Department of Water
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Salinity Situation Statement

Warren River

Water Resource Technical Series

REPORT No. WRT 32
JULY 2006

SALINITY SITUATION STATEMENT
WARREN RIVER

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Department of Water

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This report was completed but not released in 2005 by the Department of Environment and printed and released by the Department of Water in 2006, with only departmental information updated.

Information on the Warren River catchment came from a number of studies and long-term monitoring programs. Streamflows, groundwater levels and associated salinity were recorded by hydrographers from the Water and Rivers Commission (now the Department of Water) and stored in its databases. The gauging station data was reviewed by the then Hydrology and Water Resources Branch. Gauging station and groundwater data were analysed by the then Salinity and Land Use Impacts Branch.

Data preparation and modelling of revegation management options for the salt-affected areas of the Warren River catchment used the MAGIC system developed by Geoff Mauger, formerly of the Water and River Commission. General mapping and preparation of area statements used ESRI's GIS program ArcView and its extensions.

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Since this study was completed the first author, Margaret Smith, has moved to what is now the Department of Environment and Conservation.

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The Warren River at the Barker Road Crossing gauging station by Tim Sparks

Preface

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

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

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

Important components of the Department of Water's salinity program are to assess the current salinity situation of the targeted rivers, evaluate options available and prepare and implement recovery plans to recover stream salinity to drinking water levels. Salinity situation statements for the Collie and Denmark rivers were published in 2001 and 2004 respectively. The statements for the Kent and Helena catchments are in preparation as is the evaluation of options for the Denmark River and a salinity recovery plan for the Collie River.

Disclaimer

The maps and results of analyses presented in this report are products of the Department of Water (at that time the Department of Environment). Although the Department has made all reasonable efforts to ensure the accuracy of these data, the Department accepts no responsibility for any inaccuracies and persons relying on these data do so at their own risk.

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Summary

Water in the Warren River was once fresh (salinity below 500 mg/L TDS) but by the 1960s the salinities exceeded 500 mg/L TDS. This report analyses where and why the catchment became saline, describes its salinity in the intervening years and suggests the scales of intervention needed to reduce the river salinity.

The Warren River catchment was defined for purposes of this study as the area from the Warren River headwaters to the Barker Road Crossing gauging station and it comprises the Warren River Water Resource Recovery Catchment and the Unicup Lake area.

The Warren River catchment (with an area of 4000 km^2 of which 24% is cleared) was recognised as having one of the largest water resources in the south-west of Western Australia. However, the average annual salinity between 1990 and 2001 was 895 mg/L TDS. Salinity is still rising, although significantly more slowly in recent years, with 60% of the salt load coming from the Perup River and Tone River subcatchments. The *State Salinity Action Plan* recognised the importance of this water resource and set a water quality target of potable water (500 mg/L TDS) by 2030. The Warren Recovery Team was formed to recover the water quality. The team is an active partnership between the community of the Tone River and Perup River subcatchments and key government agencies led by the Department of Water.

The Warren River catchment is about 300 km south-east of Perth. The major tributaries of the upper catchment are the Tone and Perup rivers which rise in farmed land south-west of Kojonup, and join to form the Warren River east of Manjimup. This river then flows through mainly forested country and discharges into the Southern Ocean south-west of Pemberton.

The Warren River is thought to have had salinity of 120–350 mg/L TDS prior to clearing and the first indications of water quality decline were noted by the railway engineers in the 1920s. Extensive clearing of native vegetation in the upper sections of the catchment during the 1950s and 1960s led to increases in stream salinity in the 1970s. This rising salinity led the Western Australian Government to introduce clearing control legislation in 1978. Tree planting commenced during the 1990s in the subcatchments of Tone and Perup rivers.

The benefits of protecting the native vegetation and the emerging tree plantations are now evident with the mean annual salinity in the Perup River declining though still rising in the Tone River. The Warren Recovery Team with the then Department of Environment proposed the management options to be assessed. The scale of intervention required to achieve potable water is indicated by the need to: replant 70% of the pastured land back to trees; pump groundwater; or divert water from the Tone River. These options reach the target water quality of 500 mg/L TDS but the social, economic and environmental implications need to be considered as part of further evaluating these options. This indicates the scales of intervention needed and further evaluation of the management options is necessary before any on-ground activities start.

Other revegetation options include planting both commercial trees and perennial pastures. By planting commercial trees (bluegums, sawlogs and pines) on 20% of the pastured land, the water salinity through the Barker Road Crossing gauging station should go down to about 750 mg/L TDS. Planting deep- and shallow-rooted perennial pastures on 46% of the land is predicted to reduce salinity to between 720 and 790 mg/L TDS. Planting a combination of commercial trees and deep-rooted perennial pastures on 46% of the land is predicted to improve the water salinity to 675 mg/L TDS.

The impacts of shallow drains were considered. Shallow drainage is expected to have little effect on the salinity at Barker Road Crossing gauging station. Deep drainage would not help meet the water quality target unless the drainage was collected and transported out of the catchment.

The recommendations in this report relate to quantifying and testing the assumptions used in the catchment modelling and maintaining existing monitoring to allow the catchment modelling to be updated. Responsibility for carrying out the recommendations listed below should lie with the Department of Water. The Department will work with the Warren Recovery Team to form partnerships with regional groups, research institutions, industry groups and all levels of government to establish, coordinate and guide the investigations.

The current salinity situation statement for the Warren River is:

- The average annual flow-weighted salinity (1990–2001) is 895 mg/L TDS with a range 560–1270 mg/L TDS.
- The average annual salinity in the Perup River peaked in the 1990s. The average annual salinity is still rising at 51 mg/L TDS through the Tone River gauging station and at 7 mg/L TDS through the Barker Road Crossing gauging station. These rates have slowed since 1992 and the changes are attributed to land use changes such as extensive tree planting in the Perup River subcatchment. Some tree planting has occurred in the west of the Tone River subcatchment but it has not been of sufficient scale to reverse the salinity trend at this point.
- Approximately 18% of the upper Warren River catchment is at risk of developing a shallow watertable (within 2 m of surface).
- The stream salinity of the Warren River is starting to level off.

Some results of the range of management options modelled to assess their effectiveness in reducing salinity are:

- Three of the options could achieve the water quality target: replanting 70% of the current pastured land with non-commercial trees (415 mg/L TDS); pumping 13 GL groundwater from the weathered and fractured bedrock aquifer (500 mg/L TDS); and diverting all the water (31.3 GL) from the Tone River into a nearby river outside the Warren River catchment (380 mg/L TDS).
- Plantations of commercial trees (eucalypts for pulp, or hardwood sawlogs and pines) on the 20% of the pastured land rated suitable by land capability mapping lowers the salinity to about 750 mg/L TDS. This area may be conservative as plantations are being established on land rated by the land capability mapping as either unsuitable or of low suitability.
- Perennial pastures (both deep and shallow rooted) planted on 46% of the pastured land lower salinity to 720–790 mg/L TDS. Modelling used assumptions on the water use and rooting depths of perennial pastures. Not enough is known to determine LAI for deep-rooted pastures: especially since lucerne pastures can be managed under a variety of farming systems such as rotational grazing.
- A combination of commercial trees and shallow-rooted perennial pastures planted on 46% of the pastured land lowers salinity to about 675 mg/L TDS.
- Shallow drains will not reduce salinity.
- Pumping groundwater (13 GL a year from 1625 bores) from the Tone and Perup subcatchments reduces salinity to 500 mg/L TDS.
- Diversion of 20–100% of the saline water from the Tone River reduces salinity to a range of 380–775 mg/L TDS.

Recommendations

- Communicate results to all major stakeholders so that they can have input into any subsequent or on-going work.
- Assess the social, economic and environmental costs and the benefits of all management options.
- Use an additional ‘dynamic’ model to ensure accurate predictions of the effects of the management options.
- Investigate the effectiveness of deep-rooted and shallow-rooted perennials in reducing recharge to groundwater and reducing salinity. Investigate the average rooting depths of perennial plants in a range of soils.
- Investigate the accuracy and usefulness of land capability mapping at farm scale. Regional-scale information was used to identify areas suitable for planting commercial trees and deep-rooted perennial pastures but this mapping may be unnecessarily restrictive.
- Ascertain the sustainability of current commercial timber plantations on land assessed by this study’s land capability mapping as having low suitability for this purpose.
- Determine the average rooting depth across different soil types for a range of perennial pasture plants.
- Review groundwater pumping results of existing trials (such as Maxon Farm) and proposed demonstrations sites of the WA Engineering Evaluation Initiative, and identify the potential of this option for the upper catchment.
- Review and identify farming systems able to combine elements of the different land use options.
- Evaluate water management options to attain the potable target for critical parts of the years by pumping during high flow periods.
- Keep monitoring streamflow and salinity at the mainstream gauging stations to calculate whether recent trends (1992–97) continue and, in particular, if the downward salinity trend in the Perup River continues when harvesting of existing commercial timber plantations begins.
- Maintain monitoring of groundwater levels but review the frequency of measurement. The frequency needs to be at intervals appropriate to discern trends, particularly in those areas where groundwater has been rising.
- Develop Leaf Area Index (LAI) estimates for deep-rooted and shallow-rooted perennial pasture plants to confirm modelling assumptions, especially under different farming practices.

Keywords Yilgarn–Southwest Province, Albany–Fraser Province, salinity mitigation, surface water, groundwater, Warren River catchment

1 Introduction

1.1 Purpose and scope

The Warren River catchment (above the Barker Road Crossing gauging station), with a mean annual flow of 291 GL, has one of the largest surface water resources in the South-West Drainage Division of Western Australia (Fig. 1). Salinity in the Warren River exceeded 500 mg/L Total Dissolved Solids (TDS) in the 1960s (Collins & Barrett 1980) and, between 1990 and 2001, the average salinity was 895 mg/L TDS. The salinity of river water is still rising though more slowly than in the 1990s.

The government of Western Australia recognised the importance of this water resource and, in the *Western Australian Salinity Action Plan* (Government of Western Australia 1996), set a target of potable water (500 mg/L TDS) in the Warren River at the Barker Road Crossing gauging station by 2030.

The purpose of this study is to analyse where and why the river water became so saline, and provide management options to lower the salinity to the target value. Other water quality issues are beyond the scope of this study.

This study illustrates how the quantity and quality of the catchment's water resources have been affected by vegetation changes such as clearing native vegetation and later replanting some of these areas with trees, and probably by climate changes and climate variability as well.

The Warren River catchment is the area from the Warren River headwaters to the Barker Road Crossing gauging station, and includes the Unicup Lake area, which is a Biodiversity Recovery catchment. The upper catchment (called the upper Warren River catchment) comprises the Tone River, Perup River and Wheatley Farm subcatchments, and was modelled with the Unicup Lake area included. The Tone River and Perup River subcatchments, which contribute disproportionately high quantities of salt, will be targeted for salinity mitigation actions (Fig. 1).

The local community subdivided the upper Warren River catchment into 10 management units (MUs) (Fig. 2) predominantly based on surface water drainage, with some variations to account for social factors.

1.2 Objectives

The objectives of the study and report are to:

- assess the current surface water and groundwater salinity situation in the catchment
- predict the salinity situation if no additional land use changes are made or engineering works established
- provide a range of management options and their likely effects on river flow and salinity.

1.3 Overview of European settlement and land use

While Aboriginal people lived in the area for thousands of years, it could be argued that the European land management practices have most shaped the landscape we see today. Europeans explored the area in the 1850s and soon after began to use the timber and grazing resources. In the 150 years since there have been several phases in settlement, logging and farming. The more intensive farming and orcharding by the 'homesteaders' succeeded the pastoralism of the pioneer settlers. The settlers associated with the Group Settlement Scheme brought dairying and tobacco to the region. Major changes in land-clearing techniques

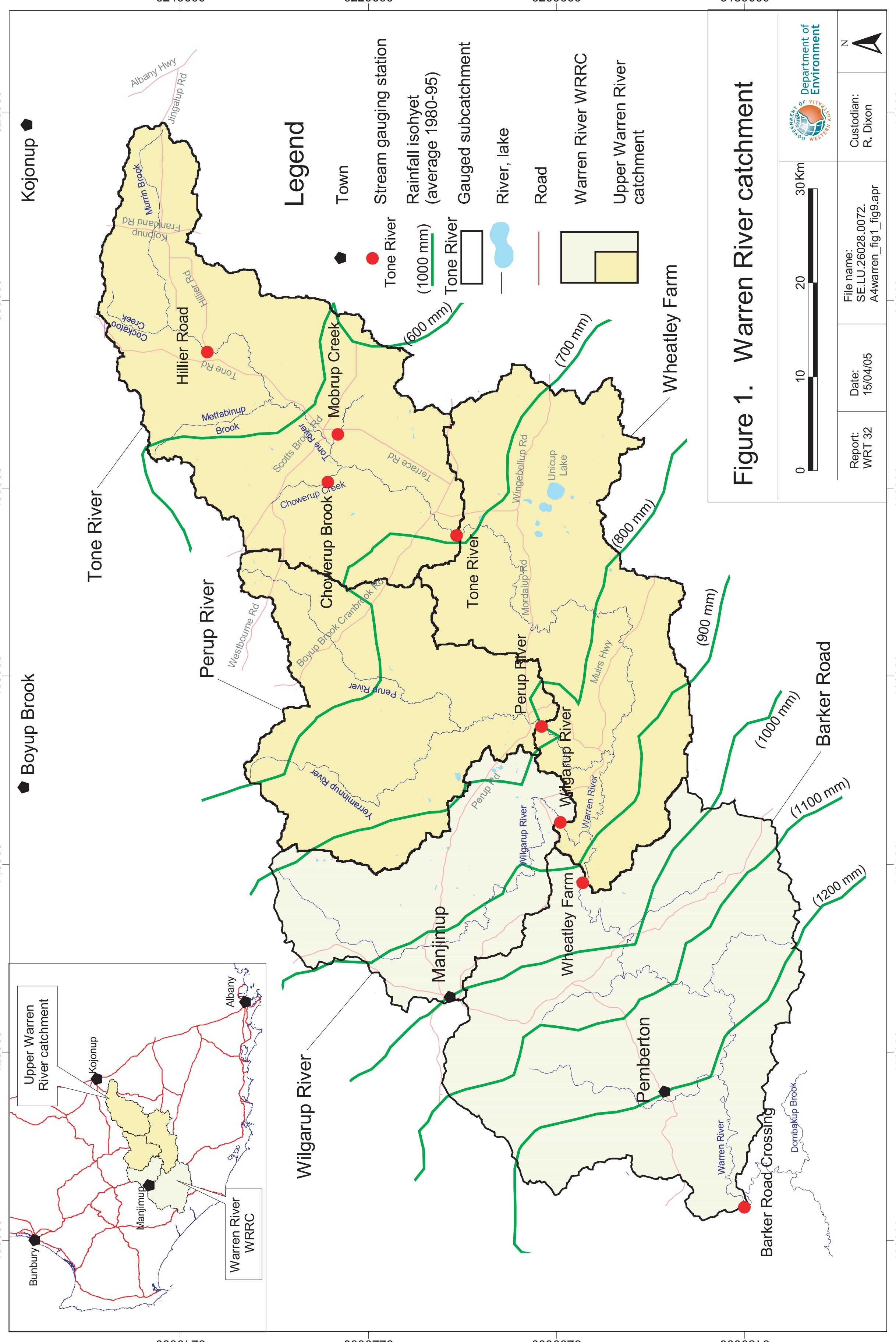


Figure 1. Warren River catchment

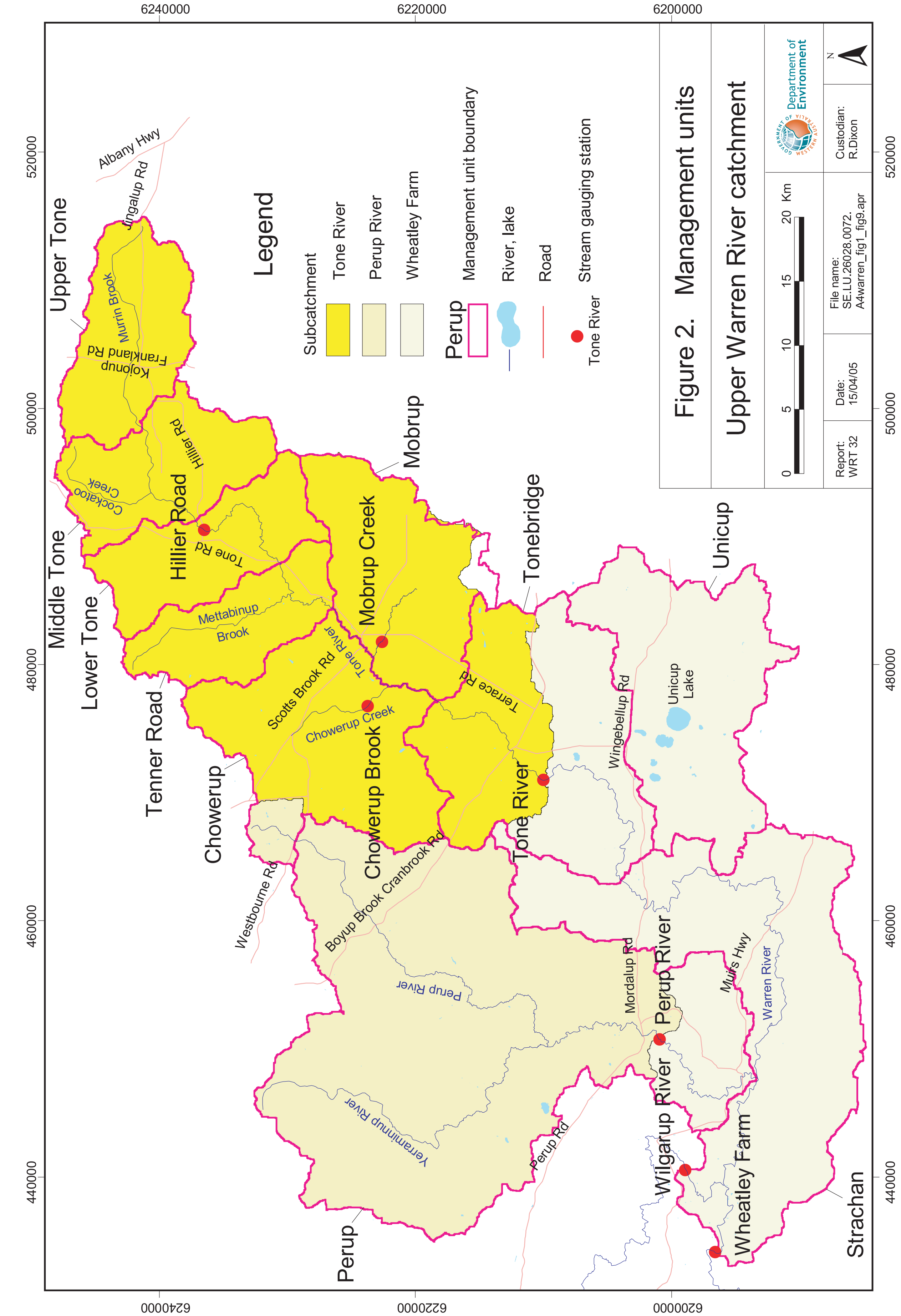


Figure 2. Management units
Upper Warren River catchment

after World War II resulted in rapid clearing of the upper catchment and allowed pastoralism to dominate again before the phase of major timber plantations of the 1990s.

1.3.1 Before World War I

The main European explorers through the area were the official survey expeditions and those seeking land suitable for stock grazing. In 1852, Gregory, a government surveyor, travelled extensively through the Warren district (Berry 1987) and traversed the Tone and Perup rivers. In the same year Thomas and Robert Muir travelled near Lake Muir through the Perup and Wilgarup areas seeking land for their stock, and developed properties at Lake Muir and Deeside (Berry 1987).

The explorers and early settlers noted that the forest understorey was sparse (Collins & Barrett 1980) — a result of Aboriginal burning practices used to create habitat for game animals. The first wave of settlers mainly grazed stock on the native grasses in the timbered country, although small areas were cleared to grow wheat to meet their own flour needs. A private flour mill was set up on Lefroy Brook at Channybearup near Manjimup (Burvill 1979).

Early attempts at grazing suffered from poisonous plants. The number of sheep and cattle deaths from poisonous indigenous plants was serious enough that the Western Australia Pastoral and Colonization Company Ltd instructed their local manager, Robert Irving, living near Jingalup, to clear the company's land of poisonous plants during the 1890s (Bignell 1982). Many hours were spent trying to eradicate these plants, predominantly of the *Oxylobium* and *Gastrolobium* genera (including plants commonly known as Box Poison and York Road Poison).

Population increases in the early 1900s resulted from actions such as *The Homestead Act* of 1893 which encouraged land settlement for farming, the arrival of the rail head at Bridgetown in 1898 and at Manjimup by 1910, and the opening of sawmills in the area between 1913 and 1916.

In this next wave of land settlement, dairying, along with fruit and vegetable growing, developed in the Manjimup area. The Jingalup Estate and the Mobrup areas were settled in the early 1900s with the land being cleared for mixed grazing by sheep, cattle and horses: the last providing remounts for the Indian and Australian armies. Early landholders were AH McKenney of Mobrup and AJ Fisher of Jingalup (Bignell 1982). Labour shortages during World War I slowed the pace of development.

Areas were set aside as timber reserves — two of the first being blocks of karri forest at Beedelup and Warren in 1901. By 1909, these reserves had been progressively reduced in size to provide land for farming and timber felling (Rundle 1996). Allocations of land to these and other timber reserves were the bases for future National Parks and conservation reserves.

1.3.2 Group Settlement Scheme after World War I

Clearing in the Manjimup district continued with the introduction, in 1921, of the Western Australian Government's Group Settlement scheme aimed to establish dairy farms in the high-rainfall areas of the lower south-west of the state. The workers and their families, working in groups of about 20, were paid to develop a number of farms, with each family allocated to one established farm. Difficult farming conditions and low prices for commodities in the 1930s Depression caused the scheme to become a social and financial tragedy. Many of the settlers were forced to leave their farms and find new livelihoods. The cleared land was amalgamated into larger farms held by those who remained. In the Manjimup area, tobacco growing began as an alternative to dairying.

1.3.3 Land Settlement Schemes after World War II

The major land use changes in the Tone River subcatchment occurred after World War II when a new War Service Land Settlement Scheme that allocated land under conditional purchase was established. With bigger and more efficient land clearing machinery and techniques available, the cleared area of the Warren River catchment jumped from about 20% in 1950 to about 36% in 1979 (Collins & Barrett 1980). At the same time, many timber mills were built to meet the major demand for timber (e.g. the Tone River Mill in 1952).

The main farming system in the Tone River subcatchment was sheep grazing on subterranean clover pastures. This farming system has remained basically unaltered from the 1950s. The main modifications have been greatly increased stocking rates, some land used for cash crops and some development of farming systems using perennial grasses and legumes. An emerging industry in the higher-rainfall areas is plantations for pulpwood production.

1.4 Salinity and government action

The rising salinity of water had been noted in the Manjimup area prior to the major clearing episodes of the 1950s and 1960s: rising salinity in the water supply for steam engines was observed at Manjimup as early as the 1920s and the Department of Agriculture records landholders in the area complaining of salinity before the 1950s (Trotman 1974).

There were concerns that the potable water source might be lost. In the 1970s, the (flow-weighted mean) salinity of the river ranged from 875 mg/L TDS at the Barker Road Crossing gauging station (607220) to 6275 mg/L TDS at the Tone River gauging station (607007) (Collins & Barrett 1980). In 1978, these concerns led the Western Australian Government to legislate to extend the powers of the *Country Areas Water Supply Act*, with the introduction of clearing control legislation to prevent additional loss of native forest in the Warren River catchment area (among other south-west catchments) and to prevent further alienation of Crown Land (*Warren River Water Reserve Alienation Control* 1978).

The Water and Rivers Commission (now the Department of Water) was made the lead agency to implement the *Salinity Action Plan* target of potable water supply by 2030 (Government of Western Australia 1996). The Warren Recovery Team was established in 1997.

1.5 The recovery approach

The Department has adopted a targeted investment approach to recovery (Fig. 3).

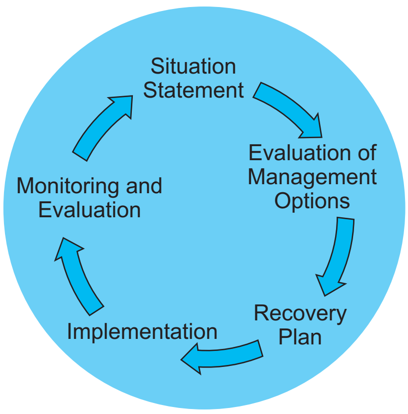


Figure 3. The recovery approach

- The *Salinity Situation Statement* (the study and this report) identifies the current and predicted salinity levels, and describes and evaluates the hydrological impacts of a suite of conceptual management options for the catchment.
- In the step, *Evaluation of Management Options*, water quality objectives are defined and, in consultation with key stakeholders, scenarios to meet these objectives are evaluated considering social, economic and environment aspects.
- In the *Recovery Plan* step the major components of management options to be implemented are identified, an implementation strategy developed and funding sources identified.
- The *Implementation* stage will coordinate on-ground planning and implementation.
- In the *Monitoring and Evaluation* stage, monitoring of the main river and subcatchments will be used to review the salinity situation.

1.6 The Warren Recovery Team

In November 1997 the Water and Rivers Commission established a local Recovery Team that encourages full stakeholder involvement and fosters partnerships between state government agencies, NRM groups, local government, industry, research institutions, local community groups and catchment landholders to achieve the water quality target.

The Warren Recovery Team (Appendix 1, Tables A1.1 & A1.2) is an active partnership between the community of the Tone River and Perup River subcatchments and key government agencies. The role of the Team is to bring parties together at the local level and implement the *Salinity Strategy* (State Salinity Council 2000). The Team is a non-statutory, non-incorporated decision-making group.

The Team has strong community representation with six well-recognised landholders from the upper catchment and locally-based representatives from the State's major Natural Resource Management agencies: the departments of Agriculture; Conservation and Land Management; and Environment. The Chairperson is Mr Chris Evans from Mobrup and executive support is provided by the Department of Water.

As required in the *State Salinity Strategy* (State Salinity Council 2000), the Recovery Team prepared *A Strategic Action Plan* (Dames & Moore 2001) that describes actions to achieve their vision for the catchment.

The Recovery Team's vision is 'The Warren River catchment has a healthy, productive and profitable environment, capable of sustaining a diversity of human activities and values and of generating potable water and a range of other products.'

2 Catchment description

This section presents characteristics of the Warren River catchment (mainly the upper catchment) relevant to defining the current salinity situation and developing the conceptual management options.

2.1 Location and climate

The Warren River catchment is about 300 km south-east of Perth and has an area of 4000 km^2 of which 24% is cleared. Boyup Brook, Kojonup, Manjimup and Frankland are the nearest towns around the upper part of the catchment. Five local government authorities — the Shires of Boyup Brook, Kojonup, Manjimup, Bridgetown and Cranbrook — administer the area.

The climate of the upper catchment is temperate with warm dry summers and cool wet winters. The average daily minimum temperature range for Kojonup is 5.8–13.6 ºC, and the average maximum temperature range is 14.4–29.5 ºC. The average annual long-term rainfall decreases from 900 mm in the west to about 500 mm in the east (Fig. 1). The annual variability of rainfall in the upper and lower sections of the catchment is shown in Figures A2.1 and A2.2 of Appendix 2. The mean annual pan evaporation (Class A) increases from 1400 to 1600 mm west to east (Luke et al. 1988).

From the mid 1970s, winter rainfall across the south-west of Western Australia has, overall, declined by between 15 to 20%, and the pattern has changed: less rain in early winter (May–July) and more in late winter (August–October) (Indian Ocean Climate Initiative Panel 2002). This changed pattern should be considered when planning salinity management actions.

2.2 Surface drainage

The Warren River has four major tributaries — the Tone, Perup, Wilgarup and Dombakup rivers (Fig. 1). The Tone River rises about 15 km south-west of Kojonup and flows south-west to the confluence with the Perup River just south of Muirs Highway. From this confluence, the river is called the Warren and flows through (mainly) forested country and discharges into the Southern Ocean south-west of Pemberton.

The Perup River subcatchment is drained by both the Yerraminnup and the Perup rivers which flow between May and November. The Yerraminnup River drains the north-western area before joining the Perup River about 8 km north of Mordalup Road.

The Wilgarup River joins the Warren River 15 km downstream of the Tone/Perup/ Warren confluence. It flows in a southerly direction and is 71 km long.

The Dombakup Brook flows in a westerly direction for about 26 km before it enters the Warren River 16 km from its mouth.

The Warren River is gauged at the Barker Road Crossing and Wheatley Farm. Other gauging stations are Bullilup on the Tone River near Tonebridge; Quabicup Hill on the Perup River, and Quintarrup on the Wilgarup River. There are three new gauging stations — Hillier Road on the Tone River, Evans Farm on the Mobrup Creek and Stretch's Tree Farm on the Chowerup Brook (Fig. 1).

2.3 Geology and geomorphology

2.3.1 Geology

The area comprises part of the southern extremity of the Darling Plateau and the northern section of the Ravensthorpe Ramp — subdivisions of the Great Plateau (Jutson 1934), which are related to the subsidence, uplift and tilting of Australia during its separation from Antarctica.

The catchment bedrock is formed of rocks of the Yilgarn Craton in the north and of the Albany–Fraser Orogen in the south (Appendix 2, Fig. A2.3). The regional geology is described by Wilde and Walker (1982, 1984), Chin and Brakel (1986) and Myers (1990). The Archaean and Proterozoic granitic and gneissic rocks are deeply weathered and partly overlain by Cainozoic sediments (Appendix 2, Fig. A2.3). The weathered and sedimentary materials form the ‘regolith’ that extensively obscures the granitic and gneissic bedrock. East-trending palaeodrainage systems are infilled with Cainozoic sediments.

Lineaments on aeromagnetic data (Appendix 2, Fig. A2.4) indicate minor faults and dolerite dykes, including a north-west-trending and a west-trending series, suggesting several episodes of intrusion. As with the bedrock, the dykes are deeply weathered and only a few outcrop in the north-eastern part of the catchment. Aeromagnetic data also indicate regional north-west faults (Appendix 2, Figs A2.3 & A2.4).

The maximum regolith thickness in Chowerup is 39 m and (up to) 46 and 48 m respectively in the Tonebridge and Mobrup MUs (Panasiewicz et al. 1997; Hundi 1999; Hundi et al. 2001; Smith in prep.). In the Tonebridge, Chowerup, Mobrup, Tenner Road and Lower Tone MUs, the regolith generally includes laterite on the ridge tops. The areal extents of the geological units are listed in Appendix 2, Table A2.1.

Thick Cainozoic sediments are preserved in the broad flat valleys of the Tonebridge, Chowerup and Mobrup MUs (Panasiewicz et al. 1997; Hundi 1999; Hundi et al. 2001; Smith in prep.). Isolated Cainozoic sediments are preserved higher in the landscape, especially in the Perup MU.

2.3.2 Geomorphology

In the upper catchment, an undulating plateau surface dissected by the Tone and Perup rivers changes to poorly drained flats. An undulating plateau surface with moderately incised valleys is the dominant landform of the Tenner Road, Lower Tone, Middle Tone, and Upper Tone MUs while in the Perup MU it is steeply incised valleys. The undulating plateau surface becomes broad flat valley floors with swampy depressions in the Mobrup, Chowerup, Tonebridge and the upper portion of Unicup MUs. The surface elevation ranges from about 200 m (AHD) in Tonebridge to about 350 m in Upper Tone (Fig. 4). These areas fall within the Darling Plateau.

Undulating low rises and swampy plains in the Strachan and the lower parts of the Perup and Unicup MUs and, in the Unicup MU, poorly drained flats with lakes fall within the Ravensthorne Ramp. The elevation ranges from about 150 to 230 m with minor peaks at 270 m east of Unicup Lake on the catchment boundary (Fig. 4).

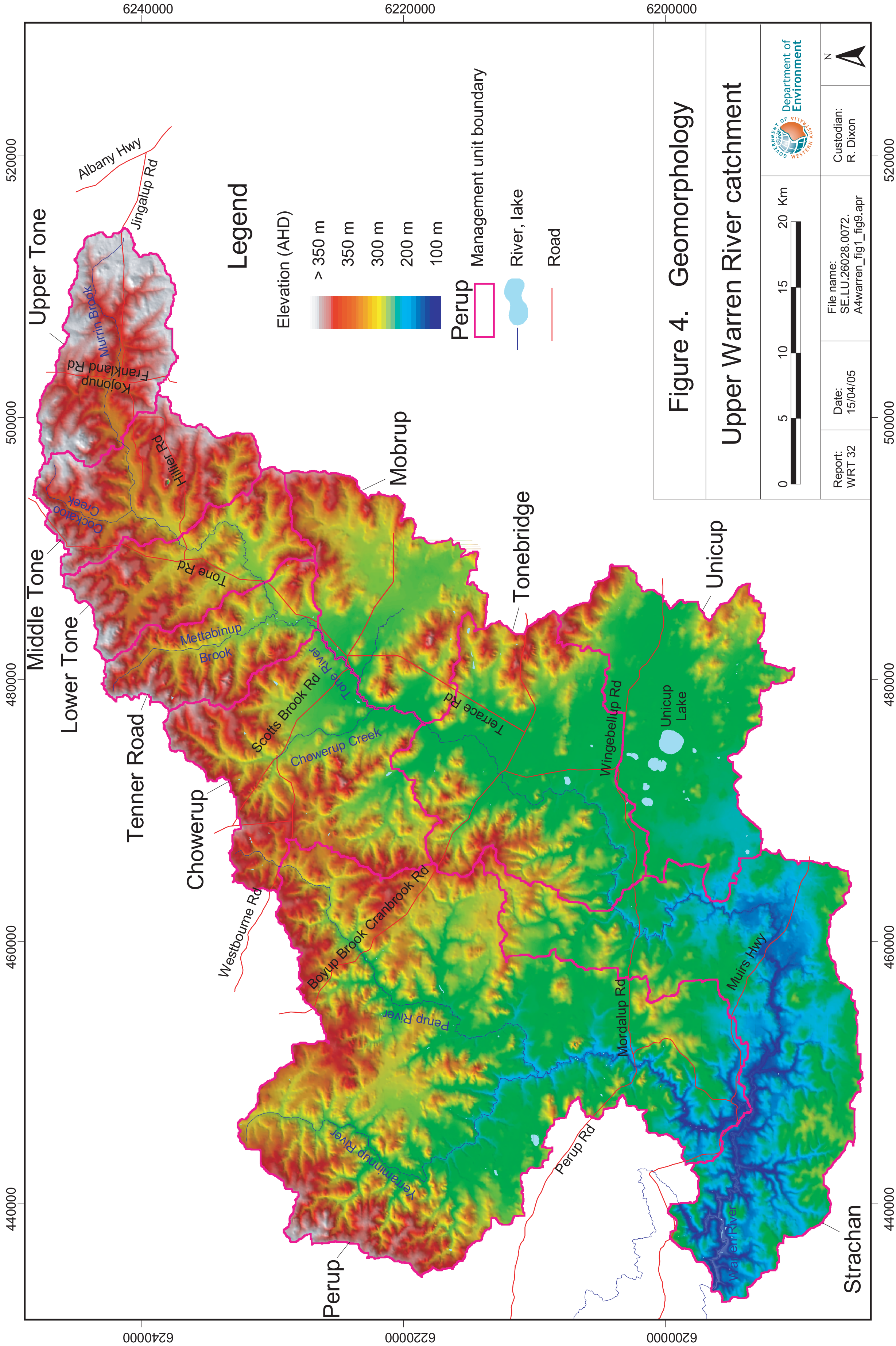


Figure 4. Geomorphology

Upper Warren River catchment

2.4 Soil–landscape

Soil development and depth (Churchward 1992; Percy 1992; Stuart-Street & Scholz in prep.) are strongly controlled by geology/geomorphology and climate. The soils of the upland plateau areas are duplex sandy gravels and loamy gravels. Semi-wet to wet soils are associated with poorly-drained flats and swampy depressions. Within the broad flat valleys of the Mobrup, Chowerup, Tonebridge and Unicup MUs are pale deep sand and grey deep sand with semi-wet to wet soils on the low-lying land.

These soils in the upper catchment are typically about 1.5 m thick and range in permeability from very low to high. Weighted averages for permeability and thickness of the A and B horizons range from 0.2 to 2.5 m/day and 1.1 to 2.1 m respectively. Soils with low permeability are the waterlogged semi-wet to wet soils between 0.3 and 0.8 m thick. The duplex sand gravels and loamy gravels consist of 0.3 to 0.8 m permeable ironstone gravel with either sandy or loam matrix over a clay layer of low permeability. The deep sands (> 0.8 m thick) are very permeable.

The soil zones and systems are detailed in Appendix 2 (Fig. A2.6, Tables A2.2 & A2.3).

2.5 Salt storage

Johnston et al. (1980) measured soluble salts in soils within the Manjimup Woodchip Licence area that includes part of the Perup River catchment (Yerraminnup North and South) and found two distinctive types of salt storage in the soil profile: monotonic and bulge. About one third of the this area, commonly the divides and upper slopes, has a monotonic type salt storage profile — salt storage increases almost linearly with depth. In the remaining two-thirds, commonly the valley floors and lower slopes, there is a salt bulge in the unsaturated zone. Within the Perup River catchment, total salt storage ranges from 10.6 to 64.7 kg/m^2 and the average salt content ranges from 1.0 to 2.0 kg/m^3.

2.6 Hydrogeology

The upper catchment includes part of the hard rock Yilgarn–Southwest and Albany–Fraser groundwater provinces (Fig. 5) with the sediments of the Bremer Basin overlying both (as far north as the Upper Tone). The regional hydrogeology is described by De Silva (2004). The prevalence of the hydrogeological units in the management units is tabulated in Appendix 2, Table A2.4.

The main aquifers are the weathered and fractured bedrock aquifers and sedimentary aquifers. The semi-confined weathered and fractured bedrock aquifers overlie fresh bedrock. Flow systems in the semi-confined weathered and fractured bedrock aquifers tend to be local; that is, water moves from the surface water divide and generally discharges at the nearest drainage line. Water enters aquifers by direct infiltration of rain or runoff and is lost by seeping into watercourses and wetlands, or by evapotranspiration from the shallow watertable. The groundwater salinity varies from 1000 to 20 000 mg/L TDS and averages 10 000 mg/L TDS.

The unconfined to semi-confined sedimentary aquifers consist of Cainozoic sediments that lie unconformably on both fresh and weathered bedrock and may be up to 48 m thick in palaeochannel deposits. Minor surficial aquifers, which overlie both these aquifer groups, are within the alluvial and colluvial sediments of Cainozoic (mainly Quaternary) age, which occupy the major stretches of the rivers and swamplands. These Cainozoic sediments are generally thin (about 3 m thick), but up to 22 m in the Tenner Road MU. Groundwater from weathered aquifers discharges into the surficial and sedimentary aquifers that occupy broad flats and valleys. Generally, these aquifers have a salinity of about 4000 mg/L TDS with a range 2000–9000 mg/L TDS.

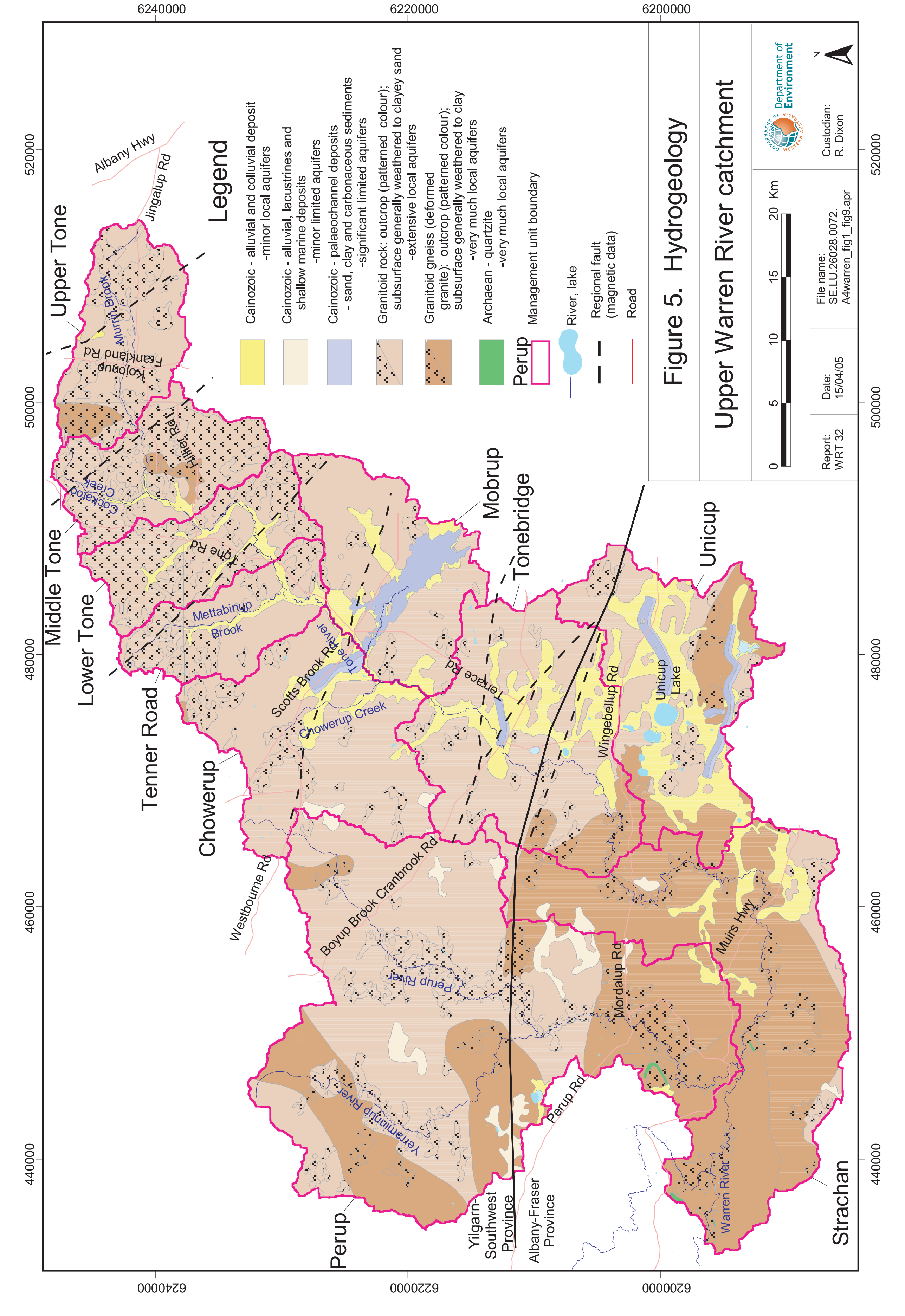


Figure 5. Hydrogeology
Upper Warren River catchment
Legend
Cainozoic - alluvial and colluvial deposit -minor local aquifers
Cainozoic - alluvial, lacustrines and shallow marine deposits -minor limited aquifers
Cainozoic - palaeochannel deposits - sand, clay and carbonaceous sediments -significant limited aquifers
Granitoid rock: outcrop (patterned colour); subsurface generally weathered to clayey sand -extensive local aquifers
Granitoid gneiss (deformed granite): outcrop (patterned colour); subsurface generally weathered to clay -very much local aquifers
Archaean - quartzite -very much local aquifers
Perup
Management unit boundary
River, lake
Regional fault (magnetic data)
Road
0 5 10 15 20 Km
Department of Environment
Report: WRT 32
Date: 15/04/05
File name: SE.LU.26028.0072. A4warren_fig1_fig9.apr
Custodian: R. Dixon
N
6240000
6220000
6200000
520000
500000
480000
460000
440000
Upper Tone
Middle Tone
Lower Tone
Tenner Road
Chowerup
Perup
Mobrup
Tonebridge
Unicup
Strachan
Albany Hwy
Jingalup Rd
Muirillup Brook
Frankland Rd
Kojonup Rd
Hillier Rd
Cockatoo Creek
Tone Rd
Mettabinup Brook
Tone River
Scotts Brook Rd
Chowerup Creek
Terrace Rd
Wingebellup Rd
Unicup Lake
Westbourne Rd
Boyup Brook Cranbrook Rd
Perup River
Mordalup Rd
Muirs Hwy
Yerraminnup River
Perup Rd
Warren River
Yilgarn-Southwest Province
Albany-Fraser Province

2.7 Land use

2.7.1 Vegetation (before European settlement)

Beard (1981) broadly classified the native vegetation before European settlement as medium forests of jarrah and marri in the west and medium forests of marri and wandoo with small areas of jarrah and wandoo to the east and, in low-lying areas, low woodlands with paperbark woods on the swampy flats. A summary of the relationships of vegetation types, soils and landform is given in Appendix 2, Table A2.2.

2.7.2 Clearing history

After the introduction of clearing control legislation in 1978 and the extensive plantations established since the 1990s, the cleared area of the Warren River catchment (4000 km^2) dropped from the 36% (~1450 km^2) maximum in 1980 to 24% or 980 km^2 in 2000 (Collins & Barrett 1980, Table 1). During this period, in the upper catchment, the extent of clearing decreased from 70% to 60% in the Tone River subcatchment and from 18% to 9% in the Perup River subcatchment (Fig. 6).

Table 1. Clearing history

Catchment	*Total area (km^2)*	*Land cleared (km^2)(%)*			
		1965*	1979+	1980*	2000
Warren River	4000		1450 (36)		980 (24)
Tone River	980	440 (45)		685 (70)	590 (60)
Perup River	660			120 (18)	60 (9)

* Rogers et al. 1999
\+ Collins & Barrett 1980

Following tree planting in the higher rainfall areas to the west, about two thirds of the upper catchment is now covered with either native forest or plantation timber. The remaining one third, in the lower rainfall area to the east, is still cleared land (Fig. 6). The land clearing changes are shown in Table 1 and pasture cover in 2000 is shown in Figure 6.

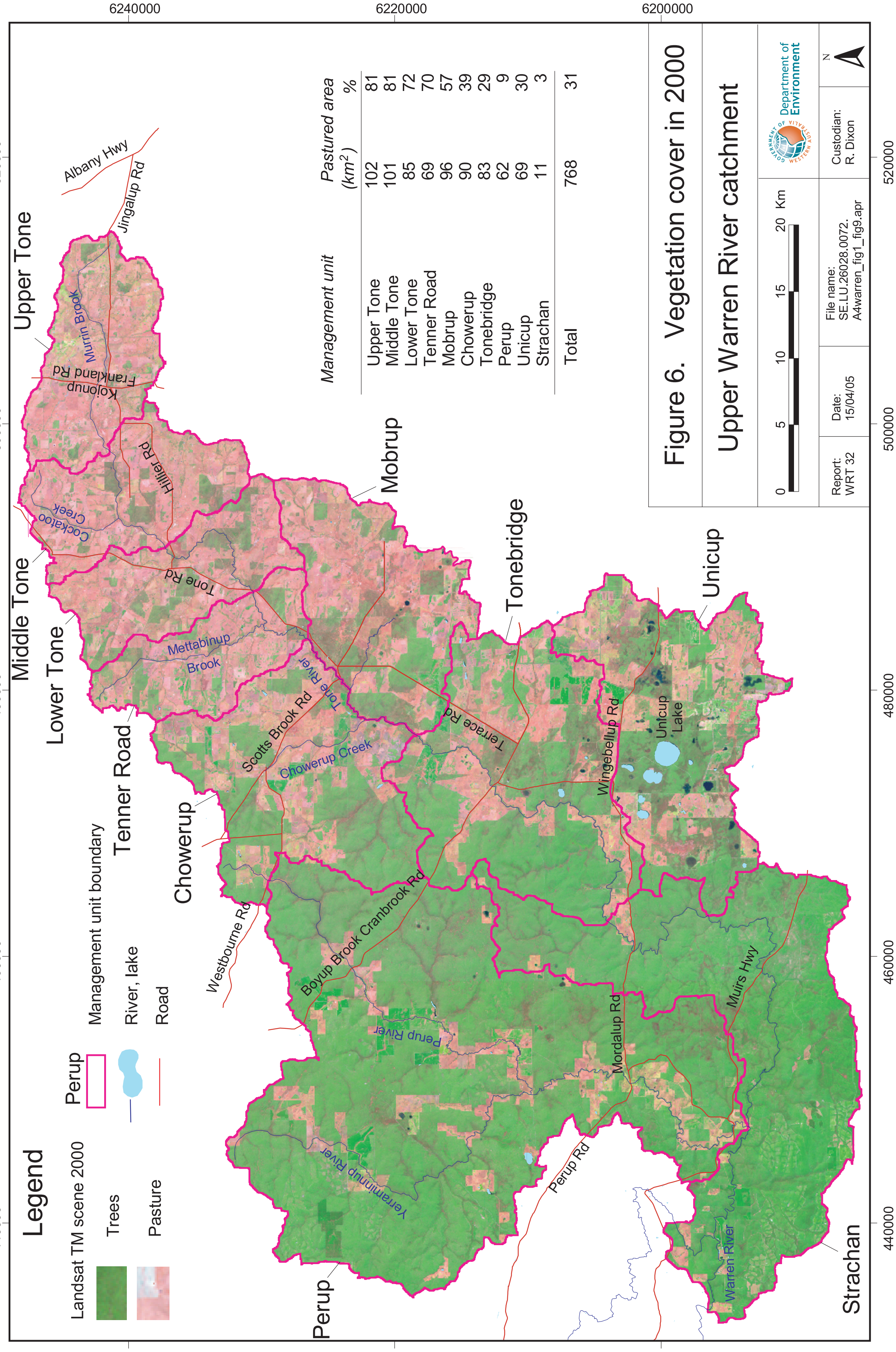
2.7.3 Plantations and harvesting

Major timber plantings began between 1994 and 1996 (Appendix 2, Table A2.5). The largest areas of plantations are in the higher rainfall areas of the Perup and Unicup MUs, followed by Chowerup and Tonebridge. By 2002, 38.7 and 24.5 km^2 had been planted in the Perup and Unicup MUs respectively. Plantings have been scattered in Chowerup and Tonebridge, with major plantings occurring in 2002. In the areas with rainfall of less than 600 mm, plantings have been limited, ranging from 0.3 km^2 in the Upper Tone to 3.8 km^2 in Tenner Road.

There has been little harvesting so far as recent plantations are still immature. Bluegums for pulpwood tend to be harvested on a 10–12 year rotation and hardwood sawlogs on a 20–25 year rotation. Harvesting has begun and will increase as plantations mature (Fig. 7). The total area harvested to 2002 was 4.2 km^2 (Appendix 2, Table A2.6), mainly from Chowerup (1.8), Unicup (1.7), Tonebridge (0.5) and Mobrup (0.3).

Commercial forestry continues in areas of native forest managed according to the Forest Management Plan (Conservation Commission of Western Australia 2004).

The areas of plantations and timber harvesting have been mapped indirectly since 1988 using satellite-data from Landsat Thematic Mapper as the locations and areas of planting and harvesting are not made public. New tree growth can be identified from Landsat TM images two years after planting.



Management unit	*Pastured area (km^2)*	*%*
Upper Tone	102	81
Middle Tone	101	81
Lower Tone	85	72
Tenner Road	69	70
Mobrup	96	57
Chowerup	90	39
Tonebridge	83	29
Perup	62	9
Unicup	69	30
Strachan	11	3
Total	768	31

Figure 6. Vegetation cover in 2000

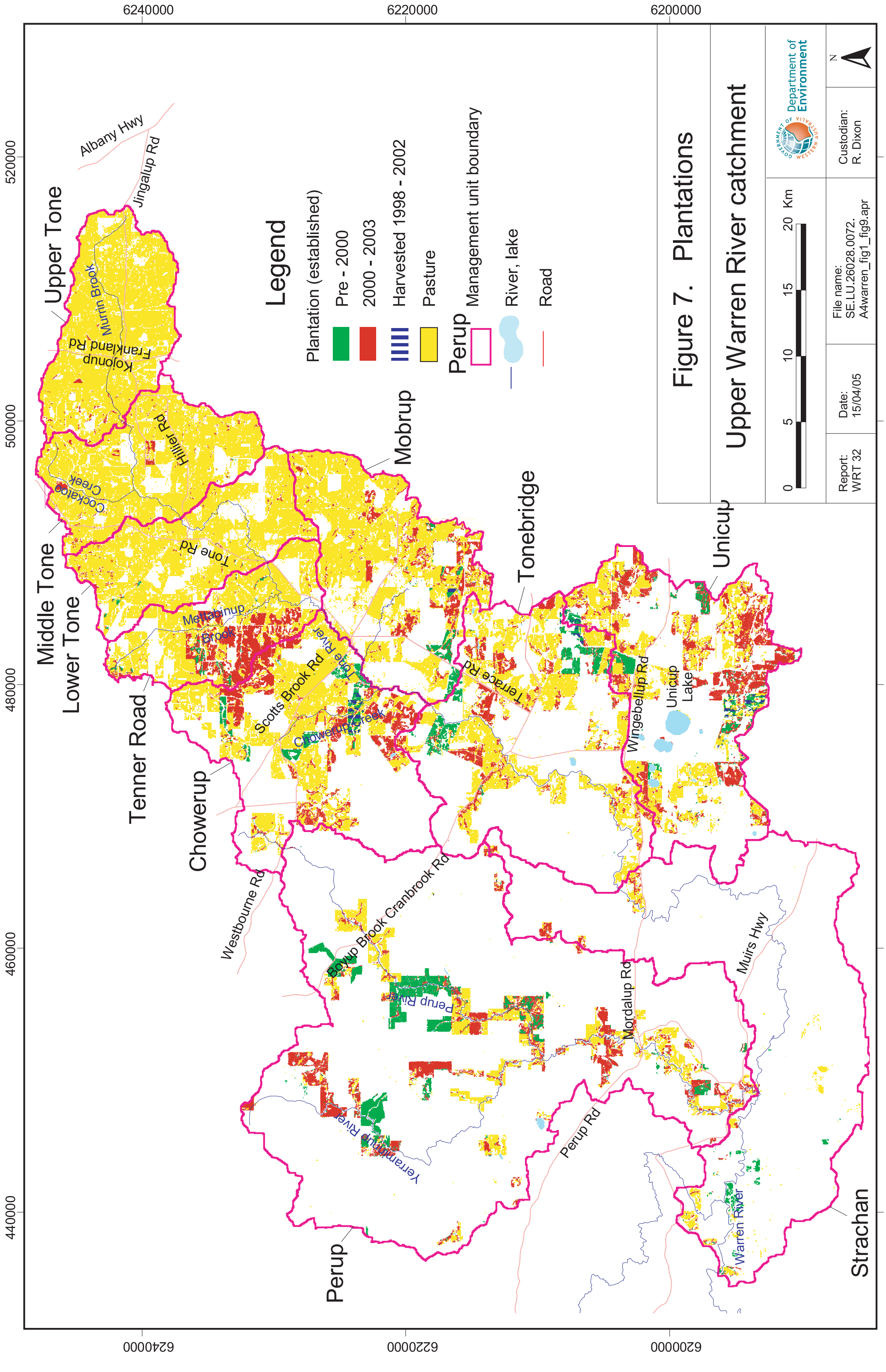


Figure 7. Plantations
Upper Warren River catchment
Legend
Plantation (established)
Pre - 2000
2000 - 2003
Harvested 1998 - 2002
Pasture
Management unit boundary
Perup
River, lake
Road
0 5 10 15 20 Km
Department of Environment
Report: WRT 32
Date: 15/04/05
File name: SE.LU.26028.0072. A4warren_fig1_fig9.apr
Custodian: R. Dixon
N
Upper Tone
Middle Tone
Lower Tone
Tenner Road
Chowerup
Mobrup
Tonebridge
Unicup
Perup
Strachan
Albany Hwy
Jingalup Rd
Murrin Brook
Frankland Rd
Kojonup Rd
Hillier Rd
Cockatoo Creek
Tone Rd
Mettabinup Brook
Tone River
Scotts Brook Rd
Chowerup Creek
Terrace Rd
Wingebellup Rd
Unicup Lake
Westbourne Rd
Boyup Brook Cranbrook Rd
Perup River
Mordalup Rd
Muirs Hwy
Perup Rd
Yerraminup River
Warren River
6240000
6220000
6200000
520000
500000
480000
460000
440000

3 Flow and salinity characteristics

This section describes the salinity situation of the Warren River catchment from 1990 to 2001 by analysing streamflow and salinity records, describing trends in surface water flow, salinity and groundwater levels across the catchment, and identifying areas at risk of dryland salinisation.

The salinity of the Warren River before European settlement is thought to have been about 120–350 mg/L TDS (Collins & Barrett 1980) but has been rising since records started. Between 1990 and 2001, the average annual flow-weighted salinity was 895 mg/L TDS (Table 2), with a range 563–1265 mg/L TDS. The long-term variations of flow and salinity calculated from gauging station records are largely due to changes in the extent of cleared land — changes which can be deduced from satellite images. The average annual stream salinity decreases from north-east to south-west coinciding with a general decrease in the extent of clearing and increasing rainfall. Salt and streamflow contributions to the Warren River from its tributaries are shown in Figure 8.

3.1 Streamflow and salinity records

The stream gauging records of five gauging stations were analysed. The records of the three new gauging stations (Hillier Road, Chowerup Brook and Mobrup Creek) were too short to analyse. The Barker Road Crossing gauging station, which started operating in 1955, has the longest record and the Tone River gauging station at Bullilup the shortest (Fig. 9). Monitoring is ongoing but flow and salinity trends can only be reported up to 1997 because the linear regression method used to analyse salinity trends requires nine years of data to determine the five-year trend. The method and results of streamflow and salinity trend analyses are shown in Appendix 3.

Table 2. Analysis of surface water data

Subcatchment (gauging station no.)	*Average annual**			*Relative contributions to the Barker Road Crossing gauging station*		*Salinity trend*	
	Streamflow (GL)	*Salt (kt)*	*Salinity (mg/L TDS)*	*Streamflow (%)*	*Load (%)*	*(mg/L TDS/year)*	
	1990–2001			1990–2001		1980–90	1992–97
Tone River (607007)	41	132	3930	14	54	+82 (S)	+51 (S)
Perup River (607004)	16	32	2430	5	13	+7 (NS)	–68 (S)
Wilgarup River (607144)	30	22	810	10	9	0 (NS)	–13 (S)
Wheatley Farm (607003)**	101	198	2340	35	81	+28 (S)	–7 (NS)
Warren River–Barker Road Crossing (607220)+	291	244	895	100	100	+15 (S)	+7 (S)

(S) – Significant trend at the 95% confidence level
(NS) – Not a significant trend at the 95% confidence level
* Arithmetic mean
**Wheatley Farm includes flows from Tone River, Perup River and Wilgarup River
+ Barker Road Crossing includes flows from Wheatley Farm and Wilgarup River

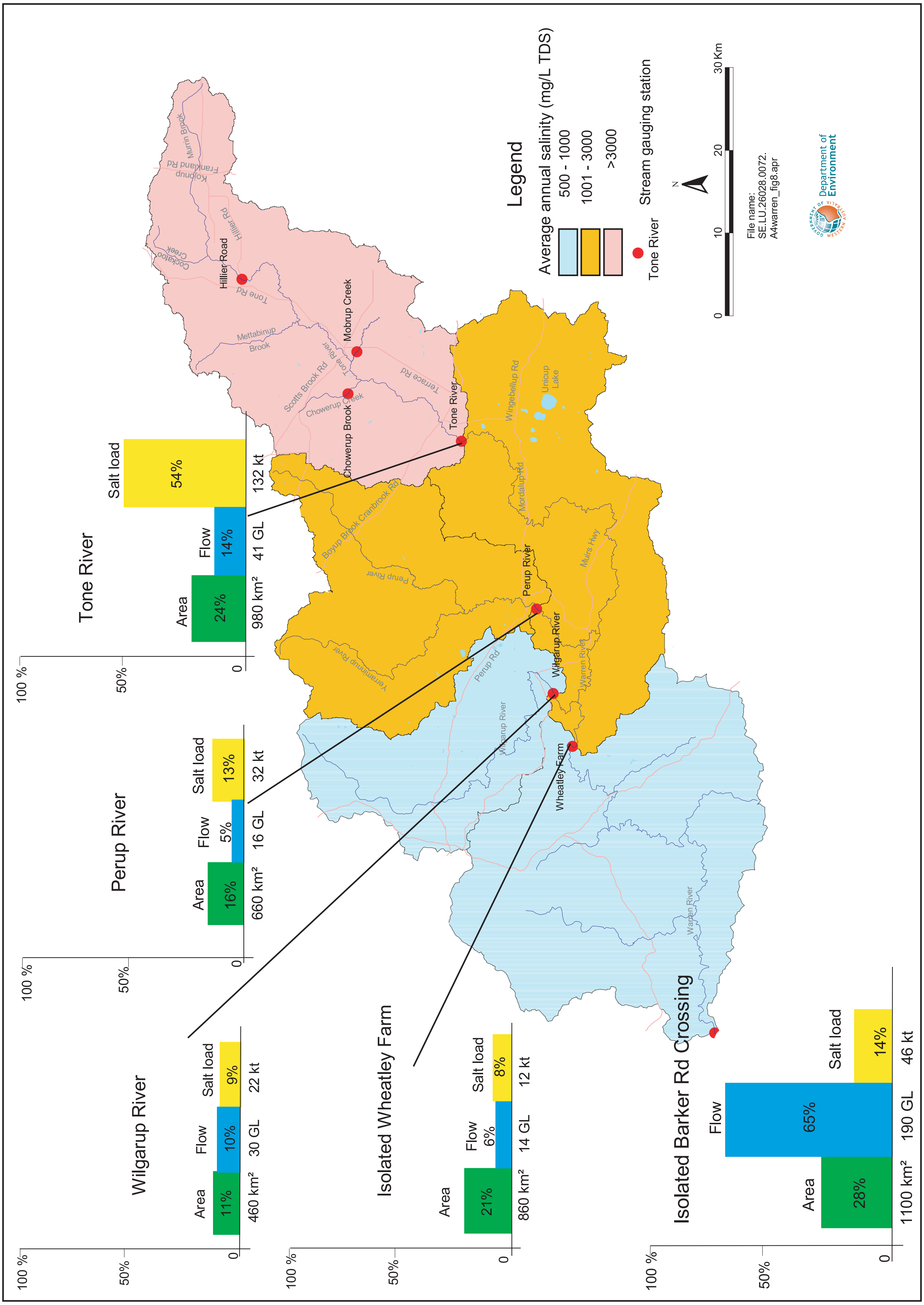


Figure 8. Salt and streamflow contributions to the Warren River

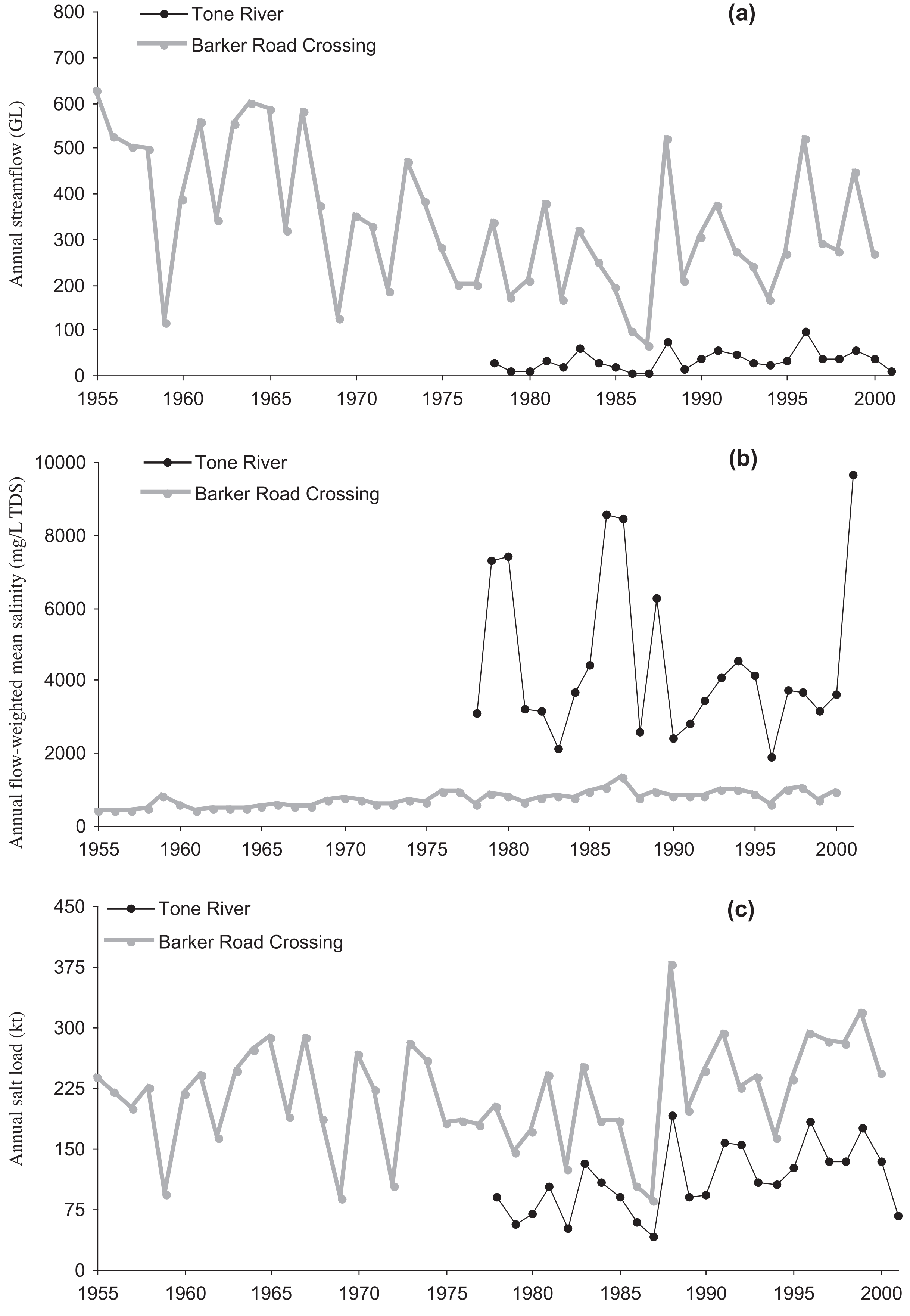


Figure 9. Annual records for a) streamflow, b) salinity and c) salt load at the Bullilup and Barker Road Crossing gauging stations

3.1.1 Streamflow

Calculating annual streamflow using mean annual rainfall (Appendix 3) theoretically removes the influence of changing climate and allows changes in annual flows related to land use changes to become evident. However, the streamflow records in this study are too short to remove totally the influence of decreasing annual rainfall (related to climate change), so increased flows resulting from land clearing are obscured, although the year-to-year fluctuations in rainfall have been removed.

The mean annual flow for the Warren River (at the Barker Road Crossing gauging station) is 291 GL (Table 2). Most of this water is from the high-rainfall lower end of the catchment (Fig. 8). In the upper catchment, the Perup River contributes about 16 GL (5%) of the annual flow at the Barker Road Crossing while the Tone River contributes, on average, 14% (Fig. 8) of the flow, with a range of 5–22%. The Tone River subcatchment is the more extensively cleared and produces more runoff (31 mm compared with the Perup's 21 mm) despite lower annual rainfall than the Perup River subcatchment.

3.1.2 Stream salinity

The average annual stream salinity decreases from the north-east of the catchment (3933 mg/L TDS at the Tone River gauging station) to the south-west (895 mg/L TDS at the Barker Road Crossing gauging station) coinciding with a general decrease in the extent of land clearing, and higher rainfall (Table 2). From 1980–90, stream salinity at mean flow at four of the five gauging stations increased at rates of 7–82 mg/L TDS per year, except for the unchanged Wilgarup River. Between 1992 and 1997, the stream salinity at mean flow decreased at three of the five gauging stations. The largest decrease was in the Perup River subcatchment where large areas of trees have been planted. For the 1992–97 period, the salinity trend at the Tone River and Barker Road Crossing gauging stations was still upward, but at a slower rate (Table 2).

The obscuring effect of stream volume on salinity was removed by calculating annual stream salinity using the mean annual streamflow (Table 2; Appendix 3, Figs A3.1–A3.5).

3.1.3 Stream salt load

The annual salt load from the Warren River catchment (recorded at the Barker Road Crossing gauging station) averaged 244 kilotonnes (kt) in the period 1990–2001. The Tone River subcatchment produced more than half of this salt load (54%) with an average annual salt load of 132 kt through the gauging station (Table 2).

3.2 Groundwater levels

The underlying changes in groundwater levels reflect changes in land use, but separating the seasonal variations from the underlying trend has been difficult, especially as there is a poor groundwater data record for this catchment.

HARTT analysis (Hydrograph Analysis: Rainfall and Time Trend) (Ferdowsian et al. 2001) was used to separate the effects of seasonal rainfall events from the underlying trend (Appendix 3).

The groundwater levels were measured in forested areas in Barker Road subcatchment, and in forested and logged sections of the Perup MU. Groundwater data from bores drilled by the Department of Agriculture in pastured areas of the Wilgarup River subcatchment and the Mobrup MU were reviewed but found not relevant for this study. Land use at the Wilgarup site had changed from irrigated potatoes to pastures in the 1990s. At the Mobrup site, bores were drilled to monitor agricultural land-use trials (Smith et al. 2003) but unfortunately the control data were no usable. The extensive bore network constructed in 1997, 1999 and 2000 (Panasiewicz et al. 1997; Hundi 1999; Smith in prep.) only has groundwater levels collected since 2001; too few for HARTT analysis.

3.2.1 Groundwater levels in forested areas

After logging between January 1982 and April 1983 and a 'regeneration' burn in October 1983, the groundwater levels at four monitored sites in the Perup MU (Fig. 10) rose at 0.04–0.33 m/year reversing the pre-logging downward trend (Fig. 11). This rise had slowed within 10 years of the burn. Regenerating jarrah–marri stands in forests reach 90% of their pre-logging cover in 10–15 years (WAWA 1987). The HARTT analysis indicates that, after 1988, the water level was stable, but visual inspection of the hydrograph shows that the groundwater levels were rising (Fig. 11).

Groundwater levels rising at up to 0.15 m/year in control bores in native forest areas of the Perup MU in the 1990s reversed the earlier trend of stable or falling levels (up to 0.18 m/year but generally less than 0.07 m/year) seen until the late 1980s.

Groundwater levels in bores in regenerated logged areas in the Barker Road subcatchment (Appendix 3, Fig. A3.6) that were rising in the 1980s were stabilised or falling by the 1990s (Fig. 12).

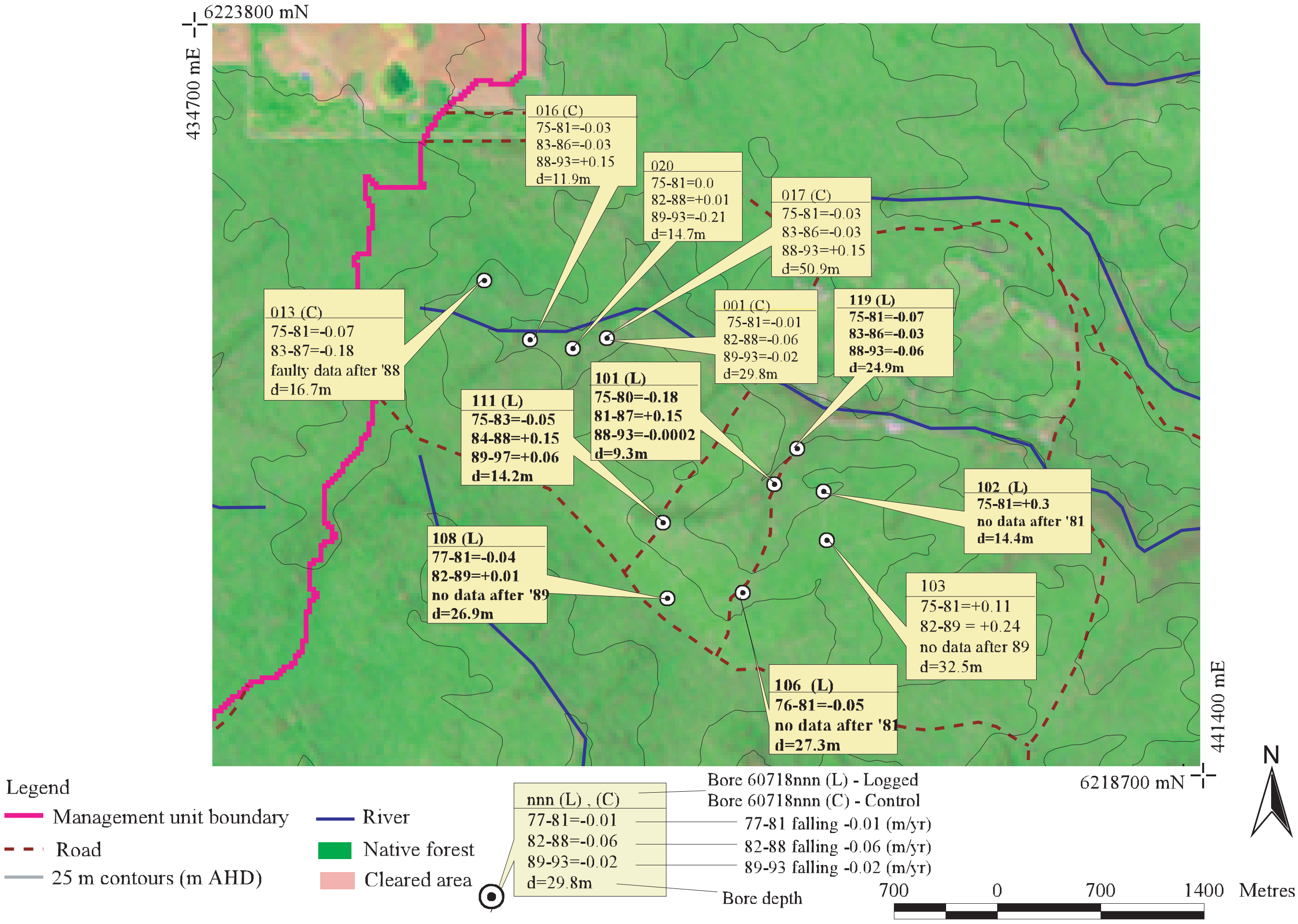


Figure 10. Changing groundwater levels in the Perup MU

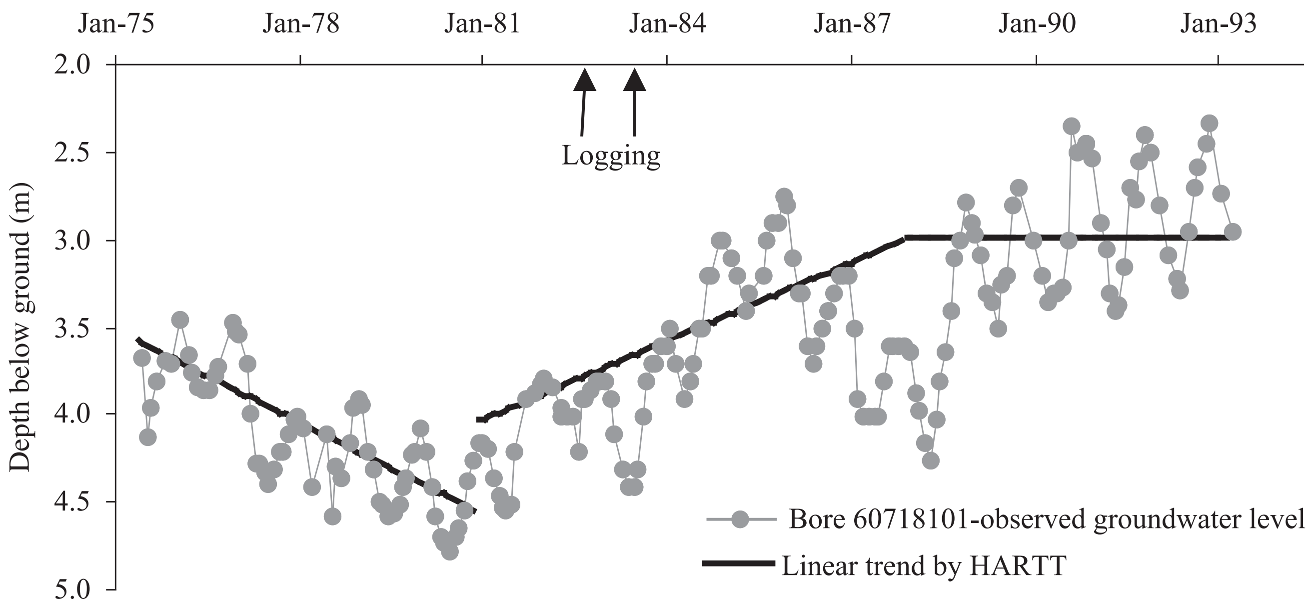


Figure 11. Hydrograph of a bore in the logged area of the Perup MU

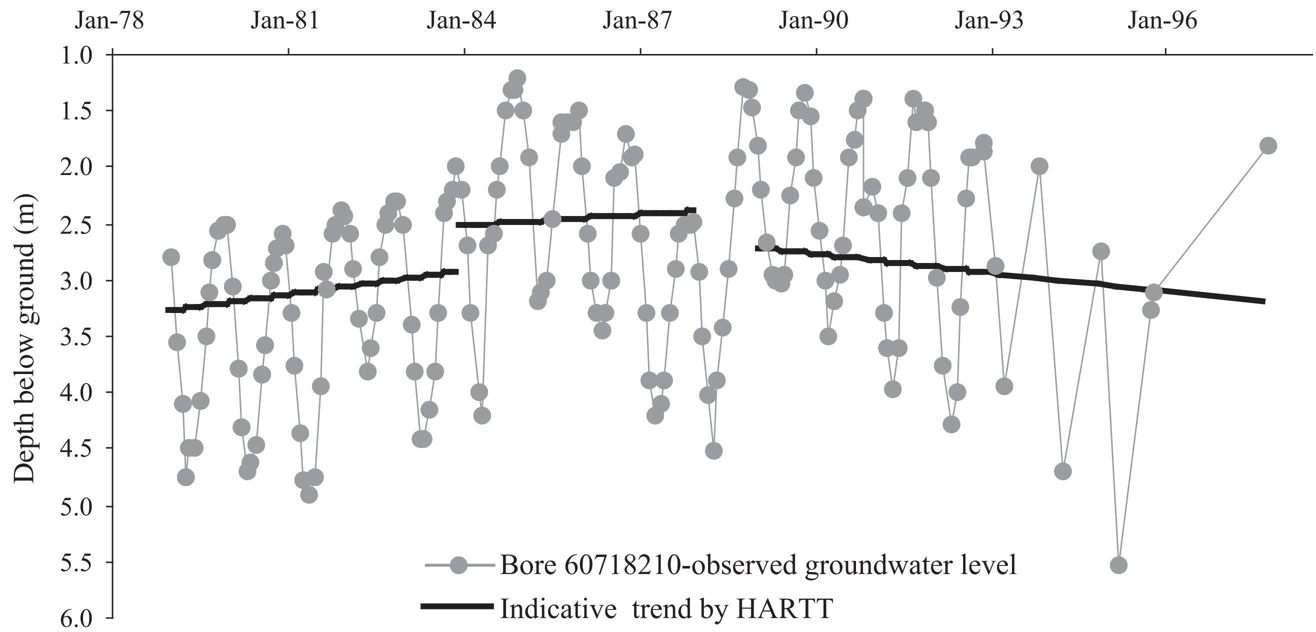


Figure 12. Hydrograph of a bore in native forest in the Barker Road subcatchment

3.3 Areas at risk of dryland salinisation

Eighteen per cent of the area of the upper catchment (excluding the Strachan and Unicup MUs) is considered to be at risk of dryland salinisation (salinity). These areas at risk are waterlogged or are areas where the watertable is now or likely to be within 2 m of the surface (Fig. 13). The criteria for defining areas at risk are summarised in Appendix 3.

The areas at risk incorporate weathered and fractured bedrock aquifers and Cainozoic sedimentary aquifers, and landforms that include valley flats, streamlines and areas adjacent to streamlines.

Salinity risk mapping shows the following areas to be at risk of developing a shallow watertable:

- 20–21% of the Tenner Road, Middle Tone and Upper Tone MUs and 25% of the Lower Tone MU (Fig. 13). Characteristically, these are flat areas (slope < 3%) along the Tone River grading into gently undulating landforms with slopes > 3%.
- about 5% of the Perup MU, including forested areas. Areas at risk are restricted to the bottom of the narrow incised valleys because the steep valley slopes limit the lateral extent of the shallow watertable.
- the broad valleys floors of the Mobrup (36%), Chowerup (23%) and Tonebridge (28%) MUs (Figs 13 & A3.7). In the Mobrup and Tonebridge MUs, the valley floors are associated with poorly-defined surface water drainage. The watertable within the Cainozoic sediments is generally within 2 m of the surface but may be deeper in well-drained sandy sediments.

3.4 Acidic groundwater

Acidic groundwater has been found in the upper catchment. Acidic groundwater has been identified in the Cainozoic sediments of the broad valley flats of the Unicup subcatchment (Roger Hearn, [CALM] 2003, pers. comm.). Groundwater with pH < 5 has been identified within 20 m of surface, associated with Cainozoic sediments found in the broad flat valleys of Mobrup and Tonebridge (Fig. 5). Mobrup has groundwater with pH between 5–6, mainly associated with the weathered bedrock aquifer.

Salinisation in the upper Warren River catchment

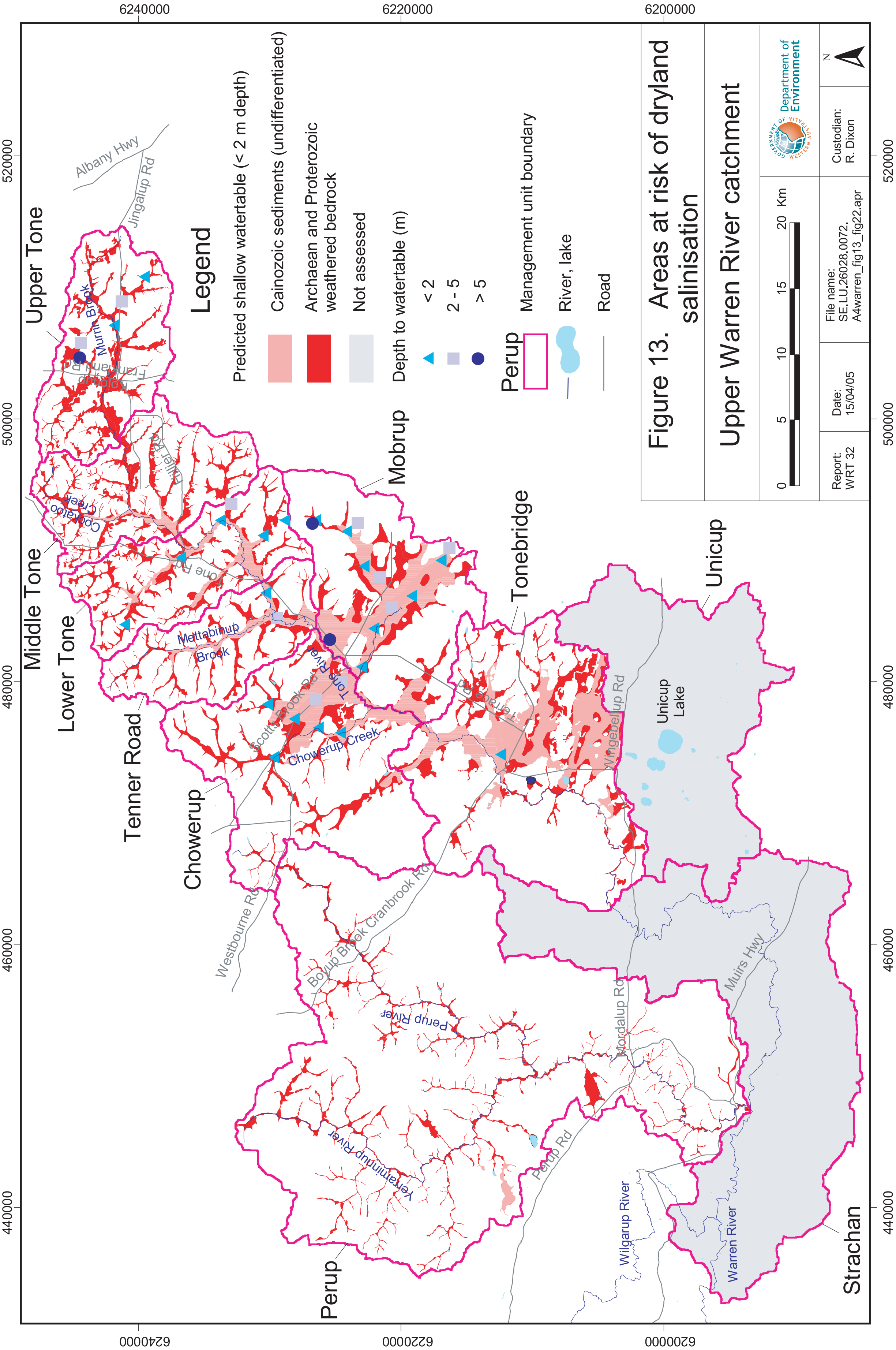


Figure 13. Areas at risk of dryland salinisation

4 Catchment 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 were modelled to validate the model, build confidence by comparing the predictions with actual records, and indicate plant-based and engineering options available to the Recovery Team to reach the target by 2030. These predictions are the 'best guesses' for catchment managers to gauge the extent of changes that may result from actions like planting, clearing, constructing drains, installing groundwater pumping schemes or diverting saline water out of the Warren River before any actions are taken.

The variations in river salinity and flow are primarily due to changes in the catchment water balance and were deduced by trend analysis.

Trend analysis was used to derive a history of river salinity and streamflow under current land use conditions (Section 3) but this method cannot predict changes in flow and salinity expected in response to salinity mitigation works to lower salinity to 500 mg/L TDS.

The Microstation And Geographic Information Computation (MAGIC) model (Mauger 1996), which simulates hydrological processes in the catchment (Fig. 14), calculated the catchment water balance and changes in groundwater seepage for a range of salinity management scenarios, some of which have been proposed as management options.

Some parameters, the calibration and validation of the model are discussed briefly in this section and in Appendix 4, while the results are discussed in Section 5.

4.1 The MAGIC model

The catchment was represented by a three-layered profile over bedrock (Fig. 14) where the weathered bedrock or bottom layer was the main aquifer, overlain by a less permeable thick clay layer topped with a layer of very permeable soil, commonly about 1.5 m thick.

The catchment was divided into a grid of 25 m x 25 m cells (Fig. 15), which were assigned properties (e.g. ground elevation, layer thickness and permeability, vegetation type and density) that represent the actual locations.

The model calculated the water balance of cells in a three-dimensional prototype of the MAGIC model of the upper catchment using hydrogeological data obtained from a drilling program and the catchment topography.

Figure 15 shows the water movements modelled. Rainfall minus 15% (to account for interception) was added to the store of water in the soil layer for transpiration by plants. The transpiration rate depended on the Leaf Area Index (LAI) and the pan evaporation rate attributed to the cell. Plants drew water from this layer until it was dry. Water could be added to the soil layer by lateral inflow from the soil of upslope adjacent cells, or lost by lateral outflow to downslope cells. The rate of lateral water movement depended on the slope of the ground, permeability and moisture content of the soil. Water could also be added by upward flow of groundwater, or lost by infiltration from the soil layer to layers below. The rate of flow depended on the vertical permeability of the lower layers. Monthly water inputs and outputs were added to the water content of the soil layer at the start of the month. If the total exceeded the saturation capacity of the layer, the excess was allocated to runoff, which was the baseflow component of the stream.

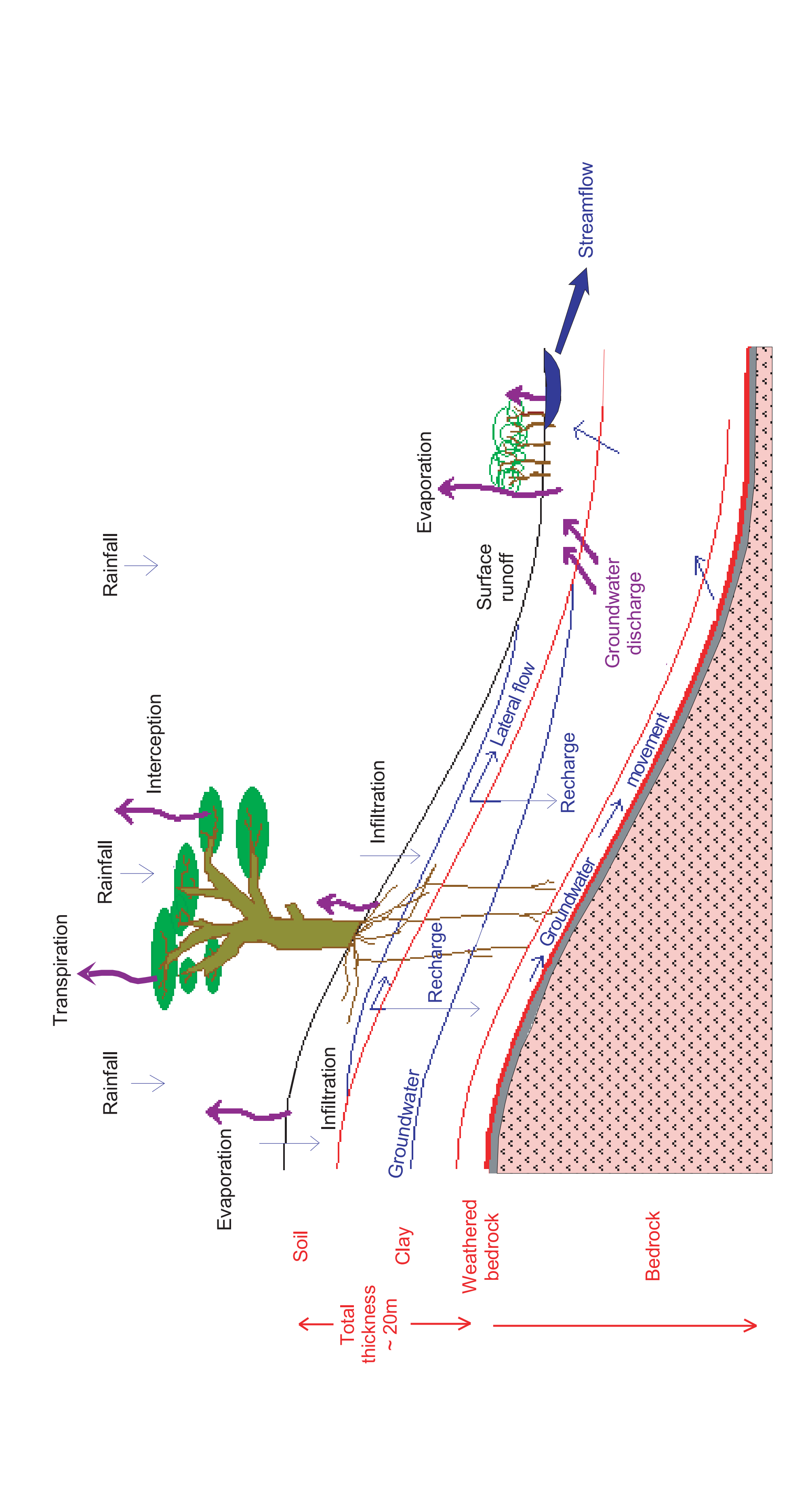


Figure 14. Representation of hydrological processes used in MAGIC model

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Date: 15/04/05

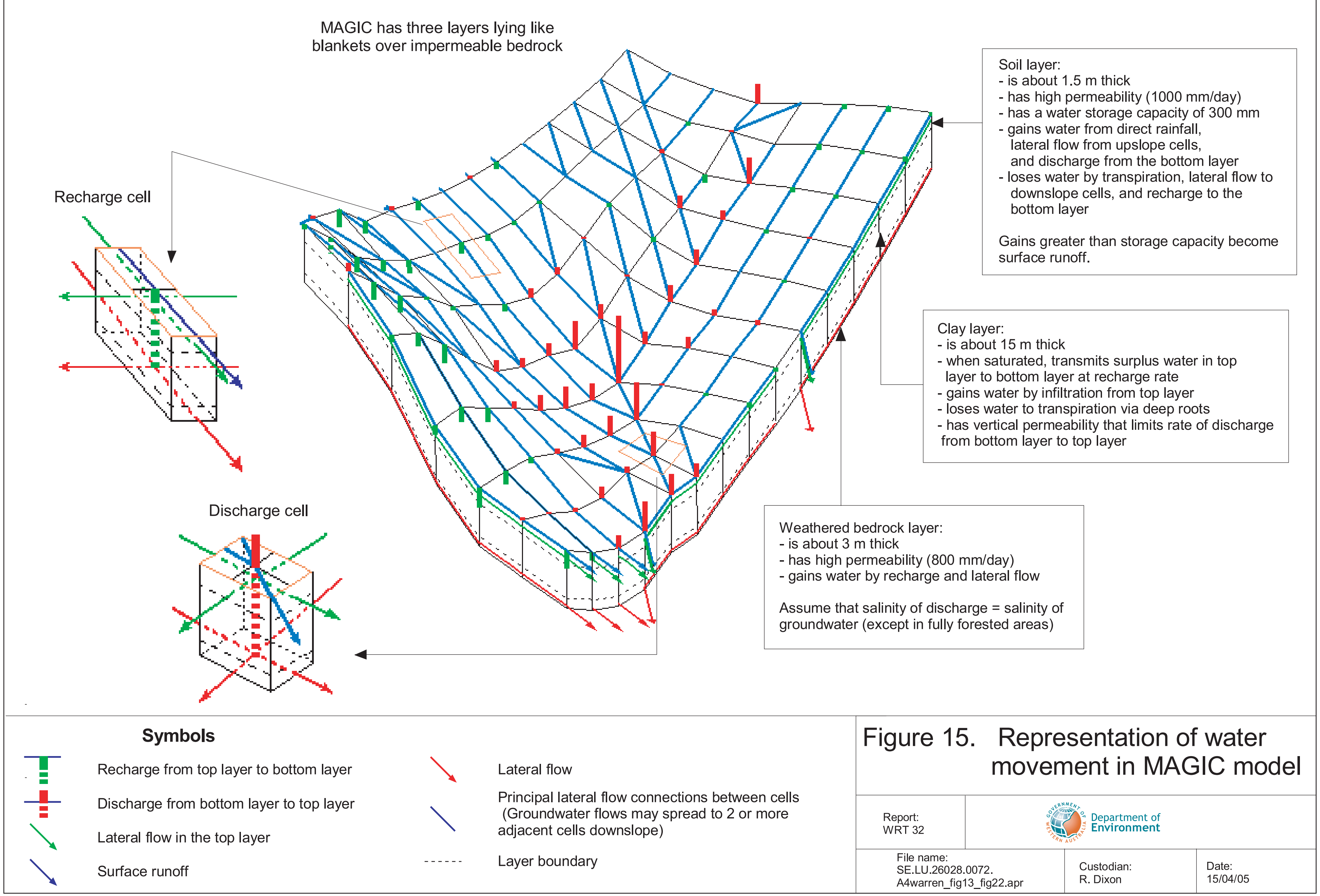

Figure 15. Representation of water movement in MAGIC model

Report: WRT 32

Department of Environment

File name: SE.LU.26028.0072. A4warren_fig13_fig22.apr

Custodian: R. Dixon

Date: 15/04/05

Below the soil layer was a thick clay layer, commonly about 15 m deep, from which plants with deep enough roots could draw water for transpiration when the soil layer was too dry. The bottom layer which is very permeable and has the main aquifer, principally in a weathered bedrock zone, was typically about 3 m thick, and allowed groundwater to move readily towards the valley bottom.

4.2 Building the MAGIC model

The steps in developing, refining and then applying the MAGIC model in the upper Warren River catchment are depicted in the chart (Fig. 16) and documented in Appendix 4.

4.2.1 Setting up the model (Step 1)

To set up the MAGIC model, the available information on geology, slope, elevation, drainage, rainfall and pan evaporation was collated and assumptions made to cover gaps in experimental or field data. Data such as evapotranspiration, infiltration, rate of groundwater movement, water quality, and surface runoff were derived from this input. Details of setting up the model are included in Appendix 4.

4.2.2 Calibrating and validating the model (Step 2)

Model results to this point were based on some estimated parameters. The suitability of these estimates was tested and refined by calibration and validation.

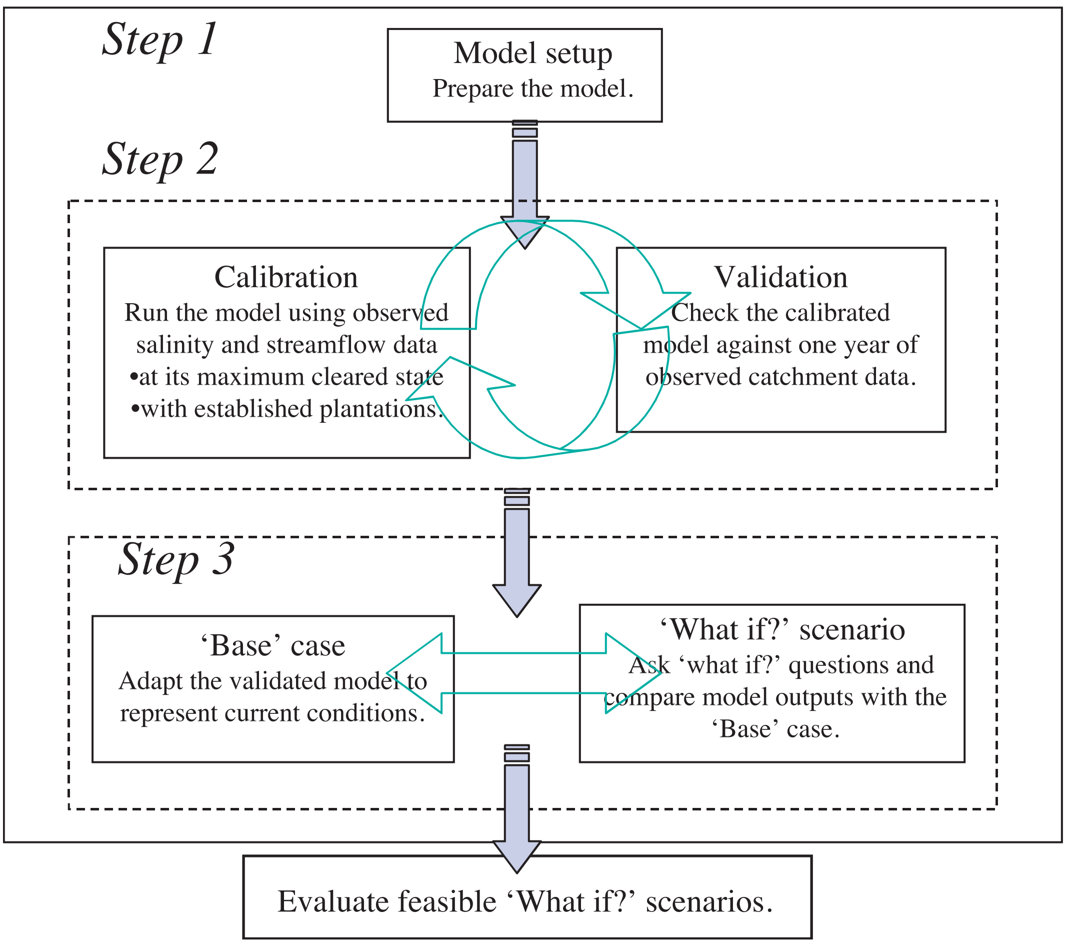

Figure 16. Application of the MAGIC model

Before modelling the catchment, the MAGIC model was calibrated and validated using two known land use states: when the catchment was at the maximum extent of clearing, and when there was a significant area of tree plantations on agricultural land. These calibrations used 1993 and 2000 data from three gauging stations. The year 1993 represented the peak values of stream salt load, while data from 2000 represented the current state of the catchment. The MAGIC model was considered to be well calibrated for the upper Warren River catchment, and the calibration details and results are presented in Appendix 4.

The calibration of the model defined the parameter set and it was validated using one year of observed data in 2000 (see Appendix 4 for details).

4.2.3 'Base' case and 'What if?' scenarios (Step 3)

The 'Base' case represents what would be expected if there were no further changes in how land is used or managed (Appendix 4). It includes the effects of recent land use changes (up to 2000) such as the establishment of tree plantations in the wetter parts of the catchment, and is discussed in Section 5.

It represents the catchment at hydrologic equilibrium under the following conditions:

- It uses the parameter set obtained in the model calibration (Appendix 4).
- It uses average monthly rainfall calculated from records between 1980 and 1995. The average annual rainfall over this period was 770 mm, similar to the 1993 rainfall of 750 mm.
- It incorporates land use (pastured land, forest, plantations) from the Landsat TM scene for February 2000. The total estimated area of plantations captured in this scene was 72 km^2, of which 36 km^2 were not fully established.

'What if?' scenarios are the prospective management options. Their outcomes predict salinity and streamflow under a range of revegetation and engineering alternatives. These predictions are compared with the 'Base' case predictions to see how streamflow, salinity and salt load alter after changes in land use. Details of all modelled 'What if?' scenarios are discussed in Section 5.

5 Catchment management options

The introduction of clearing controls, and extensive areas of tree plantations have clearly checked the rise of salinity of the Warren River but much more intervention by land use changes or engineering works will be required in order to meet the target salinity (Fig. 17). Some interventions are described in this section. If no additional work is done after 2003 it is predicted that salinity levels of the Warren River at the Barker Road Crossing gauging station will stabilise at 805 mg/L TDS.

Salinity trend analysis quantifies existing changes in salinity related to current land use and modelling quantifies the changes in flow and salinity expected after proposed salinity mitigation works. Together they were used to describe river salinity over the period of land clearing controls of 1978, the establishment of plantations during the 1990s and projected salinity mitigation works (Fig. 17).

Trend analysis revealed that established plantations combined with the decreased average annual rainfall in the Perup River and Tone River subcatchments have already had a positive impact on water quality at the Barker Road Crossing gauging station. The stream salinity at mean flow at the Perup River gauging station has been decreasing and, although stream salinities at both the Barker Road Crossing and the Tone River gauging stations are still rising, they are rising more slowly. If the clearing controls had not been introduced and all private land had been cleared, average annual salinity may have risen to 1500–1550 mg/L TDS (Fig. 17). If plantations had not been established during the 1990s the salinity of the Warren River may have risen to just over 950 mg/L TDS.

A range of management options were selected for modelling (Table 3) and the results indicate the scale of interventions still required to achieve the target. This study was initiated in 2001, so the 'current' land use was captured in the year 2000. Under current land use, salinity of the Warren River is still rising but more slowly than before and is expected to reach a mean of 870 mg/L TDS. All management options are compared to the current or 'Base' case.

The three conceptual options are predicted to achieve the target 500 mg/L TDS (the numbers in brackets are salinities at steady state):

- Planting 70% of the existing pastured area with non-commercial trees (about 415 mg/L TDS)
- Groundwater pumping (22 kL/day/bore from 1625 bores) (about 500 mg/L TDS)
- Full diversion of saline water from the Tone River (about 380 mg/L TDS)

Sections 5.2 and 5.3 discuss the results. Appendix 5 (Tables A5.10–A5.32) shows the results by management units.

Unless stated otherwise, the following results apply at the Barker Road Crossing gauging station.

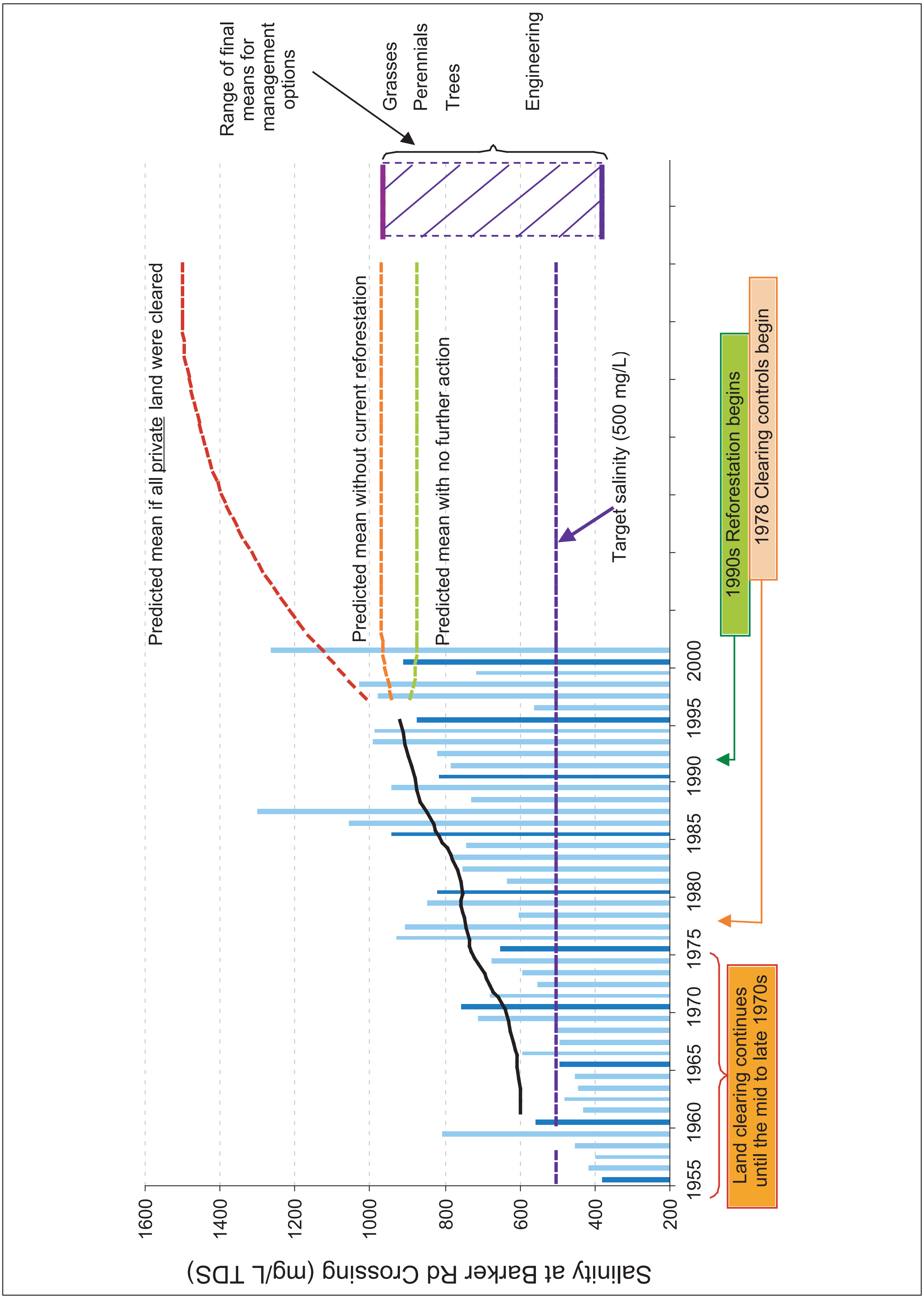

Figure 17. Warren River salinity

Table 3. Summary of analysis of management options

				At Barker Road Crossing gauging station		
	Management option	*Comments*	*Pastured land replaced* (%)*	*Salinity (mg/L TDS)*	*Streamflow (GL)*	*Salt load (kt)*
	'Base'		0	870	240	210
REVEGETATION OPTIONS	***Commercial trees****	Sited by land capability				
	Bluegums	Bluegums 3%	3	855	240	205
	Bluegums & sawlogs	Bluegums 3% & sawlogs 9%	12	805	235	190
	Bluegums, sawlogs & pines	Bluegums 3% & sawlogs 9% & pines 8%	20	750	230	175
	Non-commercial trees	Not sited by land capability	70	415	210	85
		On waterlogged land	26	940	215	205
	Perennial pastures**+					
	Deep-rooted	Sited by land capability	20	795–820	230–235	185–190
	Shallow-rooted	Sited by land capability	46	750–820	220–225	165–185
	Shallow-rooted	Using same land as deep-rooted pastures	20	820–850	230–235	190–200
	Shallow-rooted	Using land not suitable for deep-rooted pastures	26	805–845	230–235	185–195
	Perennial grasses	On waterlogged land	26	895–940	200–225	205–210
	Combinations	Commercial trees & shallow-rooted perennial pastures	46	675	220	150
		Shallow-and deep-rooted perennial pastures	46	720–790	220–225	155–180
ENGINEERING OPTIONS	***Drains***	0.5 m deep @150 m spacing		875	240	210
		1.0 m deep @ 150 m spacing		875	240	210
			Volume (GL)			
	Groundwater pumping	22 kL/day/bore from 1625 bores	13	500	230	115
	Diversion of saline water	Pipehead dam (20%)	3.98	775	235	185
		Pipehead dam (30%)	6.16	725	235	170
		Full diversion	31.3	380	205	80

* Pastured land (768 km^2) replaced by alternative crops (calculated for the upper catchment)

** Land capability maps used to site plantations and perennial pastures

\+ Results given as a range because of uncertainties of LAI for perennial pastures

5.1 'Base' case

The 'Base' case (Section 4.2.3 & Fig. 16) represents the predicted salinity, streamflow and salt load in the Warren River under the land use conditions in 2000 (including plantations of 72 km^2 of which half were not fully established) but without the additional 102 km^2 of plantations planted between the years 2000 and 2003 (totalling to 178 km^2, Table A2.5). The commercial trees (bluegums and sawlogs) case, which was the closest modelled scenario that matched the land use in 2003 predicted a salinity of 805 mg/L TDS and had an extra 92 km^2 of plantations (Table A5.11).

All modelled management options are compared with the 'Base' case: stream salinity 870 mg/L TDS (Table 3; Appendix 5, Table A5.9) with an annual streamflow of 240 GL and a salt load of 210 kt.

5.2 Revegetation options

Five revegetation categories were modelled: 1) commercial trees 2) non-commercial trees 3) perennial pastures, 4) perennial grasses and 5) combinations of trees and shallow-rooted perennial pastures.

The climatic, landscape and soil requirements for commercial trees and perennial pastures were appraised and suitable areas identified and incorporated into the catchment model. Figures 18–21 show these suitable areas of existing pastured areas as 'land capability' maps. The process for producing these maps is described in Appendix 5.

5.2.1 Commercial trees

Replanting suitable existing pastured land with commercial tree plantations will not achieve the target (Table 3; Appendix 5, Tables A5.10–A5.12).

If 3% of the pastured area is replaced with bluegum (*Eucalyptus globulus*) plantations, the annual streamflow remains at 240 GL, and salt load decreases from 210 to 205 kt (Table 3) with salinity 870–855 mg/L TDS.

If an additional 9% of the pasture area is replanted with bluegum and sawlog (*E. cladocalyx*, *E. saligna* or *Corymbia maculata*) plantations (Fig. 18) the results are salinity of about 805 mg/L TDS, and streamflow and salt load respectively 235 GL and 190 kt.

Pine trees (*Pinus pinaster*) can be planted on land suitable for bluegums and sawlogs but also on deep sandy soils unsuitable for the hardwood species (Fig. 19). Planting 20%, or 15 700 of 76 800 ha, of the pastures with a mix of bluegums, sawlogs and pines results in salinity of about 750 mg/L TDS, annual streamflow and salt load of 230 GL and 175 kt respectively.

The areas in the Mobrup and Chowerup MUs considered suitable for commercial tree plantations may be too conservative as plantations are being established on land rated in this study as unsuitable or of low suitability. Further site investigations may show that more land is actually suitable for commercial tree plantations than was selected in this study.

5.2.2 Non-commercial trees

Planting 70% of the pastured land with non-commercial trees is the most effective revegetation management scenario: salinity falls to 415 mg/L TDS and annual streamflow and salt load are 210 GL and 85 kt respectively (Table 3).

Non-commercial trees include exotic and native species grown in waterlogged areas or in areas not suitable for commercial tree plantations. They were assumed to include species that tolerate waterlogging and use water of any quality.

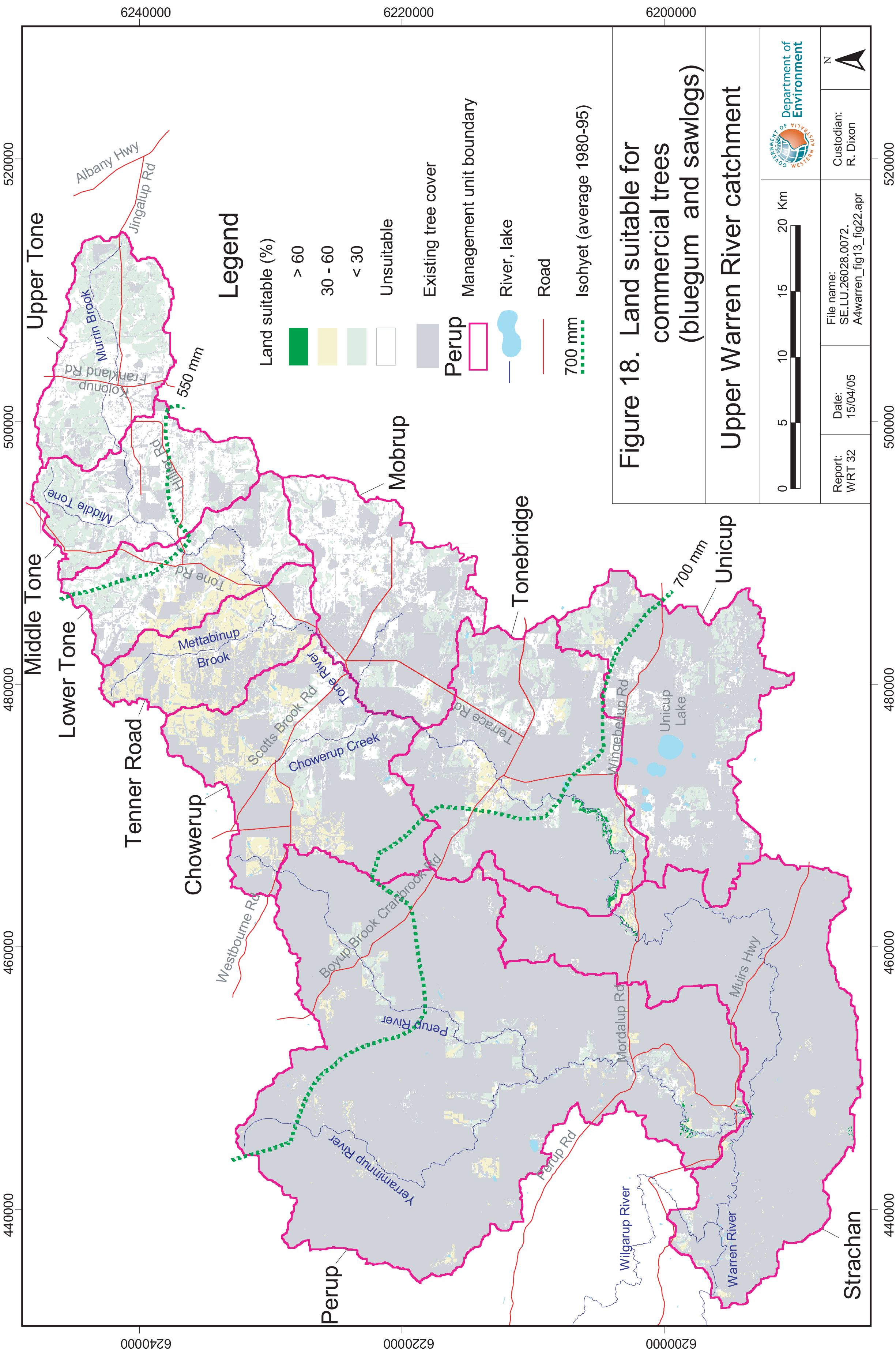

Figure 18. Land suitable for commercial trees (bluegum and sawlogs)

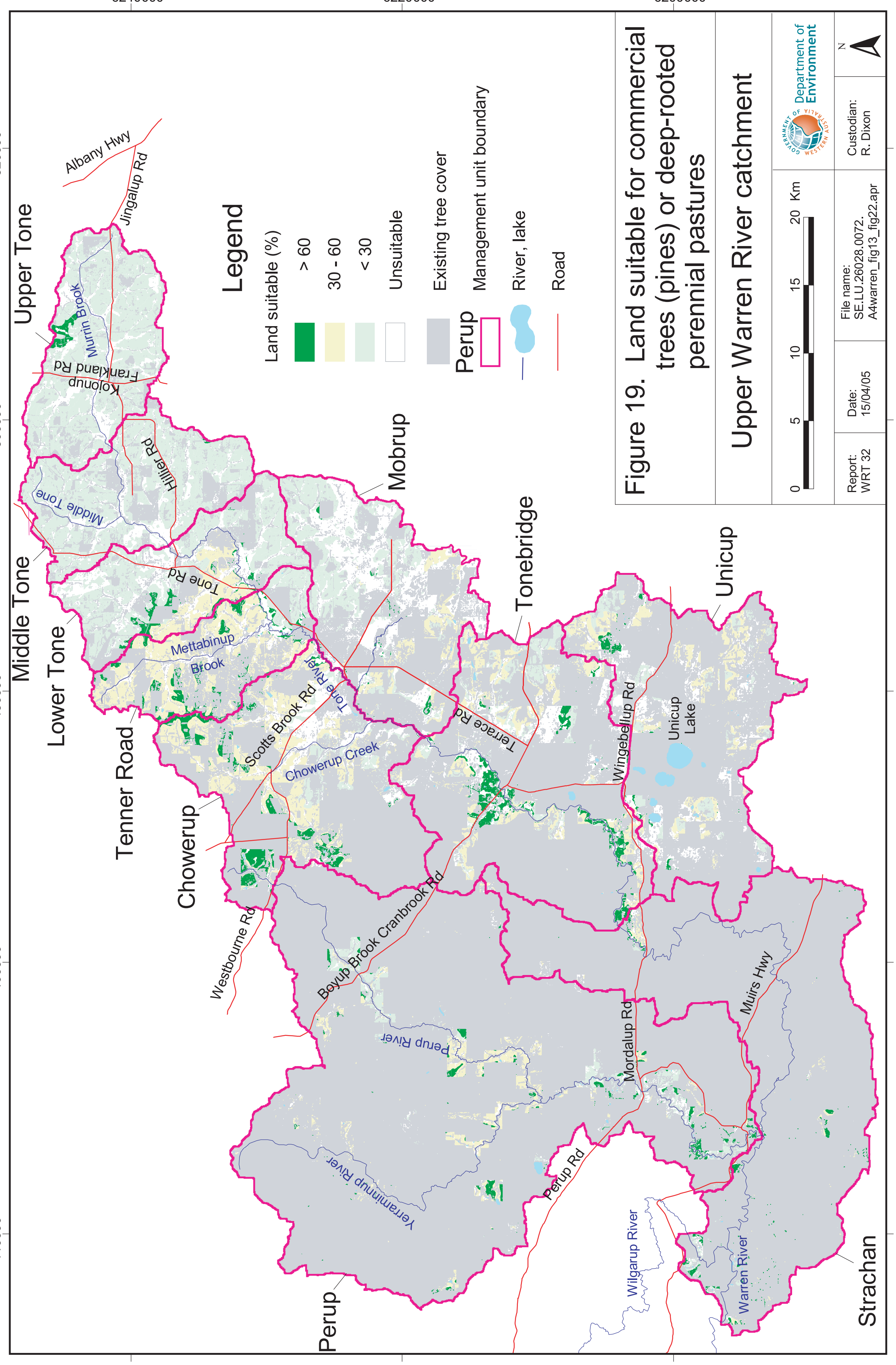

Figure 19. Land suitable for commercial trees (pines) or deep-rooted perennial pastures

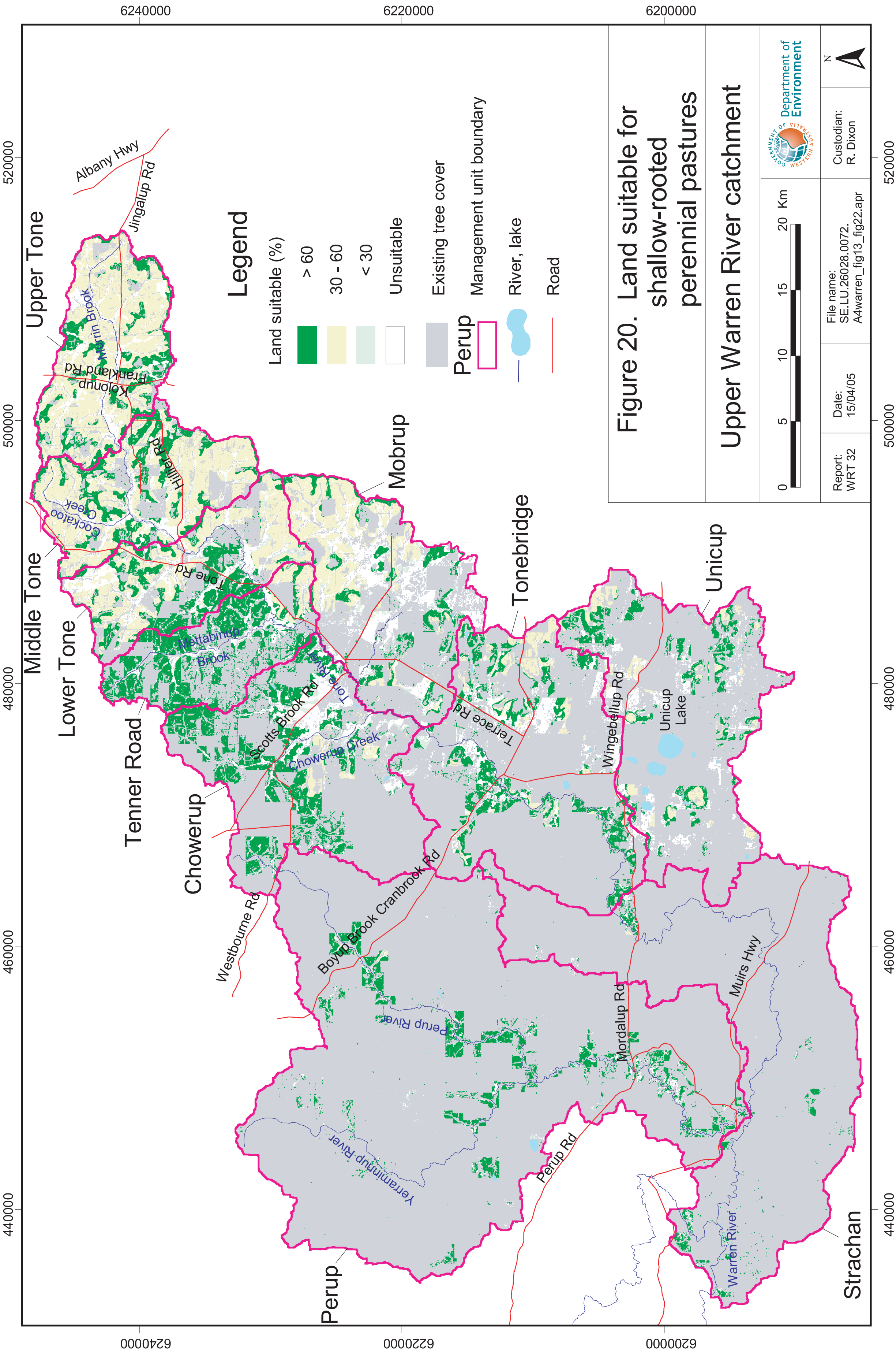
Figure 20. Land suitable for shallow-rooted perennial pastures
Upper Warren River catchment
Legend
Land suitable (%)
> 60
30 - 60
< 30
Unsuitable
Existing tree cover
Perup
Management unit boundary
River, lake
Road
Upper Tone
Middle Tone
Lower Tone
Tenner Road
Chowerup
Mobrup
Tonebridge
Unicup
Perup
Strachan
Albany Hwy
Jingalup Rd
Frankland Rd
Kolonup
Murrin Brook
Cockatoo Creek
Hillier Rd
Tone Rd
Mettabinup Brook
Tone River
Scotts Brook Rd
Chowerup Creek
Terrace Rd
Wingebellup Rd
Unicup Lake
Westbourne Rd
Boyup Brook Cranbrook Rd
Perup River
Mordalup Rd
Muirs Hwy
Yerraminnup River
Perup Rd
Warren River
0 5 10 15 20 Km
Department of Environment
Government of Western Australia
N
Report: WRT 32
Date: 15/04/05
File name: SE.LU.26028.0072. A4warren_fig13_fig22.apr
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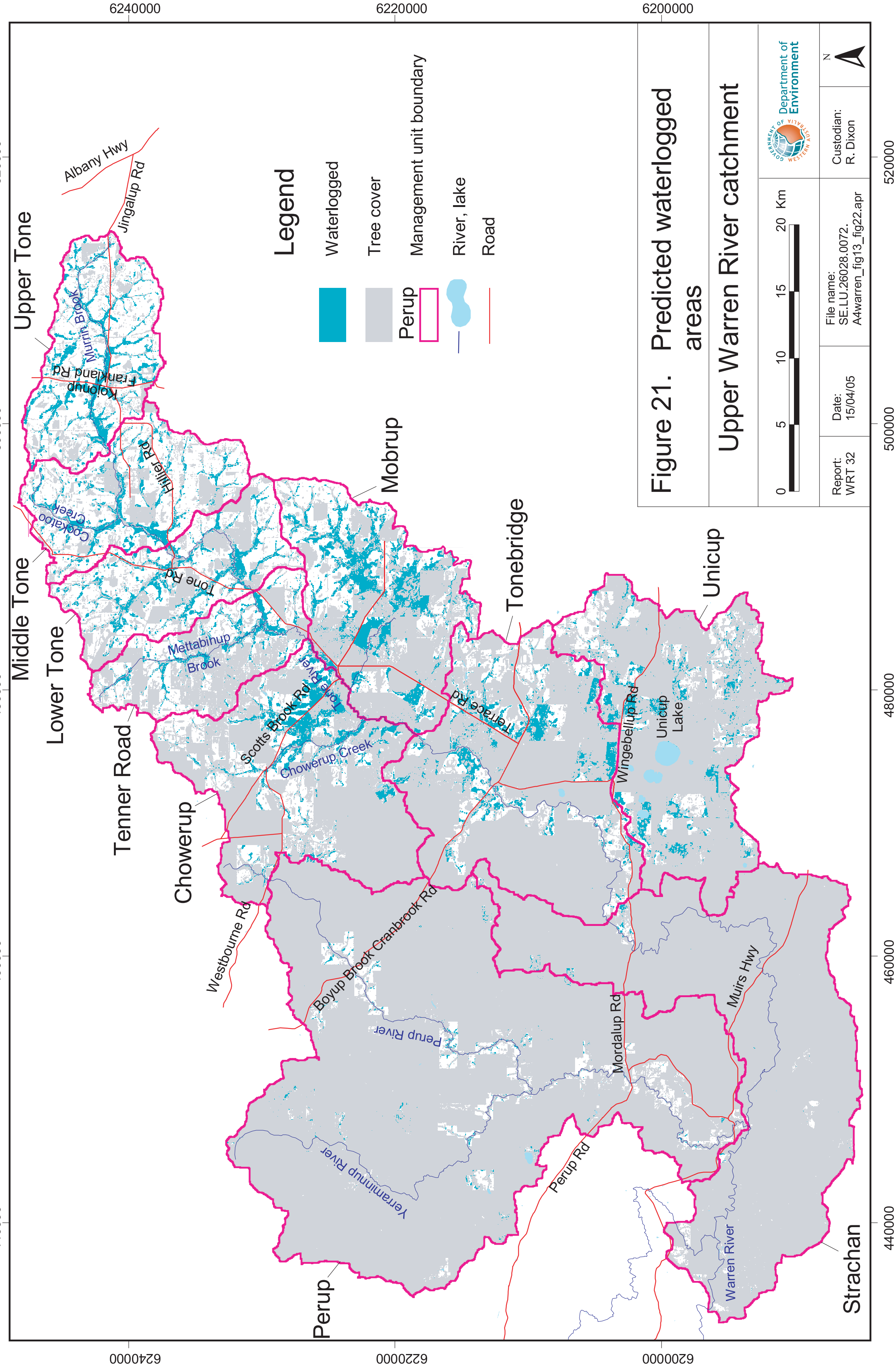

Figure 21. Predicted waterlogged areas

Upper Warren River catchment

Non-commercial trees planted on waterlogged land (26% of the pastured land) (Fig. 21) should decrease the salt load by about 5 kt (from 210 to 205 kt) but, combined with 25 GL decrease in streamflow, would result in the stream salinity rising to 940 mg/L TDS (Table 3; Appendix 5, Table A5.13).

5.2.3 Deep-rooted and shallow-rooted perennial pastures

None of the perennial pastures scenarios reduced salinity to anywhere near 500 mg/L TDS (Table 3).

Perennial pastures and crop species use more water than annual pastures and so have the potential to reduce recharge to groundwater (Latta et al. 2001; Ward et al. 2001; McDowall et al. 2003; Sanford et al. 2003). There has been research and development work to incorporate them into Western Australian dryland farming systems.

Perennial pastures are classified as either deep rooted (e.g. Lucerne (*Medicago sativa*)) or shallow rooted (e.g. Cocksfoot (*Dactylis glomerata*)). Deep-rooted species may obtain water from a depth of more than 1.5 m, while shallow-rooted species may only draw water from between 0.5 and 1.50 m. Deep-rooted pastures are restricted to land similar to that used for commercial trees (Fig. 19), whereas shallow-rooted perennials are suited to a wider range of locations (Fig. 20).

The simulations used the same LAI throughout the year (the LAI of annual pastures is changed monthly to represent the variations in water use during the growing season). Perennial pastures were assumed to be dormant (not dead) in summer when there is insufficient soil moisture, and to re-establish transpiration once enough soil water is available. The results are given as a salinity range as there has not been enough experimental work to estimate LAI values for lucerne, especially when it is cultivated under a system of rotational grazing.

Deep-rooted perennial pastures are a little more effective than shallow-rooted pastures in reducing salinity (Table 3; Appendix 5, Tables A5.14–A5.23). Planting lucerne on 20% of the suitable land reduces annual streamflow to 230–235 GL, annual salt load to between 185 and 190 kt and salinity to 795–820 mg/L TDS.

A combination of deep- and shallow-rooted perennial pastures on 46% of the cleared land gives the best results: salinity between 720–790 mg/L TDS, annual streamflow 220–225 GL and salt load 155–180 kt annually.

5.2.4 Perennial grasses on waterlogged land

Planting perennial grasses on waterlogged land (26% of the existing pastures) (Fig. 21) will raise salinity.

Streamflow is 200–225 GL (up to 40 GL less than the ‘Base’ case), salt load is 205–210 kt but the stream salinity is predicted to be 895–940 mg/L TDS (Table 3; Appendix 5, Tables A5.24–A5.26), which is higher than in the ‘Base’ case.

5.2.5 Combinations — commercial trees and shallow-rooted perennial pastures

If 46% of the existing pastures is replaced with a combination of commercial trees (20%) and shallow-rooted perennial pastures (26%), the predicted salinity is 675 mg/L TDS, streamflow 220 GL and salt load 150 kt (Table 3).

5.3 Engineering options

Engineering works modelled were groundwater pumping, shallow drains and the diversion of saline water (Appendix 5, Tables A5.27–A5.32). Section 5.3.3 discusses why deep drains were not modelled.

5.3.1 Groundwater pumping

Saline groundwater pumped at the rate of 22 kL/day/bore (total of 13 GL from 1625 bores) results in an annual salt load of 115 kt, and salinity of 500 mg/L TDS (Table 3; Appendix 5, Table A5.27).

Pumping extracts groundwater and the salt it contains from the weathered and fractured bedrock aquifer before the groundwater discharges onto the surface or into watercourses and, if transported out of the catchment, prevents the salt entering the streamflow.

Some comments on these results:

- The pumps were assumed to collect 50% of the groundwater discharged and decrease streamflow by the volume of pumped groundwater.
- Pumping the large volumes of relatively low salinity groundwater (about 4000 mg/L TDS in the areas of thick Cainozoic sediments in the Mobrup, Tonebridge, and Unicup MUs) was not considered to be useful as this would reduce streamflow more than it reduced salinity and would only have a minimal effect on the final stream salinity at the Barker Road Crossing.
- Pumping groundwater from a large discharge area introduces practical problems in locating and maintaining many bores in a simple network connected by collector pipes (Fig. 22; Appendix 5, Table A5.5).
- Additional pumping would be necessary to transport the groundwater out of the catchment. The water in the collector network in the Tone River subcatchment would almost flow by gravity once the groundwater was pumped to the surface. Disposal to the south-eastern side of the catchment would need a small boost in pressure to clear the catchment divide. Water from the lowest bores in the Perup River subcatchment would need to be lifted about 100 m (usually in stages) to clear the catchment if discharged northward.

5.3.2 Shallow drains

Neither of the two scenarios (drains 0.5 m deep and 150 m apart; and 1 m deep and 150 m apart) improved salinity. Both result in stream salinity (875 mg/L TDS) similar to the 'Base' case scenario (Table 3; Appendix 5, Tables A5.28 & A5.29).

Shallow drains are designed to allow both surface water and water moving through the soil layer to be removed from or diverted around poorly drained areas to reduce waterlogging and improve agricultural productivity. Shallow drains are sometimes constructed on hillsides (as 'grade banks') to reduce recharge in downslope areas.

Shallow drains are quite acceptable, if desired, for farm management because they will not increase stream salinity and will improve agricultural productivity in areas subject to waterlogging.

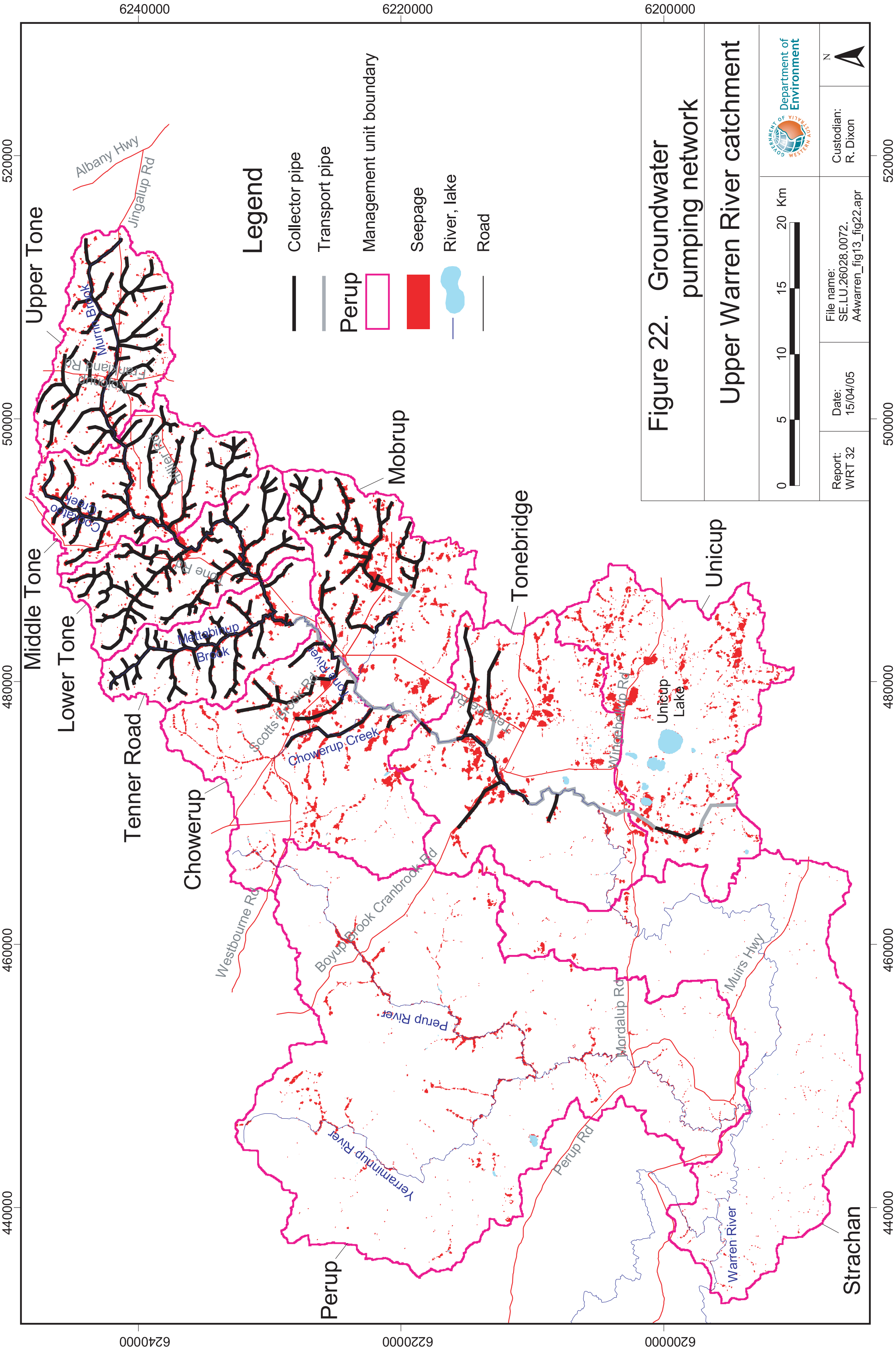

Figure 22. Groundwater pumping network Upper Warren River catchment

5.3.3 Deep drains

Deep drains were not modelled, as their effect is similar to that of groundwater pumping.

Deep drains, constructed within discharge areas, intercept saline groundwater and move it to receiving waterbodies. In favourable sites, the drains improve nearby agricultural productivity by removing the saline groundwater before it reaches and contaminates near-surface soils.

Deep drains may be closed or open. Closed drains collect only groundwater but open drains also collect local runoff. Larger and more variable water flow rates must be handled when dealing with disposal of water from open drains than when disposing of groundwater from pumping schemes.

Saline groundwater collected by deep drains and not discharged downstream contributes to improving stream salinity. If there are suitable methods to dispose of the drain water without going into the Warren River this option should be compared with the groundwater pumping option, which also withdraws groundwater before it reaches surface.

If the outflow from the end of the deep open drain is not diverted into an isolated receiving body, the total salt load delivered into the streams will not be reduced. While the annual salt load is the same, its seasonal distribution may be altered with environmental implications for downstream areas.

5.3.4 Diversion of saline water

Full diversion of the Tone River water would reduce the salinity to 380 m/L TDS (Table 3; Appendix 5, Tables A5.31 & A5.32). Diversion of 20% of the salt load (from the Tone River) using a pipehead dam would give an annual salinity of 775 mg/L TDS (Table 3; Appendix 5, Table A5.30) while diversion of 30% of the salt load would reduce stream salinity even further to 725 mg/L TDS.

Diversion of saline river water was originally addressed in the late 1970s by the Public Works Department (Public Works Department 1980). This study investigated the diversion of all or part of the Tone River streamflow and construction of a large dam on the Tone River, at the damsite recommended in the report by the PWD in 1980.

Extensive site works would be needed for a dam with a wall height of about 36 m (Appendix 5, Table A5.6). The dam would require the relocation of the Mordalup Road Crossing and would affect several roads. Complete filling of the reservoir would inundate about 1000 ha of mainly forested land along with some cleared land on the eastern side of the river.

The original proposed disposal site was the Frankland River (Public Works Department 1980). To continue with such a plan, the impacts of the saline water on existing water quality, ecosystems, and on flow within the Frankland River would need to be investigated.

Gravity channels, pumping station networks and pipelines were among options proposed for disposing of water into the Frankland River (Public Works Department 1980). The PWD study highlighted the need for caution when transporting water in channels due to the maze of lake systems in the area and the impacts of possible channel leaching.

6 Conclusions

The salinity of the Warren River at the Barker Road Crossing gauging station is currently an average 895 mg/L TDS — still significantly above the target salinity of 500 mg/L. If no additional work is done, salinity will level out about 805 mg/L TDS.

The current salinity situation statement for the Warren River is:

- The average annual flow-weighted salinity (1990–2001) is 895 mg/L TDS with a range 560–1270 mg/L.
- The average annual salinity in the Perup River peaked in the 1990s. The average annual salinity is still rising at 51 mg/L TDS through the Tone River gauging station and at 7 mg/L TDS through the Barker Road Crossing gauging station. These rates have slowed since 1992 and the changes are attributed to land use changes such as extensive tree planting in the Perup River subcatchment. Some tree planting has occurred in the west of the Tone River subcatchment but it has not been of sufficient scale to reverse the salinity trend at this point.
- Approximately 18% of the upper catchment is at risk of developing a shallow watertable (within 2 m of surface).
- The stream salinity of the Warren River is starting to level off.

Some results of the range of management options modelled to assess their effectiveness in reducing salinity are:

- Three of the options could achieve the water quality target: replanting 70% of the current pastured land with non-commercial trees (415 mg/L TDS); pumping 13 GL groundwater from the weathered and fractured bedrock aquifer (500 mg/L TDS), and diverting all the water (31.3 GL) from the Tone River into a nearby river outside the Warren River catchment (380 mg/L TDS).
- *Plantations of commercial trees* (eucalypts for pulp, or hardwood sawlogs and pines) on the 20% of the pastured land rated suitable by land capability mapping lowers the salinity to about 750 mg/L TDS. This area may be conservative as plantations are being established on land rated by the land capability mapping as either unsuitable or of low suitability.
- *Perennial pastures* (both deep and shallow rooted) planted on 46% of the pastured land lower salinity to 720–790 mg/L TDS. Modelling used assumptions on the water use and rooting depths of perennial pastures. Not enough is known to determine LAI for deep-rooted pastures: especially since lucerne pastures can be managed under a variety of farming systems such as rotational grazing.
- *A combination of commercial trees and shallow-rooted perennial pastures* planted on 46% of the pastured land lowers salinity to about 675 mg/L TDS.
- *Shallow drains* will not reduce salinity.
- *Pumping groundwater* (13 GL a year from 1625 bores) from the Tone and Perup subcatchments reduces salinity to 500 mg/L TDS.
- *Diversion of 20–100% of the saline water* from the Tone River reduces salinity to a range of 380–775 mg/L TDS.

7 Recommendations

Management options

- Communicate results to all major stakeholders so that they can have input into any subsequent or on-going work.
- Assess the social, economic and environmental costs and the benefits of all management options.
- Use an additional 'dynamic' model to ensure accurate predictions of the effects of management options.
- Investigate the effectiveness of deep-rooted and shallow-rooted perennial pastures in reducing recharge to groundwater and reducing salinity. Investigate the average rooting depths of perennial plants in a range of soils.
- Investigate the accuracy and usefulness of land capability mapping at farm scale. Regional-scale information was used to identify areas suitable for planting commercial trees and deep-rooted perennial pastures but this mapping that may be unnecessarily restrictive.
- Ascertain the sustainability of current commercial timber plantations on land assessed by this study's land capability mapping as having low suitability for this purpose.
- Determine the average rooting depth across different soil types for a range of perennial pasture plants.
- Review groundwater pumping results of existing trials (such as Maxon Farm) and proposed demonstrations sites of the WA Engineering Evaluation Initiative, and identify the potential of this option for the upper catchment.
- Review and identify farming systems able to combine elements of the different land use options.
- Evaluate water management options to attain the potable target for critical parts of the years by pumping during high flow periods.

Monitoring and evaluation

- Keep monitoring streamflow and salinity at the mainstream gauging stations to calculate whether recent trends (1992–97) continue and, in particular, if the downward salinity trend in the Perup River continues when harvesting of existing commercial timber plantations begins.
- Maintain monitoring of groundwater levels but review the frequency of measurement. The frequency needs to be at intervals appropriate to discern trends, particularly in those areas where groundwater has been rising.
- Develop Leaf Area Index (LAI) estimates for deep-rooted and shallow-rooted perennial pasture plants to confirm modelling assumptions, especially under different farming practices.

Glossary and acronyms

AQWABase	The Water and Rivers Commission's groundwater point source database for Western Australia, now incorporated in the WIN database
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 TM image that has sunlit green leaves
Groundwater level	An imaginary surface representing the total head of groundwater and defined by the level to which water will rise in a piezometer
Hectare (ha)	10 000 square metres or 2.47 acres 100 ha = 1 square kilometre
Kilolitre (kL)	1000 litres, 1 cubic metre or 220 (approx.) gallons
LAI	Leaf Area Index, defined as a ratio of single-sided area of leaves to the area of land occupied by the plants, and 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
Management unit (MU)	Land areas defined by the local community predominantly based on surface water drainage with some variations to account for social boundaries
Recharge	The downwards movement of water that is added to the groundwater system
Regolith	Geological material from fresh rock to the ground surface and in the upper catchment includes weathered bedrock, sediments and soil
Salinity (specific)	The concentration of total dissolved salts in water
Salinity (general)	Term applied to the effects on land and in water of the build up of salt in the surface as a result of rising groundwater
TDS (mg/L)	Total dissolved salts expressed as milligrams per litre
TSS (mg/L)	Total soluble salts expressed as milligrams per litre
Transpiration	Process by which water vapour is lost from the stomata (pores) of leaves
Upper Warren River catchment	Includes the gauged subcatchments of Tone River, Perup River, Wheatley Farm and Unicup Lake area
Warren River catchment	The area above the Barker Road Crossing gauging station with 5 gauged subcatchments: Tone River, Perup River, Wilgarup River, Wheatley Farm, and Barker Road. It also includes the Unicup Lake area
Warren River Water Resource Recovery Catchment	The Warren River catchment excluding the Unicup Lake area, which is a Biodiversity Recovery catchment
WIN	Department of Environment's Water Information database

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Appendix 1 Warren Recovery Team

The first meeting of the Warren Recovery Team at Kojonup Shire Office was held on 6 November 1997. The team was originally called the 'Warren–Tone Catchment Salinity Recovery Team' but changed to 'Warren Recovery Team' on 23 June 1998. Tables A1.1 and A1.2 list current and previous members of the Warren Recovery Team.

Table A1.1 Current members of the Warren Recovery Team

Representative	*Management unit*	*Organisation*
Chris Evans (Chair)	Mobrup	
Mick Mathwin	Upper Tone	
Jane Larsen		DAWA
Glen Mead	Chowerup	
Tom Muir	Perup	
Dr Erica Shedley		CALM
Digby Stretch	Mobrup	
Leanne Trappitt	Tonebridge	
John Platt		Exec Officer & DoE Rep

Table A1.2 Previous members of the Warren Recovery Team

Representative	*Management unit*	*Organisation*
William Harvey	Lower Tone	
Rod Simmonds		CALM
Ian Wilson		CALM
Marc Synnot	Tonebridge	
John Glauert		DAWA
Peter Taylor		DAWA
Peter Coffey	Jingalup	
Wade Anderson	Tenner Road	
Ben Rose		DAWA
Peter Sheddon	Chowerup	
Rob Wilson	Tenner Road	
Tim Mathwin		DAWA

The meetings are regularly attended by representatives from Kojonup LCDC, the Forest Products Commission and Edith Cowan University (PhD thesis student).

Appendix 2 Catchment description

This appendix provides more information on the catchment characteristics described in Section 2. The data have been prepared in digital form and most data here have an accuracy for planning at scales of 1:50 000 or greater. The tables and maps have been produced from this data. The maps in the body of the report provide an overview at a scale of 1:400 000. The projection is Zone 50, Map Grid of Australia 1994. Additional maps show the coverage for the geology, geophysics and soil–landscape units (Figs A2.3–A2.6).

More on Section 2.1 Climate

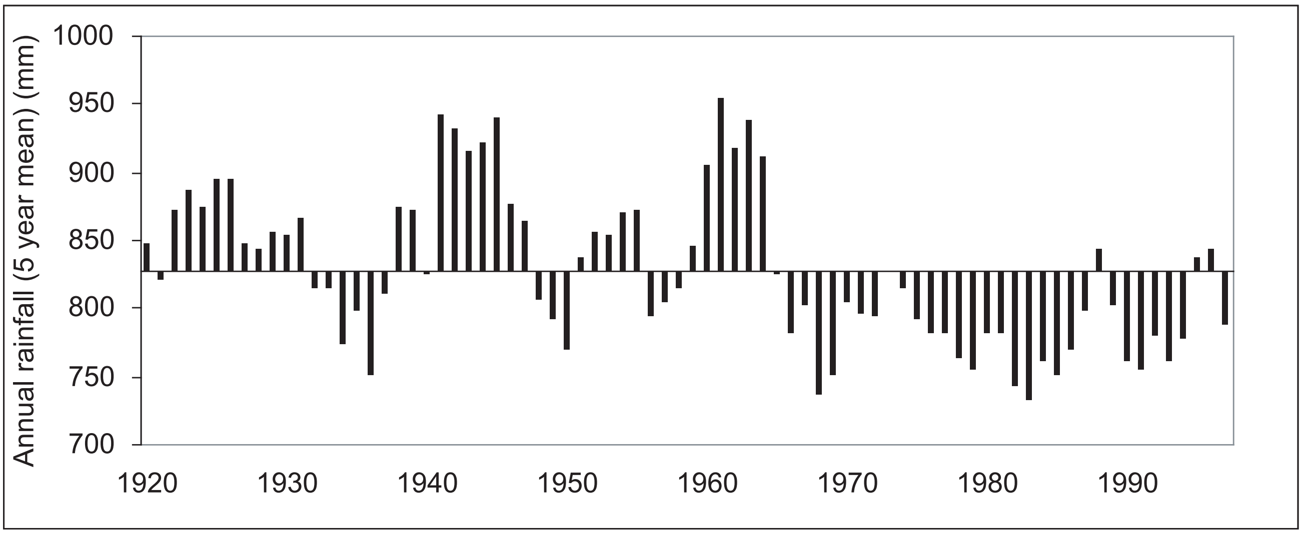

Figure A2.1 Annual rainfall of the Barker Road subcatchment

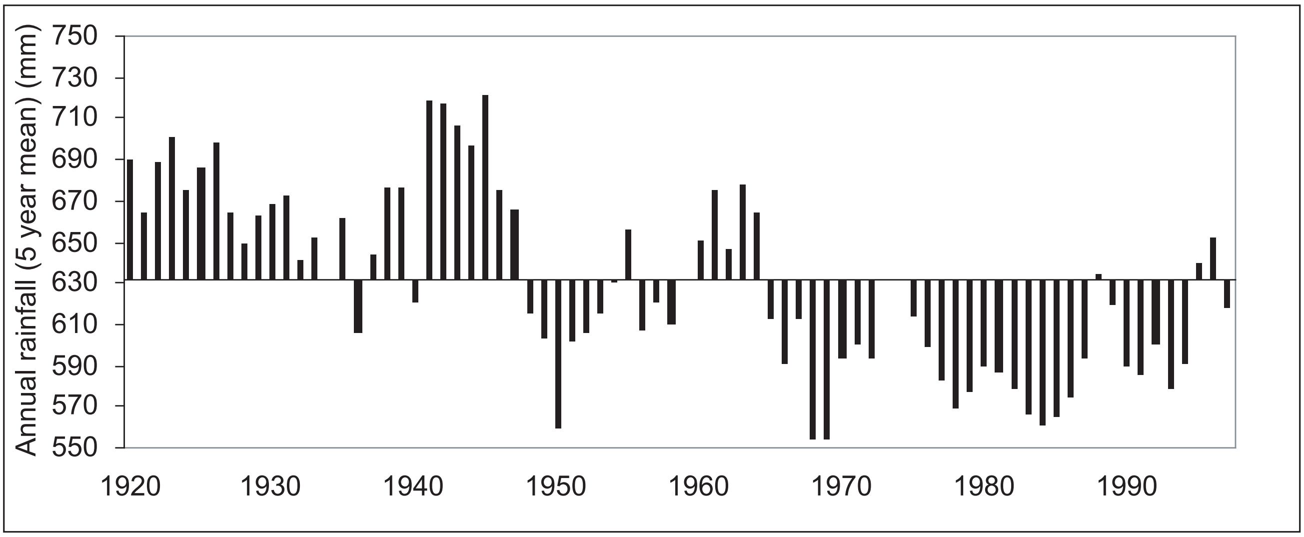

Figure A2.2 Annual rainfall of the Tone River subcatchment

More on Section 2.3.1 Geology

Table A2.1 Geology of the upper Warren River catchment

	Area within management unit (km^2)										
*Geology**	*Chowerup*	*Lower Tone*	*Middle Tone*	*Mobrup***	*Perup*	*Strachan*	*Tenner Road*	*Tonebridge*	*Unicup***	*Upper Tone*	*Upper Warren River catchment*
Cainozoic — swamp and lacustrine deposits	< 1	< 1		< 1	3	1		1	10		15
Cainozoic — alluvial and colluvial deposits	102	21	14	100	153	138	30	142	136	50	887
Cainozoic — laterite and sand overlying laterite	91	30	26	57	370	181	34	108	63	24	985
Cainozoic — alluvial, lacustrine and shallow marine deposits and sandstone	9	1	1	2	83	35		9	1	< 1	141
Proterozoic — granitic, deformed granite and migmatite					26	35		6	7		74
Archaean — granite and gneiss	26	67	82	15	87	12	34	15	18	51	408

* The distribution of these geological units is mapped in Figure A2.3

** ArcView calculated areas are 174 and 236 km^2 compared to modelled areas of 167 and 227 km^2 for these management units respectively

Geophysical data

High-resolution aerial geophysical survey data were obtained for parts of the catchment (Fugro Airborne Surveys 2000) with radiometrics and magnetics coverage of the Chowerup, Tenner Road, Lower Tone, Middle Tone, Upper Tone and Mobrup MUs (Figs A2.4 & A2.5). Additional airborne electromagnetics (AEM) were trialled over the Mobrup area (Fig. A3.7) where the datasets were interpreted to assess the land salinisation risk of the Mobrup MU (Hundi et al. 2001). Agraria–World Geoscience conducted an aerial geophysical survey covering the Lake Muir and Unicup Lake subcatchments in 1998. This survey collected high-resolution magnetic and radiometric data to help understand the hydrogeological process in catchments prone to land salinisation (Chakravartula & Street 2000).

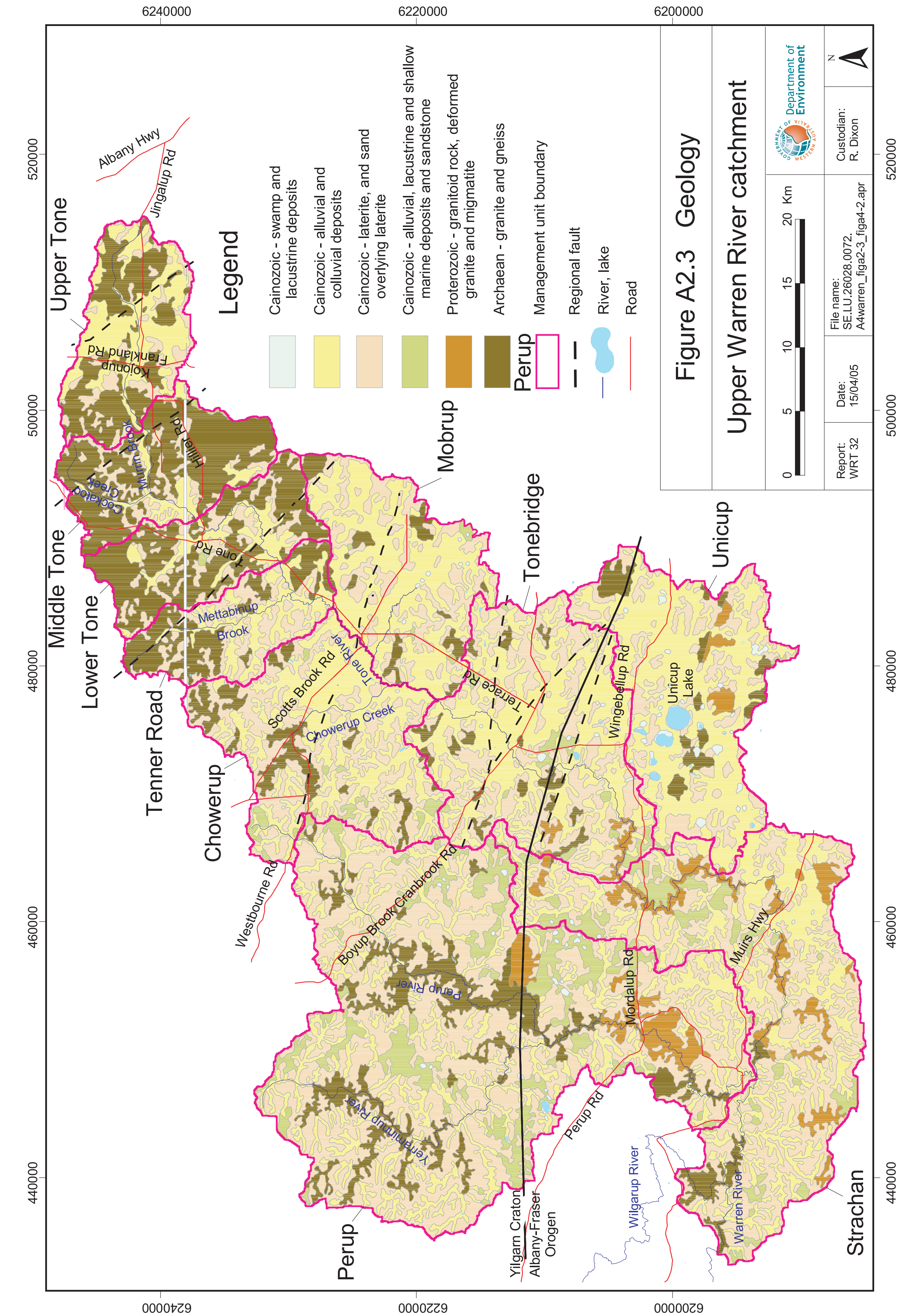
Figure A2.3 Geology
Upper Warren River catchment
Legend
Cainozoic - swamp and lacustrine deposits
Cainozoic - alluvial and colluvial deposits
Cainozoic - laterite, and sand overlying laterite
Cainozoic - alluvial, lacustrine and shallow marine deposits and sandstone
Proterozoic - granitoid rock, deformed granite and migmatite
Archaean - granite and gneiss
Perup
Management unit boundary
Regional fault
River, lake
Road
0 5 10 15 20 Km
Department of Environment
Report: WRT 32
Date: 15/04/05
File name: SE,LU,26028,0072, A4warren_figa2-3_figa4-2.apr
Custodian: R. Dixon
N
Upper Tone
Middle Tone
Lower Tone
Tenner Road
Chowerup
Mobrup
Tonebridge
Unicup
Perup
Strachan
Albany Hwy
Jingalup Rd
Frankland Rd
Kojonup
Hillier Rd
Murrin Brook
Cockatoo Creek
Tone Rd
Mettabinup Brook
Scotts Brook Rd
Tone River
Chowerup Creek
Terrace Rd
Wingebellup Rd
Unicup Lake
Westbourne Rd
Boyup Brook-Cranbrook Rd
Perup River
Mordalup Rd
Muirs Hwy
Yerramminup River
Perup Rd
Wilgarup River
Warren River
Yilgarn Craton
Albany-Fraser Orogen
6240000
6220000
6200000
520000
500000
480000
460000
440000

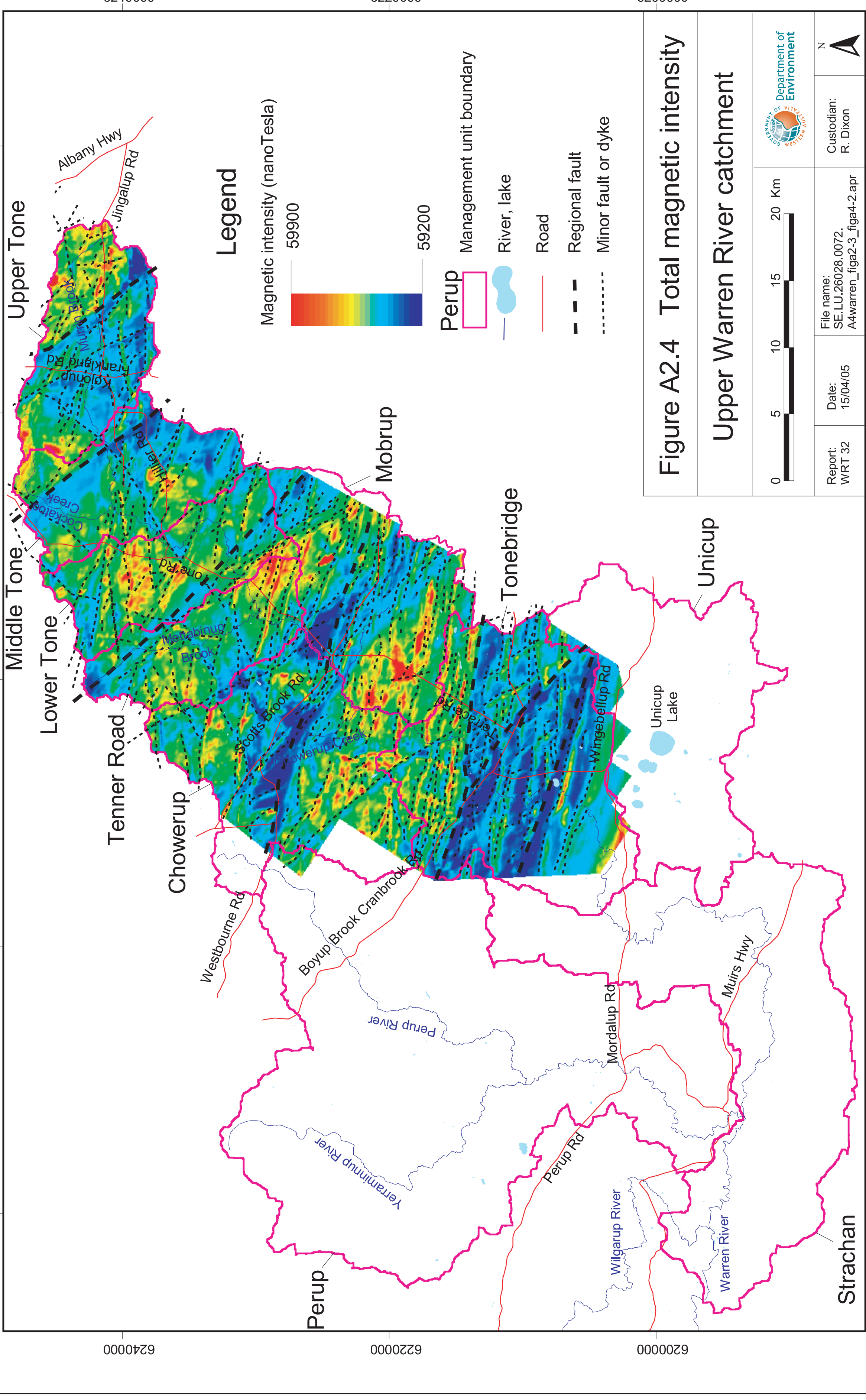

Figure A2.4 Total magnetic intensity
Upper Warren River catchment

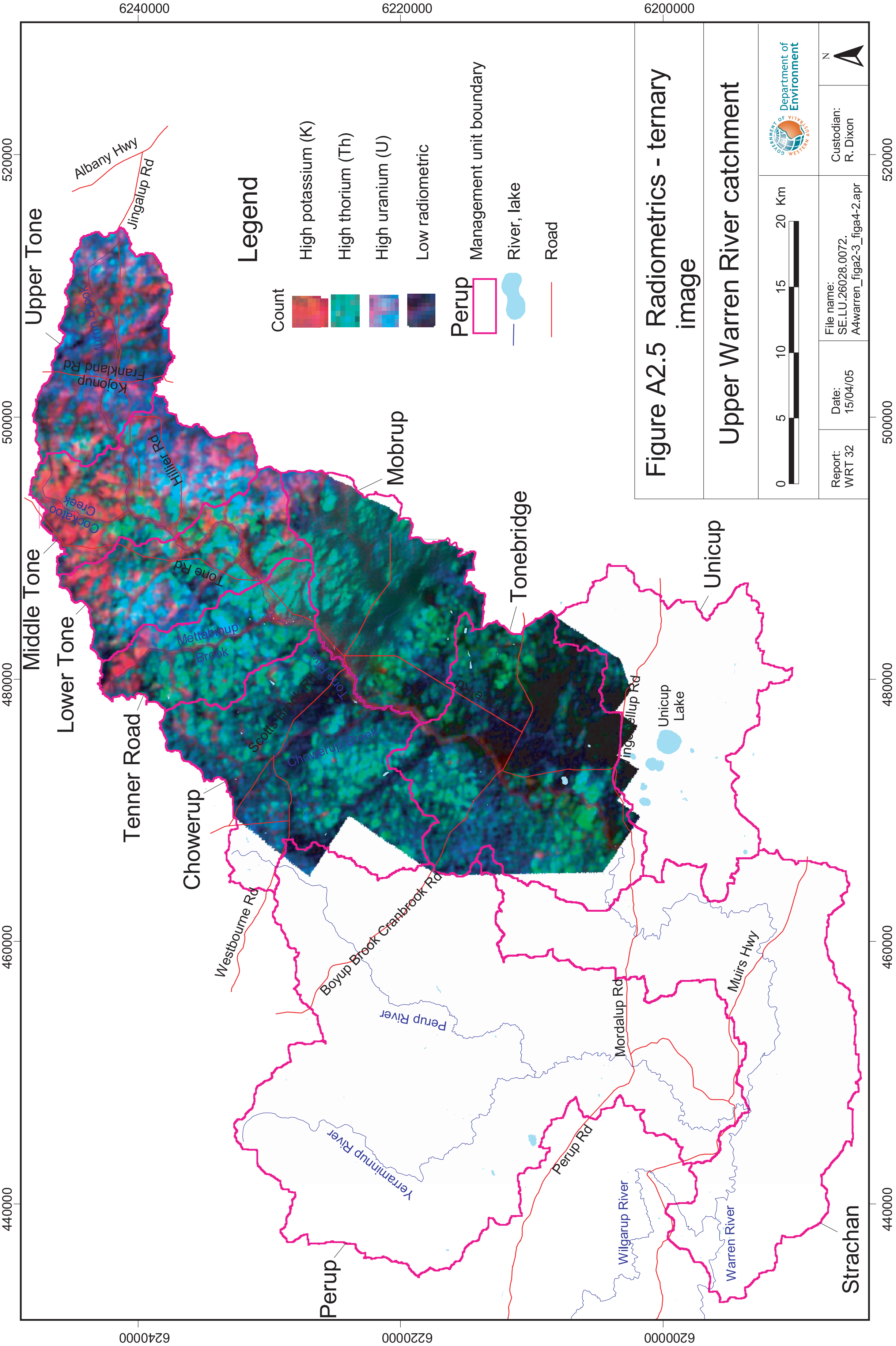
Figure A2.5 Radiometrics - ternary image
Upper Warren River catchment
Legend
Count
High potassium (K)
High thorium (Th)
High uranium (U)
Low radiometric
Perup
Management unit boundary
River, lake
Road
0 5 10 15 20 Km
Department of Environment
Report: WRT 32
Date: 15/04/05
File name: SE.LU.26028.0072. A4warren_figa2-3_figa4-2.apr
Custodian: R. Dixon
Upper Tone
Middle Tone
Lower Tone
Tenner Road
Chowerup
Mobrup
Tonebridge
Unicup
Perup
Strachan
Albany Hwy
Jingalup Rd
Frankland Rd
Kojonup
Hillier Rd
Cockatoo Creek
Tone Rd
Mettabinup Brook
Scotts Brook Rd
Chowerup Creek
Unicup Lake
Westbourne Rd
Boyup Brook Cranbrook Rd
Perup River
Mordalup Rd
Muirs Hwy
Yerraminnup River
Perup Rd
Wilgarup River
Warren River
6240000
6220000
6200000
520000
500000
480000
460000
440000

More on Section 2.4 Soil–landscape

These broadly classified soils (Table A2.5) have been mapped as 3 soil–landscape zones and 11 regional soil–landscape systems (Churchward 1992; Percy 1992; Stuart-Street & Scholz in prep.).

The Eastern Darling Range Zone contains many large remnants of the lateritic plateau formed over the granitic and gneissic rocks of the Yilgarn Craton. The lateritic plateau has been dissected by the Warren River exposing fresh rock and forming sedimentary deposits. The soils of this zone are broadly duplex sandy gravels, loamy gravels, semi-wet soils and deep grey sands of the Boyup Brook Valleys, and Eulin Uplands systems (Fig. A2.6).

The Zone of Rejuvenated Drainage comprises gently inclined rises and low hills with narrow divides and only scattered small lateritic remnants. Grey deep and shallow grey sandy duplexes and sandy gravel duplexes dominate the systems of Farrar, Gordon Flats, and Jingalup (Fig. A2.6).

The Warren–Denmark Southland Zone rises slowly from south to north across a series of indistinct steps or benches. This zone has formed on granitic and gneissic rocks of the Yilgarn Craton and the Albany–Fraser Orogen. In many areas this bedrock is overlain by deeply-weathered Cainozoic sediments. The soils are loamy gravels and duplex sandy gravels of the Dwalganup, Frankland Hills, Manjimup, Perup Plateau, Unicup and Wilgarup systems (Fig. A2.6).

The specific landforms and soils for these regional zones and systems are summarised in Table A2.2 and the areas of the soil–landscape systems for each management unit are in Table A2.3.

The regional system mapping has been refined to include soil–landscape mapping units (van Gool & Moore 1999). Van Gool and Moore (1999) detail how proportional mapping within the mapping units allows specific characteristics such as texture, coarse fragments, water regime, calcareous layer, colour, depth, pH and structure to be attributed as a percentage of the mapping unit.

Table A2.2 Soil–landscape description

Zone	*System*	*Code*	*Landform*	*Soil*	*Vegetation*
Eastern Darling Range	Boyup Brook Valleys	Bv	Deeply incised valleys with some rock outcrops	Duplex sandy gravels, grey deep sandy duplexes, loamy gravels and brown deep loamy duplexes	Marri–wandoo–jarrah forest and woodland
	Eulin Uplands	Eu	Lateritic plateau remnants with lakes and poorly drained flats	Duplex sandy gravels and loamy gravels with minor wet soils, semi-wet soils and grey deep sandy duplexes	Jarrah–marri–wandoo forest and woodland
Warren–Denmark Southland	Dwalganup	Dw	Undulating terrain with moderately incised valleys, shallow minor valleys and remnant of lateritic plateau	Loamy gravels, duplex sandy gravels, and friable red/brown loamy earths	Karri–marri–jarrah forest and woodland
	Frankland Hills	Fh	Undulating low hills and rises	Loamy gravels, duplex sandy gravels, deep sandy gravel, shallow gravel and grey deep sandy duplexes	Jarrah–marri forest and woodland
	Manjimup	Mp	Undulating low rises and swampy plains overlain by linear dunes blown from the bed of the Gordon River.	Duplex sandy gravels, loamy gravels and wet and semi-wet soils	Jarrah–marri forest and woodland

	Perup Plateau	Pp	Lateritic plateau with broad swampy depressions	Loamy gravels, duplex sandy gravels, loamy gravels and wet soils (sometimes saline)	Jarrah–marri–wandoo forest and woodland
	Unicup	Uc	Poorly drained flats with lakes and low dunes	Pale deep sand, grey deep sandy duplex, semi-wet soil, pale shallow sand, duplex sandy gravel	Banksia–paperbark scrub and jarrah–marri woodland
	Wilgarup Valleys	Wv	Major valleys	Loamy gravels, friable red/brown loamy earths, duplex sandy gravels, stony soils and semi-wet soils	Marri–jarrah–wandoo forest and woodland
Zone of Rejuvenated Drainage	Farrar	Fa	Undulating terrain with rock outcrops and narrow drainage lines	Grey deep sandy duplexes, duplex sandy and outcrops with minor red shallow loamy duplexes, grey shallow sandy duplexes and deep sandy gravels	Wandoo–jarrah–marri woodland
	Gordon Flats	Gd	Broad valley floor with low dunes, swampy depressions and low gravelly rises	Grey deep sandy duplex with semi-wet soil, pale deep sand, duplex sandy gravel, saline wet soil and grey shallow sandy duplex	Jarrah–marri and wandoo woodlands with yate and paperbark woodlands
	Jingalup	Jp	Dissected lateritic terrain	Grey deep sandy duplexes, duplex sandy gravels, deep sandy gravels and grey shallow sandy duplexes	Marri–wandoo–jarrah forest and woodland

Table A2.3 Soil–landscape systems of the upper Warren River catchment

		Area within management unit (km^2)										
*Soil–landscape system**		*Chowerup*	*Lower Tone*	*Middle Tone*	*Mobrup***	*Perup*	*Strachan*	*Tenner Road*	*Tonebridge*	*Unicup***	*Upper Tone*	*Upper Warren River catchment*
Bv	Boyup Brook Valleys	43	21					55				119
Eu	Eulin Uplands	23	8					26				57
Dw	Dwalganup					< 1	51					51
Fh	Frankland Hills	48			54	6	27		169	96		400
Mp	Manjimup					90	184					274
Pp	Perup Plateau	86				465	93		35	11		690
Uc	Unicup						2		46	128		176
Wv	Wilgarup Valleys					161	45		9	< 1		215
Fa	Farrar		12	30							33	75
Gd	Gordon Flats	28	4		56			6	22			116
Jp	Jingalup		74	95	64			12			93	337

* The distribution of these soil–landscape systems is mapped in Figure A2.6

** ArcView calculated areas are 174 and 236 km^2 compared to modelled areas of 167 and 227 km^2 for these management units respectively

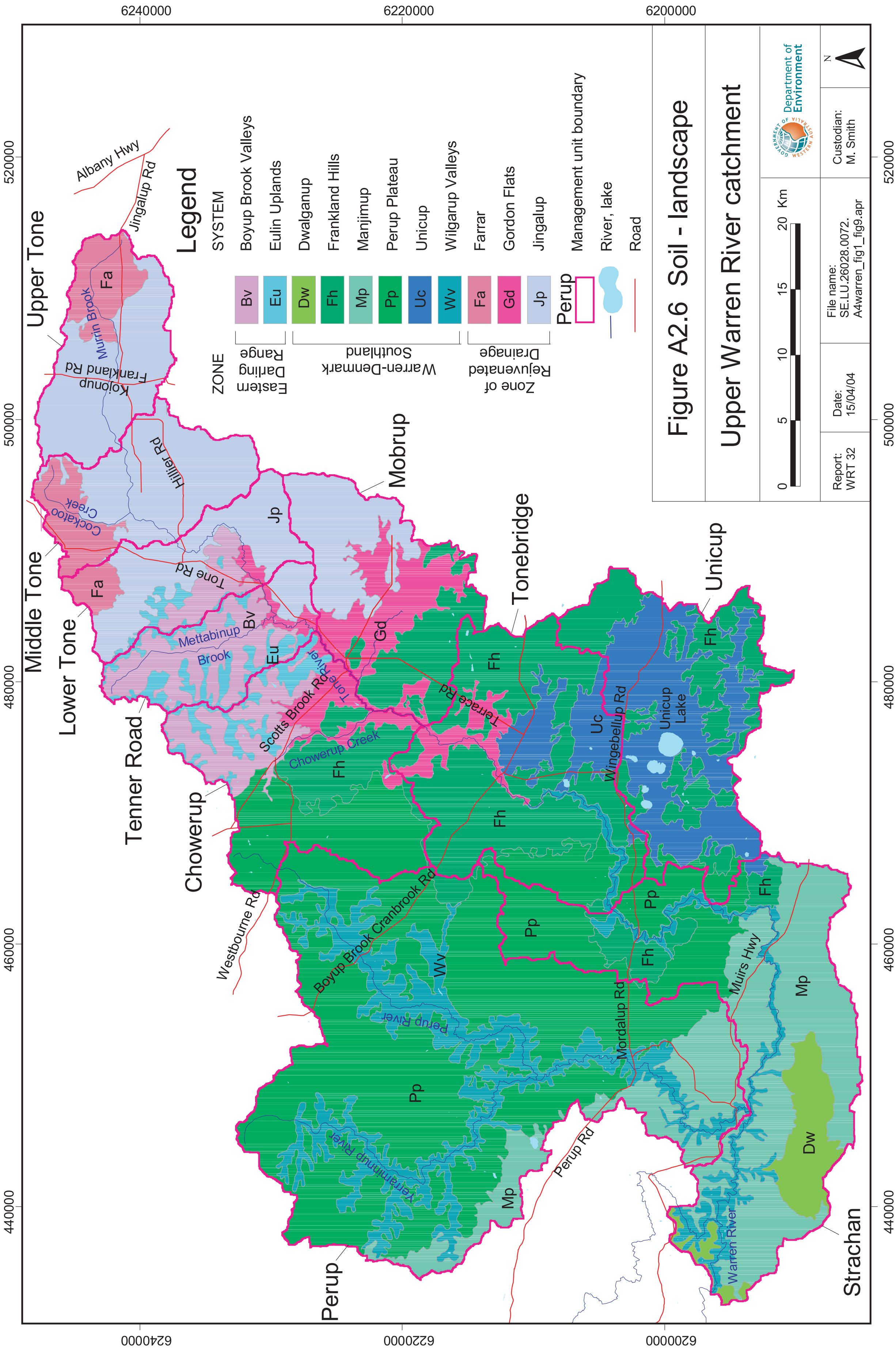

Figure A2.6 Soil - landscape

More on Section 2.6 Hydrogeology

Table A2.4 Hydrogeology of the upper Warren River catchment

	Area within management unit (km^2)										
*Hydrogeology**	*Chowerup*	*Lower Tone*	*Middle Tone*	*Mobrup***	*Perup*	*Strachan*	*Tenner Road*	*Tonebridge*	*Unicup***	*Upper Tone*	*Upper Warren River catchment*
Cainozoic — alluvial and colluvial deposits	24	12	4	21	6	27	9	59	78	1	241
Cainozoic — alluvial, lacustrine and shallow marine deposits	4				30	6					40
Cainozoic — palaeochannel deposits - sand, clay and carbonaceous sediments	4			22				2	11		39
Granitoid rock	195	107	114	131	408	29	90	186	87	113	1468
Granitoid gneiss	1		7		277	331	< 1	34	59	11	720
Archaean — quartzite					1	1					2

* The distribution of these hydrogeology units is mapped in Figure 5

** ArcView calculated areas are 174 and 236 km^2 compared to modelled areas of 167 and 227 km^2 for these management units respectively

More on Section 2.7 Land use

Table A2.5 Plantation history in the upper Warren River catchment

	Area within management unit (km^2)										
*Year**	*Upper Tone*	*Middle Tone*	*Lower Tone*	*Tenner Road*	*Mobrup***	*Chowerup*	*Tonebridge*	*Unicup***	*Penrup*	*Strachan*	*Upper Warren River catchment*
1990			< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	0.1	0.4	1.8	2.4
1992		< 0.1	< 0.1	< 0.1	< 0.1	0.7	< 0.1	0.8	< 0.1	< 0.1	1.6
1994			0.1	0.1	0.3	2.5	0.8	1.5	0.1	< 0.1	5.5
1996	< 0.1	< 0.1	< 0.1	0.2	0.3	2.1	4.1	1.9	9.6	< 0.1	18.4
1998		< 0.1	< 0.1	< 0.1	1.1	0.4	1.6	0.2	4.5	< 0.1	7.8
1999		< 0.1	< 0.1	0.8	1.8	0.3	0.8	2.7	6.5	0.1	13.2
2000	< 0.1	< 0.1	< 0.1	0.3	0.5	0.2	0.9	5.4	2.9	< 0.1	10.3
2002	0.3	0.6	0.1	2.3	2.6	6.3	3.8	11.9	14.7	0.8	43.4
2003	0.6	1.5	1.0	14.3	8.4	13.2	10.1	12.9	11.9	1.1	75.0
Totals	**0.9**	**2.1**	**1.4**	**18.1**	**15.1**	**25.7**	**22.3**	**37.5**	**50.6**	**4.0**	**177.6**

*The distribution of these plantations is mapped in Figure 7. 'Year' is the date plantations were first identified from the Landsat TM scene. The actual planting date would be 1–3 years prior to 'Year' in table

Table A2.6 Tree harvesting in the upper Warren River catchment

	Area within management unit (km^2)										
*Year**	*Upper Tone*	*Middle Tone*	*Lower Tone*	*Tenner Road*	*Mobrup*	*Chowerup*	*Tonebridge*	*Unicup*	*Penrup*	*Strachan*	*Upper Warren River catchment*
1998						< 0.1		< 0.1	< 0.1		< 0.1
1999					< 0.1	< 0.1	< 0.1	< 0.1	< 0.1		< 0.1
2000				< 0.1		< 0.1		< 0.1	< 0.1		< 0.1
2002			< 0.1	< 0.1	0.3	1.7	0.5	1.6	< 0.1		4.2
Totals			**< 0.1**	**< 0.1**	**0.3**	**1.8**	**0.5**	**1.7**	**0.1**		**4.2**

**The distribution of these harvestings is mapped in Figure 7*

Appendix 3 Flow and salinity characteristics

This appendix summarises the approach to the analysis of flow, salinity, groundwater and salinity risk assessment.

More on Section 3.1 Streamflow and salinity records

Five gauging stations monitor the subcatchments of the Warren River catchment: Tone River, Perup River, Wilgarup River, Wheatley Farm and Barker Road (Figs A3.1–A3.5).

Prior to 1990, only the Tone River gauging station provided continuous salinity recording. Before this, salinity measurements were taken using a point sampling method. To calculate trends in annual stream salinity, the missing daily values were determined using the following method.

Stream salinity is inversely proportional to streamflow, so during periods of high streamflow the average stream salinity tends to be low and during low flows the average stream salinity tends to be higher. The relationship between a point salinity sample (S_s) and its associated daily streamflow (F_d) can be described by *Equation A3.1*:

$$S_s = a' F_d^{\,b'} \qquad \text{(Equation A3.1)}$$

In the above equation the values of the two parameters (*a'*) and (*b'*) were determined using an interpolation process. Five point samples at a time were used to develop the relationship. Significant changes in land use can alter the relationship between the salinity and streamflow, thus these two parameters are variable. From *Equation A3.1*, the daily salinity for the period without continuous record, was calculated for all the gauging stations. The daily salinity and streamflow records were then summed to get the annual flow (*F*), 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 for all gauging stations were developed. In the first case, nine years of data were taken at a time and values of the parameters (*a"*) and (*b"*) were determined. In the second case, only five years of data were used each time to determine the values of parameters (*c*) and (*d*). The values of these parameters also changed with time due to changes in land use of the catchment. The annual relationships can be described as *Equation A3.2* and *Equation A3.3*:

$$S = a'' F^{\,b''} \qquad \text{(Equation A3.2)}$$

$$F = c + dR \qquad \text{(Equation A3.3)}$$

Based on the parameters of *Equation A3.3*, values of annual streamflow (F_r) under mean annual rainfall ($\overline{R}$) conditions for the duration of the trend analyses (1980–95) were determined (*Equation A3.4*):

$$F_r = c + d\overline{R} \qquad \text{(Equation A3.4)}$$

The annual stream salinities (S_f) at mean annual streamflow ($\overline{F}$) were also calculated for the analysis period (*Equation A3.5*):

$$S_f = a'' \, \overline{F}^{\,b''} \qquad \text{(Equation A3.5)}$$

The annual salt loads at mean flow (L_f) are calculated as (*Equation A3.6*):

$$L_f = S_f \overline{F} \qquad \text{(Equation A3.6)}$$

The annual stream salinity at mean flow (S_f) figures for each gauging station was obtained from *Equation A3.5* and then plotted against an annual time step. After inspecting the plots a linear regression equation was developed for the periods 1980–90 and 1992–97 to discern upward and downward trends. The slope of the regression equation is taken as the rate of change in annual stream salinity, or what is referred to as the trend (Table 2).

The trends were then tested to see if they were significant. Using a t-distribution analysis (Watts & Halliwell 1996) the linear regression applied to each trend period was analysed. Taking the correlation coefficient (r) that was obtained from each regression, the following equation was used (*Equation A 3.7*):

$$t = \frac{r\sqrt{n-2}}{r\sqrt{\text{n}-r^2}} \qquad \text{(Equation A3.7)}$$

where (n) is the number of samples. To determine if the trend was significant the value of (t) was compared to t distributions at the 95% confidence limit.

The contributions of the two subareas within the Warren River catchment were also calculated. The first is the subarea which lies between the Tone, Perup and Wilgarup rivers and the Wheatley Farm gauging stations. The second is the area between the Barker Road Crossing and the Wheatley Farm gauging stations. The contributions from these areas cannot be measured directly because the gauging station outlets are recording flows from other sources upstream. Using a process by which the flow and salt load record at these upstream gauging stations is subtracted from the outlet gauging station the annual flow, salinity and salt load for these two subareas are calculated.

When developing averages to be used in equations or as part of the summary of results, figures from the period 1980–95 were used so that values for different gauging stations were comparable.

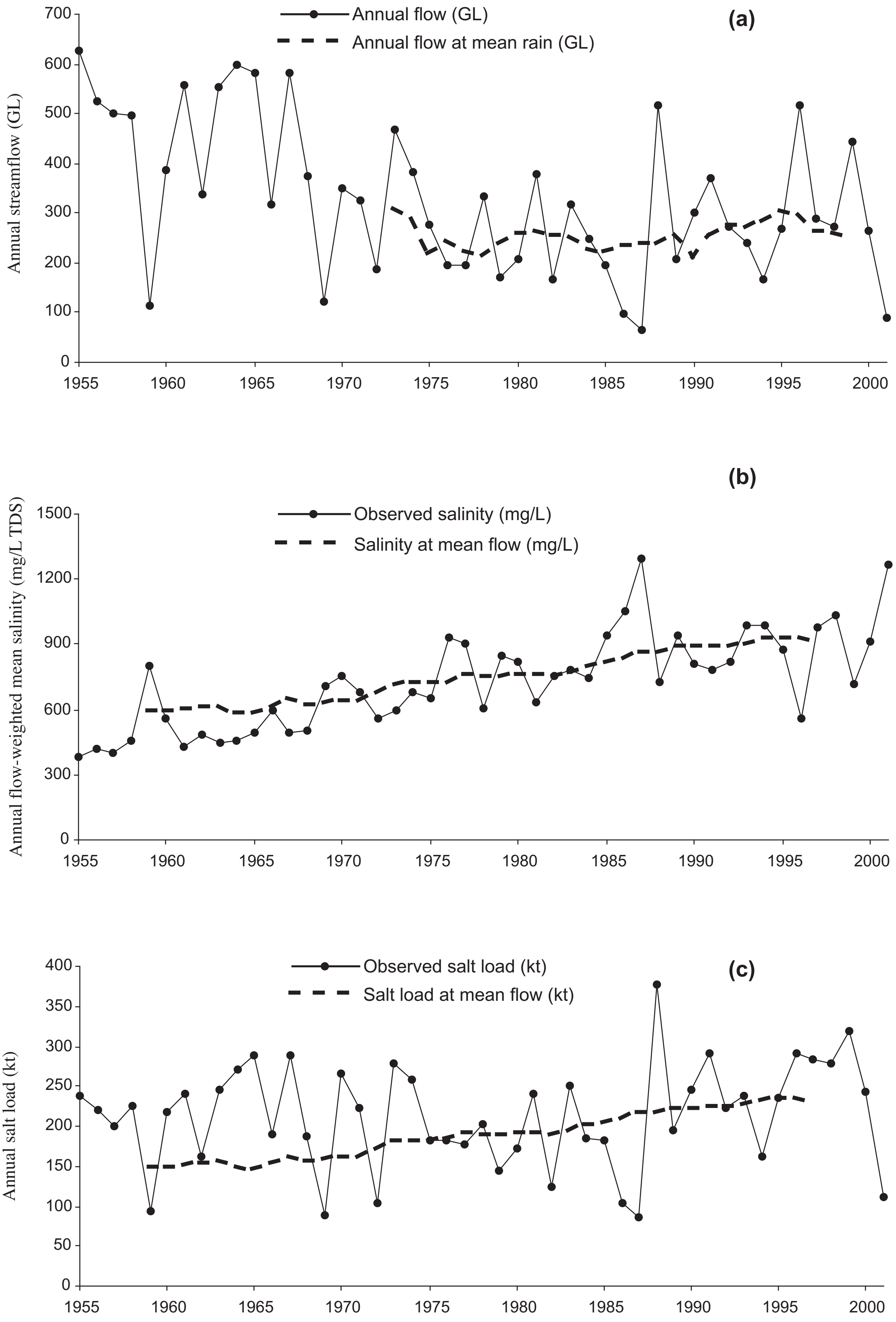

Figure A3.1 Warren River (Barker Road Crossing gauging station) a) streamflow b) salinity, and c) salt load

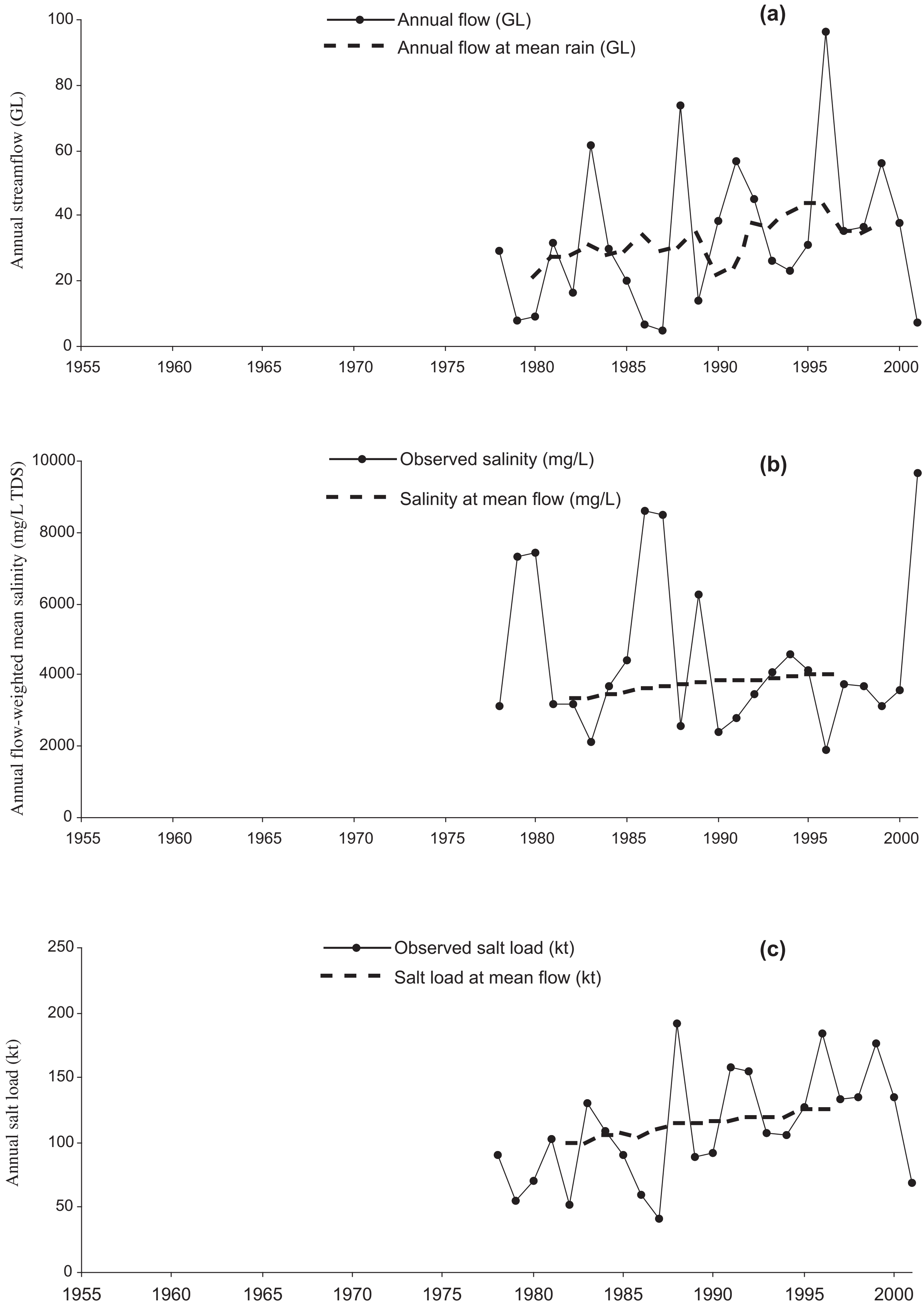

Figure A3.2 Tone River (Bullilup gauging station) a) streamflow b) salinity, and c) salt load

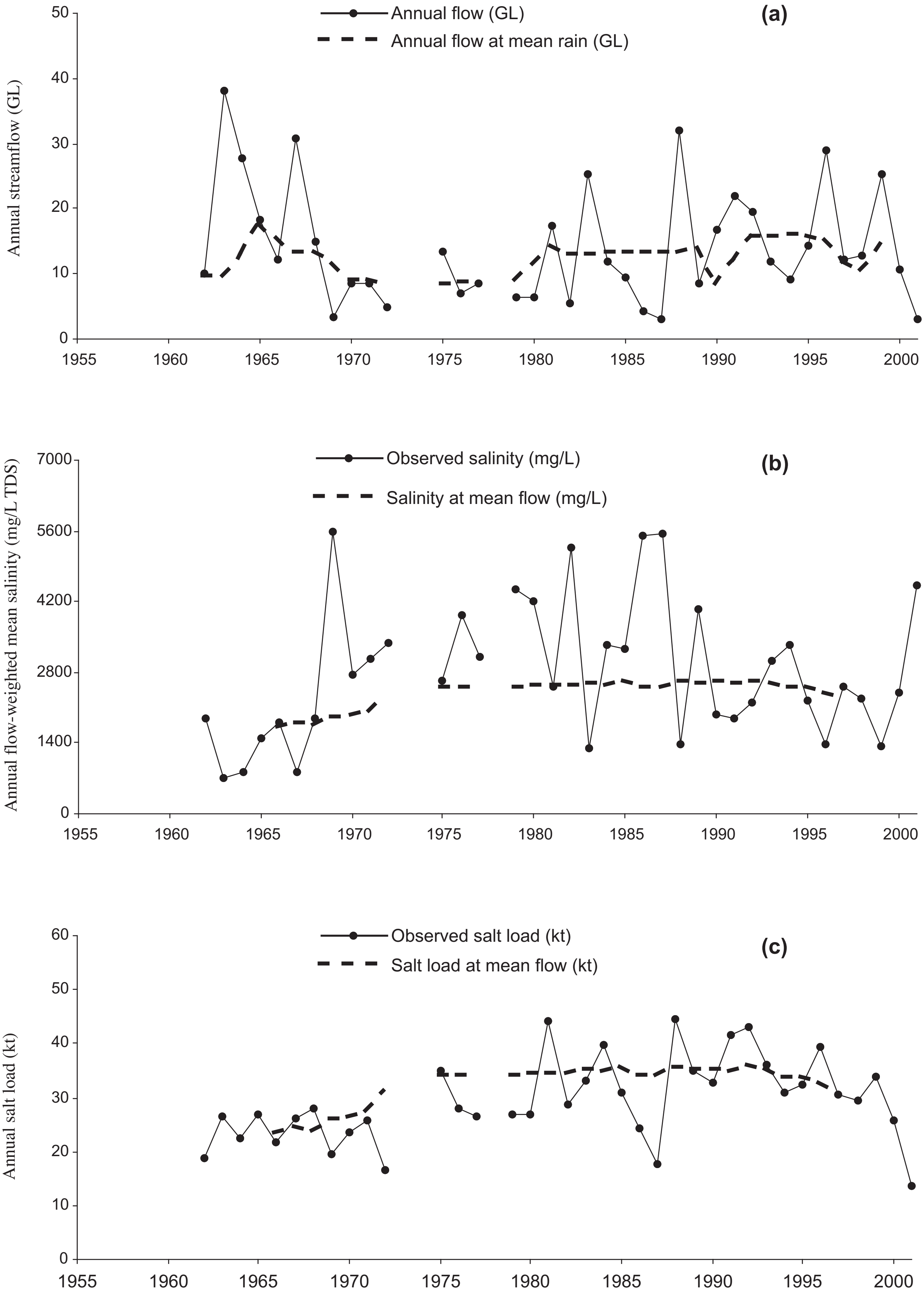

Figure A3.3 Perup River (Quabicup Hill gauging station) a) streamflow b) salinity, and c) salt load

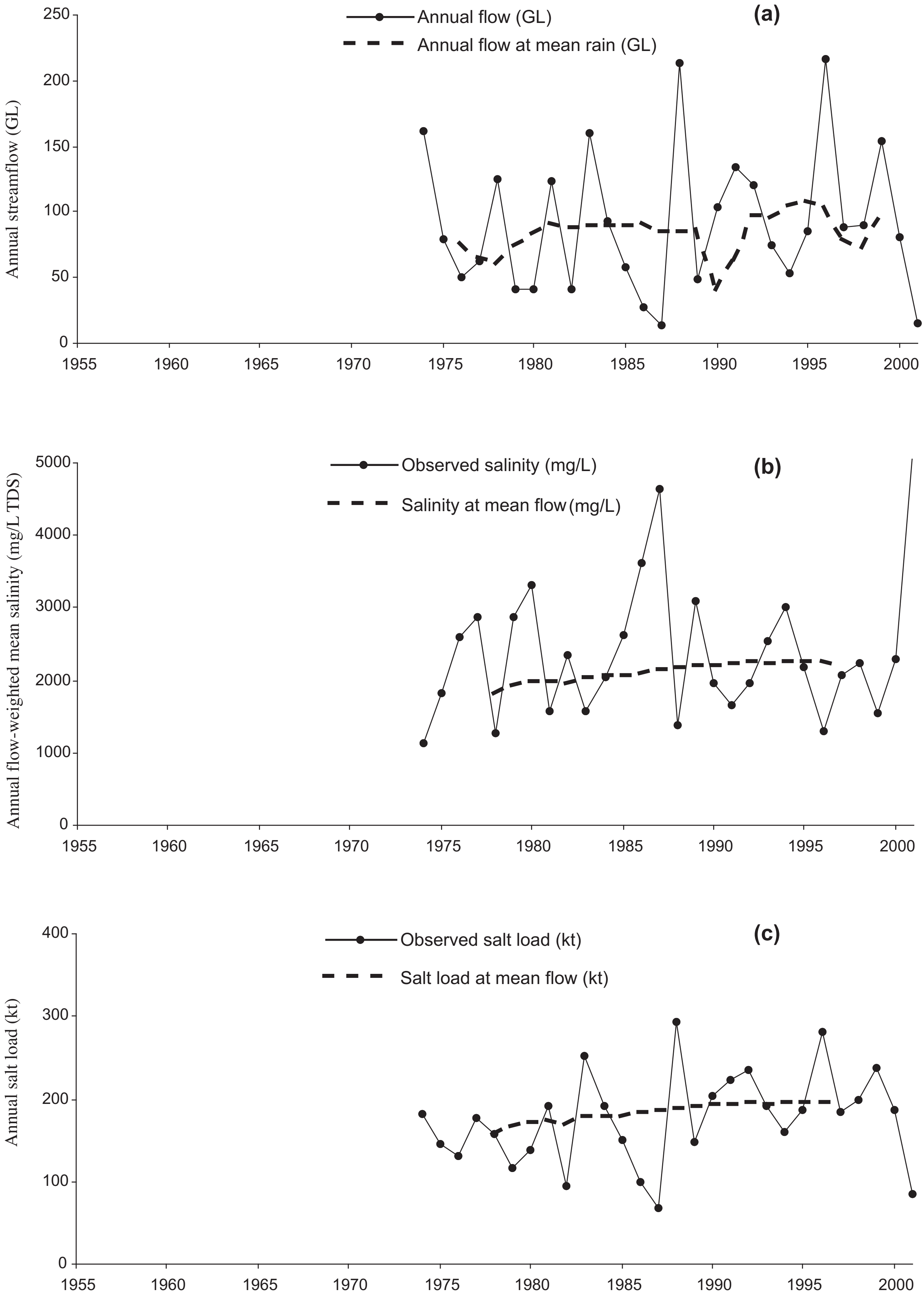

Figure A3.4 Wheatley Farm gauging station a) streamflow b) salinity, and c) salt load

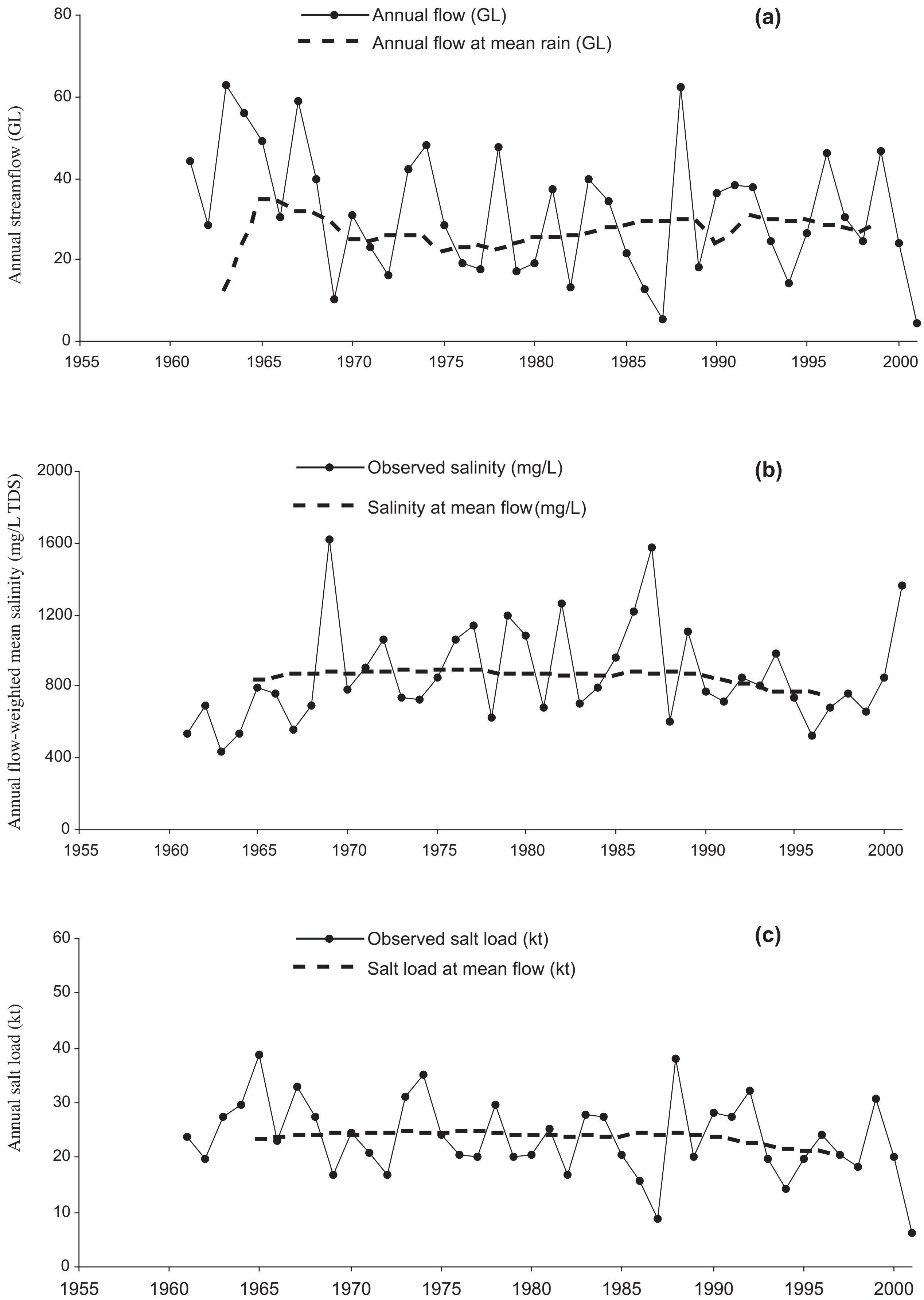

Figure A3.5 Wilgarup River (Quintarrup gauging station) a) streamflow b) salinity, and c) salt load

More on Section 3.2 Groundwater levels

Hydrograph Analysis: Rainfall and Time Trends (HARTT) is a spreadsheet-type model for statistical estimation of trends in groundwater levels (Ferdowsian et al. 2001). This method, summarised from Ferdowsian et al. (2001), separates the effects of atypical rainfall events from the underlying time trend. Multiple regression is used to assess the degree of influence of rainfall on the groundwater levels in comparison to an overall trend.

Daily rainfall is converted into

- **A**ccumulative **M**onthly **R**esidual **R**ainfall (AMRR)
- **A**ccumulative **A**nnual **R**esidual **R**ainfall (AARR).

AMRR and AARR are calculated using *Equation A3.8* and *Equation A3.9*:

$$AMRR_t = \sum_{i=1}^{t}(M_{i,j} - \overline{M}_j) \qquad (Equation\ A3.8)$$

where:

$M_{i,j}$ is rainfall (mm) in month i which corresponds to the j^{th} month of the year, $\overline{M}_j$ is the mean monthly rainfall (mm) for the j^{th} month of the year, and t is number of months since the start of data recording.

$$AMRR_t = \sum_{i=1}^{t}(M_i - \overline{A}/12) \qquad (Equation\ A3.9)$$

where:

$\overline{A}$ is the mean annual rainfall (mm).

The HARTT analysis in this study is based on the rainfall for each subcatchment that indicated a stable trend for one selected bore within this subcatchment. As a general rule, the rainfall from period between 1970–2001 is used for all subcatchments.

More on Section 3.3 Areas at risk of dryland salinisation

The areas at risk of developing dryland salinisation (when the catchment has reached hydraulic equilibrium) were defined as areas where the saline watertable is within 2 m of the ground surface or the ground is intermittently waterlogged (Hundi et al. 2001). Once the native vegetation has been removed, areas at risk of developing a shallow watertable are:

- low areas in the landscape such as flat valley floors
- areas where groundwater flow lines converge, typically along stream lines and upgradient of stream confluences
- breaks of slope (between the broad valley floors and valley sides) that restrict the volume of groundwater that can be stored.

Changes in subsurface bedrock topography and geology (Coram 1998) can also result in localised groundwater discharge sites. At a catchment scale, localised groundwater discharge sites are considered minor and have not been included in the risk assessment. Landforms not considered at risk are ridge tops and land slopes > 3% (not associated with streams).

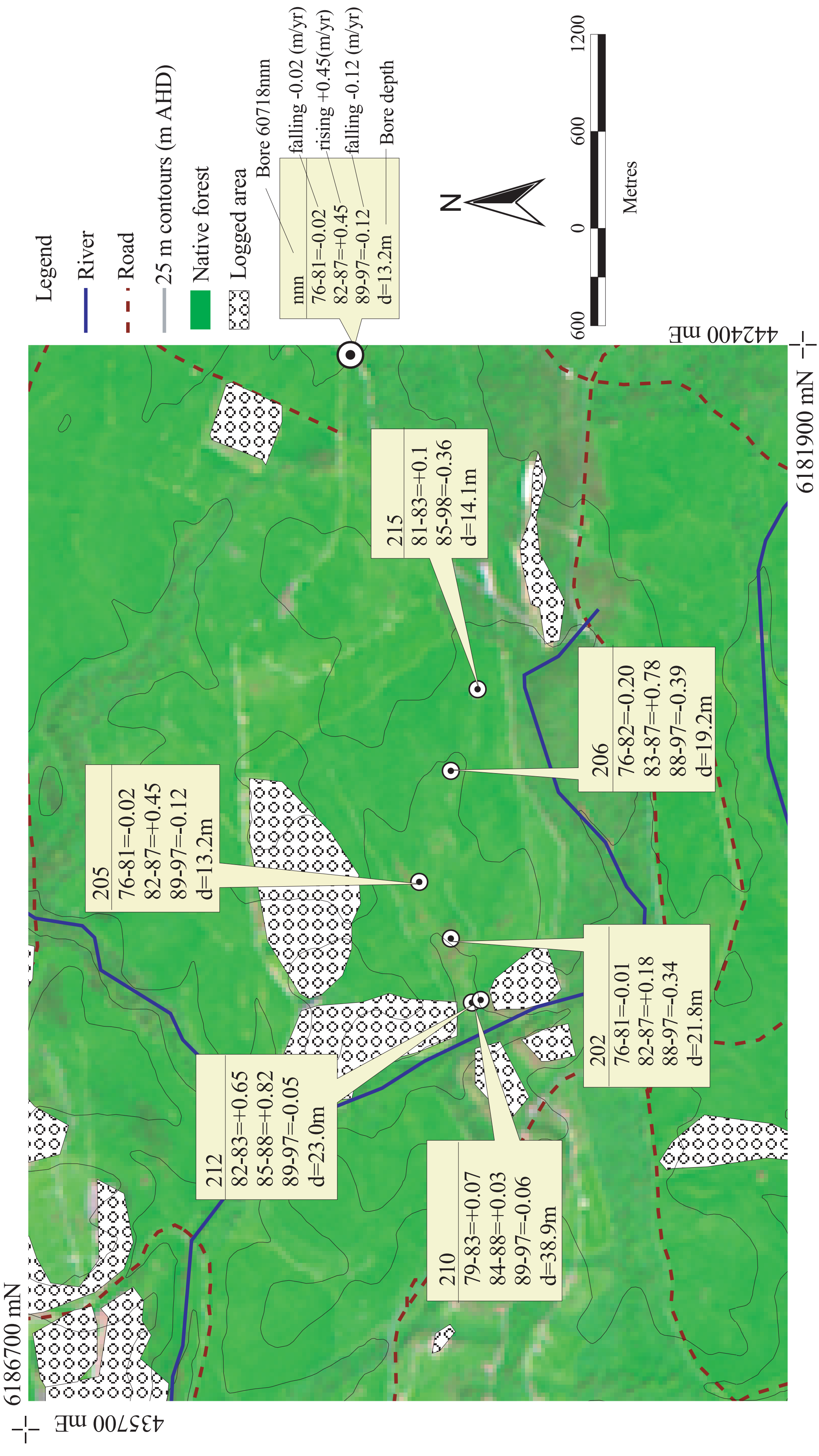

Figure A3.6 Changing groundwater levels in logged areas in the Barker Road subcatchment

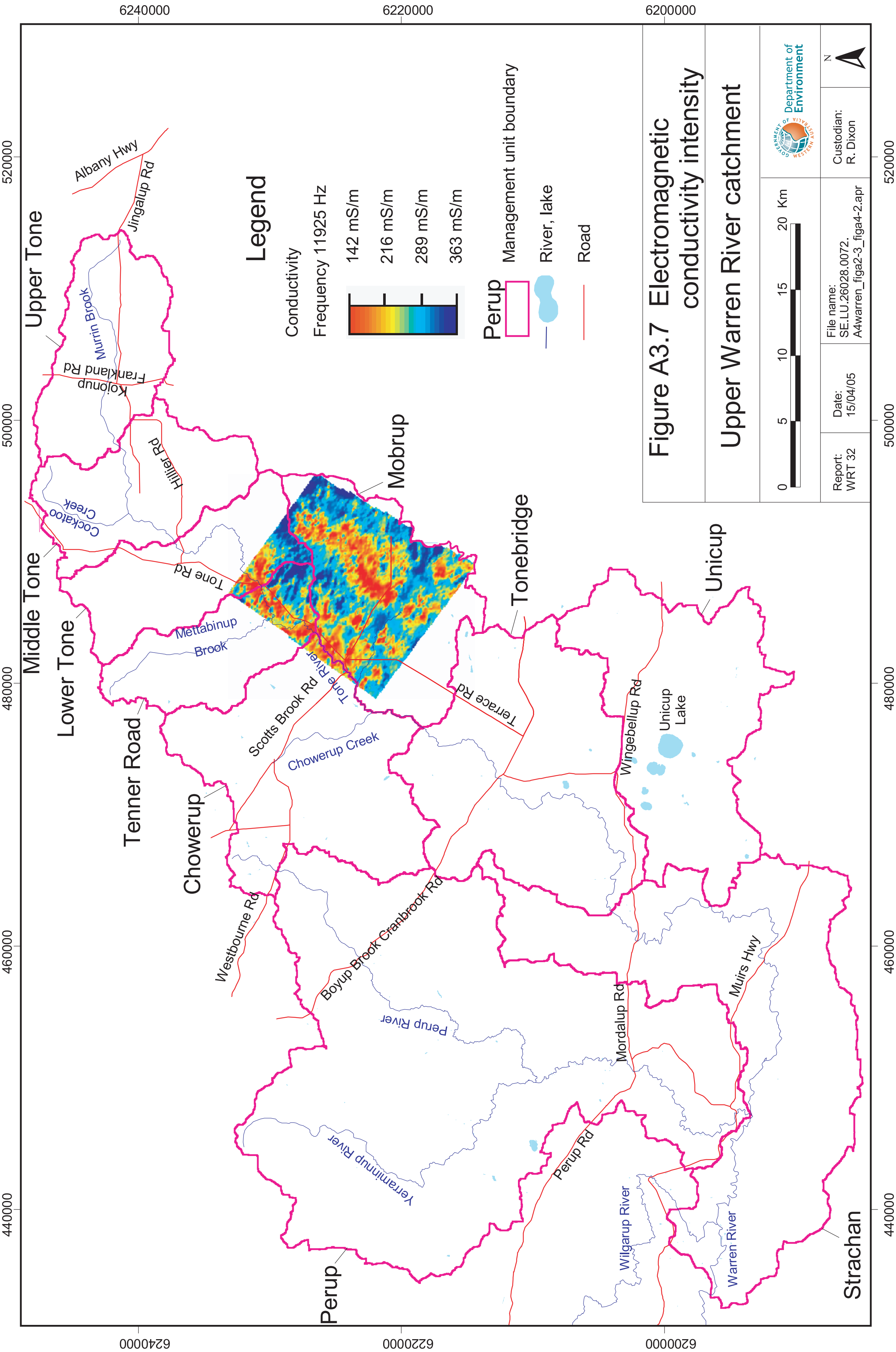

Figure A3.7 Electromagnetic conductivity intensity

Upper Warren River catchment

Appendix 4 Catchment modelling

More on Section 4.2 Building the MAGIC model of the Warren River catchment

This section summarises the steps in building the MAGIC model to simulate the upper Warren River catchment. A flow chart of these steps is shown in Figure 16. Further technical details are provided in Mauger (1996) and Rogers et al. (1999).

Setting up the model

Setting up the model for the upper Warren River catchment (the Tone River, Perup River, Wheatley Farm and the Unicup Lake area) required collating available information about the catchment. The sections below describe factors considered and assumptions made in the absence of experimental or field data.

Defining the catchment

The area of 2474 km^2 (Fig. A4.1) consisted of 182 subcatchments varying in size from 2 to 43 km^2 and was gridded into 25 x 25 m cells. The original boundaries by Rogers et al. (1999) were redefined using the current Digital Elevation Model (DEM) produced by combining the Dumbleyung DEM (Land Monitor 2002) covering the Upper Tone and the Collie–Pemberton DEM (CSIRO 2000) covering the rest. The subcatchment outlets were designed to match new sampling points established in 2000 (WIN), gauging stations (WIN) and management unit boundaries (Fig. A4.2).

Geomorphology

Information from drilling programs in 1997, 1999 and 2000 (Panasiewicz et al. 1997; Hundi 1999; Smith in prep.) showed that water moves through three layers (soil, thick clay, and weathered bedrock) (Figs 14 & 15).

The profile is of variable depth, based on an estimated depth to bedrock. Bore data from AQWABase were used to define depth to bedrock. Bores shallower than 6 m were removed from the dataset. If no geological log was available, it was assumed that the bore was drilled to bedrock. Depths for cells were estimated by interpolation between measured sites, subtracted from the surface elevation grid and incorporated into the model. Average permeabilities were applied to the three-layered regolith profile to account for the various characteristics of the regolith. Numerous faults and dykes have been interpreted from the airborne magnetic survey (Fig. A2.4).

The top layer, representing a permeable soil, was estimated from soil–landscape systems maps (Churchward 1992; Percy 1992; Stuart-Street & Scholz in prep.) that show ‘map units’ defined by distinct boundaries (van Gool & Moore 1999). Soil groups are unmapped components given as a percentage of the map unit (van Gool & Moore 1999). From each soil group, the weighted averages for permeability and thickness of the A and B horizons were incorporated into the model. Permeability and total thickness of the soil horizons ranged 0.2 to 2.5 m/day and 1.1 to 2.1 m respectively.

The middle layer represents both the clay-dominated weathered bedrock and the Cainozoic clay and sand sediments. Its thickness is variable. The clay-dominated weathered bedrock has a permeability of 0.1 m/day and Cainozoic clay and sand sediments have a permeability of 0.8 m/day.

The bottom layer, representing weathered-bedrock and corresponding to the main aquifer, is a friable zone with a high intergranular porosity. It was defined as being 3 m thick with an average permeability of 0.8 m/day.

Drainage

The model drainage code was adjusted so that the model drainage direction emulated the official rivers as the upper Warren River catchment has many very flat areas and the streamlines produced by the model occasionally varied from the official stream lines (DoE 2002) created by DOLA.

Modification to the 'dispersed drainage code' (Mauger 1996) now allows drainage to be calculated for areas greater than 500 km^2 which permits the drainage for the whole catchment to be modelled in one RASCAL project.

Vegetation

Landsat TM data captured in January 1988 (Fig. A4.1) and February 2000 were used to map areas of native vegetation and pasture cover, and to derive a 'greenness' index for the tree areas. The greenness index is an indicator of tree density and so the rate of water use by trees. The maximum cleared catchment area was represented by the 1988 scene (Fig. A4.1) and the current extent of land clearing was defined by the 2000 scene (Fig. 6).

Water use by plants

The transpiration rates of plants depend on factors like plant density, root depth, the availability of water, evaporation rates and plant growth cycles. To estimate transpiration by trees and pastures, the model uses a parameter called *Leaf Area Index* (LAI) for annual and perennial pastures. LAI is an indicator of the biomass. Extensive work on annual pastures has resulted in a good understanding of LAI changes during the growth cycle (Nulsen & Baxter 1986). This work and catchment rainfall and evaporation data were used to estimate LAI values.

The approach for calculating the annual transpiration by trees and pastures is described in Points 1 and 2. Points 3–6 describe the assumptions made for LAI definition.

1. Transpiration by trees is proportional to three factors: a) the greenness at a cell (called 'Actual Greenness'), b) the 'Natural Greenness' of undisturbed forest proportional to rainfall, and c) the monthly pan evaporation. Annual transpiration by native forest ($AT_{(F)}$) is calculated from *Equation A4.1*:

$$AT_{(F)} = AG / NG \times NT_{(F)} \qquad (\textit{Equation A4.1})$$

where:

AG = **A**ctual **G**reenness index describing the plant density and derived from the Landsat TM data

$\boldsymbol{NT_{(F)}}$ = **N**atural **T**ranspiration rate of native forest calculated as the annual rainfall reduced by interception losses (15%) and increased by a factor of 1.33 to compensate for reduced transpiration under drought stress

NG = **N**atural **G**reenness index describing the density of the natural forest that originally covered the catchment and calculated from *Equation A4.2*

$$NG = 0.043 \times R_{(A)} \qquad (\textit{Equation A4.2})$$

where:

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

0.043 was obtained by regression with extensive undisturbed forest areas in the region.

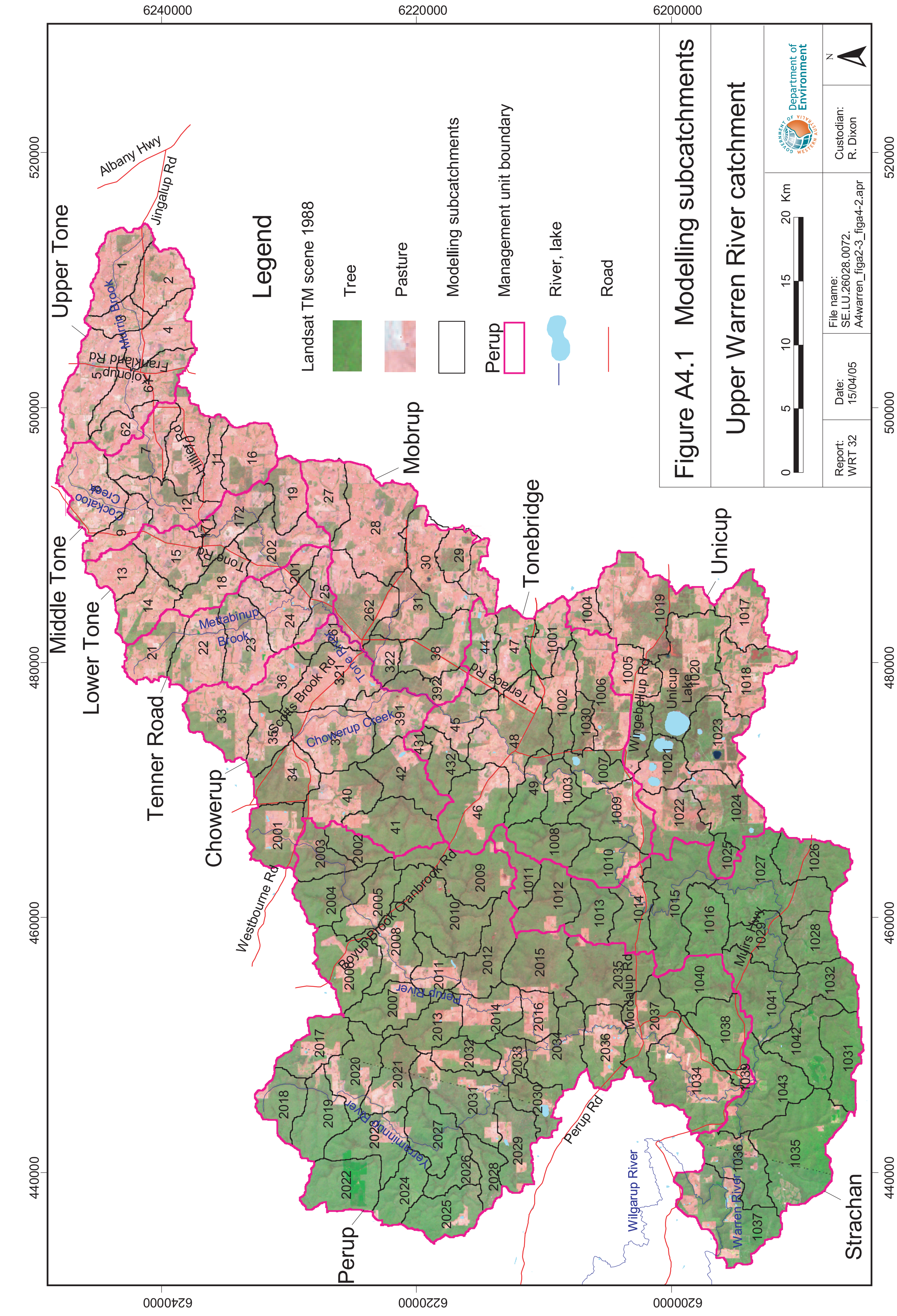

Figure A4.1 Modelling subcatchments

2. Annual Transpiration of pastures (**AT**$_{(P)}$) was set by assuming a growth cycle represented by a coefficient for each month, which is proportional to a nominated peak *LAI*. The appropriate peak *LAI* was derived from calibration of the runoff against streamflow according to Mauger (1996). The monthly transpiration of pastures ($MT_{(p)}$) is defined by *Equation A4.3*

   $$MT_{(P)} = 0.352 \times EP_{(M)} \times leafarea \qquad (Equation\ A4.3)$$

   where:

   $EP_{(M)}$ = monthly pan evaporation in mm

   leafarea is the area of leaf surface

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

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

   $$LAI_{(max)} = 0.00363 \times R_{(A)} \qquad (Equation\ A4.4)$$

   where:

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

   0.00363 was set during calibration to give a maximum pasture $LAI_{(max)}$ that varies from 1.9 to 3.4 increasing from east to west.

4. The LAI of annual pastures was set to change monthly to represent its annual growth cycle. The LAI of annual pastures is zero in summer and peaks in winter.

5. Shallow-rooted perennial pastures was assigned a constant monthly value for LAI. This constant LAI equals the maximum annual pasture LAI. The roots of shallow-rooted perennial pastures were confined to the soil layer. In practice, the plants may wither if soil moisture is depleted, but the model assumes that once soil moisture is available they can quickly re-establish.

6. The LAI for deep-rooted perennial pastures was the same as for shallow-rooted perennial pastures. The only difference in water use results from the depth of root penetration. The deep-rooted perennials were assumed to have a rooting depth of 2 m, which means that, when the soil moisture is depleted in the upper layer, they can draw water from the clay layer if it is available within the nominated depth. So deep-rooted perennials can use more water than shallow-rooted perennials. Water use from the clay layer was assumed as being used at 60% of the rate in the upper layer to account for stress of drawing it from depth.

7. The model was designed to represent different tree planting scenarios on existing pastures by changing the tree greenness on assumed planted areas and adjusting the pasture LAI to ‘no pastures’ in these areas. It is assumed that planted trees are fully-grown and they have the ‘natural’ greenness values. This greenness is proportional to rainfall.

Calibrating and validating the model

Initially, the model with maximum clearing was calibrated to produce the salt loads observed in 1993 — the peak values calculated by trend analysis. Land use derived from the 1988 Landsat TM scene represented the maximum extent of catchment clearing (Fig. A4.1). Average monthly rainfall was calculated from records between 1980 and 1995.

Calibrated parameters are listed below:

1. The maximum pasture **LAI** was set up to vary across the catchment according to *Equation A4.4*. Values ranged from 1.9 in the east to 3.4 in the west.

2. Potential tree transpiration or **N**atural **G**reenness was calculated using *Equation A4.2*. At 520 mm rainfall, the Natural Greenness value was 22, and at 940 mm it was 40.
3. The maximum rate of recharge to groundwater in a month was 3.2 mm (38 mm/year).
4. In areas within native forest where midsummer greenness was relatively low (e.g. swamps or degraded remnants), the LAI of ephemeral vegetation was added. These LAI values varied seasonally in the pattern used for annual pastures with maximum set to 2.7 for tree greenness 15 or less, and decreasing to zero for greenness 30 or greater.
5. Where the ground slope was less than 0.5%, runoff was assumed available for evaporation after the current month.
6. An annual stream loss of 12.1 GL was assumed for the upper catchment to account for filling river ponds before the water flowed downstream.

The model was then validated by running the model with the same parameters except for vegetation cover and rainfall. In 2000, a surface water sampling program provided annual salt and flow estimates at a number of points throughout the catchment. The model used monthly rainfall from observed 2000 data and land use derived from the summer 2000 Landsat TM scene (Fig. 6).

The **A**ctual **G**reenness of the 2000 image was reduced by a factor of 1.5 as the Actual Greenness between 1988 and 2000 did not match due to poor spectral standardisation.

The predicted streamflows and salt loads of both calibration and validation were comparable with the observed streamflows and salt loads for the Tone River (Bullilup), the Perup River (Quabicup Hill) and the Warren River (Wheatley Farm) gauging stations (Table A4.1).

The observed and modelled annual streamflows and stream salt loads in the initial calibration (1993) matched reasonably well (Table A4.1), though the Perup salt loads were slightly underestimated and the Warren River (at Wheatley Farm) salt loads overestimated.

The observed and modelled annual streamflows in 2000 matched reasonably well. The annual stream salt loads of the Tone and Perup rivers were slightly underpredicted and the salt load of the Warren River overpredicted, but all within 10%.

Table A4.1 Model calibration and validation for 1993 and 2000

		Tone River (Bullilup)		*Perup River (Quabicup Hill)*		*Warren River (Wheatley Farm)*	
Model calibration		1993	2000	1993	2000	1993	2000
Streamflow (GL)	Observed	30.6	37.6	13.6	11.0	87.0	81.5
	Modelled	30.7	37.0	13.8	10.7	88.7	86.6
Stream salt load (kt)	Observed	124	135	34.9	25.8	193	186
	Modelled	124	129	31.0	23.6	196	193

Overall, in the 2000 calibration, the predicted annual streamflows and stream salt loads of all three gauging stations were within 10% of the observed records. Therefore, the MAGIC model is considered to be well calibrated for the upper catchment.

During validation, modelled streamflows and salt loads were compared with measurements collected fortnightly from 21 sampling points established in 2000 across the catchment (Fig. A4.2).

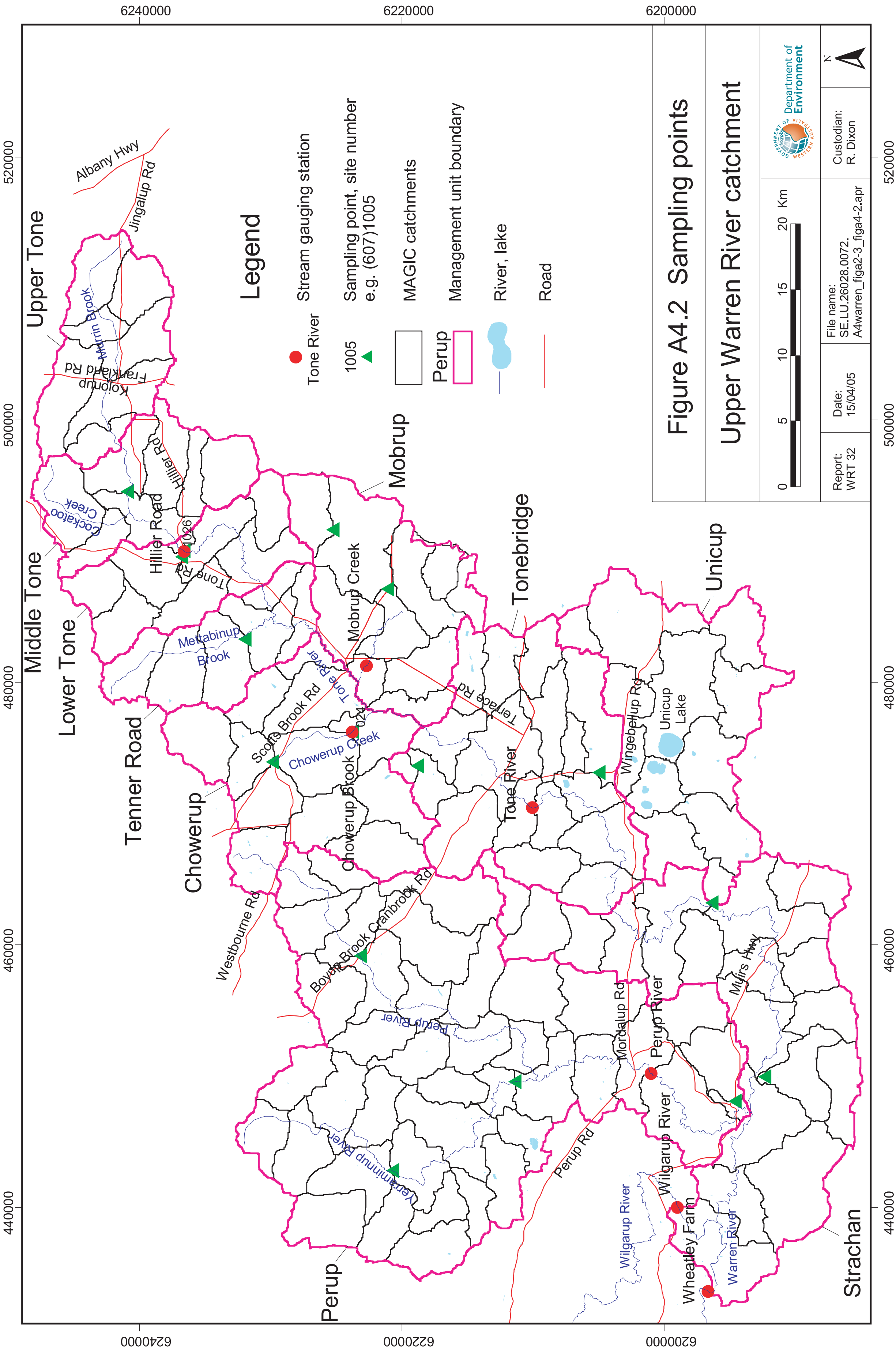
Figure A4.2 Sampling points
Upper Warren River catchment
Legend
Tone River
Stream gauging station
1005
Sampling point, site number e.g. (607)1005
MAGIC catchments
Perup
Management unit boundary
River, lake
Road
0 5 10 15 20 Km
Report: WRT 32
Date: 15/04/05
File name: SE.LU.26028.0072. A4warren_figa2-3_figa4-2.apr
Custodian: R. Dixon
Department of Environment
Upper Tone
Middle Tone
Lower Tone
Tenner Road
Chowerup
Mobrup
Tonebridge
Unicup
Perup
Strachan
Albany Hwy
Jingalup Rd
Frankland Rd
Kojonup
Hillier Rd
Hillier Road
Tone Rd
Muirs Hwy
Perup Rd
Westbourne Rd
Terrace Rd
Scotts Brook Rd
Boyup Brook Cranbrook Rd
Wingebellup Rd
Mordalup Rd
Murrin Brook
Cockatoo Creek
Mettabinup Brook
Tone River
Chowerup Creek
Chowerup Brook
Mobrup Creek
Perup River
Yerraminnup River
Wilgarup River
Warren River
Unicup Lake
Wheatley Farm
6240000
6220000
6200000
440000
460000
480000
500000
520000

The predicted and observed streamflows matched well, especially in the bigger subcatchments (Fig. A4.3), though some smaller subcatchments showed a large percentage mismatch. The predicted and observed groundwater discharges matched well (Fig. A4.4).

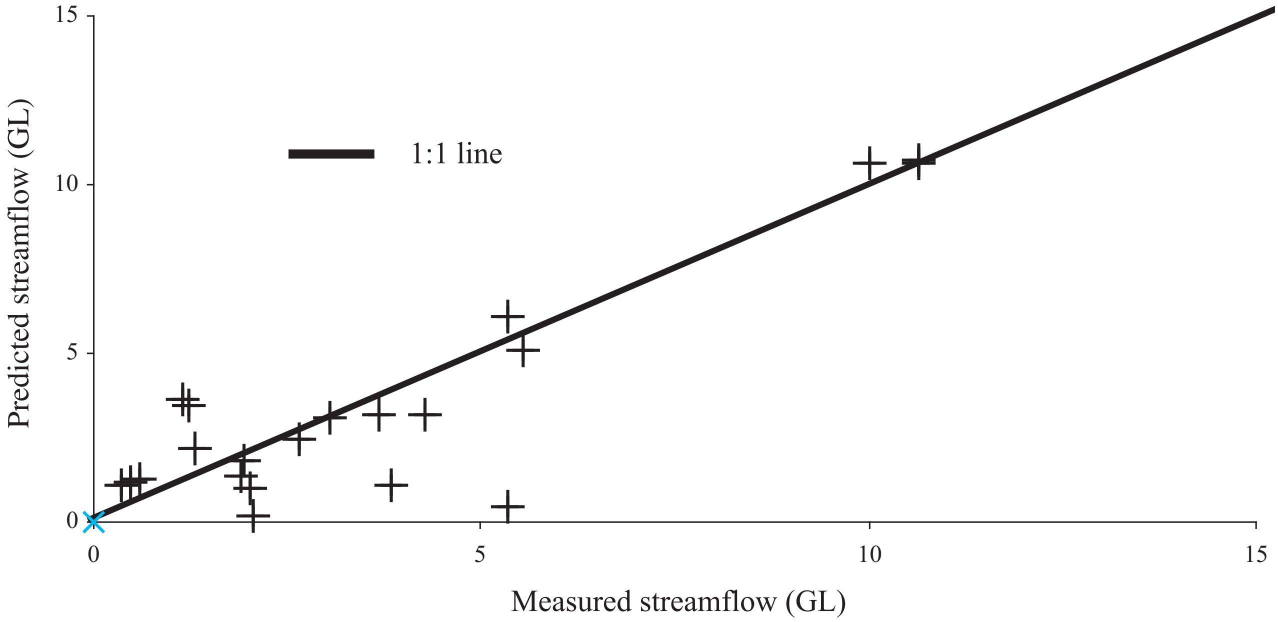

Figure A4.3 Model validation for streamflow in year 2000

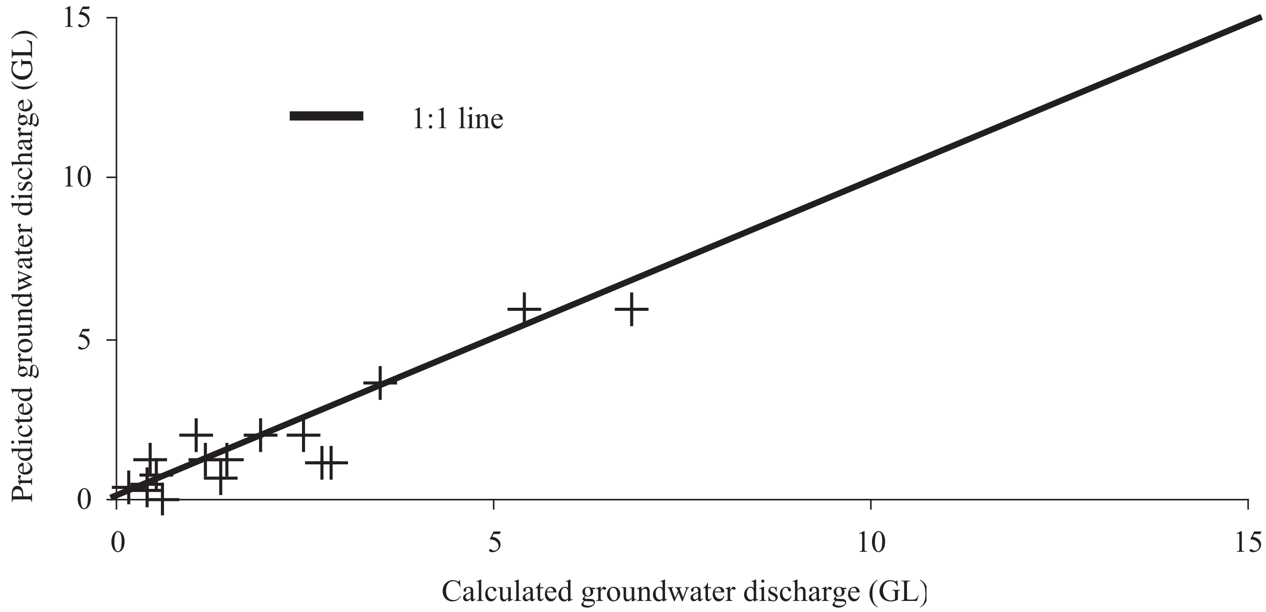

Figure A4.4 Model validation for groundwater discharge in year 2000

‘Base’ case (Sections 4.2.3 and 5.1)

This scenario predicts that 15% of the upper catchment is at risk of developing a shallow watertable (< 2 m). Comparison of these results with areas estimated to be at risk of dryland salinisation (Section 3.3) is shown in Table A4.2.

Table A4.2 Comparison of areas at risk of developing a shallow watertable

Method	*Upper Tone*	*Middle Tone*	*Lower Tone*	*Tenner Road*	*Mobrup*	*Chowerup*	*Tonebridge*	*Perup*
Areas at risk of dryland salinisation	21	20	25	20	36	23	28	5
MAGIC model ‘Base’ case	18	19	18	17	21	13	12	3

The results are within 10% for all management units, except Mobrup and Tonebridge which are very flat and, where in using the < 3% slope criterion, the dryland salinisation method may have overpredicted the areas at risk.

More on Sections 4.2.3 and 5.2 Land capability maps

To model the impacts of revegetation scenarios, land suitable for planting perennial pastures and trees was identified in ‘Land capability’ maps produced from data relating to soil–landscape system maps (Churchward 1992; Percy 1992; Stuart-Street & Scholz in prep.), rainfall, and landscape position. The information used to compile the land capability maps is discussed in Appendix 5. Predictions based on these maps are given in Section 5 and Appendix 5.

Appendix 5 Management options

Part 1 has information on the land capability maps and describes background information on processes and calculations used to make predictions in the various scenarios: the land capability mapping required for the revegetation options; and engineering options — shallow drains, the infrastructure network for groundwater pumping and the process of calculating full and partial diversions of water from the Tone River.

Part 2 presents the results of model calibration and the results of management options by management units (Tables A5.7–5.32).

Part 1 — Calculations and assumptions

More on Section 5.2 Preparation of land capability maps for revegetation scenarios

The areas suitable for commercial trees and perennial pastures are shown on three land capability maps (Figs 18–20). The environmental requirements (rainfall, position in the landscape and properties of the soils), information on waterlogging, and land stability were used to produce the maps by the process summarised below. The mathematical manipulations are detailed in File 18294 (DoE 2000).

Environmental requirements

The environmental requirements for five commercial tree species were obtained from the Forest Products Commission (D. Guille pers. comm. 2002) (Table A5.1).

The requirements for perennial pastures are less restrictive than for commercial trees as there are many varieties. Lucerne and kikuyu are examples of perennial pastures that may be suitable for cultivation in the upper catchment. They grow successfully on land with gradients of less than 14%, and in soils with both an unrestricted rooting depth greater than 50 cm and pH 4.5–8.5.

Table A5.1 Environmental requirements for commercial trees

	Preferred requirements	Bluegum for pulp (*E. globulus*)	Hardwood sawlogs (*E. cladocalyx, E. saligna and C. maculata*)	Pines (*Pinus pinaster*)
Rainfall	Average (mm/yr)	> 700	> 550 (in blocks*) 450 (in belts**)	> 400
Landscape	Inundation (months)	< 2	< 2	< 1
	Slopes (%)	< 14	< 14	< 14
Soil properties	Unrestricted rooting depth (m)	> 2	> 1.5 (in belts) > 2.0 (in blocks)	> 2.5
	Depth of sandy soil (m)	< 2	< 2	no limit
	Conductivity (EM38) (mS/m)	< 50	< 60 (*E. saligna and C. maculata*) < 90 (*E. cladocalyx*)	< 60
	Soil pH (pH_{Ca})	4.5–8.5	4.5–8.5	< 8.5

* Blocks are plantings more than three rows wide

**Belt plantings 1, 2 or 3 rows wide, alleys with other uses > 20 m

Rainfall

Adequate rainfall is a critical requirement for successful growth. The average annual rainfall between 1980 and 1995 (Fig. 1) was used to define suitable areas. Bluegums require, on average, an annual rainfall of > 700 mm so this tree crop is restricted to the more western sections of the catchment. Trees for sawlogs can be grown throughout the upper catchment. If annual rainfall is < 550 mm, block plantings of sawlog trees should be replaced with tree belts. Pines require more than 400 mm of rain annually and can be grown throughout the catchment.

Landscape

Areas with steep slopes (> 14%) and areas at risk of waterlogging were removed from the digital land capability maps using DEM (CSIRO 2000; Land Monitor 2002). Areas with slopes > 10% were also removed because machinery for planting and harvesting is restricted to slopes < 14%, and land with slopes > 10% may be unstable (van Gool & Moore 1999).

Approximately 32% (245 km^2) of pastured areas were subject to waterlogging — defined as areas up to 4 m above the streamline where the slope was less than 4% (Table A5.2 & Fig. 21).

The areas subject to waterlogging relate only to pastured areas and should not be confused with areas at risk of dryland salinisation (Section 3.3) which may develop on the valley floors of both forested areas and pastured areas. Thirty per cent or 205 km^2 of the pastured area (688 km^2) (excluding the Unicup and Strachan MUs) is at risk of waterlogging but only 23% (159 km^2) of the same pastured area is at risk of dryland salinisation.

Table A5.2 Areas at risk of waterlogging

Management unit	*Area*	*Pastured areas*		*Pastured areas at risk of waterlogging*	
	(km^2)	*(km^2)*	*(%)*	*(km^2)*	*(%)*
Upper Tone	125	102	81	23	22
Middle Tone	125	101	81	24	23
Lower Tone	119	85	72	22	26
Tenner Road	99	69	70	17	25
Mobrup	167	96	57	35	37
Chowerup	228	90	39	30	34
Tonebridge	281	83	29	35	43
Perup	722	62	9	19	34
Strachan	402	11	3	3	25
Unicup	227	69	30	37	55
Total (excluding Strachan & Unicup)	**1866**	**688**	**37**	**205**	**30**
Total	**2496**	**768**	**31**	**245**	**32**

Soil properties

The soil requirements for the commercial trees are listed in Table A5.1. Digital soil–landscape mapping (Churchward 1992; Percy 1992; Stuart-Street & Scholz in prep.) was used to identify the soil groups suitable for growing these commercial crops. These soil groups are represented as a percentage of a larger mapped area called a map unit. This type of soil mapping, by the Department of Agriculture, is called proportional mapping and the mapping process is detailed by van Gool and Moore (1999), and Schoknecht (2001). Unrestricted rooting depth and soil texture were the criteria used in this study.

Van Gool and Moore (1999) described the unrestricted rooting depth as 'the depth to a layer that restricts some or most plant roots'. The properties used to define this depth are listed in Table A5.3. If one or more of these soil properties is within the range of the limiting value, plant growth will be restricted. Soil pH and salinity were included as part of the unrestricted rooting depth. Waterlogging is also considered as part of the unrestricted rooting depth, but areas at risk of waterlogging (described above) were used.

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

Table A5.3 Limiting values for unrestricted rooting depth (van Gool & Moore 1999)

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

Soil groups are also classed according to texture. Soil groups with deep sands have sands at depths > 0.8 m. The soil groups with deep sands were identified as suitable for pine trees and deep-rooted perennial pastures, but unsuitable for the following tree species: *Eucalyptus globulus*; *E. saligna*; *Corymbia maculata*; and *E. cladocalyx*.

Land capability results for trees and perennial pastures

Little of the current pastured area is suitable for planting commercial trees or deep-rooted perennial pastures but much larger areas are suitable for shallow-rooted perennial pastures (Figs 18–20, Table A5.4).

Only 3% of the current pastured area is suitable for block bluegum plantings and this area is restricted to the part of the upper catchment with an average annual rainfall of > 700 mm (Fig. 18). Sawlog trees can be grown on about 12% of the available land but, south-west of the 700 mm isohyet, they compete with bluegums for the same area. Pine trees can be planted on about 20% of the available pastured land. About 8% of the pastured area has soil groups with deep sands unsuitable for bluegums or sawlogs but, on the remaining 12%, pine trees compete with sawlogs and bluegum plantations for the available land (Table 3).

Deep-rooted perennials can be grown on the same land as pine trees (20%), but also on an additional 26% of the pastured land (Fig. 20).

Table A5.4 Areas suitable for planting trees on existing pastures

Management unit	*Bluegums*		*Sawlogs*		*Pines*		*Deep-rooted perennials*		*Shallow-rooted perennials*		*Deep and shallow -rooted perennials*	
	(km^2)	(%)	(km^2)	(%)	(km^2)	(%)	(km^2)	(%)	(km^2)	(%)	(km^2)	(%)
Upper Tone	0	0	1	1	13	12	13	12	32	31	45	44
Middle Tone	0	0	1	1	11	11	11	11	37	36	48	47
Lower Tone	0	0	9	10	15	17	15	17	27	32	42	49
Tenner Road	0	0	23	33	26	38	26	38	23	33	49	71
Mobrup	0	0	3	3	10	11	10	11	22	23	32	34
Chowerup	0	0	20	23	28	31	28	31	20	22	48	53
Tonebridge	4	4	11	13	19	23	19	23	12	15	31	38
Unicup	3	5	5	8	11	16	11	16	11	16	22	32
Perup	13	21	16	26	20	32	20	32	17	27	37	59
Strachan	3	27	3	27	4	34	4	34	2	22	6	55
Total	**23**	**3**	**92**	**12**	**157**	**20**	**157**	**20**	**203**	**26**	**360**	**46**

More on Section 5.3 Engineering options

More on Section 5.3.1 Groundwater pumping

A possible groundwater pumping network for the upper catchment (Fig. 22) includes ‘collector’, ‘transport’ and ‘delivery’ pipes. The total infrastructure required is presented in Table A5.5. Bores are assumed to be about 400 m apart along collector pipes that traverse the areas of groundwater discharge. Isolated areas of groundwater discharge are joined by transport pipes. Delivery pipes take groundwater beyond the catchment boundary to an area where the water can be safely discharged. If the discharge sites indicated (Fig. 22) are not suitable, the delivery pipe may need to be extended. The delivery pipe to the Frankland River in the south-east is almost 23 km long and needs a diameter of 350 mm, assuming water in the pipe flows at 1 m/s. Two delivery pipes (each about 4 km long) to the Blackwood River in the north-west are shown. The larger pipe needs a diameter of 100 mm.

Modelling for the groundwater pumping network at 16.6 km^2 Maxon Farm (subcatchment in the Collie River East catchment) indicated that pumps spaced about 100 m apart along the valley floor and pumping about 22 kL/day should be able to lower water level in the entire valley floor and significantly reduce the salt discharge into the creek line (S Dogramaci pers. comm. 2004).

Table A5.27 shows detailed results of modelling the groundwater pumping scenario. Quantities associated with the network show the estimated effects on streamflow and salinity by management unit.

Table A5.5 Groundwater pumping infrastructure for the Tone and Perup rivers

Management unit or subcatchment	*Length of*		*Number of bores (spacing 0.4 km)*
	Collectors (km)	*Transport (km)*	
Upper Tone	96.3		241
Middle Tone	94.7		237
Lower Tone	107		267
Tenner Road	71.0	2.5	177
Mobrup	75.6	10.9	189
Chowerup	87.8	10.7	220
Tonebridge	54.0	15.8	135
Unicup	11.1	6.07	28
Perup	52.3	29.3	131
Total to Barker Road	**650**	**75.4**	**1625**

More on Section 5.3.4 Diversion of saline water

The results of diverting all or part of the Tone River streamflow on the volume and salinity of water left in the Warren River are presented in Tables A5.30–5.32.

Partial diversion

A pipehead dam (similar in design to the one considered in the Collie Salinity Situation Statement (Mauger et al. 2001)) was used for the low-flow diversions. To divert 20% and 30% of the salt load from the Tone River, about 12% (total of 4.25 GL) and 20% (total of 6.74 GL) respectively of the streamflow needs to be diverted (Fig. A5.1, Tables A5.30 & A5.31).

The volume of daily streamflow was used to estimate the size of the pipehead dam. In the model, the dam (potentially located near the Mordalup Road Crossing) is assumed to have a storage capacity equal to about one day's outflow volume and is expected to be about the size of a large farm dam.

Flow rates vary throughout the year so, to divert large flows, a large pump capacity would be required. The pump capacity is expressed as a multiple of mean annual flow (Fig. A5.2).

Full diversion

The dam site proposed by the PWD (1980) is near the Mordalup Road Crossing towards the outlet of the Tonebridge MU. The streamflow records of the Tone River gauging station were adjusted to account for the additional water generated between the gauging station and the outlet of the Tonebridge MU. To calculate the effects of diverting the Tone River water, the adjusted mean annual streamflow of the Tone River was subtracted from the flow predicted at the Barker Road Crossing gauging station by the 'Base' case (Tables A5.9 & A5.32).

The dam was designed to have an outflow capacity equal to one mean annual streamflow. Streamflow records show that, to prevent the dam overflowing, the storage needs to be 2.5 times the mean annual flow. Some dam site characteristics are listed in Table A5.6.

Table A5.6 Proposed damsite characteristics

Dam characteristics	
Catchment area (km^2)	1200
Mean annual flow (GL)	38
Mean annual salt load (kt)	121
Catchment area cleared (km^2)	593
Dam storage volume (GL)	100
Area inundated when at full storage (km^2)	10
Dam wall height (m)	36

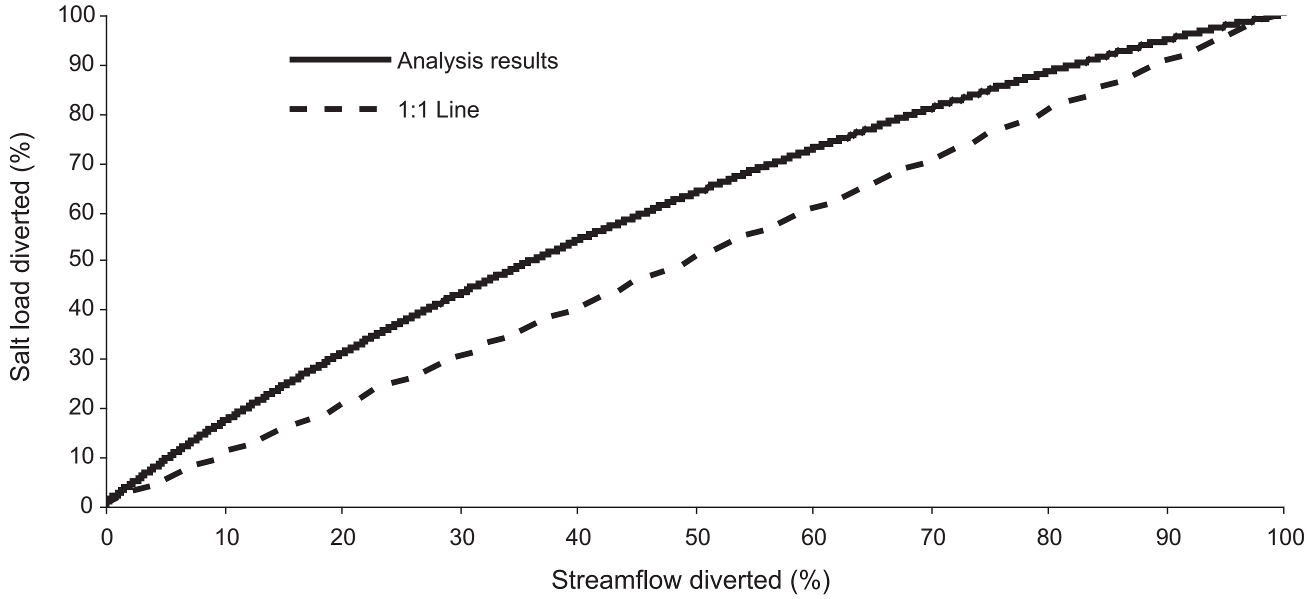

Figure A5.1 Daily flow versus load analysis used for the pipehead dam design

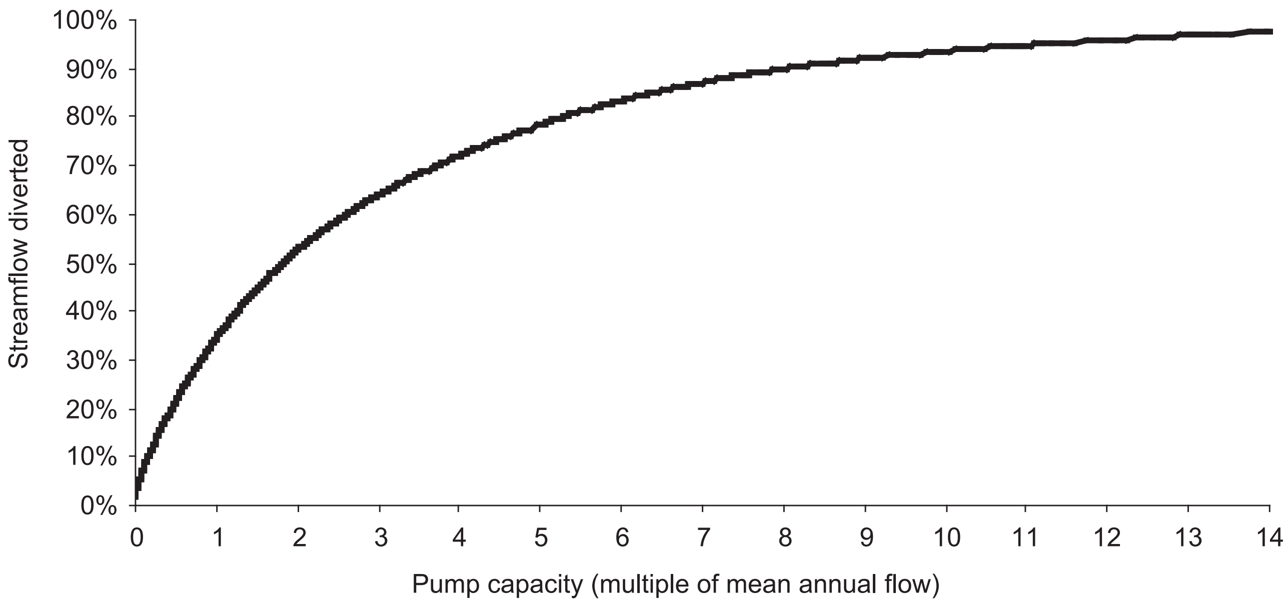

Figure A5.2 Pump capacity plot for pipehead diversion

Part 2 – Analyses of management options

Table A5.7 Model calibration for 1993

	Management unit										*Subcatchment gauging station*		
	Upper Tone	*Middle Tone*	*Lower Tone*	*Tenner Road*	*Mobrup*	*Chowerup*	*Tonebridge*	*Unicup*	*Perup*	*Strachan*	*Wilgarup*	*Wheatley Farm*	*Barker Road*
Total area (km²)	125	125	119	99	167	228	281	227	722	402	461	2966	4078
Clearing to 1988 (km²)	109	101	86	75	105	110	103	104	113	17	159	1082	1298
Clearing to 1988 (%)	87	81	73	75	63	48	37	46	16	4	34	36	32
Average rainfall (mm/yr) (1980–95)	479	495	513	539	563	590	632	671	677	769	860	671	769
Surface water													
Streamflow (GL)	4.30	4.16	4.09	3.85	5.11	6.21	6.22	3.12	16.4	8.03	27.6	89.1	252
Runoff (mm)	34	33	34	39	31	27	22	14	23	20	60	30	62
Salt load (kt)	22.7	20.6	17.7	14.2	20.3	20.5	17.3	11.0	33.1	3.4	21.9	203	243
Stream salinity (mg/L)	5271	4951	4328	3672	3980	3296	2777	3539	2024	418	791	2274	964
Groundwater													
Discharge (GL)	3.14	2.85	2.44	1.95	2.79	2.69	2.29	2.44	2.63	0.36	2.73	26.3	32.2
Discharge (mm)	25	23	21	20	17	12	8	11	4	1	6	9	8
Shallow watertable (km²)	23	22	21	17	33	32	37	42	27	3	n/a	257	257
Shallow watertable (%)*	21	22	24	23	32	29	36	40	24	19	n/a	24	20
Discharge (km²)	14	14	12	11	15	17	16	13	13	1	n/a	127	127
*Discharge** (%)*	13	14	14	15	15	15	15	13	11	7	n/a	12	10

* As a % of the cleared area to 1988

** As a % of the cleared area to 1988

Table A5.8 Model validation for 2000

	Management unit										*Subcatchment gauging station*		
	Upper Tone	*Middle Tone*	*Lower Tone*	*Tenner Road*	*Mobrup*	*Chowerup*	*Tonebridge*	*Unicup*	*Perup*	*Strachan*	*Wilgarup*	*Wheatley Farm*	*Barker Road*
Total area (km²)	125	125	119	99	167	228	281	227	722	402	461	2966	4078
Clearing to 2000 (km²)	102	101	85	69	96	90	83	69	62	11	83	851	979
Clearing to 2000 (%)	81	81	72	70	57	39	29	30	9	3	18	29	24
Average rainfall (mm/yr) (1980–95)	519	536	555	584	609	639	684	727	733	832	860	715	854
Surface water													
Streamflow (GL)	4.84	5.47	5.38	4.66	6.34	6.86	6.89	3.12	12.7	5.86	23.9	86.0	270
Runoff (mm)	39	44	45	47	38	30	24	14	18	15	52	29	66
Salt load (kt)	23.6	22.3	19.3	15.3	20.7	20.4	16.7	10.0	24.8	3.3	20.3	197	210
Stream salinity (mg/L)	4886	4075	3583	3280	3258	2970	2430	3194	1948	560	850	2286	776
Groundwater													
Discharge (GL)	3.31	3.08	2.67	2.13	2.86	2.76	2.28	2.30	2.08	0.33	2.54	26.3	35.0
Discharge (mm)	26	25	22	21	17	12	8	10	3	1	6	8	9
Shallow watertable (km²)	23	24	22	18	35	31	36	38	22	3	n/a	253	253
Shallow watertable (%)*	23	23	26	26	37	35	43	56	36	27	n/a	30	26
Discharge (km²)	18	20	18	14	25	21	21	18	12	1	n/a	168	168
*Discharge** (%)*	18	20	21	20	26	23	26	26	19	12	n/a	20	17

* As a % of the cleared area to 2000

** As a % of the cleared area to 2000

Table A5.9 'Base' case

	Management unit										*Subcatchment gauging station*		
	Upper Tone	*Middle Tone*	*Lower Tone*	*Tenner Road*	*Mobrup*	*Chowerup*	*Tonebridge*	*Unicup*	*Perup*	*Strachan*	*Wilgarup*	*Wheatley Farm*	*Barker Road*
Total area (km²)	125	125	119	99	167	228	281	227	722	402	461	2966	4078
Clearing to 2000 (km²)	102	101	85	69	96	90	83	69	62	11	83	851	979
Clearing to 2000 (%)	81	81	72	70	57	39	29	30	9	3	18	29	24
Average rainfall (mm/yr) (1980–95)	480	495	513	540	563	590	632	672	677	769	860	671	769
Surface water													
Streamflow (GL)	4.20	4.78	4.62	3.90	5.16	5.52	5.56	1.73	11.9	6.49	24.9	78.8	241
Runoff (mm)	34	38	39	39	31	24	20	8	17	16	54	27	59
Salt load (kt)	22.8	21.3	18.4	14.1	20.0	18.7	15.7	9.4	22.3	3.0	19.1	185	210
Stream salinity (mg/L)	5415	4466	3992	3632	3880	3397	2816	5425	1869	457	769	2347	871
Groundwater													
Discharge (GL)	3.19	2.95	2.55	1.97	2.78	2.55	2.14	2.18	1.89	0.29	2.09	24.6	28.5
Discharge (mm)	25	24	21	20	17	11	8	10	3	1	5	4	7
Shallow watertable (km²)	23	24	22	17	35	30	35	38	21	3	n/a	249	249
Shallow watertable (%)*	22	23	26	25	37	34	43	55	34	25	n/a	29	25
Discharge (km²)	14	16	14	11	17	14	14	9	8	1	n/a	118	118
*Discharge** (%)*	14	16	17	16	17	16	17	12	12	7	n/a	14	12

* As a % of the cleared area to 2000

** As a % of the cleared area to 2000

Table A5.10 Commercial trees (bluegums)

	Management unit										*Subcatchment gauging station*		
	Upper Tone	*Middle Tone*	*Lower Tone*	*Tenner Road*	*Mobrup*	*Chowerup*	*Tonebridge*	*Unicup*	*Perup*	*Strachan*	*Wilgarup*	*Wheatley Farm*	*Barker Road*
Total area (km²)	125	125	119	99	167	228	281	227	722	402	461	2966	4078
Clearing to 2000 (km²)	102	101	85	69	96	90	83	69	62	11	83	851	979
Clearing to 2000 (%)	81	81	72	70	57	39	29	30	9	3	18	29	24
Planted area (km²)	0	0	0	0	0	0	4	3	13	3	0	23	23
Planted area (%)	0	0	0	0	0	0	4	5	21	27	0	3	2
Surface water													
Streamflow (GL)	4.20	4.78	4.62	3.90	5.16	5.52	5.32	1.57	10.8	5.91	24.9	77.2	240
Runoff (mm)	34	38	39	39	31	24	19	7	15	15	54	26	59
Streamflow (%)*	100	100	100	100	100	100	96	90	91	91	100	98	99
Salt load (kt)	22.8	21.3	18.4	14.1	20.0	18.7	14.9	9.0	18.0	2.69	19.1	180	205
Mean stream salinity (mg/L)	5415	4466	3992	3632	3880	3397	2793	5735	1663	455	769	2327	855
Groundwater													
Shallow watertable (km²)	23	24	22	17	35	30	35	37	19	3	n/a	245	245
*Shallow watertable** (%)*	100	100	100	100	100	100	98	98	88	90	n/a	98	98
Discharge (km²)	14	16	14	11	17	14	14	8	6	1	n/a	115	115
*Discharge*** (%)*	100	100	100	100	100	100	96	95	79	79	n/a	97	97

* As a % of the 'Base' case streamflow

** As a % of 'Base' case shallow watertable area

*** As a % of the 'Base' case discharge area

Table A5.11 Commercial trees (bluegums & sawlogs)

	Management unit										*Subcatchment gauging station*		
	Upper Tone	*Middle Tone*	*Lower Tone*	*Tenner Road*	*Mobrup*	*Chowerup*	*Tonebridge*	*Unicup*	*Perup*	*Strachan*	*Wilgarup*	*Wheatley Farm*	*Barker Road*
Total area (km²)	125	125	119	99	167	228	281	227	722	402	461	2966	4078
Clearing to 2000 (km²)	102	101	85	69	96	90	83	69	62	11	83	851	979
Clearing to 2000 (%)	81	81	72	70	57	39	29	30	9	3	18	29	24
Planted area (km²)	1	1	9	23	3	20	11	5	16	3	0	92	92
Planted area (%)	1	1	10	33	3	23	13	8	26	27	0	11	9
Surface water													
Streamflow (GL)	4.18	4.70	4.01	2.66	4.87	4.33	4.82	1.47	10.5	5.91	24.9	72.5	235
Runoff (mm)	33	38	34	27	29	19	17	6	15	15	54	24	58
Streamflow (%)*	99	98	87	68	94	78	87	85	88	91	100	92	97
Salt load (kt)	22.6	21.1	16.6	9.1	19.4	14.2	13.2	8.7	16.8	2.69	19.1	164	189
Mean stream salinity (mg/L)	5420	4488	4131	3431	3977	3288	2736	5932	1598	455	769	2262	805
Groundwater													
Shallow watertable (km²)	23	23	21	14	35	26	33	36	18	3	n/a	232	232
*Shallow watertable** (%)*	100	99	94	79	98	87	93	96	85	90	n/a	93	93
Discharge (km²)	14	16	13	8	16	11	12	8	6	1	n/a	104	104
*Discharge*** (%)*	99	99	90	70	96	79	87	93	74	79	n/a	88	88

* As a % of the 'Base' case streamflow

** As a % of Base' case shallow watertable area

*** As a % of the 'Base' case discharge area

Table A5.12 Commercial trees (bluegums, sawlogs & pines)

	Management unit										*Subcatchment gauging station*		
	Upper Tone	*Middle Tone*	*Lower Tone*	*Tenner Road*	*Mobrup*	*Chowerup*	*Tonebridge*	*Unicup*	*Perup*	*Strachan*	*Wilgarup*	*Wheatley Farm*	*Barker Road*
Total area (km²)	125	125	119	99	167	228	281	227	722	402	461	2966	4078
Clearing to 2000 (km²)	102	101	85	69	96	90	83	69	62	11	83	851	979
Clearing to 2000 (%)	81	81	72	70	57	39	29	30	9	3	18	29	24
Planted area (km²)	13	11	15	26	10	28	19	11	20	4	0	157	157
Planted area (%)	12	11	17	38	11	31	23	16	32	34	0	18	16
Surface water													
Streamflow (GL)	3.67	4.24	3.78	2.42	4.42	3.73	4.18	1.19	10.2	5.75	24.9	69.2	232
Runoff (mm)	29	34	32	24	26	16	15	5	14	14	54	23	57
Streamflow (%)*	87	89	82	62	86	68	75	69	85	89	100	88	96
Salt load (kt)	19.8	18.8	15.0	8.3	17.7	12.6	11.5	8.0	15.6	2.62	19.1	149	174
Mean stream salinity (mg/L)	5386	4439	3979	3422	4006	3384	2750	6715	1534	455	769	2154	752
Groundwater													
Shallow watertable (km²)	21	22	20	13	33	25	31	35	18	2	n/a	220	220
*Shallow watertable** (%)*	91	93	89	74	94	82	88	92	83	87	n/a	88	88
Discharge (km²)	13	15	12	7	15	10	11	7	5	1	n/a	95	95
*Discharge *** (%)*	88	90	85	64	89	71	77	85	68	73	n/a	81	81

* As a % of the 'Base' case streamflow

** As a % of 'Base' case shallow watertable area

*** As a % of the 'Base' case discharge area

Table A5.13 Non-commercial trees on waterlogged land

	Management unit										*Subcatchment gauging station*		
	Upper Tone	*Middle Tone*	*Lower Tone*	*Tenner Road*	*Mobrup*	*Chowerup*	*Tonebridge*	*Unicup*	*Perup*	*Strachan*	*Wilgarup*	*Wheatley Farm*	*Barker Road*
Total area (km²)	125	125	119	99	167	228	281	227	722	402	461	2966	4078
Clearing to 2000 (km²)	102	101	85	69	96	90	83	69	62	11	83	851	979
Clearing to 2000 (%)	81	81	72	70	57	39	29	30	9	3	18	29	24
Planted area (km²)	17	16	16	11	37	25	31	30	11	3	0	197	197
Planted area (%)	17	16	19	16	39	28	37	43	18	24	0	23	20
Surface water													
Streamflow (GL)	1.86	2.38	2.19	1.98	1.85	2.38	2.25	0	9.7	5.36	24.9	54.5	217
Runoff (mm)	15	19	18	20	11	10	8	0	13	13	54	18	53
Streamflow (%)*	44	50	47	51	36	43	40	0	81	83	100	69	90
Salt load (kt)	22.4	21.6	18.3	14.2	18.0	18.0	12.3	0	23.6	2.95	19.1	179	204
Mean stream salinity (mg/L)	12 017	9061	8353	7138	9738	7546	5443	0	2434	550	769	3288	942
Groundwater													
Shallow watertable (km²)	19	21	19	16	27	25	30	32	20	2	n/a	213	213
*Shallow watertable** (%)*	85	89	88	94	78	83	84	85	92	86	n/a	85	85
Discharge (km²)	5	6	5	5	4	4	4	2	4	<1	n/a	39	39
*Discharge *** (%)*	38	38	33	45	23	30	26	21	52	32	n/a	33	33

* As a % of the 'Base' case streamflow

** As a % of 'Base' case shallow watertable area

*** As a % of the 'Base' case discharge area

Table A5.14 Deep-rooted perennial pastures (100% of LAI)+

	Management unit										*Subcatchment gauging station*		
	Upper Tone	*Middle Tone*	*Lower Tone*	*Tenner Road*	*Mobrup*	*Chowerup*	*Tonebridge*	*Unicup*	*Perup*	*Strachan*	*Wilgarup*	*Wheatley Farm*	*Barker Road*
Total area (km²)	125	125	119	99	167	228	281	227	722	402	461	2966	4078
Clearing to 2000 (km²)	102	101	85	69	96	90	83	69	62	11	83	851	979
Clearing to 2000 (%)	81	81	72	70	57	39	29	30	9	3	18	29	24
Planted area (km²)	13	11	15	26	10	28	19	11	20	4	0	157	157
Planted area (%)	12	11	17	38	11	31	23	16	32	34	0	18	16
Surface water													
Streamflow (GL)	3.64	4.21	3.73	2.33	4.36	3.58	4.08	1.16	10.0	5.72	24.9	68.5	231
Runoff (mm)	29	34	31	24	26	16	14	5	14	14	54	23	57
Streamflow (%)*	87	88	81	60	84	65	73	67	84	88	100	87	96
Salt load (kt)	20.3	19.3	15.8	9.9	18.3	14.4	12.5	8.5	17.8	2.73	19.1	158	183
Mean stream salinity (mg/L)	5577	4592	4231	4239	4208	4008	3067	7353	1780	478	769	2306	793
Groundwater													
Shallow watertable (km²)	21	22	20	14	34	26	32	35	18	2	n/a	225	225
*Shallow watertable** (%)*	92	94	91	80	95	85	91	94	85	90	n/a	90	90
Discharge (km²)	13	15	12	7	15	10	11	7	5	1	n/a	97	97
*Discharge*** (%)*	88	90	85	67	90	72	79	86	70	75	n/a	82	82

+ The constant year-round LAI used for perennial pastures is 100% of the peak (winter) LAI of annual pastures

* As a % of the 'Base' case streamflow

** As a % of the 'Base' case shallow watertable area

*** As a % of the 'Base' case discharge area

Table A5.15 Deep-rooted perennial pastures (80% of LAI)+

	Management unit										*Subcatchment gauging station*		
	Upper Tone	*Middle Tone*	*Lower Tone*	*Tenner Road*	*Mobrup*	*Chowerup*	*Tonebridge*	*Unicup*	*Perup*	*Strachan*	*Wilgarup*	*Wheatley Farm*	*Barker Road*
Total area (km²)	125	125	119	99	167	228	281	227	722	402	461	2966	4078
Clearing to 2000 (km²)	102	101	85	69	96	90	83	69	62	11	83	851	979
Clearing to 2000 (%)	81	81	72	70	57	39	29	30	9	3	18	29	24
Planted area (km²)	13	11	15	26	10	28	19	11	20	4	0	157	157
Planted area (%)	12	11	17	38	11	31	23	16	32	34	0	18	16
Surface water													
Streamflow (GL)	3.65	4.23	3.76	2.41	4.41	3.71	4.19	1.20	10.3	5.79	24.9	69.2	232
Runoff (mm)	29	34	32	24	26	16	15	5	14	14	54	23	57
Streamflow (%)*	87	88	81	62	85	67	75	69	86	89	100	88	96
Salt load (kt)	20.5	19.5	16.0	10.3	18.5	14.8	12.7	8.7	18.3	2.76	19.1	161	186
Mean stream salinity (mg/L)	5618	4611	4257	4281	4199	4000	3042	7202	1775	477	769	2321	802
Groundwater													
Shallow watertable (km²)	21	22	20	14	34	27	33	36	18	3	n/a	228	228
*Shallow watertable** (%)*	93	95	92	83	96	87	92	94	87	92	n/a	92	92
Discharge (km²)	13	15	12	8	15	11	11	7	6	1	n/a	98	98
*Discharge*** (%)*	89	91	86	70	91	75	81	87	72	77	n/a	83	83

\+ The constant year-round LAI used for perennial pastures is 80% of the peak (winter) LAI of annual pastures

* As a % of the 'Base' case streamflow

** As a % of the 'Base' case shallow watertable area

*** As a % of the 'Base' case discharge area

Table A5.16 Deep-rooted perennial pastures (60% of LAI)+

	Management unit										*Subcatchment gauging station*		
	Upper Tone	*Middle Tone*	*Lower Tone*	*Tenner Road*	*Mobrup*	*Chowerup*	*Tonebridge*	*Unicup*	*Perup*	*Strachan*	*Wilgarup*	*Wheatley Farm*	*Barker Road*
Total area (km^2)	125	125	119	99	167	228	281	227	722	402	461	2966	4078
Clearing to 2000 (km^2)	102	101	85	69	96	90	83	69	62	11	83	851	979
Clearing to 2000 (%)	81	81	72	70	57	39	29	30	9	3	18	29	24
Planted area (km^2)	13	11	15	26	10	28	19	11	20	4	0	157	157
Planted area (%)	12	11	17	38	11	31	23	16	32	34	0	18	16
Surface water													
Streamflow (GL)	3.69	4.26	3.82	2.55	4.48	3.93	4.37	1.27	10.7	6.01	24.9	70.3	233
Runoff (mm)	29	34	32	26	27	17	16	6	15	15	54	24	57
Streamflow (%)*	88	89	83	65	87	71	79	73	90	93	100	89	97
Salt load (kt)	20.8	19.7	16.3	10.8	18.7	15.5	13.1	8.8	19.2	2.81	19.1	164	189
Mean stream salinity (mg/L)	5634	4629	4269	4257	4185	3952	3002	6973	1788	467	769	2333	813
Groundwater													
Shallow watertable (km^2)	21	23	21	15	34	27	33	36	19	3	n/a	232	232
*Shallow watertable** (%)*	94	96	93	86	97	90	94	96	91	94	n/a	93	93
Discharge (km^2)	13	15	13	8	15	11	12	8	6	1	n/a	101	101
*Discharge*** (%)*	90	92	88	73	92	78	84	89	76	80	n/a	85	85

\+ The constant year-round LAI used for perennial pastures is 60% of the peak (winter) LAI of annual pastures

* As a % of the 'Base' case streamflow

** As a % of the 'Base' case shallow watertable area

*** As a % of the 'Base' case discharge area

Table A5.17 Deep-rooted perennial pastures (50% of LAI)+

	Management unit										*Subcatchment gauging station*		
	Upper Tone	*Middle Tone*	*Lower Tone*	*Tenner Road*	*Mobrup*	*Chowerup*	*Tonebridge*	*Unicup*	*Perup*	*Strachan*	*Wilgarup*	*Wheatley Farm*	*Barker Road*
Total area (km²)	125	125	119	99	167	228	281	227	722	402	461	2966	4078
Clearing to 2000 (km²)	102	101	85	69	96	90	83	69	62	11	83	851	979
Clearing to 2000 (%)	81	81	72	70	57	39	29	30	9	3	18	29	24
Planted area (km²)	13	11	15	26	10	28	19	11	20	4	0	157	157
Planted area (%)	12	11	17	38	11	31	23	16	32	34	0	18	16
Surface water													
Streamflow (GL)	3.74	4.30	3.90	2.71	4.55	4.15	4.53	1.32	11.0	6.07	24.9	71.4	234
Runoff (mm)	30	34	33	27	27	18	16	6	15	15	54	24	57
Streamflow (%)*	89	90	84	70	88	75	81	76	92	93	100	91	97
Salt load (kt)	21.1	19.9	16.6	11.4	18.9	16.1	13.4	8.9	19.6	2.84	19.1	167	192
Mean stream salinity (mg/L)	5640	4624	4265	4202	4151	3872	2955	6766	1788	468	769	2341	822
Groundwater													
Shallow watertable (km²)	22	23	21	15	34	28	34	37	19	3	n/a	235	235
*Shallow watertable** (%)*	95	96	95	89	97	92	95	96	91	96	n/a	94	94
Discharge (km²)	13	15	13	8	16	12	12	8	6	1	n/a	103	103
*Discharge*** (%)*	91	93	89	77	93	81	86	91	79	84	n/a	87	87

+ The constant year-round LAI used for perennial pastures is 50% of the peak (winter) LAI of annual pastures

* As a % of the 'Base' case streamflow

** As a % of the 'Base' case shallow watertable area

*** As a % of the 'Base' case discharge area

Table A5.18 Shallow-rooted perennial pastures on 20% of the cleared land (100% of LAI)+
(using land suitable for deep-rooted perennial pastures)

	Management unit										*Subcatchment gauging station*		
	Upper Tone	*Middle Tone*	*Lower Tone*	*Tenner Road*	*Mobrup*	*Chowerup*	*Tonebridge*	*Unicup*	*Perup*	*Strachan*	*Wilgarup*	*Wheatley Farm*	*Barker Road*
Total area (km²)	125	125	119	99	167	228	281	227	722	402	461	2966	4078
Clearing to 2000 (km²)	102	101	85	69	96	90	83	69	62	11	83	851	979
Clearing to 2000 (%)	81	81	72	70	57	39	29	30	9	3	18	29	24
Planted area (km²)	13	11	15	26	10	28	19	11	20	4	0	157	157
Planted area (%)	12	11	17	38	11	31	23	16	32	34	0	18	16
Surface water													
Streamflow (GL)	3.67	4.24	3.78	2.32	4.42	3.72	4.15	1.10	10.3	5.15	24.9	68.7	231
Runoff (mm)	29	34	32	23	26	16	15	5	14	13	54	23	57
Streamflow (%)*	87	89	82	60	86	67	75	63	86	79	100	87	96
Salt load (kt)	20.9	19.8	16.4	11.1	18.8	15.5	13.0	8.8	19.2	2.72	19.1	165	190
Mean stream salinity (mg/L)	5704	4674	4345	4800	4245	4153	3144	7990	1864	528	769	2396	821
Groundwater													
Shallow watertable (km²)	21	23	21	15	34	27	33	36	19	2	n/a	232	232
*Shallow watertable** (%)*	94	96	94	87	97	89	93	95	91	85	n/a	93	93
Discharge (km²)	13	15	13	8	15	11	12	8	6	1	n/a	100	100
*Discharge*** (%)*	90	92	88	74	92	77	83	88	75	69	n/a	85	85

\+ The constant year-round LAI used for perennial pastures is 100% of the peak (winter) LAI of annual pastures

* As a % of the 'Base' case streamflow

** As a % of the 'Base' case shallow watertable area

*** As a % of the 'Base' case discharge area

Table A5.19 Shallow-rooted perennial pastures on 20% of cleared land (80% of LAI)+ (using land suitable for deep-rooted perennial pastures)

	Management unit										*Subcatchment gauging station*		
	Upper Tone	*Middle Tone*	*Lower Tone*	*Tenner Road*	*Mobrup*	*Chowerup*	*Tonebridge*	*Unicup*	*Perup*	*Strachan*	*Wilgarup*	*Wheatley Farm*	*Barker Road*
Total area (km²)	125	125	119	99	167	228	281	227	722	402	461	2966	4078
Clearing to 2000 (km²)	102	101	85	69	96	90	83	69	62	11	83	851	979
Clearing to 2000 (%)	81	81	72	70	57	39	29	30	9	3	18	29	24
Planted area (km²)	13	11	15	26	10	28	19	11	20	4	0	157	157
Planted area (%)	12	11	17	38	11	31	23	16	32	34	0	18	16
Surface water													
Streamflow (GL)	3.69	4.26	3.82	2.52	4.47	3.89	4.33	1.25	10.7	5.95	24.9	70.2	233
Runoff (mm)	29	34	32	25	27	17	15	5	15	15	54	24	57
Streamflow (%)*	88	89	83	65	87	71	78	72	89	92	100	89	96
Salt load (kt)	21.2	20.0	16.6	11.3	18.9	15.8	13.3	8.9	19.8	2.83	19.1	167	192
Mean stream salinity (mg/L)	5734	4696	4360	4483	4223	4070	3062	7101	1856	475	769	2383	827
Groundwater													
Shallow watertable (km²)	22	23	21	15	34	28	34	36	20	3	n/a	235	235
*Shallow watertable** (%)*	95	97	95	88	97	91	95	96	93	94	n/a	94	94
Discharge (km²)	13	15	13	8	16	11	12	8	6	1	n/a	102	102
*Discharge*** (%)*	91	92	88	75	92	79	84	89	78	81	n/a	86	86

+ The constant year-round LAI used for perennial pastures is 80% of the peak (winter) LAI of annual pastures

* As a % of the ‘Base’ case streamflow

** As a % of the ‘Base’ case shallow watertable area

*** As a % of the ‘Base’ case discharge area

Table A5.20 Shallow-rooted perennial pastures on 20% of cleared land (60% of LAI)+ (using land suitable for deep-rooted perennial pastures)

	Management unit										*Subcatchment gauging station*		
	Upper Tone	*Middle Tone*	*Lower Tone*	*Tenner Road*	*Mobrup*	*Chowerup*	*Tonebridge*	*Unicup*	*Perup*	*Strachan*	*Wilgarup*	*Wheatley Farm*	*Barker Road*
Total area (km²)	125	125	119	99	167	228	281	227	722	402	461	2966	4078
Clearing to 2000 (km²)	102	101	85	69	96	90	83	69	62	11	83	851	979
Clearing to 2000 (%)	81	81	72	70	57	39	29	30	9	3	18	29	24
Planted area (km²)	13	11	15	26	10	28	19	11	20	4	0	157	157
Planted area (%)	12	11	17	38	11	31	23	16	32	34	0	18	16
Surface water													
Streamflow (GL)	3.72	4.29	3.88	2.69	4.54	4.15	4.53	1.33	11.1	6.12	24.9	71.4	234
Runoff (mm)	30	34	33	27	27	18	16	6	15	15	54	24	57
Streamflow (%)*	89	90	84	69	88	75	81	77	93	94	100	91	97
Salt load (kt)	21.4	20.2	17.0	12.0	19.2	16.8	13.7	9.1	20.6	2.87	19.1	171	196
Mean stream salinity (mg/L)	5755	4713	4374	4463	4220	4053	3030	6825	1858	468	769	2399	840
Groundwater													
Shallow watertable (km²)	22	23	21	16	35	29	34	37	20	3	n/a	239	239
*Shallow watertable** (%)*	96	97	96	92	98	94	97	97	95	96	n/a	96	96
Discharge (km²)	13	15	13	9	16	12	12	8	6	1	n/a	104	104
*Discharge*** (%)*	91	93	90	78	94	83	87	91	83	84	n/a	88	88

\+ The constant year-round LAI used for perennial pastures is 60% of the peak (winter) LAI of annual pastures

* As a % of the 'Base' case streamflow

** As a % of the 'Base' case shallow watertable area

*** As a % of the 'Base' case discharge area

Table A5.21 Shallow-rooted perennial pastures on 20% of cleared land (50% of LAI)+ (using land suitable for deep-rooted perennial pastures)

	Management unit										*Subcatchment gauging station*		
	Upper Tone	*Middle Tone*	*Lower Tone*	*Tenner Road*	*Mobrup*	*Chowerup*	*Tonebridge*	*Unicup*	*Perup*	*Strachan*	*Wilgarup*	*Wheatley Farm*	*Barker Road*
Total area (km²)	125	125	119	99	167	228	281	227	722	402	461	2966	4078
Clearing to 2000 (km²)	102	101	85	69	96	90	83	69	62	11	83	851	979
Clearing to 2000 (%)	81	81	72	70	57	39	29	30	9	3	18	29	24
Planted area (km²)	13	11	15	26	10	28	19	11	20	4	0	157	157
Planted area (%)	12	11	17	38	11	31	23	16	32	34	0	18	16
Surface water													
Streamflow (GL)	3.77	4.34	3.95	2.85	4.61	4.36	4.69	1.39	11.4	6.23	24.9	72.4	235
Runoff (mm)	30	35	33	29	28	19	17	6	16	15	54	24	58
Streamflow (%)*	90	91	86	73	89	79	84	80	95	96	100	92	97
Salt load (kt)	21.6	20.5	17.4	12.6	19.4	17.3	13.9	9.2	21.0	2.89	19.1	174	199
Mean stream salinity (mg/L)	5747	4725	4395	4417	4206	3960	2974	6584	1850	464	769	2407	849
Groundwater													
Shallow watertable (km²)	22	23	21	17	35	29	35	37	21	3	n/a	242	242
*Shallow watertable** (%)*	97	98	97	95	99	96	98	98	97	98	n/a	97	97
Discharge (km²)	13	15	13	9	16	12	13	8	7	1	n/a	106	106
*Discharge*** (%)*	92	94	91	82	95	85	89	93	85	74	n/a	90	90

+ The constant year-round LAI used for perennial pastures is 50% of the peak (winter) LAI of annual pastures

* As a % of the 'Base' case streamflow

** As a % of the 'Base' case shallow watertable area

*** As a % of the 'Base' case discharge area

Table A5.22 Shallow-rooted perennial pastures on 26% of cleared land (100% of LAI)+ (using land not suitable for deep-rooted perennial pastures)

	Management unit										*Subcatchment gauging station*		
	Upper Tone	*Middle Tone*	*Lower Tone*	*Tenner Road*	*Mobrup*	*Chowerup*	*Tonebridge*	*Unicup*	*Perup*	*Strachan*	*Wilgarup*	*Wheatley Farm*	*Barker Road*
Total area (km^2)	125	125	119	99	167	228	281	227	722	402	461	2966	4078
Clearing to 2000 (km^2)	102	101	85	69	96	90	83	69	62	11	83	851	979
Clearing to 2000 (%)	81	81	72	70	57	39	29	30	9	3	18	29	24
Planted area (km^2)	32	37	27	23	22	20	12	11	17	2	0	203	203
Planted area (%)	31	36	32	33	23	22	15	16	27	22	0	24	21
Surface water													
Streamflow (GL)	2.84	2.99	3.06	2.50	3.69	4.16	4.44	1.08	10.5	5.59	24.9	65.5	228
Runoff (mm)	23	24	26	25	22	18	16	5	15	14	54	22	56
Streamflow (%)*	68	63	66	64	71	75	80	63	88	86	100	83	94
Salt load (kt)	18.0	16.9	14.6	11.5	17.5	16.2	13.6	8.7	19.7	2.80	19.1	159	184
Mean stream salinity (mg/L)	6349	5654	4769	4594	4747	3909	3059	8064	1865	500	769	2422	806
Groundwater													
Shallow watertable (km^2)	19	21	19	15	33	28	34	36	20	2	n/a	227	227
*Shallow watertable** (%)*	85	87	88	88	93	92	95	95	92	90	n/a	91	91
Discharge (km^2)	11	11	11	8	14	12	12	8	6	1	n/a	94	94
*Discharge*** (%)*	74	69	77	77	84	82	86	87	78	79	n/a	79	79

\+ The constant year-round LAI used for perennial pastures is 100% of the peak (winter) LAI of annual pastures

* As a % of the 'Base' case streamflow

** As a % of the 'Base' case shallow watertable area

*** As a % of the 'Base' case discharge area

Table A5.23 Shallow-rooted perennial pastures on 26% of cleared land (50% of LAI)+ (using land not suitable for deep-rooted perennial pastures)

	Management unit										Subcatchment gauging station		
	Upper Tone	*Middle Tone*	*Lower Tone*	*Tenner Road*	*Mobrup*	*Chowerup*	*Tonebridge*	*Unicup*	*Perup*	*Strachan*	*Wilgarup*	*Wheatley Farm*	*Barker Road*
Total area (km²)	125	125	119	99	167	228	281	227	722	402	461	2966	4078
Clearing to 2000 (km²)	102	101	85	69	96	90	83	69	62	11	83	851	979
Clearing to 2000 (%)	81	81	72	70	57	39	29	30	9	3	18	29	24
Planted area (km²)	32	37	27	23	22	20	12	11	17	2	0	203	203
Planted area (%)	31	36	32	33	23	22	15	16	27	22	0	24	21
Surface water													
Streamflow (GL)	3.09	3.33	3.40	2.97	4.06	4.64	4.87	1.39	11.4	6.32	24.9	70.4	233
Runoff (mm)	25	27	29	30	24	20	17	6	16	16	54	24	57
Streamflow (%)*	74	70	74	76	79	84	88	80	96	97	100	89	97
Salt load (kt)	19.9	18.9	16.4	12.8	18.7	17.6	14.3	9.2	21.2	2.92	19.1	171	196
Mean stream salinity (mg/L)	6435	5679	4830	4299	4613	3797	2936	6610	1853	461	769	2431	843
Groundwater													
Shallow watertable (km²)	21	22	21	17	34	29	35	37	21	3	n/a	240	240
*Shallow watertable** (%)*	92	94	95	95	97	97	98	98	97	98	n/a	96	96
Discharge (km²)	12	13	12	9	15	13	13	8	7	1	n/a	102	102
*Discharge*** (%)*	81	77	85	84	89	89	91	93	87	83	n/a	86	86

+ The constant year-round LAI used for perennial pastures is 50% of the peak (winter) LAI of annual pastures

* As a % of the 'Base' case streamflow

** As a % of the 'Base' case shallow watertable area

*** As a % of the 'Base' case discharge area

Table A5.24 Grass on waterlogged land (100% of LAI)[+]

	Management unit										*Subcatchment gauging station*		
	Upper Tone	*Middle Tone*	*Lower Tone*	*Tenner Road*	*Mobrup*	*Chowerup*	*Tonebridge*	*Unicup*	*Perup*	*Strachan*	*Wilgarup*	*Wheatley Farm*	*Barker Road*
Total area (km²)	125	125	119	99	167	228	281	227	722	402	461	2966	4078
Clearing to 2000 (km²)	102	101	85	69	96	90	83	69	62	11	83	851	979
Clearing to 2000 (%)	81	81	72	70	57	39	29	30	9	3	18	29	24
Planted area (km²)	17	16	16	11	37	25	31	30	11	3	0	197	197
Planted area (%)	17	16	19	16	39	28	37	43	18	24	0	23	20
Surface water													
Streamflow (GL)	1.61	2.14	2.01	1.85	1.74	2.24	2.16	0	9.75	5.36	24.9	53.4	216
Runoff (mm)	13	17	17	19	10	10	8	0	13	13	54	18	53
Streamflow (%)*	38	45	44	47	34	41	39	0	82	83	100	68	89
Salt load (kt)	22.8	21.9	18.6	14.2	19.4	18.6	12.8	0	22.4	2.92	19.1	182	207
Mean stream salinity (mg/L)	14151	10224	9222	7710	11153	8281	5916	0	2292	544	769	3409	960
Groundwater													
Shallow watertable (km²)	19	20	19	16	29	26	32	34	20	3	n/a	217	217
*Shallow watertable** (%)*	81	87	87	92	82	85	89	90	93	91	n/a	87	87
Discharge (km²)	1	<1	1	<1	1	1	1	1	3	1	n/a	8	8
*Discharge*** (%)*	6	2	4	1	3	4	7	13	33	123	n/a	7	7

+ The constant year-round LAI used for perennial grasses is 100% of the peak (winter) LAI of annual pastures

* As a % of the 'Base' case streamflow

** As a % of the 'Base' case shallow watertable area

*** As a % of the 'Base' case discharge area

Table A5.25 Perennial grasses on waterlogged land (75% of LAI)[+]

	Management unit										*Subcatchment gauging station*		
	Upper Tone	*Middle Tone*	*Lower Tone*	*Tenner Road*	*Mobrup*	*Chowerup*	*Tonebridge*	*Unicup*	*Perup*	*Strachan*	*Wilgarup*	*Wheatley Farm*	*Barker Road*
Total area (km²)	125	125	119	99	167	228	281	227	722	402	461	2966	4078
Clearing to 2000 (km²)	102	101	85	69	96	90	83	69	62	11	83	851	979
Clearing to 2000 (%)	81	81	72	70	57	39	29	30	9	3	18	29	24
Planted area (km²)	17	16	16	11	37	25	31	30	11	3	0	197	197
Planted area (%)	17	16	19	16	39	28	37	43	18	24	0	23	20
Surface water													
Streamflow (GL)	1.84	2.31	2.21	2.05	1.90	2.55	2.40	0	10.1	5.38	24.9	55.3	218
Runoff (mm)	15	18	19	21	11	11	9	0	14	13	54	19	53
Streamflow (%)*	44	48	48	53	37	46	43	0	85	83	100	70	90
Salt load (kt)	22.9	21.3	18.6	14.3	19.9	18.8	13.1	0	22.2	2.95	19.1	183	208
Mean stream salinity (mg/L)	12500	9214	8455	6972	10 488	7385	5452	0	2194	549	769	3304	955
Groundwater													
Shallow watertable (km²)	19	20	19	16	29	27	32	35	19	3	n/a	220	220
*Shallow watertable** (%)*	84	86	88	94	83	87	91	92	91	94	n/a	88	88
Discharge (km²)	1	<1	1	<1	1	1	1	1	3	1	n/a	8	8
*Discharge*** (%)*	6	2	4	1	3	4	7	13	33	123	n/a	7	7

\+ The constant year-round LAI used for perennial grasses is 75% of the peak (winter) LAI of annual pastures

* As a % of the 'Base' case streamflow

** As a % of the 'Base' case shallow watertable area

*** As a % of the 'Base' case discharge area

Table A5.26 Perennial grasses on waterlogged land (50% of LAI)+

	Management unit										*Subcatchment gauging station*		
	Upper Tone	*Middle Tone*	*Lower Tone*	*Tenner Road*	*Mobrup*	*Chowerup*	*Tonebridge*	*Unicup*	*Perup*	*Strachan*	*Wilgarup*	*Wheatley Farm*	*Barker Road*
Total area (km^2)	125	125	119	99	167	228	281	227	722	402	461	2966	4078
Clearing to 2000 (km^2)	102	101	85	69	96	90	83	69	62	11	83	851	979
Clearing to 2000 (%)	81	81	72	70	57	39	29	30	9	3	18	29	24
Planted area (km^2)	17	16	16	11	37	25	31	30	11	3	0	197	197
Planted area (%)	17	16	19	16	39	28	37	43	18	24	0	23	20
Surface water													
Streamflow (GL)	2.49	3.01	2.81	2.58	2.44	3.33	3.02	0	10.7	5.60	24.9	60.8	223
Runoff (mm)	20	24	24	26	15	15	11	0	15	14	54	21	55
Streamflow (%)*	59	63	61	66	47	60	54	0	90	86	100	77	93
Salt load (kt)	23.0	21.2	18.7	14.4	20.5	19.2	13.4	0	22.4	2.98	19.1	185	210
Mean stream salinity (mg/L)	9246	7064	6650	5560	8414	5784	4434	0	2088	532	769	3037	940
Groundwater													
Shallow watertable (km^2)	21	21	21	17	32	28	34	37	20	3	n/a	234	234
*Shallow watertable** (%)*	91	90	94	96	90	93	96	98	95	99	n/a	94	94
Discharge (km^2)	1	<1	1	<1	1	1	1	1	3	1	n/a	8	8
*Discharge*** (%)*	6	2	4	1	3	4	7	13	33	123	n/a	7	7

+ The constant year-round LAI used for perennial grasses is 50% of the peak (winter) LAI of annual pastures

* As a % of the 'Base' case streamflow

** As a % of the 'Base' case shallow watertable area

*** As a % of the 'Base' case discharge area

Table A5.27 Groundwater pumping (22 kL/day/bore from 1625 bores)

	Management unit										*Subcatchment gauging station*		
	Upper Tone	*Middle Tone*	*Lower Tone*	*Tenner Road*	*Mobrup*	*Chowerup*	*Tonebridge*	*Unicup*	*Perup*	*Strachan*	*Wilgarup*	*Wheatley Farm*	*Barker Road*
Groundwater													
Volume pumped (GL/yr)	1.92	1.89	2.13	1.42	1.51	1.75	1.08	0.22	1.04	0	0	13.0	13.0
Discharge pumped (%)	61	64	84	73	55	71	52	11	62	0	0	59	59
Salt in pumped water (kt/yr)	13.63	13.41	15.15	10.05	10.71	12.43	7.65	0.92	12.00	0	0	95.94	95.94
Surface water													
Stream flow (GL)	2.28	2.89	2.48	2.48	3.65	3.77	4.49	1.51	10.89	6.49	24.9	65.8	228
Salt load (kt)	9.1	7.9	3.3	4.1	9.3	6.3	8.0	8.5	10.3	3.0	19.1	89	114
Mean stream salinity (mg/L)	3997	2742	1322	1652	2551	1683	1787	5610	946	457	769	1352	500

Table A5.28 Shallow drains 1 metre deep

	Management unit										*Subcatchment gauging stations*		
	Upper Tone	*Middle Tone*	*Lower Tone*	*Tenner Road*	*Mobrup*	*Chowerup*	*Tonebridge*	*Unicup*	*Perup*	*Strachan*	*Wilgarup*	*Wheatley Farm*	*Barker Road*
Total area (km²)	125	125	119	99	167	228	281	227	722	402	461	2966	4078
Clearing to 2000 (km²)	102	101	85	69	96	90	83	69	62	11	83	851	979
Clearing to 2000 (%)	81	81	72	70	57	39	29	30	9	3	20	29	24
Surface water													
Streamflow (GL)	4.26	4.81	4.65	3.94	5.21	5.60	5.64	1.83	12.0	6.51	24.9	79.3	242
Runoff (mm)	34	39	39	40	31	25	20	8	17	16	54	71	59
Streamflow (%)*	101	101	101	101	101	102	101	105	100	100	100	101	100
Salt load (kt)	22.6	21.5	18.5	14.1	20.4	18.7	15.7	9.4	22.2	2.96	19.1	185	210
Mean stream salinity (mg/L)	5561	4675	4131	3775	4020	3466	2864	5370	1845	452	769	2374	875
Groundwater													
Shallow watertable (km²)	22	23	22	17	34	30	35	37	21	3	n/a	247	247
*Shallow watertable** (%)*	99	99	99	100	97	99	100	98	101	100	n/a	99	99
Discharge (km²)	10	12	11	9	12	11	11	7	7	1	n/a	91	91
*Discharge*** (%)*	72	75	75	80	73	77	79	80	92	88	n/a	77	77
Drains													
Length of drains (km)	810	752	644	420	625	553	479	335	301	50	0	4968	4968
Water in drains (GL/yr)	3.52	4.06	3.97	3.02	5.74	4.07	4.59	2.19	2.83	0.82	0	34.8	34.8
Water in drains (mm/yr)	28	33	33	30	34	18	16	10	4	2	0	12	9

* As a % of the 'Base' case streamflow

** As a % of the 'Base' case shallow watertable area

*** As a % of the 'Base' case discharge area

Table A5.29 Shallow drains 0.5 metres deep

	Management unit										*Subcatchment gauging station*		
	Upper Tone	*Middle Tone*	*Lower Tone*	*Tenner Road*	*Mobrup*	*Chowerup*	*Tonebridge*	*Unicup*	*Perup*	*Strachan*	*Wilgarup*	*Wheatley Farm*	*Barker Road*
Total area (km^2)	125	125	119	99	167	228	281	227	722	402	461	2966	4078
Clearing to 2000 (km^2)	102	101	85	69	96	90	83	69	62	11	83	851	979
Clearing to 2000 (%)	81	81	72	70	57	39	29	30	9	3	21	29	24
Surface water													
Streamflow (GL)	4.22	4.79	4.63	3.91	5.18	5.55	5.58	1.76	11.9	6.50	24.9	78.9	241
Runoff (mm)	34	38	39	39	31	24	20	8	17	16	54	71	59
Streamflow (%)*	100	100	100	100	100	100	100	102	100	100	100	100	100
Salt load (kt)	22.7	21.5	18.4	14.1	20.2	18.7	15.6	9.4	22.3	2.96	19.1	185	210
Mean stream salinity (mg/L)	5518	4594	4055	3709	3951	3440	2840	5487	1869	456	769	2376	874
Groundwater													
Shallow watertable (km^2)	23	24	22	17	35	31	36	38	21	3	n/a	249	249
*Shallow watertable** (%)*	100	100	101	100	100	100	100	100	101	101	n/a	100	100
Discharge (km^2)	13	14	13	10	15	13	13	8	8	1	n/a	106	106
*Discharge*** (%)*	87	88	88	92	87	90	89	91	98	96	n/a	89	89
Drains													
Length of drains (km)	810	752	644	420	625	553	479	335	301	50	0	4968	4968
Water in drains (GL/yr)	3.30	3.92	3.86	2.89	5.72	3.79	4.31	2.05	2.14	0.66	0	32.6	32.6
Water in drains (mm/yr)	26	31	32	29	34	17	15	9	3	2	0	11	8

* As a % of the 'Base' case streamflow

** As a % of the 'Base' case shallow watertable area

*** As a % of the 'Base' case discharge area

Table A5.30 Partial diversion (20% of Tone River salt load)

	Management unit										*Subcatchment gauging station*		
	Upper Tone	*Middle Tone*	*Lower Tone*	*Tenner Road*	*Mobrup*	*Chowerup*	*Tonebridge*	*Unicup*	*Perup*	*Strachan*	*Wilgarup*	*Wheatley Farm*	*Barker Road*
Salt load (kt)	18.2	17.1	14.7	11.3	16.0	15.0	12.5	9.4	22.3	2.83	19.1	159	184
Flow (GL)	3.68	4.18	4.04	3.41	4.52	4.83	4.87	1.73	11.9	6.43	24.9	74.5	237
Salinity (mg/L)	4945	4078	3646	3317	3543	3102	2572	5425	1869	440	769	2127	775

Table A5.31 Partial diversion (30% of Tone River salt load)

	Management unit										*Subcatchment gauging station*		
	Upper Tone	*Middle Tone*	*Lower Tone*	*Tenner Road*	*Mobrup*	*Chowerup*	*Tonebridge*	*Unicup*	*Perup*	*Strachan*	*Wilgarup*	*Wheatley Farm*	*Barker Road*
Salt load (kt)	15.9	14.9	12.9	9.9	14.0	13.1	11.0	9.4	22.3	2.77	19.1	145	171
Flow (GL)	3.38	3.84	3.71	3.13	4.14	4.43	4.47	1.73	11.9	6.40	24.9	72.0	234
Salinity (mg/L)	4720	3893	3480	3166	3382	2961	2455	5425	1869	432	769	2018	727

Table A5.32 Full diversion (Tone River)

	Management unit										*Subcatchment gauging station*		
	Upper Tone	*Middle Tone*	*Lower Tone*	*Tenner Road*	*Mobrup*	*Chowerup*	*Tonebridge*	*Unicup*	*Perup*	*Strachan*	*Wilgarup*	*Wheatley Farm*	*Barker Road*
Salt load (kt)	-	-	-	-	-	-	-	9.4	22.3	2.30	19.1	53	78
Flow (GL)	-	-	-	-	-	-	-	1.73	11.9	6.00	24.9	44.5	207
Salinity (mg/L)	-	-	-	-	-	-	-	5425	1869	384	769	1193	378

Appendix 6 Conversion units

Area	
1 km^2 (square kilometre)	= 1 000 000 m^2 (square metres)
	= 100 ha (hectares)
	= 247 ac (acres)
Volume	
1 GL (gigalitre)	= 1 000 000 000 L (litres)
	= 1 million (m^3) cubic metres
	= 220 million gallons
Salinity TDS*	**Electrical conductivity**
5.5 mg/L (milligrams per litre)	~ 1 mS/m (millisiemens per metre)
	~ 10 µS/cm (microsiemens per centimetre)
	~ 0.01 mS/cm (millisiemens per centimetre)
	~ 0.385 gr/gl (grains per gallon)
Mass	
1 kt (kilotonnes)	= 1000 t (tonnes)

* conversions between TDS and electrical conductivity are approximate

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