Government of **Western Australia**
Department of **Water**

Denmark River water resource recovery plan

Looking after all our water needs

Salinity and land use impacts series

Report no. SLUI 40
December 2011

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by

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Department of Water

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Disclaimer

Cover photograph: Denmark pipe head dam
Photographer: Brett Ward

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Preface

This recovery plan covers the Denmark River water resource recovery catchment. The plan is the culmination of over 20 years of work towards reversing salinity in the Denmark River, with water now becoming ‘fresh’ (below 500 mg/L TDS) and the river now being recognised as an important fit-for-purpose water resource in the Denmark region of Western Australia.

In 1961 a ban was placed on the release of crown land in the Collie, Kent and Denmark River catchments in recognition of the problem of increasing salinity. In 1978 the Denmark River catchment was constituted as a *Country Areas Water Supply Act 1947* catchment area and made subject to clearing controls, but salinity in the river continued to rise until the early 1990s and has only recently been decreasing.

The *Salinity action plan* (Government of Western Australia 1996) declared the Denmark River catchment, upstream of the Mt Lindesay gauging station, one of five water resource recovery catchments. The others are the Collie, Warren, Kent and Helena catchments. The Department of Water is leading efforts to halt and reverse rising salinity in the rivers of these catchments to ensure that the water quality meets public needs.

This recovery plan is an important step in the Department of Water’s water resource recovery process. It follows the development of the *Salinity situation statement: Denmark River* (Bari et al. 2004) in which the department and its predecessors, the Water and Rivers Commission and the Department of Environment, through the Kent-Denmark Salinity Recovery Team, assessed the salinity risk and guided salinity management efforts. This was helped in a large part by the establishment of over 5200 ha of private tree plantations in the upper catchment area as well as natural resource management projects focused on revegetation and fencing of environmentally sensitive areas.

With salinity in the Denmark River now decreasing it is important that these achievements are retained so that this important water resource can be used into the future.

Summary

The Denmark River will soon be fresh enough for drinking water supply, making it the first river in Australia to be recovered from salinity. These improvements increase its importance as a strategic regional potable or fit-for-purpose water resource in an area where future water source options are limited.

The *Denmark River water resource recovery plan* outlines a strategic approach for recovery of the Denmark River from its current salinity-affected status. The river is a strategic fit-for-purpose surface water resource for the Great Southern region and this plan is a fundamental aspect of ensuring the river reaches its full potential.

Clearing native vegetation in the upper part of the Denmark River catchment resulted in stream salinity exceeding potable levels 500 mg/L total dissolved solids and peaking at an annual salinity at mean flow of 700 mg/L (1980–95) at the Mt Lindesay gauging station.
To work out the best course of action to lower salinity, vegetative and engineering options were investigated and reported in the *Salinity Situation Statement: Denmark River* (Bari et al. 2004).

In 2009, annual mean salinity had dropped to around 540 mg/L following the establishment of additional commercial forestry plantations in the catchment from 2007 and is projected to fall to potable levels within the next decade. The recovery of the water resource as a result of these commercial tree plantations means that further significant land-use change is not needed and that there will be minimal additional social and environmental costs.

The Denmark Dam is a source of public drinking water for Denmark and any further development of the river for potable water supplies will be subject to source planning by the Department of Water and the Water Corporation. No decision on further resource development has been made by government. The Department of Water considers the resource to have strategic value for increased potable or industrial use, for drought relief during periods of low rainfall, and for private use by local landholders.

Although there has been success in lowering the salinity of the river water, the recovery process faces some risks in terms of retaining the current plantation areas because of the ownership of plantations by timber companies and economic uncertainty in the industry.

The principal objective of the *Denmark River water resource recovery plan* is to manage land use in the upper catchment to keep salinity below 500 mg/L total dissolved solids. To achieve this target various management options have been evaluated and recommendations are made for the implementation of the following key actions:

1. Secure existing plantations

Maintaining tree cover above 90% (~220 km^2) of the upper catchment will ensure salinity remains low in the Denmark River. This may involve monitoring harvest and rotation patterns of existing plantations, building partnerships with landholders to ensure plantation areas are maintained, and government intervention.

2. Facilitate the establishment of new plantations

This has been achieved to some extent with over 700 ha of plantations established since 2007.

3. Revegetate areas not considered suitable for commercial forestry

Some areas in the upper catchment are considered unsuitable for commercial forestry. It is suggested that, in partnership with plantation companies and land owners, these areas could be revegetated with native species and include establishing wildlife corridors and repairing riparian vegetation.

4. Protect native vegetation

Areas of native vegetation in the Denmark water resource recovery catchment are extensive (~84%) and essential not only for the salinity benefit but catchment ecology as well. Since July 2004 native vegetation protection is facilitated by *Environmental Protection Act 1986* clearing controls that are supported by the *Country Areas Water Supply Act 1947* Part IIA Control of Catchment Areas *(CAWS Act)* clearing legislation. It is important that the now secondary *CAWS Act* legislation continues in order to preserve a direct interest in the areas of native vegetation stands where compensation has been paid to land owners to retain native vegetation that would otherwise have been cleared.

5. Continue monitoring streamflow, salinity and groundwater levels

There will always be knowledge gaps in terms of the impacts of climate change and continuing land-use change. Furthermore, there are currently no long-term groundwater monitoring sites in the upper catchment. The establishment of groundwater monitoring sites and continued streamflow and salinity measurements of the Denmark River and its tributaries will allow catchment managers to investigate plantation and climate change impacts on groundwater, surface water and water quality.

6. Update existing catchment models

Catchment models are useful for appraisal and simulating salinity and streamflow based on potential land use and/or climate change. It is proposed that the Department of Water catchment models for the Denmark River (Land-use change incorporated catchment model LUCICAT and Catchment hydrology annual model for Western Australia CHAMWA) are updated every five years with the latest climate and hydrological data.

7. Communicate the plan to stakeholders

The plan is essential to keep stakeholders in and around the Denmark River catchment informed about the recovery plan and processes.

If these actions are implemented and successful the Denmark River will be the first river in Australia to be recovered from salty to fresh water status.

1 Introduction

1.1 Recovering the Denmark River

The pipe head dam on the Denmark River (the Denmark Dam) was the main source of fresh water for the town of Denmark until salt originating from the upper catchment made it too saline and it was then not used for nearly 20 years (cover photo; Bari et al. 2004). Recently, the combined effects of reduced flow and increased demand have put pressure on supplies from the replacement Quickup Dam and made it urgent to lower salinity in the Denmark Dam, which remains a contingency option during drier times and a potentially large source of potable or fit-for-purpose water for the district.

Purpose

The main purpose of this plan is to recommend how to reduce the average annual salinity currently measured in the Denmark River (the 2009 average was 540 mg/L), to below 500 mg/L total dissolved solids (TDS) at the Mt Lindesay gauging station, by 2020. The plan describes our understanding of how stream salinity has changed since 1955 and discusses the processes used to develop the salinity management options. It outlines computer modelling of the likely responses to the most viable management options and evaluates them according to hydrologic, social, economic, environmental and timing criteria. The recovery plan recommends management actions to ensure salinity remains within drinkable limits.

Objectives

The objectives for the plan are:

- Outline our current understanding of stream salinisation in the Denmark River.
- Describe the social, environmental and economic impacts of the various management options.
- Summarise the computer modelling of selected management options for reducing stream salinity to meet the target of 500 mg/L by 2020.
- identify the most suitable options for lowering salinity in the Denmark River and recommend actions for carrying these out.

1.2 The Denmark River water resource recovery catchment

Denmark River as a water resource

The Denmark River water resource recovery catchment (Denmark WRRC) is the area (503 km^2) upstream of the Mt Lindesay gauging station, a previously planned abstraction point for public water supply, within the Denmark River basin in the south coast region of Western Australia (Fig. 1).

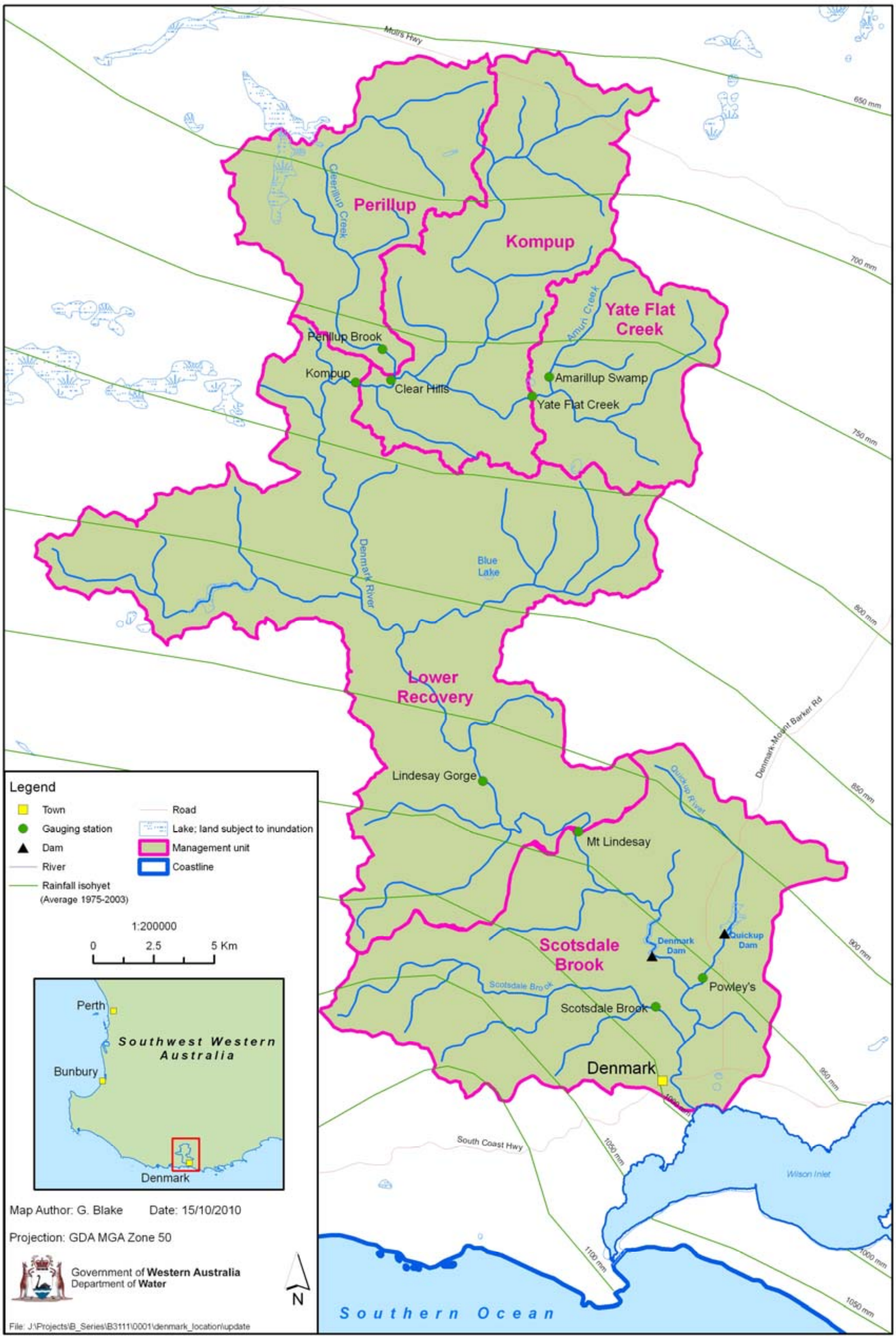


Figure 1 The Denmark River basin: the water resource recovery catchment extends south as far as the Mt Lindesay gauging station

The water in the Denmark River was fresh (that is; salinity was below 500 mg/L) until the mid 1970s. Since then it has usually been too saline for public water supply. With demand from the town of Denmark currently at around 0.45 GL per year (Water Corporation 2010) and further pressure on water resources from regional population growth, industry and expected climate change, the Denmark River ha s become a strategically important water resource for regional development – hence the need to restore its water quality. The Denmark River was first dammed in 1960–61, when a 0.42 GL concrete pipe head dam was constructed 5 km north of Denmark for town water supply (Ruprecht et al. 1985; Fig. 1).

By the late 1960s, catchment clearing had caused significant increases in salinity in the dam which precluded use of the water for public water supply other than opportunistically during high rainfall years. The dam's small capacity exacerbated the effects of increased salinity as low salinity winter water could not be stored to dilute saline summer flows. For some years, water from Scotsdale Brook was used to dilute the saline Denmark Dam water but, without a storage dam, it could not be relied on during low rainfall years. The Quickup Dam was built in 1990 to replace the Denmark Dam as Denmark's water supply source. The Quickup River, a fresh tributary of the Denmark River, had a suitable site for a storage dam and its catchment is mostly forested (Collins & Fowlie 1981; Water Corporation 2004).

There is a compelling need to make Denmark River water potable well before the 2020 target. Recently, critically low levels in the Quickup Dam (Fig. 2) have forced the Water Corporation to supply the town of Denmark with water from the Denmark Dam, despite elevated salinities, and from Albany sources. Although mean salinity at the Mt Lindesay gauging station is around 640 mg/L, at times actual salinities in the dam are well above the mean. For example, in October 2007 salinity ranged from approximately 900 mg/L at the surface to 1400 mg/L at the bottom of the reservoir. To provide water to Denmark during periods of shortage, the Water Corporation diluted the Denmark Dam water with fresh water carted from Albany (Department of Water 2010a). After mixing, the salinity of the water was 830 mg/L, still above the accepted potable level of 500 mg/L. Subsequently, the Water Corporation installed a desalination unit at Denmark Dam as a short-term measure to improve the quality of the water supply.

Since 2007 the Water Corporation has also taken water from the Denmark Dam to supplement low storage levels in the Quickup Dam. Storage in the Quickup varied from as little as 199 ML (17% full) in 2008 to full capacity (1189 ML) in 2009 (Water Corporation 2010a).

Private water use is principally for stock and domestic purposes, with water pumped from the river or captured in dams away from the river. Annually, about 40 ML is pumped from the Denmark River (above its confluence with Scotsdale Brook and excluding tributaries) for private use (Department of Water 2009). Farm dam storage in the Scotsdale Brook catchment was estimated to be 720 ML/yr or about 5.5% of the mean annual streamflow of that catchment (Department of Water 2009). To date, no estimate of water stored in farm dams has been made for the entire Denmark catchment.

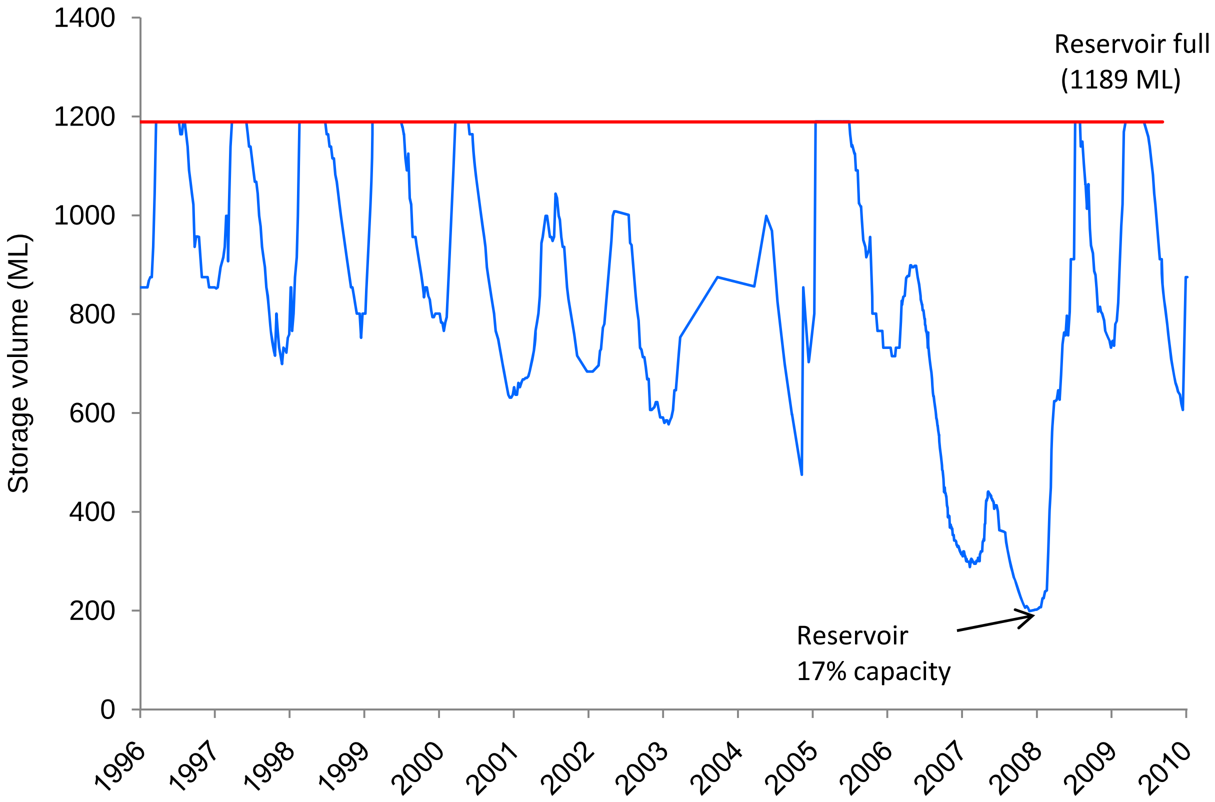


Figure 2 Quickup Dam storage levels

Source: Water Corporation 2010

Past water resource management for salinity

For planning and research, the Denmark WRRC was divided into four management units based on drainage, land use and the land-use planning objectives of stakeholders. The catchment boundary has been amended since the 2004 *Salinity situation statement: Denmark River* (Bari et al. 2004) to more accurately reflect the actual catchment watershed boundary (the management unit boundaries are the same). The three northernmost management units – Perillup, Kompup and Yate Flat Creek – are collectively referred to as the upper catchment. The mostly forested area between the Kompup and Mt Lindesay gauging stations makes up the Lower Recovery management unit (Fig. 1).

This area upstream of the Mt Lindesay gauging station was specified as a recovery catchment in the *Salinity action plan* (Government of Western Australia 1996) and considered to be one of the potential water sources for the south coast region. The implementation of the *Salinity action plan* led to the establishment of the Kent-Denmark Recovery Team, which built on the previous plan, *Integrated catchment management – Upper Denmark catchment* (Ferdowsian & Greenham 1992) and contributed to the recent successes in lowering Denmark River salinity.

One of the keys to the recovery approach has been working in partnership with the community. In Denmark, the major vehicle for this was the Kent-Denmark Recovery Team (Bari et al. 2004).The Water and Rivers Commission formed the recovery team in 1998 with the charter of recovering salinity to potable levels in both the Kent and Denmark rivers. The team had strong community representation consisting of local landholders, representatives from local councils, the Water and Rivers Commission, the Department of Agriculture and the Department of Conservation and Land Management. After the *Salinity situation statement: Kent River* (De Silva et al. 2007) was released, and following confirmation that the water in the Denmark River was likely to reach potable levels within the next 10 years, the recovery team was disbanded on 31 December 2007, after nearly a decade of service.

The recovery team built on earlier efforts to provide frameworks for natural resource management at the catchment level. From 1988 to 1992, the Department of Agriculture coordinated the preparation of an integrated catchment management plan for landholders of the upper catchment (Ferdowsian & Greenham 1992). The plan, funded by the National Soil Conservation Program, suggested options for reducing salinity and remediating major land management problems. In the neighbouring Kent River catchment, the National Dryland Salinity Program sponsored a four-year study (1994–98) into salinity management.

The recovery team provided valuable guidance for preparing the Denmark and Kent salinity situation statements that laid the foundations of this recovery plan.

1.3 The water resource recovery approach

The Department of Water’s Water Resource Recovery Program builds on work previously coordinated by the Water and Rivers Commission, the Department of Environment and their predecessors. The program’s focus is to meet a goal of the *State salinity strategy*: ‘To protect and restore the key water resources to ensure salinity is at a level that permits safe, potable water supplies in perpetuity’ (Government of Western Australia 2000).

The program uses both engineering and vegetation solutions and takes into account economic, social and environmental factors.

Working in partnership with stakeholders is central to achieving good salinity outcomes. Stakeholders include catchment and natural resource management groups, local communities, recovery teams and other state government agencies, industry, and local government.

The recovery program’s approach has five stages (Fig. 3):

- Monitoring and evaluation: monitoring the main rivers and subcatchments and assessing their status and trends (monitoring in the Denmark River began in 1954 and continues).
- Situation statement: a study that identifies current and projected salinities and evaluates hydrological effects of salinity management and recovery options. The *Salinity situation statement: Denmark River* was published in 2004.
- Evaluation of management options: defines technical aspects of salinity management options identified in the salinity situation statement, and evaluates the economic, social and environmental aspects in consultation with stakeholders. This was completed in 2007.
- Recovery plan: identifies the major components of the options selected for implementation, develops an implementation strategy and may identify funding sources.

- Implementation: coordinates ‘on-ground’ planning and implementation.

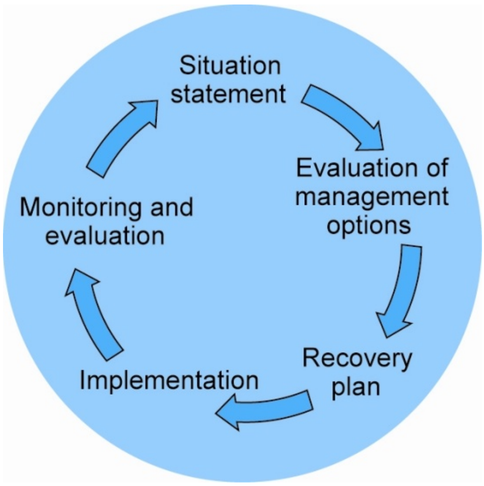


Figure 3 The water resource recovery approach

As well as facilitating partnerships with catchment stakeholders, the recovery planning process also tries to integrate with relevant Department of Water and Water Corporation regional water plans, strategies and policy initiatives. These include the *Lower Great Southern water resource development strategy* (Department of Water 2010a), *Water Forever* (Water Corporation 2010b), *Southern Prospects 2011–2016 (South Coast NRM 2011)*, *Great Southern regional water plan (DoW* in prep), drinking water source protection planning and the *Wilson Inlet nutrient reduction action plan (WRC 2003)*.

This plan also acknowledges that the catchment repair works of several of these plans, including revegetation and perennial pasture establishment, have contributed to lowering salinity in the Denmark River. The revegetation options recommended in this plan have multiple environmental benefits, like lowering nutrients entering waterways, and increasing and sustaining biodiversity, that will contribute to achieving the goals of other plans.

1.4 Catchment characteristics

Location

The Denmark River drains into the Wilson Inlet at the town of Denmark on the south coast of Western Australia (Fig. 1). The catchment area to the mouth of the river is 671 km^2 and falls within two shire boundaries: the Shire of Plantagenet in the north and the Shire of Denmark in the south.

Physiography and vegetation types

The catchment is characterised by undulating lateritic plains and poorly drained flats, hilly terrain with rock outcrops and deeply incised valleys where the Denmark River and tributaries have incised the surface and exposed the weathered profile and underlying bedrock (Collins & Fowlie 1981; Kern 1992; Bari et al. 2004). The area overlies Pre-Cambrian gneiss and granitic rocks with a deeply weathered mantle. The hills that are a feature of the landscape, particularly near the coast, are an expression of this basement. Several landform units reflect the major soils and vegetation types and include (Collins & Fowlie 1981):

- lateritic sandplain – scrub jarrah and sandplain heaths
- sandy/swampy flats and drainage lines – paperbark, dense scrub and scattered trees
- lateritic plateau and uplands – jarrah forest
- rolling, dissected lateritic country – jarrah, wandoo and swamp yates
- Moderately incised valleys – jarrah–marri forest
- deeply incised valleys – jarrah–marri forest.

1.5 Clearing and revegetation

Clearing native forest for agriculture in the Denmark River basin began in 1870 and continued at a steady rate until it rapidly expanded after World War II when heavy machinery became more widely available (Collins & Fowlie 1981; Fig. 4). The native, deep-rooted perennial vegetation was replaced by annual shallow-rooted pasture and crops changing the water balance. The lower evapotranspiration rate of the new vegetation and the consequent increased infiltration of rainfall to groundwater stores resulted in higher groundwater levels, saline valley floors and hillsides, and increased saline discharge into rivers and streams. As recognition of the salinity problem spread, in 1961 the government placed a ban on further alienation of crown land for agricultural development.

In 1978, the Denmark River catchment was constituted as a *Country Areas Water Supply Act 1947* catchment area and made subject to clearing controls to limit salinisation. By then 34% of the upper catchment had been cleared and over the following years $3.63 million compensation was paid to landholders not to clear 2750 ha of native vegetation on farms. The Yate Flat Creek management unit was the most extensively cleared with 58% or 33 km^2 converted to agricultural land use (Bari et al. 2004). There had been only minimal clearing (just 6% cleared by 1979) in the Lower Recovery management unit. Overall, 25% of the Denmark River basin had been cleared by 1979 (Table 1; Fig. 4).

Table 1 Cleared area in the Denmark River basin

Year	Management unit area cleared km^2 (%)						
	Kompup	Perillup	Yate Flat Creek	Total upper catchment	Lower Recovery	Scotsdale Brook	Total cleared
1979	38 (35)	11 (15)	33 (58)	82 (34)	15 (6)	71 (44)	169 (25)
1988	30 (28)	10 (13)	30 (52)	70 (29)	10 (4)	30 (19)	111 (16)
2006	14 (13)	4 (5)	8 (14)	26 (11)	5[1] (2)	29 (18)	60 (9)
2009	4 (5)	4 (5)	3 (5)	11 (5)	5[1] (2)	29 (18)	45 (7)

[1] *Does not include other shallow-rooted agricultural land uses that are classified as trees in the satellite analysis*

Tree planting in the catchment began in the early 1990s with the Integrated Catchment Management – upper catchment project promoted by the then Water Authority and the Department of Agriculture (Ferdowsian & Greenham 1992). This project helped farmers prepare farm plans that identified areas suitable for planting trees and constructing fences and drains. The Water Authority supplied investment capital and the Department of Conservation and Land Management's Timberbelt Sharefarming Scheme acted as a vehicle for managing the plantations (Schofield et al.1989; Bartle 1991). Some farmers also used their own capital to plant additional trees. These projects proved to be the catalyst for the commercial blue gum (*Eucalyptus globulus*) industry in the south-west of Western Australia and from the late 1990s extensive areas were planted with blue gums. By 2007, 4500 ha had been planted, predominantly in the upper catchment. A further 700 ha were planted during 2008–09 and by 2010 over 5200 ha of plantations had been established (Fig. 5). Small areas of the northern and south-western Lower Recovery management unit had also been planted with blue gums.

A significant trend over the last 20 years has been the establishment of other types of land uses in the Lower Recovery and Scotsdale Brook management units: predominantly vineyards, horticulture, and native revegetation for biodiversity conservation. These land uses are hard to distinguish from tree plantations in satellite data and are therefore mapped as 'plantations' in Figure 5 (i.e. a change in land use from pasture to perennial vegetation). They are mainly in the high rainfall zone in coastal areas and do not affect salinity at the Mt Lindesay gauging station or plantation area calculations.

1.6 Rainfall

Annual rainfall ranges from 650 mm in the upper catchment to 1100 mm by the coast (1975–2003 average; Fig. 1). Since the mid 1970s, average annual rainfall in the south-west of Western Australia has decreased by an average of 10% (Hope & Foster 2005; Smith et al. 2009). Climate-change models project that it will keep decreasing, resulting in reduced streamflow (Section 1.7; Appendix C).

1.7 The impacts of climate change

Recent studies have indicated that mean annual rainfall has decreased in the south-west of Western Australia since the mid 1970s (Hope & Foster 2005; Bari 2008; Smith et al. 2009). As a result of global warming and changed patterns of atmospheric circulation, this trend, coupled with an increase in temperature, is expected to continue (Smith et al. 2009).

Mean annual rainfall is projected to decline by a further 2–8% and flow by 10–43% by the end of the century, depending on the greenhouse gas emission scenario used (Smith et al. 2009; Department of Water 2010b; Appendix C). Lower rainfall and less flow are likely to increase salinity in the short to medium term and put at risk the declines in stream salinity observed in the river (Table 2). If these conditions were to continue and recharge was to decline due to reduced rainfall, then salinity may decline in the medium to long term as groundwater becomes disconnected from the streams (Mayer et al. 2005). Further monitoring and investigations are required to better understand the implications of the various climate change scenarios on salinity.

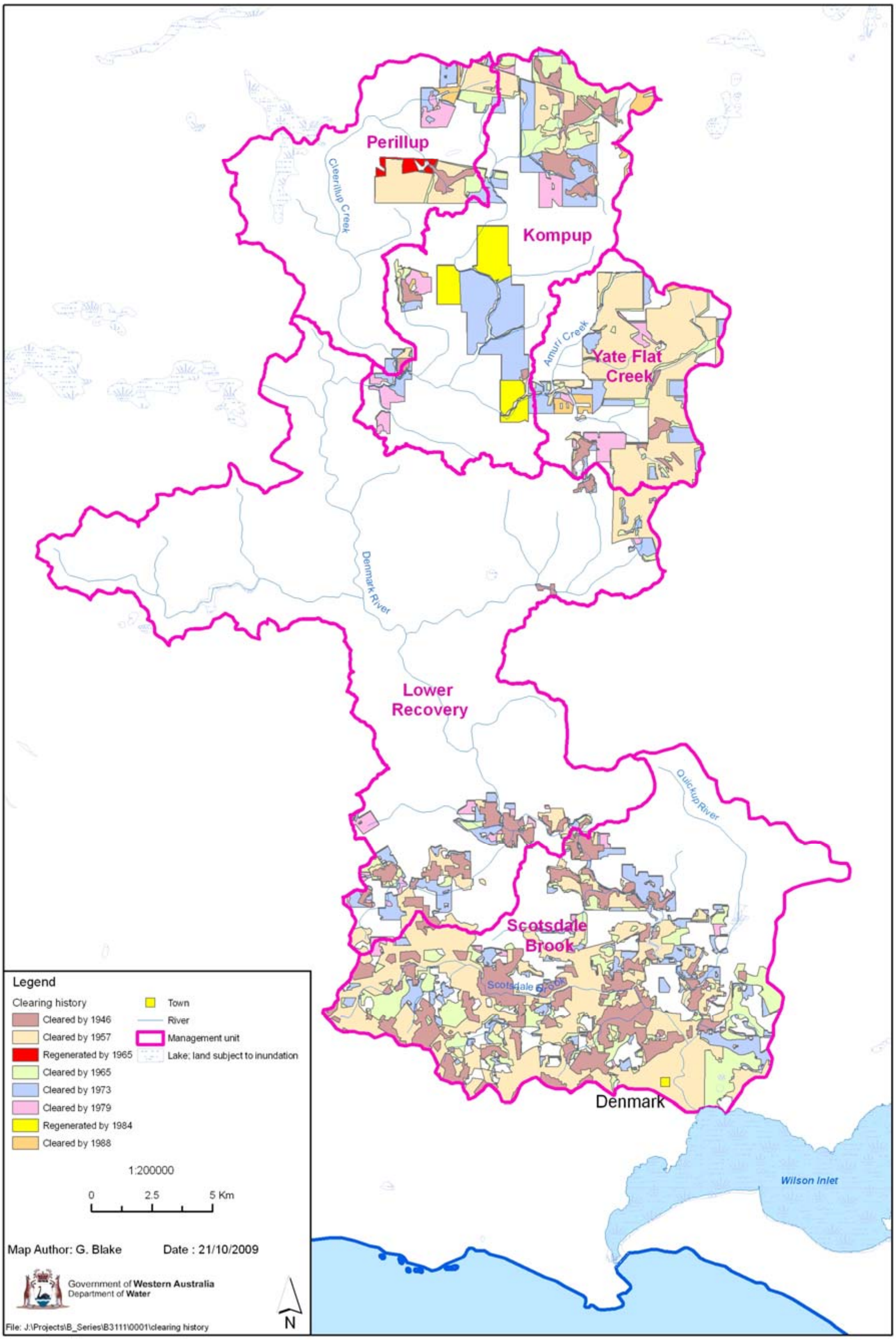


Figure 4 Denmark River basin clearing history

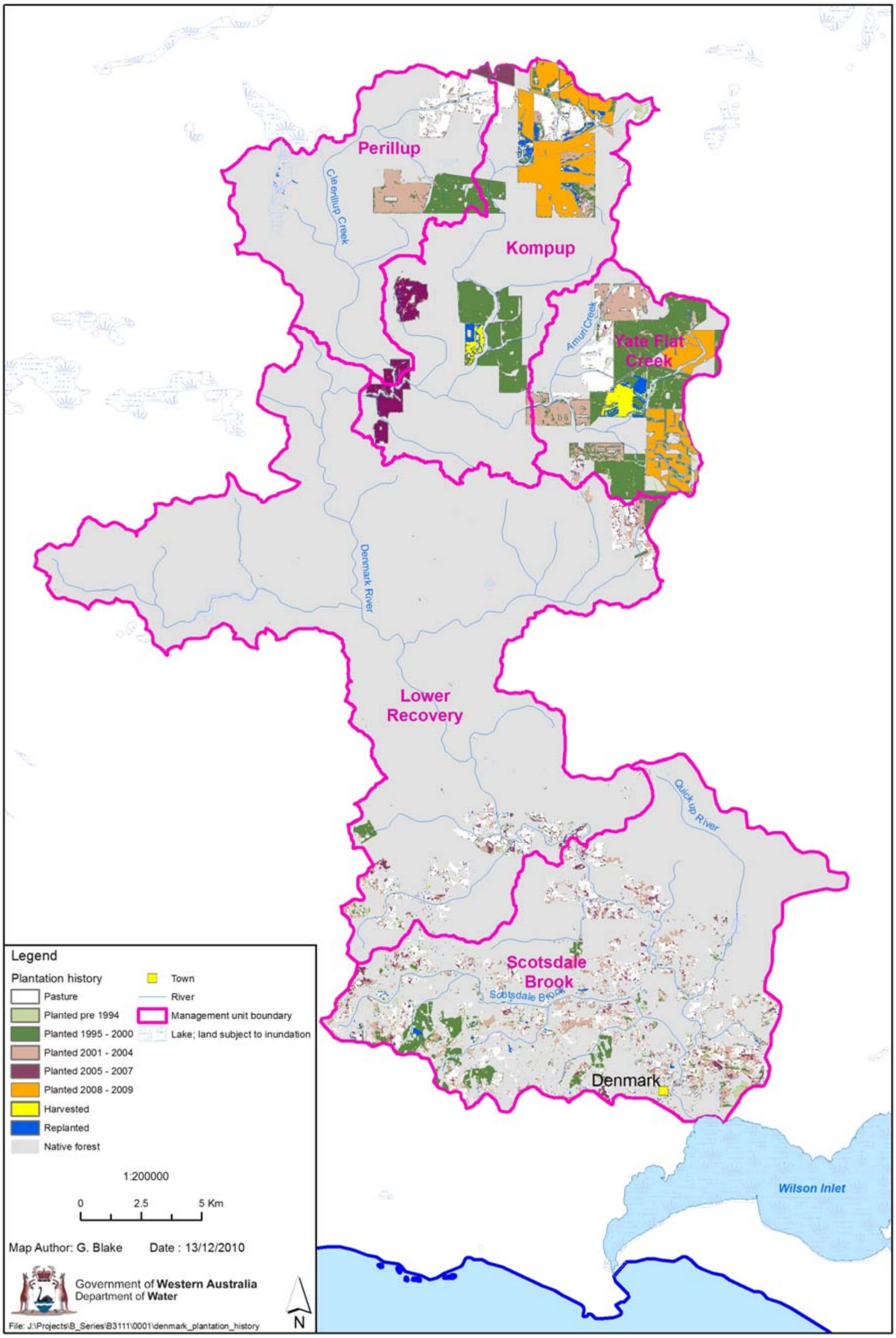


Figure 5 Plantation and revegetation history of the Denmark River basin

1.8 Groundwater

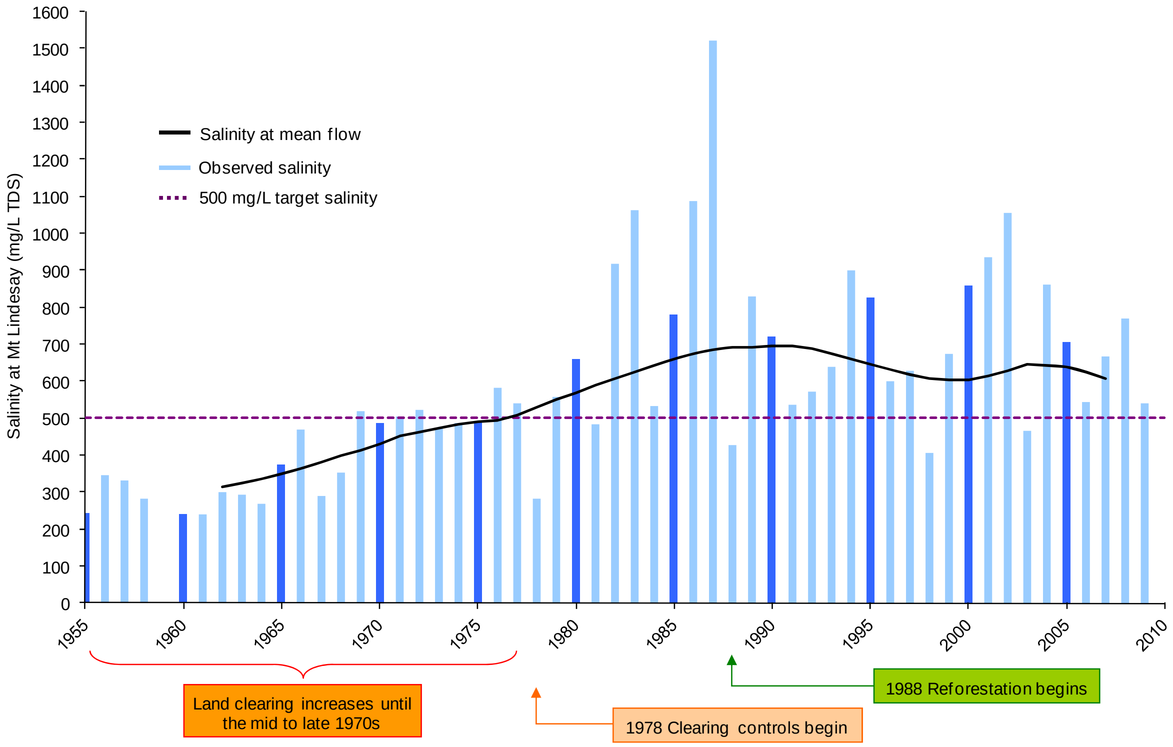
Groundwater discharge carries salt into streams and this process is accelerated by clearing (Bari et al. 2004; Mayer et al. 2005; Smith et al. 2007; see also Appendix A). Groundwater monitoring did not begin in the upper Denmark until 1985 when some piezometers were established on farms. A more comprehensive piezometer network was established in 1990 in three experimental catchments in the upper Yate Flat Creek and Kompup management units and in the neighbouring Hay River catchment to demonstrate changes in streamflow and salt loads following reforestation (Bari et al. 2004). Groundwater levels in the upper catchment generally rose under cleared areas, resulting in the observed surface water salinity increases throughout the 1980s. The rise was up to 0.3 m/yr between 1985 and 1993 in almost all monitored bores in Yate Flat Creek and Kompup (correction to Bari et al. 2004). Currently, no piezometers are operating in the upper Denmark catchment and data collected during the 1994–99 period was not sufficient to enable trends to be determined.

1.9 Salinity trends and contributions

Catchment managers use their understanding of the trends in salinity and the contributions of salt from the various management units to evaluate the relative successes of management actions.

Salinity trends were calculated using data from seven Department of Water gauging stations (Fig. 1). Some of these have been decommissioned so it is only possible to directly compare stream salinity for certain time periods. The Mt Lindesay gauging station has the longest record, dating back to 1954. Salinity at mean flow peaked at around 700 mg/L in 1991 and has since been decreasing at a rate of around 7 mg/L/yr (Table 2). By 2009 salinity was down to an average of around 540 mg/L (Fig. 6). Salinities vary widely and are related to rainfall. Average annual salinity tends to be higher in low rainfall years and lower in high rainfall years. To reduce this effect so that salinity trends can be better related to changing land use and negate the effects of fluctuating rainfall, salinity is reported as salinity at mean flow.

The mean flow at each station for the period 1992–2005 was calculated so that values would be comparable (Table 2). During 1992–2005, salinity generally decreased at all stations, with the biggest decrease (30 mg/L/yr) at the Yate Flat Creek gauging station. These decreases contrast sharply with the rising salinity recorded at all gauging stations in the period 1980–87 when salinity at the Mt Lindesay gauging station increased at around 17 mg/L/yr (Bari et al. 2004).



Land clearing increases until the mid to late 1970s

1978 Clearing controls begin

1988 Reforestation begins

Figure 6 Flow-weighted salinity at the Mt Lindesay gauging station

Table 2 Mean annual streamflow, salt load and salinity trends observed at gauging stations

Gauging station	Mean annual data (1992–2005)			Annual mean salinity trend (mg/L/yr[1])	Relative contribution to Mt Lindesay (1992–2005) %	
	Streamflow GL	Salt load kt	Salinity mg/L	1992–2005	Streamflow	Salt load
Yate Flat Creek	4.0	4.5[1]	3410[2]	–30	15	28
Kompup[3]	10.0	13.0	3430	–26	37	80
Mt Lindesay	26.9	16.3	780	–7	100	100

[1] *Trend for salinity at mean flow*

[2] *Yate Flat Creek does not include a full record for 2005*

[3] *Includes Yate Flat Creek and Perillup management units*

The contributions of each management unit to the aggregate salinity and streamflow at the Mt Lindesay gauging station depend on the unit's area, the proportion cleared and rainfall. Salinity is higher in low rainfall years because there is less surface water to dilute groundwater. However,if dry conditions persist, salinity may decline as the generally saline groundwater is so deep there is little discharge to the waterways and there is less salt reaching the Mt Lindesay gauging station (Table 2).

The stream salinity is highest in the upper catchment where the rainfall is the lowest and the cleared areas are proportionally greatest. Recent analysis of rainfall/runoff/salinity models (Appendix B) indicates that 82% of the salt load to the Mt Lindesay gauging station comes from the upper catchment in only 28% of the streamflow. It is projected that, under the current (2009) land use, by 2020, the upper catchment will contribute 55% of the salt load in 16% of the streamflow with a mean annual salinity of 1244 mg/L (Fig. 7). Surface water will continue to be diluted by the much fresher waters of the Lower Recovery management unit, and will be around 300 mg/L before reaching the Mt Lindesay gauging station. The Lower Recovery management unit, where only 2% is currently cleared and which has higher rainfall, is projected to contribute 45% of the salt load in nearly 85% of the streamflow, resulting in a salinity of 145 mg/L.

Streamflow variations relative to rainfall are largely due to changes in vegetation cover. Since 1993 a decline in streamflow relative to rainfall has been found in all parts of the upper catchment. Mean annual flows of the Denmark River (at the Mt Lindesay gauging station) have also decreased from around 30 GL (1961–2009) to around 23 GL (2000–09), a 24% reduction. The flow in 5 of the 10 years from 2000–09 was below 10 GL (Fig. 8).

1.10 Messages from previous studies

Four important messages can be drawn from the *Salinity situation statement: Denmark River* (Bari et al. 2004) and the subsequent analysis and evaluation of the suggested management options (URS 2006; 2007a):

- The salinity at mean flow at the Mt Lindesay gauging station peaked in 1991 and has since declined, most likely due to the effects of plantations established after 1988.
- The existing plantations, when fully established, are projected to reduce salinity and meet the 500 mg/L target at the Mt Lindesay gauging station.
- Technically feasible options such as engineering (groundwater pumping or saline water diversions) or a combination of vegetation and engineering options can reduce salinity more and faster.
- Existing native vegetation must be further protected to prevent the development of new areas of saline groundwater discharge, as this would undermine other efforts to reduce salinity.

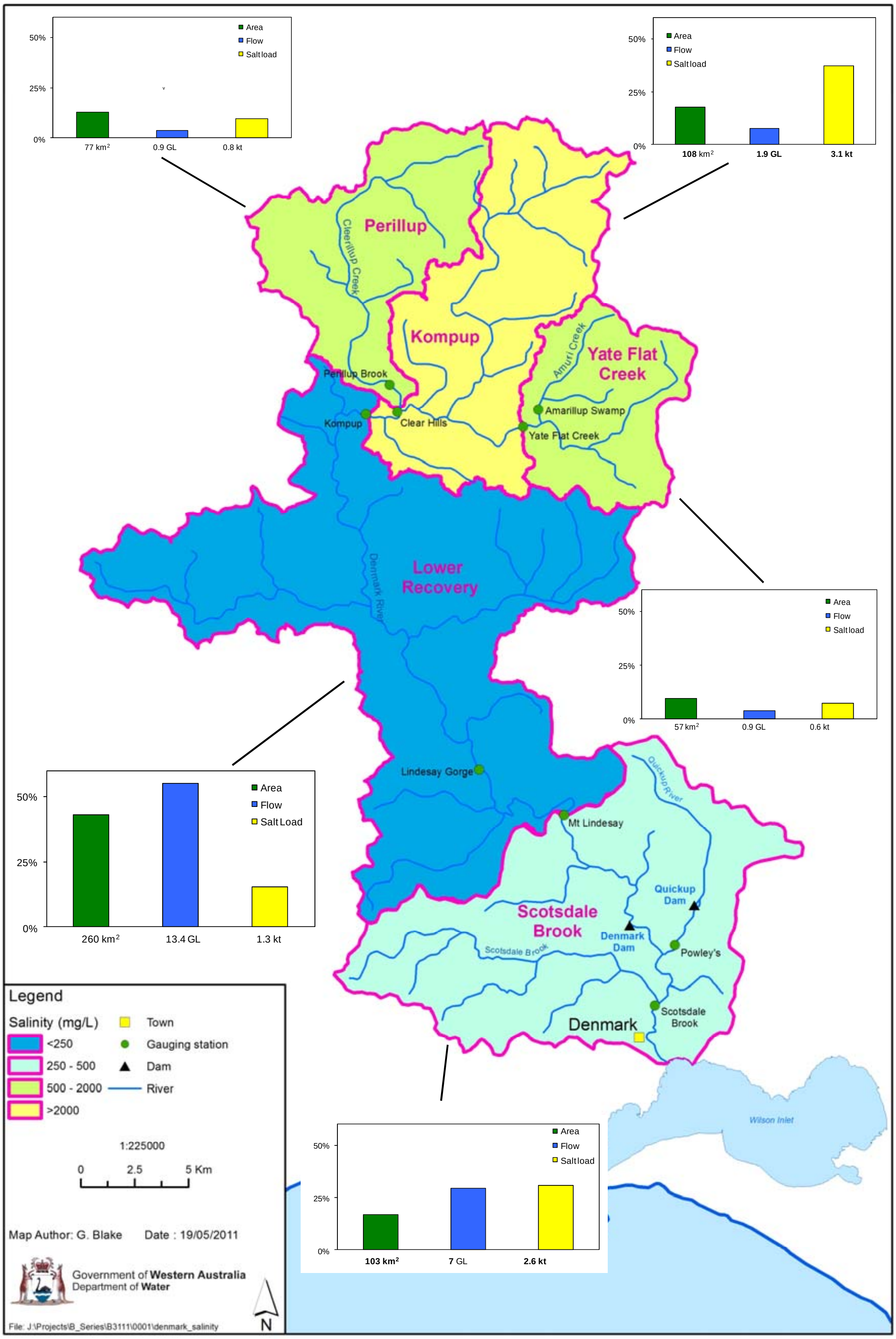


Figure 7 Projected salinity and flow contributions of Denmark WRRC management units (2020)

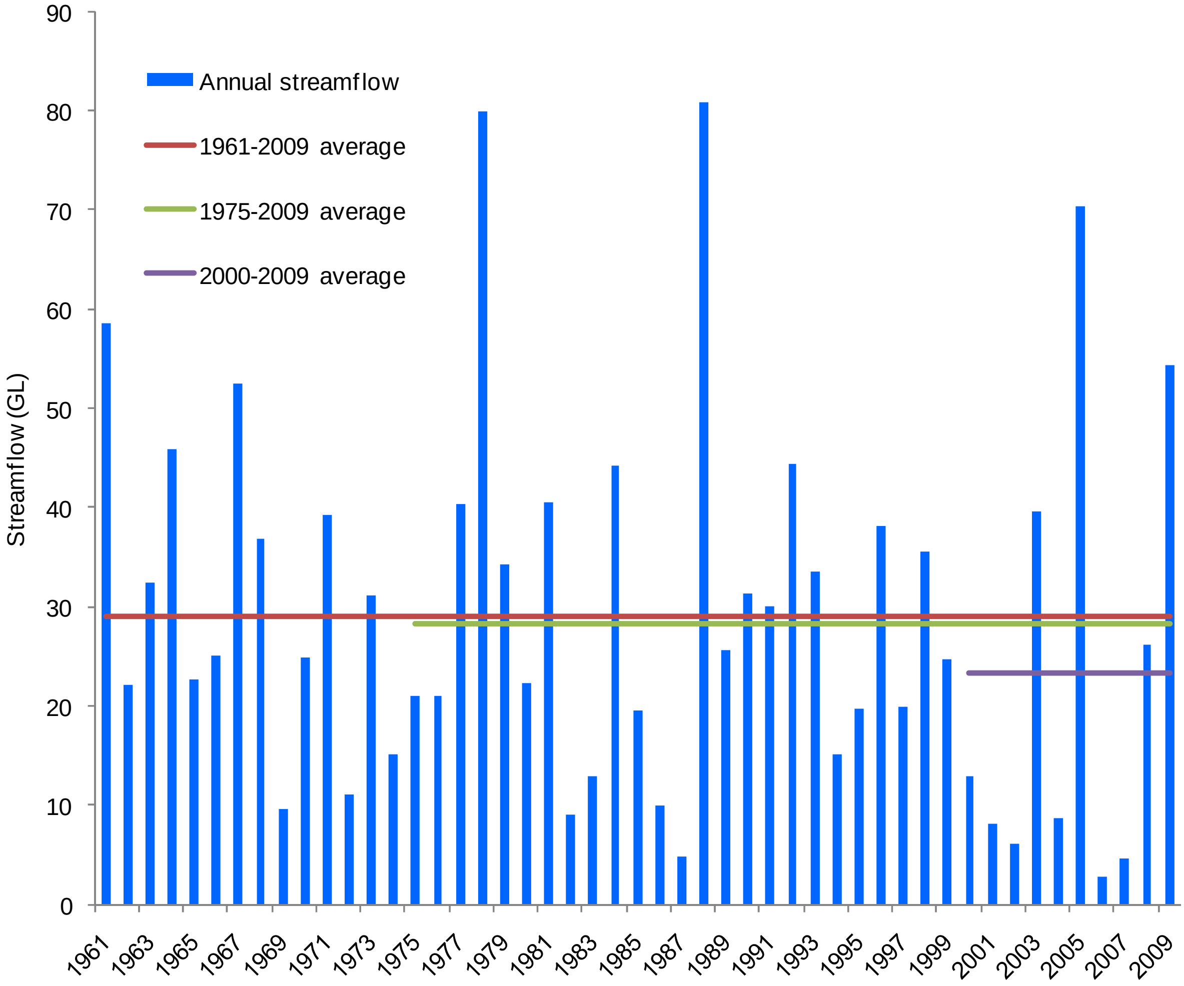


Figure 8 Annual streamflow at the Mt Lindesay gauging station

2 Development of the recovery plan

The key to managing salinity in the Denmark River is perennial and/or deep-rooted vegetation, such as plantations and native vegetation, which has high water use (see Appendix A). However, in the development of this recovery plan, engineering options such as desalination of river water and groundwater pumping were also evaluated as they may be suitable and cost-effective methods for water supply and lowering groundwater respectively.

2.1 Management options

Sixteen management options for reducing salinity were considered and analysed after the report S*alinity situation statement: Denmark River* was published (Bari et al. 2004). They were developed in consultation with the Kent-Denmark Recovery Team and all were evaluated for their hydrologic effect on stream salinity, salt load and flow. Eleven were also subjected to economic, environmental and social analyses (URS 2006; 2007a). These were:

1. Use the saline water as is – ‘do nothing option’.
2. Government purchases 900 ha of land and establishes managed plantations – ‘government plantations option’.
3. Government purchases 900 ha of land and leases it to forestry companies – ‘government plantation – leased option’.
4. Government purchases 900 ha of land, imposes a caveat, then sells the land – ‘caveat and sell option’.
5. Government leases 900 ha of land from farmers then subleases it to forestry companies – ‘government lease and sublease option’.
6. Government pays the Forest Products Commission to increase incentives for 1375 ha of plantations in the catchment – ‘FPC incentives option’.
7. Government pays incentives directly to landholders to encourage the establishment of 1375 ha of plantations in the upper – ‘incentives to landholders option’.
8. 2948 ha of perennial pastures established via an incentive scheme – ‘perennial pastures option’.
9. Extraction of groundwater either in the north or south-east of the catchment using 58 pumps, and disposal outside the catchment – ‘groundwater pumping option’.
10. Diversion of 6 GL of the most saline flows around the Mt Lindesay gauging station and the potential dam site at Mt Lindesay – ‘diversion option’.
11. Desalination of river water as a substitute for land-use change – ‘desalination option’.

The other five options evaluated just for their hydrologic effects were:

12. Base case – vegetation at 2007 (took into account plantations established since 2004).
13. Harvest all plantations and revert to 1988 conditions.
14. Plant an additional 1400 ha of plantations.
15. Convert all cleared land to plantations.
16. Convert all pastured land to native forest.

2.2 Projected hydrological impacts of the management options

Two computer catchment models were used to simulate the effects of land-use scenarios on stream salinity, streamflow and salt load and to see if the target salinity of 500 mg/L would be achieved under the current land use. The models were the ‘Microstation and geographic information catchment model’ (MAGIC; Mauger 1996) and the more recent ‘Land use change incorporated catchment model’ (LUCICAT; Bari 2005; Appendices A & B). MAGIC is a ‘steady state’ model and the outputs assume the catchment has reached equilibrium under a particular land use. LUCICAT is a ‘dynamic’ model where projections can be made to any time once a particular change is applied in the model. Both models use tree leaf area index (LAI) as a proxy for tree water use.

The 16 management options were investigated using these models. Both models were also used to project the salinity under the land-use conditions at the time of modelling. The MAGIC model used the estimated 2006 land use as the base case (do nothing) while LUCICAT used the estimated 2007 land-use scenario which included an additional 450 ha of plantations. The LUCICAT modelling also reflected the 10-year planting and harvest rotation that is undertaken in the management of the plantations.

Under 2011 land-use conditions salinity at mean flow in the Denmark River at the Mt Lindesay gauging station is projected to fall below the 500 mg/L target salinity well before 2020 and stabilise below 300 mg/L (Table 3; see also Fig. 9). This corresponds to a projected annual streamflow of around 16 GL and annual salt load of around 4 kt (Table 3).

The simulations suggest that no further plantations are required to achieve the 500 mg/L target by 2020, as long as the vegetation cover remains at or above the 2007 level (Table 3; see also Appendix B).

Engineering options would also reduce salinity below the 500 mg/L target, but they failed the economic, social and environmental requirements for implementing the options because they had little support from local stakeholders, were prohibitively expensive and raised issues of how to dispose of the saline water from activities like groundwater pumping and diversion of saline river flows (see Sections 2.3 & 2.4; Appendices A & B).

The modelling of the options by the MAGIC model (Appendix D) and LUCICAT gave similar results. The options were based on the effort required (e.g. area of land-use change) to lower annual average salinity from the projected outcome of the 2006 land use of 570 mg/L to below 500 mg/L. The ‘do nothing’ option (2006 land use) and the desalination option required no land-use change in the modelling (Table 4). The areas of plantation needed to reach the 500 mg/L target (900 to around 1400 ha) depended on the location of the trees in the upper catchment. Perennial pastures were also modelled using MAGIC. Nearly 3000 ha of perennial pasture would be needed to reach the target salinity.

Table 3 Projected streamflow, salt loads and salinities in 2020 (LUCICAT)

Option	Upper recovery catchment			Mt Lindesay gauging station		
	Salinity (mg/L)	Streamflow (GL/yr)	Total salt load (kt/yr)	Salinity (mg/L)	Streamflow (GL/yr)	Total salt load (kt/yr)
Base case – vegetation as at 2007	1645	3.7	4.6	410	17.1	5.9
Harvest all plantations and revert to 1988 conditions	1490	10.3	13.8	735	23.7	14.6
An additional 1400 ha plantations in upper catchment (approximate 2011 land use)	1244	2.6	2.2	290	16.2	3.9
All cleared land to plantations	655	1.8	0.8	195	14.8	2.5
All pastured areas to native forest	810	2.2	1.1	235	15.7	3.1

2.3 Economic impacts of the management options

Eleven management options were costed and compared to the ‘do nothing’ option (average salinity of ~ 570 mg/L at equilibrium). This is equivalent to a situation where about 1700 ha of ‘at risk’ plantations may not be replanted following harvest (Section 3.1).

As some options may generate future incomes the costs over 20 years have been estimated. This analysis was completed before the 2008 and 2009 plantations were established, and before the collapse of the managed investment scheme companies. Table 5 summarises the costs (see also Appendix D).

Table 4 Projected hydrological impacts of the various management options relative to the ‘Do nothing option (MAGIC)’

Option	Mt Lindesay gauging station			Land-use change (ha)
	Salinity (mg/L)	Streamflow (GL/yr)	Total salt load (kt/yr)	
Do nothing (use saline water)	570	21.9	12.4	None
Govt plantations	500	–1.1	–2.1	902
Govt plantation - leased	500	–1.1	–2.1	902
Caveat and sell	500	–1.1	–2.1	902
Govt lease and sub-lease	500	–1.1	–2.1	902
FPC incentives	500	–1.6	–2.3	1375
Incentives to landholders	500	–1.6	–2.3	1375
Perennial pastures	500	–1.4	–2.2	2948
Groundwater pumping	500	–0.4	None	None
Diversion	500	-6.0	None	None
Desalination	570	0.0	None	None

Source URS 2007

Negative values indicate reductions in streamflow or salt load below the ‘Do nothing option’

All plantation forestry options were more cost effective than the engineering options analysed and most were more cost effective than perennial pastures when plantation revenues were considered. Although perennial pastures were cost effective, experience has shown that the scale of intervention (~3000 ha) needed to meet the salinity target is difficult to achieve, even when incentives have been offered.

The incentives to landholders option had the lowest upfront costs. It provides incentives for stakeholders to establish 1375 ha of plantations, estimated to cost $0.7–2.4 million over the 20-year time frame considered. The second cheapest option was establishing perennial pastures, although the likelihood of full implementation was seen as low due to the large area (2950 ha) needed, and minimal adoption in the past despite incentives.

Desalination was the most expensive option, followed by groundwater pumping. The ‘do-nothing’ option, because of the cost of damage to industrial and urban consumers from using the salty water, was nearly as expensive as groundwater pumping.

Other options such as piping water from alternative sources such as the Great Southern Towns Water Supply would require taking water from fully committed resources with already strong demands and were not comprehensively analysed. This option however provides a useful benchmark. An extension of this supply to Denmark is estimated to cost more than $400 million.

Table 5 Summary of costs of the 11 management options evaluated

Option	Capital & operating $m	Damages $m	Upfront land use change $m	Costs c/kL[1]	Potential revenue $m[2]	Net cost $m	CO_2e benefits $m	Net costs inclusive of CO_2e benefits $m
Do nothing – use saline (2004 land use)		17.4–20.9		10.35		17.4–20.9		17.4–20.9
Government plantations 900 ha			6.6–12.5	2.1–4.0	7.2–10.0	0.6–2.5	1.3–1.8	–1.9–0.7
Government plantations - leased			5.2–11.0	1.7–3.5	3.1–5.1	2.1–5.9	1.3–1.8	0.8–4.1
Caveat & sell			5.2–11.0	1.7–3.5	3.8–6.8	1.4–4.2	1.3–1.8	0.1–2.4
Government lease & sub-lease			4.0–6.1	1.3–2.0	3.1–5.1	0.9–1.0	1.3–1.8	0.4–0.8
FPC incentives for 1375 ha			0.7–2.4	0.2–0.8		0.7–2.4	2.0–2.7	–1.3–0.3
Incentives to landholders			0.7–2.3	0.2–0.8		0.7–2.3	2.0–2.7	–1.3–0.4
Perennial pastures 2948 ha			1.9–3.3	0.6–1.1		1.9–3.3		1.9–3.3
Groundwater pumping 58 pumps	16–23			5.0–7.1		16–23	–0.7	16.7–23.7
Diversion 6 GL saline flows	8–14			3.4–5.9		8–14	0.2	8.2–14.2
Desalination of river water	60–90			35–50		60–90	–10.0	70–100

Source: URS 2007a

[1] *Cents per kilolitre*

[2] *Monies gained from sale or lease of properties or products*

2.4 Social and environmental impacts

The social impacts of the 11 options evaluated were assessed as being minimal (URS 2007a). While the vegetation options had the benefit of sequestering carbon dioxide, the engineering options, to varying degrees, were identified as producing carbon dioxide emissions in addition to causing localised physical disturbance. The pumping and disposal of groundwater in an adjacent catchment may contribute significantly to salinity in the receiving catchment, with implications for waterbodies of the surrounding Walpole Wilderness Area which maintains valuable ecosystems and provides recreational opportunities.

The main social impact that could result from the transition from cropping or pastoral agricultural enterprises to plantation forestry is rural decline. Rural decline affects business activity, regional employment and the availability of services such as health and education. However, according to reports by the Bureau of Rural Sciences (BRS 2005) and the Cooperative Research Centre for Forestry (Schirmer 2009), plantation expansion in the Great Southern Region has not been associated with accelerated rates of rural population decline. On the contrary, when plantations come into the harvesting stage there has been a major increase in employment within the plantation sector. Where plantation expansion occurs as part of a mix of land-use changes, it may increase rural populations, especially where there are associated processing industries (BRS 2005; URS 2007a; Schirmer 2008).

The effects of plantation forestry, real and perceived, are mixed. Community perceptions are that forestry may have some benefits for flora and fauna species (CRC for Forestry Limited 2008) but that it may also increase the risk of weed and feral animal invasion into tracts of native vegetation (Appendix D). Some reports indicate that forestry is likely to raise the risk of wildfire (URS 2007a) but other studies, and anecdotal evidence, suggest that plantations may dampen wildfires (Williams 2008).

The rates of erosion and sedimentation of waterways may rise during establishment and harvest of plantations if best practice is not applied (Lacey 2000; Environmental Protection Authority 2007). Between these times, reduced erosion, sedimentation, and flood peaks are likely.

2.5 Plantations as the preferred option

Taking into account the evaluation of options (URS 2007a) and the continued expansion of plantations in the catchment, it is apparent that commercial forestry is the primary salinity management option because:

- Plantations are technically feasible.
- There have been salinity reductions since their introduction.
- Plantations will reduce salinity in the Denmark River even further.
- Plantations are the most cost-effective option, even if government needs to invest in their establishment (Table 5).
- If established, federal government carbon trading schemes could add further financial incentives to the establishment of plantations.
- There is minimal social impact associated with the establishment of new plantations in the upper Denmark catchment.

Furthermore, forestry options have the potential to generate additional income or credits as a result of carbon sequestration (URS 2007a). This value may be credited to the forester, farmer or government depending on contractual arrangements. Regardless, this potential increases the relative attractiveness of forestry options over alternative engineering options and over existing agricultural activities. The additional incentives may be between $1500 and $2000 per hectare as a one-off payment, given a value of $15–25 per tonne of CO_2e. This is roughly equivalent to the estimated required incentive payments. The forces of a market in carbon may generate a shift of land use from agriculture into plantation forestry.

2.6 Risks associated with plantations

The risks associated with having predominantly blue gum plantations as the preferred way of managing salinity in the Denmark River catchment include:

- Maintaining the cover required to reduce salinity (~90% vegetation cover in the upper catchment)
- Disease, pests and pathogens
- Bushfire
- Reduced rainfall (drought)
- Collapse of the world market for woodchips
- Water allocation where the plantation area is restricted to 'free up' water for other land uses (not likely at present because the Denmark catchment is not proclaimed under the *Rights In Water and Irrigation Act 1914*)
- Land-use planning – If the Denmark or Plantagenet shires chose to encourage other land uses they could restrict areas that could be planted to trees.

3 The recovery plan

The recent story of salinity reduction in the Denmark River is one of successful management, with salinity at the Mt Lindesay gauging station already close to the target (mean annual salinity 540 mg/L in 2009). Even with current land use, mean salinity should drop to the potable level well before the state's *Salinity action plan* target of 2020 (Government of Western Australia 1996). However, there are risks with relying on plantations in the upper catchment. For example, two of the managed investment scheme companies that effectively drove the establishment of plantations collapsed and went into administration in 2008–09. Recent research by URS, the Forests Products Commission and the Department of Water (URS 2009) suggests that plantations in some areas of the upper catchment may not be retained in the future due to the inability of lower rainfall plantation areas to produce target harvest yields. If these plantations are not replanted once harvested, then action will be required to deal with subsequent salinity rises in the Denmark River.

The plan proposes the following steps to ensure that the gains made in salinity reduction achieved so far will not be lost. The steps are explained in more detail in the indicated sections of the report:

- Secure existing plantations (Section 3.1).
- Facilitate the establishment of new plantations (Section 3.2).
- Revegetate areas not considered suitable for commercial forestry (Section 3.3).
- Protect native vegetation (Section 3.4).
- Continue monitoring streamflow, salinity and groundwater levels (Section 3.5).
- Update existing catchment models (Section 3.6).
- Communicate the plan to stakeholders (Section 3.7).

The recommended actions have been drawn up from a review of the *Denmark River evaluation* (URS 2006; 2007a) and *The sustainable production and landscape repair in salinity-affected water supply catchments* (URS 2009), and are considered to be feasible means for managing salinity. In Section 4 the recommended actions are assigned priorities and the agencies likely to be responsible are identified.

3.1 Secure existing plantations

Under current land use, the river water is expected to fall below the target salinity well before the 2020 target date (Fig. 9). The Department of Water recognises that the long-term benefits of plantations that could be at risk if they are not re-established following harvesting (blue gums are harvested after around 10 years and are either coppiced or re-planted if they are to undergo a second rotation). If the cleared area in the upper catchment rises above 2007 levels (~10% or 25 km^2) there is a risk that the target salinity will not be met (Appendix B). The inability to retain plantations in the upper catchment poses the greatest risk to maintaining and lowering salinity, as the plantations are privately owned and planned second rotations may not be undertaken (URS 2009).

When the two managed investment scheme companies with blue gum plantation assets in the catchment went into administration their plantations were taken over by other companies. However, about 1740 ha of plantations (of 5200 ha) are most at risk of not being replanted after harvesting. It is estimated that a minimum of 3300 ha of plantations need to be retained to effectively control salinity, so with this loss there would be a ‘safety margin’ of around 160 ha.

The productivity and economics of plantation forestry are expected to be even more at risk in a drying climate as the current plantations are already near the limit of minimum annual rainfall (Forest Products Commission 2002) and any changes in rainfall patterns may have added adverse effects.

There may be a need, therefore, to help retain sufficient areas of private plantations in the medium to long term. For example, agreements could be negotiated with private foresters to secure the long-term future of plantations. Such agreements may involve government acknowledgement of the contribution of private forestry to reducing stream salinity and private forestry acknowledgement of the importance of retaining plantations to keep stream salinity low.

The potential for tree plantings for other purposes, like planting for carbon credits, that may have a longer future than blue gum plantations should be considered and encouraged.

Action 1.1 Plan a retention incentive program to maintain plantations at 2007 levels and develop funding options.

Action 1.2 Investigate an incentive program for farmers to improve water quality in the catchment (e.g. by revegetation or establishing plantations).

Action 1.3 Monitor plantation coverage and the viability of the plantation industry in the region.

Action 1.4 Maintain and form partnerships with landowners, plantation companies and other tree investors.

3.2 Facilitate the establishment of new plantations

If currently planned commercial tree plantations do not proceed, it will be important to ensure that plantations are established in alternative areas to achieve the required reduction in stream salinity. This has been achieved to some extent with 700 ha of plantations established by private industry since 2007 (Fig. 10). The Wellington Estate is an example of such an initiative, where the Department of Water owns and manages commercial tree plantings established for salinity control in the Collie catchment (DoW 2001).

Action 2.1 Monitor land use in the upper catchment and facilitate the establishment of new plantations if necessary. This could be similar to the Department of Water’s Wellington Estate.

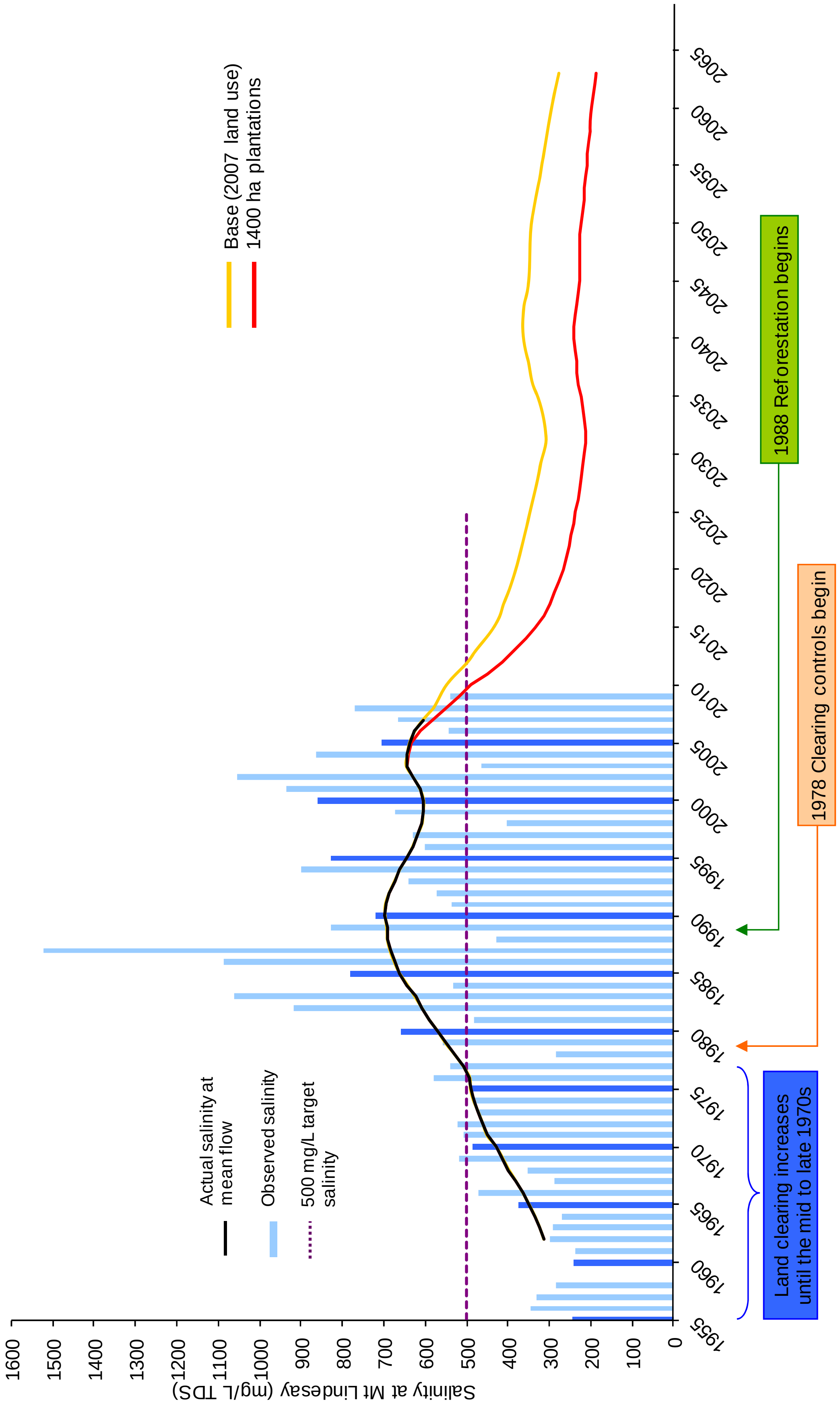


Figure 9 Projected salinity for current land use in the Denmark water resource recovery catchment

3.3 Revegetate areas not considered suitable for commercial forestry

Some areas in the upper catchment are considered unsuitable for commercial plantations for various reasons, including soil type, rainfall and current land use (URS 2009). It is suggested that revegetation primarily be in partnership with forestry companies, who have in previous cases agreed to revegetate areas adjacent to plantations with funding support from the Department of Water via South Coast Natural Resource Management Inc. (South Coast NRM). The department, together with South Coast NRM Inc., has also encouraged landholders to repair and revegetate riparian zones and areas of bushland, and build wildlife corridors connecting native vegetation. These planted areas lower localised groundwater levels and reduce saline discharge into streams (Mauger et al. 2001; Smith et al. 2007).

Action 3.1 Plan a scheme to revegetate land not suitable for plantations within plantation plots (this could be similar to the Department of Water's Wellington Estate).

Action 3.2 Engage local NRM groups to facilitate revegetation projects.

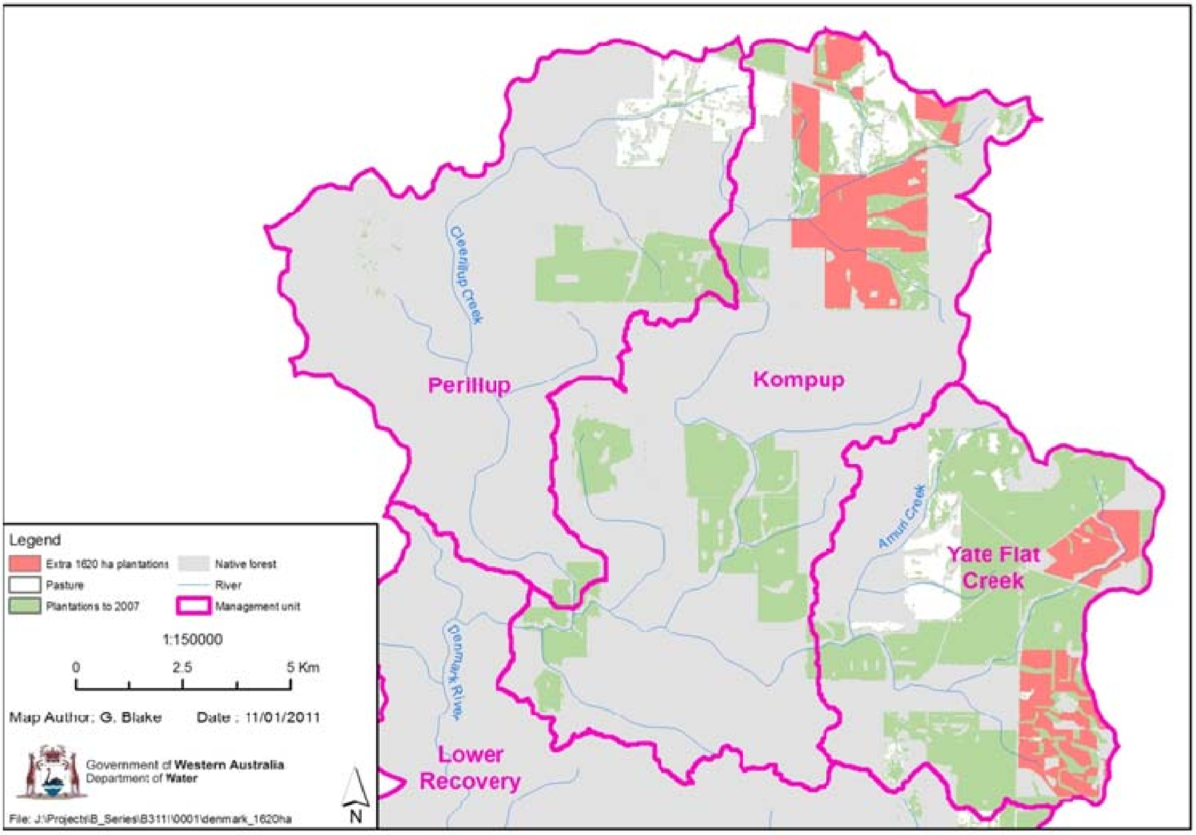


Figure 10 Locations of plantations established in the Upper Recovery catchment since 2007

3.4 Protect native vegetation

More than 84% of the upper catchment is native vegetation that lies within national parks of the Walpole Wilderness Area and is protected from threatening processes like grazing and weed invasion. Following the introduction of clearing controls in 1978, compensation was paid to landholders not to clear 2750 ha of native vegetation on farms and within blue gum plantations – about 5% of the upper catchment. This compensated native vegetation and other native vegetation on farms and within plantations could deteriorate if not protected and managed well.

Areas of native vegetation are important as they keep groundwater levels low and prevent development of new stream recharge areas that would counteract the existing water resource benefits (Bari et al. 2004; Appendix A).

Action 4.1 Keep communicating to landholders the importance of fencing existing native vegetation to protect it.

Action 4.2 Engage local NRM groups to facilitate protection of native vegetation.

Action 4.3 Continue to apply the *Country Areas Water Supply Act 1947* clearing controls policy and guidelines.

3.5 Continue monitoring streamflow, salinity and groundwater levels

Continued monitoring of the upper catchment streamflow and salinity is essential if the effects of changing land use, planting and harvest rotations and climate on salinity are to be detected and managed. There are currently no long-term groundwater monitoring sites in the upper catchment area and so the immediate effects of the establishment and harvesting of plantations on groundwater levels cannot be monitored. If this monitoring was in place, optimum areas of plantation area could perhaps be managed.

Continued stream gauging and the establishment of groundwater monitoring networks contributes to the development of more accurate catchment models that allow rapid assessment of the possible effects of land-use changes and therefore more reliable decision making.

Action 5.1 Continue monitoring the following gauging stations:

Station	Station number	Purpose	Period of record
Mt Lindesay	603136	Streamflow, EC[1], rainfall	1960–current
Kompup	603003	Streamflow, EC	1974–current
Yate Flat Creek	603190	Streamflow, EC	1963–current

[1] *Electrical conductivity*

Action 5.2 Continue in-situ sampling for streamflow and salinity on currently ungauged tributaries and old monitoring sites.

Action 5.3 Re-establish stream gauging on Perillup Brook at site 603177.

Action 5.4 Establish a groundwater monitoring network at key locations in the upper catchment.

3.6 Update existing catchment models

Catchment models are used to assess the effects on salinity and streamflow of land use and climate changes. The models used by the department are constantly being reviewed and improved to make them easier and faster to use as well as to provide more relevant information to decision makers. The Denmark LUCICAT model, updated since Bari (2005), needs further work so that it can analyse land-use change in the catchment more efficiently, with the final goal being its development into a web based application. The ‘Catchment hydrology annual model for Western Australia’ (CHAMWA) is a simple spreadsheet model specifically designed to analyse plantation water use in a particular catchment (Dixon and Mauger in prep.). MAGIC still provides the land history used in these other modelling systems.

Action 6.1 Calibrate the LUCICAT model using latest stream gauging and land-use data. Continue development of base code.

Action 6.2 Calibrate the CHAMWA model for rapid assessment of plantation water-use effects.

3.7 Communicate the plan to stakeholders

The development of this plan is a culmination of more than 20 years of work by landowners, shire councils, plantation companies and government. To keep improving the Denmark River it is essential to communicate this plan effectively and to involve all relevant stakeholders.

Action 7.1 Continue to engage with stakeholders during the recovery process.

Action 7.2 Communicate the recovery plan to major stakeholders (Water Corporation (WC), local shires, landholders, plantation companies, Department of Agriculture and Food Western Australia (DAFWA), Department of Environment and Conservation (DEC), Forest Products Commission and NRM groups.

4 Recommended priorities and responsibilities for implementation

This section lists all the recommended actions, their priorities and the agencies likely to be responsible for carrying them out. Priorities are high (H), medium (M) or low (L).

The Department of Water will lead the implementation of the recovery plan in consultation with the relevant stakeholders (Government of Western Australia 1996).

Table 6 Priorities and responsibilities for implementing the recovery plan

Action	Priority	Responsibility	Notes
Secure existing plantations			
Action 1.1 Plan a retention incentive program to maintain plantation land use at 2007 levels and develop funding options.	H	Department of Water	Includes landholders and plantation companies. Could involve government ownership of land and plantations to provide long-term security for water resource.
Action 1.2 Investigate an incentive program for farmers to improve water quality in the catchment (e.g. by revegetation or establishing plantations).	L	Department of Water	Recognises that public investment is warranted to ensure land-use change that has a high public benefit.
Action 1.3 Monitor plantation coverage and the viability of the plantation industry in the region.	M	Department of Water, FPC	To give early warning if industry is becoming unviable.
Action 1.4 Maintain and form partnerships with landholders, plantation companies and other tree investors.	M	Department of Water	Communication will remain the key to maintaining the water quality benefits already gained in the catchment.
Facilitate establishment of new plantations			
Action 2.1 Monitor land use in the upper catchment and facilitate establishment of new plantations if necessary. This could be similar to Department of Water's Wellington Estate.	L	Department of Water	Plantation coverage is sufficient at present but it is important to monitor the status of plantations to ensure they remain at the required level.

Action	Priority	Responsibility	Notes
Revegetate areas not considered suitable for commercial forestry			
Action 3.1 Plan a scheme to revegetate land not suitable for plantations within plantation plots (this could be similar to Department of Water’s Wellington Estate).	L	Department of Water, DEC, South Coast NRM, WC	Will predominantly involve state/federal NRM funding.
Action 3.2 Engage local NRM groups to facilitate revegetation projects.	L	Department of Water, DEC, South Coast NRM	Will also require assistance from local shire councils.
Protect native vegetation			
Action 4.1 Keep communicating to landholders the importance of fencing existing native vegetation to protect it.	L	Department of Water, South Coast NRM	Ongoing health of native vegetation is important to maintain water quality gains.
Action 4.2 Engage local NRM groups to facilitate protection of native vegetation.	L	Department of Water	NRM groups are efficient at working with landholders to implement land-use change.
Action 4.3 Continue to apply CAWS Act legislation.	H	Department of Water, DEC	CAWS Act is one of the main instruments for clearing controls in the Denmark catchment
Continue to monitor streamflow and salinity and groundwater levels			
Action 5.1 Continue monitoring current gauging stations.	H	Department of Water	This is the current Department of Water gauging network in the catchment.
Action 5.2 Continue in-situ sampling for streamflow and salinity on currently ungauged tributaries and old monitoring sites.	H	Department of Water	Many smaller streams are ungauged but still need to be monitored for salinity and streamflow.
Action 5.3 Re-establish stream gauging on Perillup Brook at site 603177.	H	Department of Water	This site is not currently gauged.
Action 5.4 Establish a groundwater monitoring network at key locations in the upper catchment.	H	Department of Water	There are currently few bores in the catchment. More bores are needed to adequately monitor effects of land-use change.

Action	Priority	Responsibility	Notes
Update existing catchment models			
Action 6.1 Calibrate the LUCICAT model using latest stream gauging and land-use data. Continue development of base code.	H	Department of Water	Not currently calibrated. Needed for rapid assessment of effects of land-use change.
Action 6.2 Calibrate CHAMWA for rapid assessment of plantation water-use effects.	M	Department of Water	Specifically developed for plantation water use.
Communicate the plan to stakeholders			
Action 7.1 Continue to engage with stakeholders during the recovery process.	H	Department of Water	Could involve workshops and call for public comment.
Action 7.2 Communicate the recovery plan to major stakeholders (WC, local shires, landholders, DAFWA, DEC, FPC and local NRM).	H	Department of Water	Could involve workshops and call for public comment.

5 Conclusion

Widespread clearing of deep-rooted perennial vegetation in the upper catchment was the cause of salinisation, and halting the clearing and reversing it by widespread revegetation with commercial forestry and native vegetation has already resulted in much lower salinity in the Denmark River. Government and community action over the past decades has been the key to this success and will continue to be critical in the future, in order to continue the improvements and to make sure that the gains already made are not lost.

An understanding of the process of stream salinisation requires an ongoing study of the relationships between rainfall, streamflow, groundwater, and land use, as well as the catchment setting and its physical characteristics such as its geology and hydrogeology.

Because the social, economic and environmental effects of land use will change over time, they need monitoring and reviewing. The projected hydrological effects of implementing the recovery plan are based on long-term groundwater and surface water measurements and projections from computer models that are simplified versions of real world processes. These models have inherent uncertainties and the results can therefore only be approximations. Ongoing measurements and updated modelling are required to retain confidence in the processes and predictions. Furthermore, the effects of climate change may differ in nature and extent from those currently identified and be hard to quantify for some time, highlighting the need for ongoing monitoring.

Given that no decision has been made by government regarding further water source development for Denmark, the best way to restore the water quality of the Denmark River and to secure increased water supply for the Denmark region is to protect native vegetation, maintain existing plantations and to establish new ones. Plantations are currently the best way to improve water quality with minimal additional social and environmental impacts.

All of the plantation forestry is in the private sector and hence is subject to the economic climate, so there is no guarantee that they will continue to exist. Government involvement is recommended to ensure that any reductions in the area covered by plantations are detected promptly and the effects of these on salinity are managed.

Appendices

Appendix A The LUCICAT model and data assumptions

Following publication of the *Salinity situation statement: Denmark River* in 2004, the LUCICAT (Land-use change incorporated catchment) model was applied to the catchment and its results compared with those of the MAGIC (Microstation and geographic information catchment model) model (URS 2007a). LUCICAT is a dynamic conceptual model that simulates the effects of land use and climate change on daily streamflow and salinity within catchments, taking into account the subsurface, stream zone and groundwater stores. The model incorporates catchment attributes such as topsoil thickness, hydraulic conductivity and vegetation water use. The model uses daily time-steps and can estimate how long it will take to attain the outcomes and whether this will be in time for the 2020 target. At this stage projections do not account for the possible impacts of climate change.

Where MAGIC assumes long-term land use and ground cover and that all groundwater discharge that enters the top layer will eventually discharge to the stream zone, LUCICAT allows for groundwater disconnection beneath revegetated areas of the catchment. LUCICAT also accounts for salt leaching that may occur while MAGIC does not.

The streamflow and salinity projections in this report are mean values calculated using modelling assumptions and simplified hydrological processes. There is inherent uncertainty associated with them and actual streamflow and salinity values will vary in response to rainfall variability, the success of plantation establishment and the assumptions behind the models. Salinity is related to rainfall patterns and variations in annual average salinity at Mt Lindesay can be as high as 650 mg/L (1992–2005) and within-year variation (from day to day) can be as high as 1370 mg/L (2005).

Measuring the effectiveness of land-use change

Three outputs were analysed for each option considered: projected salinity at the Mt Lindesay gauging station given as mg/L TDS, projected salt load entering streams as kt/yr and projected streamflow given as GL/yr.

Using or extracting subsurface flow and/or groundwater or diverting saline water from rivers to reduce groundwater recharge and discharge, and thus lower salinity, reduces streamflow at the Mt Lindesay gauging station. So the flow reduction resulting from each option must be considered (Fig. 11).

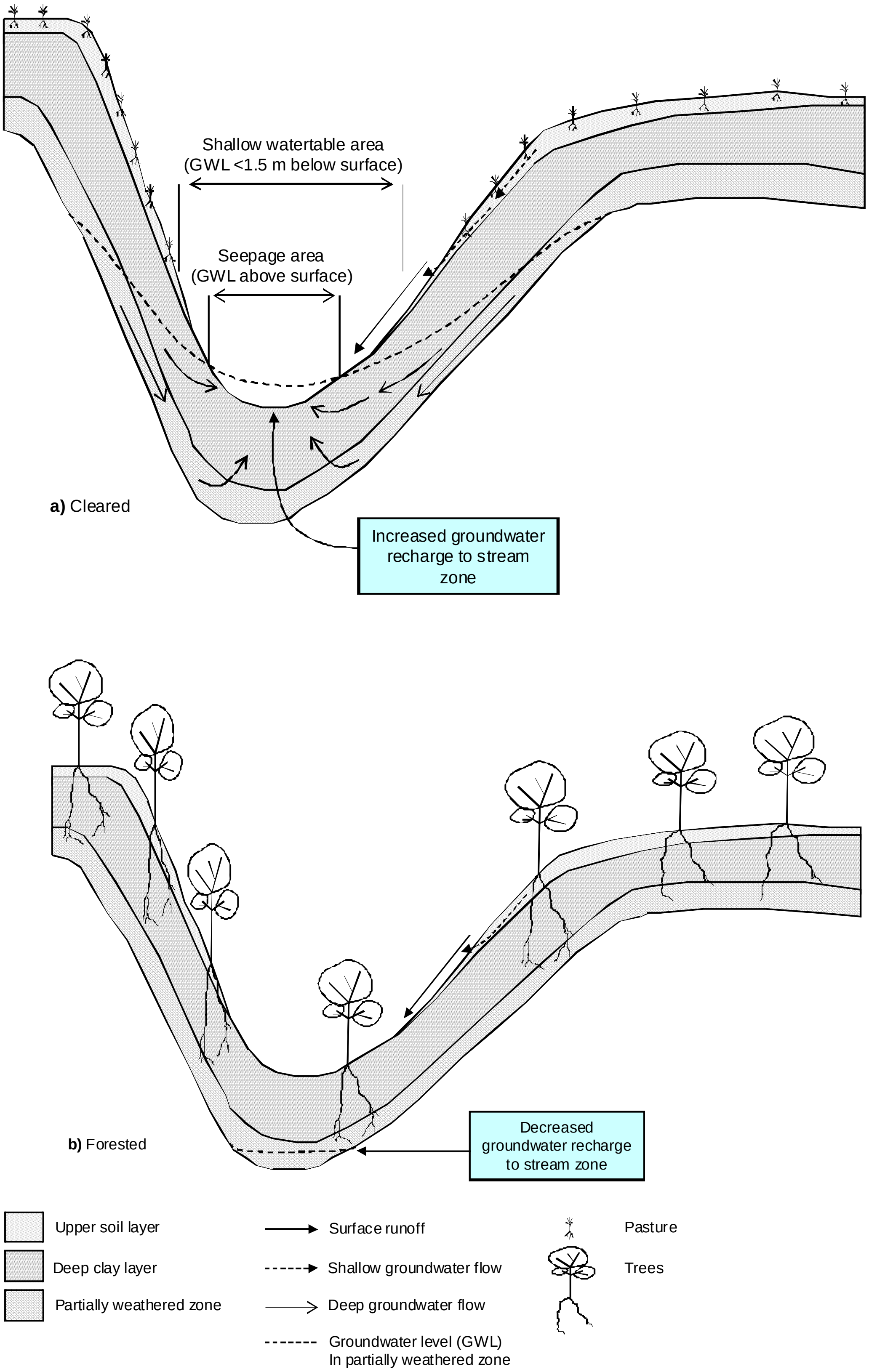


Figure 11 Cross-section showing the effect of groundwater levels on stream recharge with a) clearing and b) after revegetation with trees

Source: after Mauger et al. 2001

Input data assumptions

The vegetation history, LAI (leaf area index) and report were prepared by Geoff Mauger, Geographic Information Analysis Pty Ltd in 2007.

The following assumptions were used for the development of vegetation input data for the LUCICAT model.

1 The areas of plantations to be subject to 10-year cycles were mapped as polygons labelled by the first year of harvest. These were obtained from a shapefile 'Harvestpols.shp' supplied by Brett Ward, Department of Water, Albany, August 2007.

2 A table prepared in the generating program (LVEGMODDNMKROT.FOR) gave the area of each polygon type in each subcatchment (response unit) expressed as a percentage of the 'Frac 1' area (area clear in 1988) of the subcatchment. The source data for the table was a file prepared by the MAGIC command OVROU where the plantation dates were overlaid on the subcatchment fractions. The grid of plantation dates was prepared from analysis of Landsat scenes from 1988 to 2006. The Landsat scenes were previously classified to identify pasture areas and were then considered in chronological sequence to decide whether a change from pasture to forest was a result of a plantation appearing or due to random misregistration or misclassification of the scene. The logic is set out in the MAGIC command file 'pasthist.dat'.

3 LAI was used as the primary indicator of vegetation water usage. Root depth determines the depth in the soil structure at which soil moisture and groundwater can be taken up by plants. Profiles of LAI and rooting depth through the years of a 10-year cycle were prepared. The LAI profile was based on the actual LAI recorded in the plantation polygons. The time-series of annual LAI were displaced so that the dates of harvest were aligned and an average profile calculated. Based on the average, an 'ideal' profile which allowed that some historical areas had performed poorly was propounded. In the ideal profile, the year of harvest has the maximum LAI of 2.5. The next year, being the first year of the next cycle, has zero tree LAI but the land is treated as annual pasture. Over the next six years the LAI increases to the maximum which is then maintained to the end of the cycle. The rooting depth is assumed to be zero in year 1, then increases at increments of 4 m/yr until reaching the maximum of 16 m in year 5, and then is maintained to the end of the cycle. The profiles are illustrated in Figures 12 and 13.

4 The plantation LAI in a subcatchment in a particular year is the area-weighted average of the LAIs applicable to the various plantation polygons in the subcatchment. Areas that are year 1 in the plantation cycle are transferred to the pasture land-use fraction and the plantation LAI is the average over the remaining area. Rooting depth is calculated as an area-weighted average in the same way.

5 The vegetation history prior to 2006 was retained as previously calculated using historical Landsat scenes. After 2006, areas within the plantation polygons were driven by the plantation cycles while areas outside the polygons remained as in 2006. If the polygon area was larger than the 2006 reforested area, the pasture area was reduced by the excess (i.e. taken over by the increased plantation area). If the

polygon areas were smaller in total than the 2006 reforested area, the extra area was assumed to remain with constant LAI and rooting depth as calculated for all the 2006 reforested area. The extra area was then incorporated into the area-weighted averaging of the polygon areas when determining the subcatchment's LAI and rooting depth in subsequent years.

6 In the options where areas, in addition to the mapped polygons, were identified as having plantations, the additional areas were assumed to have a first harvest date of 2016, i.e. 2007 was year 1 of the first cycle.

7 In options where plantations were not rotated, in all years where the date was past the first harvest date, the relevant polygon area was converted to pasture. When the last polygon areas were converted in 2017, any extra plantation areas (referred to in 5 above) were also converted to pasture.

8 The boundary of the area giving an additional 1400 ha in Jenkin's and Alison's farms was at 6172150 N, which happens to go through the bend in Muir's Highway as that road passes through the properties.

9 In the option 'cleared land replanted to native forest in 2007', maximum LAI and rooting depth in the new native forest is the same as the forest fraction (Frac 2) in 2006. LAI and rooting depth are increased linearly over five years from 2007, with 2007 having the first fifth. Rather than introducing a third land-use type of 'pasture' for year 1 of the plantation rotations, the first plantation year is treated as plantation with LAI = 0.1 and rooting depth = 4 m. Subsequent years are the same as for other options.

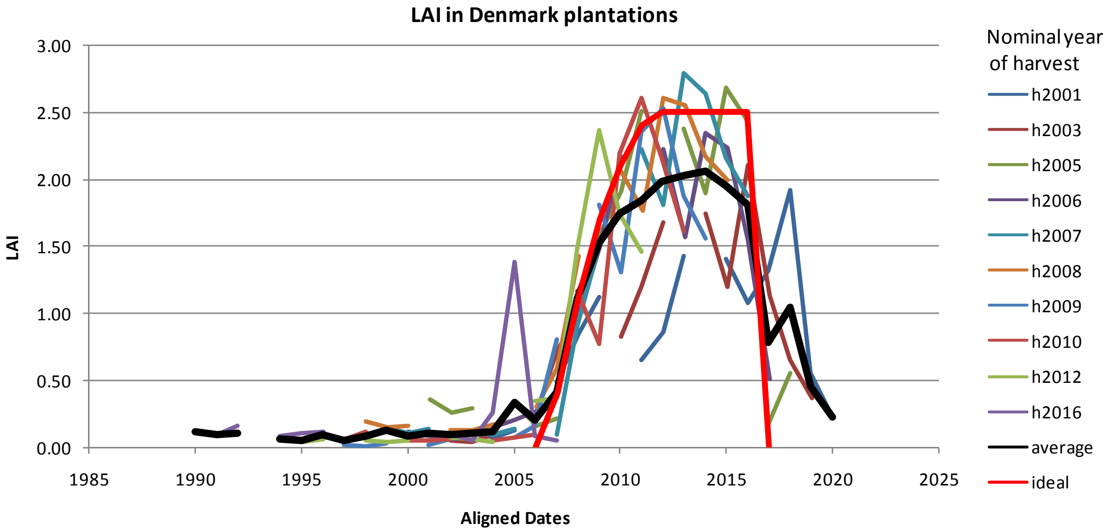


Figure 12 LAI values for plantations in the Denmark River basin

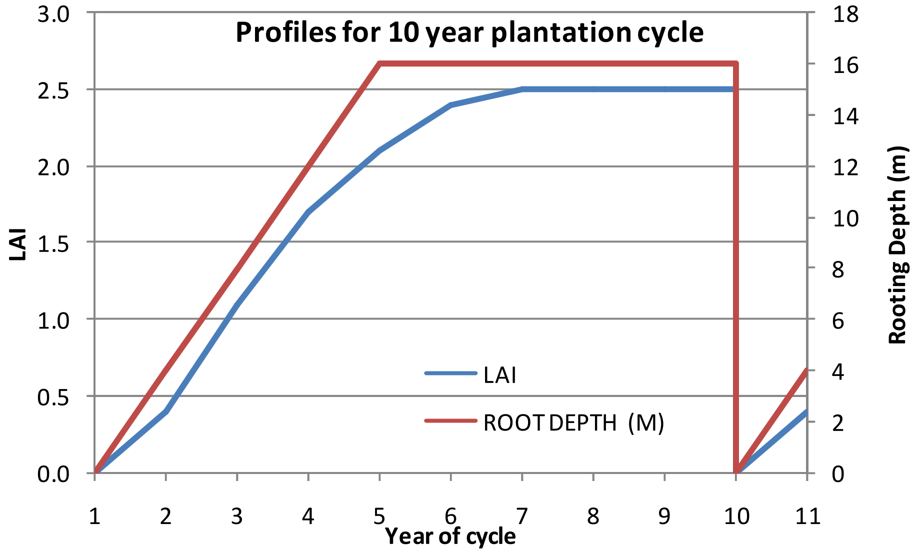


Figure 13 LAI and rooting depth plantation profile

Appendix B Summary of LUCICAT modelling

Options modelled with LUCICAT

In 2007, LUCICAT was used to model several scenarios of second-rotation tree plantations. Estimates of vegetation water use under different land-use regimes were based on estimates of LAI. The base case and all of the proposed options were modelled assuming a maximum LAI of 2.5 (Tables 3 & 7).

- Base case – assumes that land use and vegetation remain as at 2007 and existing plantations are operated on a 10-year growth-and-harvest cycle. Note that the MAGIC base case is based on 2005 land use.
- 1988 – assumes all plantations are harvested and the land use reverts to 1988 conditions.
- 1400 ha – assumes an additional 1400 ha of plantations are established in the upper catchment and operated on a 10-year growth-and-harvest cycle.
- All cleared land to plantations – assumes all cleared land is converted to plantations operated on a 10-year growth-and-harvest cycle.
- Pasture to native vegetation – assumes all pastured land is revegetated to native plants and there is no harvesting.

In addition, modelling was repeated for the base case scenario with lower maximum LAIs to allow for uncertainty as to the actual maximum LAI (Appendix C).

- Base case LAI = 2.0 – similar to the base case but assumes a lower maximum LAI, representing vegetation cover that uses 20% less water.
- Base case LAI = 2.2 – similar to the base case but assumes a lower maximum LAI, representing vegetation cover that uses 12% less water.

The assumptions used to develop the vegetation input data are described in Appendix A.

Modelling outputs

As expected the most to least effective salinity reducing conceptual options are:

1. Establish plantations on all cleared land.
2. Revegetate all pastured areas.
3. Plant 1400 ha in the upper catchment.
4. Do nothing, leaving vegetation as it was in 2007.
5. Harvest all plantations and revert to 1988 conditions.

Reverting to 1988 conditions would increase salinity to approximately 735 mg/L by 2020. All the other options would reduce salinity below the 500 mg/L target by 2020.

Assuming lower LAI values for the base case did not significantly change the effectiveness of the options but salinity would take two to three years longer to reach 500 mg/L (Appendix C).

Table 7 Projected streamflow, salt load and salinities in 2020 from LUCICAT

Option	Upper recovery catchment			Mt Lindesay gauging station		
	Salinity mg/L	Streamflow GL/yr	Total salt load kt/yr	Salinity mg/L	Streamflow GL/yr	Total salt load kt/yr
All cleared land to plantations	655	1.8	0.8	195	14.8	2.5
All pastured areas to native forest	810	2.2	1.1	235	15.7	3.1
An additional 1400 ha plantations in upper catchment (approximate 2011 land use)	1244	2.6	2.2	290	16.2	3.9
Base case – vegetation as at 2007	1645	3.7	4.6	410	17.1	5.9
Harvest all plantations and revert to 1988 conditions	1490	10.3	13.8	735	23.7	14.6
Base case with 20% less vegetative cover (max LAI = 2.0)	1645	4.1	4.6	450	17.4	5.7
Base case with 12% less vegetative cover assumed (max LAI = 2.2)	1645	4.0	5.0	435	17.4	6.2

The following tables (Tables 8–12) summarise LUCICAT results for modelled scenarios (Section 3). Note that the Scotsdale Brook management unit and the Scotsdale Brook and Powleys gauging stations refer to areas and gauging stations downstream of the Mt Lindesay gauging station (i.e. outside the recovery catchment) and are included for data preservation.

Note: salinities shown are 10-year arithmetic means and therefore do not directly correlate with the flow and salt load values for any given year.

Table 8 LUCICAT base case: 2006 land use with plantations on a 10 year harvest rotation

LUCICAT base case - 2006 land use with plantations on a 10 year harvest rotation.

	Management unit (MU)			**Gauging Stations (GS)**							
	Perillup MU	**Kompup MU**	**Yate Flat Creek MU**	**Total Upper MU / Kompup GS**	**Lower Recovery MU**	**Scotsdale Brook MU**	**Amarillup Swamp GS**	**Lindesay Gorge GS**	**Mt Lindesay GS**	**Scotsdale Brook GS**	**Powleys GS**
Area (km^2)	77	108	57	243	260	161	20	445	503	65	38
Lake area (km^2)	0	0	0	0	0	0	0	0	0	0	0
Native forest 2006 (km^2)	67	78	27	173	250	132	12	371	423	50	37
Native forest 2006 (%)	87	72	48	71	96	82	59	83	84	76	99
Plantation 2006 (km^2)	6	16	22	44	1	0	6	45	46	0	0
Plantation 2006 (%)	8	14	39	18	0	0	30	10	9	0	0
Cleared area 2006 (km^2)	4	14	8	26	5	8	2	27	30	3	0
Cleared area 2006 (%)	5	13	14	11	2	5	11	6	6	4	0
Other land use 2006 (km^2) [a]	0	0	0	0	4	21	0	2	4	14	0
Other land use 2006 (%)	0	0	0	0	2	13	0	0	1	21	1
Average for 2020 [b]											
Annual rainfall (mm)	710	725	738	723	816	971	734	875	807	1055	889
Streamflow (GL)	0.94	1.86	0.93	3.72	13.39	11.72	0.30	11.84	17.11	7.12	1.81
Runoff (mm)	12.12	17.12	16.22	15.32	51.47	72.89	14.58	26.61	34.02	109.01	47.69
Salt load (kt)	0.81	3.14	0.61	4.57	1.29	4.42	0.23	4.81	5.86	2.60	0.32
Salinity (mg/L)	1222	2092	1069	1643	85	452	1223	498	411	433	216
Groundwater discharge to stream zone (mm)	1.02	3.77	0.40	1.02	2.29	11.76	0.70	1.56	2.20	21.37	1.01
Baseflow (mm)	0.15	0.89	0.62	0.15	1.69	8.53	1.05	0.74	1.16	15.66	0.88
Average for 2050 [c]											
Annual rainfall (mm)	710	725	738	723	816	971	734	875	807	1055	889
Streamflow (GL)	0.94	1.83	0.83	3.59	13.33	11.69	0.25	11.65	16.92	7.11	1.81
Runoff (mm)	12.10	16.87	14.46	14.79	51.23	72.72	12.23	26.19	33.63	108.80	47.65
Salt load (kt)	0.76	2.88	0.26	3.90	1.21	3.43	0.12	4.26	5.11	1.88	0.28
Average annual salinity (mg/L)	1153	1916	453	1441	77	347	680	451	362	309	187
Groundwater discharge to stream zone (mm)	0.98	3.67	0.81	0.98	2.13	12.33	1.21	1.58	2.14	22.26	1.06
Baseflow (mm)	0.15	0.89	0.96	0.15	1.64	9.08	1.40	0.78	1.17	16.81	0.90
Representative year at equlibrium [d]											
Annual rainfall (mm)	702.54	706.11	701.31	703.83	792.14	960.89	695.53	845.69	783.99	1056.47	856.16
Streamflow (GL)	0.94	1.69	0.40	3.03	13.28	10.94	0.14	10.49	16.30	7.34	1.33
Average annual salinity (mg/L)	949	1937	417	1431	86	316	640	439	336	265	183
Runoff (mm)	12.11	15.59	6.98	12.46	51.03	68.01	6.90	23.58	32.41	112.26	35.13
Salt load (kt)	0.89	3.28	0.17	4.33	1.14	3.45	0.09	4.60	5.47	1.95	0.24

a includes biodiversity plantings, vineyards, horticulture and green pastures

b annual mean for the period 2015-2025

c annual mean for the period 2047-2057

d annual for 2055 (1991 MAGIC comparison)

Table 9 LUCICAT 1988: all plantations harvested, catchment reverts to 1988 land use

LUCICAT 1988 - assumes all plantations are harvested and catchment reverts back to 1988 land use.

	Management unit (MU)						**Gauging Stations (GS)**				
	Perillup MU	**Kompup MU**	**Yate Flat Creek MU**	**Total Upper MU / Kompup GS**	**Lower Recovery MU**	**Scotsdale Brook MU**	**Amarillup Swamp GS**	**Lindesay Gorge GS**	**Mt Lindesay GS**	**Scotsdale Brook GS**	**Powleys GS**
Area (km^2)	77	108	57	243	260	161	20	445	503	65	38
Lake area (km^2)	0	0	0	0	0	0	0	0	0	0	0
Forest 1988 (km^2)	67	78	27	173	250	132	12	371	423	50	37
Forest 1988 (%)	87	72	48	71	96	82	59	83	84	76	99
Cleared area 1988 (km^2)	10	30	30	70	10	29	8	74	81	15	1
Cleared area 1988 (%)	13	28	52	29	4	18	41	17	16	24	1
Average for 2020 [a]											
Annual rainfall (mm)	710	725	738	723	816	971	734	875	807	1055	889
Streamflow (GL)	1.53	4.14	4.66	10.33	13.33	12.12	1.24	18.47	23.67	7.51	1.83
Runoff (mm)	19.77	38.20	81.57	42.55	51.25	75.36	61.11	41.52	47.05	114.91	48.21
Salt load (kt)	1.94	6.83	5.06	13.84	0.75	4.49	1.49	13.58	14.60	2.71	0.32
Salinity (mg/L)	1578	1825	1195	1492	-5	440	1337	875	736	424	215
Groundwater discharge to stream zone (mm)	4.24	10.64	17.42	4.24	2.87	12.10	16.01	6.32	6.41	22.19	1.01
Baseflow (mm)	0.87	1.79	2.88	0.87	1.82	8.85	3.21	1.45	1.79	16.47	0.88
Average for 2050 [b]											
Annual rainfall (mm)	710	725	738	723	816	971	734	875	807	1055	889
Streamflow (GL)	1.70	4.71	5.46	11.88	13.42	12.11	1.53	20.12	25.30	0.00	1.83
Runoff (mm)	22.02	43.45	95.57	48.91	51.59	75.28	75.56	45.22	50.29	114.92	48.15
Salt load (kt)	1.93	6.57	5.12	13.62	0.83	3.49	1.61	13.63	14.45	1.98	0.28
Average annual salinity (mg/L)	1324	1490	994	1228	15	339	1118	780	665	305	186
Groundwater discharge to stream zone (mm)	4.18	10.59	17.80	4.18	2.71	12.61	16.39	6.34	6.35	22.94	1.06
Baseflow (mm)	0.88	1.79	2.96	0.88	1.76	9.35	3.32	1.46	1.77	17.46	0.90
Representative year at equlibrium [c]											
Annual rainfall (mm)	702.54	706.11	701.31	703.83	792.14	960.89	695.53	845.69	783.99	1056.47	856.16
Streamflow (GL)	1.78	4.76	4.88	11.42	13.44	11.44	1.37	19.15	24.86	7.84	1.35
Average annual salinity (mg/L)	1245	1559	1062	1298	76	306	1206	783	637	257	181
Runoff (mm)	23.03	43.90	85.28	47.00	51.68	71.16	67.48	43.05	49.42	119.91	35.57
Salt load (kt)	2.22	7.42	5.18	14.82	1.02	3.50	1.65	14.99	15.83	2.02	0.24

a annual mean for the period 2015-2025

b annual mean for the period 2047-2057

c annual for 2055 (1991 MAGIC comparison)

Table 10 LUCICAT 1400: additional 1400 ha of plantations in the upper catchment

LUCICAT 1400 - additional 1400ha of upper catchment revegetated.

	Management unit (MU)			Gauging Stations (GS)							
	Perillup MU	**Kompup MU**	**Yate Flat Creek MU**	**Total Upper MU / Kompup GS**	**Lower Recovery MU**	**Scotsdale Brook MU**	**Amarillup Swamp GS**	**Lindesay Gorge GS**	**Mt Lindesay GS**	**Scotsdale Brook GS**	**Powleys GS**
Area (km^2)	77	108	57	243	260	161	20	445	503	65	38
Lake area (km^2)	0	0	0	0	0	0	0	0	0	0	0
Native forest 2006 (km^2)	67	78	27	173	250	132	12	371	423	50	37
Native forest 2006 (%)	87	72	48	71	96	82	59	83	84	76	99
Plantation 2006 (km^2)	6	25	27	58	1	0	6	45	60	0	0
Plantation 2006 (%)	8	23	47	24	0	0	30	10	12	0	0
Cleared area 2006 (km^2)	4	5	3	12	4	8	2	27	16	2	0
Cleared area 2006 (%)	5	5	5	5	2	5	11	6	3	3	0
Other land use 2006 (km^2) [d]	0	0	0	0	4	21	0	2	4	14	0
Other land use 2006 (%)	0	0	0	0	2	13	0	0	1	21	1
Average for 2020 [a]											
Annual rainfall (mm)	710	725	738	723	816	971	734	875	807	1055	889
Streamflow (GL)	0.94	0.84	0.87	2.64	13.55	11.72	0.30	10.91	16.19	7.12	1.81
Runoff (mm)	12.12	7.74	15.15	10.88	52.07	72.90	14.58	24.53	32.18	109.01	47.69
Salt load (kt)	0.81	0.79	0.56	2.16	1.78	4.44	0.23	2.87	3.94	2.60	0.32
Salinity (mg/L)	1222	1664	1048	1244	145	454	1223	310	288	433	216
Groundwater discharge to stream zone (mm)	1.02	0.58	0.25	1.02	2.29	11.77	0.70	0.76	1.49	21.37	1.01
Baseflow (mm)	0.15	0.29	0.38	0.15	1.68	8.54	1.05	0.56	1.00	15.66	0.88
Average for 2050 [b]											
Annual rainfall (mm)	710	725	738	723	816	971	734	875	807	1055	889
Streamflow (GL)	0.94	0.80	0.77	2.50	13.51	11.70	0.25	10.75	16.01	0.00	1.81
Runoff (mm)	12.10	7.34	13.49	10.30	51.93	72.73	12.23	24.16	31.83	108.80	47.65
Salt load (kt)	0.76	0.45	0.22	1.43	1.80	3.45	0.12	2.37	3.24	1.88	0.28
Average annual salinity (mg/L)	1153	802	401	847	153	350	680	252	232	309	187
Groundwater discharge to stream zone (mm)	0.98	0.57	0.56	0.98	2.13	12.34	1.21	0.79	1.44	22.26	1.06
Baseflow (mm)	0.15	0.29	0.67	0.15	1.64	9.08	1.40	0.60	1.01	16.81	0.90
Representative year at equlibrium [c]											
Annual rainfall (mm)	702.54	706.11	701.31	703.83	792.14	960.89	695.53	845.69	783.99	1056.47	856.16
Streamflow (GL)	0.94	0.47	0.36	1.77	13.50	10.95	0.14	9.45	15.27	7.34	1.33
Average annual salinity (mg/L)	949	865	429	820	130	318	640	244	210	265	183
Runoff (mm)	12.11	4.38	6.33	7.30	51.89	68.09	6.90	21.25	30.36	112.26	35.13
Salt load (kt)	0.89	0.41	0.16	1.45	1.75	3.49	0.09	2.31	3.20	1.95	0.24

a annual mean for the period 2015-2025

b annual mean for the period 2047-2057

c annual for 2055 (1991 MAGIC comparison)

d includes biodiversity plantings, vineyards, horticulture and green pastures

Table 11 LUCICAT: all cleared land to native vegetation (no harvesting)

LUCICAT - pasture to native vegetation allowing vegetation to mature with no harvesting.

	Management unit (MU)						**Gauging Stations (GS)**				
	Perillup MU	**Kompup MU**	**Yate Flat Creek MU**	**Total Upper MU / Kompup GS**	**Lower Recovery MU**	**Scotsdale Brook MU**	**Amarillup Swamp GS**	**Lindesay Gorge GS**	**Mt Lindesay GS**	**Scotsdale Brook GS**	**Powleys GS**
Area (km^2)	77	108	57	243	260	161	20	445	503	65	38
Lake area (km^2)	0	0	0	0	0	0	0	0	0	0	0
Native forest 2006 (km^2)	71	93	35	199	259	161	14	400	457	65	38
Native forest 2006 (%)	92	86	61	82	100	100	70	90	91	100	100
Plantation 2006 (km^2)	6	16	22	44	1	0	6	45	46	0	0
Plantation 2006 (%)	8	14	39	18	0	0	30	10	9	0	0
Cleared area 2006 (km^2)	0	0	0	0	0	0	0	0	0	0	0
Cleared area 2006 (%)	0	0	0	0	0	0	0	0	0	0	0
Other land use 2006 (km^2) [a]	0	0	0	0	4	21	0	2	4	14	0.40
Other land use 2006 (%)	0	0	0	0	0	0	0	0	0	0	0
Average for 2020 [b]											
Annual rainfall (mm)	710	725	738	723	816	971	734	875	807	1055	889
Streamflow (GL)	0.89	0.69	0.58	2.16	13.53	11.72	0.17	10.41	15.69	7.12	1.81
Runoff (mm)	11.51	6.35	10.17	8.89	52.01	72.91	8.62	23.41	31.19	109.01	47.69
Salt load (kt)	0.73	0.19	0.17	1.09	2.03	4.44	0.07	2.04	3.12	2.60	0.32
Salinity (mg/L) [c]	1184	-1327	459	811	177	455	638	224	235	433	216
Groundwater discharge to stream zone (mm)	0.91	0.00	0.01	0.91	2.24	11.77	0.01	0.54	1.30	21.37	1.01
Baseflow (mm)	0.14	0.00	0.00	0.14	1.63	8.53	0.00	0.41	0.86	15.66	0.88
Average for 2050 [d]											
Annual rainfall (mm)	710	725	738	723	816	971	734	875	807	1055	889
Streamflow (GL)	0.89	0.67	0.55	2.11	13.48	11.70	0.16	10.31	15.58	0.00	1.81
Runoff (mm)	11.48	6.15	9.65	8.67	51.80	72.73	7.82	23.19	30.98	108.80	47.65
Salt load (kt)	0.68	0.20	0.14	1.02	1.86	3.45	0.05	2.02	2.88	1.88	0.28
Average annual salinity (mg/L)	1114	2539	322	771	161	350	380	223	214	309	187
Groundwater discharge to stream zone (mm)	0.87	0.00	0.01	0.87	2.07	12.33	0.01	0.53	1.21	22.26	1.06
Baseflow (mm)	0.14	0.00	0.00	0.14	1.56	9.09	0.00	0.40	0.83	16.81	0.90
Representative year at equlibrium [e]											
Annual rainfall (mm)	702.54	706.11	701.31	703.83	792.14	960.89	695.53	845.69	783.99	1056.47	856.16
Streamflow (GL)	0.88	0.46	0.28	1.62	13.45	10.95	0.09	9.25	15.07	7.34	1.33
Average annual salinity (mg/L)	897	370	348	653	134	319	390	213	190	265	183
Runoff (mm)	11.41	4.24	4.85	6.67	51.71	68.09	4.41	20.80	29.96	112.26	35.13
Salt load (kt)	0.79	0.00	0.10	1.06	1.81	3.49	0.03	1.97	2.87	1.95	0.24

a includes biodiversity plantings, vineyards, horticulture and green pastures

b annual mean for the period 2015-2025

c negative salinity levels in modelling is due to loss of salt between Yate Flat Creek and Kompup gauging station

d annual mean for the period 2047-2057

e annual for 2055 (1991 MAGIC comparison)

Table 12 LUCICAT: all cleared land to plantations with 10 year rotation

LUCICAT - all cleared land to plantations with 10 year harvest rotation.

	Management unit (MU)		Gauging Stations (GS)								
	Perillup MU	Kompup MU	Yate Flat Creek MU	Total Upper MU / Kompup GS	Lower Recovery MU	Scotsdale Brook MU	Amarillup Swamp GS	Lindesay Gorge GS	Mt Lindesay GS	Scotsdale Brook GS	Powleys GS
Area (km^2)	77	108	57	243	260	161	20	445	503	65	38
Lake area (km^2)	0	0	0	0	0	0	0	0	0	0	0
Native forest 2006 (km^2)	67	78	27	173	250	132	12	371	423	50	37
Native forest 2006 (%)	87	72	48	71	96	82	59	83	84	76	99
Plantation 2006 (km^2)	10	30	30	70	1	0	6	45	46	0	0
Plantation 2006 (%)	13	28	52	29	0	0	30	10	9	0	0
Cleared area 2006 (km^2)	0	0	0	0	0	0	0	0	0	0	0
Cleared area 2006 (%)	0	0	0	0	0	0	0	0	0	0	0
Other land use 2006 (km^2) [a]	0	0	0	0	4	21	0	2	4	14	0
Other land use 2006 (%)	0	0	0	0	0	0	0	0	0	0	0
Average for 2020 [b]											
Annual rainfall (mm)	710	725	738	723	816	971	734	875	807	1055	889
Streamflow (GL)	0.56	0.66	0.58	1.81	12.98	9.97	0.19	10.20	14.79	6.12	1.75
Runoff (mm)	7.30	6.12	10.22	7.46	49.90	62.00	9.42	22.94	29.41	93.58	46.13
Salt load (kt)	0.18	0.30	0.27	0.75	1.77	3.19	0.13	1.86	2.52	1.96	0.26
Salinity (mg/L)	414	635	804	657	156	371	1195	206	193	366	172
Groundwater discharge to stream zone (mm)	0.00	0.00	0.02	0.00	1.38	8.44	0.05	0.39	0.72	17.20	0.23
Baseflow (mm)	0.00	0.00	0.02	0.00	1.33	6.56	0.04	0.39	0.69	12.85	0.66
Average for 2050 [c]											
Annual rainfall (mm)	710	725	738	723	816	971	734	875	807	1055	889
Streamflow (GL)	0.59	0.69	0.58	1.87	13.04	10.18	0.17	10.25	14.91	0.00	1.75
Runoff (mm)	7.61	6.39	10.22	7.68	50.13	63.29	8.29	23.04	29.63	96.31	46.23
Salt load (kt)	0.19	0.23	0.14	0.55	1.79	2.62	0.05	1.76	2.34	1.62	0.25
Average annual salinity (mg/L) [d]	443	-247	325	376	166	313	388	195	183	306	171
Groundwater discharge to stream zone (mm)	0.00	0.00	0.05	0.00	1.21	8.40	0.13	0.38	0.63	16.87	0.26
Baseflow (mm)	0.00	0.00	0.07	0.00	1.25	6.83	0.20	0.38	0.66	13.32	0.68
Representative year at equlibrium [e]											
Annual rainfall (mm)	702.54	706.11	701.31	703.83	792.14	960.89	695.53	845.69	783.99	1056.47	856.16
Streamflow (GL)	0.50	0.39	0.25	1.13	12.54	7.62	0.08	8.89	13.67	4.99	1.26
Average annual salinity (mg/L)	373	430	373	392	129	249	426	175	151	226	160
Runoff (mm)	6.46	3.55	4.34	4.66	48.19	47.36	4.06	19.97	27.18	76.40	33.08
Salt load (kt)	0.19	0.17	0.09	0.44	1.62	1.90	0.04	1.56	2.06	1.13	0.20

a includes biodiversity plantings, vineyards, horticulture and green pastures
b annual mean for the period 2015-2025
c annual mean for the period 2047-2057
d negative salinity levels in modelling is due to loss of salt between Yate Flat Creek and Kompup gauging station.
e annual for 2055 (1991 MAGIC comparison)

In Tables 11 and 12 the conceptual groundwater levels below the planted areas fall substantially over time, resulting in large reductions in groundwater discharge and therefore baseflow to the stream zone. Beneath native forest the groundwater level was essentially stable for the whole simulation period. In terms of within-year variations, the peak flow, recession and flow duration all reduced.

Relationships between clearing and salinity, salt load and streamflow

The scenario modelling allowed for the analysis of the specific relationships between cleared area and streamflow, salt load and salinity in the Denmark River. Projections for 2015–25 show that mean annual salinity (Fig. 14), mean annual salt load (Fig. 15), and mean annual flow (Fig. 16) are proportional to the cleared area to the Mt Lindesay gauging station.

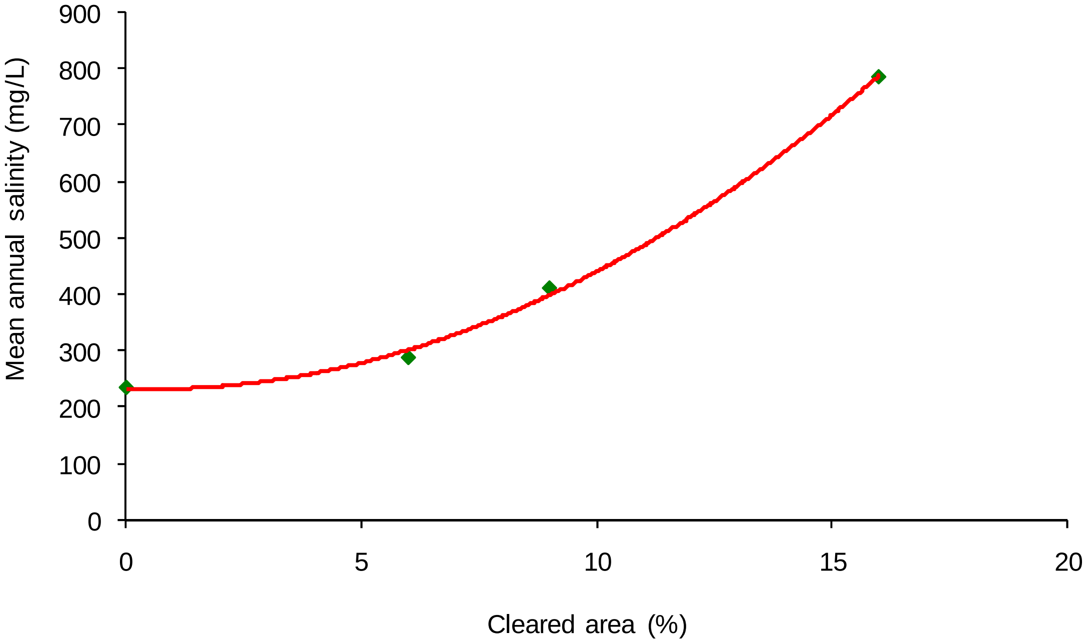


Figure 14 Mean salinity versus cleared area

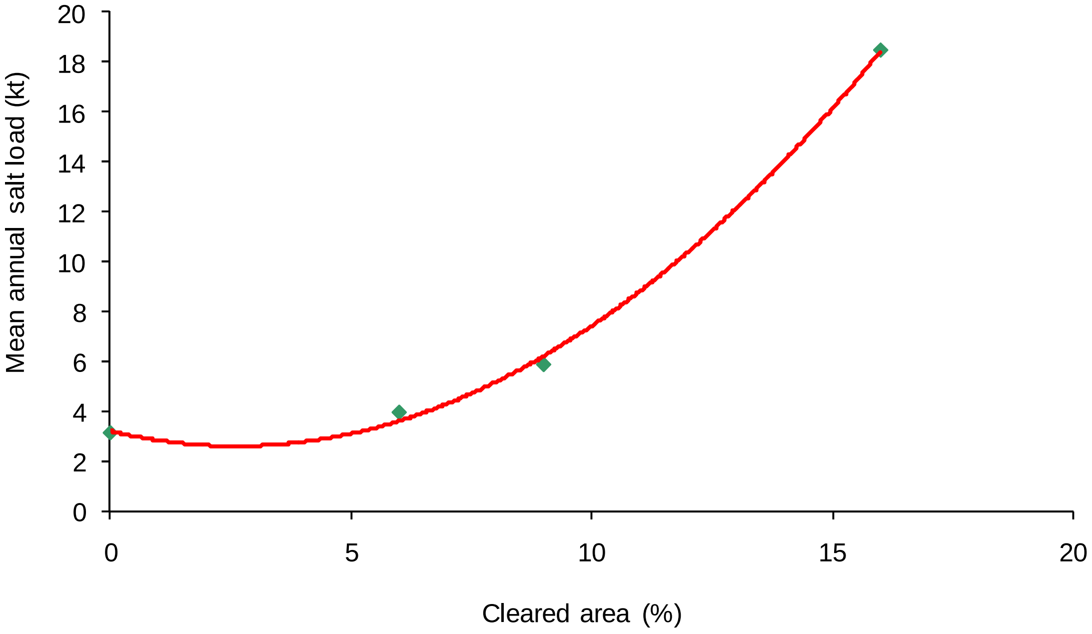


Figure 15 Mean salt load versus cleared area

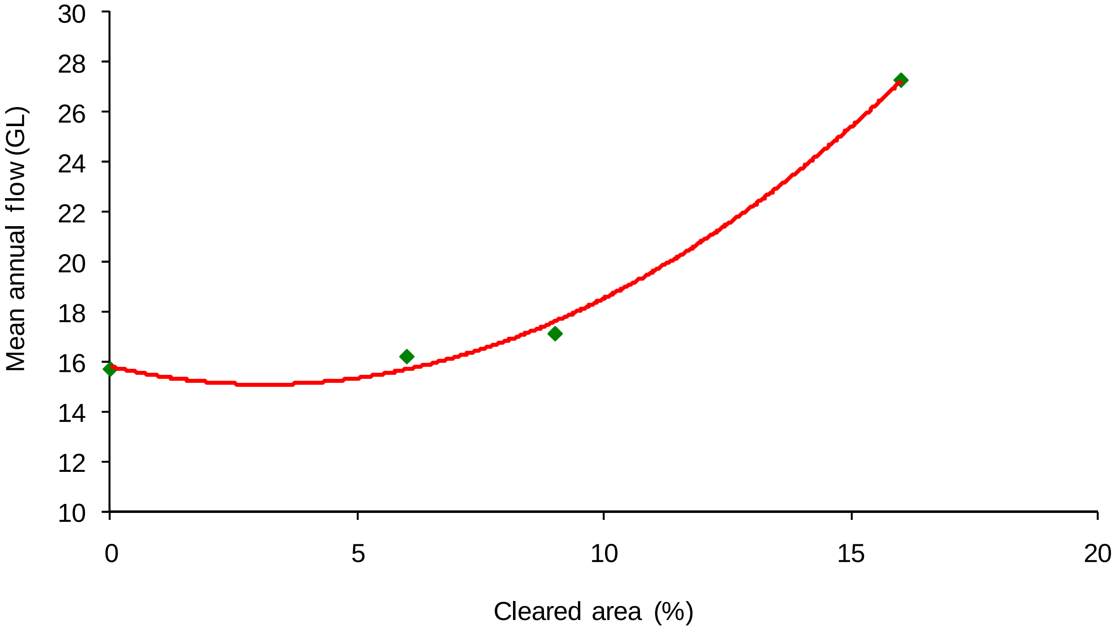


Figure 16 Mean streamflow versus cleared area

Summary of LUCICAT modelling results for multiple LAI values

Leaf area index is the ratio of the single-sided area of leaves on plants to the area occupied by those plants. It is used as a proxy for water use by plants through evapotranspiration; i.e. a forest with a thick canopy will generally use more water than a forest with a sparse canopy. Also, a denser canopy will intercept more precipitation and catch and hold more water on vegetation and subsequently evaporate more without it reaching the ground (Bari et al. 2004).

In assessing the reliability of the LUCICAT model, the maximum LAI value of 2.5 initially used may be too high. The base case scenarios were rerun with lower maximum LAI values (2.0 and 2.2) for blue gum plantations. The results for the Mt Lindesay gauging station are presented in Figure 17 and results for all the gauging stations and management units in Tables 13 and 14.

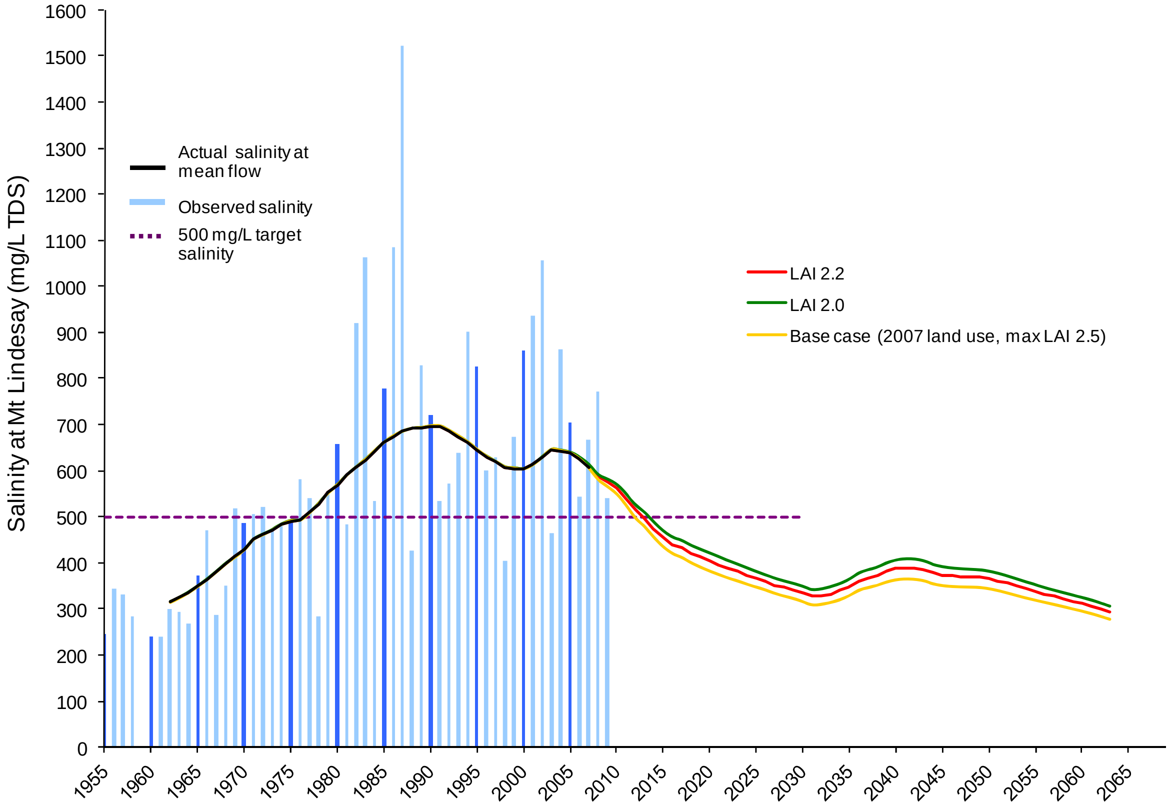


Figure 17 Base case modelled salinity using various maximum LAI values

Table 13 LUCICAT base case: LAI 2.2 allowing all plantations to mature

LUCICAT base case - 2006 land use allowing all plantations to be mature with a maximum LAI of 2.2.

	Management unit (MU)				**Gauging Stations (GS)**						
	Perillup MU	**Kompup MU**	**Yate Flat Creek MU**	**Total Upper MU / Kompup GS**	**Lower Recovery MU**	**Scotsdale Brook MU**	**Amarillup Swamp GS**	**Lindesay Gorge GS**	**Mt Lindesay GS**	**Scotsdale Brook GS**	**Powleys GS**
Area (km^2)	77	108	57	243	260	161	20	445	503	65	38
Lake area (km^2)	0	0	0	0	0	0	0	0	0	0	0
Native forest 2006 (km^2)	67	78	27	173	250	132	12	371	423	50	37
Native forest 2006 (%)	87	72	48	71	96	82	59	83	84	76	99
Plantation 2006 (km^2)	6	16	22	44	1	0	6	45	46	0	0
Plantation 2006 (%)	8	14	39	18	0	0	30	10	9	0	0
Cleared area 2006 (km^2)	4	14	8	26	5	8	2	27	30	3	0
Cleared area 2006 (%)	5	13	14	11	2	5	11	6	6	4	0
Other land use 2006 (km^2) [a]	0	0	0	0	4	21	0	2	4	14	0
Other land use 2006 (%)	0	0	0	0	2	13	0	0	1	21	1
Average for 2020 [b]											
Annual rainfall (mm)	710	725	738	723	816	971	734	875	807	1055	889
Streamflow (GL)	0.95	1.99	1.07	4.00	13.37	11.72	0.33	12.10	17.38	7.12	1.81
Runoff (mm)	12.32	18.32	18.64	16.49	51.40	72.89	16.31	27.20	34.54	109.01	47.69
Salt load (kt)	0.82	3.39	0.80	5.01	1.24	4.41	0.28	5.20	6.24	2.60	0.32
Salinity (mg/L)	1216	2078	1151	1646	78	451	1267	530	434	433	216
Groundwater discharge to stream zone (mm)	1.04	4.09	1.02	1.04	2.30	11.76	1.25	1.73	2.34	21.37	1.01
Baseflow (mm)	0.15	0.94	1.16	0.15	1.69	8.53	1.46	0.82	1.23	15.66	0.88
Average for 2050 [c]											
Annual rainfall (mm)	710	725	738	723	816	971	734	875	807	1055	889
Streamflow (GL)	0.95	1.97	0.97	3.89	13.31	11.69	0.29	11.93	17.20	0.00	1.81
Runoff (mm)	12.28	18.17	16.96	16.02	51.15	72.71	14.22	26.82	34.19	108.80	47.65
Salt load (kt)	0.77	3.10	0.43	4.30	1.16	3.42	0.18	4.61	5.45	1.88	0.28
Average annual salinity (mg/L)	1146	1881	676	1440	70	347	911	479	382	309	187
Groundwater discharge to stream zone (mm)	0.99	3.98	1.52	0.99	2.14	12.33	1.81	1.75	2.29	22.26	1.06
Baseflow (mm)	0.15	0.94	1.44	0.15	1.64	9.08	1.70	0.86	1.24	16.81	0.90
Representative year at equlibrium [d]											
Annual rainfall (mm)	702.54	706.11	701.31	703.83	792.14	960.89	695.53	845.69	783.99	1056.47	856.16
Streamflow (GL)	0.95	1.84	0.47	3.27	13.26	10.93	0.16	10.71	16.52	7.34	1.33
Average annual salinity (mg/L)	945	1915	633	1447	83	315	895	463	352	265	183
Runoff (mm)	12.29	17.00	8.28	13.45	50.95	68.00	8.02	24.08	32.84	112.26	35.13
Salt load (kt)	0.90	3.53	0.30	4.73	1.10	3.45	0.15	4.96	5.82	1.95	0.24

a includes biodiversity plantings, vineyards, horticulture and green pastures

b annual mean for the period 2015-2025

c annual mean for the period 2047-2057

d annual for 2055 (1991 MAGIC comparison)

Table 14 LUCICAT base case: LAI 2.0 allowing all plantations to mature

LUCICAT base case - 2006 land use allowing all plantations to be mature with maximum of LAI 2.0.

	Management unit (MU)						Gauging Stations (GS)				
	Perillup MU	**Kompup MU**	**Yate Flat Creek MU**	**Total Upper MU / Kompup GS**	**Lower Recovery MU**	**Scotsdale Brook MU**	**Amarillup Swamp GS**	**Lindesay Gorge GS**	**Mt Lindesay GS**	**Scotsdale Brook GS**	**Powleys GS**
Area (km^2)	77	108	57	243	260	161	20	445	503	65	38
Lake area (km^2)	0	0	0	0	0	0	0	0	0	0	0
Native forest 2006 (km^2)	67	78	27	173	250	132	12	371	423	50	37
Native forest 2006 (%)	87	72	48	71	96	82	59	83	84	76	99
Plantation 2006 (km^2)	6	16	22	44	1	0	6	45	46	0	0
Plantation 2006 (%)	8	14	39	18	0	0	30	10	9	0	0
Cleared area 2006 (km^2)	4	14	8	26	5	8	2	27	30	3	0
Cleared area 2006 (%)	5	13	14	11	2	5	11	6	6	4	0
Other land use 2006 (km^2) [a]	0	0	0	0	4	21	0	2	4	14	0
Other land use 2006 (%)	0	0	0	0	2	13	0	0	1	21	1
Average for 2020 [b]											
Annual rainfall (mm)	710	725	738	723	816	971	734	875	807	1055	889
Streamflow (GL)	0.96	2.08	1.17	4.21	13.36	11.72	0.36	12.30	17.57	7.12	1.81
Runoff (mm)	12.47	19.19	20.46	17.35	51.34	72.88	17.59	27.64	34.93	109.01	47.69
Salt load (kt)	0.83	3.56	0.95	5.33	1.20	4.41	0.32	5.48	6.53	2.60	0.32
Salinity (mg/L)	1210	2069	1186	1643	73	451	1291	552	450	433	216
Groundwater discharge to stream zone (mm)	1.04	4.30	1.47	1.04	2.30	11.76	1.62	1.84	2.44	21.37	1.01
Baseflow (mm)	0.15	0.97	1.45	0.15	1.70	8.52	1.65	0.87	1.28	15.66	0.88
Average for 2050 [c]											
Annual rainfall (mm)	710	725	738	723	816	971	734	875	807	1055	889
Streamflow (GL)	0.96	2.07	1.09	4.12	13.29	11.69	0.31	12.14	17.41	0.00	1.81
Runoff (mm)	12.42	19.12	18.99	16.96	51.08	72.71	15.47	27.30	34.61	108.80	47.65
Salt load (kt)	0.77	3.24	0.58	4.59	1.12	3.42	0.22	4.87	5.71	1.88	0.28
Average annual salinity (mg/L)	1139	1848	801	1437	64	346	1049	499	397	309	187
Groundwater discharge to stream zone (mm)	1.00	4.20	2.01	1.00	2.14	12.34	2.24	1.87	2.39	22.26	1.06
Baseflow (mm)	0.15	0.97	1.63	0.15	1.65	9.08	1.83	0.90	1.27	16.81	0.90
Representative year at equlibrium [d]											
Annual rainfall (mm)	702.54	706.11	701.31	703.83	792.14	960.89	695.53	845.69	783.99	1056.47	856.16
Streamflow (GL)	0.96	1.94	0.54	3.45	13.24	10.93	0.18	10.87	16.68	7.34	1.33
Average annual salinity (mg/L)	942	1897	812	1459	80	315	1066	480	365	265	183
Runoff (mm)	12.40	17.91	9.53	14.19	50.88	68.00	9.08	24.44	33.16	112.26	35.13
Salt load (kt)	0.90	3.68	0.44	5.03	1.06	3.45	0.20	5.22	6.09	1.95	0.24

a includes biodiversity plantings, vineyards, horticulture and green pastures

b annual mean for the period 2015-2025

c annual mean for the period 2047-2057

d annual for 2055 (1991 MAGIC comparison)

Appendix C Climate-change modelling

To try to quantify the projected effects of climate change on streamflow, three scenarios from the IPCC *Special report on emission scenarios*, A1B, A2 and B1, were selected for the Denmark River basin (Smith et al. 2009). These scenarios represent a range of greenhouse gas emissions and atmospheric carbon dioxide levels for 1990–2100 and are related to different levels of global warming. The A2 scenario represents a worst-case situation in terms of greenhouse gas emissions and the B1 scenario represents a more desirable emissions outcome, with scenario A1B somewhere in between (IPCC 2000).

Regional atmospheric predictors for 1971 to 2100 from global circulation models (Mark 3.5, CCAM global climate model, CSIRO) were statistically down-scaled to multi-site daily rainfall for the Denmark region. By the end of the 21st century rainfall in the Denmark River basin is projected to fall by around 2% under the B1 scenario (Table 15) and by around 8% under the A2 scenario (Table 15). There were some differences of within-year distributions between the observed and projected rainfalls for 1990–2006 (Fig. 18) when the model was run to assess calibration.

Table 15 Mean annual observed and projected rainfall

	Observed rainfall (mm)	A2 rainfall (mm)	A2 change (%)	A1B rainfall (mm)	A1B change (%)	B1 rainfall (mm)	B1 change (%)
1975–2006	826.0	775.8	0.0	777.0	0.0	779.6	0.0
2014–2045	-	751.7	–3.1	759.9	–2.2	760.4	–2.5
2068–2099	-	715.1	–7.8	722.8	–7.0	763.4	–2.1

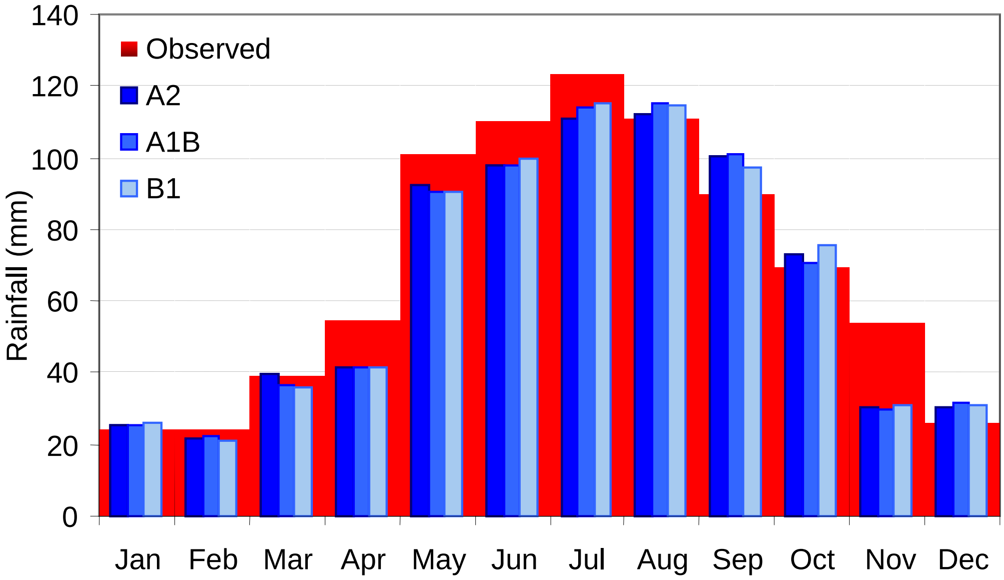


Figure 18 Observed and predicted mean monthly rainfall (1990–2006)

The calibrated LUCICAT model used the down-scaled rainfall projections to estimate the changes in runoff for current and projected climates. Runoff at the Mt Lindesay gauging station could decline by up to 34% from the 1975–2006 average by the end of the century, depending on the scenario used (Bari 2008; Table 16).

Table 16 Mean observed and projected runoff at Mt Lindesay for the A2, A1B & B1 scenarios

	Observed (mm)	A2 (mm)	A2 change (from present) %	A1B (mm)	A1B change from present) (%)	B1 (mm)	B1 change (from present) (%)
1975–2006	50.4	38.5	-	39.4	-	39.6	-
1975–2006 (adjusted for land-use change)	35.5	27.6	-	28.3	-	28.4	-
2014–2045	-	23.4	–15.1	25.0	–11.8	25.2	–11.5
2068–2099	-	18.3	–33.8	18.9	–33.5	25.6	–9.8

With significant differences between observed and projected data for 1975–2006, there is significant uncertainty in projecting within-year streamflow (Fig. 19). Within-year distributions of streamflow are also likely to change under all three emissions scenarios, with the largest reductions projected for early winter (Fig. 20).

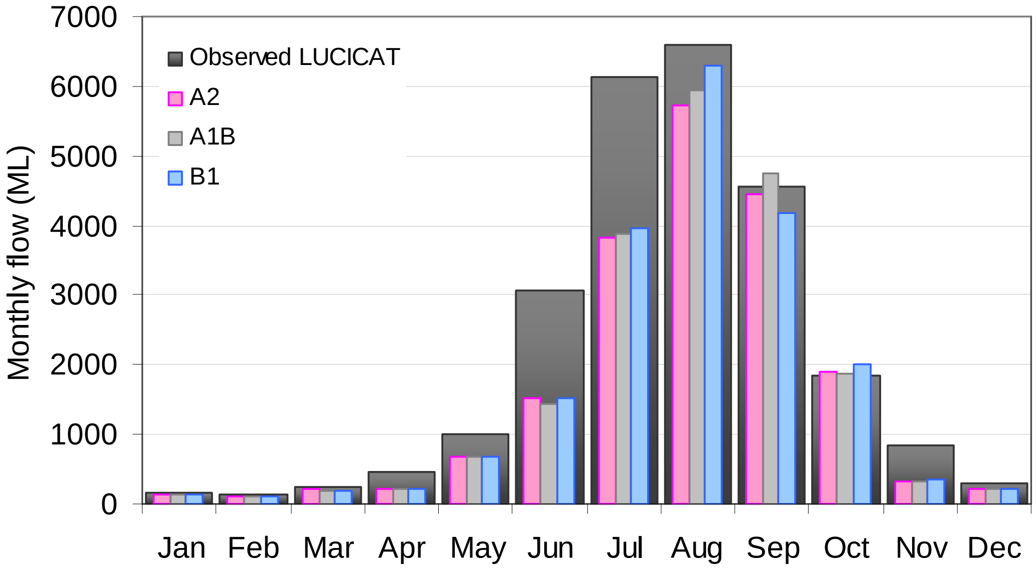
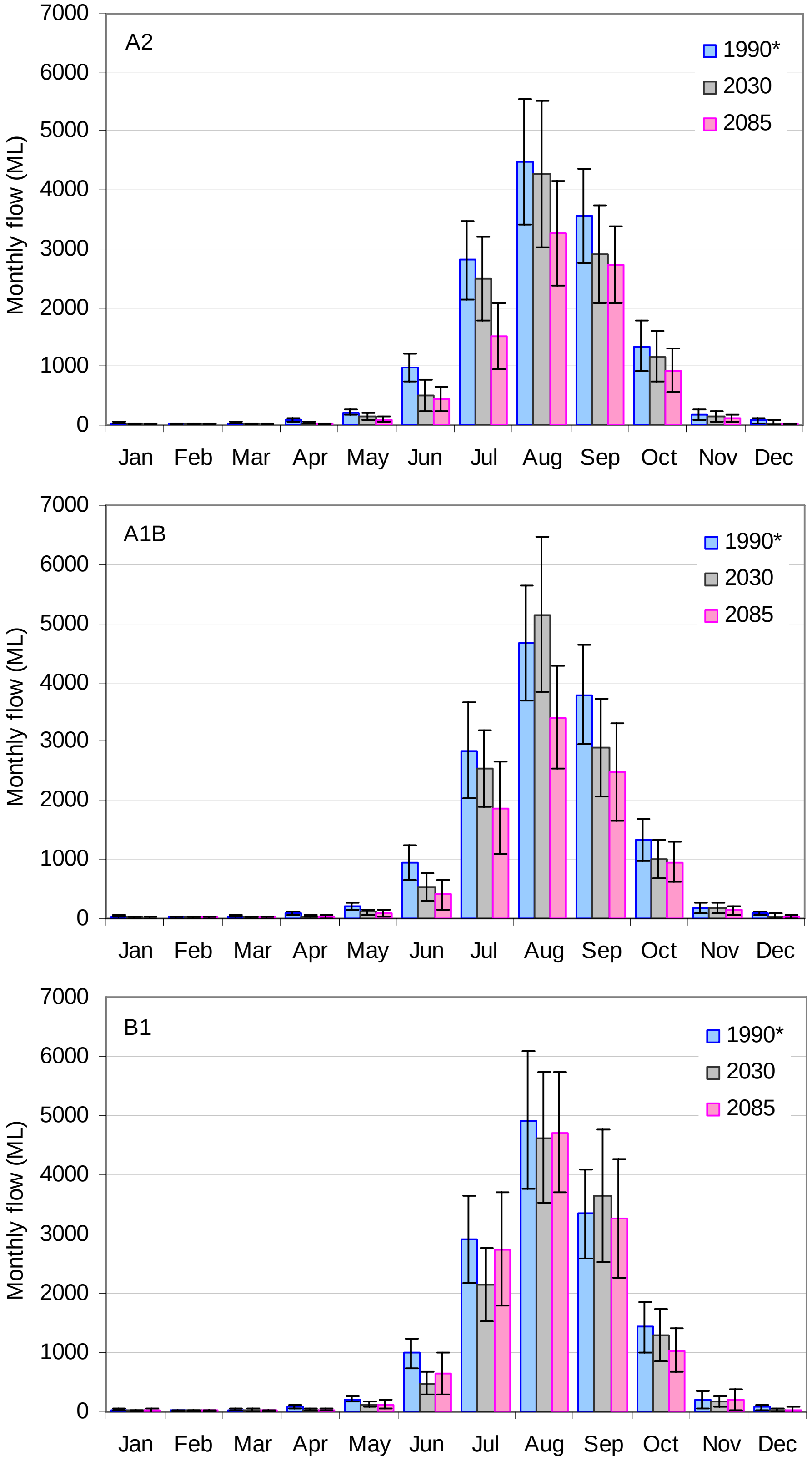


Figure 19 Mean monthly modelled streamflow at Mt Lindesay for 1975–2006



*1990 values have been adjusted to account for changes due to land use

Figure 20 *Modelled mean monthly streamflow at Mt Lindesay for the A2, A1B and B1 scenarios*

Appendix D Evaluation of management options

Following a process developed by the Department of Water, a cost-benefit analysis of nominated options for salinity reduction was done and the likely social and environmental impacts of each were discussed, based on the projections given by the MAGIC model (URS 2006). They included a range of options identified by Plantall (2006) for implementing land-use changes to forestry. An updated report was produced in 2007 (URS 2007a), which also revised the economic analyses and included an analysis of the value of CO_2 sequestration and emissions for plantations. A summary of the URS report forms this section.

Economic analysis

The costs of implementing these land-use change and engineering management options were compared. Table 17 presents estimated costs of the options modelled by MAGIC (Section 2.3; Table 4), using various incentives to establish tree plantations. These are compared to the 'do nothing' management option which is estimated to have mean flow-weighted salinity ultimately stabilising at ~570 mg/L. As some land-use change options have the potential to earn incomes (i.e. from the sale of harvested trees and carbon credits) net costs over 20 years have been estimated to account for future income as well. The management options compared were:

- Use the saline water as is – 'do nothing option'.
- Government purchases 900 ha of land and establishes managed plantations – 'government plantations option'.
- Government purchases 900 ha of land and leases it to forestry companies – 'government plantation – leased option'.
- Government purchases 900 ha of land, imposes a caveat, then sells the land – 'caveat and sell option'.
- Government leases 900 ha of land from farmers then subleases it to forestry companies – 'government lease and sublease option'.
- Government pays the Forest Products Commission to increase incentives for 1375 ha of plantations in the catchment – 'FPC incentives option'.
- Government pays incentives directly to landholders to encourage the establishment of 1375 ha of plantations – 'incentives to landholders option'.
- 2948 ha of perennial pastures established via an incentive scheme – 'perennial pastures option'.
- Extraction of groundwater either in the north or south-east of the catchment using 58 pumps, and disposal outside the catchment – 'groundwater pumping option'.
- Diversion of 6 GL of the most saline flows around the Mt Lindesay gauging station and the potential dam site at Mt Lindesay – 'diversion option'.
- Desalination of river water as a substitute for land-use change – 'desalination option'.

The forestry options considered were:

- Establish 900 ha of plantations in the most strategic areas (i.e. where the salinity target can be achieved with the smallest area) in Kompup.

- Establish 1375 ha of plantations across the upper catchment, in areas where there has been the most interest expressed by landholders in establishing plantations (URS 2007a).

Along with the option of using the water at current salinity, the options of desalination and importing potable water from outside the catchment provide benchmark comparisons.

Table 17 Summary of scenario costs modelled by MAGIC

	Do nothing (use saline)	Govt plantations	Govt plantation-leased	Caveat & sell	Govt lease & sub-lease	FPC incentives	Incentives to landholders	Perennial pastures	Ground-water pumping	Diversion	Desal
MAGIC outputs[1]											
Salinity — Mt Lindesay (mg/L)	570	500	500	500	500	500	500	500	500	500	570
Streamflow (GL/yr)	21.9	–1.1	–1.1	–1.1	–1.1	–1.6	–1.6	–1.4	–0.4	–6.0	0.0
Total salt load (kt/year)	12.4	–2.1	–2.1	–2.1	–2.1	–2.3	–2.3	–2.2	–1.7	-	-
Area of land use change (ha)	-	900	900	900	902	1375	1375	2950	-	-	-
Implementation issues											
Ease of staged implementation	-	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No
Timescale for full benefits (Quick=<5 yr; Med=5–15 yr; Slow=>15 yrs.	-	Slow	Slow	Slow	Slow	Slow	Slow	Slow	Med	Quick	Quick
Mean Yield — 75% of flow (GL/yr)	16.4	15.6	15.6	15.6	15.6	15.2	15.2	15.4	16.1	11.9	16.4
Costs											
Capital & operating ($m)	-	-	-	-	-	-	-	-	16–23	8–14	60–90
Damages ($m)	17.4–20.9	-	-	-	-	-	-	-	-	-	-
Upfront land-use change ($m)	-	6.6–12.5	5.2–11	5.2–11	4–6.1	0.7–2.4	0.7–2.3	1.9–3.3	-	-	-
Costs c/kL[2] (excl future revenues)	5.3–6.4	2.1–4	1.7–3.5	1.7–3.5	1.3–2	0.2–0.8	0.2–0.8	0.6–1.1	5–7.1	3.4–5.9	35–50
Potential revenues[3]	-	7.2–10	3.1–5.1	3.8–6.8	3.1–5.1	-	-	-	-	-	-
Net costs ($m)	17.4–20.9	-0.6–2.5	2.1–5.9	1.4–4.2	0.9–1	0.7–2.4	0.7–2.3	1.9–3.3	16–23	8–14	60–90
CO_2e benefits ($m)	0.0	1.3–1.8	1.3–1.8	1.3–1.8	1.3–1.8	2–2.7	2–2.7	0.0	–0.7	–0.2	–10.0
Net costs inclusive of CO_2e benefits ($m)	17.4–20.9	–1.9–0.7	0.8–4.1	0.1–2.4	–0.4–0.8	–1.3–0.3	–1.3–0.4	1.9–3.3	16.7–23.7	8.2–14.2	70–100

[1] URS 2007a from Table 4 Section 3.2

[2] cents per kilolitre

[3] monies gained from the sale or lease of property or products

Social and environmental impacts

The social impacts considered (associated with land-use changes from traditional agricultural enterprises to plantation forestry) were changes in local population, business activity, regional employment and the availability of services such as health and education. The Bureau of Rural Sciences (BRS 2005) suggests that plantation expansion in the Great Southern Region of Western Australia has not been associated with any increased rates of rural population decline. Now that plantations are coming into harvesting cycles there has been a major increase in employment within the plantation sector, and two-thirds of that was located locally in the Great Southern region. In fact, where plantation expansion occurs as part of a mix of land-use changes, it can increase rural populations, especially where there are processing industries associated with the plantations. The likely social impacts of the other options were assumed to be minimal. Potential environmental issues associated with the various options were evaluated (Table 18).

Table 18 Assessment of potential environmental issues of the management options

Environmental issues	Forestry	Perennial pastures	Groundwater pumping	Diversion	Desalination
Flora and fauna	Some beneficial	No change	Little change	Little impact	Little impact
Wetlands and water-bodies	Some drying probable	Some drying probable	Some drying probable	Increased salinity downstream	No upstream impacts
Water quality	Reduced salinity — some temporary sedimentation with establishment and harvest	Reduced salinity, lower risk of sedimentation during drier months	Reduced salinity in catchment but major issues with disposal outside catchment	Reduced flows and disposal of saline water from diversion will be an important issue	Depends on location and disposal arrangements, potential negative impacts
Change in water quantity (GL)	–1.1 to –1.6[1]	–1.2	–0.4	–6.0	No effect upstream of desalination
Weeds and feral animals	Increased risk	No change	Some increased risk	Some increased risk	Localised effect only
Physical impacts	Impact on soil increasing erosion risk at establishment and harvest	Reduced soil erosion, particularly in the drier months	Some disturbance during drilling and installation of bores and equipment	Localised disturbance at site of diversion and pipeline	Localised disturbance at site of diversion and pipeline
Greenhouse implications	Substantial CO_2 sequestration	Some CO_2 sequestration	Some CO_2 emissions	Some CO_2 emissions	Large amounts of CO_2 emissions
Fire risk	Conflicting data[2]	Minimal change	No change	No change	Little effect

[1] Depending on whether the 900 ha of plantations are established in the most strategic areas or the 1375 ha in the most likely areas

[2] While the URS report says that forestry is likely to increase the risks of fires, some reports and anecdotal evidence suggest that plantations may actually dampen fire.

Evaluation of MAGIC options

Economic appraisal

A benefit-cost approach requires a comparison between ‘with option’ and ‘without option’ actions. The difference between the two outcomes is then an economic measure of net benefit that encompasses any change in benefit and differences in cost. Assuming that current market forces are maintained, it is anticipated that some land-use changes will occur even without the need for incentives. The advantage of using incentives is an acceleration of any benefit. Plantall (2006) provides a comparative cost analysis and an overview of strengths, weakness, and business risks associated with each of the forestry options.

The benefits of the options, with the exception of the 'do nothing' options, are the provision of the required quantity of potable water. For the 'do nothing' option the benefit is that nothing has to be done. The evaluations are summarised below and in Table 17.

Do nothing — use the water at the current salinity

One option is to use water at its current projected salinity of 570 mg/L. If this option was taken, the costs of achieving the salinity target would be avoided and shifted onto urban and industrial consumers of saline water in the form of damage costs. Thomas (2001) developed an estimated cost that can be used to calculate the marginal cost of consuming blended water with an elevated salinity.

The assumed cost range that has been used for this analysis is 5.3–6.4 cents per kL, with a cost of $17.4–20.9 million if 16.4 GL were used (URS 2007a).

Government-owned and managed plantations

This option consists of the government acquiring 900 ha of land in the most strategic areas for salinity mitigation to establish and operate plantations. This option provides the highest certainty but incurs large upfront costs of $6.6–12.5 million. Most landholders seem open to the notion of leasing or selling if the price is right. Potential revenues from plantations suggest positive net returns for the government but this may take about 20 years to be realised.

Government-owned land leased to forestry companies

This option consists of the government purchasing 900 ha of land and leasing it to forestry companies. Upfront costs for this are estimated to be $5.2–11.0 million, giving a cost per kL of water of 1.7–3.5 cents (URS 2007a). The potential revenue within 20 years is not likely to exceed the upfront costs.

Caveat and sell

In this option the government would buy 900 ha of land, impose a forestry caveat on the land and then sell it. This option also has high upfront costs of $5.2 to $11.0 million but does not have the potential for positive returns in the long run. On the contrary, it is estimated that the government would incur a net cost of $1.4–4.2 million partly as a result of the 15% assumed drop in land values caused by the imposition of the caveat.

Government-lease from landholder and sublease to forestry company

Also involving 900 ha of land, this option is estimated to incur upfront costs of $4–6.1 million, although potential lease revenues from plantations suggest that the net cost over 20 years would be reduced to approximately $1.0 million.

Forestry with government incentives — direct or via the Forest Products Commission

It has been identified that landholders outside the most strategic areas for salinity mitigation would be willing to take up an offer of monetary incentives to convert cleared land to plantations. To achieve this, 1375 ha of plantations would be required to meet salinity targets. Administratively, paying the Forest Products Commission to pay out the incentives is simpler but slightly more expensive. Both options have the lowest upfront costs: $0.7–2.4 million. They also have the advantage of helping to retain existing plantations, albeit at an additional cost. These incentives have an upfront cost per kL of 0.2–0.8 cents.

Deep-rooted perennial pastures

This scenario involves changing farming practices and replacing annual pastures with perennial pastures. The most likely species would be lucerne, which has higher water use than annual pasture.

The cost of establishing lucerne has been estimated in previous studies by URS (2002), and assessed as part of studies for the Warren Recovery Catchment (URS 2007b). Costs include direct establishment costs, a loss of productivity as the pasture develops, and the difference in ongoing productivity or management expenses. Upfront costs have been estimated to be $1.9 to $3.3 million, giving a cost per kL of 0.6–1.1 cents. The large area involved (2950 ha) is seen as a difficulty.

Groundwater pumping

The estimated cost of pumping groundwater and disposing of the saline water outside the catchment, $16–23 million, is based on data previously gathered for the Collie Recovery report (URS 2002), the infrastructure needs estimated in the *Salinity situation statement: Denmark River* (Bari et al. 2004) and costings in the *Salinity investment framework report* (URS 2004). This estimate includes operation and maintenance expenses for 20 years but excludes any salvage value from the equipment after that. This revised report has also estimated disposal costs. The assumption is for a pipeline of sufficient size to deliver 0.5 GL to a point 20 km outside the catchment. This estimate was made without specific design specifications and needs to be recognised as such.

Diversion

A small diversion dam would be constructed upstream from the potential water storage site at Mt Lindesay. Low flow rates of higher salinity water would be diverted into the dam, piped around and downstream of the water supply works and discharged into the river system downstream of Mt Lindesay. This would cost $8–14 million, a cost per kL of 3.4–5.9 cents. About 6 GL would need to be diverted (Bari et al. 2004). The cost to provide such infrastructure has been estimated by comparing against estimated costs for the Collie diversion (URS 2002), which was designed to divert some 15 GL. This estimate was made without specific design specifications and needs to be recognised as such.

Desalination

The specifications for the Perth Seawater Desalination Plant in Kwinana (45 GL output) suggest a cost of $1.17 per kL, using seawater with a salinity of 35 000 mg/L (URS 2006). As a general indication, the cost for treating low salinity water is about a third of the cost of high salinity water (Department of Agriculture, Forestry and Fisheries 2002), which suggests a cost of some 40 cents per kL. This estimate is based on a much larger plant than would be contemplated to either desalinate seawater instead of obtaining water from the Denmark River, or to desalinate water from the Denmark River as a substitute for land-use change. Another estimate suggests operating costs of desalination plants with a capacity of 45 000 kL daily (about the size required for the Denmark storage) and treating water of salinities 2000–3000 mg/L TDS to be 40 cents per kL (Department of Agriculture, Forestry and Fisheries 2002). Costs of 40–50 cents per kL have been assumed for this analysis.

Other water sources

Piping water from alternative sources such as the Great Southern Town Water Supply would require taking water from fully committed resources. Still, it can be used to provide a useful benchmark. An extension of the GSTWS pipe to the Denmark region is estimated to cost in excess of $400 million.

Cost comparisons

Evaluations of these options need to consider their performance against potential budgetary constraints, timeliness, social and environmental values, and potential future benefits such as the value gained from carbon sequestration. For example, an option that may provide a positive net return may have high upfront costs and a long payback period to government and thus require a long-term budget outlay whereas another option may indicate a net cost to government but require lower upfront and total costs.

The options with the lowest upfront costs are either for government to pay the Forest Products Commission to increase incentives or for government to directly pay incentives to landholders. Administratively this might be a relatively simple option that also has little risk. It would also serve to keep existing leased areas in plantation forestry, albeit at an additional cost.

The next cheapest option is to convert annual to perennial pastures, which requires farming practices to change over a large area. The process has not been entirely successful to date. Perennial pasture requires more intensive and ongoing management than annual pasture. The modelled costs only provide an upfront incentive to establish perennial pastures – the mechanism does not provide ongoing incentives to maintain pastures.

The options of groundwater pumping, the diversion at Mt Lindesay and desalination of river water also require ongoing management costs beyond the 20-year budget period. They will continue to incur power costs and will have negative greenhouse effects that will require ‘neutralisation’ by purchasing carbon offsets.

The estimated damage costs of simply consuming the water without treating its salinity are similar to the costs of groundwater pumping. Desalination of river water is by far the most expensive and one of the most difficult options.

Market-driven forestry

From 2007 to 2009 forestry companies showed interest in buying or leasing agricultural land to establish plantations, suggesting that forestry was returning and that the marketplace was driving the establishment of plantations. Consultations with local farmers in 2006 and the forest industry suggested that net returns from farmer operated forestry or from leasing to forestry companies are higher than net returns from grazing enterprises. The potential prices that forestry companies may pay to acquire land reflect the higher returns likely from forestry.

Plantall (2006) estimated the areas of land suitable for forestry across the catchment to be 65% of all properties. Given that the required area to achieve the 500 mg/L target is between 900 and 1375 hectares, a sufficient level of plantation establishment could be achieved in 3 to 5 years. At the time this was in line with the objective to meet the target by 2020, and for all salinity management works to be in place by 2010 to meet the 2020 target. If market forces achieve the desired levels of planting without any intervention then there should be no additional cost to government.

It is important to note that high land prices (2006) may lead to blue gum companies leasing or targeting more affordable land outside the catchment. If the market stagnates or landholders are reluctant to sell or lease there is a risk of not achieving sufficient revegetation by the desired times.

A survey of landholders in the upper catchment has shown that some were interested in leasing or selling their properties to managed investment scheme companies to plant blue gums. Early indications were that there was the required area of land suited to blue gums on the target properties to achieve salinity targets (Section 3.1; Fig. 8) and that in fact, over 1600 ha of plantations had been established. If there was less land suited to blue gums then other species could be established in order to achieve the target area of plantations.

Purchase by government would secure the land required but not address the risk associated with the future retention of other privately owned blue gum plantations. Decisions about growing plantations in the medium to long term would be made by the private companies based on the economics of the day.

Carbon benefits

Timber plantations have the potential to generate additional income by selling carbon credits as a result of carbon sequestration. This will increase the relative attractiveness of forestry options over alternative engineering options and over existing agricultural activities. The additional incentive may be $1500–2000 per hectare as a one-off payment, given a value of $15–25 per tonne of CO_2e. This is roughly equivalent to the incentive payments estimated to be suitable. The market forces of CO_2e should accelerate the shifting of agriculture into plantation forestry.

Cost of land acquisition

Up to $15.63 million would be required to purchase two key properties in the target area (Plantall 2006). One of the properties recently listed for sale was informally valued at between $4.4–4.7 million. By comparison, with lease rates around $460 ha/yr, $644 000/yr or

$6.4 million over a 10-year rotation of blue gums would be required to lease the target area of 1400 ha. The cost of leasing land for non-commercial tree establishment would be less, but both options would incur the additional expense of tree establishment at around $1000/ha (Plantall 2006).

Partnership approach

In this model, commercial forestry companies lease land to establish plantations and government revegetates unplanted areas. There is scope under this model for partnering with South Coast Natural Resource Management Inc. and Forest Products Commission to achieve revegetation of target areas. Initial discussions have been positive and demonstrate a willingness by all parties to collaborate.

Perpetuating private forestry

An element of risk exists with private forestry because of uncertainty about the retention of plantations into the future. A need exists, therefore, to develop instruments to assist the retention of sufficient areas of private plantations in the medium to long term. For example, agreements could be negotiated with private forestry to secure the long-term future of plantations in the area. Such agreements may involve government acknowledgement of the contribution of private forestry to reducing stream salinity in the catchment and private forestry acknowledgement of the importance of retaining plantations to keep stream salinity low. There may also be scope in future water planning by government to provide private forestry with more secure entitlements to water to encourage the retention of plantations.

Environmental evaluation

The likely major environmental issues associated with increased forestry in the catchment are increased rates of erosion and sedimentation risk during establishment and harvest (Table 18). However prior to harvesting, established plantations may actually reduce soil erosion and sedimentation and also reduce flood peaks. The environmental issues associated with groundwater extraction are the disposal of saline water outside the catchment and localised physical disturbance. Some reports indicate that forestry is likely to raise the risk of wildfire (URS 2007a). Other reports (ICS 2003; Geddes 2006), along with anecdotal evidence suggest that plantations actually dampen wildfires.

The option of groundwater pumping requires that the saline water will be disposed of in either the adjacent Hay or Kent rivers which would increase the salinity of these receiving bodies. This option needs to be considered in the context of the Walpole Wilderness Area (conglomerate of national parks) that encompasses the whole of the forested portions of the upper Denmark River, the Kent River and extends into the Hay River catchment where forested. Water resources in the Walpole Wilderness Area are important for the maintenance of biotic and aquatic systems and the provision of recreational opportunities.

Conversely, plantations, and possibly also perennial pastures, have high rates of carbon sequestration whereas desalination, and groundwater pumping to a lesser extent, would emit greenhouse gases.

Conclusion

This evaluation provides an indication of the potential costs and impacts of the various mitigation options available. Of these, plantation forestry emerged as the most economically efficient option to achieve the salinity target in the catchment, with overall potentially positive social and environmental effects.

At the time of writing their report (URS 2007a), the Water Corporation had not forecast the need to take water from the Denmark Dam, and URS did not have the results of the LUCICAT modelling. This new information gave added impetus to intervene to reduce salinities to less than 500 mg/L sooner than 2020, but reduced the need to further engineering options for salinity mitigation in the catchment.

Following LUCICAT modelling, it was anticipated that the required land-use change would be achieved by forestry without the need for government investment. In 2008 about 900 ha of blue gum plantations were being established as a result of negotiations between private landholders and forestry companies. With potential for increased value to be gained from carbon sequestration, forestry is likely to continue to be economically competitive against agriculture.

Shortened forms

BRS	Bureau of Rural Sciences
CAWS Act	*Country Areas Water Supply Act 1947*
CHAMWA	Catchment hydrology annual model for Western Australia
CRC	Co-operative Research Centre
DAFWA	Department of Agriculture and Food Western Australia
DEC	Department of Environment and Conservation
EC	Electricity conductivity
GSTWS	Great Southern Towns Water Supply scheme
IPCC	Intergovernmental Panel on Climate Change
LAI	Leaf area index
LUCICAT	Land use change incorporated catchment model
MAGIC	Microstation and geographic information catchment model
NHMRC	National Health and Medical Research Council
NRM	Natural resource management
SRES	Special report on emissions scenarios (IPCC)
TDS	Total dissolved solids
WC	Water Corporation
WRRC	Water resource recovery catchment

Volumes of water

One litre	1 litre	1 litre	(L)
One thousand litres	1000 litres	1 kilolitre	(kL)
One million litres	1 000 000 litres	1 megalitre	(ML)
One thousand million litres	1 000 000 000 litres	1 gigalitre	(GL)

Glossary

Capital and operating costs	The costs of setting up and running a process; in this case, the engineering-based options.
Carbon sequestration	A technique for the permanent storage of carbon dioxide so it will not remain in the atmosphere to contribute to the greenhouse gas effect.
Caveat	A stipulation on a title deed that imposes certain conditions on the land to which it refers.
CO_2e	Carbon dioxide equivalent: the standard measure for greenhouse gas emissions, expressing the global warming potential of various gases over 100 years in terms of carbon dioxide equivalents. Used when evaluating potential financial gains or losses that may be made by either selling carbon credits produced by plantations, or purchasing carbon credits as a way of offsetting carbon emissions produced (IPCC 2005).
Damage costs	The costs arising from damage being caused; in this case, the costs associated with damages (excessive scaling on pipes and appliances, corrosion) incurred by urban and industrial consumers (e.g. reduced productivity, maintenance of water infrastructure) as a result of using water with salinity above 500 mg/L.
Dryland salinity	The salinisation of unirrigated land. Occurs when salt builds up in surface soil layers as a result of rising groundwater and evaporation.
Electrical conductivity (EC)	Used to measure the ability of a medium to conduct electricity. EC is measured to estimate the concentration of dissolved solids in water.
Ecosystem	A biological community of interacting organisms and their physical environment.
ha	Hectare; 10 000 m^2
IPCC SRES	Intergovernmental Panel on Climate Change — Special report on emissions scenarios
IWSS	Integrated Water Supply Scheme that supplies water to 1.5 million of the 1.9 million people living in Western Australia including metropolitan Perth and many towns in the south-west.

LAI	Leaf area index; vegetation cover measured as the total one-sided area of leaves on plants divided by the area of land containing the plants. As transpiration is related to the leaf area through which it occurs, LAI is used as an indicator for estimating the evapotranspiration (similar to water use) of native vegetation, plantations and agricultural lands. It is a proxy for water use.
Lucerne	A leguminous deep-rooted perennial pasture species that can draw water from deep in the soil profile.
Mean flow	The average volume of water measured at a particular point on a stream over a representative rainfall period.
Pipe head dam	A dam allowing the diversion of some of the water flowing in a stream into a pipe. Supply relies on ‘run of the river’ flows.
Potable water	‘Drinkable’ water. Potable water has salinity below 500 mg/L (NHMRC 2004).
Projection	An estimate or forecast of a future situation based on a study of the present trends.
Riparian zone	The zone along or surrounding a waterway where the vegetation and natural ecosystems benefit from and are influenced by the presence of water.
Salinity TDS (mg/L)	Total dissolved solids expressed as milligrams per litre. Usually used for the salinity of groundwater which may have significant silica and bicarbonate.
Salinity at mean flow	Calculation that returns a salinity value assuming average streamflow. Usually a period of representative rainfall is chosen, the average streamflow calculated and the salinity value averaged over five years.
Salt load	A measure of the mass of salt carried by a waterway. Measured as kilotonnes per year (kt/yr).
Scenario	Hypothetical salinity management option used as input to catchment models for analysing the option’s impact on salinity.
Steady-state	A state of equilibrium in which salinity is neither rising nor falling, reached after the impacts of land-use changes have fully come into effect.

Upfront land-use change costs	The costs of generating the desired change in land use, be it establishing commercial tree plantations, replacing annual pasture species with perennial species, or revegetating land not suited to commercial purposes. Includes the costs of buying or leasing land, imposing forestry caveats and/or providing incentives to landholders to implement the above changes.

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