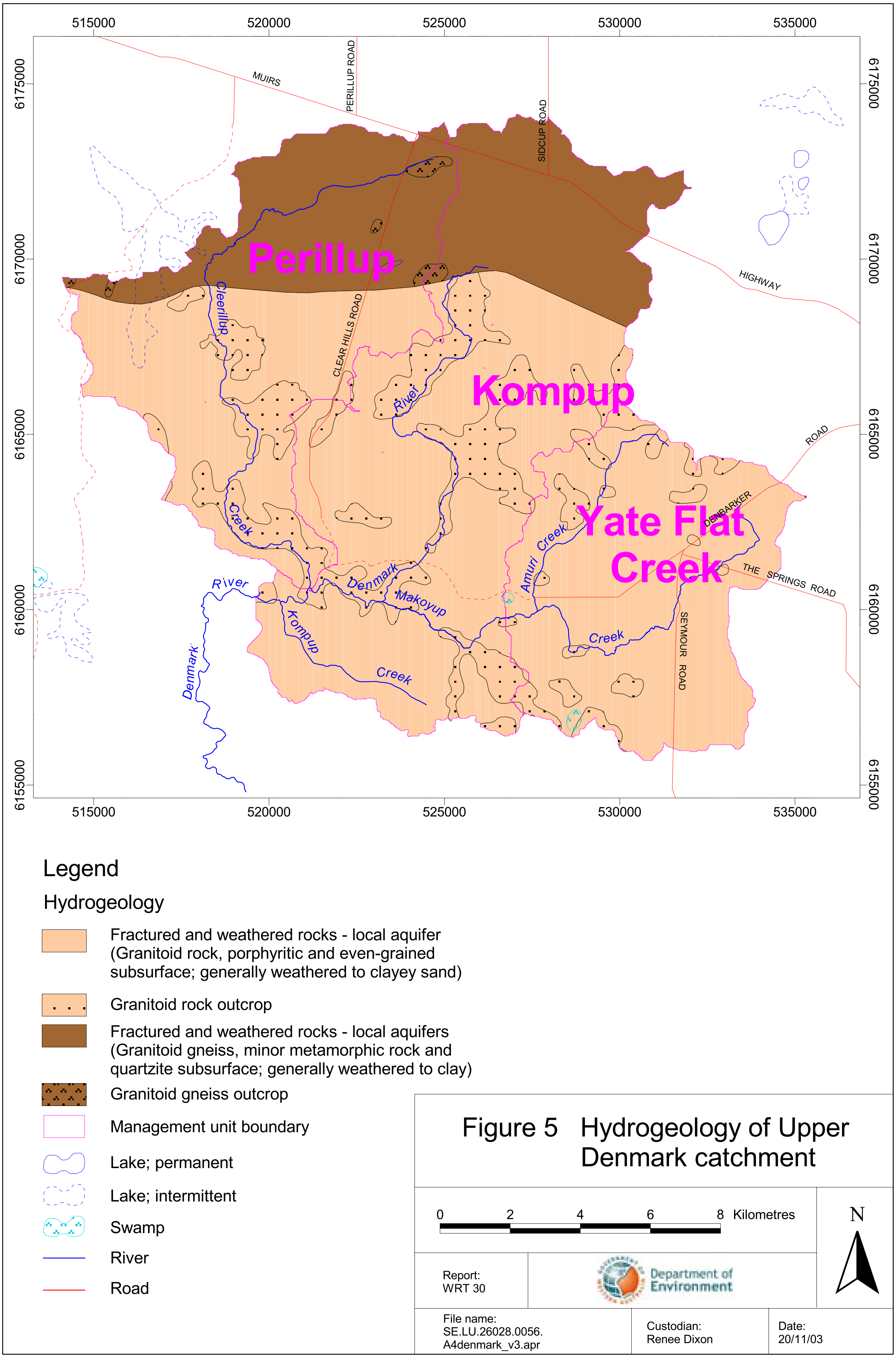

Figure 5 Hydrogeology of Upper Denmark catchment

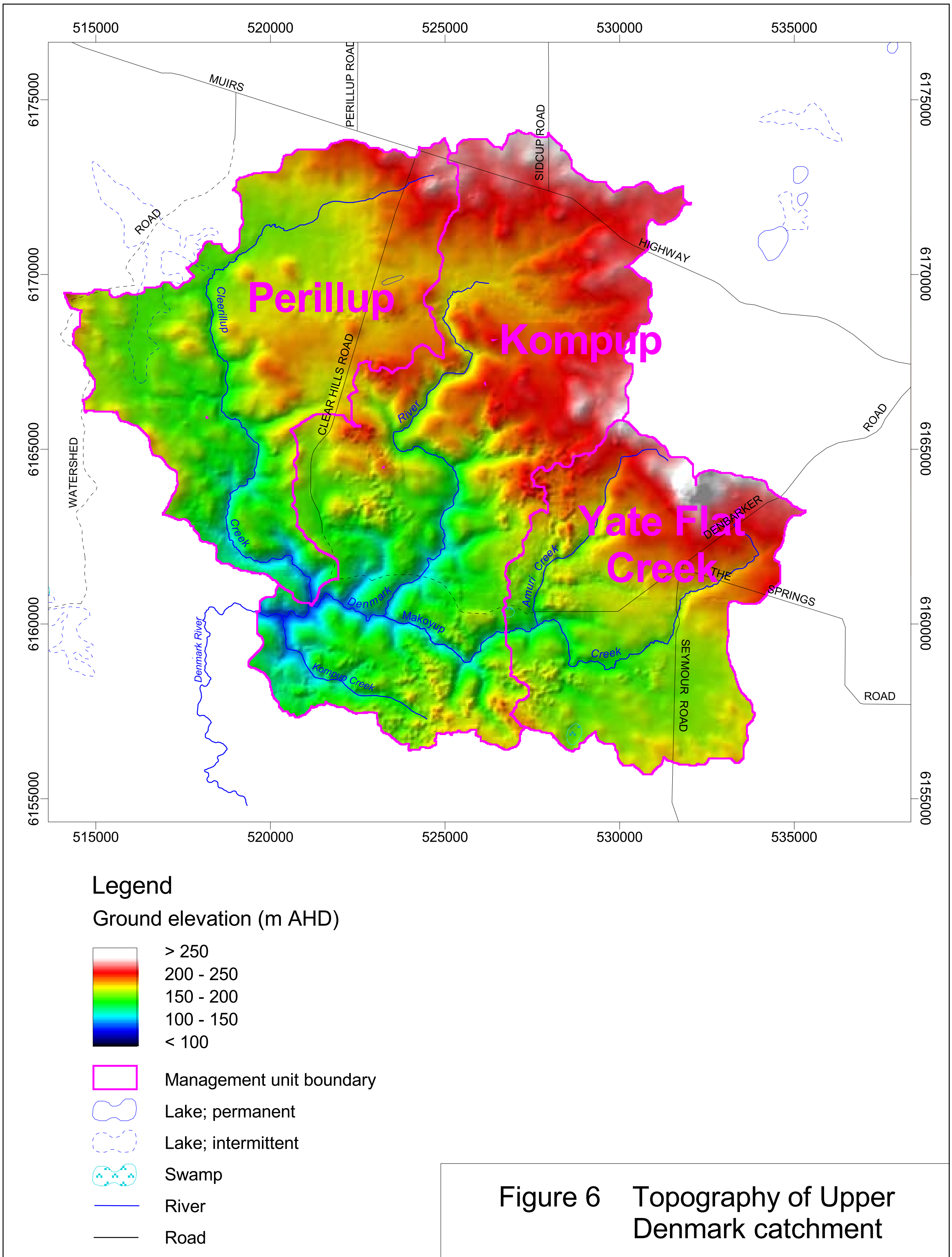

Figure 6 Topography of Upper Denmark catchment

0 2 4 6 8 Kilometres

N

Report: WRT 30

Department of Environment

File name: SE.LU.26028.0056. A4denmark_v3.apr

Custodian: Renee Dixon

Date: 20/11/03

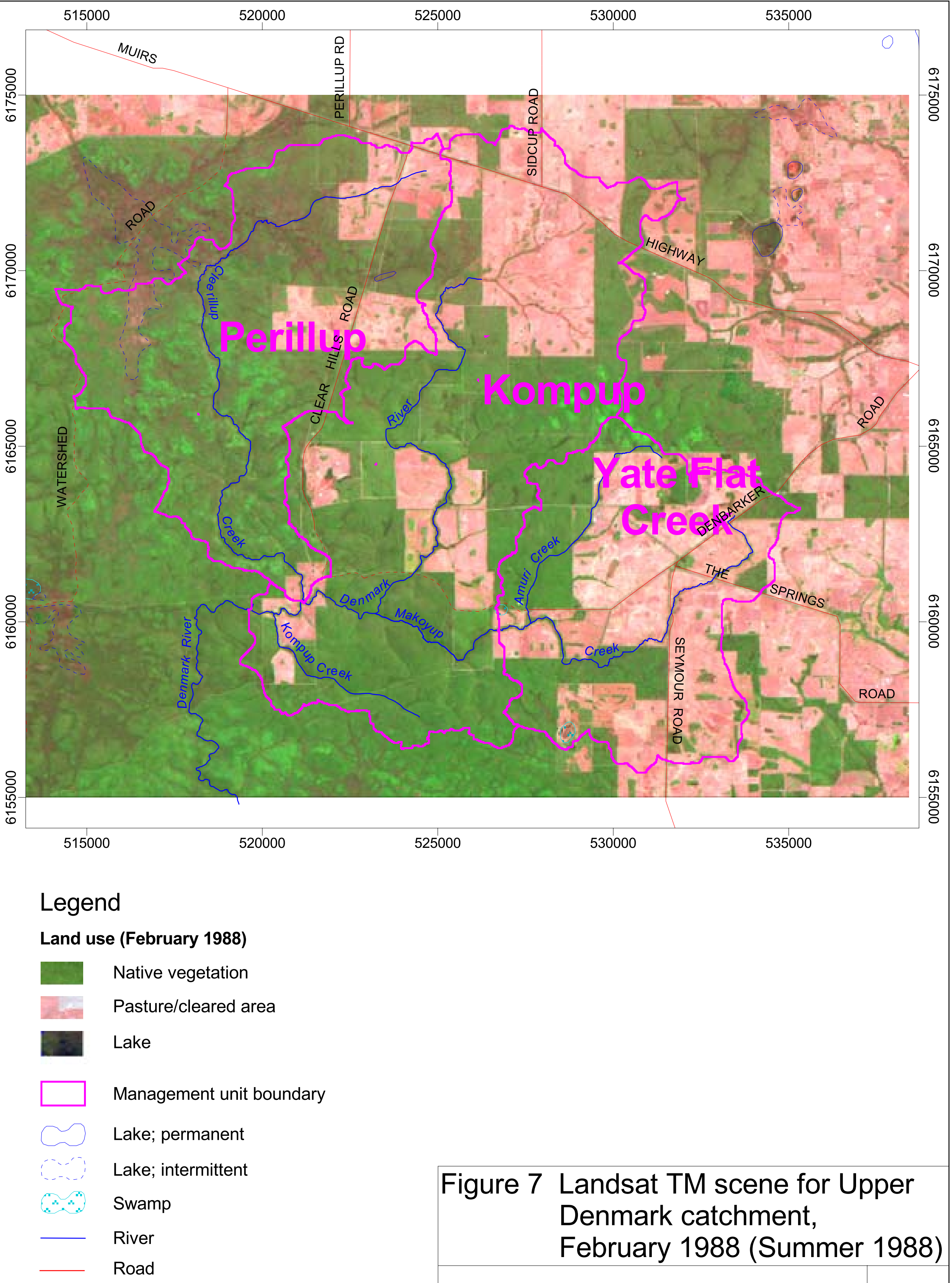

Figure 7 Landsat TM scene for Upper Denmark catchment, February 1988 (Summer 1988)

0 2 4 6 8 Kilometres

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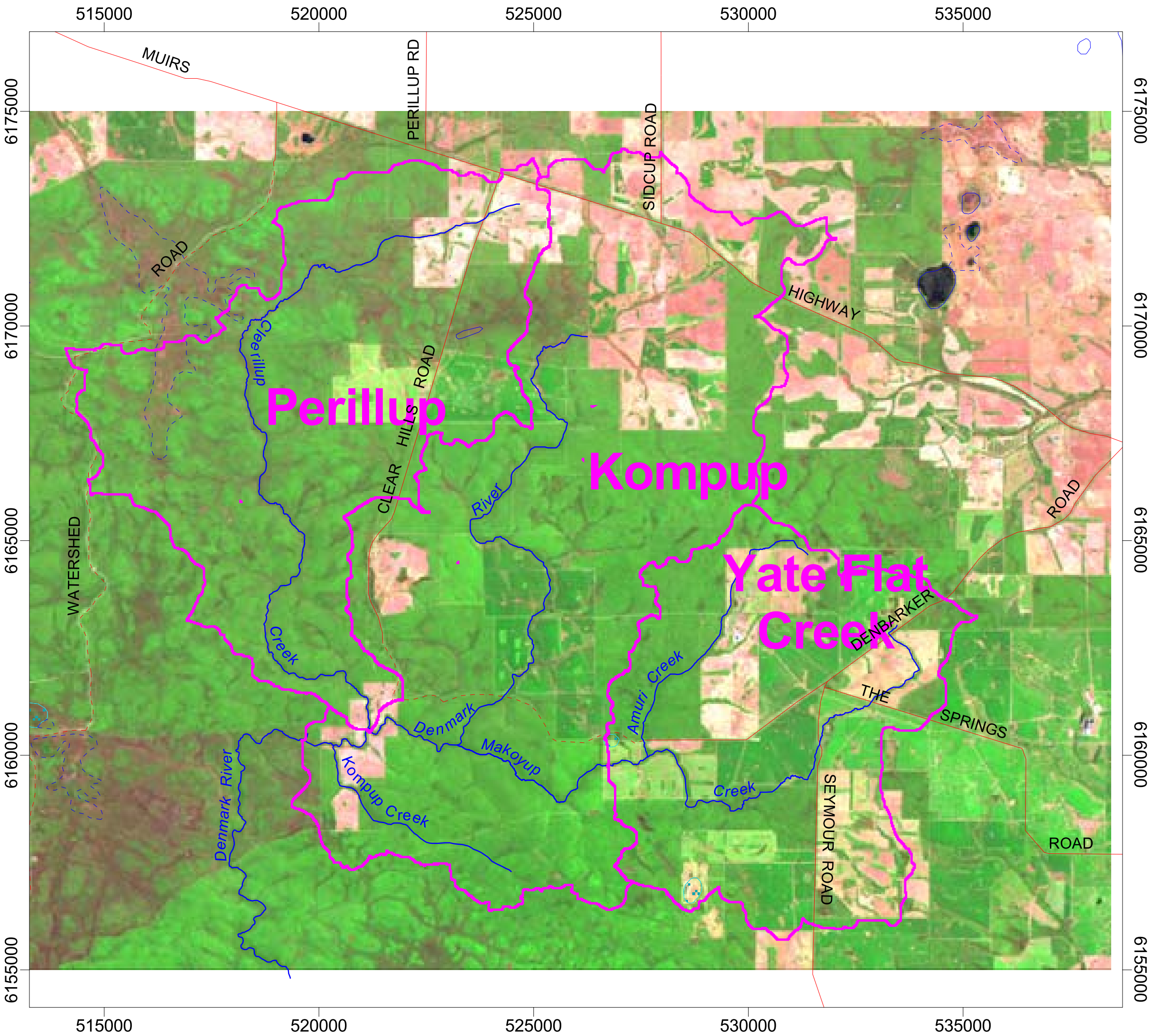
Report: WRT 30

Department of Environment

File name: SE.LU.26028.0056. A4denmark_v3.apr

Custodian: Renee Dixon

Date: 20/11/03



Legend

Landuse (December 2001)

- Native vegetation
- Pasture/cleared area
- Plantation
- Lake
- Management unit boundary
- Lake; permanent
- Lake; intermittent
- Swamp
- River
- Road

Figure 8 Landsat TM scene for Upper Denmark catchment, December 2001 (Summer 2002)

0 2 4 6 8 Kilometres

N

Report: WRT 30

Department of Environment

File name: SE.LU.26028.0056. A4denmark_v3.apr

Custodian: Renee Dixon

Date: 20/11/03

3 Flow and salinity characteristics

The first signs of rising salinity in the Denmark River came from stream gauging records on the main stream and tributaries. The stream salinity of the Denmark River is estimated to have been between 150 and 350 mg/L TDS before European settlement (Collins & Fowlie 1981). The rising salinity trend was also reported by Ruprecht et al. (1985) and Moulds and Bari (1995). Stream salinity increased as a consequence of replacing high-water-use native forest with lower-water land uses like pasture and cropping. The land use changes altered the components of the water balance. Evapotranspiration decreased allowing more of the rainfall to infiltrate past the root zone to recharge groundwater stores. Rising groundwater brought stored soil salt and salt in groundwater to the stream. This section presents links land use changes like clearing and planting within the catchment with data on groundwater level, streamflow, salinity and salt loads.

This section presents the streamflow and salinity records of the Denmark River catchment, traces the variations in time and place of clearing and plantations and describes the trends in surface water and groundwater. We examine the contributions of the various gauging stations to the outputs at the Mt Lindesay gauge in order to understand the processes of salt generation, and to identify the appropriate option and target areas for salinity management.

3.1 Streamflow and salinity records

Records of seven gauging stations within the Denmark River catchment were used in this study. Four of these stations were decommissioned well before 2002 when this study ended. The Kompup gauging station collects flow from all three management units (Table 2). There are two gauging stations in the Yate Flat Creek management unit and one in the Perillup. Records of three experimental subcatchments of the Upper Hay River catchment (Fig. 3), each with a gauging station, were also used. The periods of streamflow and stream salt load records of the gauging stations vary and cannot be directly compared. So, Table 2 presents the average for the period of record. For example, the Amarillup gauging station operated between 1963 and 1976 and average annual streamflow was 1540 ML. The stream salinity record was limited to 1974–76 and the annual mean salt load and salinity were 1600 tonnes and 1430 mg/L TDS respectively.

Table A3.1 in Appendix 3 lists the gauged catchment areas within the management units.

Table 2. Gauged catchment record summary

Gauging station	*Station No*	*Rainfall (mm)*	*Period of streamflow*	*Mean streamflow (ML/yr)*	*Period of salt load record*	*Mean salt load (t/yr)*	*Mean annual flow-weighted Salinity (mg/L)*
Lindesay Gorge	603 002	785	1974–1986	20 200	1974–1986	13 300	655
Kompup	603 003	733	1964–2001	11 700	1964–2001	11 400	974
Pardelup*	603 008	649	1991–1996	95	1991–1996	106	1120
Barrama*	603 009	705	1990–1996	143	1990–1996	292	2040
Willmay*	603 010	623	1990–1998	135	1994–1996	446	3630
Pipehead Dam	603 014	n/a**	1952–1960	n/a**	1952–1958	n/a**	352
Mt Lindesay	603 136	878	1954–2001	31100	1955–2001	15 100	478
Amarillup	603 172	730	1963–1976	1540	1974–1976	1600	1430
Clear Hills	603 173	733	1964–1977	9900	1974–1976	9900	1460
Perillup Brook***	603 177	729	1963–1972	1980	1962–1972	n/a**	282
Yate Flat Creek	603 190	735	1963–2001	5030	1963–2001	4840	962

* *Experimental catchments in Upper Hay River catchment*
** *n/a – not available due to incomplete streamflow records*
*** *salinity is estimated to have increased significantly since the gauging station has closed*

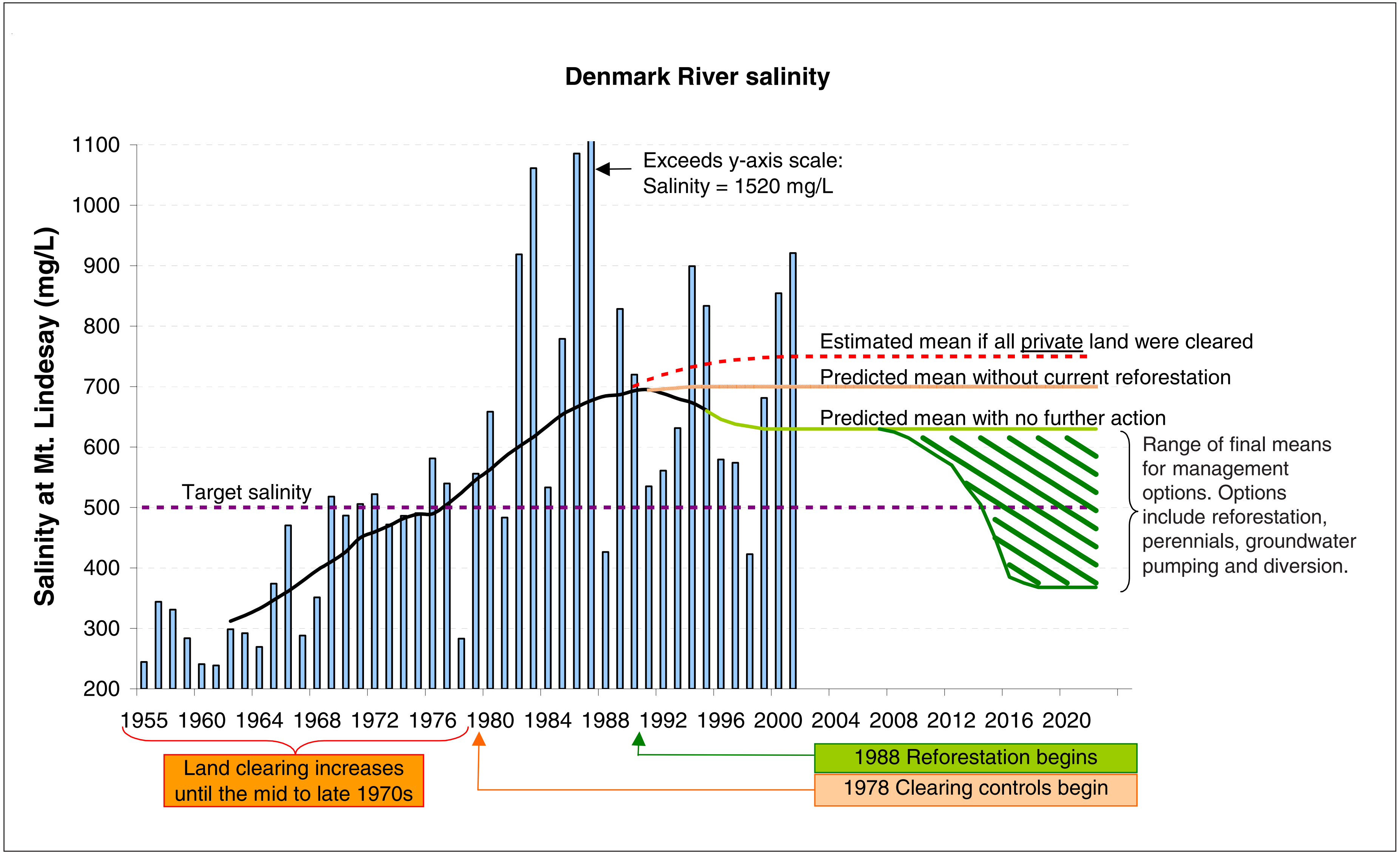


Figure 9. Denmark River salinity

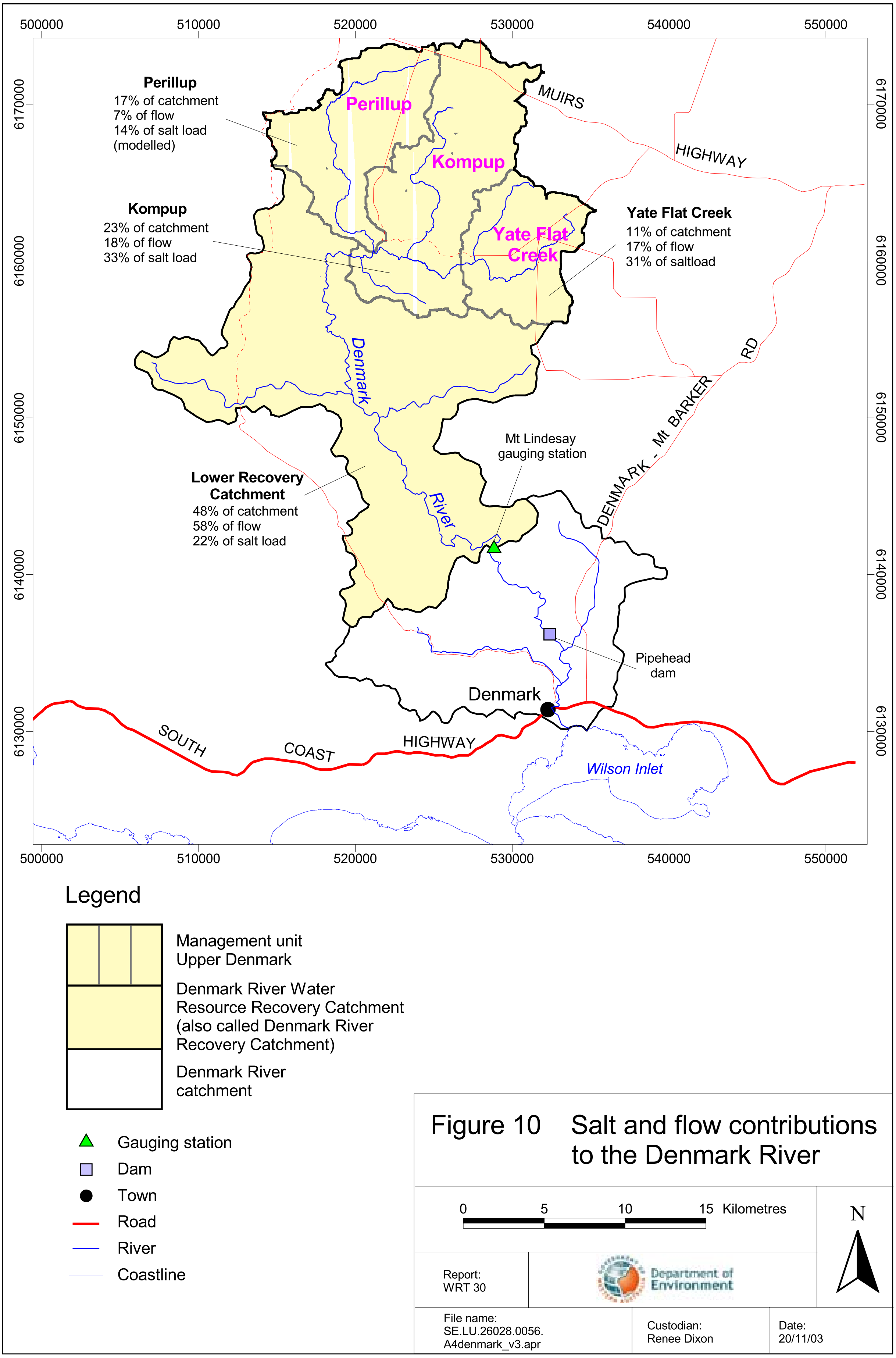


Figure 10 Salt and flow contributions to the Denmark River

The annual mean rainfall at the centroid of the catchment over the stated period of streamflow record was calculated according to the Dean and Snyder (1977) method. Mean annual rainfall ranges from 623 to 878 mm (Table 2), with annual streamflow and annual rainfall both decreasing inland from the coast. The lowest average annual runoff (26 mm) was recorded at the Perillup Brook gauging station. The Yate Flat Creek gauging station has similar annual rainfall to that at Perillup Brook, despite its average annual runoff being 87 mm. Annual streamflow at the two main gauging stations (at Kompup and Mt Lindesay) averaged 48 and 59 mm respectively.

Runoff coefficient is defined as the runoff as a percentage of the rainfall. The annual runoff coefficient ranges from 3.6% for Perillup Brook to 10.7% for Mt Lindesay, and the values generally increase with annual rainfall towards the coast. The runoff rate of the Yate Flat Creek catchment is 11.8%, nearly three times greater than that at Perillup Brook (Table 2). The cause of this higher runoff rate is due mostly to land or water use changes within the catchment areas.

Stream salinity generally increases with distance from the coast, with increasing cleared area and with decreasing annual rainfall. Stream salinity also becomes more variable in the low rainfall regions. Annual stream salinity recorded at the Mt Lindesay gauging station averaged 478 mg/L TDS (Table 2).

Average salt loads at the Kompup and Mt Lindesay gauging stations are 467 and 285 kg/ha respectively.

3.2 Land use changes

3.2.1 Clearing

Clearing native forest for agricultural development within the Denmark River catchment began in 1870 (Collins & Fowlie 1981). The clearing history of the catchment was reviewed and reported by Ruprecht et al. (1985). The earliest aerial photograph is dated 1946 and at this time only 3% of the Upper Denmark catchment had been cleared. By 1957 (the time of the next aerial photograph), 17% had been cleared. By 1965, another 6% had been cleared although about 1 km^2 in the Perillup subcatchment had reverted to native vegetation. The distribution of clearing varied with time (Fig. 11). Most of the clearing in the Upper Denmark catchment was done between 1956 and 1975 (Fig. 11). The photographs in 1979 show the catchment substantially in the condition it was when Clearing Control Legislation was applied in 1978, that is, about one third (84 km^2) cleared. By 1984, there had been minor additional clearing, but about 7 km^2 within the Kompup area had been replanted. Since 1988, the area of cleared land has been assessed by analysing Landsat scenes.

The extent of cleared area for agricultural development varied. The Yate Flat Creek management unit (MU) had the greatest cleared area — 35 km^2 or 61% of the total subcatchment area. Perillup Brook MU had the smallest cleared area — only 12.5% of the catchment area (Fig. 11). When the Clearing Control Legislation was enacted, 34% of the Upper Denmark catchment area was cleared. Details of the clearing history are given in Table A3.2 of Appendix 3.

3.2.2 Plantations

In 1990, the *Integrated Catchment Management - Upper Denmark Catchment* project helped farmers prepare farm plans that identified suitable areas to plant trees and to construct fences and drains. Tree planting in accordance with the plans began in 1991, with the Water Authority supplying investment capital and using CALM's *Timberbelt Sharefarming Scheme* as a vehicle for managing the tree crops. Planting continued with 35 ha in 1991, a further 36 ha in 1992, and finally 71 ha in 1993. Some farmers used their own capital to plant even more trees. Later in the 1990s, some farms were converted to fence-to-fence plantations of Tasmanian bluegums. The plantations dates were not publicly recorded but can be estimated because the new growth can be distinguished in Landsat scenes about two years later. In this study, these plantations are recorded by the date of the Landsat scene when the trees first appear to be substantially dense (which occurs when the trees become very effective water users). Extensive plantation areas first appear on the January 1998 scene. Since then, plantation areas have increased by several square kilometres per year, (Appendix 3 Table A3.3). By 2002, 34.5 km^2 of the Upper Denmark catchment had been replanted with trees (Appendix 3 Table A3.3).

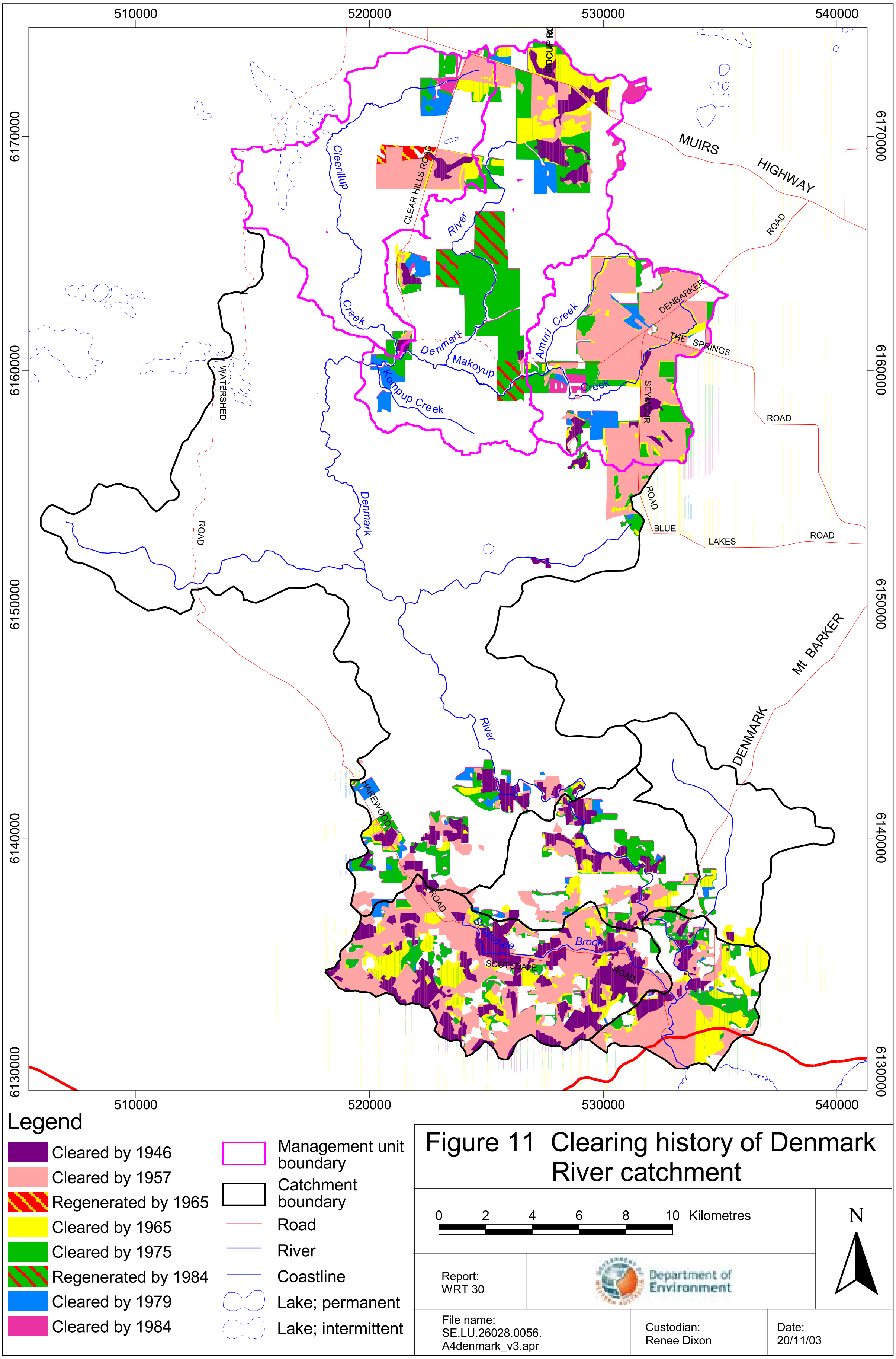


Figure 11 Clearing history of Denmark River catchment

Figure 12 shows the dramatic growth in areas of plantation between 1990 and 2002 and the decrease in areas of pasture and crops. In 1990, 16%, 29% and 56% respectively of the Perillup, Kompup, Yate Flat Creek management units and 31% of the Upper Denmark catchment had been cleared and were being used for pasture or cropping, but, by 2002, the figures were down to 9%, 19%, 24% and 17% (Table A3.3b, Fig. 12). There was very little tree planting in the northern parts of the Perillup Brook and Kompup management units where the annual rainfall is the lowest (Fig. 12).

3.3 Streamflow and salinity trends

Daily streamflow recording at the Mt Lindesay gauging station began in 1954. Some salinity samples and associated flow were also recorded. Most of the continuous salinity recording began in the 1980s and 1990s. The formula used to calculate stream salinity from streamflow is given in Appendix 3.

The streamflow and salinity data recorded at the Mt Lindesay gauging station are used as examples to explain the procedure described in the Appendix 3. Salinity samples had been collected from the gauging station between 1954 and 1991 before the conductivity meter was installed. Therefore, for that period, the annual stream salinity and salt load were calculated using Equation 1 (Appendix 3). The annual salinity at the gauging station rose steadily from about 250 in 1955 to 1500 mg/L TDS by 1987 (Fig. 13a). There was an increasing trend of annual stream salinity at mean flow and salinity at mean rainfall (Fig. 13a). The trend analysis showed that the annual stream salinity at the Mt Lindesay gauging station was increasing at 17 mg/L/yr between 1980 and 1987. Annual stream salinity peaked in the 1990s and is now decreasing at 8 mg/L/yr (Table 3). The mean annual streamflow and salt load during the period 1980–95 was 29 GL and 18.5 kilotonnes (kt) respectively (Table 3).

Similar analyses were also performed for the Kompup and Yate Flat Creek main stream gauging stations as well as for the subcatchments contributing to those gauging stations (Figs. 13b, c). The salinity graph reflects the changes in cleared area within the gauging station catchments. The streamflow, salinity and salt load information for the sections of catchment between the Kompup and Mt Lindesay, and the Yate Flat Creek and Kompup gauging stations have been estimated by subtracting annual streamflow and salt load data at the upstream gauge from data contained in the annual downstream gauge records. The result is taken to be the contribution of that catchment area (Figs. 13d, e).

The mean flow for the period 1980 to 1995 is used for all stations so that values for different stations are comparable. The graph of salinity at mean flow reveals time trends largely independent of variations in rainfall. All stations show a consistent upward trend between 1980 and 1987. The highest increase in stream salinity, 47 mg/L/yr, was observed at the Kompup gauging station (Table 3). The stream salinity of the catchment between the Yate Flat Creek and Kompup gauging stations increased at 44 mg/L/yr in the same period. Since 1991, the stream salinities of the three gauges indicate declining trends, although salinity through the Kompup gauging station without the contribution of Yate Flat Creek is still rising (though more slowly at 10 mg/L/yr). The water from the almost-fully-forested area between the Kompup and Mt Lindesay gauges has a low and unvarying salinity (Fig. 13d, Table 3).

Variations of streamflow over time should be largely due to changes in vegetation cover, although some will occur because streamflow is not perfectly linearly related to rainfall. The salinity of the streamflow at mean rainfall can also be estimated from the same equation used to evaluate the salinity at mean flow.

A decline in streamflow relative to rainfall since 1993 is found in all parts of the upper catchment. The trend is most marked at the Yate Flat Creek gauging station, where flow has dropped by 30% from its average during the 1980s (Fig. 13c). The reduction is due to planting trees over 18% of the catchment area. At the Kompup gauging station, a recent downward trend is also evident, but analysis has produced similar downwards trends in the past and the current value is not yet lower than the historical minimum. There has been no significant reduction through the Mt Lindesay gauge because there has been no reduction in streamflow from the uncleared catchment between the Kompup and Mt Lindesay gauging stations.

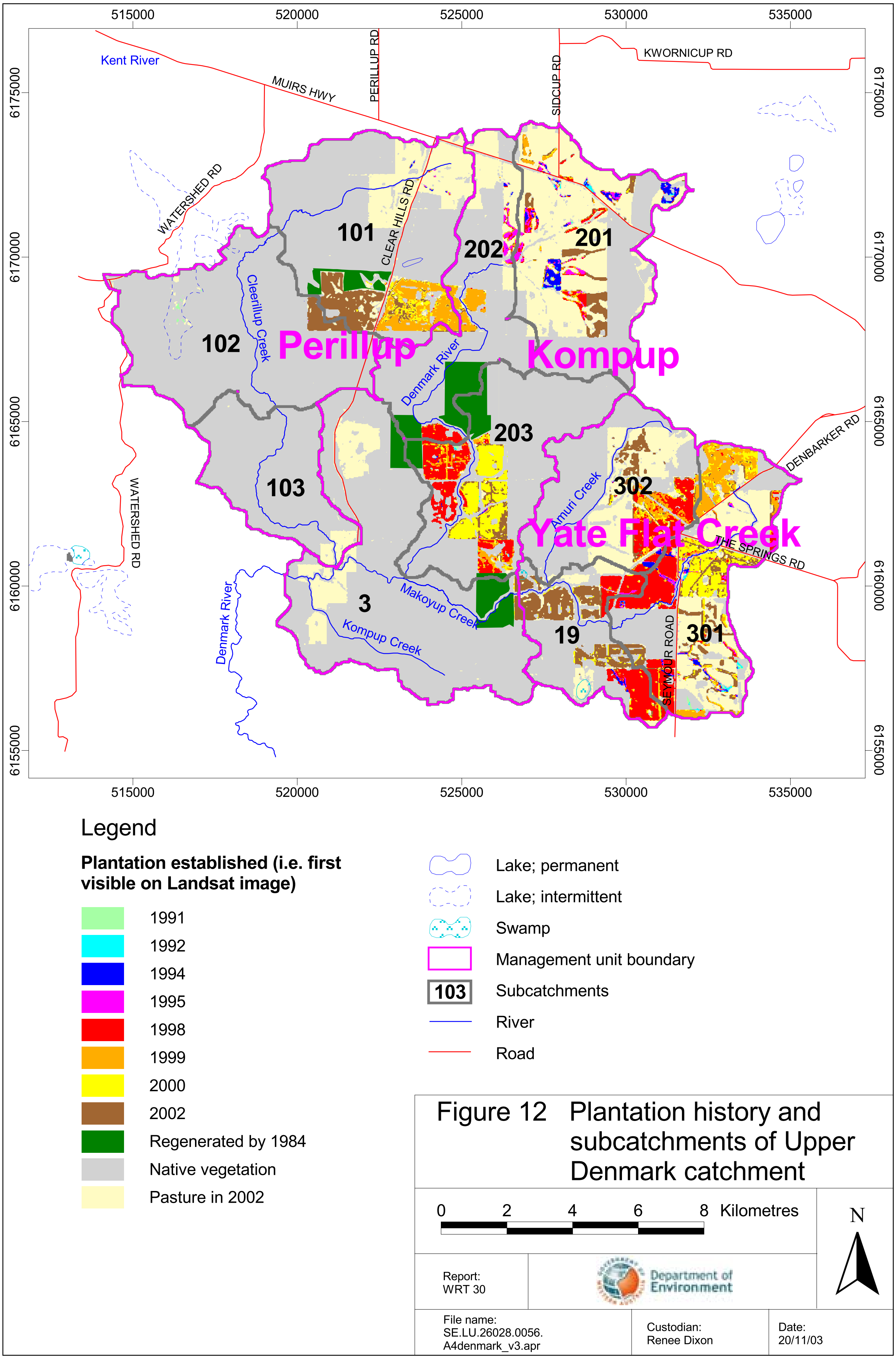


Figure 12 Plantation history and subcatchments of Upper Denmark catchment

Table 3. Mean annual streamflow (1980–95), salt load and salinity trend

Catchment	*Mean annual data (1980–95)*			*Salinity trend (mg/L/year)*		*Relative contribution (%)*	
	Streamflow (GL)	*Salt load (kt)*	*Salinity (mg/L TDS)*	*1980–87*	*1991–95*	*Streamflow*	*Salt load*
Yate Flat Creek	4.9	5.8	960	29(S)	-32 (S)	17	31
Between Yate Flat and Kompup	7.3	8.7	1191	44(S)	10 (S)	25	47
Kompup	12.2	14.5	1188	47(S)	-7 (S)	42	78
Between Kompup and Mt Lindesay	16.8	4.0	248	-5(S)	2 (S)	58	22
Mt Lindesay	29.0	18.5	638	17(S)	-8 (S)	100	100

(S) *Statistically significant trend at 95% confidence level*

3.4 Relative contribution

Between 1980 and 1995, the mean annual streamflow of the Denmark River at the Mt Lindesay gauging station averaged 29 GL (Table 3). This does not include the high-yielding southern portion of the catchment near the coast (Fig. 1). Annual runoff and rainfall decrease with increasing distance from the coast (Table 3). The Yate Flat Creek MU constitutes 11% of the catchment area and generates 17% of the flow of the Denmark River at Mt Lindesay. The Kompup gauging station collects the water from the three management units collectively called the Upper Denmark catchment (Perillup, Kompup and Yate Flat Creek). This catchment area is 45% of the total catchment area upstream of the Mt Lindesay gauging station (Fig. 10) and generates 42% of the total streamflow (Table 3).

Table 3 also shows the average stream salt load for each of the selected catchments during the period 1980–95. As Mt Lindesay is the major gauging station (Fig. 10) for the Denmark River Recovery Catchment, the relative contribution of salt load from each catchment to the total at Mt Lindesay was calculated. Yate Flat Creek contributes 31% of total salt load to Mt Lindesay (Table 3). The Kompup gauging station covers most of the catchment areas receiving low rainfall and contributes 78% of the total salt load (Fig. 10). So, most of the salt is produced from the areas with low rainfall.

3.5 Groundwater levels

Groundwater levels in the Upper Denmark catchment were generally rising under cleared areas of the catchment through the 1980s when stream salinity was on a strong upward trend. In recent years, since the stream salinity has peaked, remaining piezometers indicate that groundwater levels are still rising under cleared land, but falling where trees have been densely planted.

In this study ‘groundwater level’ describes the pressure in the deep groundwater in the regolith expressed as height above or below ground. It is measured as a water level in deep piezometers and is sometimes referred to as ‘piezometric surface’. The watertable is the level/height at which groundwater pressure equals atmospheric pressure, that is, approximately the level of water in a shallow bore (Davis & DeWiest 1966). When the groundwater level is higher than the watertable, there is a tendency for upward movement from the deep groundwater to the surface. Conversely, a watertable higher than groundwater level indicates a potential for recharge to the deep groundwater at that location. Recording groundwater level over time indicates how the volume and/or flow rates of the deep groundwater are responding to changes in recharge to the deep groundwater.

Hydrograph Analysis: Rainfall and Time Trend (HARTT) was devised to separate the groundwater level changes due to variations in vegetation cover from groundwater responses to short-term variations in rainfall. HARTT is a spreadsheet-type computer model developed by the Department of Agriculture and the Faculty of Agriculture at the University of WA (Ferdowsian et al. 2000). Based on monthly rainfall and observed groundwater levels HARTT predicts what

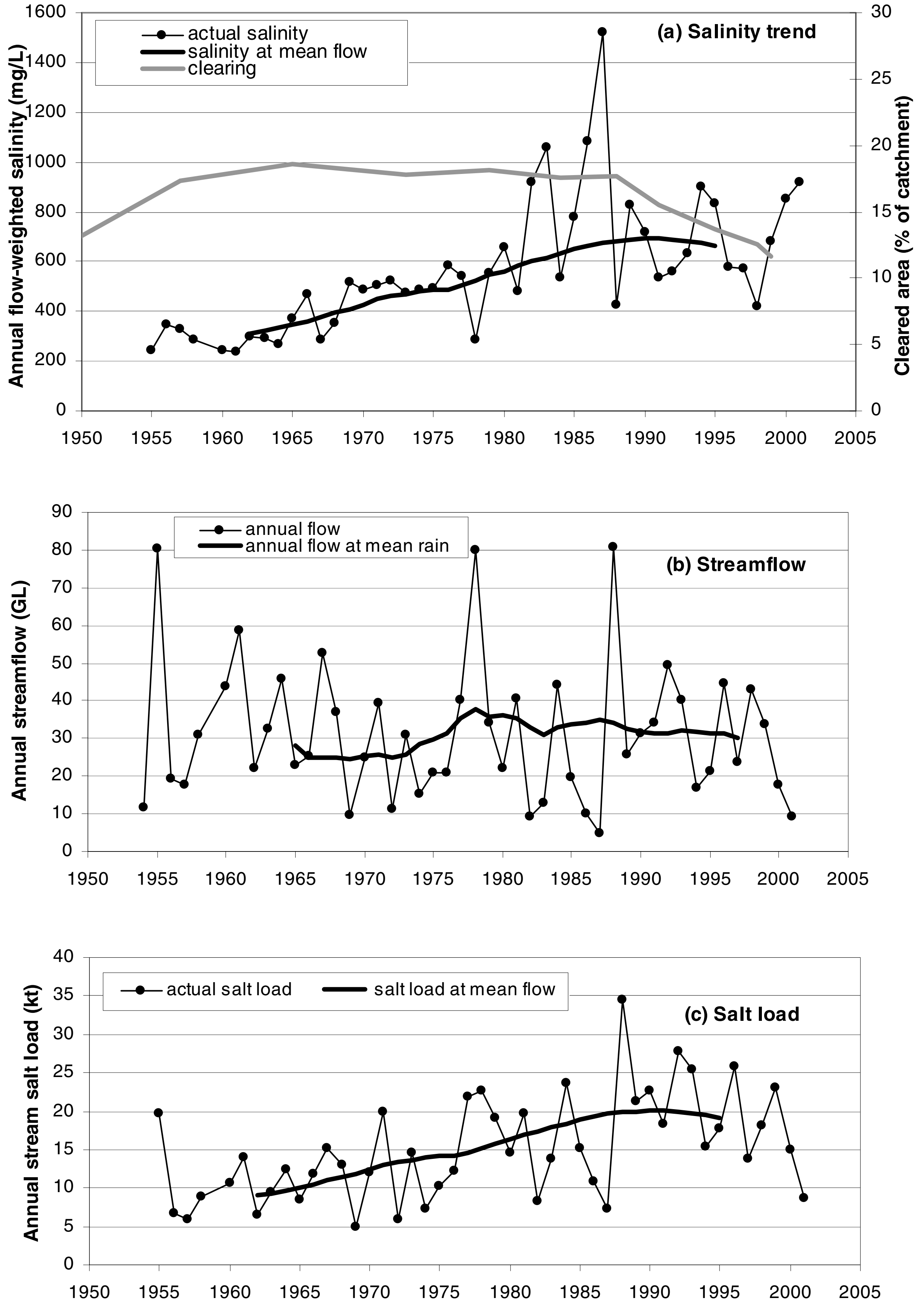


Figure 13a. Stream salinity trend of the Denmark River at the Mt Lindesay gauging station

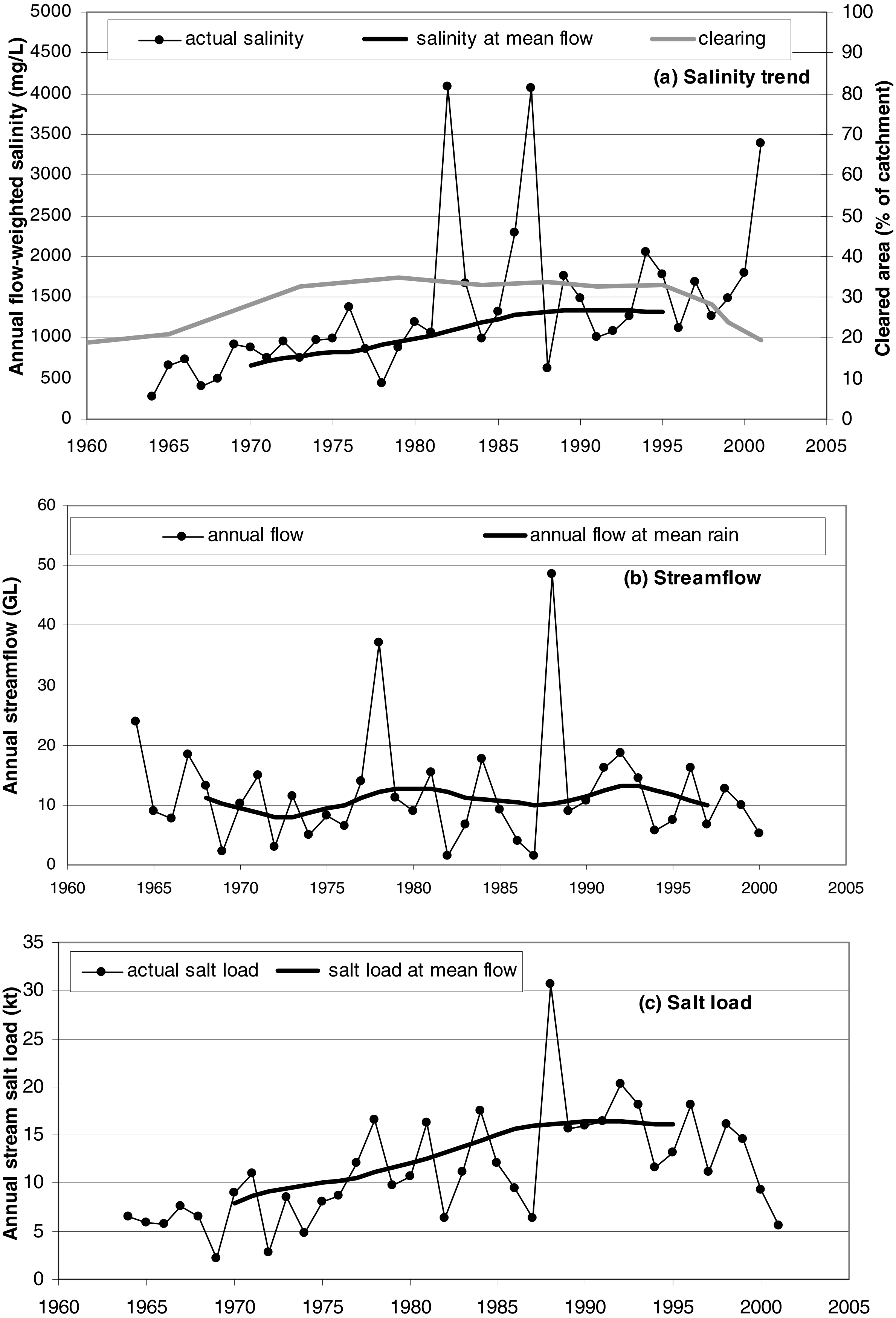


Figure 13b. Stream salinity trend of the Denmark River at the Kompup gauging station

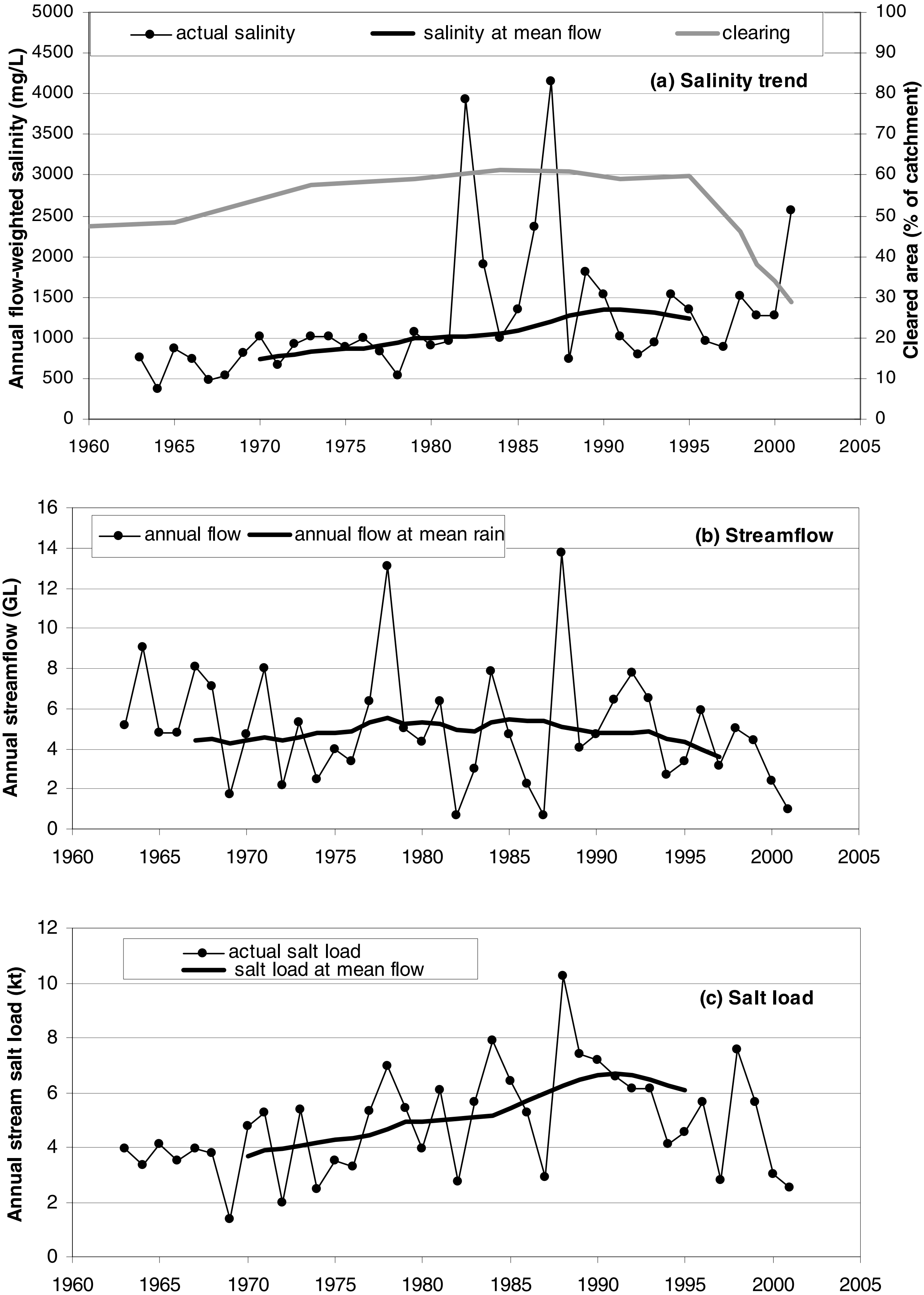


Figure 13c. Stream salinity trend of the Denmark River at the Yate Flat Creek gauging station

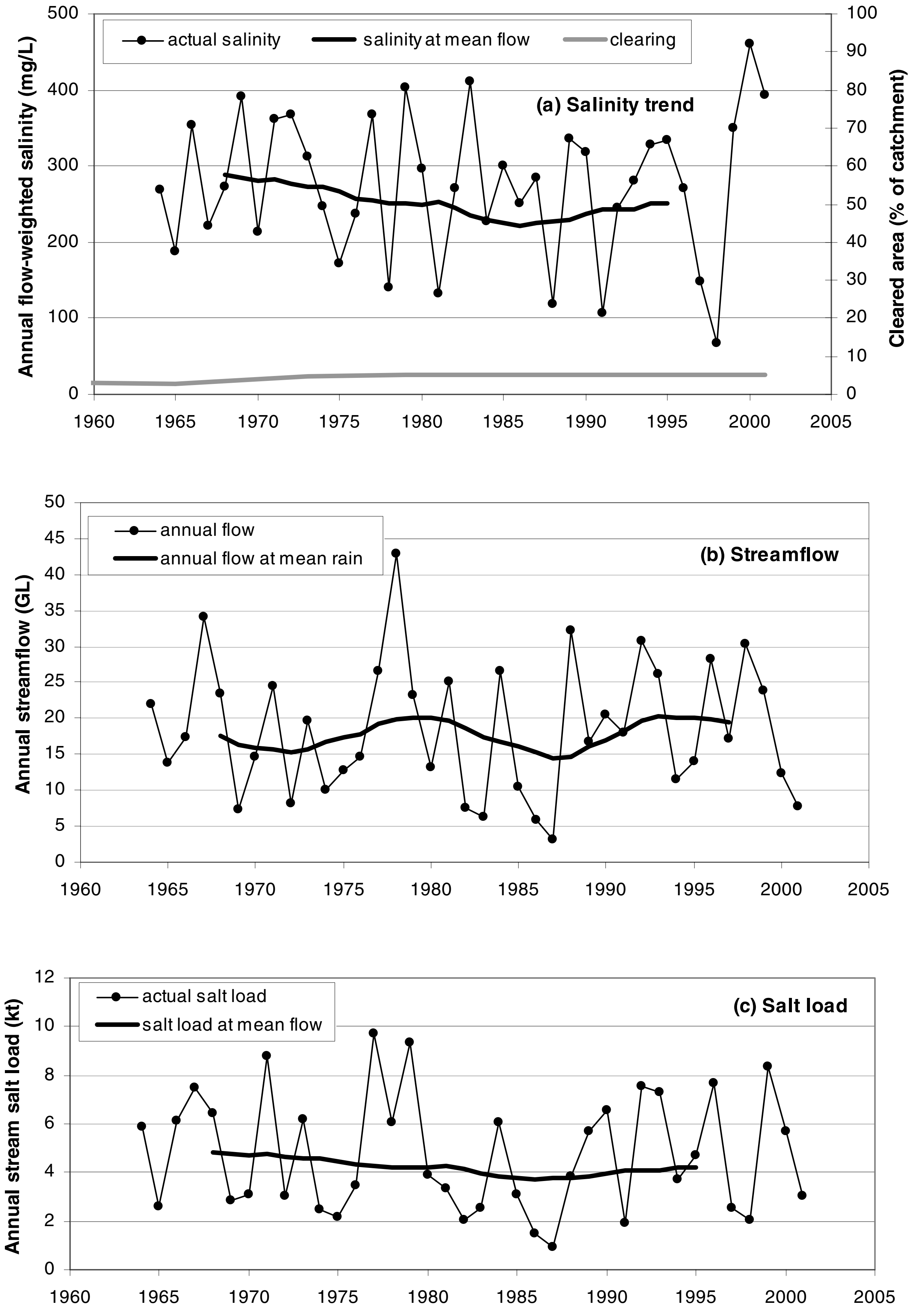


Figure 13d. Stream salinity trend of the Denmark River between the Kompup and Mt Lindesay gauging stations

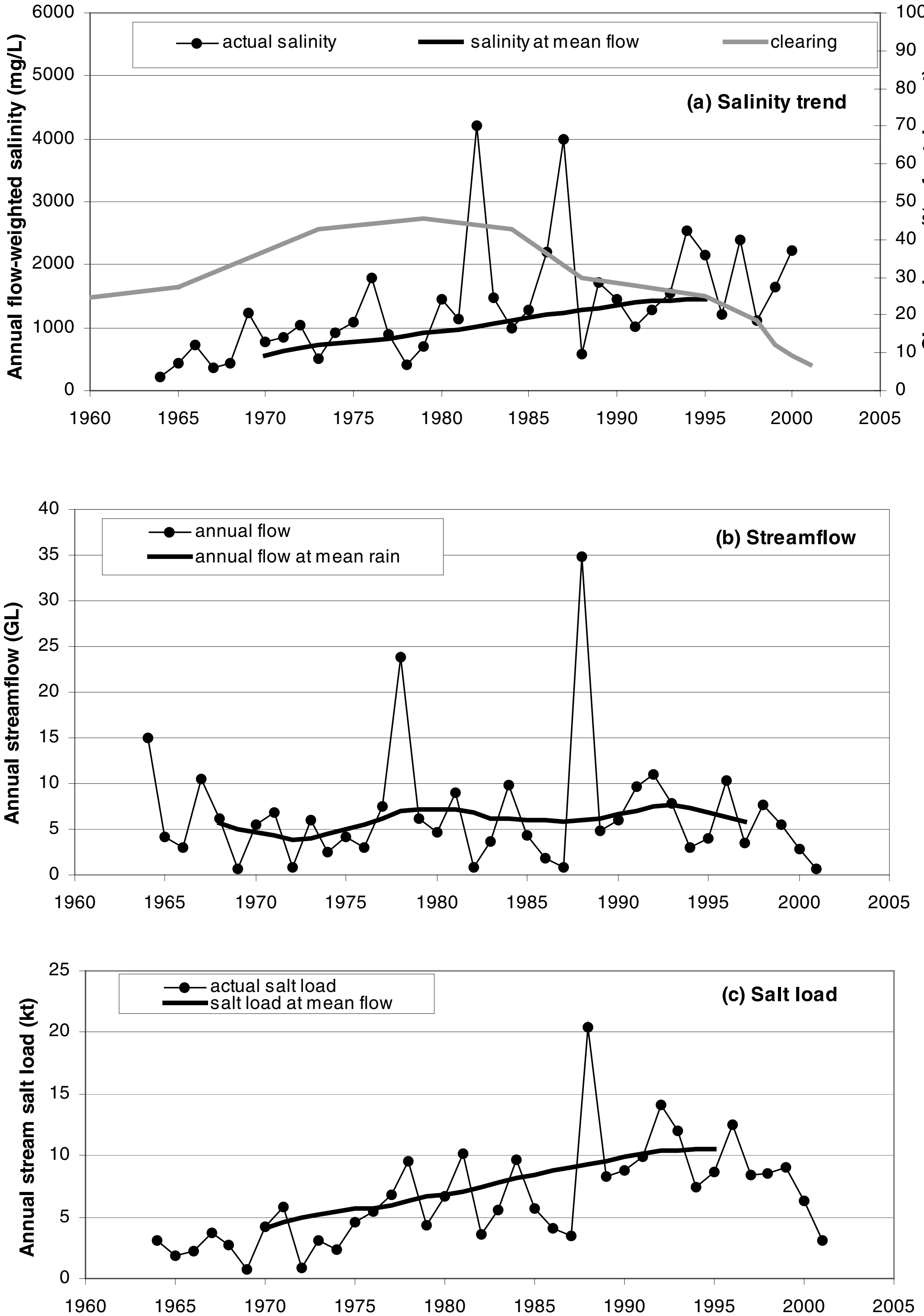


Figure 13e. Stream salinity trend of the catchment between the Yate Flat Creek and Kompup gauging stations

the trend of the groundwater level would be at a nominated average annual rainfall. As the analysis assumes that drawdown by evapotranspiration is constant with time, results will be less reliable if vegetation cover has varied significantly during the analysis period: for example, if trees are planted nearby.

Most of the available piezometer records for the Upper Denmark catchment have been analysed by the HARTT method. Some piezometers were established on farms in the catchment in 1985 and monitored until the early 1990s while many more piezometers were established in 1990 in three experimental catchments (Fig.3) Trend analysis has been separated into two periods, pre-1993 and post-1994, as tree planting in the experimental catchments occurred principally in 1993. All analyses were based on the rainfall that gave a zero trend in the piezometer located in native forest near Kompup Creek (Fig. 14) Groundwater trend results from the experimental catchments are detailed in Section 3.6.2 and Appendix 3. Most of the groundwater bores are in the Yate Flat Creek and Kompup management units. The bores along the Muirs Highway section of the Kompup management unit were rising between 1.5 and 3 m/yr during 1985 to 1993. (Fig. 14). Except for two bores, the systematic rise of all other bores in Yate Flat Creek was smaller than for bores in Kompup. Two bores were even showing a declining trend in the order of 0–1 m/yr (Fig. 14). There were not enough data to analyse the trend for the period 1994–99.

Although the HARTT method is fundamentally different from the method applied in Section 3.6.2 (comparison to control piezometer), the results are generally similar. The HARTT results have not distinguished the short-term fall with subsequent rise in the Barrama piezometer group, but show a net rising trend after 1994 for those piezometers.

3.6 Experimental catchments

In 1988, three subcatchments (Willmay, Barrama and Pardelup) in the Upper Hay River catchment were chosen as experimental catchments (Fig. 3) to demonstrate the changes in the streamflow and salt load that follow partial reforestation of cleared land in this region. The sites were chosen for the convenience of landowners who were prepared to maintain the proposed ‘treatments’ although the results were to be used for the Upper Denmark catchment study.

The three catchments (each with an area about 1 km^2) were similar in being predominantly cleared and used for annual pastures and crops. They had been cleared more than 30 years earlier and showed strong evidence of well-developed dryland salinity. The salinity of summer streamflows was often well over 10 000 mg/L TDS and that of winter flows was seldom less than 1000 mg/L. The catchments were monitored with a network of deep and shallow piezometers and with continuously recorded streamflow and salinity at the catchments’ discharge points. They were monitored for three years in order to establish relationships between the catchments before they were ‘treated’ with replanting.

The Willmay catchment was designated as the ‘control’ catchment on which the land use did not change throughout the experiment. In 1993, the other two catchments were ‘treated’. Trees were planted on 45 ha (40%) of the cleared areas of the Pardelup subcatchment (located within the Pardelup Prison Farm) and on 15 ha (17%) of the Barrama catchment. The trees were planted in accordance with a farm plan developed in consultation with the land owner as part of the *Integrated Catchment Management — Upper Denmark Catchment* project (Ferdowsian & Greenham 1992).

The final year of complete records of stream gauging and piezometers in these catchments was 1996. Land use on Pardelup and Willmay has still not changed, but the property containing Barrama was completely replanted with plantation trees after 1997. Substantial tree cover from this new plantation was first visible in the February 2000 Landsat scene.

3.6.1 Changes in flow and load

Streamflow and salt output decreased substantially on the 40%-replanted catchment but were unchanged on the 17%-replanted catchment when monitoring stopped. More information on these topics is presented in Appendix 3.

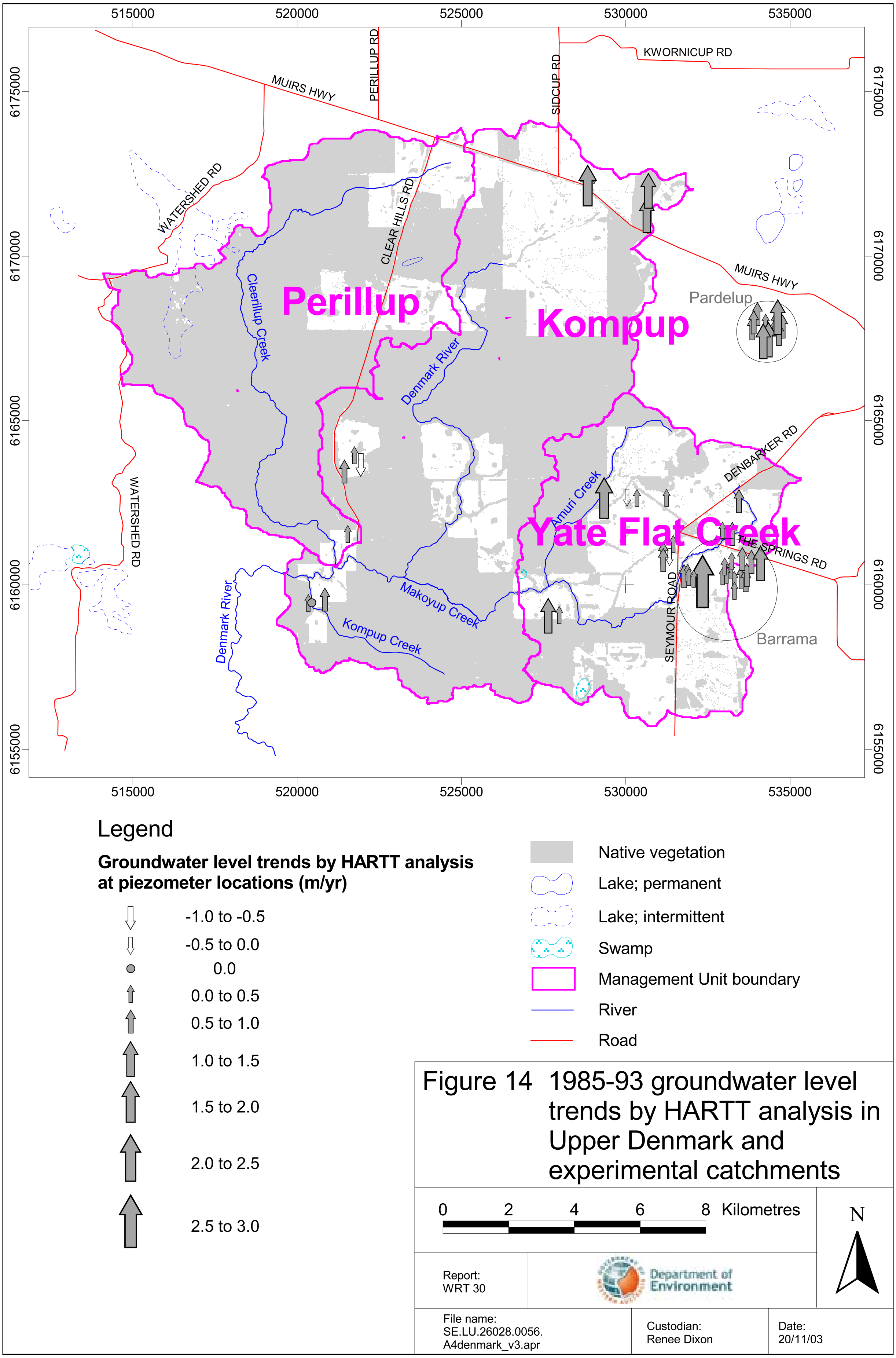


Figure 14 1985-93 groundwater level trends by HARTT analysis in Upper Denmark and experimental catchments

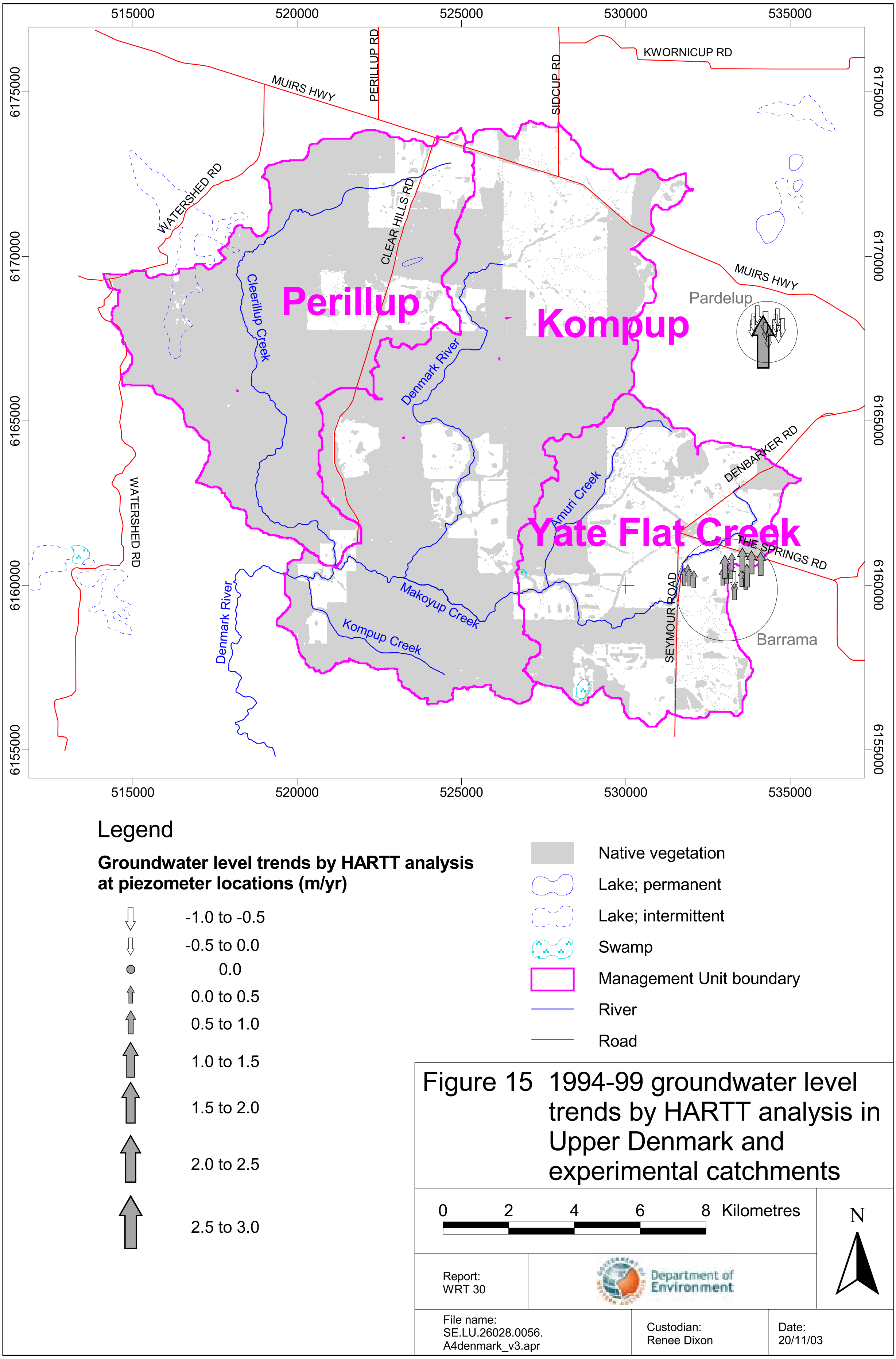


Figure 15 1994-99 groundwater level trends by HARTT analysis in Upper Denmark and experimental catchments

The streamflow and salt load outputs from the treated catchments were compared with those of the control catchment by plotting each cumulative total from the treated catchments against the corresponding cumulative total from the control catchment. The resulting graphs are shown in Figures 16 and 17. The response of the treated catchment in the absence of treatment is estimated by extrapolating the section of the graph between 1991 and 1993, the two years prior to treatment. This response is shown by the thin line on the graphs. The line is also marked with a cross at the data point for each year.

Streamflow and salt load of Pardelup were markedly reduced from their pre-planting rates. From 1993 to 1996, streamflow and salt load were respectively 76% and 71% of their former rates (Fig. 16). There was no discernible reduction in Barrama streamflow and salt load. For the 1993–96 period, the Barrama streamflow and salt load were respectively 102 % and 99% of their former rates (Fig. 17). Experience from other sites such as Maxon Farm and Maringee Farm (Mauger et al. 2001) suggests that trees take more than three years to show the full effects on streamflow and salinity reduction.

3.6.2 Changes in groundwater level

Two methods of analysing groundwater level data were available:

(i) HARTT analysis described in 3.6.2.

(ii) Comparison with the control bores. This method is described in Appendix 3.

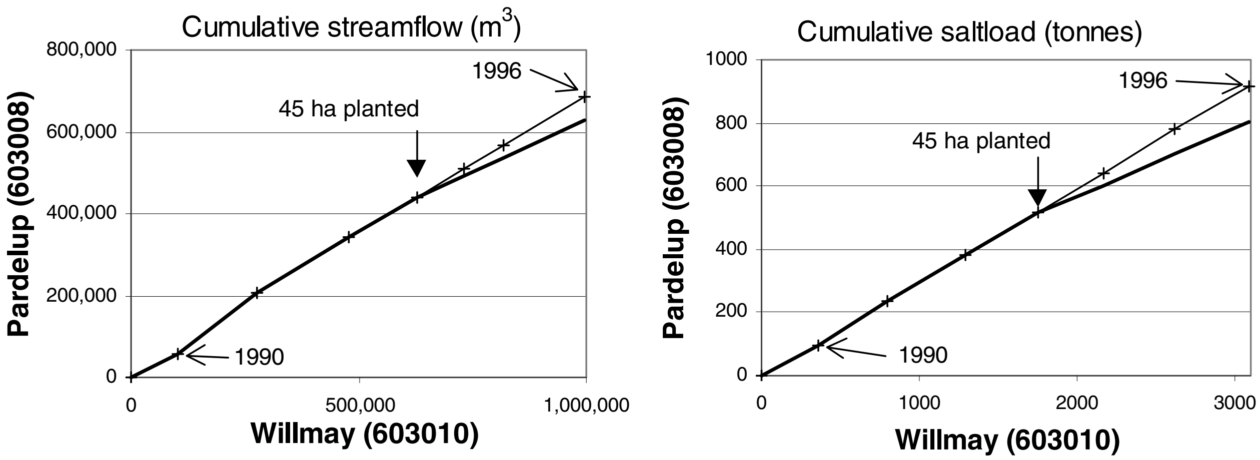


Figure 16. Double mass curves — Pardelup compared with Willmay

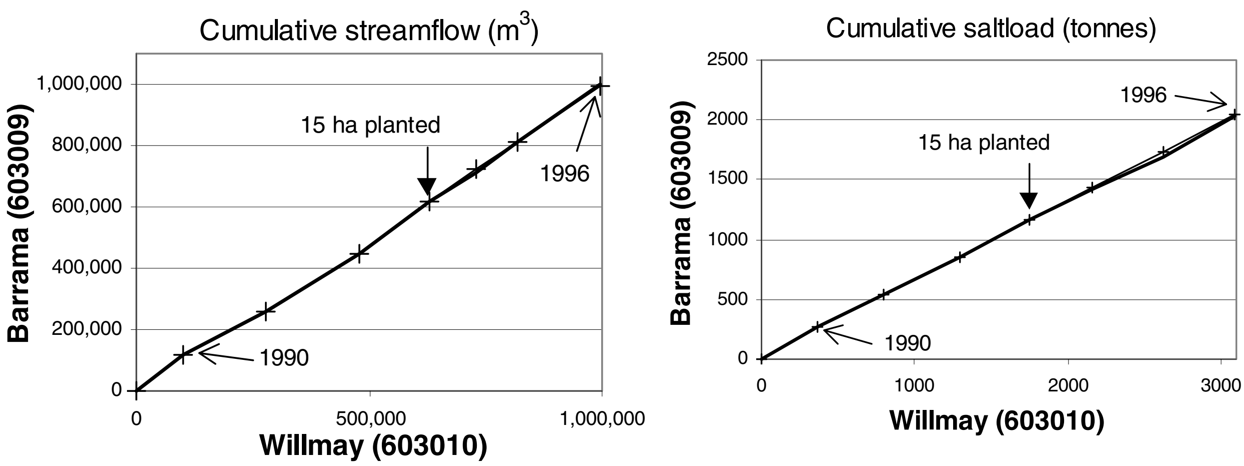


Figure 17. Double mass curves — Barrama compared with Willmay

Willmay piezometers

Groundwater level data from this 'control' subcatchment were analysed only by method (ii). All the trends are quoted relative to the centrally located piezometer 60319186 (or Willmay 186) (Fig. 18). Willmay 175, 450 m north towards the catchment outlet, showed a negligible trend. The graph of Willmay 175 (Fig. A3.5) is included with graphs from the Pardelup and Barrama catchments to show how much variation to expect when there is no real trend. Willmay 198, 100 m north of Willmay 175, also had no real trend. Six other piezometers in Willmay, located in the eastern, higher part of the catchment, showed rising trends of about 150 mm/yr before 1993. After 1993, their trend was slightly downwards but almost insignificant. Willmay 189, on the western edge of the catchment, had a downwards trend of 210 mm/yr before 1993, and a negligible trend thereafter (Fig. 18).

Pardelup piezometers

The groundwater trend analysis by the HARTT method for the period 1985 to 1993 showed a rising trend ranging from 0.5 to 2.5 m/yr for all bores (Fig. 14). The groundwater level trends of all but one bore reversed during the period 1994–99, mainly due to tree planting over 40% of the catchment area (Fig. 15). The declining trend ranged from 0.5 to 1 m/yr. The exception was a bore in the cleared area, which showed a rising trend of 3 m/yr. The groundwater level trend was also analysed by comparing it with the control. Before 1993 none of the piezometers had a significant trend compared with the control (Willmay bore 186). After 1993, the trends were insignificant in three situations: (a) adjacent to existing forest, (b) in pasture near the top of the catchment, and (c) in an area of high groundwater discharge and poor tree establishment near the catchment outlet. Elsewhere, piezometers within planted areas or in pasture areas, but within 100 m or so of planted areas, developed significant downwards trends of up to 300 mm/yr (Fig. 19).

Barrama piezometers

HARTT analysis shows that, between 1985 and 1993, the groundwater level was rising at the rate of 0.5 to 3 m/yr (Fig. 14) but in the mid 1990s tree planting slowed this rising trend (Fig. 15). Piezometers in the catchment showed a general rising trend of about 100 mm/yr before 1993 except Barrama 127, 129, 131 and 132 in the west and three piezometers in existing planted areas (Barrama 137, 149 and 152) all of which showed negligible trend before planting (Fig. 20) and the piezometer nearest the gauging station (Barrama 170) where the upward trend was 250 mm/yr, even though the site was close to existing trees. After 1993 (Fig. 20), there were two distinct trends, the first to the start of 1996, and the second 1996–99. From 1993 to 1996, there was a general falling trend of from 90 to 390 mm/yr, with the exception of Barrama 129 which continued to have a negligible trend, and Barrama 170

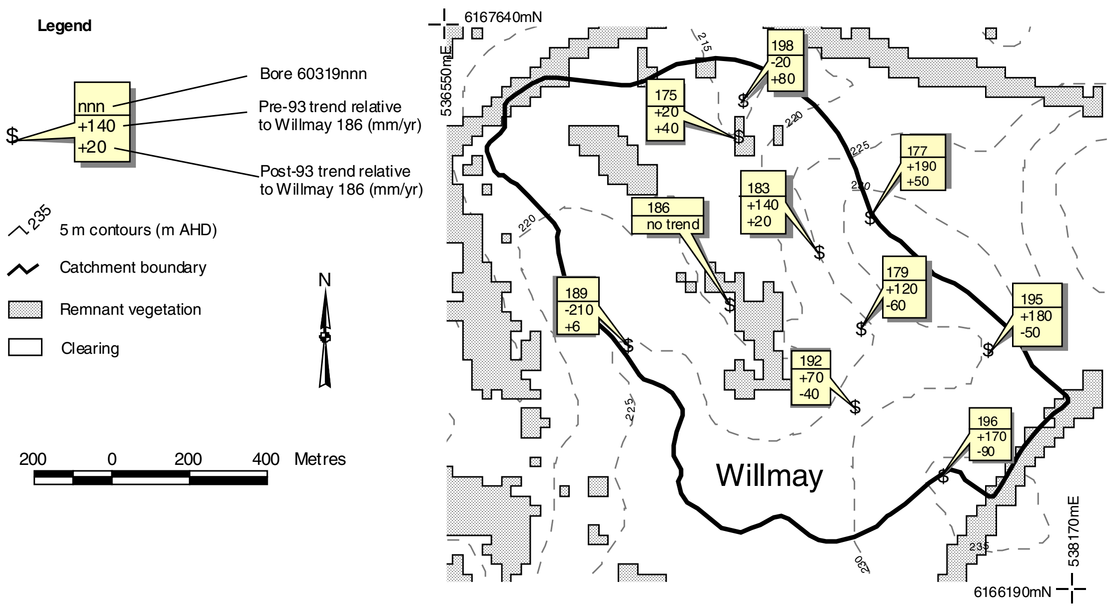


Figure 18. Willmay piezometer trend

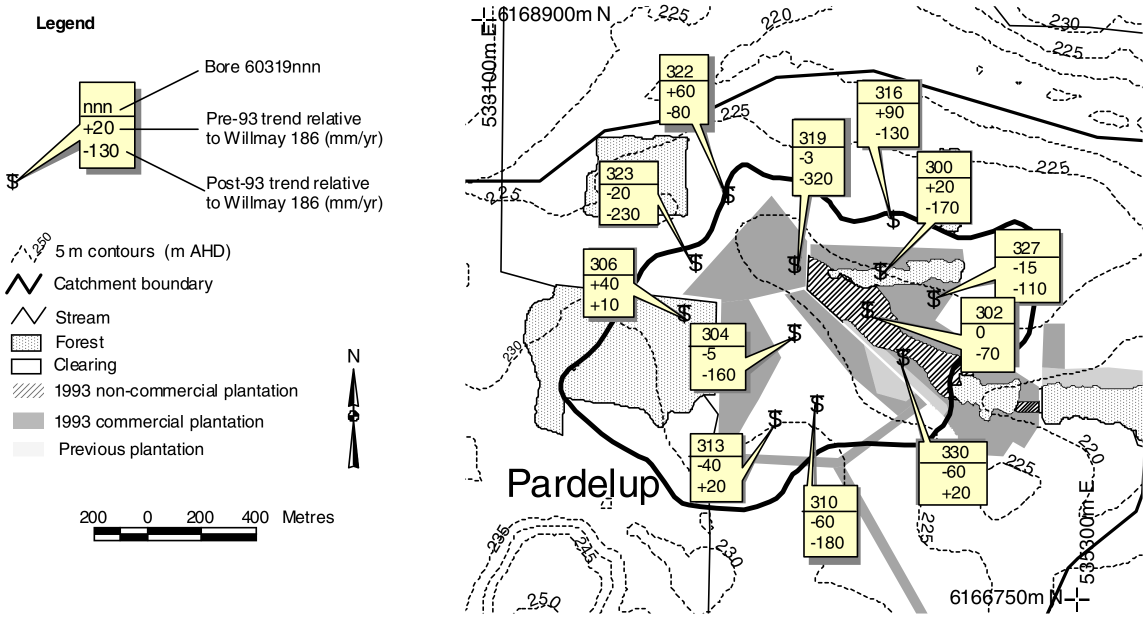


Figure 19. Pardelup piezometer trend

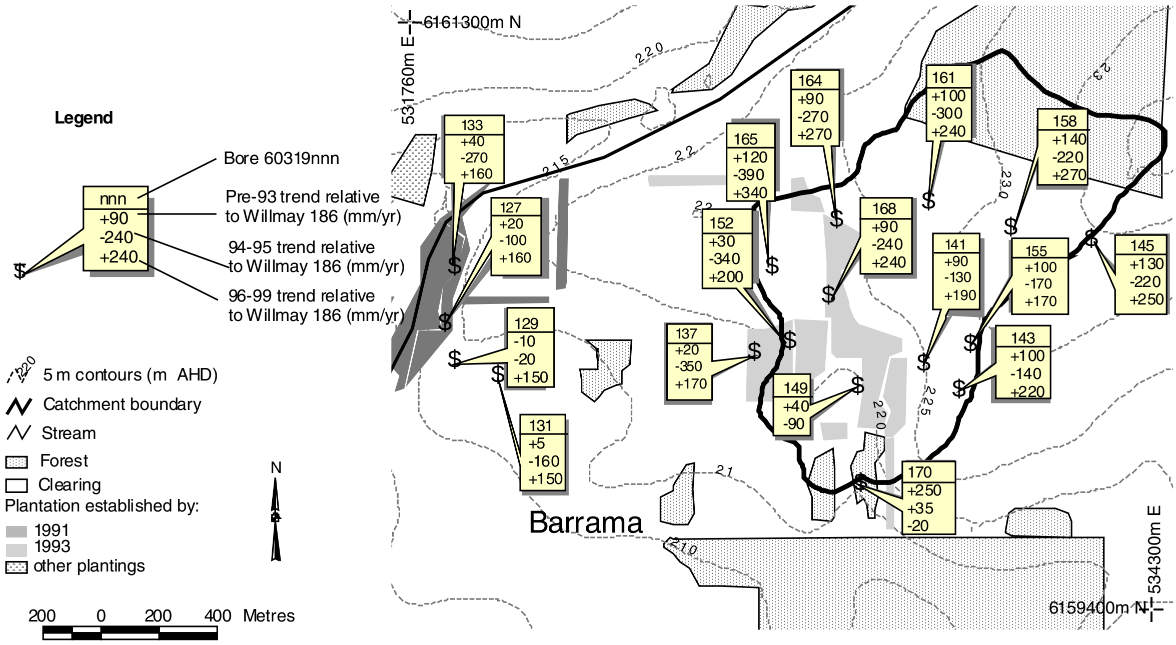


Figure 20 Barrama piezometer trend

which stopped rising. The falling trends were not limited to areas near planted trees. In comparison to Willmay, rainfall was marginally higher than before 1993. So the falling trends have not entirely followed an expected pattern. After 1996, the trends reversed to be generally rising at from 150 to 340 mm/yr. The exception was Barrama 170 that continued to have a negligible trend. During this time the land was being prepared for tree plantations and in the early stages of tree establishment. In February 1999, trees could only just be detected in the Landsat scene, implying that tree water use was very low until then. At this time, piezometer recording stopped. By February 2000, there was extensive tree coverage.

3.7 Salt leaching from the Upper Denmark catchment

The observed reduction in stream salinity (Table 3, Fig. 13a) could be due to falling groundwater salinity (as salt stored in the soil is gradually leached into the discharge) rather than a falling flow discharge rate. What is the evidence for the likely cause and what are the implications to reducing salinity in the Upper Denmark catchment?

A simple model of the leaching process assumes that the salt is discharged at a rate proportional to the amount of salt remaining in the soil. A model of this type has been proposed and discussed as a method of estimating the time for the salinity of streamflow from a salt-affected catchment, at hydraulic equilibrium after clearing, to fall to a specified level (Hatton et al. 2002). With this assumption, and that land management practices were the same as in 1988, the salinity at the Kompup gauging station should be falling at about 10 mg/L/yr. It would then take more than 50 years for salinity at the Mt Lindesay gauging station to reach the target 500 mg/L. Other assumptions are that mean depth to bedrock, and water content and salt content in the catchment, are the average of data from 20 piezometers installed throughout the catchment in 1980. This gives an estimated 36 kg of salt per square metre, applied over an area where deep groundwater is discharging from the clay. By calibrating the MAGIC model (see Section 4), the discharge area (shallow watertable area) is estimated to be 35 km^2, which is about half the cleared area.

If the stream salinity is declining as a result of leaching, there should be a corresponding decline in the salinity of the source — deep groundwater. According to the leaching model, the estimated current rate would be 56 mg/L/yr. Trend analysis of piezometer records from the Barrama catchment (Fig. 20) indicates an average decline of 79 mg/L/yr over the period 1989–1994, which is compatible with the model estimate. In contrast to the Barrama catchment, the Willmay catchment shows no significant decline in either stream salinity or deep groundwater salinity. As the Willmay catchment has been cleared for as long, if not longer, than Barrama, this suggests that significant salinity reduction by leaching is not necessarily a normal or expected progression of the salinity process in the short term. Similarly, monitoring after clearing in the experimental Collie River catchments did not clearly indicate leaching after groundwater levels reached their maximum height (Mauger et al. 2001).

Streamflow salinity at the Kompup gauging station — just before flow ceases in summer — was initially shown to be increasing to 1984 (Ruprecht & Stokes 1985) and decreasing since 1988 (Moulds & Bari 1995). The salinity of this flow depends on the relative contributions of shallow and deep groundwater discharges. While streamflow salinity is influenced by the salinity of the deep groundwater contribution, it is not a reliable measure of that salinity.

Reduction of streamflow salinity is not necessarily an indicator that the deep groundwater salinity has reduced; it may be that the flow rate of deep groundwater has fallen. A proper explanation of the observed flows and salinity would require detailed monitoring of salt storage and movement within the catchment.

There is some indication that leaching may be responsible for decreasing stream salinity. However, this is not consistent with all datasets. If leaching was the cause of the reduction in salt storage it would still take 50 years to reach the salinity target at Mt Lindesay (Hatton et al. 2002).

4 Catchment modelling

4.1 What is modelling?

A catchment model is a mathematical tool to predict flow and salinity changes in the catchment. The construction of the model requires a good understanding of the system and either a lot of data or, in their absence, assumptions or data from related areas.

Subcatchments (Upper Denmark, Pardelup, Barrama) were modelled to validate the model, build confidence by comparing actual records with predictions and indicate plant-based and engineering options available to the Recovery Team to reach the target salinity by 2020. The predictions for Pardelup and Barrama were compared with actual data to validate the model for use in the Upper Denmark. The Upper Denmark catchment predictions are the 'best guesses' we have and allow catchment managers to have a feel for the extent of changes that may result from actions like planting, clearing, constructing a drain or installing groundwater pumps before actually taking any of those actions.

The variations in river salinity and flow in the Denmark River catchment are primarily due to changes in the catchment water balance. The variations were deduced from trend analysis of actual data(Figs 13a–e). Trend analyses cannot predict the salinity and flow that would result from salinity mitigation works in the catchment but these projections can be made with a numerical model which calculates changes in the catchment water budget.

4.2 The MAGIC model

The numerical model used in this study was the Microstation and Geographic Information Computation (MAGIC) model. It simulates hydrological processes in the catchment. The modelling process normally used is based on the description in Mauger (1996) with modifications as described in Mauger et al. (2001).

It is based on the water balance equation calculated cell by cell:

water in = change in water storage + water out

The model simulates the steady state of a catchment and it generally runs on a monthly time step. The MAGIC model calculates the catchment water budget and also predicts the groundwater seepage if particular salinity management options are 'implemented'.

Figure 21 shows the model's conceptual representation of the three-layer system of a typical hill slope applicable to the south-west of Western Australia (Sharma & Williamson 1984). Hydrogeological data from a drilling program confirmed the validity of this representation. This data and the catchment topography were used to construct a three-dimensional prototype model of the Upper Denmark catchment.

Horizontally, the area of the catchment is subdivided into a grid with row and column spacing of 25 m on the ground. Each cell of the grid is assigned a series of properties (e.g. ground elevation, soil layer thickness and permeability, vegetation type and density) to represent what physically exists at the cell location. The MAGIC model then generates the water balance for each cell in the catchment. Figure 22 shows a typical representation of a landscape and the water movement components.

Rainfall is one of the model inputs. To allow for losses such as interception, and evaporation from the soil, the rainfall is reduced by 15% before being added to the store of water in the top layer, The top layer is commonly about 1.5 m thick and very permeable. Plants draw and transpire water from this layer until the layer becomes dry. The rate of transpiration depends on the Leaf Area Index (LAI) attributed to the cell and the pan evaporation rate at the time.

Water may be added to the top (soil) layer by lateral inflow from the top layer 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 top layer. Water may also be added by upward flow of deep groundwater, or lost by downward movement from the top layer to layers below. The rates of flow depend on the vertical permeability of the lower layers. Water inputs and

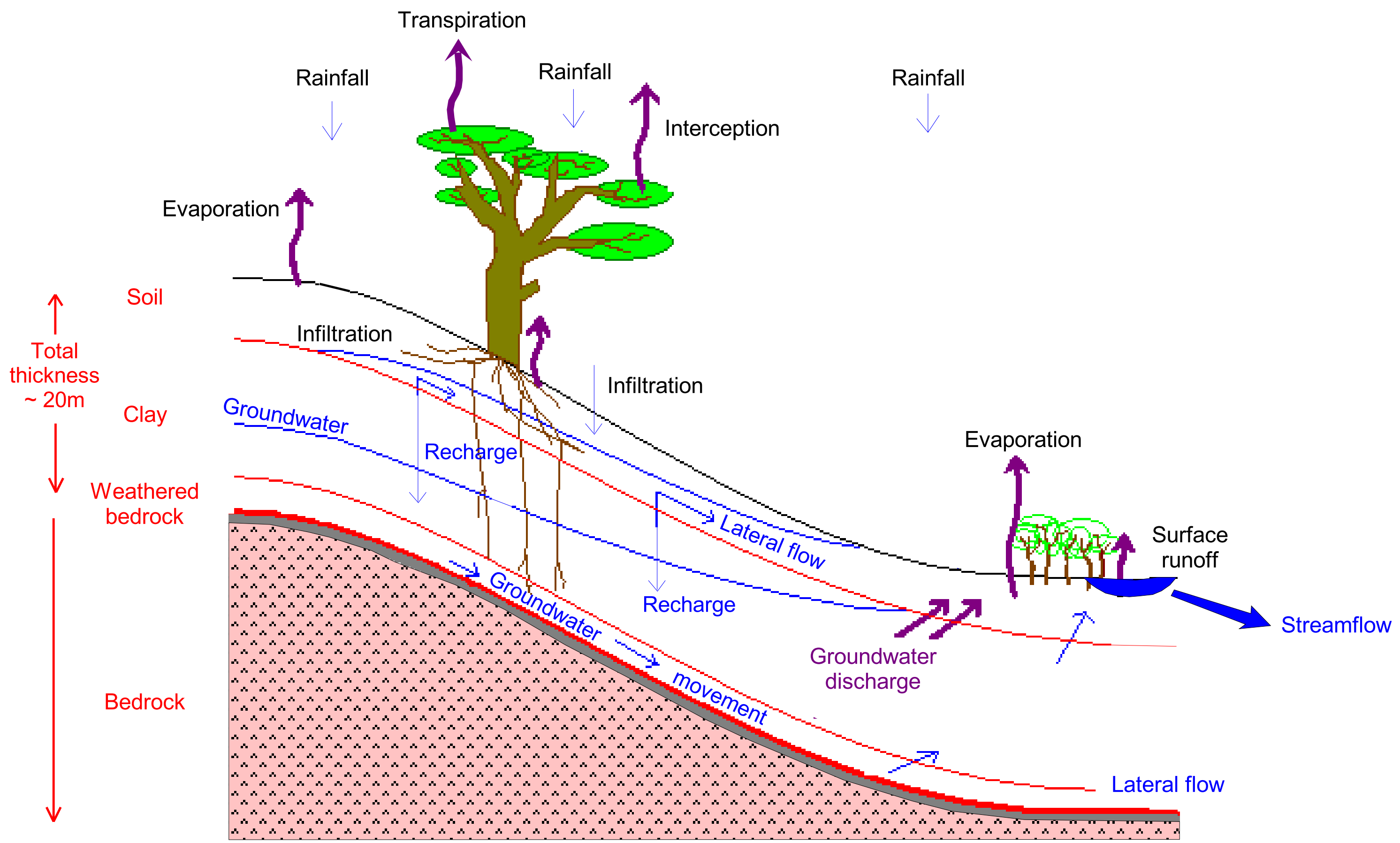


Figure 21 Representation of hydrological processes used in MAGIC model			
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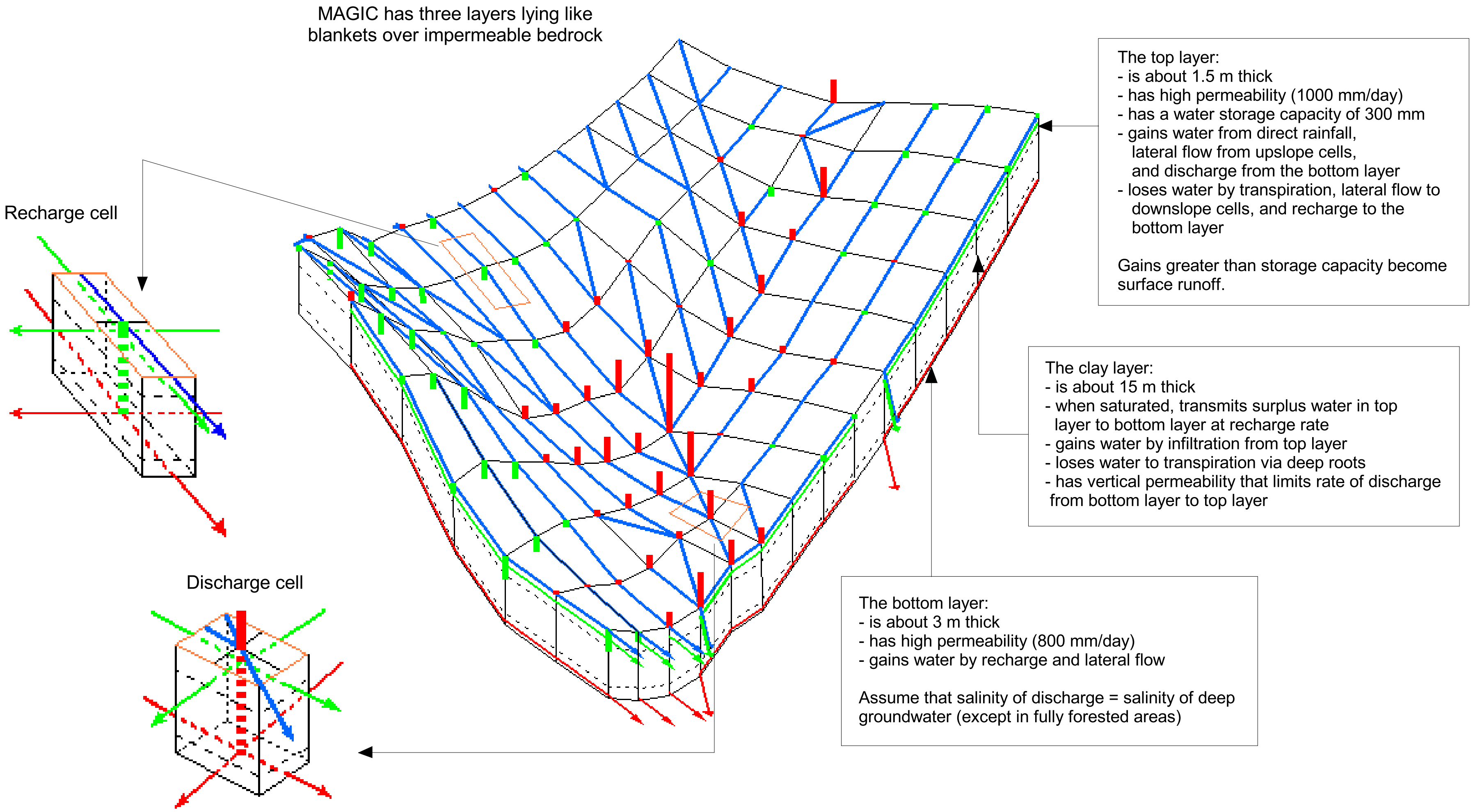

Symbols

- Recharge from top layer to bottom layer
- Discharge from bottom layer to top layer
- Lateral flow in the top layer
- Surface runoff
- Lateral flow
- Principal lateral flow connections between cells (Groundwater flows may spread to 2 or more adjacent cells downslope)
- Layer boundary

Figure 22 Representation of water movement in MAGIC model

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outputs for the month are added to the water content of the top layer at the start of the month. If the total exceeds the saturation capacity of the layer, the excess is allocated to runoff, which is the base flow component of the stream.

Below the top layer is a thick clay layer, commonly about 15 m deep, which stores water available for transpiration by deep-rooted plants when the top layer is too dry. The rooting depth of the plants probably limits the extent of water use. This layer gains water by infiltration from the top layer or vertical discharge from the bottom layer and loses water by uptake (and transpiration) by deep roots or by downward movement into the bottom layer. Vertical movement from this layer to the top and bottom layers is limited by the vertical permeability.

The bottom layer is typically about three metres deep and composed of highly permeable partially weathered bedrock and is the main aquifer containing (saline) groundwater. Groundwater moves readily down the slope through this permeable material towards the valley bottom. Water is gained by lateral movement from adjacent cells upslope and by recharge from the middle layer and lost by discharge into the middle layer and lateral movement downslope.

An assumption of the model is that, except in fully forested areas, the salinity of groundwater discharged from the bottom layer equals the salinity of deep groundwater.

4.3 Model calibration

Catchment modelling requires much data on the physical characteristics of a catchment. Since many assumptions are needed to extrapolate point-source data over the whole catchment, model results can be highly speculative. To reduce this problem, the model can be validated on catchments with enough data to compare actual catchment data and model outputs.

Before the Denmark River catchment was modelled with MAGIC, the model was used in two well-studied small nearby experimental subcatchments, Pardelup and Barrama (Fig. 3). Pardelup data were used to confirm that running the MAGIC model on the whole Upper Denmark catchment could be expected to give reasonable estimates of changes in streamflow and salt load following tree planting. Salinity and flow data showed a clear response to the selected planting in the Pardelup subcatchment (Section 3.6) and were well modelled by MAGIC. The Barrama subcatchment data were also simulated with the MAGIC model to demonstrate that the small responses obtained were to be expected.

Detailed descriptions of model calibration using the Pardelup and Barrama subcatchment data are presented in Appendix 4.

4.4 Upper Denmark modelling

The Upper Denmark catchment was divided into ten subcatchments (Fig. 12) and an earlier version of the MAGIC model was applied to the catchment in 1994 (Arumugasamy & Mauger 1994). The most recent version of the model was calibrated on the Collie Recovery Catchment (Mauger et al. 2001). Significant modifications to the hydrological process for its application to the Upper Denmark catchment were as follows:

1. In areas within native forest where midsummer greenness was relatively low (e.g. swamps or degraded remnants), ephemeral vegetation, whose LAI varied seasonally in the same pattern as that used for pasture, was added (with the maximum LAI set to 3 for greenness 20 or less and grading to zero for greenness 30 or more).
2. Where the ground slope was less than 1%, it was assumed that runoff could remain available for evaporation after the current month. (Normally one month of evaporation is allowed before runoff is accumulated into streamflow.)

These changes had most effect in reducing streamflow from forested areas, where overestimation had previously been a problem.

The model was calibrated using the streamflow and salt load data from the gauging stations corresponding to the peak values found in 1991. In 1991, stream salinity and salt load peaked (Fig. 9) and there was very little tree planting in the Upper Denmark catchment (Fig. 12). The rainfall for 1991 was also very close to the mean for the period 1980–95. Landsat TM data for

1988 were used to define the 1991 vegetation cover. Calibrated parameters changed from the values used in the Collie Recovery Catchment model were:

1. Maximum pasture LAI was changed from 2.4 to a formula based on rainfall, which gave values ranging from 2.5 to 3.3. Similar modifications were also necessary for calibrating the model at the Pardelup and Barrama experimental subcatchments.
2. The formula for natural forest greenness, used to calculate potential tree transpiration, was changed from [0.0104 x (annual rain in mm) + 17.3] to [0.043 x (annual rain in mm)]. At 700 mm rainfall, the value would change from 24 to 30, and, at 840 mm, from 26 to 36.
3. The maximum rate for recharge to deep groundwater in a month was changed from 4 mm to 6.4 mm (48 to 78 mm/yr).

Model outputs were selected and aggregated to management unit totals (Table 4). The observed and predicted annual streamflows for the Yate Flat Creek and Kompup gauging stations were 4.95, 5.21 and 4.97, 5.36 GL respectively. The predicted annual mean stream salinity at the Yate Flat Creek gauging station was 1435 mg/L TDS, slightly higher than the observed salinity of 1351 mg/L. The predicted salinity at the Kompup gauging station was 1196 mg/L TDS, 101 mg/L lower than the observed salinity. Overall, the predicted annual streamflow and salt load for both gauging stations were within 10% of the observed values. Therefore, the MAGIC model was considered to be well calibrated for the Upper Denmark catchment.

Table 4. Model calibration to representative year 1991 flow year

Model Calibration	*Management units*			*Upper*	*Kompup to*	*Total at*
	Perillup	*Kompup*	*Yate Flat Cree k*	*Denmark*	*Mt Lindesay*	*Mt Lindesay*
Catchment area (km^2)	75.0	108.8	57.7	241.5	283.6	525.1
1988 Cleared area (km^2)	11.3	33.2	32.4	76.9	0	76.9
1988 Cleared area/Catchment area (%)	16	41	45	0	0	16
Area regenerated by 1984	0.8	5.7	-0.1	6.5	0	6.5
Rainfall (mm)	688	714	689	699	795	750
Streamflow based on 1991 (GL)			4.95	12.20	16.79	28.99
Mean stream salinity based on 1991 (mg/L)			1350	1350	225	697
Salt load based on 1991 (t)			6690	16 400	3780	20 200
Modelled streamflow (GL)	1.91	5.36	4.97	12.2	16.8	29.0
Modelled streamflow (mm)	25	57	69	51	59	55
Modelled stream salinity (mg/L)	1420	1200	1470	1340	225	696

4.5 Concluding remarks

Comparison of the treated subcatchments (Pardelup and Barrama) with the control (Willmay) detected some changes in groundwater levels, streamflow and salt discharge resulting from trees planted in 1993. At Pardelup, where 40% of the cleared area was replanted, streamflow and salt load up to 1997 were reduced to 76% and 71% respectively of their pre-planting rates. After planting, groundwater levels in the treated catchments trended strongly downwards compared with the control. At Barrama, where only 17% of cleared area was replanted, changes in streamflow and salt load to 1997 were very small. Groundwater levels declined sharply compared with the control for two years, but the decline was also noted in bores far from planted areas. After 1996, there was a sharp reversal to a trend of rising groundwater level, which corresponded to the time when the land was being prepared for total conversion to tree plantation; that is, it was cleared. Unfortunately, streamflow and groundwater level recordings stopped before the plantations established significant leaf area.

The MAGIC model used for the Upper Denmark catchment was applied first to the Pardelup and Barrama catchments to check that the modelling processes were appropriate. Although modelling small catchments can give insights into the hydrological processes, the results need careful consideration when compared with field observations.

Firstly, modelling outputs may not physically correspond precisely with measured quantities. For example, in the version of the MAGIC model applied to the Upper Denmark catchment: (a) runoff is reported at the time that it is generated at the ground surface with no delay allowed for the time taken to reach the gauging station, and (b) deep groundwater discharge (with accompanying salt) is reported when it enters the surface soil layer from the underlying clay. This ignores the period during which salt may be temporarily stored in shallow soils before reaching the ground surface and being transported to the gauging station. However, the totals of the modelled quantities should correspond well with gauging station totals when summed over a sufficiently long period.

Secondly, some model input data that are determined by calibration may vary significantly between areas the size of small catchments. In this model, important examples of such data were the peak LAI of pasture, and clay layer permeability (which affects the limit rate for infiltration of recharge to deep groundwater). When modelling larger catchments, average values for the whole catchment will be found by calibration. While the modelled outputs for the whole catchment may have acceptable accuracy, a greater variation from actual outputs should be expected from small areas within the whole catchment. If it is important to improve estimates for specific smaller areas, there should be more investigation to obtain data for local calibration.

5 Catchment management options

The effects of seven 'treatments' (or cases) on streamflow, salinity, the shallow watertable area and seepage area are presented in Table 5 and discussed in Sections 5.1–5.6. Extremes from 'all remaining cleared' areas planted with trees or perennial pastures to 'no planting' are modelled to provide a feasible and more socially acceptable set of management options. Additional information is detailed in Appendix 5.

These cases constitute a suite of technically feasible management options for achieving the salinity target at Mt Lindesay by 2020.

5.1 Base case

The calibrated MAGIC model was run with 1988 actual vegetation cover which included 6.5 km^2 of regenerated area, mainly in the Kompup management unit (Fig. 23). There was a reasonable match between the observed and predicted streamflow, salinity and salt load for major gauging stations within the Upper Denmark catchment. In the base case, the streamflow, salinity and annual salt load at the Mt Lindesay gauging station were 29.0 GL, 697 mg/L TDS and 20.2 kt respectively. The effects of tree planting and perennial pastures on streamflow and salinity were estimated by modelling the 1988 vegetation as a base case, and then, for each case being tested, substituting all areas of annual pasture with the new perennial vegetation (trees or pasture).

5.2 Cases 1 and 2

The MAGIC model was calibrated to the Upper Denmark catchment for the year 1991 when there was negligible tree planting. (Table 4). Three other cases of tree planting (over varying proportions of the cleared areas) were simulated by the MAGIC model. Details of the modelling assumptions and results are presented in Appendix 5.

1. Case 1. Maximum cleared area. This is the 'worst-case scenario'. This simulates what the streamflow, salinity and salt load might have been at hydrological equilibrium when salinity was fully expressed.

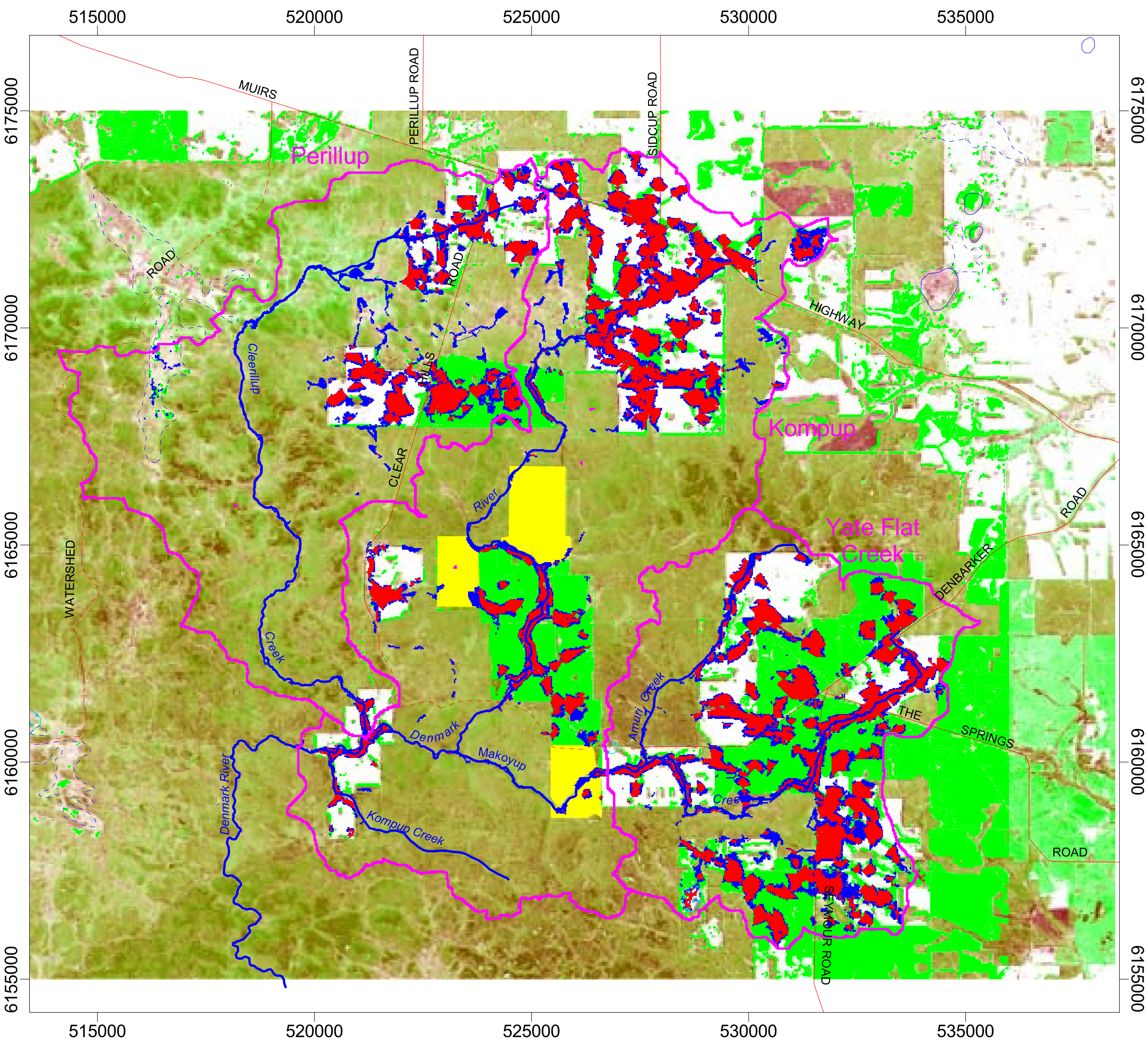
2. Case 2. Actual tree plantations to 2001.

5.2.1 Case 1 Maximum cleared area

This represents the maximum cleared area had trees not been planted or allowed to regenerate in the Upper Denmark catchment. Streamflow, salt load and seepage area would have increased compared with the average flow year of 1991. Modelled streamflow and salt load were 30.1 GL and 21.4 kt respectively, which means that the salinity at the Mt Lindesay gauging station would have decreased from 697 to 678 mg/L TDS (Table 5). The groundwater seepage area would have increased from 26 to 28% of the catchment area (Table 5). However, this increase would mostly have been confined to the regenerated areas within the Kompup management unit (Appendix 5, Table A5.1, Fig. 24).

5.2.2 Case 2 Actual plantations to 2001

Between 1990 and 2001, 39 km^2 of the Upper Denmark catchment were replanted with trees. The replanted areas were limited to the central portions of the Kompup, Yate Flat Creek and Perillup management units, with very little tree planting in the cleared areas along the Muirs Highway (Fig. 25). The MAGIC model predicted a significant reduction in groundwater seepage area, particularly in the areas where the trees were planted (Fig. 25). The seepage area would decline to 65% of seepage of the maximum cleared area (Appendix 5, Table A5.2). The biggest reduction in seepage area would be in the Yate Flat Creek management unit, and the smallest in Perillup. There would be reductions in streamflow (29.03 to 23.51 GL), salt load (20.2 to 14.8 kt) and salinity (696 to 631 mg/L TDS) at the Mt Lindesay gauging station (Appendix 5, Table A5.2). So, when the landscape achieved its new hydrological equilibrium, the net reduction in average annual stream salinity at the Mt Lindesay gauging station would be 65 mg/L. Modelling of tree planting in the Collie Recovery Catchment indicates that the catchment should reach a new hydrological equilibrium within 10 years of the trees having been planted (Bari et al. 2003).



Legend

Land use

- Native vegetation
- Regenerated before 1984
- Plantations (2001)
- Pasture/cleared area

Groundwater

- Shallow watertable area
- Seepage area
- Lake; permanent
- Lake; intermittent
- Swamp
- Management unit boundary
- River
- Road

Figure 23 Modelling output of Base Case of Upper Denmark catchment

0 2 4 6 8 Kilometres

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Table 5. Summary of analysis of management options

	Cleared area		*At Mt Lindesay gauging station**			*Shallow watertable in MU*		*Seepage area in MU*	
Modelled cases	*Area (km^2)*	*% max cleared area*	*Salinity (mg/L)*	*Flow (GL)*	*Salt load (kt)*	*Area (km^2)*	*% max cleared area*	*Area (km^2)*	*% max cleared area*
Base case	**6.5**	**8**	**697**	**29.03**	**20.2**	**35**	**42**	**22**	**26**
Case 1. Maximum cleared area			678	30.1	21.4	35	44	23	28
Case 2. Actual plantations established by 2001	39.0	47	631	23.5	14.5	24	29	11	12
Case 3.1 Actual plantations plus trees on all remaining clearaed land	83.4	100	368	18.2	5.9	8	8	0	
Case 3.2 Actual plantations plus deep-rooted perennials (eg. lucerne) on all remaining cleared land	83.4	100	380	18.1	6 8	8	10	0	0
Case 3.3 Actual plantations plus shallow-rooted perennials (eg kikuyu) on all remaining cleared land	83.4	100	714	18.5	12. 5	21	25	2	2
Case 4. Groundwater pumping in absence of second rotation of actual plantations.	6.5	8	528	27.9	14.7	Not estimated		Not estimated	
Case 5. Groundwater pumping with ongoing rotations on actual plantations	39.0	47	476	22.8	10.9	Not estimated		Not estimated	
Case 6. Diversion at Mt Lindesay gauging station	6.5	8	500	25.6	12.8	35	42	22	26
Case 7. Diversion at Kompup gauging station	6.5	8	500	24.6	12.3	35	42	22	26

** Data are for 1991 which is considered to be a typical rainfall year*

5.3 Cases 3.1 – 3.3

5.3.1 Case 3.1 All remaining cleared areas are replanted with trees

The model predicts that the volume of streamflow at the Mt Lindesay gauging station will fall to 18.3 GL, 61% of Case 1 (Table 5). The streamflow reduction will be limited to the Upper Denmark catchment (where the trees have been planted). When the Upper Denmark catchment reaches its new steady state, the streamflow from it will be 1.55 GL, only 12% of the pre-replanting streamflow. Within this catchment, the reduction in

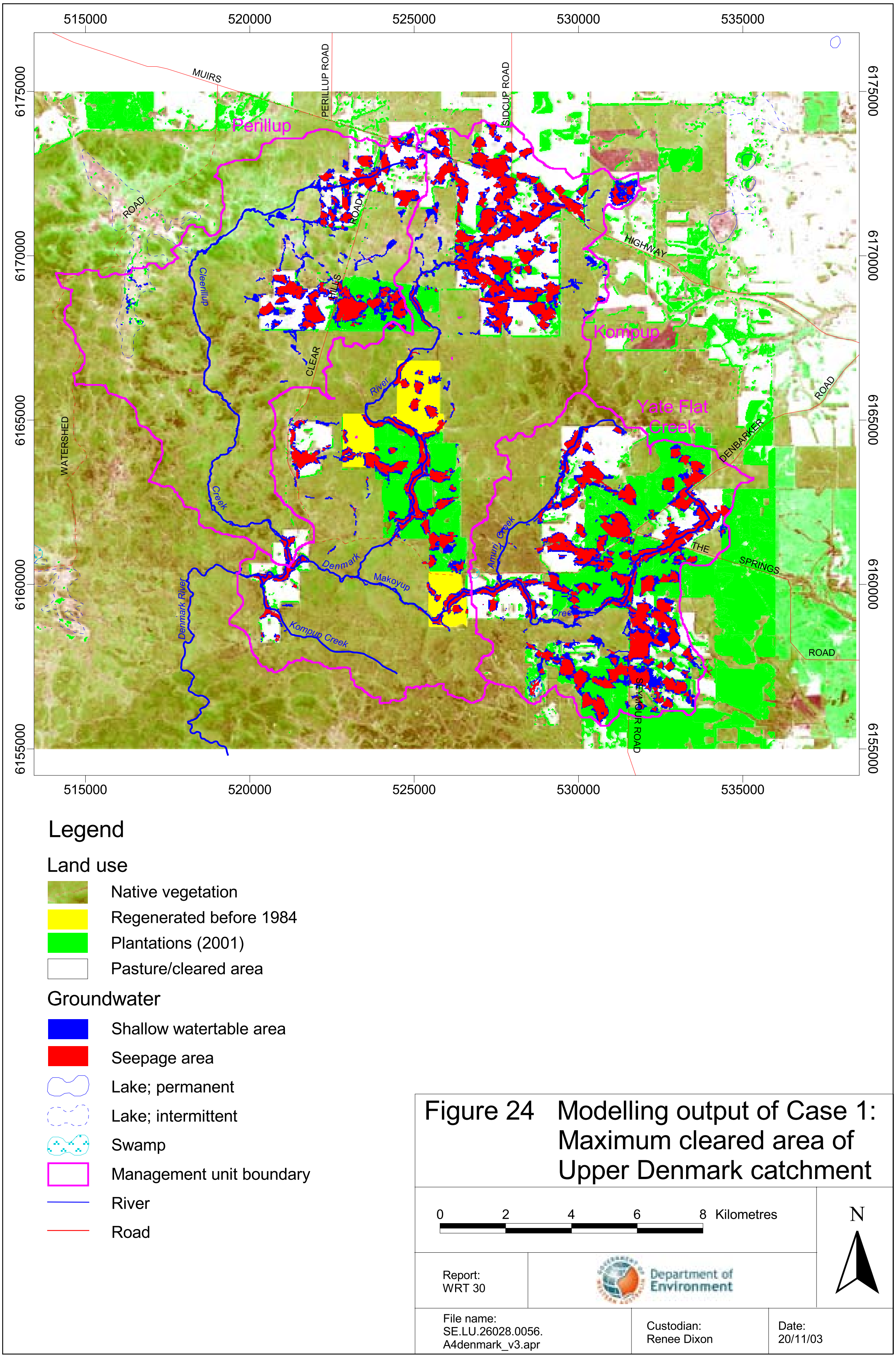

Figure 24 Modelling output of Case 1: Maximum cleared area of Upper Denmark catchment

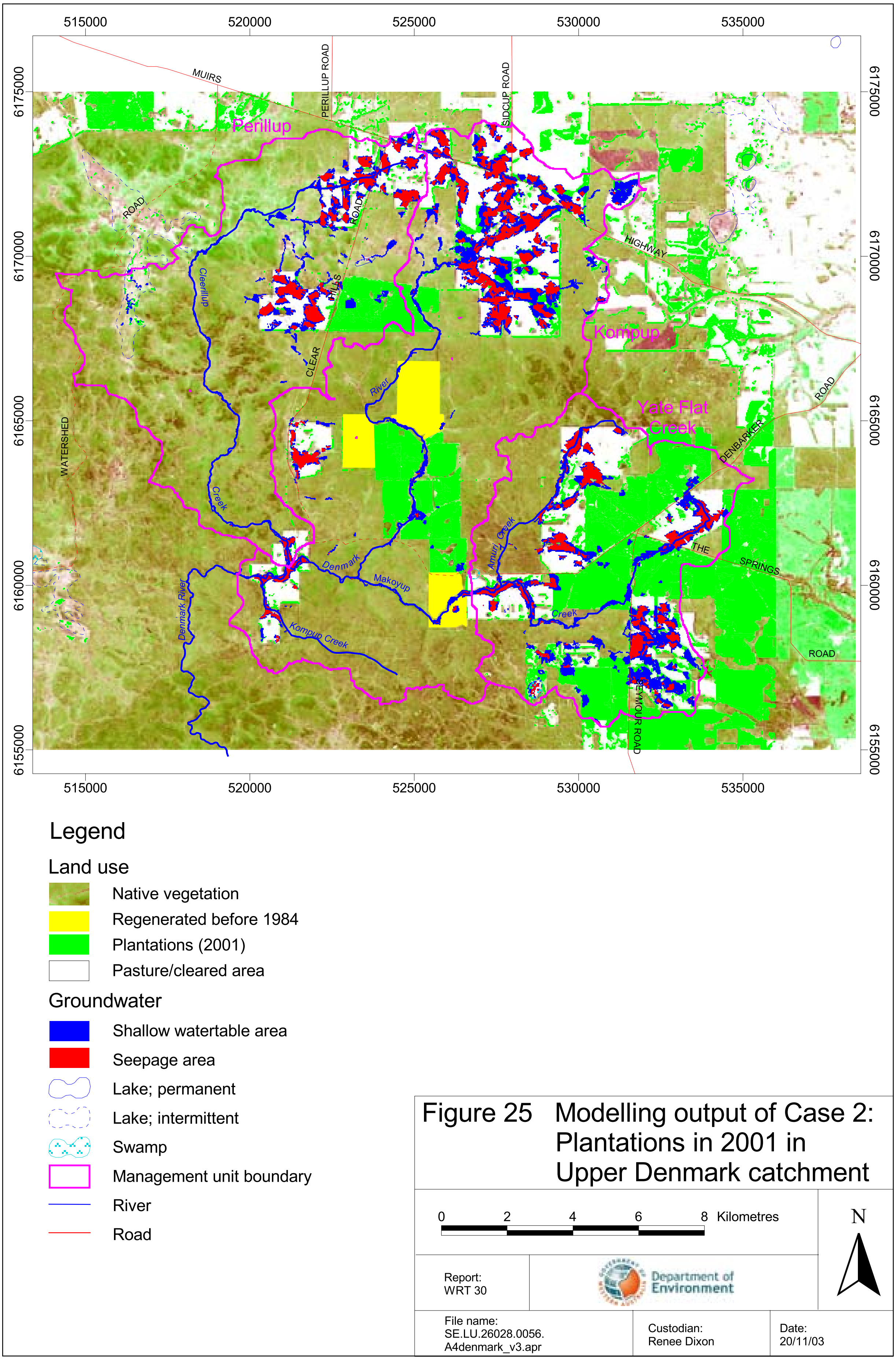

Figure 25 Modelling output of Case 2: Plantations in 2001 in Upper Denmark catchment

streamflow will vary between the management units — the Yate Flat Creek would have the biggest reduction (streamflow is predicted to fall to just 5% of the pre-replanting value) while Perillup is predicted to have only 15% reduction (Appendix 5, Table A5.3). The groundwater seepage areas would disappear completely (Table 5), although some shallow watertable areas, mainly along the stream lines and valley floors, would remain (Appendix 5, Table A5.3). The average annual stream salinity and salt load at the Mt Lindesay gauging station will fall to 368 mg/L and 5.86 kt respectively (Table 5).

Plotting the proportions of the cleared area replanted with trees against annual streamflow, salinity or salt loads at Mt Lindesay has revealed some interesting facts (Figs. 26–28). The annual streamflow and salt load are approximately linearly proportional to the remaining cleared area, whereas the salinity reduction is clearly non-linear. The annual streamflow and salt load at Mt Lindesay would fall at the rate of approximately 0.15 GL and 173 tonnes per square kilometre of cleared area planted (Figs. 26, 28). That means the annual salinity would decrease at the rate of approximately 3 mg/L TDS per square kilometre of the cleared area planted (Fig. 28).

Figures 26–28 can be used as characteristic curves for determining the effects of tree planting within the Upper Denmark catchment on annual streamflow and salinity at the Mt Lindesay gauging station. For example, if no trees were planted and all the remaining privately-owned land in the Upper Denmark catchment (an additional 25 km^2) were cleared, the annual stream salinity at the Mt Lindesay gauging station would be about 750 mg/L (Fig. 27).

5.3.2 Cases 3.2 and 3.3 Deep-rooted and shallow-rooted perennial pastures

The performance of a particular pasture in the MAGIC model is wholly determined by two factors: its LAI (Leaf Area Index) and its depth of rooting in the clay layer. In model calibration, the annual pasture is represented by a rooting depth of 2 m and the LAI for each month of the year is set representing a growth cycle. The annual pasture LAI varies from nil to 2.1 within a year. In simulating perennial pasture, a year-round constant LAI is set. Plants can only draw water within the range of their nominated rooting depths. In reality, the plants may wither if the soil water is depleted, but, in the model, it is assumed that they can quickly re-establish the maximum transpiration rate (defined by their LAI) as soon as water re-enters their root zone. Kikuyu is considered to be a ‘shallow-rooted’ perennial with a rooting depth of 1.5 m, and so can access water only in the upper soil layer (the A plus B Horizons defined by soil maps) most of the time. ‘Deep-rooted’ perennials (e.g. lucerne) had a nominated rooting depth of 2.0 m and so could access all the water in the upper soil layer plus water from the clay layer. As there are limited data on the rooting depth and LAI of both the shallow- and deep-rooted perennials, several model simulations based on LAI (from 50% to 100% LAI of annual pasture) and rooting-depth distribution (1.5–2.0 m) were performed.

Figure 26. Modelled streamflow for Denmark River at Mt Lindesay

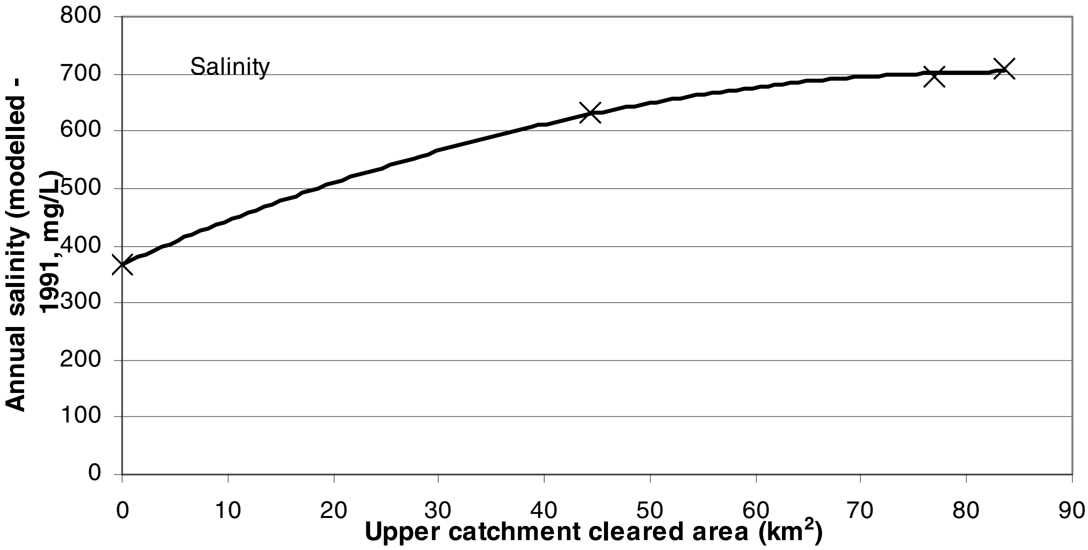

Figure 27. Modelled stream salinity for Denmark River at Mt Lindesay

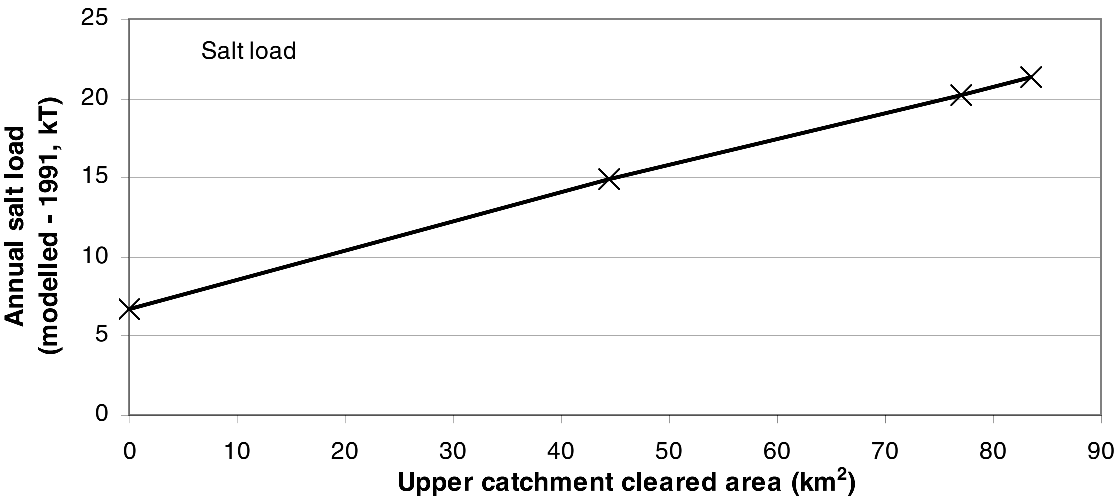

Figure 28. Modelled salt load for Denmark River at Mt Lindesay

For the base case of 1988, the total transpiration by annual pasture from the Upper Denmark catchment was 31 GL. Simply changing from annual pasture to perennial pasture, with a minimum rooting depth of 1.5 m and LAI 100% of annual pasture, increases the total transpiration volume to 44.9 GL, a 43% increase. The total volume transpired by perennials increases with increasing rooting depths and LAI, with a maximum transpiration of 46.3 GL.

As the total transpiration increases, the volume of streamflow decreases. Just converting from annual to perennial pasture with a maximum rooting depth of 1.5 m (eg. kikuyu), the streamflow volume at the Mt Lindesay gauging station is predicted to decrease from the base case of 29 GL to between 18.5 and 20.2 GL (Table 6). With a maximum rooting depth and LAI of 2.1, the annual streamflow volume is predicted to decrease from a base case of 29 to 18.1 GL.

Just changing the annual pasture to perennial is predicted to reduce the total salt load at the Mt Lindesay gauging station from a base case of 20.2 kt. With a maximum rooting depth of 1.5 m and LAI ranging from 50 to 100% of pasture LAI (eg. kikuyu), the reduced salt load would range from 13.2 to 17.5 kt. The MAGIC model predicts that the rate of salt load reduction is almost linearly proportional to increasing rooting depth and LAI of perennial pastures. If the LAI ranges from 50% to 100% of annual pasture and the rooting depth is 2.0 m, the corresponding salt load volume would range from 13.6 to 6.9 kt.

The MAGIC model predicts that some combinations of rooting depth and LAI of perennial pastures could actually result in the Mt Lindesay salinity exceeding the base case salinity of 697 mg/L TDS. If the rooting depth is less than 1.5 m, all combinations of LAI result in higher salinity than the base case. The corresponding stream salinity ranges from 715 to 860 mg/L (Table 6). The higher salinity could be explained by disproportionate reduction in streamflow and salt load. Annual stream salinity at the Mt Lindesay gauging station is predicted to decrease below the base case with perennial LAI and rooting depth greater than 60% of annual pasture and 1.8 m respectively.

A combination of perennial pastures and tree planting may provide a practical solution to the salinity problem in the Denmark Recovery Catchment. By the end of 2001, 39 km^2 of the Upper Denmark catchment had been replanted with trees (Fig. 25). Cultivating annual and perennial pasture is also necessary for the livelihood of the farming community of this catchment. If no more trees were planted and the remaining cleared areas were planted with lucerne (LAI of 2.1 and rooting depth of 2.0 m), then the streamflow and salinity at the Mt Lindesay gauging station is predicted to decrease to 18.1 GL and 380 mg/L respectively (Table 5). The groundwater seepage areas are predicted to disappear completely once equilibrium had been achieved, probably in about 10 years (Bari et al. 2003; Bari 1998). If the shallow-rooted kikuyu (LAI 2.1 and rooting depth 1.5 m) is planted on the remaining cleared area instead of lucerne, then the annual streamflow and salinity is predicted to decrease to 18.5 GL and 715 mg/L respectively (Table 6).

Like the effects of tree planting on streamflow, salinity and salt load (Figs 26–28), characteristic curves to calculate salinity reduction due to shallow- or deep-rooted pastures could be developed. In fact, the combination of the two sets of characteristic curves could be used to estimate the effects on streamflow, salt load and salinity of any proportion of the cleared area planted with trees and the remaining area cultivated with shallow- or deep-rooted pasture.

5.4 Cases 4 and 5 Groundwater pumping

The results from modelling tree plantations were used to evaluate the effects of pumping groundwater and disposing of it outside the catchment. A conceptual layout of collector pipes to cover the main areas of discharge in the north and east of the catchment is shown in Figure 29. In the model, the production bores are about 400 m apart along the collector pipes. The 400 m spacing is suggested by the MODFLOW modelling of the experimental catchment groundwater pumping scheme within the Collie Recovery Catchment (Dogramaci et al. 2001). The collection areas are connected by lengths of 'transport' pipe, with a final length of transport pipe taking all the pumped water to an outfall point in an established creek line outside the Upper Denmark catchment. Cleared areas to the south and west were omitted because of their remoteness from possible outfall sites. The pumps are assumed to draw 50% of the deep groundwater discharge calculated by modelling.

The design considered two cases:

- Case 4 — there are ongoing rotations of the plantations in place in 2001.
- Case 5 — there is no second rotation of the plantations. This case could arise if landowners harvested the plantations and returned the land to pasture.

Table 6. Effects of perennial vegetation on streamflow and salinity

	50% of LAI	*100% of LAI*	*50% of LAI*	*100% of LAI*
Perennial vegetation	*Streamflow (GL/yr)*		*Salinity (mg/L)*	
Lucerne *	19.6	18.1	690	380
Kikuyu **	20.2	18.5	860	715

* *assumes rooting depth = 2 m*
** *assumes rooting depth = 1.5 m*

When changing from the case without plantations to the case with plantations, collector mains for discharge areas within the plantation areas were not required, but some sections need to be retained as transport mains to cross plantation areas. The basic quantities and estimated effects on stream salinity are summarised in Table 7. With the combination of groundwater pumping and plantations, the annual streamflow and salt load in the Upper Denmark catchment will be reduced from 6.7 GL and 1660 mg/L TDS to 6 GL and 1250 mg/L respectively. If groundwater pumping occurs in the absence of the plantations, the mean annual salinity in the Upper Denmark catchment will fall from 1380 to 1020 mg/L, which is a reduction of 360 mg/L (Table 7). However, at the Mt Lindesay gauging station, the effect of groundwater pumping (with ongoing plantations) in annual salinity reduction will be 141 mg/L TDS. Without ongoing plantations, the relative reduction will be a greater 170 mg/L, and the annual stream salinity will fall to 528 mg/L TDS (Table 7).

5.5 Shallow drains

Shallow drains are designed to allow surface water and shallow groundwater to be removed from, or diverted around, poorly drained areas, thereby reducing waterlogging and improving agricultural productivity. Shallow drains are also sometimes constructed on hillsides (as 'grade banks') to reduce recharge in downslope areas. Modelling in the Collie Recovery Catchment showed that such drains increased streamflow a little, mainly at the expense of transpiration, with a very minor reduction in recharge and corresponding minor reduction in deep groundwater discharge and salt output. Draining 30% of the cleared land in the Collie Recovery Catchment was modelled to increase inflow to the Wellington Reservoir by less than 1% and to reduce salt discharge about 1%, giving about 2% reduction in salinity (Mauger et al. 2001). Given this small benefit, shallow drainage has not been quantified as a salinity management option.

Table 7. Upper Denmark catchment groundwater pumping options

	Ongoing rotations of plantations	*No second rotation of plantations*
Length of pipes within catchment (km)	65	74
Pipe diameters required (mm) from 25 mm up to:	130	150
No. of bores at 400m spacing	127	173
Pumping rates required (kL/day)	15	17
Total outflow rate (L/s)	22	34
Volume of water pumped annually (GL)(=50% deep g/w discharge in area)	0.7	1.1
Annual salt load diverted (kt)	3.65	5.48
Upper Denmark catchment without pumping		
Streamflow (GL/yr)	6.7	12.2
Salinity (mg/L)	1663	1384
Upper Denmark catchment with pumping		
Streamflow (GL/yr)	6.0	11.1
Salinity (mg/L)	1249	1023
Total Mt Lindesay without pumping		
Streamflow (GL/yr)	23.5	29.0
Salinity (mg/L)	617	698
Total Mt Lindesay with pumping		
Streamflow (GL/yr)	22.8	27.9
Salinity (mg/L)	476	528

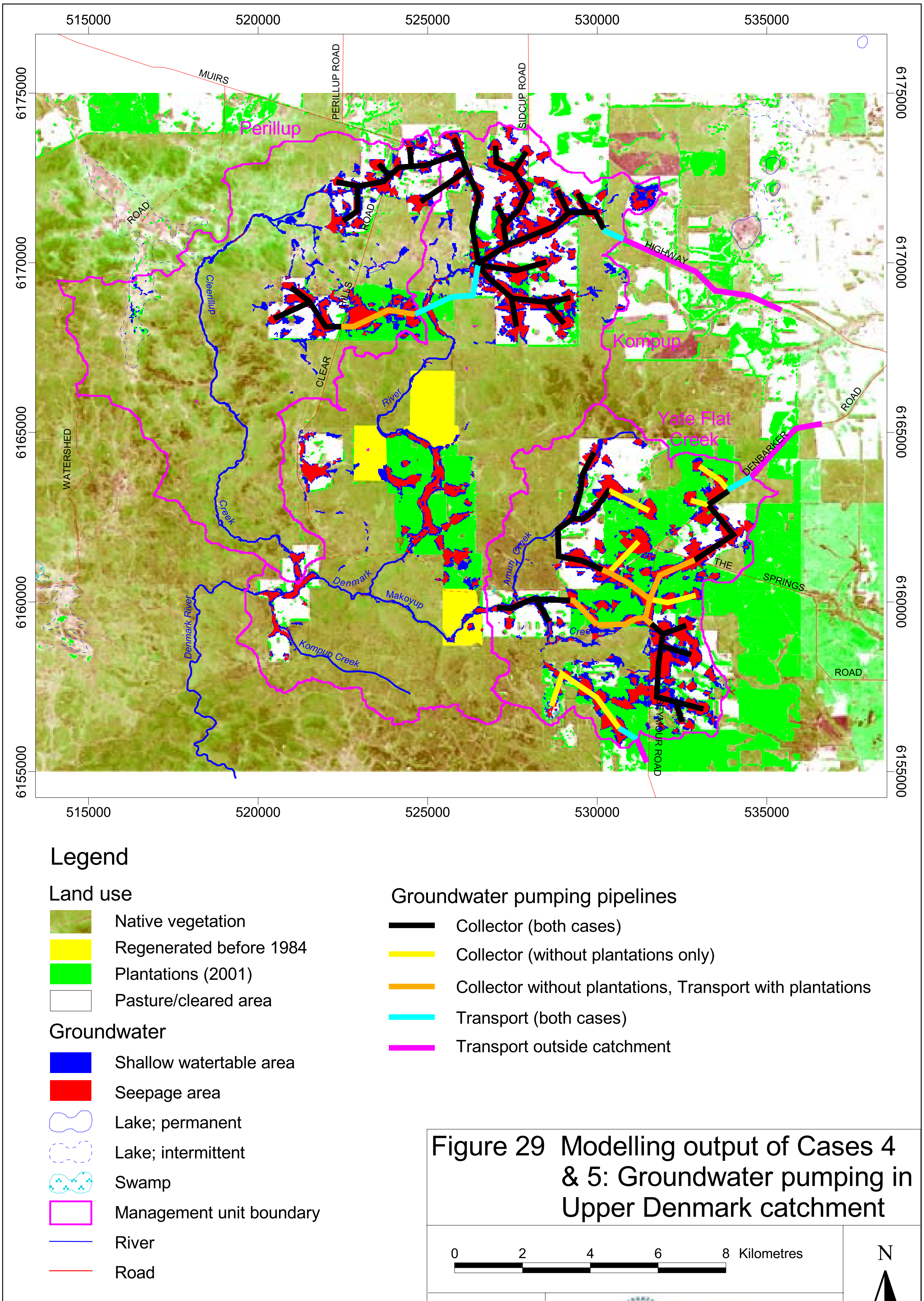

Figure 29 Modelling output of Cases 4 & 5: Groundwater pumping in Upper Denmark catchment

Report: WRT 30

Department of Environment

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Custodian: Renee Dixon

Date: 20/11/03

5.6 Deep drains

Deep drains are constructed within discharge areas to intercept deep groundwater. In favourable sites, the drains improve nearby agricultural productivity by allowing the high-salinity deep groundwater to escape before it reaches and contaminates near-surface soils. Lowering the watertable also reduces waterlogging.

To contribute to lowering stream salinity, the deep groundwater collected by a deep drain must be prevented from re-entering watercourses downstream. In considering methods of disposing of the drain outflow, this option should be compared with groundwater pumping, which uses the same mechanism of withdrawing deep groundwater from the ground before it reaches surface soils. If the outflow from the end of the drain is not suitably diverted, the total salt load delivered into the streams is unchanged, while the seasonal distribution of flow and salt could be altered with possible environmental implications for downstream areas. For identical volumes of drained and pumped deep groundwater, deep drain disposal must deal with larger and more variable water flow rates since deep drains also collect runoff and shallow groundwater from their catchment areas. The outflow must also be transported from the downstream end of the scheme. In the Upper Denmark catchment, this would result in pipes and pumps that must carry higher flows longer distances up greater heights than is required for an equivalent groundwater pumping scheme in which the collection points are distributed along the valleys. Consequently, deep drainage has not been quantified as an option. Deep drains for dryland salinisation are unlikely to reduce stream salinity.

5.7 Surface water diversion

5.7.1 Case 6 Diversion at the Mt Lindesay gauging station

The effect of diverting flow past the point of water supply abstraction near Mt Lindesay was analysed. The engineering works required would be a small pipehead dam, just upstream of the water supply works, that would allow relatively low flow rates to enter a short pipe to carry the diverted water and discharge it back into the river downstream of the water supply works. The daily streamflow record at the Mt Lindesay gauging station from 1983 to 1999 was used to represent likely flow variation in the near future, as it is 8 years each side of 1991, the year when average salinity peaked. Two operational criteria were tested for making the decision on whether the flow on a particular day should be used or discarded by diversion. They are: (i) if the flow rate was less than a critical value, or (ii) if the salinity exceeded a critical value, but with a flow diversion limit that would prevent excess flow rates being diverted. The critical values were determined from the whole (1983–99) record such that the mean salinity of all the non-discarded water was 500 mg/L. The critical values were: (i) divert a daily flow less than 200 ML, (ii) and/or the salinity is greater than 850 mg/L TDS up to the daily flow of 400 ML. They were then used to simulate the operation and summarise the results on an annual basis.

Figures 30 and 31 show that the flow-limit criterion leads to higher mean salinity of the usable water in low-flow years, and a smaller volume of usable water in all except the lowest flow years, than the salinity-limit criterion. The mean usable water is 22.6 GL/year (72% of streamflow) with the flow-limit criterion set at 200 ML/day, and 25.6 GL/year (81% of streamflow) with the salinity-limit criterion set at 850 mg/L. The associated flow-diversion limit was 400 ML/day. It is evident from the graphs that inclusion of the salinity criterion is highly desirable because it results in more usable water at lower mean salinity in nearly every year.

While the flow-weighted average salinity for the whole of the analysed period was 500 mg/L, the graph shows that only in one-third of years was the annual flow-weighted average less than 500 mg/L (Fig. 30). By testing different salinity criteria, it was found that the limit had to be reduced to 650 mg/L before another year had a mean less than 500 mg/L — and this would result in a further 15% loss of usable water. Thus, to be useful as a source for water supply, the scheme using the water must be able to absorb above average salinity water for extended periods.

Reducing the flow diversion limit to 200 ML/day, with a corresponding salinity limit of 820 mg/L, resulted in annual salinities within 15 mg/L of the 400 ML/day limit, except for the low flow year of 1987 when the salinity of non-diverted (‘usable’) water rose from 800 mg/L to 1008 mg/L. There was also one less year less than 500 mg/L.

Diversion of 200 ML/day needs a pipe with diameter of about 1 m (assuming water velocity about 1 m/s). Higher diversion capacities would probably be implemented using multiple pipes.

5.7.2 Case 7 Diversion at the Kompup gauging station

The diversion of all or part of the streamflow generated in the Upper Denmark Catchment at the Kompup gauging station is considered to be an alternative but has several disadvantages compared to groundwater pumping.

The Kompup gauging station is the highest point at which all streamflow from cleared areas could be captured (Fig. 1). Diversion would require construction of a storage dam near the gauging station site to provide an intake for pumping, and a pipeline to transport the diverted water outside the catchment. The storage dam would need sufficient capacity for one or two days pumping. All flows less than the pumping capacity would be diverted, and only that part of daily flows which exceeded the pump capacity would continue downstream. To assess the concept, daily flow records were analysed from all of 1993 and 1994, which were

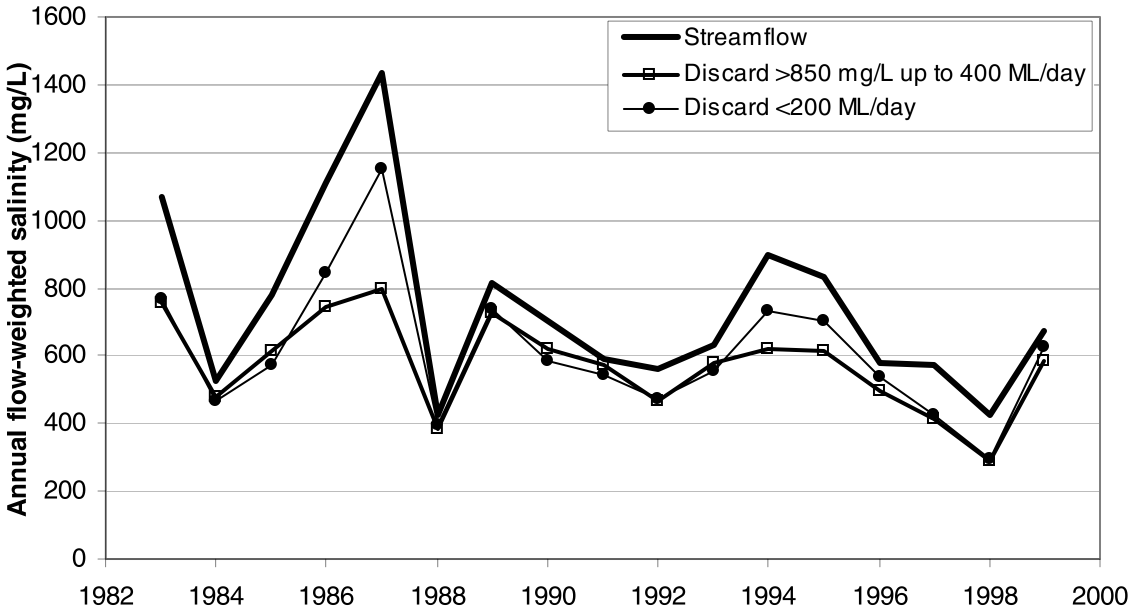

Figure 30. Effect on salinity of using the criteria for diversion to achieve 1983–99 mean of 500 mg/L

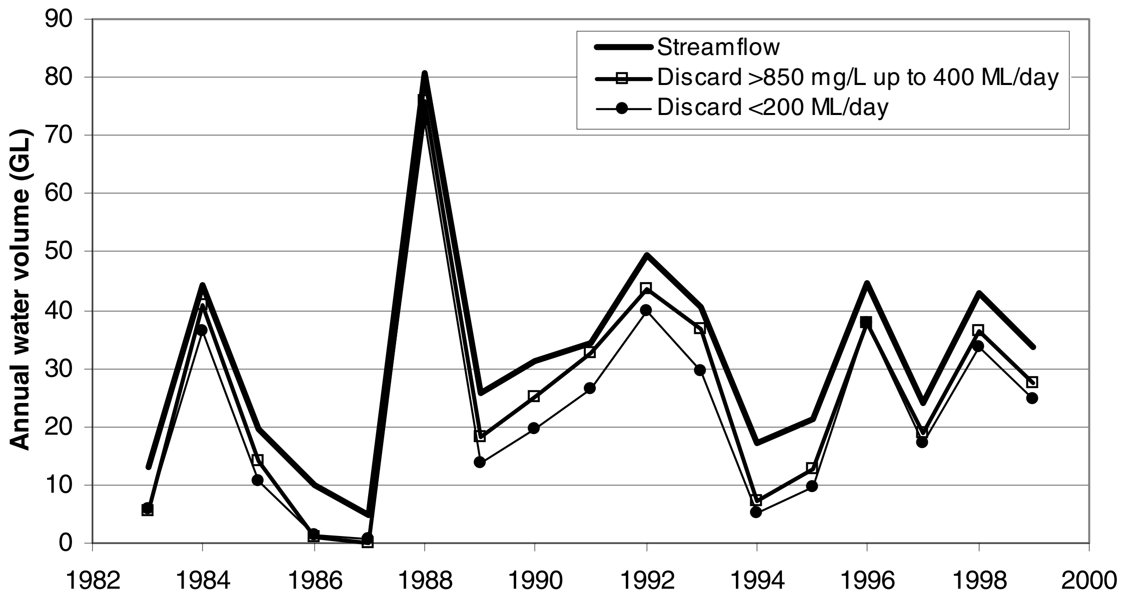

Figure 31. Effect on water volume of using the criteria for diversion to achieve 1983–99 mean of 500 mg/L

close to average streamflow in the period when mean salinity was near its peak. Figure 32 shows the average result at Mt Lindesay gauging station for the two years, for varying capacities of pumping. To achieve an average 500 mg/L TDS at the Mt Lindesay gauging station, a pump capacity of 33 ML/day would be required to divert 4 GL per year at the Kompup gauging station (Fig. 32). At that pump capacity, mean salinity in 1993 would have been 485 mg/L instead of 632 mg/L, and in 1994 it would have been 535 mg/L instead of 900 mg/L. So this diversion could be expected to strongly dampen the variation in salinity as well as reduce it.

5.7.3 How do groundwater pumping and diversion compare?

A comparison of the diversion concept with groundwater pumping shows the following:

- Both schemes cause a relatively large reduction of stream salinity but a relatively minor reduction of streamflow to the Mt Lindesay gauging station, resulting in reduced salinity at this station. The mean usable water due to diversion at the Mt Lindesay gauging station is more than 72% available without diversion. The usable water would be 80% if the high-salinity water is diverted at the Kompup gauging station.
- Diversion would need to transport about three times the volume of water, using about eight times the pumping capacity of groundwater pumping to achieve the same salinity result close to the target at the Mt Lindesay gauging station.
- The full volume of diverted water needs to be pumped for a longer distance and to a greater height than pumped groundwater. The Kent River catchment is only about 5 km away, but would not be available as a disposal site because it is also earmarked for stream salinity reduction. Disposal in the Hay catchment (about 15 km away) would require further study to ensure that environmental impacts were acceptable.

The diversion scheme has no secondary benefits to agriculture whereas groundwater pumping improves productivity by lowering watertables. The diversion will mean that agricultural land will be inundated after construction of the storage dam.

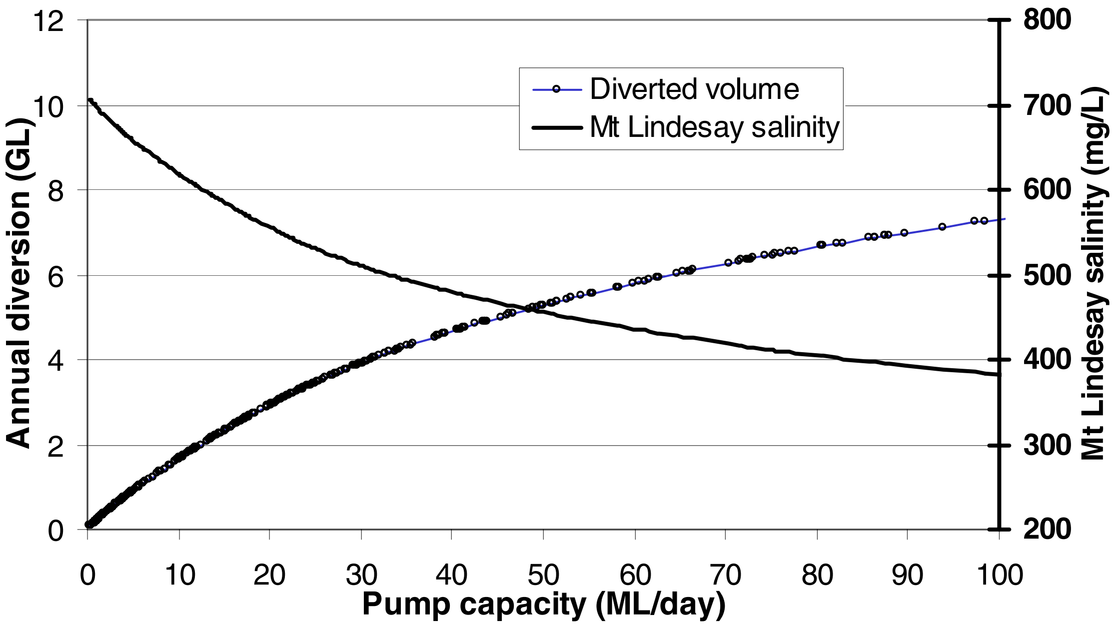

Figure 32. Effect of diverting water at the Kompup gauging station on mean salinity at the Mt Lindesay gauging station

6 Conclusions

The State's Salinity Strategy charged the Water and Rivers Commission (now Department of Environment) to review the effects of private reforestation in the Denmark Recovery Catchment and recommend additional activities, if necessary, to achieve potable water supply levels (500 mg/L TDS) by 2020 at the Mt Lindesay gauging station.

The Denmark Recovery Catchment is upstream of the Mt Lindesay gauging station and consists of the fully forested catchment (between the Kompup and Mt Lindesay gauging stations), which does not contribute to the salinity problem and the Upper Denmark catchment which is divided into three management units contributing the salt load to the Denmark River. Salinity reduction measures are needed in these management units to reduce the salinity in the river.

Five significant conclusions of this review of the salinity situation in the Denmark Recovery Catchment are:

1. The salinity of mean streamflow at the Mt Lindesay gauging station peaked in 1991 and has declined slightly since then. This decline is probably partly due to the nearly completed catchment response to clearing (namely a groundwater rise) and partly to the effects of plantations established after 1988.
2. Further reduction in salinity is expected once all existing and planned plantations are fully established. This reduction will not be sufficient to meet the inflow salinity targets.
3. Modelling indicates other technically feasible management options with the potential to achieve the target inflow salinity. These include either engineering options or further tree planting or a combination of engineering and tree planting.
4. Full effects of management options should be realized within 10 years of commencement. Hence, all selected options should be implemented by 2010 in order to meet the 2020 target.
5. Continued protection of areas of remnant vegetation is important to prevent the development of new recharge areas that would counter other efforts to reduce salinity.

The survey of clearing history showed that 99 km^2 of the total Upper Denmark catchment area of 525 km^2 (about 19%) had been cleared by 1979 after Clearing Control legislation was introduced in 1978. An additional 3 km^2 was cleared earlier but had regenerated by 1965. A further 6 km^2 was regenerated by 1984. Since 1995, nearly 50% of the cleared area has been converted to plantations of Tasmanian Bluegums; these have been mapped from Landsat scenes.

The records of streamflow and stream salinity for the mainstream gauging stations at Mt Lindesay, Kompup and Yate Flat Creek (Woonanup) were used for modelling. The peak salinity at mean annual flow in 1991 at these stations was 700 mg/L, 1410 mg/L and 1350 mg/L respectively. A trend analysis suggests that mean salinity has been falling at the rates of 8 mg/L/yr, 7 mg/L/yr, and 32 mg/L/yr respectively since then.

An alternative option is to wait for salt to be leached from the catchment. However it would probably take more than 50 years to reach drinking-water levels. As such, this is not considered a realistic management option.

Groundwater levels from a network of piezometers monitored from 1985 to the early 1990s showed rising trends. Piezometers installed more recently in experimental catchments showed some decline in levels in response to trees planted nearby after 1993, but elsewhere some rising trend was still evident.

Three partly cleared experimental subcatchments in the nearby Upper Hay catchment closely associated with the Upper Denmark catchment were modelled to check if the model was appropriate to the much larger Upper Denmark catchment. Trees were planted on 40% of the cleared area of the Pardelup catchment and on 17% of the Barrama catchment while the Willmay catchment (the control) was left 'untreated'. There were large reductions in salt load and streamflow through the gauging station of the more extensively planted Pardelup catchment, as well as falling groundwater levels in the areas of tree planting. In the Barrama catchment only groundwater levels fell in response to tree planting. The model outputs fitted the observed records sufficiently well to conclude that it would be appropriate to use the model to estimate mean annual flows and salinities in the Upper Denmark catchment.

All of the Upper Denmark catchment above the Kompup gauging station was modelled and the effects of planting trees and perennial pastures estimated. These estimates could be refined as improved information becomes available since some assumptions were made and generalised data used where detailed information was not available.

A range of feasible management options was assessed for their effectiveness in reducing salinity at the Mt Lindesay gauging station:

- *Planted trees* reduce the salinity by reducing deep groundwater discharge from the upper catchment, largely by reducing recharge to deep groundwater. The benefit of reduced discharge is partially offset by an associated reduction in streamflow. The results suggest that a salinity of 500 mg/L at Mt Lindesay could be achieved with 23 km^2 left cleared, which is 30% of the area cleared before recent plantations were established.
- Increasing the water use of pasture by using *perennial pasture* species could also contribute to reducing salinity at Mt Lindesay. Results suggest that it would not be possible to reach the target salinity by this means alone unless deep-rooted species are used. In addition, if the pasture's transpiration power was too low (as a result of pasture management) when soil moisture was available, this option could lead to increased salinity due to streamflow reduction being much greater than deep groundwater discharge reduction.
- If *groundwater pumping* is chosen, it is assumed that streamflow will reduce by the volume of water pumped, and that the salt load reduction will equal the product of volume pumped and deep groundwater salinity. If groundwater pumping were the only option used in addition to the existing plantations, the 40% reduction in salt load delivered by this option would be enough to reach the target.
- *Shallow drainage* is expected to have minimal effect on salinity at Mt Lindesay, although any effect would be beneficial. *Deep drainage* would be detrimental to the target salinity unless the drainage water was collected and transported out of the catchment. However, any benefits resulting from deep drainage would be more efficiently achieved with groundwater pumping.
- *Diversion of higher salinity flows* around the water supply abstraction point *near the Mt Lindesay gauging station* could improve the long-term average quality of the remaining streamflow but the annual average values in most years would still be above the target.
- *Diversion of about 30% of streamflow from the Kompup gauging station* could substantially achieve the target and would be technically feasible, subject to resolution of potential environmental impacts in those catchment receiving the diverted water. Again, potentially, groundwater pumping has fewer negative impacts and provides more direct benefits at a lower cost for an equivalent reduction in salinity at the Mt Lindesay gauging station.

Estimates of the effects of the principal treatments for salinity are summarised in Table 8.

This report focuses on conceptual salinity reduction options. This was important in order to understand the extent of the land use changes needed to achieve the salinity target. The next steps are to talk to the stakeholders about the options and evaluate the social, economic and environmental implications of each option prior to finalising a salinity recovery plan.

The final step would be to implement this plan and to recover a major river from salinity – a national first!

Table 8. Summary of modelled effects of management options

Case	*Modelled Mt Lindesay salinity (mg/L)*	*Modelled Mt Lindesay volume (GL)*	*Estimated shallow watertable area (km²)*	*Comments***
Base case	697	29.0	35	
Case 2 Actual plantations established by 2001	631	23.5	24	
Case 3.1 Actual plantations plus trees on all remaining cleared land	368	18.2	7	
Case 3.2 Actual plantations plus deep-rooted perennials (lucerne)* on all cleared land	380	18.1	8	
Case 3.3 Actual plantations plus shallow-rooted perennials (kikuyu)* on all cleared land	714	18.5	21	
Case 4 Groundwater pumping in the absence of ongoing rotations of the actual plantations	528	27.9	No estimate, but a substantial reduction expected	Groundwater pumping discharge requires safe disposal
Case 5 Groundwater pumping with ongoing rotations of actual plantations	476	22.8	No estimate, but a substantial reduction expected	Groundwater pumping discharge requires safe disposal
Case 6 Diversion at the Mt Lindesay gauging station	500	25.6	35	
Case 7 Diversion at the Kompup gauging station	500	25	35	

* *Note that the figures quoted for kikuyu and lucerne pastures assume that their leaf area is the same as the maximum leaf area of annual pastures all year round. Used average rainfall year (1991) volumes and salinity.*

** *Assess the social, environmental and economic impacts of all management options.*

7 Recommendations

Management options

- Associate the economic and social costs and benefits of the various management options with their physical impacts on streamflow, salinity and salt-affected land. In particular, assess the environmental impacts of water diverted out of the catchment water.
- Determine the long-term sustainability of commercial plantations. Issues to be addressed include the incentives for private owners to embark on a new rotation after harvesting, maintenance of soil fertility, and the possibility of salt accumulation in the root zone if trees are planted where deep groundwater is discharging.
- Review the practicality of groundwater pumping when the results of the current trial at Maxon Farm in the Collie Recovery Catchment are available.
- Investigate the viability of perennial pastures in reducing stream salinity, taking into account localised leaf area index and rooting depth issues.

Monitoring and evaluation

- Update this report at five-year intervals until the salinity target at the Mt Lindesay gauging station is reached.
- Continue monitoring streamflow and salinity at mainstream gauging stations to confirm the recent indications of downwards trends in salinity, and to confirm the projected changes in salt load and streamflow resulting from further changes in land management in the catchment.
- Re-activate monitoring of Perillup River to confirm assumptions of salinity and salt load from this catchment.
- Establish a program of monitoring the salinity of groundwater from deep piezometers to ascertain whether leaching of salt from the Upper Denmark catchment will be a significant contributor to reduction of the salinity of streamflow. Monitor some of the piezometers for which there exist old records, but also establish some new ones at sites likely to be good indicators of the leaching process.
- Resume monitoring of selected piezometers and stream gauging (flow and salinity) in the Barrama and Pardelup experimental catchments for at least two years: to confirm model estimates of the effects of reforesting all cleared areas with tree plantations in the Barrama catchment, and to confirm the longer term outcomes of the original tree planting treatment in the Pardelup catchment.
- Review the network of piezometers in the Upper Denmark catchment to ensure that the response of groundwater levels to land use changes can be efficiently monitored, and establish a monitoring program to record each piezometer level at least four times a year.

Glossary

aquifer	A geological formation or group of formations able to receive, store and transmit significant quantities of water
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 image that is 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 total (single-sided) area of leaves on plants divided by 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 downward movement of water that is added to the groundwater system
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
transpiration	Process by which water vapour is lost from the stomata (pores) of leaves

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Appendix 1 Kent–Denmark Recovery Team

Formation

The Kent–Denmark Recovery Team formed in September 1998 to oversee the 'recovery' of water quality to potable levels in both rivers. Appointment to the Team was originally by invitation with the endorsement of the Board of the Water and Rivers Commission.

The Team is a partnership of the community of the Kent and Denmark catchments and key government agencies and originally comprised 12 landholders actively farming in the catchments. The rest of the Team were representatives from the major natural resource management agencies, including the then Water and Rivers Commission, Department of Agriculture and the Department of Conservation and Land Management. The landholders were selected to represent their subcatchments because of their community standing and leadership. The local government of Plantagenet and Cranbrook were represented by Council members residing in the catchments (see table below).

From 1995 to 1998 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. 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.

The Team still has most of its inaugural members.

Current membership and affiliation

Member	*Role*	*Affiliation*	*Management Area represented*
Lyn Slade	Chairman	Landholder	Wamballup
Brian Bunker	Vice chairman	Landholder	Nukennulup
John Gillam	Member	Landholder	Nunijup
Norm Beech	Member	Landholder	Middle Kent
Ron Watterson	Member	Landholder	Headwaters
Bruce Parsons	Member	Landholder, chairman of Kent River LCDC	
Murray Hall	Member	Landholder	Lake Katherine
Joan Cameron	Member	Landholder, Vice president Plantagenet Shire	Rocky Gully
Dean Trotter	Member	Landholder	Perillup
Michael Jenkins	Member	Landholder, member of Wilson Inlet Catchment Committee	Denbarker
John Blake	Member	Department of Agriculture, Program manager: Sustainable Rural Development	
Peter Bidwell	Member	Department of Conservation and Land Management, District Manager Walpole	
Naomi Arrowsmith	Member	Department of Environment, Regional Manager South Coast	
Brett Ward	Executive officer	Department of Environment, Manager Western District	

Other attendees

Others are invited to attend meetings to brief the Team if the business at hand warrants it. The Team has hosted several forums to inform the catchment community of its activities and to seek feedback.

Strategic approach

The landcare movement of the 1980s and 1990s arising from government and community consciousness of the need to more closely manage the land and water quality of catchments across WA resulted in federally-funded catchment and property plans being prepared in the Denmark Catchment in 1992. This activity was principally coordinated by the Department of Agriculture. 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 establishment of the fledgling bluegum plantation industry in the Upper Denmark catchment was assisted by the Water Authority and Department of Conservation and Land Management which funded experimental plantations and provided funding incentives to landholders to plant bluegums. This early work quickly lead to the establishment by private investors of bluegum plantations that have significantly changed land use in the Upper Denmark Catchment and have contributed to improved river water quality as salinity levels declined.

Building on the foundations of its 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, including:

- 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 4 years engaging the wider catchment community to implement on-ground works necessary to manage salinity.

Appendix 2 Catchment characteristics

This appendix provides additional information supporting Section 2: Catchment characteristics.

In many instances, the data have been prepared in digital form, maps at a scale of 1:400 000 for a general overview and as tables summarising quantities and qualities within management units and the Upper Denmark catchment overall. Some explanatory notes are included. The maps and tables also indicate the availability of data that actually contain more detail; most data here have accuracy useful for planning studies at scales of 1:50 000 or greater. Graticules have been plotted over the maps with coordinates shown around the map border. The coordinate system is MGA Zone 50, using the GDA94 projection that became the standard for Australia in December 2000.

More information on Soil–landscape systems and subsystems (Section 2.5)

Figure 4 and Table 1 in the text illustrate the main features of the three systems and illustrate the prevalence of the subsystems and phases while Tables A2.1, A2.2 and A2.3 show this information in table form. The whole catchment lies in Zone 254 Warren–Denmark Southland. Note that some subsystems and phases occur in more than one main system.

The soil–landscape mapping shown in Figure 4 came from the "South Coast and Hinterland Survey" from the Natural Resources Assessment Group at the Department of Agriculture Western Australia (Churchward et al. 1988). The survey shows geomorphology, geology, soil properties and vegetation for evaluation for agriculture and grazing. Since the original publication this mapping has been updated. Numerous changes have been made to map unit names in order to comply with Agriculture Western Australia's mapping hierarchy. Changes have also been made to match adjoining mapping. The data collected for this dataset were from field soil surveys and interpretation of aerial photography. The data were digitised from 1:100 000-scale published maps.

The following table shows the prevalence of the soil and landscape systems shown in Section 2.5 Table 1 and Figure 4.

Table A2.1. Soil and landscape system areas

Soil–landscape system	*Area within management unit (km^2)*			*Area in Upper Denmark (km^2)*
	Perillup	*Kompup*	*Yate Flat Creek*	
Kent (Ke)	70.3	47.4	49.7	167.4
Roe Hills (Rh)	21.3	27.6	5.0	53.9
Wilgarup Valleys (Wv)	17.2		3.0	20.2
Total	108.8	75.0	57.7	241.5

Table A2.2. Soil–landscape subsystem and phase descriptions

The distribution of these subsystems is mapped in Figure 4.

Symbol	*System*	*Subsystem and phase*	*Thickness (m)*	*Permeability (mm/hr)*	*Summary description*
CM	Kent	Camballup Subsystem	1.15	28	Swampy plains with some broad drainage lines and salt lakes.
Cop	Roe Hills, Kent	Collis shallow gritty yellow duplex phase	1.81	52	Shallow gritty yellow duplex soils; jarrah–bullich woodland.
COy	Roe Hills	Collis yellow duplex phase	1.77	59	Gravelly yellow duplex soils; jarrah–marri forest.
HYu	Wilgarup Valleys	Hay upstream phase	1.53	47	Valleys in granitic areas; 20 m relief; rocky slopes; terrace. Yellow duplex soils on slopes; jarrah–marri–yellow tingle forest. Deep sands on terrace; Wattle–paperbark low forest.
LDp	Roe Hills	Lindesay shallow gritty duplex phase	1.63	45	Shallow gritty yellow duplex soils; jarrah–bullich woodland.
MTb	Roe Hills	Mattaband brown gravelly duplex phase	1.64	55	Brown gravelly duplex soils; karri–marri–yellow tingle–jarrah forest.
MTp	Roe Hills, Kent	Mattaband shallow gritty duplex phase	1.72	62	Shallow gritty yellow duplex soils: jarrah woodland.
MTy	Roe Hills	Mattaband yellow duplex phase	1.73	62	Gravelly yellow and yellow duplex soils; jarrah–marri–yellow tingle forest.
MW	Kent	Mallawillup Subsystem	1.61	20	Undulating rises with broad flat swampy depressions. Soils are formed in colluvium and weathered granite. Gravelly soils (bog iron ore) are common.
NYu	Kent	Naypundup upstream valley phase	1.75	67	Low relief (< 20 m) valleys. Saline in some areas. Soils are formed in weathered colluvium from gneiss.
PP	Kent	Perillup Plain Subsystem	1.66	28	Gently undulating plain with some swamps.
QN	Roe Hills, Kent	Quindabellup Subsystem	1.40	60	Shallow, elongate sandy depressions and valley divides. Humus podzols and sandy yellow duplex soils; paperbark woodland.
S1	Roe Hills, Kent	Minor Valleys 1 Subsystem	1.70	61	Valleys in granitic terrain, narrow swampy floor; < 20 m relief. Gravelly yellow duplex soils on smooth flanks; jarrah–marri–karri forest. Peaty soils on narrow floor; wattle low forest.
SC	Kent	Sidcup Subsystem	1.75	31	Narrow shallow drainage depressions; deeply weathered granite; deep sands, grey shallow sandy duplex.
V2	Roe Hills	Major Valleys 2 Subsystem	1.53	47	Valleys in granitic areas; 20–40 m relief; smooth, moderate slopes; narrow terrace.
V3	Roe Hills	Major Valleys 3 Subsystem	1.53	47	

Table A2.3. Soil–landscape subsystem and phase areas – supports Figure 4

	Area within management unit (km^2)			*Upper Denmark (km^2)*
Subsystem	*Perillup*	*Kompup*	*Yate Flat Creek*	
CM	8.3	32.6		40.9
COp	9.1	14.4	1.3	24.8
COy	0.4	0.5		0.9
HYu	17.2		3.0	20.2
LDp			1.1	1.1
MTb	0.8			0.8
MTp	3.7	2.2	1.9	7.8
MTy	2.0			2.0
MW	33.7	9.2	21.5	64.4
NYu	2.0		3.5	5.5
PP	8.9	3.0	17.7	29.6
QN	12.9	3.4	3.7	20.0
S1	6.3		3.8	10.1
SC	1.1		0.2	1.3
V2	2.6	2.6		5.2
V3		7.1		7.1
Total	109.0	75.0	57.7	241.7

Pre-European vegetation complexes. Information on vegetation used in modelling.

A vegetation complex is the mix of native vegetation that characterised the area prior to European settlement. The custodian for the digital data is the Department of Conservation and Land Management. The metadata date is 24/03/1998 and the digital capture of vegetation complexes is from 1:50 000 source data, supplemented with 1:10 000 vegetation survey sites. Vegetation attributes were derived and classified from survey and samples. The following notes extracted from Mattiske and Havel (1998) describe the vegetation complexes for the codes shown on Figure A2.1. Table A2.4 lists the prevalence of these complexes within the Upper Denmark catchment and the management units.

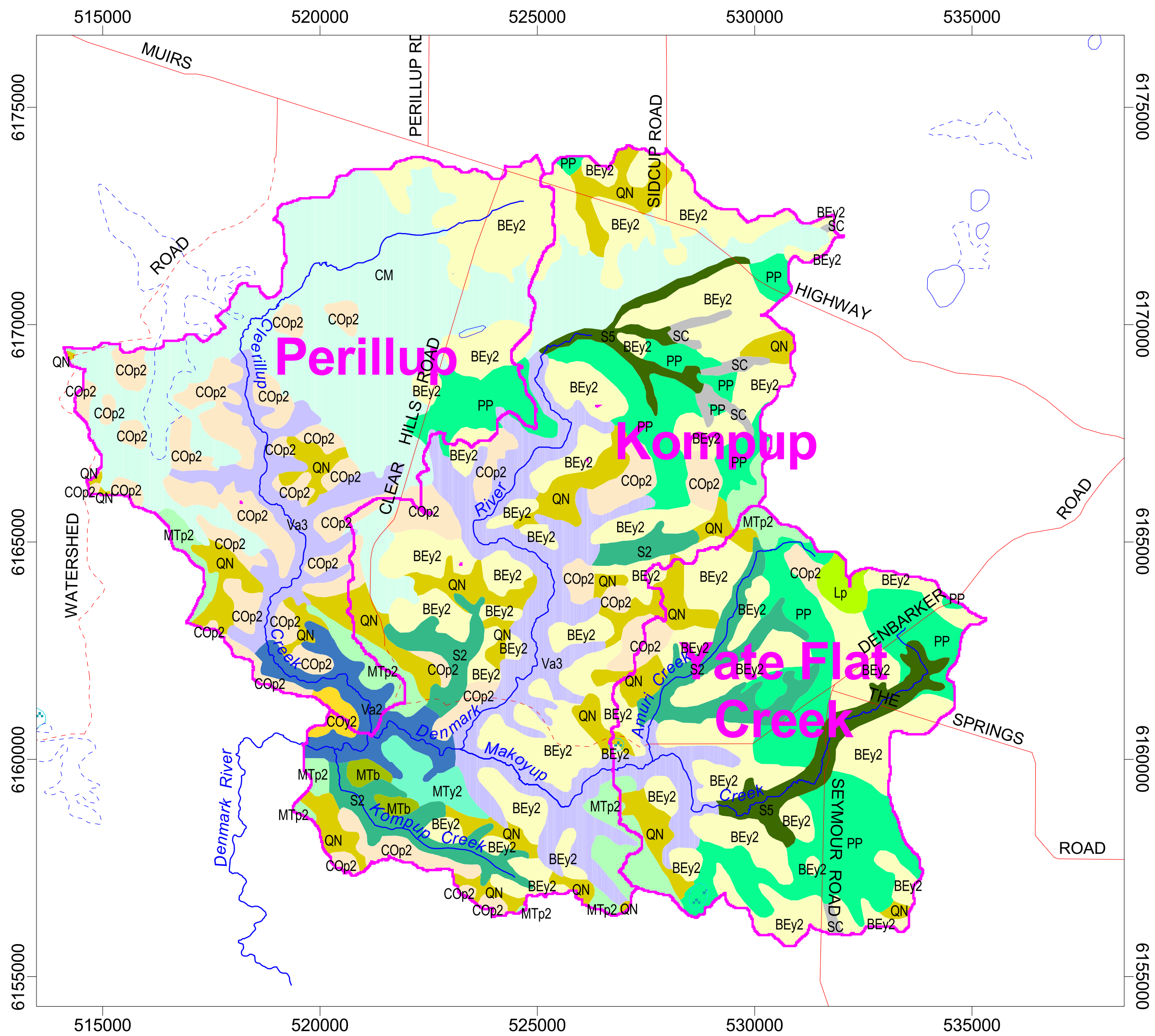
Table A2.4 Areas of pre-European vegetation complexes

The distribution of these complexes is mapped on Figure A2.1 Vegetation classes

Complex and symbol	*Location and description*	*Area within management unit*			*Total area in Upper Denmark*
		Perillup (km^2)	*Kompup (km^2)*	*Yate Flat Creek (km^2)*	*(km^2)*
	Darling Plateau— Uplands				
Bevan 2 (BEy2)	Open forest of *Eucalyptus marginata* subsp. *marginata-Corymbia calophylla–Banksia grandis* on undulating uplands in humid and subhumid zones.	9.1	32.9	21.3	63.3
Collis 2 (COp2)	Low woodland of *Eucalyptus marginata* subsp. *marginata* on low granite rises in the humid zone.	14.5	8.9	1.1	24.5
Collis 2 (COy2)	Open forest of *Eucalyptus marginata* subsp. *marginata–Corymbia calophylla–Banksia grandis–Allocasuarina fraseriana* on low hills in the humid zone.	0.4	0.3		0.7
Mattaband (MTb)	Mixture of tall open forest of *Eucalyptus diversicolor–Corymbia calophylla* and woodland of *Eucalyptus marginata* subsp. *Eucalyptus marginata–Corymbia calophylla–Agonis flexuosa* on small hills arising above the coastal plain with some outcrops in hyperhumid and perhumid zones.		0.8		0.8
Mattaband 2 (MTp2)	Open forest of *Eucalyptus marginata* subsp. *marginata–Corymbia calophylla* on low hills with scattered granite on slopes in the humid zone.	2.1	3.8	2.0	7.9
Mattaband 2 (Mty2)	Mixture of open forest of *Eucalyptus marginata* subsp. *Marginata–Corymbia calophylla–Banksia grandis* on hills in the humid zone.		1.9		1.9
Lindesay (Lp)	Open forest of *Eucalyptus marginata* subsp. *marginata–Corymbia calophylla – Eucalyptus megacarpa* on steep slopes of major granite hills in perhumid and humid zones.		1.1	1.1	
Perillup (PP)	Open forest to woodland of *Corymbia calophylla–Eucalyptus marginata* subsp. *marginata* on low undulating hills and low woodland of *Melaleuca preissiana* on depressions in humid to semiarid zones.	3.0	8.0	16.4	27.4

Table A2.4 Areas of pre-European vegetation complexes *(continued)*

Complex and symbol	*Location and description*	*Area within management unit*			*Total area in Upper Denmark*
		Perillup (km²)	*Kompup (km²)*	*Yate Flat Creek (km²)*	*(km²)*
	Darling Plateau — Depressions and Swamps on Uplands				
Camballup (CM)	Mosaic of woodland of *Eucalyptus marginata* subsp. *marginata–Corymbia calophylla* on slopes, and woodland of *Eucalyptus occidentalis–Melaleuca cuticularis–Melaleuca rhaphiophylla*, low woodland of *Melaleuca preissiana–Banksia littoralis* and tall shrublands of *Melaleuca viminea* on broad depressions in humid to semiarid zones.	35.4	8.7		44.1
Quindabellup (QN)	Low woodland of *Eucalyptus marginata* subsp. *marginata* on slopes and low open woodland of *Banksia littoralis–Melaleuca preissiana* on broad depressions in perhumid and humid zones.	3.4	12.1	3.6	19.1
Sidcup (SC)	Woodland of *Eucalyptus marginata* subsp. *marginata–Nuytsia floribunda* on slopes and woodland of *Melaleuca preissiana – Banksia littoralis* on lower slopes in humid and subhumid zones.		1.4	0.2	1.6
	Darling Plateau — Valleys				
Granite Valleys (S2)	Mixture of woodland of *Eucalyptus rudis*, woodland of *Eucalyptus occidentalis* on valley floor and woodland of *Eucalyptus decipiens* and *Eucalyptus marginata* subsp. *marginata* on slopes in humid to semiarid zones.		6.8	5.0	11.8
Narrow Valleys (S5)	Woodland of *Corymbia calophylla* on shallow gullies in humid to semiarid zones.		2.4	4.1	6.5
Granite Valleys (Va2)	Open forest of *Corymbia calophylla–Eucalyptus marginata* subsp. *marginata* on slopes, low forest of *Allocasuarina decussata – Banksia seminuda* on valley floors in perhumid to subhumid zones.	2.5	2.6		5.1
Granite Valleys (Va3)	Open forest of *Corymbia calophylla–Eucalyptus marginata* subsp. *marginata* with some *Eucalyptus wandoo* on slopes and *Melaleuca rhaphiophylla* on valley floors in the humid zone.	7.4	17.2	2.9	27.5
	Total	77.8	107.8	57.7	243.3



Legend

Vegetation classification by Mattiske

- Bevan 2 (BEy2)
- Collis2 (COp2)
- Collis2 (COy2)
- Mattaband (MTb)
- Mattaband 2 (MTp2)
- Mattaband 2 (MTY2)
- Camballup (CM)
- Lindesay (Lp)
- Perillup (PP)
- Quindabellup (QN)
- Sidcup (SC)
- Granite Valleys (S2)
- Narrow Valleys (S5)
- Granite Valleys (Va2)
- Granite Valleys (Va3)

- Lake; permanent
- Lake; intermittent
- Swamp
- Management unit boundary
- River
- Road

Figure A2.1 Pre-European vegetation classes

0 2 4 6 8 Kilometres

N

Report: WRT 30

Department of Environment

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Date: 20/11/03

More information on Hydrogeology (Section 2.6)

The following table shows the prevalence of the hydrogeological units mapped on Figure 5.

Table A2.5 Areas of hydrogeological units

*Hydro-geological unit**	*Area within management unit* *Perillup (km²)*	*Kompup (km²)*	*Yate Flat Creek (km²)*	*Area Upper Denmark (km²)*
Pg	35.5	62.5	52.1	150.1
Pgo	9.4	19.3	5.5	34.2
Pn	32.1	25.5		57.6
Pno	1.0	0.3		1.3
Total	78.0	107.6	57.6	243.2

* The codes for the hydrogeological units are described as:
Pg: Granitoid rock, porphyritic and even-grained subsurface; generally weathered to clayey sand.
Pgo: Granitoid rock outcrop.
Pn: Granitoid gneiss, minor metamorphic rock and quartzite subsurface; generally weathered to clay.
Pno: Granitoid gneiss outcrop.

Additional information for Vegetation scenes from Landsat (Section 2.8)

Figures 7 and 8 show Landsat scenes for summer 1988 and 2002.

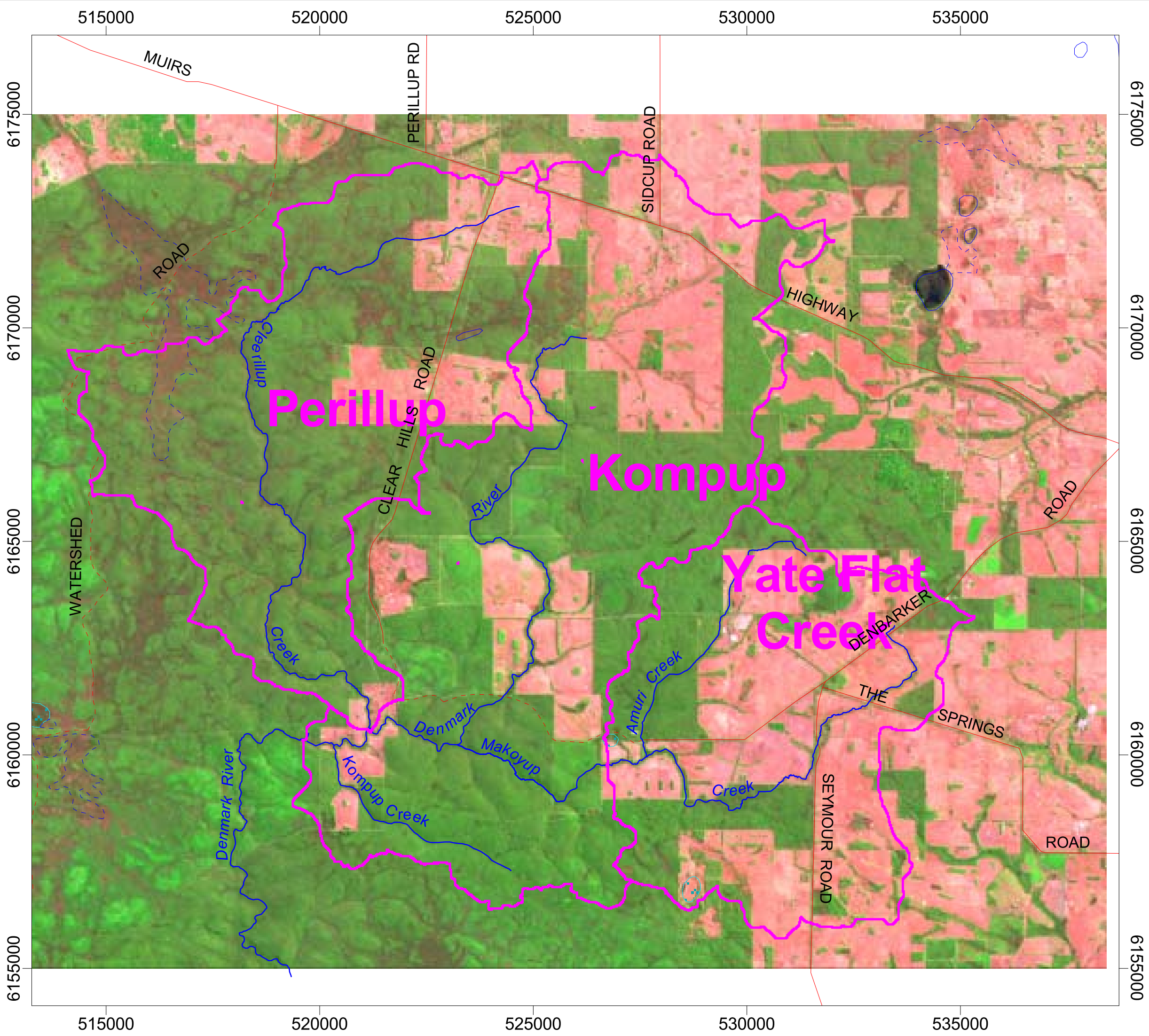
Four additional scenes — the summers of 1995, 1998, 1999, 2000 — are shown here.

In the 1995 scene, some plantations associated with the Denmark Integrated Catchment Management project have appeared. Some new clearing is visible outside the Denmark River catchment. Plantations that are part of the regional woodchip industry can first be seen on the 1998 scene. The remaining scenes show the rapid growth of these plantations.

See Section 4 for further discussion of the increase in plantations, especially Figure 12 which shows the progression of plantations within the catchment. Scenes are also available for 1990, 1992 and 1994.

Modelling uses reflectances and greenness in Landsat scenes for modelling. False colours of blue, green and red were assigned to the reflectances of Bands 3, 4 and 5 respectively. In the resulting image, the interpretation was that the brighter the green, the more vigorous and dense is the tree cover. Cleared land appears as a range of pinks to greys. One point of data every 25 m on the ground represents an average of vegetation conditions around that point.

The tree density is expressed by a “greenness” index derived using Bands 3, 4 and 5. In the derivation, each pixel is “unmixed” on the assumption that the land surface comprised a mixture of four components: shade, bare clayey sand, green leaves, and dead vegetation. The method requires assumed values of reflectances for pixels comprising purely one of each of these components. Because the reflectances in all the scenes have been rescaled to a standard, the same values for pure components can be used in any scene. Pixels containing significant areas of other components, such as open water or pure clay, can be identified by classification, and the greenness index is recognised as invalid in these pixels. Classification that uses the greenness index as well as the original reflectances produces a map of areas of pasture, and also a map of the greenness index produced by remnant trees. In the tree greenness map, pixels with no trees have a value of zero.



Legend

Land use (March 1995)

- Native vegetation
- Pasture/cleared area
- Lake
- Management unit boundary
- Lake; permanent
- Lake; intermittent
- Swamp
- River
- Road

Figure A2.2 Landsat TM scene of Upper Denmark, March 1995 (Summer 1995)

0 2 4 6 8 Kilometres

N

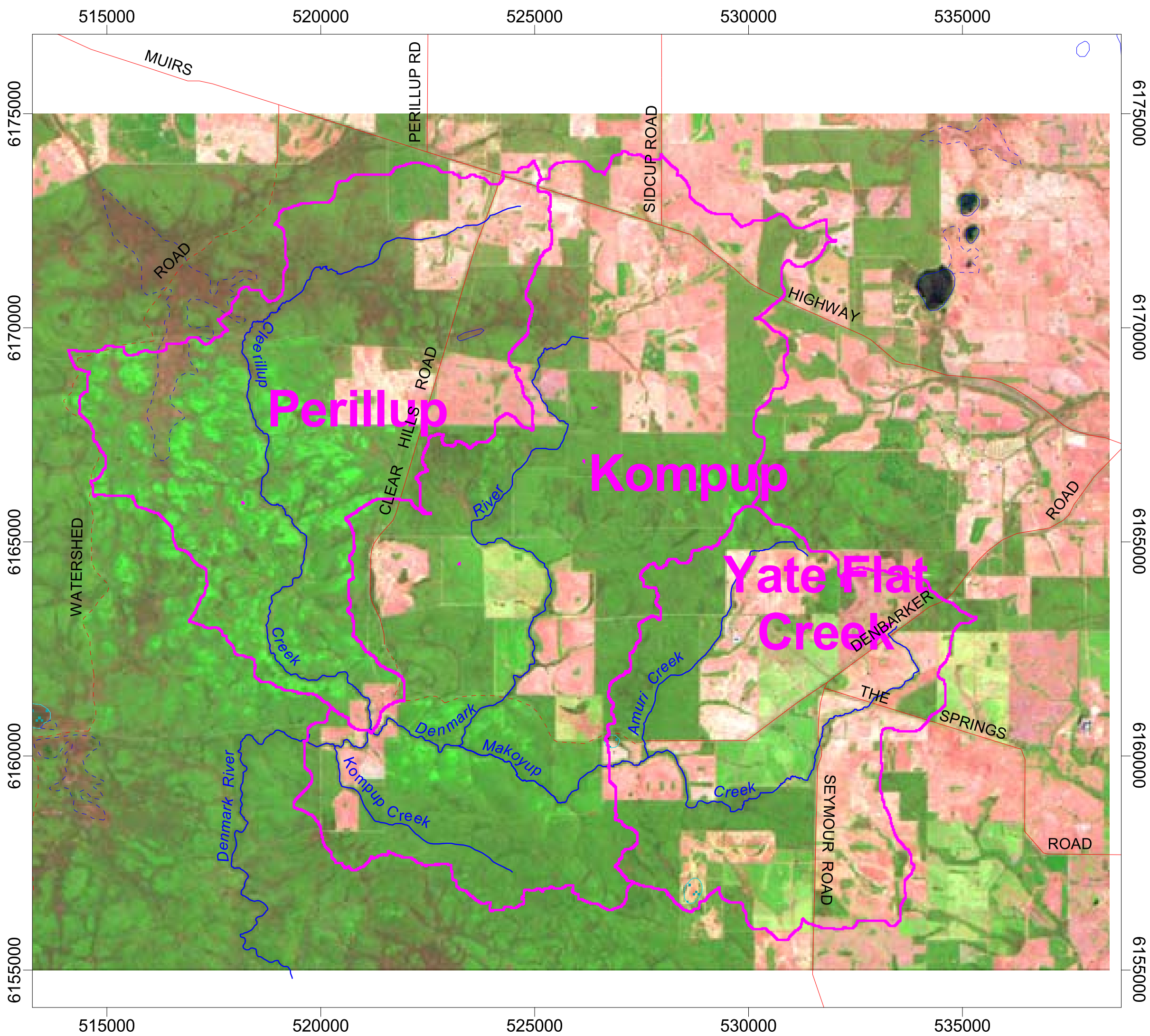
Report: WRT 30

Department of Environment

File name: SE.LU.26028.0056. A4denmark_v3.apr

Custodian: Renee Dixon

Date: 20/11/03



Legend

Land use (January 1998)

- Native vegetation
- Pasture/cleared area
- Lake
- Management unit boundary
- Lake; permanent
- Lake; intermittent
- Swamp
- River
- Road

Figure A2.3 Landsat scene of Upper Denmark, January 1998 (Summer 1998)

0 2 4 6 8 Kilometres

N

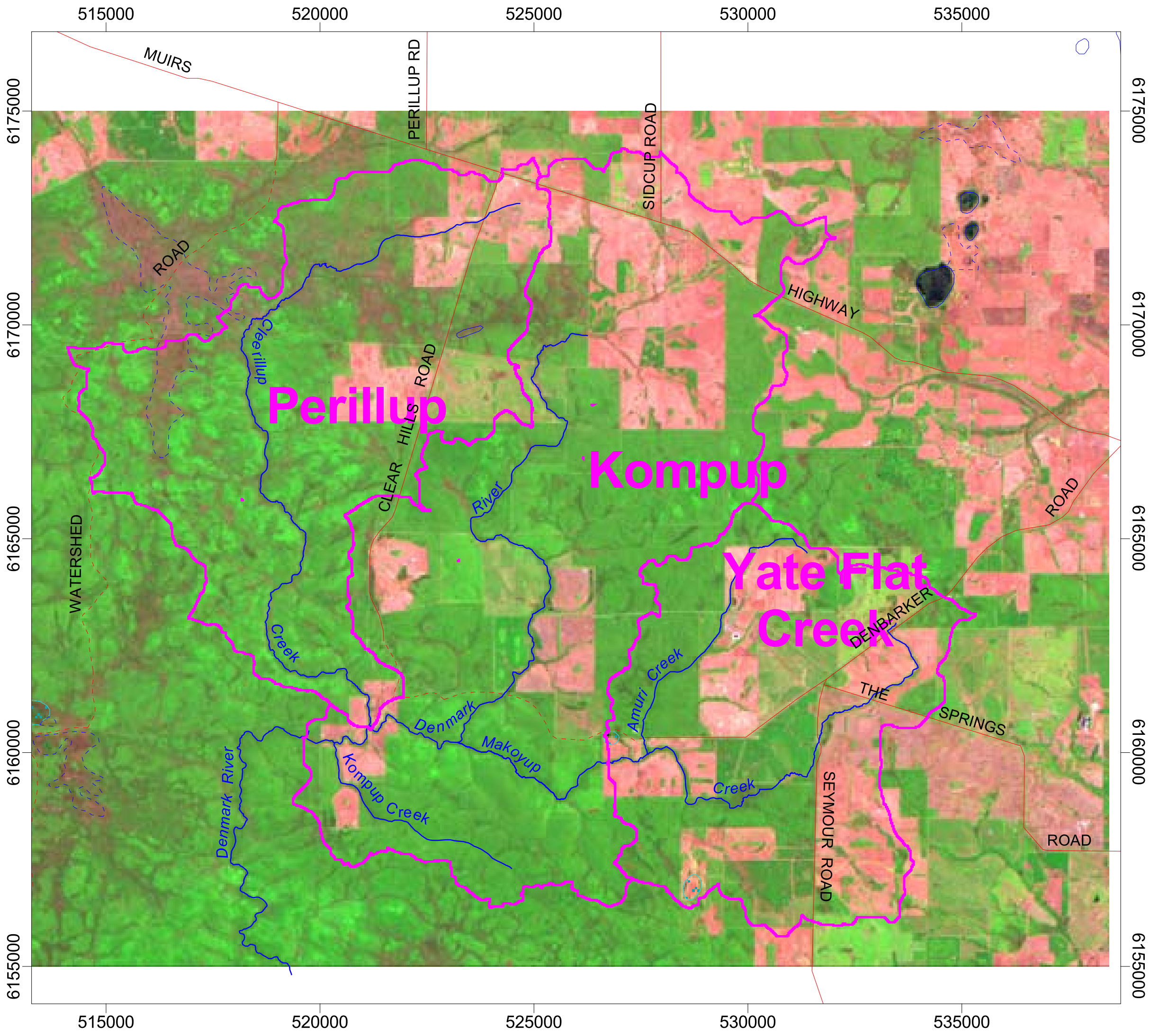
Report: WRT 30

Department of Environment

File name: SE.LU.26028.0056. A4denmark_v3.apr

Custodian: Renee Dixon

Date: 20/11/03



Legend

Land use (January 1999)

- Native vegetation
- Pasture/cleared area
- Lake
- Management unit boundary
- Lake; permanent
- Lake; intermittent
- Swamp
- River
- Road

Figure A2.4 Landsat scene of Upper Denmark, January 1999 (Summer 1999)

0 2 4 6 8 Kilometres

N

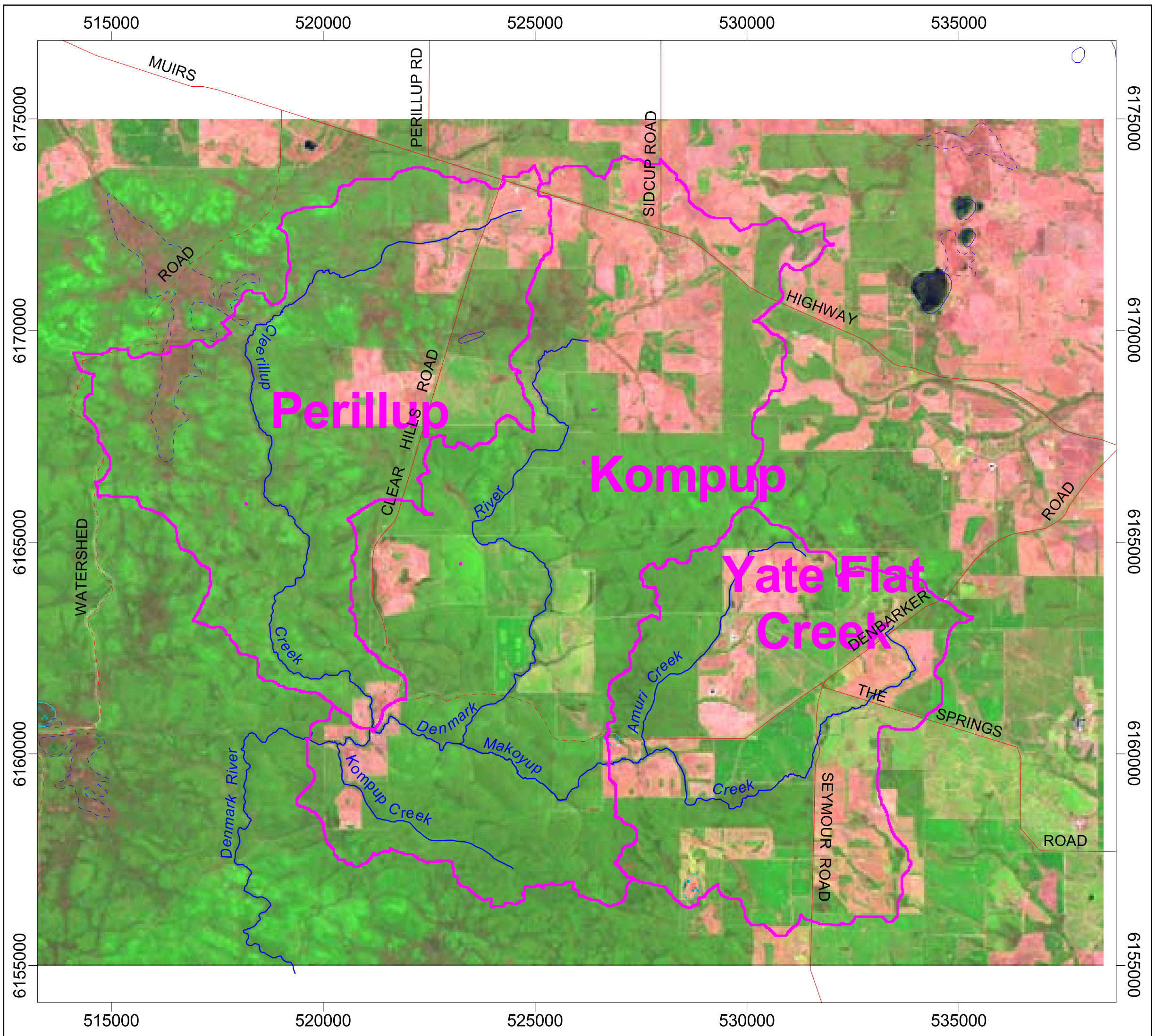
Report: WRT 30

Department of Environment

File name: SE.LU.26028.0056. A4denmark_v3.apr

Custodian: Renee Dixon

Date: 20/11/03



Legend

Land use (February 2000)

- Native vegetation
- Pasture/cleared area
- Lake
- Management unit boundary
- Lake; permanent
- Lake; intermittent
- Swamp
- River
- Road

Figure A2.5 Landsat scene of Upper Denmark, February 2000 (Summer 2000)

0 2 4 6 8 Kilometres

N

Report: WRT 30

Department of Environment

File name: SE.LU.26028.0056. A4denmark_v3.apr

Custodian: Renee Dixon

Date: 20/11/03

Appendix 3 Flow and salinity characteristics

The following information supports Section 3: Flow and salinity characteristics.

More on Section 3.1: Streamflow and salinity records

Table A3.1 Gauged catchment areas within management units

		Gauged catchment areas ((km^2)				
Gauging Station	*Gauging Station No.*	*Perillup*	*Kompup*	*Yate Flat Creek*	*Between Kompup and Mt Lindesay*	*Total Mt Lindesay*
Lindesay Gorge	603 002	77.9	107.5	57.5	226	469
Kompup	603 003	77.9	107.5	57.5		243
Pardelup*	603 008					
Barrama*	603 009					
Willmay*	603 010					
Pipehead Dam	603 014	77.9	107.5	57.5	320.0	563
Mt Lindesay	603 136	77.9	107.5	57.5	285	528
Amarillup Swamp	603 172			20.3		20.3
Clear Hills	603 173	77.9	97.2	57.5		233
Perillup Brook	603 177	76.4				76.4
Yate Flat Creek	603 190			57.5		57.5

* *Experimental subcatchments in Upper Hay catchment.*

More on Section 3.2.1

Table A.3.2 Clearing history of the Denmark Recovery Catchment

	Management unit			*Total in*	*Upper Denmark*	*Total*
	Perillup	*Kompup*	*Yate Flat Creek*	*Upper Denmark*	*to Mt Lindesay catchment*	*Mt Lindesay*
Management unit (MU) area (km^2)						
	78	107.7	57.6	243.3	281.7	525
Clearing increment to year (km^2)						
1946	1.0	4.6	1.4	7.0	5.1	12.1
1957	6.1	3.0	25.1	34.2	4.6	38.8
1965	1.7	6.2	1.3	9.2	-2.2	7.0
1973	1.8	15.5	5.4	22.7	6.4	29.1
1979	1.1	3.1	0.8	5.0	1.6	6.6
1988	0.6	0.9	1.3	2.8	0	2.8
Clearing accumulated to year (km^2)						
1946	1.0	4.6	1.4	7.0	5.1	12.1
1957	7.1	7.7	26.4	41.2	9.7	50.9
1965	8.7	13.8	27.7	50.2	7.5	57.7
1973	10.5	29.3	33.1	72.8	13.9	86.7
1979	11.5	32.5	33.9	77.9	15.5	93.4
1988	12.2	33.3	35.2	80.7	15.5	96.2
Areas regenerated (km^2)						
1965	0.8	0	0	0.8	2.2	3.0
1984	0	5.9	0	5.9	0	5.9
Effective maximum clearing (1979 + Kompup regeneration) (%)						
	11.5	38.4	33.9	83.8	15.5	99.3
Accumulated clearing of MU area (%)						
1946	1	4	2	3	2	2
1957	9	7	46	17	3	10
1965	11	13	48	21	3	11
1973	13	27	58	30		17
1979	15	30	59	32	5	18
1988	16	31	61	33	5	18
Effective maximum clearing (1979 +Kompup regeneration) (%)						
	15	36	59	34	5	19

The following table assigns the areas of plantations visible from Landsat to management units.

Table A3.3a Tree planting in the Upper Denmark catchment

Plantation areas visible by Landsat	*Management unit*			*Total area in Upper Denmark*
	Perillup	*Kompup*	*Yate Flat Creek*	
Plantation increment to year (km²)				
1990	0	0.1	0.1	0.2
1992	0	0.1	0.1	0.2
1994	0	0.7	0.3	1.0
1995	0	0.7	0.3	1.0
1998	0	3.2	6.9	10.1
1999	1.9	1.7	3.2	6.8
2000	0.5	2.8	2.7	6.0
2002	2.7	1.9	4.6	9.2
Accumulated plantations to year (km²)				
1990	0	0.1	0.1	0.2
1992	0	0.2	0.2	0.4
1994	0.1	0.8	0.5	1.4
1995	0.1	1.5	0.8	2.4
1998	0.1	4.7	7.7	12.5
1999	2.0	6.4	10.9	19.3
2000	2.5	9.1	13.6	25.2
2002	5.2	11.1	18.2	34.5
Maximum effective cleared area occupied by plantations (%)				
1990	0	0	0	0
1992	0	0	0	1
1994	0	2	2	2
1995	1	4	2	3
1998	1	12	24	18
1999	16	17	34	27
2000	20	24	42	36
2002	42	29	57	49

Table A3.3b. Remaining cleared areas in the Upper Denmark catchment

Plantation areas	*Management unit*			*Upper*
visible by Landsat	*Perillup*	*Kompup*	*Yate Flat Creek*	*Denmark*
Area remaining clear (km²)				
1990	12.2	31.7	32.1	76.0
1992	12.2	31.6	32.0	75.8
1994	12.2	30.9	31.7	74.8
1995	12.2	30.3	31.3	73.8
1998	12.2	27.2	24.5	63.8
1999	10.3	25.4	21.2	56.9
2000	9.8	22.6	18.6	51.0
2002	7.1	20.7	14.0	41.8
Management unit remaining cleared (%)				
1990	16	29	56	31
1992	16	29	56	31
1994	16	29	55	31
1995	16	28	54	30
1998	16	25	43	26
1999	13	24	37	23
2000	13	21	32	21
2002	9	19	24	17

The formula for calculating stream salinity from streamflow supports Section 3.3: Streamflow and salinity trends.

Before calculating trends in annual stream salinity daily for all the gauging stations, streamflow was calculated based on the following method.

Stream salinity is inversely proportional to streamflow. During the period of high runoff the average stream salinity tends to be low and, during period of low runoff, the average stream salinity tends to be higher. The relationship between salinity sample (S_s) and associated daily streamflow (F_d) can be described as:

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

In the above equation the values of the two parameters (a', b') were determined by interpolation method. Five sample points were taken at a particular time to develop the relationship. As the relationship between the salinity and streamflow changes in response to significant changes in land use, the values of these two parameters were different with different sets of interpolations. From Equation 1, the daily salinity for the period without continuous recording was calculated for all the gauging stations. The daily salinity and streamflow records were then summed to calculate the annual flow , salinity (S) and salt load (L). The annual rainfall (R) for all subcatchments was also calculated.

The annual relationships between (i) streamflow and salinity and (ii) streamflow and rainfall were developed for all gauging stations. For this, nine years of data were taken as one set, and values of the parameters determined. The values of these two parameters also changed with time owing to changes in land use of the catchment. The annual relationships can be described as:

$$S = a'' F^{b''} \qquad (2)$$

$$F = c + dR \qquad (3)$$

Based on the parameters of the above two equations, annual streamflow for the annual mean rainfall (R) for the duration of the trend analyses (1980–95) were determined:

$$F_r = c + dR \qquad (4)$$

The annual stream salinity at mean annual streamflow for the duration of the trend analysis (F) and mean annual rain were calculated as:

$$S = a'' F^{b''} \qquad (5a)$$

$$S_r = a'' F_r^{\,b''} \qquad (5b)$$

The annual salt load at mean flow (L) and at mean rain (L_r) were calculated as:

$$L = SF \qquad (6a)$$

(6b)

The annual stream salinity at mean flow and mean annual rainfall (S_r) obtained from Equation 5 were plotted against annual time step. A new linear regression equation was developed for the periods 1990–90 and 1992–95. The slope of the regression equation is taken as rate of change in annual stream salinity.

Groundwater trend analysis of piezometers in experimental catchments – additional information for Section 3.6.2

The following is a description of method (ii) mentioned in 3.6.2.

Trends in groundwater levels were checked by comparison with piezometer records at Willmay. The following procedure was used.

1. Piezometer 60319186 at Willmay was chosen to be the base record against which other records were compared, because it had a good quality record with significant seasonal fluctuation and no apparent long-term trend.

2. Other piezometer records were then compared to the base record. The end of 1993 was chosen to be the end of the period when land use was unchanged in all catchments (time 'zero'). Time-series graphs of the base record and a piezometer for which trends were to be calculated (the 'test record') were examined and, if a consistent difference in the timing of seasonal fluctuations was evident, the graph of the base record was shifted in time to align the principal peaks and troughs. The shifts varied from zero up to 11 weeks for different piezometers. Then the vertical difference between the graphs was calculated at each point in time when there was an observation in the 'test record' and plotted as a new time-series graph. Integration of the difference graph over time enabled the calculation of the accumulated difference to be made at the end of each year. From the yearly figures, trends over two or more years could be estimated by using regression to fit a quadratic equation to the accumulated differences, namely:

   $$(\text{accumulated difference}) = a\,(\text{time})^2 + b\,(\text{time}) + c$$

   where a, b and c are coefficients found by regression.

   The trend in m/year is twice the coefficient of the time squared term of the equation, with time expressed in years, i.e:

   $$(\text{trend}) = 2a$$

   where a is from equation for accumulated difference.

   This method uses all the available data to estimate the trends while simplifying the calculation of the regression equations. Trends were estimated for the period to the end of 1993 and for the period after that to the end of records. The results are shown on the detailed maps of each catchment in Figures 18, 19 and 20. Computed trends less than about 0.050 m/yr (50 mm/yr) should generally not be considered significant.

3. To give a visual appreciation of the comparison of the time series of the groundwater levels, the records were transformed to more closely coincide with one another over the period before trees were planted. The 'normalisation' process rescaled the test record by the ratio of standard deviations of the base record and the test record, calculated over the preplanting period, and then moved the test record vertically to coincide with the base record at the end of 1993. The resulting graphs are shown in Figures A3.1, A3.3 and A3.5.

4. The graph of accumulated differences before and after the end of 1993 was calculated from the normalised records and is shown in Figures A3.2, A3.4 and A3.6. In these graphs, a period of constant gradient is a period when the test record is displaced a constant depth from the base record. A period when there is a linear trend in the difference between the test and base records produces curvature in the accumulated difference graphs: curvature that is concave down shows a declining trend, while concave upwards shows a rising trend. Short-term fluctuations should be ignored as they are produced by seasonal variability and data imprecision caused by lack of continuous level recording.

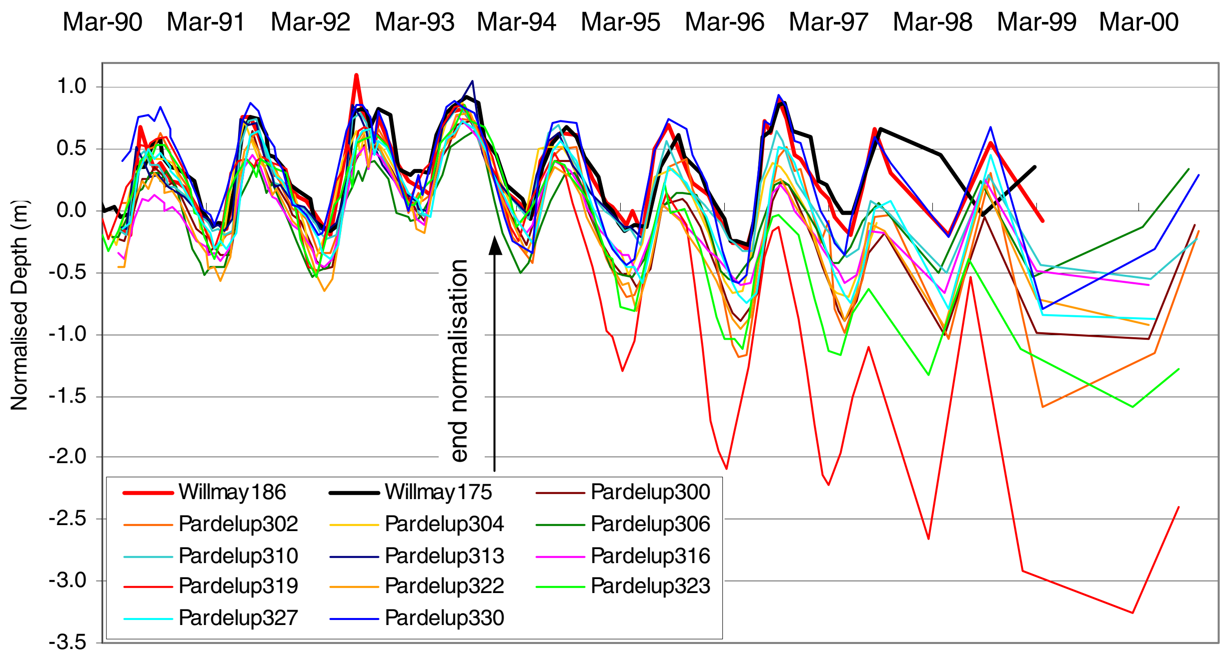


Figure A3.1 Normalised piezometer records from Pardelup compared with selected Willmay peizometers

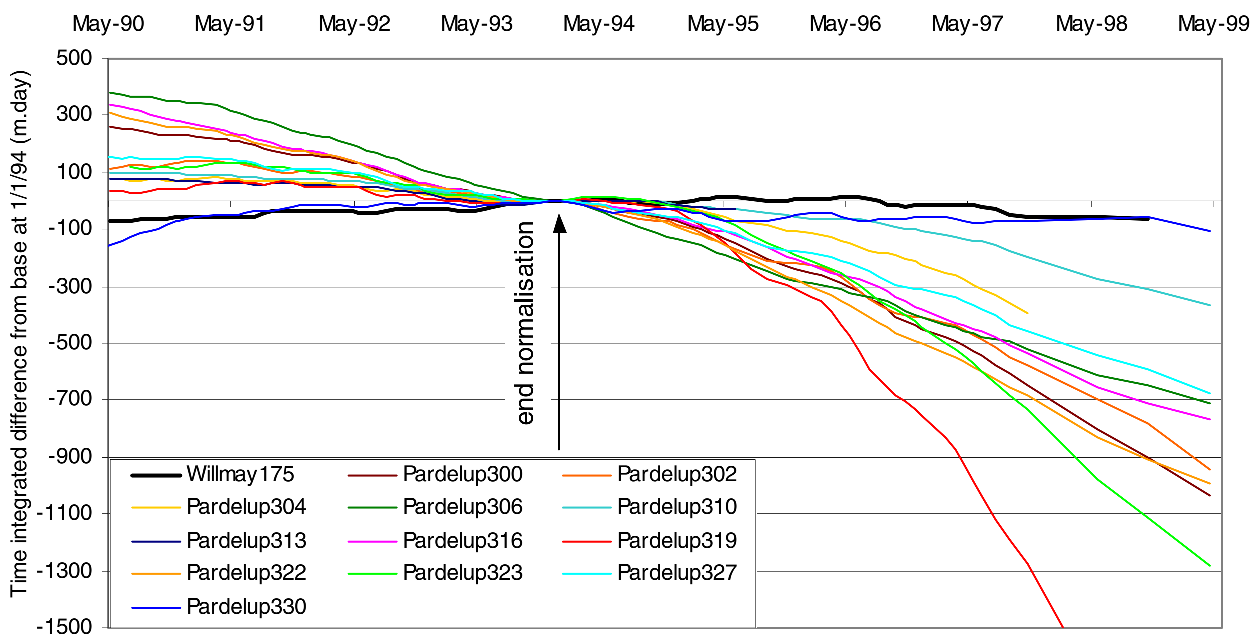


Figure A3.2 Accumulated differences of normalised piezometer records from Willmay 186 (Pardelup)

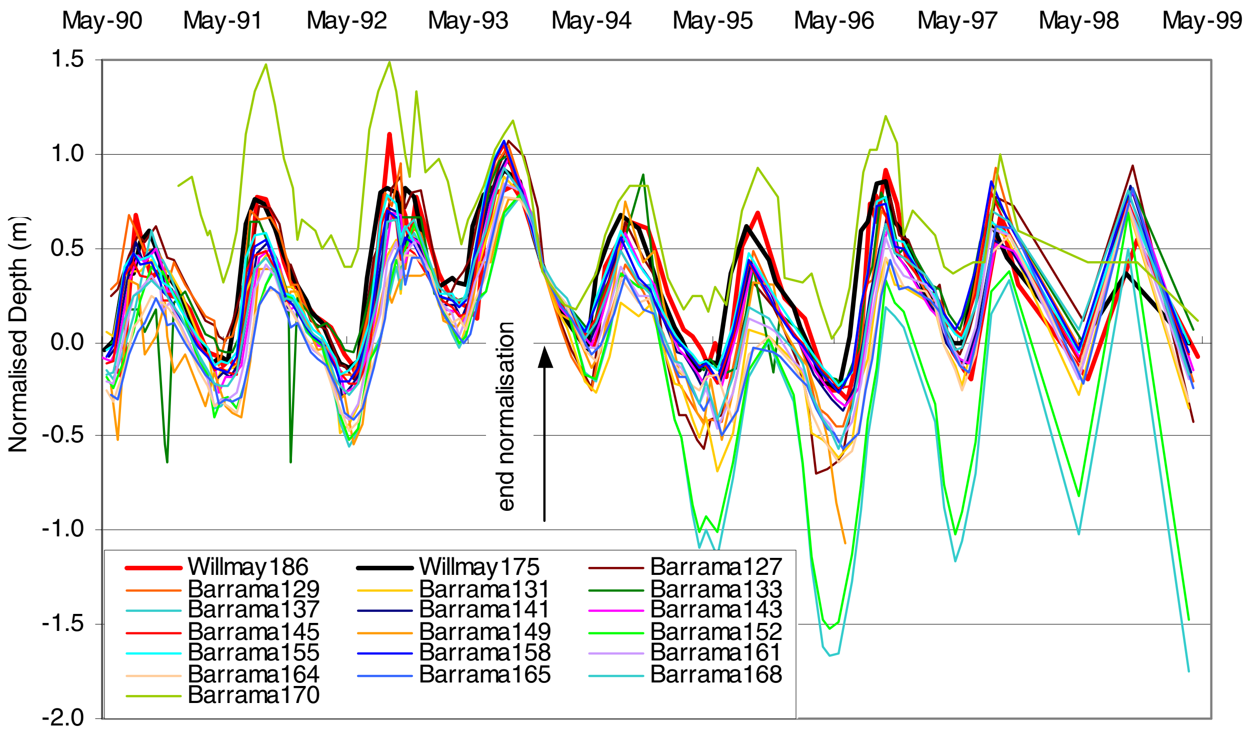


Figure A3.3 Accumulated differences of normalised piezometer records from Willmay 186 (Barrama)

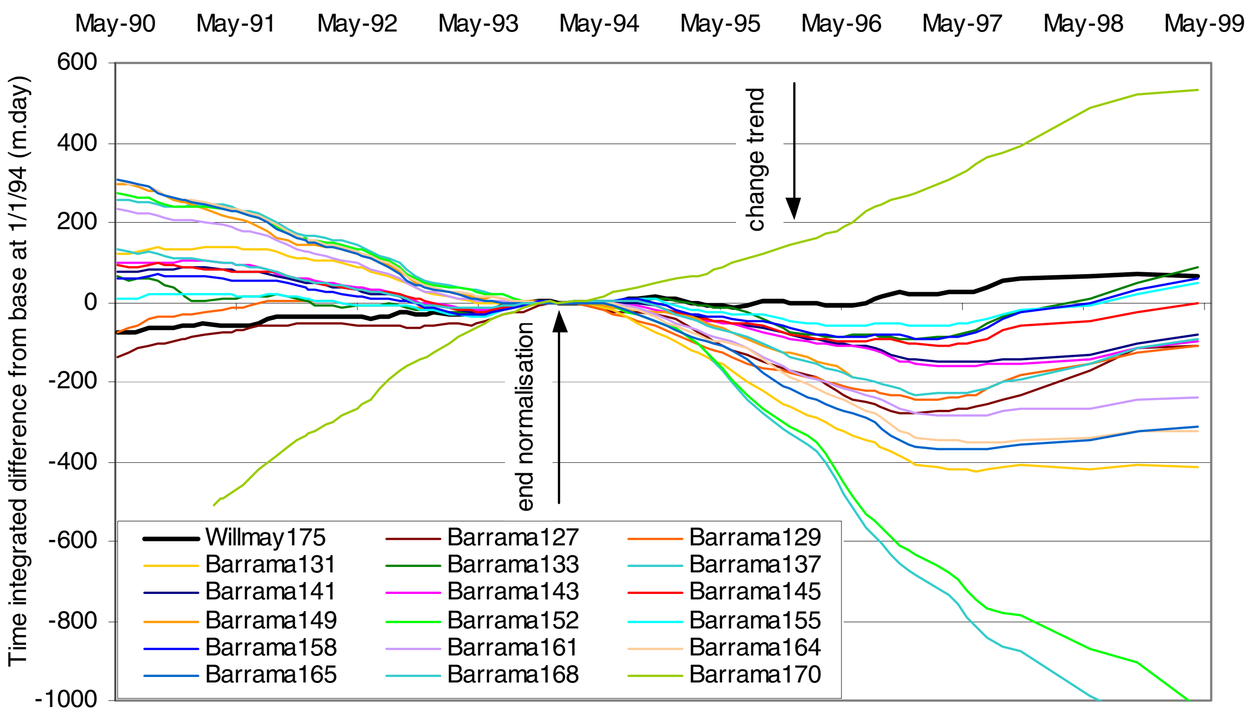


Figure A3.4 Accumulated differences of normalised piezometer records from Willmay 186 (Barrama)

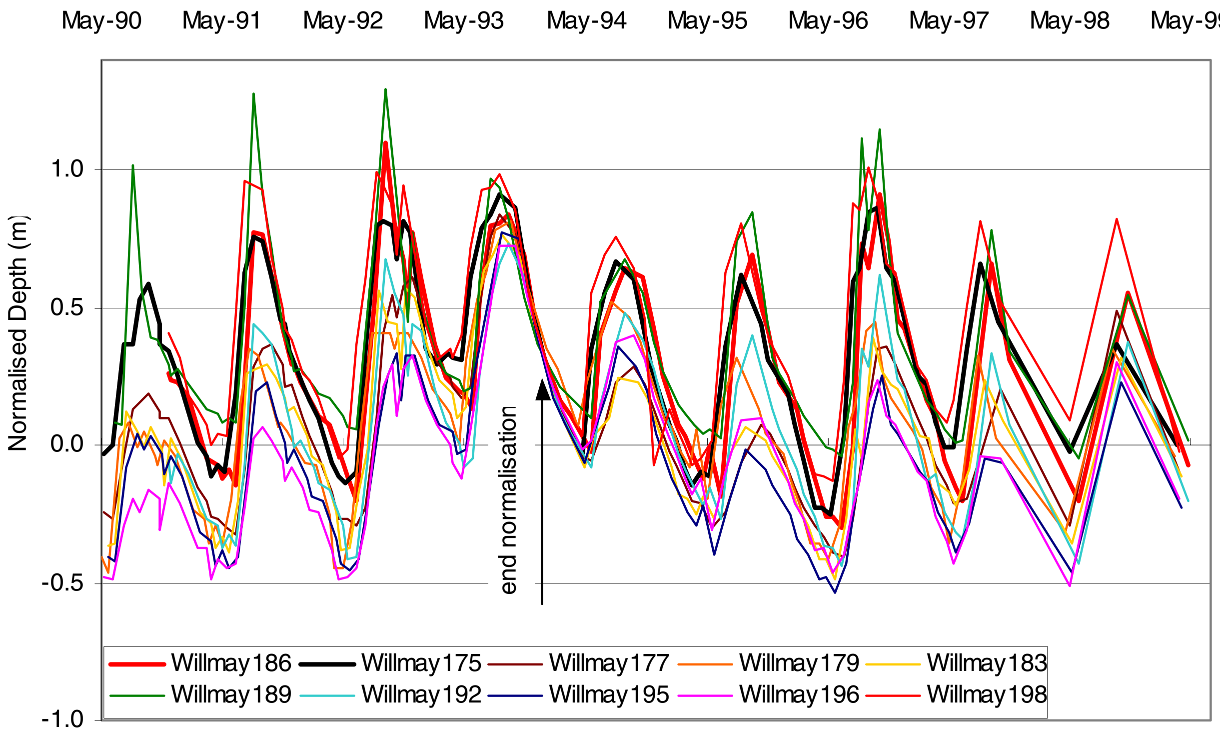


Figure A3.5 Normalised piezometer records from Willmay

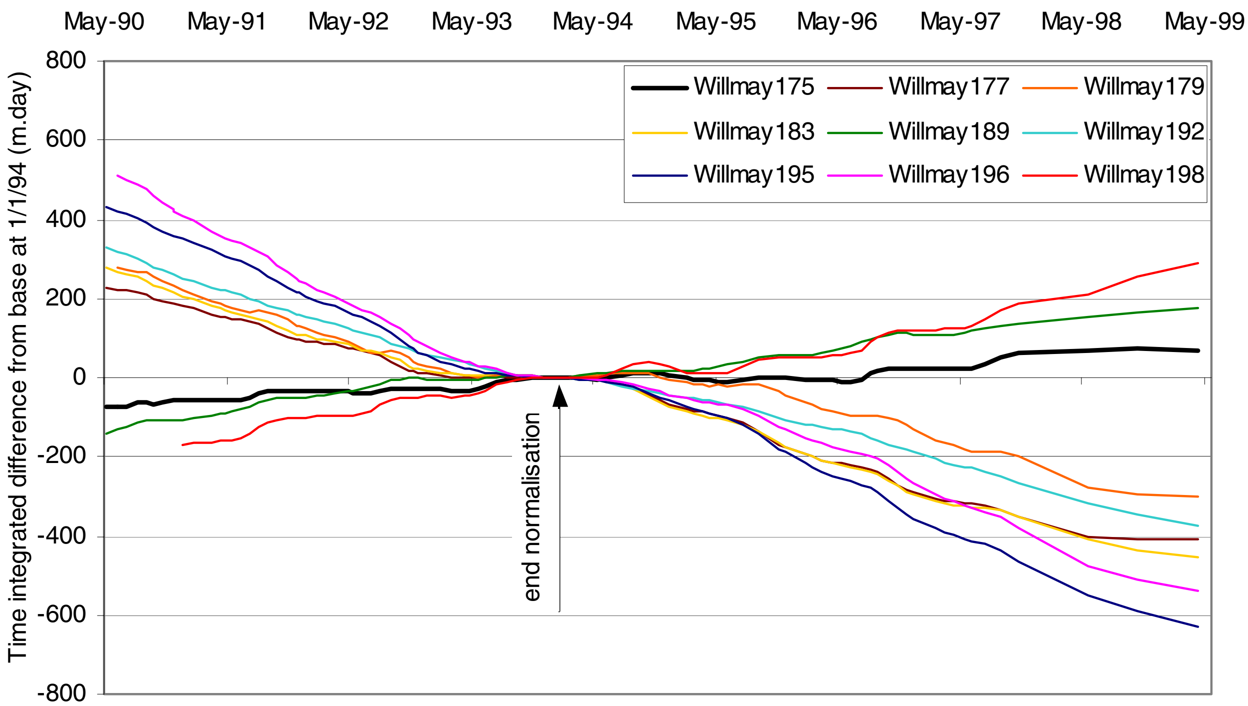


Figure A3.6 Accumulated differences of normalised piezometer records from Willmay 186 (Willmay)

Appendix 4 Catchment modelling

4.2.1 Pardelup catchment

The MAGIC model was applied to the Collie Recovery Catchment in order to develop management options (Mauger et al. 2001). The following further modifications were made to the model to allow comparison with actual gauging station records instead of the normal procedure of simulating an average rainfall year in the steady state and comparing the output with mean annual estimates based on gauging records.

a) *Initial conditions* The initial soil water storage values were taken from the final soil water storage values of a steady-state run of the model using the 1988 vegetation mapping. The steady-state run also determined the first year rates of gain or loss ('net gain') of deep groundwater at each cell of the model. At the end of each simulation year, the rates of net deep groundwater gains were updated from the simulation of the year just finished, and the new rates were used in the simulation of the following year.

b) *Monthly data* The rainfall for each month was read from an additional data file instead of being the standard average monthly values. The net runoff produced by the model each month was also reported to allow comparison with monthly gauged records.

c) *Vegetation variation with time* The run commenced in September 1988 using the 1988 Landsat scene to define vegetation cover. The first available Landsat scene that could detect the trees after planting was March 1995. After the planting in autumn 1993, vegetation was updated annually in September at the start of the next year's simulation. When the run reached September 1993, the vegetation was set to be the average of the 1988 and 1995 Landsat scenes — to account for tree growth in the first year. The vegetation was set to the March 1995 view in September 1994. Landsat scenes were then available for January 1998 and February 2000. These scenes were used at the prior September, and other Septembers were interpolated between the preceding and succeeding scenes.

d) *Extended rainfall* There were no rainfall records available after December 1998. Therefore, from January 1999, the average rainfall for the month of the year was used in each month. September 1999 was the last time a change was made to the vegetation. When the simulation reached September 2000, the model was run for one more year at average rainfall to produce a year that was close to steady-state conditions.

e) *Salt calibration* Deep groundwater salinity was well mapped from the piezometer network in the catchment. Thus the model's output of salt in deep groundwater discharge was well defined. Calibration with the salt load recorded at the gauging station was achieved by effectively altering the vertical permeability of the clay. The model has two parameters based on this permeability: one is the 'limiting rate for recharge to deep groundwater', and the other is the clay permeability that resists discharge of deep groundwater. If the limiting rate is reduced, then the total recharge is reduced and, consequently, the total discharge and salt load. If the clay permeability is reduced, then the higher head required for discharge causes the discharge to be spread over a larger area. This area becomes unavailable for recharge, and the reduced recharge leads to reduced discharge.

The monthly streamflow generated by the model was compared with the actual record obtained from the Pardelup catchment (Fig. A4.1). Records before 1991 should be ignored because of possible problems in operating the gauging station in its early years and because the model could still be under the influence of initial conditions. The model reports higher streamflow in early winter months because it does not have a process to delay the drainage of surface water to the gauging station in the current month. This is because the model normally reports only annual totals. On flat areas (< 1% slope) where significant delays could be expected, all the runoff accumulated there from the start of the year is assumed to be available for surface evaporation. The total for the year may therefore decline in later months, which will then be reported as a negative streamflow for that month. This compensates for the early over-reporting. Allowing for the delay effect, the magnitude and timing of generated streamflow with planting matches reasonably well with the actual record (Fig. A4.1).

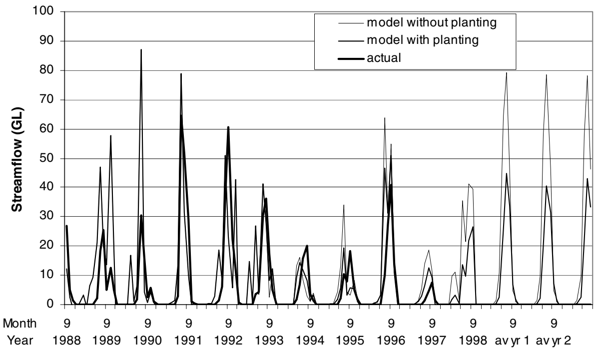


Figure A4.1 Pardelup actual and modelled monthly streamflows

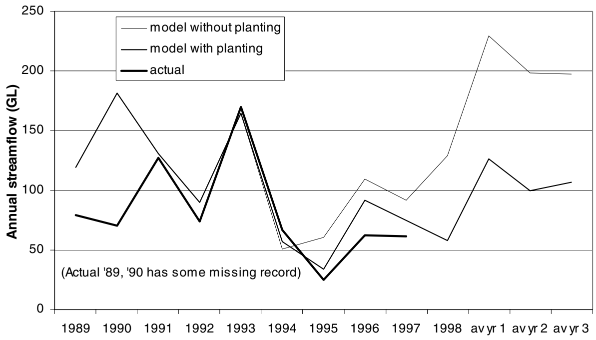


Figure A4.2 Pardelup actual and modelled annual flows (Sept–Aug)

The monthly model outputs were summed to annual totals and compared with the observed annual streamflow records at the Pardelup catchment (Fig. A4.2). This highlights differences between the simulated and actual records. Again, 1989 and 1990 should be ignored. The observed and predicted annual streamflow matched reasonably well except for the years 1996 and 1997 when the model over-predicted (Fig. A4.2). The over-predictions are largely explained by the model's assumptions of leaf area which drives transpiration. Overall, the mean observed and predicted annual streamflows at the Pardalup catchment for the period 1991–97 were 84 and 92 GL respectively (Table A4.1).

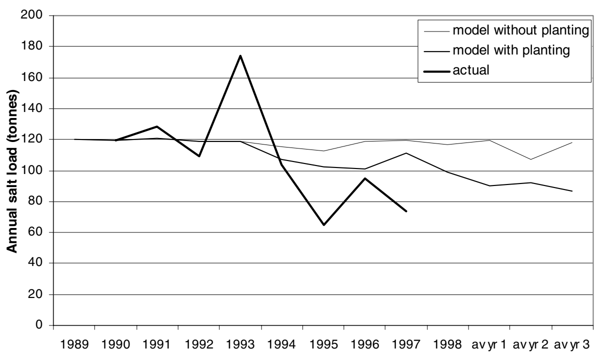


Figure A4.3 Pardelup actual and modelled annual salt load (Sept–Aug)

In pasture areas, the model assumes an identical annual cycle of leaf development and decay. In practice, the cycle may not be the same every year owing to variations in farming or response to rainfall. There are no records of the actual variations of pasture leaf area. The magnitude of pasture LAI in the cycle is expressed as a fraction of its peak value. The cycle applied at Pardelup was the result of calibrating a model of the experimental Lemon subcatchment in the Collie River catchment (Croton & Bari 2001). The peak LAI is set by calibration. Calibration of the larger Upper Denmark and Warren catchments produced a formula that linearly related the peak LAI to mean annual rainfall. By that formula (LAI = 0.0033 x Rain + 0.3), the LAI for Pardelup should be 2.58. A value of 2.3 was determined by calibration. The assumed leaf area development of planted trees also could be different at times other than the dates of Landsat scenes, particularly years estimated by interpolation. Thus the model probably represents more nearly a catchment where the leaf area variation was as specified, rather than a catchment experiencing the actual leaf area variation. The difference is minor, but it means that comparisons of the effects of changing vegetation should be made with the modelled outputs as a base instead of actual outputs.

It is most noticeable that the actual annual salt load output from the Pardelup catchment is more variable than the modelled output (Fig. A4.3). This is again attributed to discharge delay processes that are not included in the modelling. The model reports transport of salt from the clay layer into the surface layer. From this point it is inevitable that the salt will pass out of the catchment through the gauging station, and, hence, it is an appropriate quantity to represent the steady-state output of the catchment. However, the actual amount of salt moved through the gauging station each year depends on processes of storage and flushing in the surface soil layer, with higher loads likely in higher rainfall years and vice versa. Overall the mean annual observed and predicted salt load from Pardelup catchment was 134 kt and 124 kt respectively, representing a 7% under-prediction (Table A4.1).

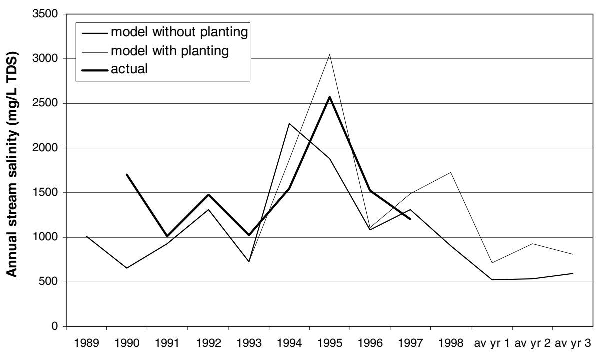


Figure A4.4 Pardelup actual and modelled flow-weighted salinity (Sept–Aug)

The annual flow-weighted salinity is the result of dividing annual salt load by annual flow, and reflects the differences between the actual records and modelling of those quantities (Fig. A4.4). In 1994, 1995 and 1997, the predicted annual stream salinity was higher than that observed, while the predicted values of the other years were lower (Fig. A4.4). However, the graph does highlight that, after the plantations are fully established, salinity from the catchment in an average rainfall year could be higher than if the planting had not occurred.

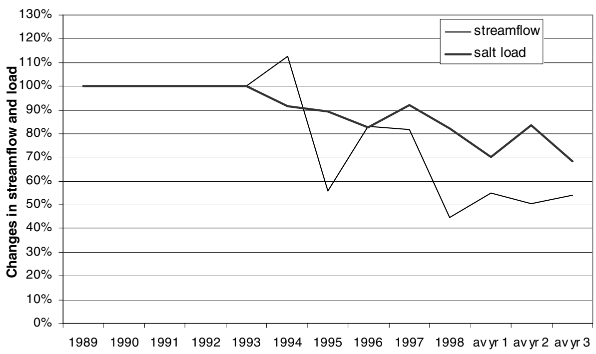


Figure A4.5 Pardelup change in modelling flow and salt load with planting

To simulate the catchment without tree planting, all that was required was to not update the vegetation cover as the simulation progressed. However, local redistribution of deep groundwater discharge caused some changes to appear just outside the defined catchment boundary. To properly assess the change produced by the trees, outputs over an area larger than the catchment needed to be accumulated. Thus the basic quantities defined for the catchment area were taken from the run without planting. Then the quantities with planting were the differences determined over a larger area but subtracted from the basic quantities for the catchment area.

The relative changes in streamflow and salt load at the Pardelup catchment was estimated by the MAGIC model. It is the differences between the simulated values with or without tree planting. In the final year of average rainfall, streamflow has dropped to 54% while salt load has only dropped to 66% (Fig. A4.5). The simulated results are reasonably comparable to the paired catchment study, which predicts that annual streamflow and salt load reduced to 76% and 71% of the pre-treatment values (see Section 3.6.1 for details). Both reductions are commensurate with the cleared area being reduced to 60%.

4.2.2 Barrama

The MAGIC model was also calibrated at the Barrama experimental catchment. There was a good match between the observed and predicted streamflow salinity and salt load. As only 17% of the cleared area of the Barrama catchment was replanted in 1993, there was very little difference in streamflow and salt load between the ‘planted’ and ‘not planted’ cases. However, the remaining cleared area of catchment was replanted in 1997. Simulation of the total cleared area replanted shows that a large decrease in streamflow could be expected in an average rainfall year. The annual average

Table A4.1 Comparison of mean annual observed and predicted flows at the Pardelup and Barrama subcatchments

Gauging station	*Observed mean streamflow (GL)*	*Modelled mean annual streamflow (GL)*	*Observed mean salt load (kt)*	*Modelled mean salt load (kt)*
Pardelup	84	92	107	111
Barrama	134	124	285	279

streamflow and salt load are predicted to decrease by 20% and 10% of their present values once the catchment reaches a new stability. The model estimates stream salinity of 5600 mg/L TDS in an average rainfall year.

The monthly and annual streamflow records at Barrama (Figs. A4.6 and A4.7) show characteristics similar to those at Pardelup for the same reasons. The peak pasture LAI used for Barrama was calibrated to be 2.1. (The regional formula mentioned above gives a value of 2.63 for Barrama.) The last month of actual flow record was July 1997, which causes the annual actual total for 1997 to be less than expected. The annual graph shows very little difference between the 'planted' and 'not planted' cases by 1996. However, after the whole catchment was replanted in 1997, a large decrease in streamflow is to be expected in an average rainfall year.

Calibration of the salt load output of the catchment required the limit rate of recharge to be set to 190 mm/year, and also the vertical permeability of the clay to be increased proportionately to 5 m/year. Figures A4.8, A4.9 and A4.10 show the changes in salt load and salinity, and the relative changes in salt load and streamflow. As with the streamflow, up to 1996 there were only minor reductions in salt load compared with the 'not planted' case. The model estimates a large reduction in salt load as a result of the current plantations, but, with an even larger relative reduction in streamflow, the salinity of the remaining stream as it leaves the plantation area could become quite high — the model estimates 5600 mg/L in an average rainfall year.

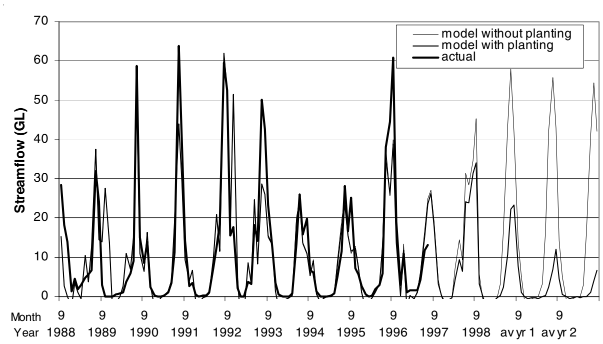


Figure A4.6 Barrama actual and modelled monthly streamflows

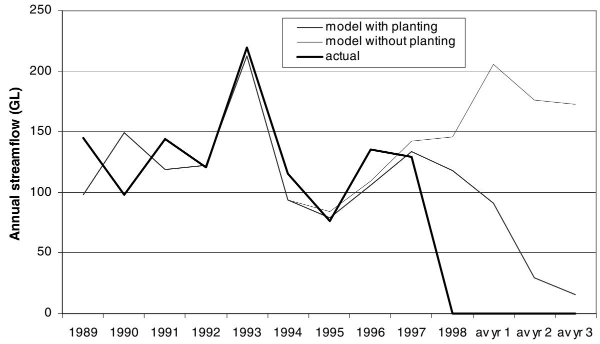


Figure A4.7 Barrama actual and modelled annual flows (Sept–Aug)

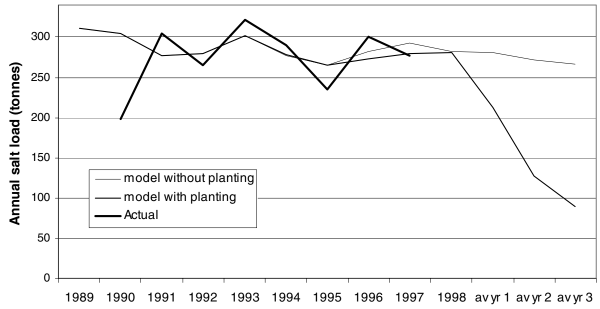


Figure A4.8 Barrama actual and modelled annual salt loads (Sept–Aug)

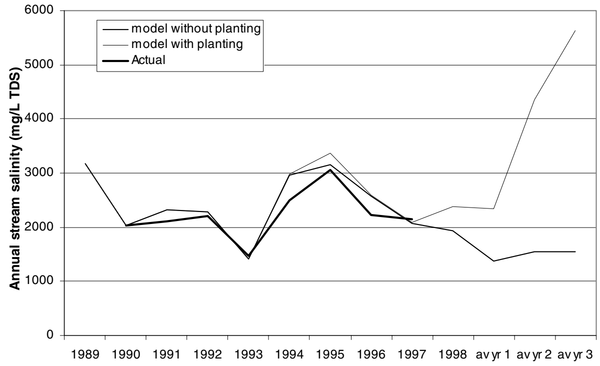


Figure A4.9 Barrama actual and modelled flow-weighted salinity (Sept–Aug)

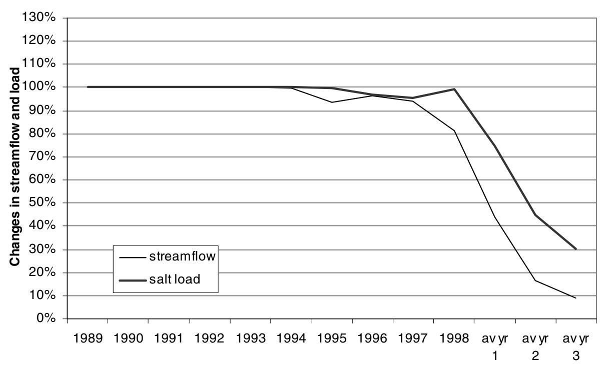


Figure A4.10 Barrama change in modelled flow and salt load with planting

Appendix 5 Catchment management options

The following information presents more on assessing tree planting options by the MAGIC model and supports Section 5.1: Tree planting.

To make the MAGIC model represent the different tree-planting cases, the map of tree greenness was changed and the map of pasture LAI adjusted to conform to the different tree areas. The tree greenness map is derived from Landsat scenes of the catchment. The January 1988 Landsat scene (Fig. 7) was used for Case 2 because the areas regenerated before 1984 had reached a density similar to that of native forest, and there had been no significant tree planting on other cleared areas. Case 1 used the same scene with the greenness in the known regeneration areas set to zero. The scene from March 1995 (Fig. A2.2) shows some relatively small areas of tree planting that were established through the Denmark Integrated Catchment Management Project, including use of CALM's Timber belt share farming scheme. The February 1999 scene (Fig. A2.4) shows plantations emerging over large areas in three or four main locations. In the February 2000 scene (Fig. A2.5), the 1999 plantation areas have achieved native forest density, and two or three more areas are at the emerging stage. To represent Case 3, the Landsat 2000 scene was used, with the modification that areas identified as emerging plantations were assigned a higher greenness equal to the native forest average. Established plantation areas used the greenness derived from the Landsat scene. In Case 4, all remaining areas of cleared land were assigned the native forest average greenness.

In each modelled case(described in Section 5: Catchment management options) outputs from the model included mapping the sites of deep groundwater discharge. (Figs 24, 25, 29 and A5.1). The figures show two categories of discharge based on the estimated groundwater level (i.e. piezometric head of deep aquifer):

- *Shallow watertable area*: This applies when the groundwater level is above the clay (generally 1.5 m below ground) which would prevent seasonal water from percolating deeper.
- *Seepage area:* These are the areas where the groundwater level is above the ground surface, that is, which may result in seepage at the surface.

These results are also tabulated by management units in Tables A5.1, A5.2 and A5.3 below.

Table A5.1: Case 1 — Modelling the maximum cleared area

Pre-regeneration case	*Management unit*			*Total Upper Denmark*	*Between Kompup and Mt Lindesay*	*Total at Mt Lindesay*
	Perillup	*Kompup*	*Yate Flat Creek*			
Catchment area (km^2)	75.0	108.8	57.7	241.5	283.6	525.1
Cleared area (km^2)	12.2	39.0	32.3	83.5	0	83.5
Cleared area/catchment area (%)	16	41	45	0	0	16
Rainfall (mm/yr)	688	714	689	699	795	750
Streamflow (GL/yr)	1.96	6.16	5.29	13.41	16.79	30.20
Streamflow (mm/yr)	26	65	74	56	59	58
Mean stream salinity (mg/L)	1391	1081	1378	1244	225	678
Seepage from pasture (GL/yr)	0.43	1.32	1.32	3.06	0.00	3.06
Seepage from pasture (mm/yr)	35	34	41	37	0	37
Seepage salt load (kt/yr)	1.96	6.05	6.15	14.15	0.40	14.56
Shallow watertable area (km^2)	6.0	14.5	14.6	35.1	0	35.1
Seepage area (km^2)	3.6	9.9	9.9	23.2	0	23.2

Table A5.2 Case 2 — modelling actual plantations to 2001

Modelling tree plantations to 2001	*Management unit* Perillup	*Kompup*	*Yate Flat Ck*	*Total Upper Denmark*	*Between Kompup & Mt Lindesay*	*Total Mt Lindesay*
Catchment area (km²)	75.0	108.8	57.7	241.5	283.6	525.1
Maximum cleared area (km²)	12.2	38.3	33.0	83.5	0	83.5
Cleared area/catchment area (%)	16	35	57	35	0	16
Planted area (km²)	3.4	18.4	17.2	39.0	0.00	39.0
Planted area/maximum cleared area (%)	28	48	52	47	0	47
Streamflow (GL/yr)	1.44	3.28	2.00	6.72	16.79	23.51
Streamflow (mm/yr)	19	30	35	28	59	45
Streamflow % of pre-regeneration case	73	53	38	50	100	78
Mean stream salinity (mg/L)	1546	1398	2123	1645	225	631
Seepage from pasture (GL/yr)	0.33	0.92	0.73	1.98	0.00	1.98
Seepage from pasture (mm/yr)	38	46	46	45	0	45
Seepage salt load (kt/yr)	1.46	3.98	3.10	8.53	0.40	8.93
Seepage % of pre-regeneration case	77	70	55	65	0	65
Shallow watertable area (km²)	4.5	11.3	8.2	23.9	0	25.0
Shallow watertable area/pre-regeneration shallow watertable area (%)	75	78	57	68	0	68
Seepage area (km²)	2.33	5.12	3.13	10.5	0	10.5
Seepage area/pre-regeneration seepage area (%)	64	52	32	46	0	46

Table A5.3 Case 3 — modelling tree plantations on all cleared land

Modelling tree plantations on all cleared land	*Management unit* Perillup	*Kompup*	*Yate Flat Ck*	*Total Upper Denmark*	*Between Kompup & Mt Lindesay*	*Total Mt Lindesay*
Catchment area (km²)	75.0	108.8	57.7	241.5	283.6	525.1
Cleared area (km²)	12.2	39.0	32.3	83.5	0.00	83.5
Cleared area/catchment area (%)	16	41	45	0	0	16
Planted area (km²)	0	0	0	0	0	0
Planted area/pre-plantation cleared area (%)	0	0	0	0	0	0
Streamflow (GL/yr)	0.35	0.91	0.29	1.55	16.79	18.34
Streamflow (mm/yr)	5	10	4	6	59	35
Streamflow % of pre-plantation case	18	15	5	12	100	61
Mean stream salinity (mg/L)	2490	772	4784	1909	225	368
Seepage from old pasture areas (GL/yr)	0.02	0.02	0.05	0.08	0.08	0.16
Seepage from old pasture areas (mm/yr)	0	0	0	0	0	0
Seepage salt load (kt/yr)	0.10	0.92	0.24	0.44	0.40	0.84
Seepage % of pre-plantation case	5	1	4	3	0	5
Shallow watertable area (km²)	1.6	3.1	3.4	8.1	0	8.1
Shallow watertable area/pre-plantation shallow watertable area (%)	26	21	24	23		23
Seepage area (km²)	0	0.1	0.1	0.2	0	0.2
Seepage area/pre-plantation seepage area (%)	1	1	1	1		1

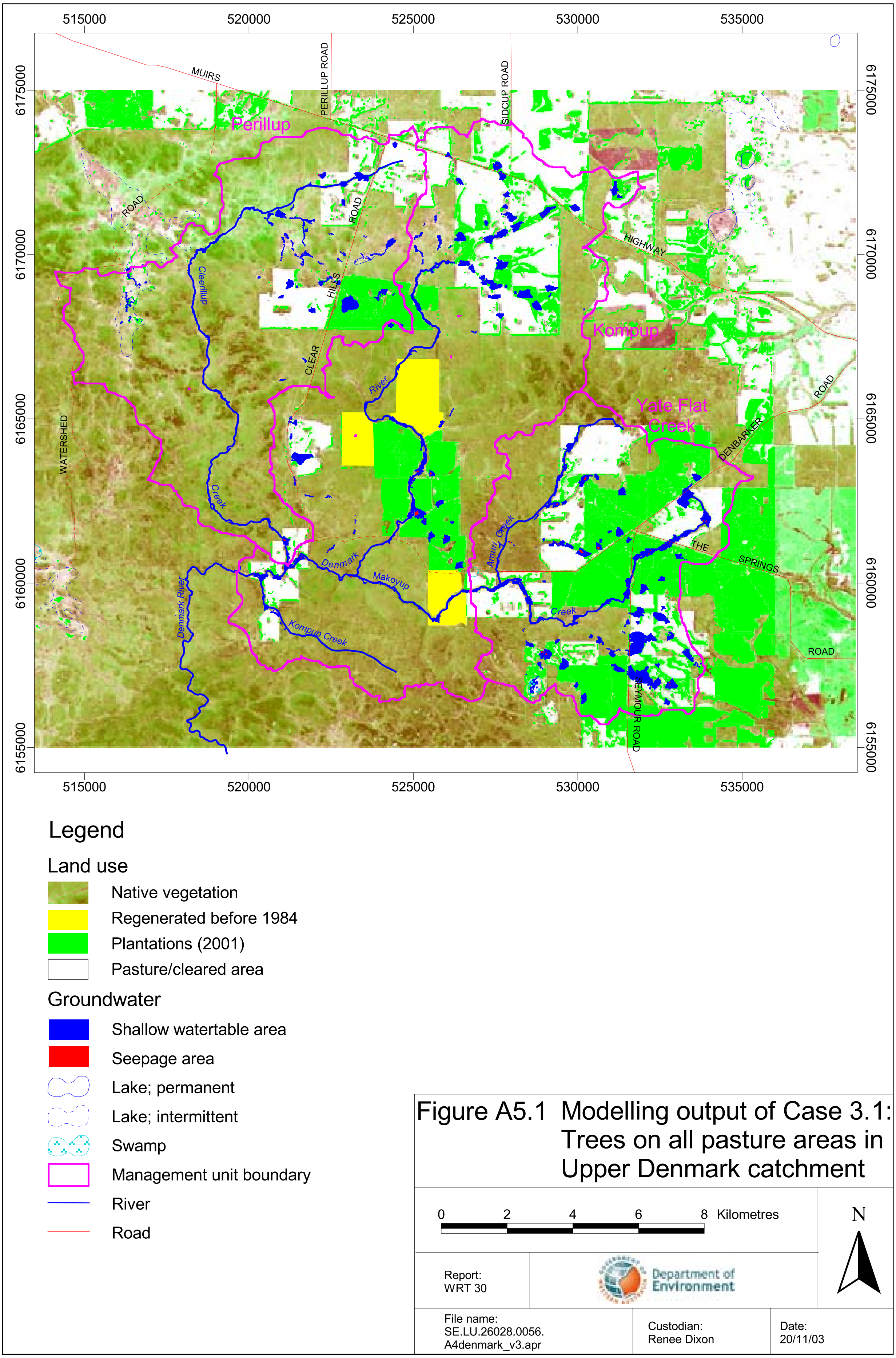


Figure A5.1 Modelling output of Case 3.1: Trees on all pasture areas in Upper Denmark catchment

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