Department of Water
Government of Western Australia

Helena River
Salinity Situation Statement

REPORT No. WRT 34
MAY 2007

Water Resource Technical Series

Department of **Water**
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by

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Water Resource Management Division

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Acknowledgments

This report is based on information provided by colleagues in the Department of Water and present and former staff of the Water Corporation and the former Department of Conservation and Land Management. In particular, the authors are grateful to Tim Sparks who championed this project, to Artemis Kitsios for work on figures and land tenure, to Lidia Boniecka for maps for LUCICAT, to Melinda Burton for revising Section 1, to Jayath De Silva for hydrogeological consultation on previous technical work, to Phil Roberts for advice on the land management and Kevin Pollock for advice on catchment access, to Annette Crean and Graeme Blake for GIS figures, to Alex Waterhouse for editing advice and assistance and to Amanda Ellis and Glyn Kernick for assistance with desktop publishing. The authors acknowledge the reviewers whose feedback improved this report (Steve Appleyard, Keith Barrett, Frank Batini, Christopher Clarke, Bishnu Devkota, Geoff Mauger, Jasmine Rutherford, Roger Underwood and Ryan Vogwill).

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Recommended reference

The recommended reference for this publication is: Smith, RA, Bari, MA, Dixon, RNM & Rowlands, DW 2007, *Helena River Salinity Situation Statement*, Western Australia Department of Water, Water Resource Technical Series, no. WRT 34, 190p.

ISBN 978-1-920947-48-4 [pbk] and 978-1-920947-49-1 [pdf]
ISSN 1327-8436 [pbk] and 1449-8901 [pdf]

Printed on recycled stock

May 2007

Cover photograph:
Lake CY O'Connor floods the Helena valley above the Darkin River in the background
by Robin Smith

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Preface

The Mundaring Weir catchment was in 1978 proclaimed a clearing control catchment, under the *Country Areas Water Supply Act 1947*, to curtail salinisation of the water resources in the Helena River.

The State Salinity Strategy designated the Water and Rivers Commission (subsequently the Department of Environment and now the Department of Water) as the lead agency for coordinating efforts to limit or lower salinisation of existing or potential water supplies in five key Water Resource Recovery Catchments. These catchments of the Kent, Denmark, Warren, Collie and Helena rivers have now been subject to clearing controls for more than 25 years.

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

An important component of the program is to assess both the current state of the targeted rivers and to evaluate options available to recover/retain stream salinity to drinking water levels. The Salinity Situation Statements for the Collie River, the Denmark River, the Warren River and Kent River catchments were published in 2001, 2004, 2006 and 2007 respectively.

Disclaimer

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

Summary

Inflow to the Mundaring Reservoir now has a flow-weighted average salinity that is relatively stable at 510 mg/L but has exceeded the desired potable limit of 500 mg/L in seven of the 10 years up to 2002. Over 60% of the salt load comes in 30% of the inflow from the north-east of the catchment by way of the Helena River. Even though 97% of the catchment is forested, the salinity of runoff is very sensitive to the remaining 3% clearing. Land clearing remains the major evident risk to the reservoir salinity so the catchment requires a level of salinity management. There are also options to enhance the 17.1 GL/yr inflow to the reservoir (1992–2000) from the higher rainfall western portion of the catchment by forest management, specifically controlling the density of regrowth forest and pine plantations through thinning.

The predominantly below-average rainfall since 1974, if continued, has the potential to further reduce the catchment water resources, in quantity directly and less obviously in quality. Rainfall at Mundaring itself, in the north-west of the catchment, is 13% below the 1053 mm/yr for 1907–2003. Providing 49% of the runoff, the Helena West management unit has between the highest annual rainfall in the catchment (from 800 and 1050 mm since 1990), with the remainder of the catchment between 500 and 850 mm. The most recent mean whole-of-catchment annual rainfall – 660 mm for the period 1997–2003 – is 4% below that for 1975–2003. If this 1997–2003 rainfall regime continues, the inflow to the reservoir would decrease by a further 20%. As 25–30% of its capacity is pumped out each year the reservoir cannot tolerate a prolonged series of dry years with high inflow salinities. The low residence time for storage is also reflected in the periods between overflow (the last in 1996).

The Helena River was typically fresh when the Mundaring Weir was constructed in the early 1900s with inflow containing 290–370 mg/L. Salinity, a threat revealed following ringbarking to kill trees near the new Weir, caused the reservoir salinity to rise to 550 mg/L TSS with a 100 mg/L jump in the 1908 inflow alone. The understanding that the permanent clearing of native vegetation would lead to significantly increased stream salinity in all but the highest rainfall areas of the Darling Plateau was clearly established by the 1920s, and awareness of this had already influenced the management of the catchment (by the Forests Department and later CALM). Following the resumption of clearing between the 1940s and the 1970s, the State Government saved the catchment from rapid salinisation for the second time by controlling clearing, and by purchasing freehold land to both prevent clearing and to reforest.

Modelling of management scenarios, including the ‘do nothing’ or ‘base’ case and a range of potential land-use and rainfall scenarios, demonstrates our current understanding of the salinity situation. In modelling scenarios for future management, the 1970s land (re)purchases and clearing controls are revealed to have prevented salinity increasing to 1500 mg/L. Even now just a few km^2 cleared will push the mean annual reservoir inflow salinity beyond 510 mg/L. Fortunately, prescribed burns and even hot wildfires increase rainfall runoff, reducing inflow salinity. These effects are temporary unless dense regrowth can be restricted, particularly in higher rainfall catchment areas. Complete reforestation of the cleared areas (30 flowing and 9 km^2 rarely flowing) could lower the inflow salinity to 230 mg/L.

The small residual clearings from the 1970s total only 3% but remain a significant concern

for the salinity of inflow to the reservoir. The recent proclamation of four National and one Conservation park comprising about 38% of the catchment, while protecting against alienation and clearing, restricts silvicultural treatments that can maintain or increase water yield, particularly in the higher rainfall west.

Recent recognition of significant sedimentary aquifers that discharge saline groundwater more readily than the weathered and/or fractured granitic bedrock seepages, provided a key to understanding the catchment hydrology. Perennial discharge, due to nearby clearing, flows through the Ngangaguringuring gauging station on the Helena River, the tributary with most clearing, and reaches the Reservoir except in summer when it is used by plant transpiration. At Darkin Swamp, despite significant upstream clearing, the low relief, lack of dissection and evapotranspiration by vegetation are thought to prevent similar groundwater discharge from the sedimentary aquifer, and also greatly inhibit surface water discharge. Although no site-specific investigation and monitoring bores are available, the water balance of Darkin Swamp formed part of a 2006 UWA Honours project.

The plantation at Flynn, comprising reforestation of most of the area cleared on Flynn's Farm, highlights the key management strategy – to disconnect groundwater discharge from surface water flow in the Ngangaguringuring and Poison Lease management units (MUs) that provide most salt (load) and (by extension) prevent their connection in the Darkin Swamp MU that currently provides little salt. Further investigation may reveal that to maintain minimal flow through Darkin Swamp may also require reforestation upstream.

Ongoing good management of the forests is necessary. Plantations of high-water-use trees, such as pines rather than (most) native vegetation, could be used over sedimentary aquifers to reduce recharge and hence saline discharge such as near the Ngangaguringuring gauging station. Conversely, pines are not the ideal vegetation in the western half of the catchment and near streams as they use too much water and reduce yield (runoff). In these areas, appropriately managed native vegetation could be used to increase yield without increasing salinity. Pine plantations managed at less than 100% cover also could increase runoff in the higher rainfall west of the catchment where salt stores are less than in the east.

Logging since the construction of the Weir has reduced the maturity of the native forest, possibly increased its water use and depressed the reservoir inflow.

Pumping groundwater from the sedimentary aquifer near Ngangaguringuring would lower the salinity of reservoir inflow. Diverting the (saline-to-brackish) flow at Ngangaguringuring and/or Poison Lease would reduce both flow and salinity.

Keywords: Yilgarn South-west Groundwater Province, Helena River, Mundaring Weir, water resources, land salinisation, dryland salinity, aquifers, springs, hydrology, catchment management, computer simulation.

Recommendations

Management options

Communicate results to all major stakeholders (Department of Environment and Conservation, Forestry Products Commission, Water Corporation) so that they can action or have input into any subsequent or ongoing work.

Maintain clearing controls. Since July 2004, clearing applications in these areas have been regulated under the Environmental Protection Act 1986 and no clearing should be permitted.

Specifically retain the options for silviculture (thinning), on government freehold land and of wandoo, throughout the catchment. Reforest government freehold land, especially that near Abercorn Road, to the appropriate density; so, to allow management of density by thinning/ burning/logging, do not include in a National or Conservation park. Map the areas where, to increase runoff, pines could be less than maximum density. Negotiate with the Forest Products Commission (FPC).

Manage the remaining cleared areas forming 3% of the catchment. Advise landholders near Mt Observation and Dobaderry Swamp (Localities F & E) that they are within the Mundaring catchment and brief them regarding land use. Consider more land purchases at Abercorn and Goods roads, Wundabiniring Road, Talbot Road West, Mt Observation and Flynn Road (Localities B, C, D, F & H) in no priority order, and monitor the areas near Qualen Road and Dobaderry Swamp (Localities A & E) in case they discharge into the Darkin River.

Focus on management of the subcatchments with highest salinities under the 1990–2003 rainfall.

Examine in more detail the impacts of prescribed burning regimes and forest fires on hydrology and salt load by extending the results of this study's modelling. Investigate whether silviculture, specifically burning and thinning for enhanced water yield, is desirable in the area that may for increased security against clearing-related salinity, be added to the Helena National Park. Thinning, in addition to just prescribed burning, should be a management option.

Investigate the hydrogeology, flow or discharge from Darkin Swamp to determine the risk of it beginning to discharge water and salt.

Establish targets and standards against which management progress can be measured.

Examine the status of the catchment area below Mundaring Weir and its effects on management of the Helena Water Resource Recovery Catchment.

Consider pumping and draining the sedimentary aquifer near Ngangaguringuring and diversion of the Helena River there or at Poison Lease to reduce runoff from the east.

Prepare a catchment management plan from this Salinity Situation Statement, detailing actions, timelines and responsibilities.

Monitoring and evaluation

Continue streamflow and salinity monitoring at the gauging stations to determine whether recent trends, particularly runoff decline, continue. Continue monitoring to assess for rainfall trends. In particular, revise the saltfall data and examine the chemistry for changes in NO_2 and $S\text{-}SO_4$ as they both pre-date the 30-year-old rainfall change.

Expand monitoring of groundwater levels and salinity beyond a few representative bores in Flynn plantation by constructing multi-level investigation bores in sedimentary aquifers north of Darkin Swamp and Ngangaguringuring.

Continue Landsat monitoring to assess changes in forested land, the impacts of fires of different intensity and vegetation recovery after fire, especially in Darkin Swamp where vegetation reduction could lead to export of water and salt.

Where to from here?

This study focuses on conceptual salinity reduction options — to understand the extent of the land-use changes needed to reach the salinity target. It is the first step in the recovery approach.

The next step will be the evaluation of the management options from this study. For this the water quality objectives will be defined and, in consultation with key stakeholders (considering social, economic and environment aspects) scenarios to meet these objectives will be evaluated. Additional and more detailed modelling will be used. In the recovery plan step the major components of management options to be implemented will be identified, an implementation strategy developed and funding sources identified.

The final step will be to implement this plan and to recover this catchment from salinity.

1 Introduction

1.1 Background and purpose

The Helena River (Appendix A2.1, Photos 1–4 & 6–8) was fresh but of variable salinity where and when the Mundaring Weir was constructed in 1898–1902. Estimates in Power (1963, pp. 90 & 95) indicate the reservoir inflow salinity was 290–370 mg/L. The reservoir salinity rose to 550 mg/L Total Soluble Salts (TSS see Glossary; Stokes & Batini 1985, 1986) following clearing in 1902, including a jump of 100 mg/L in 1908 (Power 1963, p. 90). It fell and rose a second and third time through 500 mg/L in the 1960s and in 1996. This report considers the impacts of land-use change, together with the rainfall decrease, on the water resources of the catchment. Both water resource quantity and quality may be affected by removing (deep-rooted) native vegetation, changes in vegetation (growth, dieback, death, etc.), reduction in rainfall, increasing water supply demand and nearby suburban development.

That the permanent clearing of native vegetation would greatly raise stream salinity in all but the highest rainfall areas of the Darling Plateau was clearly known by the 1920s (Schofield et al. 1988), and had already influenced the management of the catchment (Reynoldson 1909; Department of Planning and Urban Development 1993). Continuation of the below-average rainfall since 1970 may further diminish the catchment water resources, in quantity directly and less obviously in quality. The decline in yearly inflows to the major metropolitan surface water sources is evident in the Water Authority Planning for Perth's Water Future (Stokes et al. 1995 Fig. 2-1) and the most recent Water Corporation Source Development Plan (Water Corporation 2005 Fig. 3.1). At the same time, increasing demand for the surface water resources is met by transfers from the Canning Dam and more recently from the Gnangara Mound to the Mundaring Reservoir.

The Helena Water Resource Recovery Catchment (WRRC) is that part of the Helena River catchment upstream of the Mundaring Weir and is termed the Mundaring catchment in this report (Fig. 1.1 & Glossary). This report describes where changes might affect this catchment by subdividing it into five management units. The additional area draining to the pumpback dam 12 km downstream of the Weir and supplying water to freshen the Mundaring Reservoir is not considered.

1.2 Scope

This report focuses on salinity – its current status and the potential effects of future work. The scope of this Salinity Situation Statement is to provide guidance for water resource management in the Mundaring catchment (not the reservoir). It describes the catchment, its history, the salinity situation, management scenarios and compatible land uses. It presumes ongoing good management of the forest (fighting fires, burning, regenerating and replanting (Underwood pers. comm. 2006)).

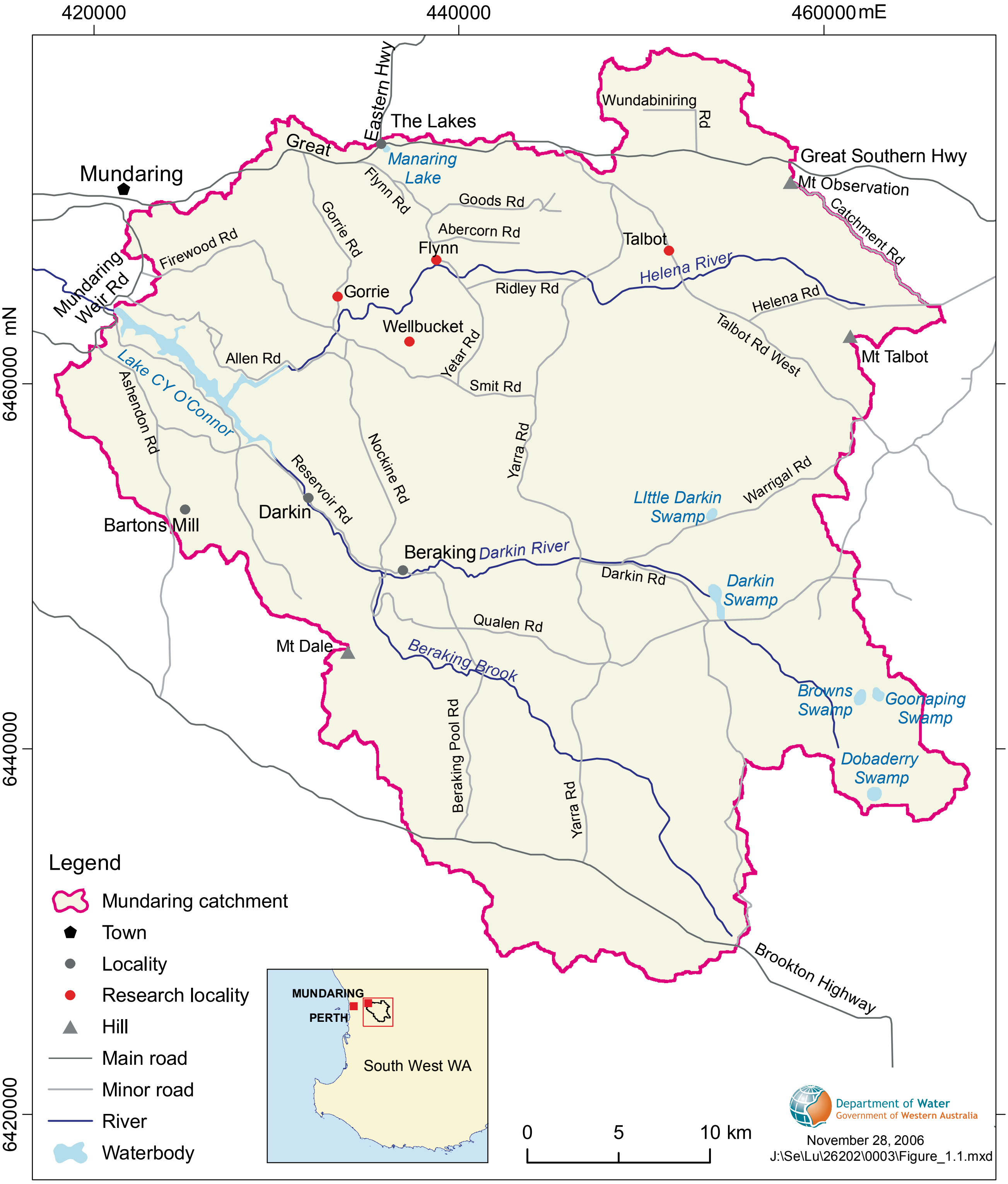


Figure 1.1 Mundaring catchment

1.3 Brief history – history repeats itself

Richard Dale who named the Helena River, probably after his sister, twice travelled upstream into the catchment in 1829 under the instruction of Governor Stirling, and certainly on the first expedition reached near where the Mundaring Weir stands today (Quicke 1983). As a result, most of about 20 land allocations along the Helena River that followed immediately were upstream of the junction with Piesse Brook, around where the Mundaring Weir is located. The primary assignment, and farthest downstream, was Location 16, some 1.6 km^2 (4000 acres), to Sir James Stirling. The areas of the Helena valley that were of most interest to the early European settlers were the local, broader sections where the landforms, soils and groundwater conditions were favourable for settlement and farming (Appendix A2.1, Photos 9–10). The wide distribution of the shrub 'York Road Poison' (hence Poison Lease gauging station) and the infertile lateritic soil saved the catchment from early clearing (Quicke 1979). Timber milling was commonplace along the Darling Scarp in the 1880s. By the end of the 19th century the western part of the Helena catchment had been heavily logged (and revegetated). Heberle (1997) describes timber harvesting of Crown land and maps cutting by decades in the south-west of Western Australia.

The Coolgardie Gold Rush began in 1893 and the population of Western Australia soared as thousands of people flocked to the Goldfields seeking riches (Ewers 1935). Many of the prospectors came from what later became the eastern states but were then colonies in the grip of economic depression. Prospectors constructed 'tent cities' out of calico, hessian, blankets and bark. Rainfall was unreliable, sanitation poor and soon scurvy, typhoid and dysentery were commonplace – all highlighting the need for a clean water supply.

The metropolitan area and goldfields needed an assured water source, not just pools in the Avon (River) that varied in quantity and particularly in reliability. Freighting water from the Avon by rail was expensive. The cost of piping water was also high enough to be limiting on use in the goldfields.

In 1896, Premier Sir John Forrest instructed CY O'Connor to investigate a water-supply scheme able to deliver 25.5 ML (5.6 million gallons) per day of clean water to the Goldfields (O'Connor 1896; Hartley 2000). The scheme involved a 20.9 GL (4600 million gallon) reservoir on the Helena River together with a 530 km pipeline and 8 pumps to transport and raise the water from the Weir to about 400 m AHD (metres above Australian Height Datum) in the Coolgardie Goldfield. Critics of such a big project were many and CY O'Connor was damned persistently until, just before the scheme water reached Coolgardie, he committed suicide.

The Mundaring Weir was completed in 1900 and in 1902 the pipeline, described by O'Connor's successor (Palmer 1905), reached the Coolgardie Goldfield. The construction of the Weir and pipeline was a major engineering feat in a time without the earthmoving and excavation equipment of today. The Weir used the concrete gravity design that (unlike the convex design) does not apply great pressure to the sides of the valley. This was considered favourable for the Helena River valley, as major tectonic movement had fractured the ancient granitic bedrock. The Mundaring Reservoir that was formed has been known as Lake CY O'Connor since its centenary (Appendix A2.1, Photos 1–4).

The concrete Weir was constructed 230 m (755 ft) wide and 30.5 m (100 ft, Le Page 1986) above streambed level (100 m AHD). Eight pumps raised the water about 300 m and moved it more than 530 km (in about 10 days) at 0.62 m/s. Originally, Collie coal was the primary fuel source for the pumps but, less than a year after pumping began, was abandoned in favour of timber – a far cheaper alternative that was readily cut locally. Timber reserves were created in the Wheatbelt to ensure availability of this natural resource (Batini pers. comm. 12.2.2004).

Water pumped for the Goldfields and Agricultural Water Supply (GAWS) reached the Coolgardie Goldfield in 1902 in readiness for the official turning-on of both supply and equipment early in 1903. By June 1904 the Goldfields water supply was connected to 75% of Boulder, 63% of Kalgoorlie and 40% of Coolgardie residences and commercial premises. This translated to an average of 5.73 ML (1.26 million gallons) of water per day. The quantity of water supplied increased to an average of 7.23 ML (1.59 million gallons) per day in 1906–07 and then to 10.0 ML (2.2 million gallons) in 1910–11. The Goldfields Water Supply Administration (GWSA) was responsible for managing the scheme from the beginning of pumping until 1912 when it was abolished and the management passed to the Public Works Department of the State Government.

During construction of the Weir, and up to 1904, about 8100 ha (20 000 acres) of the State Forest had been ringbarked, although sources vary in their details (Power 1963; Ward 1977; Dixon 1996), and this far surpassed clearing up to that time. It seems 4455 ha (11 000 acres) was ringbarked near the dam and as 1902 had below-average rainfall and therefore a small inflow into the reservoir, a further 3240–3425 ha (8000–8500 acres) were ringbarked above the junction of the Helena with the Darkin River with the intention of increasing runoff and inflow. Salt concentrations rose within 4 years of the ringbarking (Reynoldson 1909). Not all this area (5% of the catchment) was subsequently cleared; much grew back naturally from seed and jarrah coppice (Power 1963, p. 44) and very little (less than 1%) is now (pine) plantations.

One of CY O'Connor's most able assistant engineers, WC Reynoldson (1909), noticed in 1908 that the Darkin River carried much less salt than the Helena River. Samples showed a 5-fold salinity increase in the Helena River (and therefore an increase in salinity in the reservoir), whereas salinity in the Darkin River had not changed appreciably. Comparisons showed that no ringbarking and practically no clearing had taken place in the Darkin River subcatchment while a portion of the Helena subcatchment had been ringbarked, cleared and cultivated above the junction with the Darkin River. The link was made between clearing and rising salinities.

Reynoldson made recommendations to the Public Works Department to help manage the high salinities in the Mundaring catchment. He investigated and reported on scouring and diversion as management tools to mitigate the rising salinity. Scouring – the release of saline water through a valve deep inside the base of the dam coincident with fresher inflows to the reservoir – proved ineffective and difficult because the incoming flows and salinities were too hard to predict. Investigation into diversion concluded that it would only be effective in lowering salinity if a considerable proportion of flows could be diverted.

The link between ringbarking and clearing and increasing salinity levels was clear to Reynoldson. He effectively made this the first salinity recovery catchment by recommending:

- cessation of ringbarking on unalienated (Crown) land
- resumption of alienated land wherever possible
- reforestation of the cleared and resumed land
- no scouring.

Areas of the Mundaring catchment were replanted with pines as the first recorded remedial measure taken in response to stream salinity in the south-west of Western Australia. The recommendations parallel the actions taken today in the other Water Resource Recovery Catchments, highlighting the early understanding of the role of forests in salt and water balance. Government purchasing and clearing controls have meant that only about 5% of the Mundaring Weir Catchment Area is now privately owned and two-thirds of this area is cleared (described in Section 2, but much of it in the 1950s after salinity development was understood).

By 1914 an average of 15 ML (3.3 million gallons) was being pumped from the Mundaring Reservoir (O'Brien 1917) under the management of the Public Works Department which had been handed the responsibility two years earlier. From 1925 the pipe also supplied farmland (Le Page 1986), so that the full pipe capacity was first reached in 1928, serving both the goldfields and 284 256 ha of the agricultural area. In 1943–44 the average daily pumping rate first exceeded O'Connor's planned 5.6 million gallons per day.

The Mundaring Weir overflowed as early as 1903 and nearly every year after until the wall was raised in 1951 (Munro & Hunt 1953 & Fig. A3.8). Work started in 1946 to raise the height from 30.5 to 40.2 m (100 to 132 ft), increasing the capacity of the reservoir from 20.9 to 68.2 GL (4600 to 15 000 million gallons). Had the Weir been this height to begin with, the reservoir would still have filled 27 times from 1900 to 1944. The new overflow height of 137.4 m AHD was topped in four successive years, 1955–58 until the height was increased by a further 1.1 m with the addition of crest gates on the spillway in 1959 (capacity 77.3 GL, 17 000 million gallons). The overflow years continued aplenty and included 1963–68 (Bowman & Jha 2004) and 1973–75, but then became 'just trickles' in 1970, 1981 and 1983 (Jeevaraj pers. comm. Water Corporation April 2005). Since the gates were decommissioned in 1990, the only overflow year was 1996. This probably reflects both decreased rainfall and increased demand. The reservoir capacity was revised to 63.6 GL (14 000 million gallons) following an aerial survey in 1988 when storage was relatively low and the upper banks were exposed (Summerford pers. comm. Water Corporation December 2006).

In 1945, the water supply scheme was expanded to deliver water to eastern Wheatbelt towns. The comprehensive Goldfields and Agricultural Water Scheme was completed in the 1950s and coincided with infrastructure upgrades to ensure the supply. The original steam pumps were upgraded to electric pumps.

In the 1940s to the 1960s land releases and significant further clearing for agriculture pushed reservoir inflow salinity upward for a second time. Land (re)purchase by the State Government and reforestation followed in the 1970s and 1980s, together with the introduction of pumpback from below the Weir.

In 1971 the Lower Helena Pumpback Dam was constructed 12 km downstream of the Mundaring Weir. The Pumpback Dam collects runoff from the Middle Helena Catchment Area, a 120 km^2 gazetted water catchment. The Dam is only 5 m high and just 9 km west of Mundaring Weir so effectively increases water capture, with only 0.13 GL of storage (Mauger 1989). This supplementary water source is connected to the Lake CY O'Connor storage via the pumpback pipeline. Lake CY O'Connor is sometimes supplied with water from other metropolitan water sources, delivered via the Pumpback Dam. On average, the Pumpback contributes 25% to Lake CY O'Connor but up to 60% in dry years (Schofield et al. 1988; Itzstein-Davey & Conacher 2001).

During the 1970s mining production fell to the lowest level in the twentieth century. Demand for water in the Goldfields correspondingly decreased until the mid 1970s when the gold price began to rise steadily. The mining boom that followed was the third in the history of Western Australia and is continuing. Water demand increased with the mining boom. The Goldfields and Agricultural Water Supply Scheme serves the Goldfields and many towns in the eastern Wheatbelt. A number of suburbs in the Hills (Mundaring, Glen Forrest, Mahogany Creek, Hovea, Stoneville and Sawyers Valley) are also supplied with water from the scheme (Department for Planning and Infrastructure & Water and Rivers Commission 2003). In 1997–98 the scheme supplied 31 GL (84 ML per day), split between agricultural and goldfields use (Water Corporation 1998, p. 66).

Mauger (1989), in reviewing future sources for Perth's water supply, looked at raising Mundaring Weir to store 200 GL (a 3-fold increase), damming the Upper Helena to store 247 GL or damming the Upper Darkin (Appendix A2.1, Photo 38) to store up to 200 GL. Given the sequences of low rainfall and the lack of overflow from Mundaring Weir these options are now not considered viable.

1.4 The Water Resource Recovery approach

The Department of Water (DoW) Salinity Management Program builds on a program previously coordinated by the Water and Rivers Commission (Government of Western Australia 1996a,b). At its heart is one of the goals of the State Salinity Strategy: *To protect and restore the key water resources to ensure salinity levels are kept to a level that permits safe, potable water supplies in perpetuity* (Government of Western Australia 2000a,b).

Delivery is through highly focused strategic programs, such as the Water Resource Recovery Catchment program, as well as more general support and advice for regional NRM groups, for investigation of groundwater, arterial and small catchment drainage, and input to state-wide clearing regulation and water salinity monitoring. This targeted approach is expected, as with the Collie and Denmark catchments, to provide bigger improvements sooner than if efforts and funds are spread more thinly resulting in slow, insignificant or imperceptible salinity improvements. It seeks solutions with big enough effects on catchment water balances to meet salinity targets. Solutions also need to take into account economic, social and environmental impacts of both the engineering and the vegetative approaches to salinity recovery or containment.

The approach (Fig. 1.2) has the following stages:

- *Monitoring and Evaluation* monitors the main rivers and major subcatchments of the Water Resource Recovery Catchments and assesses their status and trends. Subsequent cycles of monitoring will be used to review the ongoing salinity situation after *Implementation*.
- *Salinity Situation Statement* identifies current and predicted salinity levels, estimates how long before water quality entering the reservoir returns to potable levels and the salt is leached from soil profiles, and so evaluates hydrological impacts of salinity management/ recovery options.

- *Evaluation of Management Options* defines technical aspects of management options identified in the salinity situation statement, and evaluates the economic, social and environmental aspects in consultation with key stakeholders.
- *Salinity Recovery Plan* identifies the major components of the option(s) selected for implementation, develops an implementation strategy, and identifies funding sources.
- *Implementation* coordinates 'on-ground' planning and implementation.

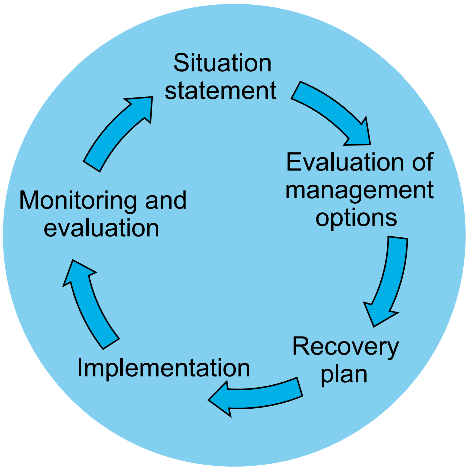


Figure 1.2 Stages of the Water Resource Recovery approach

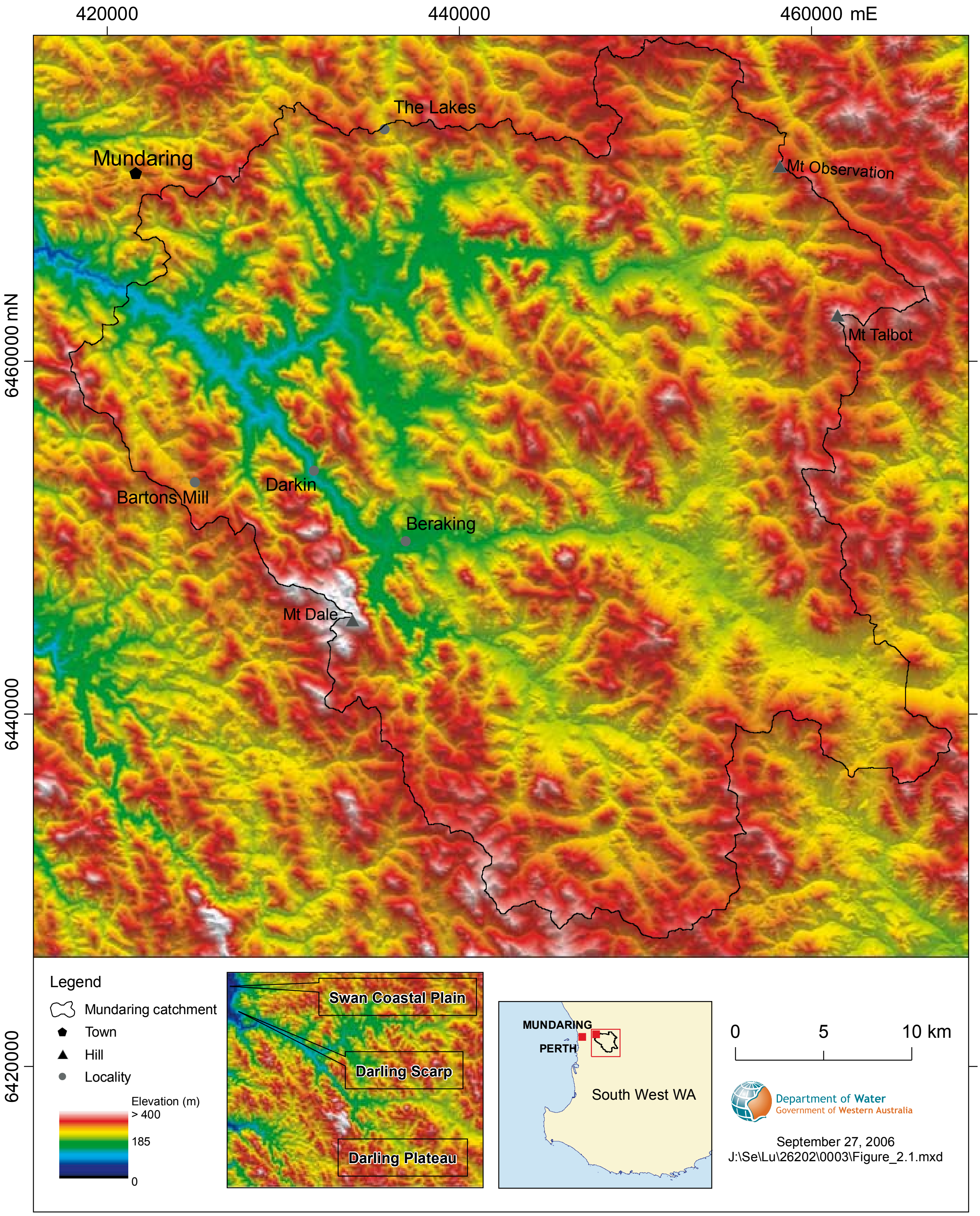


Figure 2.1 Topography and physiographic divisions

2 Catchment characteristics

Awareness of the catchment characteristics that influence the salinity, runoff and salt load is important for the interpretations (Section 3), modelling (Section 4) and scenarios (Section 5) that follow. This section summarizes the topography, outlines the perceived rainfall shifts, describes the role of geology, the significance of groundwater, and the vegetation status.

2.1 Location and topography

The Mundaring Weir is 29 km east of Perth and dams the Helena River near the western edge of the Darling Plateau (Figs 1.1 & 2.1). The long north-south Darling Scarp marks where many rivers of south-western Australia descend to the coastal plain from the Darling Plateau and is generally the downstream limit for suitable dam sites (Sadler & Williams 1981). The Weir dams the most northerly water supply catchment in the Darling Plateau. The catchment extends about 55 km from east to west and 50 km north to south with an area of about 1480 km^2.

The catchment contains both major valleys with slopes and floors (Appendix A2.1, Photos 9–10), and minor valleys (Appendix A2.1, Photo 5) that dissect the plateau extending east from the Darling Scarp (Murdoch University 1987). It is mostly 200 to 350 m AHD with the topography much less incised towards the eastern boundary (Fig. 2.1; Appendix A2.1, Photos 33–35). The general elevation of the landscape increases from the west, where the Mundaring Reservoir inundates the junctions of both the Helena with the Darkin River (Appendix A2.1, Photo 4) and the Darkin with the Little Darkin River. The Helena River (Appendix A2.1, Photos 6–8, 23, 25–27 & 29–32) rises east of the reservoir just north of Mount Talbot. The Darkin River (Appendix A2.1, Photos 35–38) rises among swamps found mostly in the south-east of the catchment but gains almost all flow below the largest of these, the Darkin Swamp. Plugging the low point of this catchment the Mundaring Weir rises from about 100 to 140 m AHD. The highest points of the catchment are on the boundary: Mount Dale (545+ m AHD) at the head of the Little Darkin River in the south-west, and Mounts Talbot (395+ m AHD) and Observation (355+ m AHD) in the north-east (Appendix A2.1, Photo 39).

The Great Eastern and Great Southern highways twine along the northern boundary, the former connecting a string of settlements in the north-west, while the Brookton Highway crosses the south of the catchment. Further semi-rural subdivisions adjoining the south-western boundary are linked to suburban roads. Unsealed roads and forestry tracks cross the catchment, with the roads continuing east of the catchment as the forest yields to farmland (Fig. 1.1; Appendix A2.1, Photos 33–35).

2.2 Climate

The climate is temperate with cool wet winters and hot dry summers. Mean monthly minimum and maximum temperature ranges are 7–17 and 15–30 °C respectively at Kalamunda 10 km west of the Weir (Murdoch University 1987). The elevation of the catchment is generally lower

Figure 2.2 Hydrology, subcatchments, gauging stations, rainfall and potential evaporation

than at this recording site, increasing local temperatures. Figure 2.2 shows mean annual rainfall to 1981 and mean pan evaporation to 1986 (Luke et al. 1988). The rainfall for the 12-year period of 1990–2002 ranged from about 500 mm in the east to 1050 mm at the western edge of the catchment (Fig. 2.2). Of this, 80% falls between May and October, coming mostly from fronts associated with low-pressure systems passing eastward over or just south of the area. Less common large rainfall events in summer are associated with thunderstorms or tropical cyclones from the north-west. Potential evapotranspiration is about 1900 mm/yr and very similar to Perth with 80% of pan evaporation between November and April (Stokes & Batini 1986).

From work on the bauxite leases (Department of Conservation and Environment 1979) in areas of jarrah-forest salinity, managers have introduced and extended the classifications of high, intermediate and low rainfall over the south-west region of Western Australia. These terms indicate respectively zones from the scarp eastwards to the 1100 mm/yr rainfall isohyet, between approximately 1100 and 900 mm/yr of rainfall, and inland from the 900 mm/yr isohyet (Sadler & Williams 1981). These zones reflect the increasing potential for salt release following clearing (see Section 2.5). They are not adopted strictly in this report as the 1100 mm/yr rainfall isohyet barely lies within the Mundaring catchment and the use of a specific rainfall boundary implies an unwarranted precision in these relative (not absolute) terms.

Winter rainfalls, since the mid 1970s, have declined 10% across the south-west of Western Australia (Indian Ocean Climate Initiative Panel 2002). The rainfall pattern has also changed – less in early winter (May–July) and more in late winter (August–October). At Mundaring Weir (Fig. 2.3) the average annual rainfalls of 938 (1990–2003) and 921 mm (1975–2003) are 11 and 13% below the long-term average of 1053 mm (1907–2003). Such point data are not representative of the whole catchment.

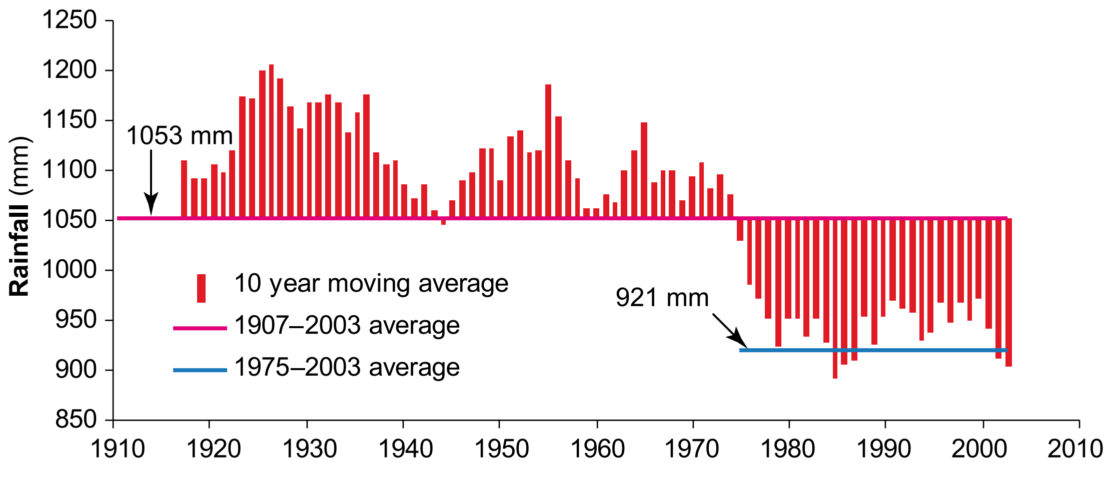


Figure 2.3 Average annual rainfall for Mundaring Weir

Hingston and Gailitis (1976) provided the original estimate of saltfall in rain at the Weir as 10 mg/L, giving a spatial average of about 8 mg/L (A4.2.1.1). Saltfall decreases with distance from the coast and is now estimated to be 11.1 mg/L at the Weir and 7.9 mg/L in the east of the catchment (A4.1.5). Bawden (1991) suggests the saltfall composition and pattern may now be different with more nitrogen and sulfur dioxides, different rainfall distribution and wind conditions (Appleyard pers. comm. 2006). Rutherford (pers. comm. 2006) found increased S-SO_4 after clearing in the Collie WRRC.

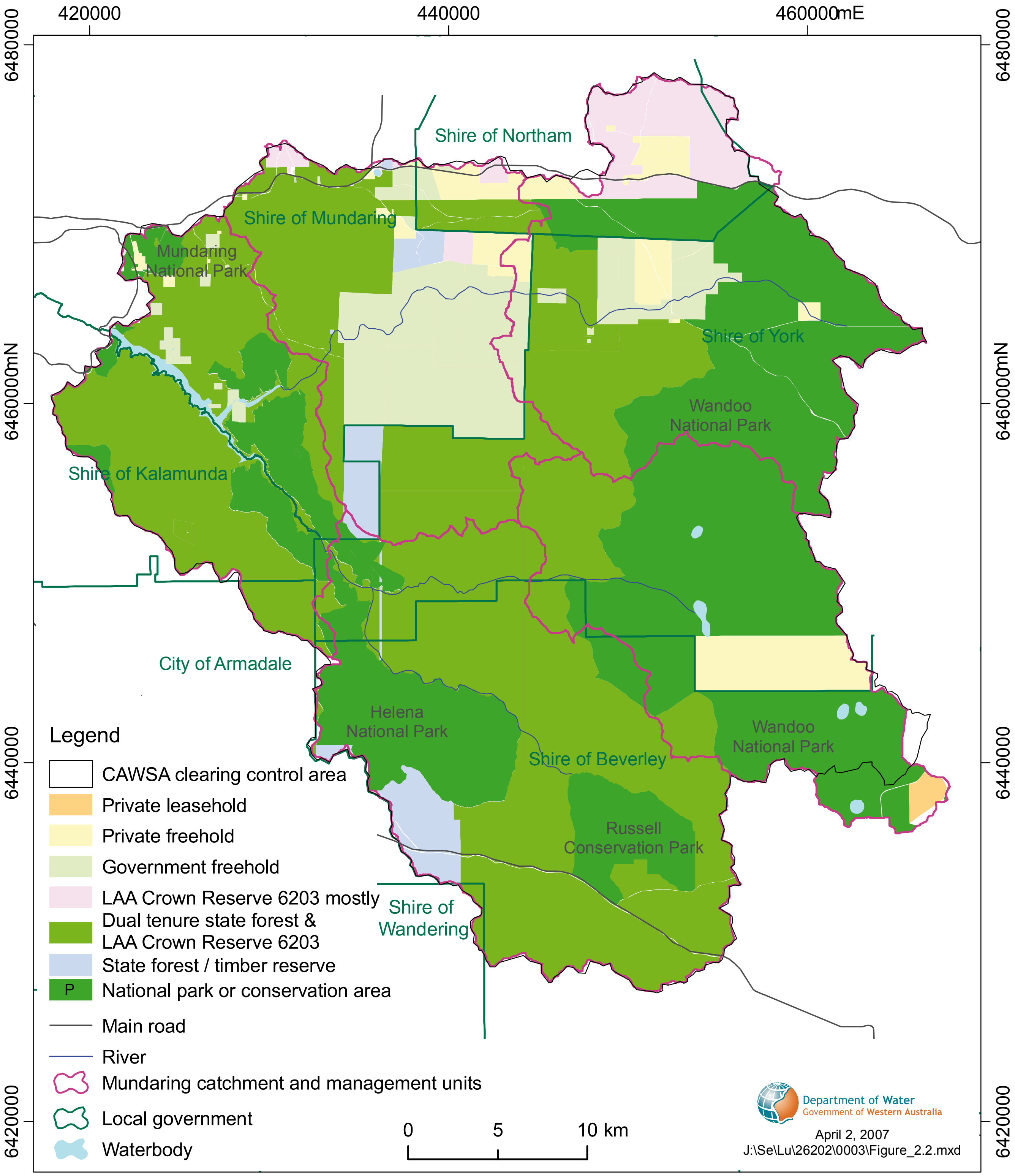


Figure 2.4 Land use, National and Conservation parks and shire boundaries

2.3 Land administration, cadastre and shires

The area administered under the CAWSA has a slightly different boundary from the watershed, especially in the salt-sensitive south-east and north-east (Fig. 2.4). Private lease/freehold areas are substantially smaller than in the 1970s when much private freehold became government freehold. A large portion of Crown Reserve 6203 has dual tenure as State Forest. Smaller areas comprise Crown reserves and timber reserves. The forest and pools attract 4WDers, campers, trail bikers, car-body dumpers, vandals and pigs.

About 38% of the Mundaring catchment has been declared part of the Helena, Mundaring, Pickering Brook and Wandoo National parks gazetted in 2005 (Bailey & Hanf 2004) and the Russell Conservation Park administered by the Department of Environment and Conservation. The proposed designation of the recently split-up unallocated freehold land near the Brookton Highway as State Forest is likely to proceed and is so shown (Fig. 2.4), but the mooted addition of the southern half of Government freehold land (excluding some plantations), in the Shire of Mundaring not adjoining the Helena National Park, is not delineated. While these parks may be seen to protect against alienation and clearing, their management restricts silvicultural treatment. Increased forest density through regrowth within the higher rainfall areas may increase evapotranspiration, decreasing the lower salinity runoff and overall increasing the salinity of inflow to the Mundaring Reservoir. The proposed addition of the south of Flynn to the Helena NP is of less concern due to its low 700–800 mm/yr rainfall and, as with those additions in the drier eastern portion of the catchment (Wandoo National Park and Russell Conservation Park), could be considered to provide security against salinity.

The shires of Kalamunda, south of the Helena River, and Mundaring govern the north-western third of the catchment (Fig. 2.4). The shires of Beverley and York administer most of the remainder with only small areas falling into the local government of the city of Armadale, shire of Northam and shire of Wandering.

2.4 Gauging stations, subcatchments and management units

Seven stream gauging stations on six waterways were constructed between 1966 and 1973 – two on the Helena River that are distinguished by using their site names, usually without the waterway name, and Helena Brook, Darkin River, Pickering Brook, Rushy Creek and Little Darkin River (Fig. 2.2, Table 2.1). Due to the higher rainfall in the west of the catchment, significant flow is contributed to the reservoir from the smaller western subcatchments, some of which are not directly gauged. Nearly all (92%) of the catchment area drains through these seven gauging stations (Table 2.1, Fig. 2.2), most of which have data from the 1970s to the 1990s. Some of the original location data tabled (Water and Rivers Commission 1996) are imprecise. The Ngangaguringuring, Poison Lease and Darkin River stations were upgraded to supply continuous (rather than monthly) salinity and flow data from 2000, 1992 and 2000 respectively. The three stations located in the western subcatchments were decommissioned in 1999 but two (on the Little Darkin River and Pickering Brook) were reopened in 2005 (Barrett pers. comm. 2006) to study the influence of the January 2005 wildfire on runoff, although gauging was affected by serious post-fire erosion and siltation. The Helena and Darkin River subcatchments are the areas above the Poison Lease and Darkin River gauging stations respectively (rather than strictly above the junction of the two rivers).

Five management units (MUs) covering the NE, SE, S, W and N of the Mundaring catchment are used and named (Fig. 2.2). Management unit boundaries have been drawn across the Helena and Darkin rivers through the Ngangaguringuring, Poison Lease and Darkin River gauging stations where relevant data are recorded. Within the MU boundaries are fitted 66 modelling subcatchments, ranging from 4.7 to 41 km^2, used in Section 4. The MU boundaries are therefore not coincident with the downstream limits of the Helena and Darkin River subcatchments that extend to their junction (beneath the Mundaring Reservoir). The detailed descriptions below, together with the terms in the Glossary, reveal how the gauging station positions determine where these three MU boundaries cross the rivers and are taken as the downstream limits of the Helena and Darkin River subcatchments.

Table 2.1 Stream gauging stations above Mundaring Weir

Site Name	Waterway	Site No.	Record (years)	Area (km^2)	Permanent clearing (%)	Rain 1990–2002 (mm/yr)	Easting	Northing
	HELENA SUBCATCHMENT							
Ngangaguringuring	Helena River	S616013	1972–2006	328.2	6.5	598	443592	6466110
Trewd Road	Helena Brook	S616012	1972–2006	26.4	2.5	792	431639	6468449
Poison Lease	Helena River	S616216	1966–2006	**592.9**	3.8	647	432948	6462327
	DARKIN SUBCATCHMENT							
Pine Plantation	Darkin River	S616002	1968–2006	**665.4**	2.7	640	433339	6451769
	HELENA WEST SUBCATCHMENT					902		
Hairpin Bend	Little Darkin River	S616010	1969–2006	37.6	0	892	428049	6456449
Slavery Lane	Pickering Brook	S616009	1969–2006	29.5	0	962	423139	6461229
Byfield Road	Rushy Creek	S616007	1969–1999	39.3	3.9	868	425739	6463849
Downstream of gauging stations (includes reservoir)				115.2				
Total catchment area above Mundaring Weir				**1480.0**				

2.4.1 Helena River — Ngangaguringuring

The Ngangaguringuring gauging station (Appendix A2.1, Photos 25–26 & 40) is located at the point of discharge from the Ngangaguringuring subcatchment and management unit (328 km^2) to the Poison Lease management unit (593 km^2), both on the Helena River (Fig. 2.2). It records the flow of the Helena River in the north-eastern sector of the Mundaring catchment, including the saline Wundabiniring Brook from north of the Great Southern Highway. Some permanent clearing has affected this section of the catchment and remnant native vegetation is very sparse. Flow and salinity measurements began in 1972 with continuous daily measurements from 2000. It is the only gauging station to have perennial flow (sustained by discharge from Tertiary sediments).

2.4.2 Helena Brook

The Helena Brook gauging station is sited near Trewd Road below a small, little-disturbed subcatchment in the north-west of the Poison Lease management unit (Fig. 2.2). The Helena

Brook flows into the Helena River upstream of the Poison Lease gauging station. Flow and salinity sample measurements began in 1972 and continue.

2.4.3 Helena River — Poison Lease

The Poison Lease gauging station (Appendix A2.1, Photo 6) is located at the point of discharge from the Helena subcatchment comprising both the Poison Lease (593 km^2) and Ngangaguringuring management units (328 km^2). It records the flow of virtually all the northern sector of the Mundaring catchment, immediately prior to discharge into the reservoir but just upstream from what strictly is the outlet of the hydrologic subcatchment (Fig. 2.2). Flow and salinity measurements began in 1966 with transition to continuous daily sampling in 1992. Streamflow and water salinity are affected by permanent clearing in the north-east. Flow from Ngangaguringuring reaches the Poison Lease gauging station except during summer, but similar (saline) flow emanating from cleared private freehold land near Wariin Well and entering the Helena River via Wariin Brook is not gauged.

2.4.4 Darkin River

The Darkin River gauging station, sited at the Pine Plantation, records the discharge of the Darkin River to the reservoir (Fig. 2.2). The flow is derived from virtually the south-eastern half of the Mundaring catchment, including the Beraking Brook management unit (274 km^2, not just the Beraking Brook hydrologic subcatchment) and the Darkin Swamp management unit (392 km^2), although about half of the latter drains to swamps rather than directly forming the headwaters of the Darkin River. The term 'Darkin subcatchment' is used for this area, even though the Darkin River below the Pine Plantation gauging station drains into the Helena West management unit further than does the Helena River below the Poison Lease gauging station. Flow and salinity measurements began in 1968 and 1969 respectively with transition to continuous daily sampling in 2000.

2.4.5 Little Darkin River

The Little Darkin River gauging station is sited near Hairpin Bend Road below two small non-cleared subcatchments in the Helena West management unit (Fig. 2.2). The Little Darkin River discharges directly into the Darkin River arm of the reservoir. Flow and salinity measurements, begun in 1969, do not include flow measurements for 1999–2005. It had 2.2 times the normal flow in the first year after the 2004 wildfire (Barrett pers. comm. 2006).

2.4.6 Pickering Brook and Rushy Creek

The Pickering Brook and Rushy Creek (Appendix A2.1, Photo 5) gauging stations are respectively beside Slavery Lane and Byfield Road within the Helena West management unit (Fig. 2.2). Their small subcatchments discharge from opposite sides into the reservoir approximately 4 km from Mundaring Weir. Although the Pickering Brook subcatchment is largely undisturbed, some of the Rushy Creek subcatchment along the north-western boundary is cleared. Flow and salinity measurements began in 1969, continued to the end of the 1998 water year, and for Pickering Brook resumed in 2005.

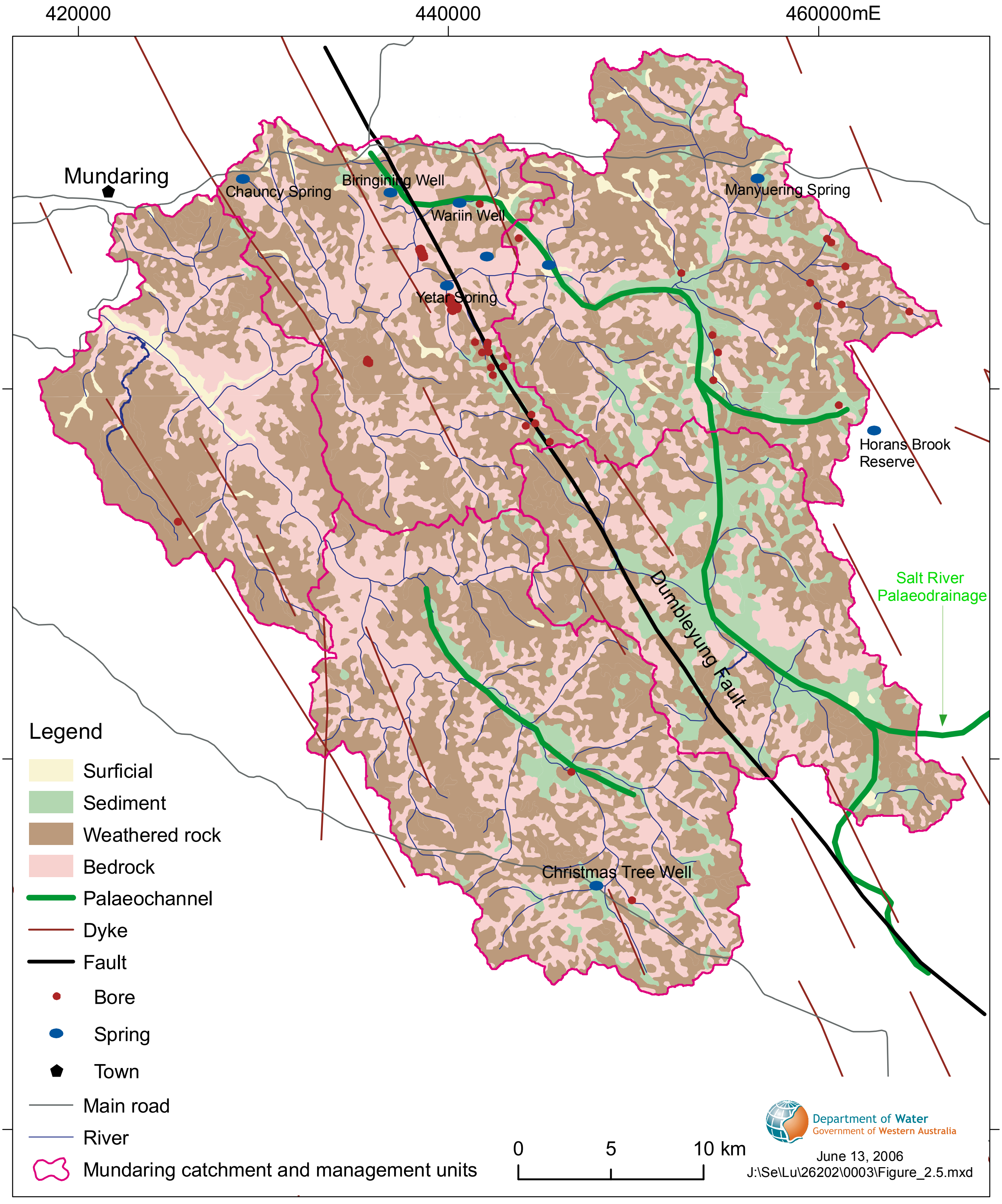


Figure 2.5 Hydrogeology

2.5 Geological setting

The Mundaring catchment lies within the Western Gneiss Terrane of the Yilgarn Craton (Myers 1990). Forming the western boundary of the Yilgarn Craton is the Darling Fault, about 15 km west of the Mundaring catchment. During the Cretaceous this fault formed the eastern margin of the major rift zone by which Greater India was split from Australia. The Dumbleyung Fault is the only major regional shear zone mapped crossing the catchment (Fig. 2.5 shows the hydrogeology not the geology) despite prominent lineations revealed on the DEM (Fig. 2.1) and the fracturing that influenced the design of the Weir. It passes near Yetar Spring and the Flynn plantation (Fig.1.1). Uplift of the Darling Plateau in the Cainozoic (Cope 1975) altered the ancient drainage (Salama 1997) so that palaeochannel sediments are rarely coincident with the present drainage lines. The landform linear direction is north-west, following the lithological and structural trend of the Precambrian (predominantly Archaean) bedrock, and swings more northerly in the north of the catchment and as the lineaments converge on the Darling Fault (Figs 2.1 & 2.5). A few east-trending lineations are also apparent. Figure 2.5 omits surficial units (Table 2.2) that are thin and unsaturated, so the bedrock appears more extensive than on a geological map of outcrop.

2.5.1 Geology, soils, landforms and the weathering profile

Bedrock (Appendix A2.1, Photos 5, 10, 21, 23 & 25–27) is primarily granite that invaded linear belts of metamorphosed sedimentary rocks (Biggs et al. 1980). Whincup (1969), in detailing the geology and geomorphology for the siting of the Lower Helena Pumpback Dam, describes both north-west and south-west shearing in the bedrock. Whincup (1970) also mapped potential dam sites on the Darkin and Helena rivers just above the Mundaring Reservoir. Here more dykes were oriented almost north than were oriented between north and east.

Capping the bedrock are undulating lateritic duricrusts (Murdoch University 1987; Appendix A2.1, Photo 5) that merge with very sandy, lateritic duricrusts associated with patchy areas of (recently interpreted inset-valley or palaeochannel) sand, some gravel and clay, mapped by Wilde and Low (1978 & 1980). These Tertiary sediments occur high within the Mundaring catchment, at about 250 to 300 m AHD (Table 2.3; Appendix A2.1, Photos 11–15). Research for this report indicates that these sediments probably represent an ancient infilled drainage system (Smith & Smith 2005). The sands themselves have been deeply weathered and even their quartz grains have fractured since deposition within a north-west draining landscape of at least 60 m relief (Asumadu et al. 1991). Apart from local depressions and identified palaeochannels, Cainozoic sediments are thin.

Commander et al. (2001) describe the better known palaeochannels in the Wheatbelt to the east of the Mundaring catchment as infilled river courses containing up to 60 m of Eocene or Pliocene sediments. These are overlain by up to 20 m of more recent sediments, and soils of colluvial, alluvial, lacustrine and aeolian origin. The term 'buried inset-valleys', only recently introduced by de Broekert and Sandiford (2005), encompasses valley-fill deposits associated with palaeochannel sediments. Salama (1997) indicates that the Salt River palaeodrainage approaches the Mundaring catchment from the east, hence the name on Figure 2.5. Beneath the present Salt River, sediments at depths approaching 60 m (about 160 m AHD) and dated as Miocene may represent the post-fluvial, lacustrine deposition following uplift of the area west of Darkin Swamp, or a significant climate change.

Table 2.2 Stratigraphy and aquifers

Stratigraphy (columns 1–5) after Wilde and Low (1978 & 1980)

Age			Geological unit	Lithology	Aquifer		
Cainozoic	Quaternary	Recent	Swamp and lacustrine deposits (Qrw)	Peat, peaty sand and clay	Surficial	500–1000 mg/L (west catchment)	> 3000 mg/L (east catchment)
			Alluvium (Qra), some associated with palaeochannels*	Sand, clay and loam			
		Recent to Pleistocene	Colluvium including valley-fill sediments (Qrc); and sand associated with older drainage courses (Qrcs)	Clay and sandy clay, variably lateritized and podsolized; Sand			
			Alluvium and minor colluvium developed on laterite (Qa)	Sand and clay			
			Sand, variously reworked, associated with older stream channels* (Qas)	Sand			
			Sand, hummocky deposits marginal to stream channels (Qs)	Sand, bright yellow			
			~~ Unconformity ~~~~~~~~				
	Tertiary	Late Eocene	Sand (Czs) overlying laterite, often associated with drainage courses*	Sand, yellow, white or grey	Sedimentary*	Typically 100–2000 mg/L and some 3000 mg/L	
			Laterite (Czl)	Ferruginous duricrust, chiefly massive, but includes overlying pisolithic gravel and lateritized sand			
			*Palaeochannel sediments infilling buried inset valleys (Ts)	Also overlies palaeochannel gravel and sand			
Mesozoic			~~~~~~~~ Unconformity ~~~~~~~~				
Undetermined Precambrian			Mafic dykes (d)	Dolerite and gabbro, fine to coarse-grained	Weathered and/or fractured rock	140–1000 mg/L (west catchment)	3000 to 5000 typically but up to 18 000 mg/L (east catchment)
Archaean			Quartz dykes and veins (q)	Quartz			
			Granitoid bedrock (Age, Agg, Agp, Agv, Agm, Am, Amh) and weathered profile	Mostly various granites, minor migmatite, sandy clay			

*The sedimentary aquifer comprises discontinuously mapped palaeochannel sediments (Ts) associated with Qra, Qas and Czs

Table 2.3 Elevation of topmost Tertiary sediments

Location	**Elevation** (m AHD)
Browns and Goonaping Swamps (to the south)	260–265
Darkin Swamp	240–245
Little Darkin Swamp	255
Horans Brook Reserve (to the ESE of Mt Talbot)	310–320
Ngangaguringuring waterpoint	255
Goods Road quarry	225–245
The Lakes (to the north-west)	275

2.5.2 Soil—landscape systems

The soil (and vegetation) maps strongly reflect the geology and landform distribution (Table 2.4, Figs 2.5 & 2.6) and have as their basis the work of Churchward and McArthur (1980).

Laterite duricrust up to 5 m thick (Murdoch University 1987) appears high in the landscape and, where occurring on slopes, diminishes downslope. The lateritic duricrust is not preserved east beyond the Mundaring catchment (Wilde & Low 1978, 1980), indicating greater erosion in catchments toward the Salt River (Salama 1997). The corresponding soil–landscape systems are Darling Plateau (Dp), occupying the western part of the catchment, and Wundowie (Wn) in the central part of the catchment.

The soil on slopes typically lies on duricrust above a sandy loam over a mottled iron-rich zone and a pallid iron-poor zone. Within this typical weathered bedrock profile the mottled zone contains a higher proportion of macropores and less clay than the pallid zone beneath (saprolite, see Glossary). The corresponding soil–landscape systems are Murray Valleys (Mv) in the deep western valleys, Clackline (Cc) in the eastern Helena valley, and Boyagin (By) near the eastern headwaters of the catchment. The final soil–landscape system is Dale (Da) corresponding to swamps in the east.

Table 2.4 Soil—landscape system names and descriptions

System	Landform	Geology	Soil type	Vegetation
Murray Valleys (Mv)	Deeply incised valleys	Colluvium over granitic rocks	Red loamy earths, shallow duplexes and rock outcrops	Jarrah–marri–wandoo forest and woodland with mixed shrubland
Darling Plateau (Dp)	Lateritic plateau	Deeply weathered granitic rocks	Duplex sandy gravels, loamy gravels, shallow and deep gravels, deep sands, wet and semi-wet soils	Jarrah–marri–wandoo forest and woodland
Wundowie (Wn)	Lateritic plateau with some rock outcrops	Deeply weathered granitic rocks	Deep sandy gravels, loamy gravels and shallow gravels	Jarrah–marri–wandoo forest and woodland
Clackline (Cc)	Moderately dissected areas with gravelly slopes and ridges and minor rock outcrops	Deeply weathered granitic rocks, plus colluvium over metamorphic and granitic rocks	Grey sandy duplexes, some gravels, rock and loamy duplexes	Wandoo–jarrah–marri–jam–York gum woodland
Boyagin (By)	Terrain rejuvenated by headward incision of Dale River, exposing irregularly undulating granite with prominent isolated and extensive lateritic mesas	Margins of granite pluton (adamellite, some granodiorite, minor migmatite, dolerite intrusions)	Sandy and loamy gravels and sands on mesas, gradational and duplex soils on granitic slopes, colluvial loamy and gravelly duplexes and clays below scarps	Jarrah, marri, powderbark and dryandra on laterite, sheoak near granite, York gum on loams, wandoo on duplexes and flooded gum in wet positions
Dale (Da)	Broad and swampy flat valleys with low rises	Partially lateritized alluvium and colluvium over sediments associated with palaeodrainage courses	Deep pale sand, pale gravelly sand, sandy duplexes, wet soil and minor rock outcrop	Marri, wandoo, jarrah, sheoak and Proteaceae heath on gravelly rises, York gum and jam near rocks. Swamp paperbark (*Melaleuca* sp.), rushes (*Juncus* sp.)

Source: Department of Agriculture 2004

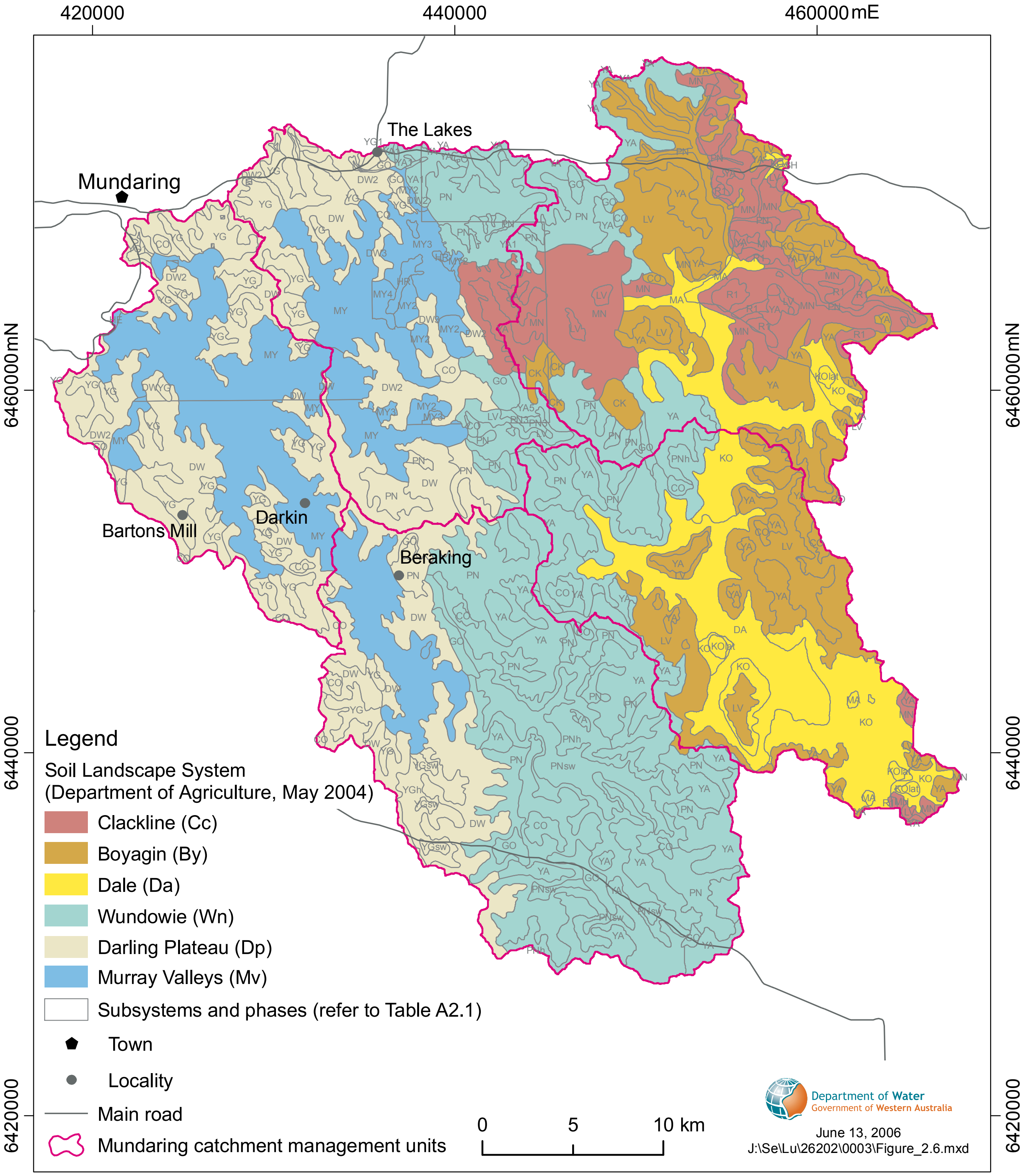


Figure 2.6 Landforms and soils

Soil between 1 and 3 m depth is less clayey and more permeable than the deeper weathered profile. The Department of Agriculture (2004) soil–landscape systems database provided the properties – thickness, (saturated) permeability, ratio of voids, field capacity, and wilting point – used in the top layer of the MAGIC model (Section 4.1.1).

2.6 Groundwater occurrence and conceptual models

The weathered profile (Czl), fractures and joints of the mainly granitoid bedrock (Ag*, together with migmatite Am), quartz veins (q) and possibly some conduits associated with dolerite (d), are collectively referred to as weathered and/or fractured rock aquifers (Table 2.2, Fig. 2.5). Sedimentary aquifers comprise the terrestrial sediments. They are discontinuous, not mapped in detail (Ts associated with Qra, Qas & Czs) and some are discharging saline groundwater. Surficial Quaternary aquifers (Q*) overlie both these aquifer groups and comprise mainly unconsolidated sediments. Most groundwater occurs in the weathered profile (Czl), fractures and joints of the mainly granitic (Ag*) bedrock. Groundwater movement is extremely slow with hydraulic gradients strongly influenced by topography. Groundwater flow systems are mostly shallow, discharging via the surficial aquifer into dissecting drainages or lakes.

The groundwater parameters for catchment modelling (e.g. MAGIC), in the absence of specific testing, are generalised as follows:

- Surficial units up to 5 m thick (most of the Q* in Table 2.2) are widespread but depending on lithology and elevation are not usually saturated, forming only local ephemeral aquifers with saturated thicknesses of just 1 m. Vertical conductivity may be as high as 1 m/d in these thin sands.
- Sedimentary units (mostly Qra & Qas with Czs in the north, Table 2.2, Fig. 2.5) form an extensive aquifer up to 40 m thick. They rest directly on impermeable bedrock, have sloping bases with varied thickness and so may average 25 m thick. They have estimated vertical and horizontal conductivities of 1 m/d.
- Weathered bedrock averages 20 m thick on the hills but only 5 m in the valleys and at seeps (Fig. 2.5). It has horizontal and vertical conductivities up to 0.1 and 0.005 m/d. Directly above the impermeable bedrock it may contain 3 m of saprolite grit with a hydraulic conductivity up to 0.8 m/d.

Figure 2.7 illustrates the two main conceptual groundwater models for the Mundaring catchment; that is, the presence or absence of Tertiary (palaeochannel) sand. For most of the catchment, where the weathered bedrock extends to the stream, imagine weathered bedrock in place of the Tertiary sand on the right. Granitoid bedrock commonly forms the base of the system as it has negligible transmissivity.

2.6.1 Surficial aquifers

The unconfined surficial aquifers (Qrw, Qra, Qrc, Qrcs, Qa, Qas, Qs) (Fig. 2.5), situated within discrete occurrences of surficial material overlying the basement rocks and possibly Tertiary sediments (Czs) in some locations, are typically up to 5 m thick. Their composition and occurrence are summarised in Table 2.2. They consist of lacustrine (Qrw), alluvial (Qra) and

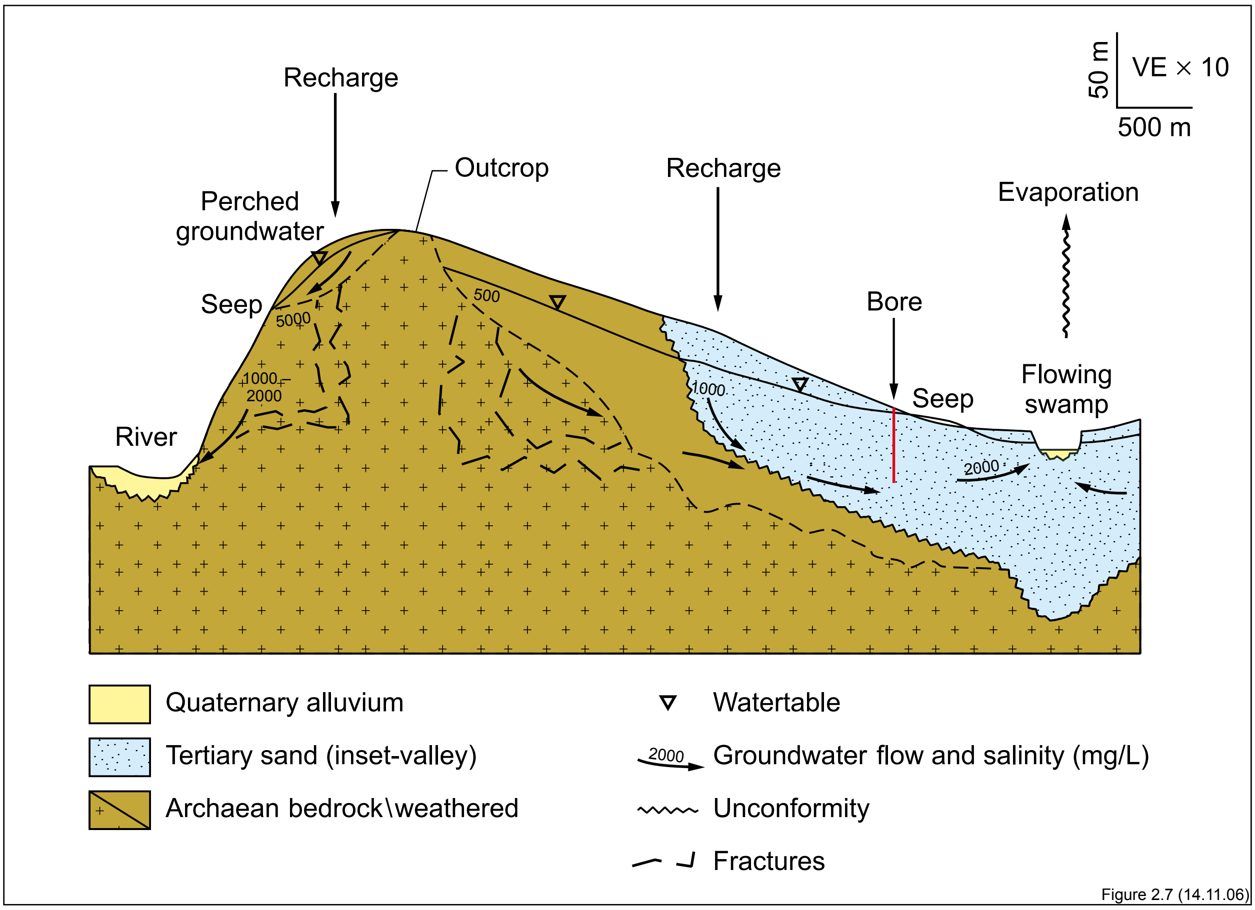


Figure 2.7 Diagrammatic section of hillside seeps and valley floor springs near the Ngangaguringuring gauging station

colluvial (Qrc & Qrcs) deposits, and are widespread but not extensive within valleys, broad flats, wetlands, some lower slopes, high in the landscape (Qa), and associated with stream channels (Qas & Qs). These aquifers are recharged by direct infiltration of excess rainfall or runoff. They also transmit upward discharge from the weathered and/or fractured rock aquifers and sedimentary aquifers. Groundwater loss is mainly through evapotranspiration. These aquifers form a minor water source only in the higher rainfall areas towards the south-west of the catchment. The salinity of the groundwater varies significantly depending on the long-term rainfall.

2.6.2 Sedimentary aquifers

The unconfined to semi-confined sedimentary aquifers (Ts mapped mostly as Qra, Qas & Czs) are now recognised as significant sources of saline water in the Helena subcatchment (Fig. 2.5). The largest of these minor local aquifers extends north-north-west through Goonaping, Darkin and Little Darkin swamps (Appendix A2.1, Photo 35). The sediments comprise mostly sand and gravel deposited in palaeovalleys and topographic depressions eroded into weathered bedrock and are suspected to be Late Eocene in age (Table 2.2). The discrete occurrences appear to have been connected with ancestral drainages east of the catchment (Commander et al. 2001; Salama 1997). These sediments extend north-west for about 50 km across the east of the Mundaring catchment (about half in the each of the Darkin and Helena subcatchments). In

Figure 2.7 they resemble valley-fill deposits (de Broekert & Sandiford 2005) although they are referred to as palaeochannel sediments in this report.

Other Tertiary sediments in the south-west of Western Australia have been dated as Late Eocene (although Salama (1997) located Miocene sediments). These sediments lie unconformably on Precambrian and mostly Archaean basement rocks and have been correlated to the Werillup Formation of the Eucla Basin (Clarke et al. 2003). The setting and characteristics of the sedimentary sequences within the catchment (Smith 2003a; Wilde & Low 1980) appear to be synonymous with the Plantagenet Group, in the absence of confirmation using palynology or water-quality fingerprint sampling (for high sulfite concentrations due to oxidation of pyrite in lignite lenses).

The sediments appear as predominantly fluvial and lacustrine (gravel, sand, silt and clayey sand) deposited unconformably on fresh and weathered bedrock. The maximum aquifer thickness reported is 40 m in bores near Goods Road where multiple layers of very coarse-grained angular sand are exposed in a quarry (Smith 2003a; Appendix A2.1, Photos 11–15). The top of the formation has not been identified but prior to dissection may have been planar, as on the south coast (Smith 1997). Indeed, present levels indicate a westward decline from about 300 to 225 m AHD (Table 2.3, Fig. 2.5).

A comparison to sand north of Perth indicates that since vegetation clearing between Goods and Abercorn roads (Fig. 1.1, Appendix A2.1, Photo 18), and in the absence of overland flow (see Glossary), recharge to the aquifer may be as high as 30% (Davidson 1995 Fig. 27). Before clearing, rainfall recharge under low-rainfall conditions may have been around 1% for weathered bedrock. Groundwater salinity, obtained only for this area, is about 2000 mg/L and indicates low salt storage with high recharge and throughflow. On Figure 2.7 the sediments to the right have much greater salt storage and throughflow and therefore impact on catchment salinity than those on the left. Their characteristics reflect permanent clearing in the 1970s and with salt being exported from storage the salinity should now be falling. Reforestation could reduce recharge and halt the saline-to-brackish discharge (Appendix A2.1, Photos 16–18, 27 & 28). To better characterise the groundwater in this catchment requires substantial geochemical sampling.

2.6.3 Extensive weathered and/or fractured rock aquifers

Groundwater in the totally weathered bedrock profile occurs mainly in the saprock horizon (see Glossary) overlying hard granitic (Ag*) and migmatitic (Am*) bedrock (Appendix A2.1, Photos 19–27). This aquifer is commonly semi-confined to confined and comprises more resistant coarse-grained quartz grit, sand and gravel in a clay matrix. Among the totally weathered rock aquifers, sandy profiles tend to be derived from weathered granitic rocks and the more clayey profiles tend to be derived from the total weathering of migmatite. Thus the aquifers associated with the totally weathered profile of granitic rocks can produce higher yields than those associated with migmatite. Clay layers can occur anywhere in the profile and the permeability can vary significantly over a small scale or appear uniform in a subcatchment. The totally weathered rock aquifer is largely very permeable to infiltration, although hydraulic connection to the profile is poorer and commonly controlled by an aquiclude (no infiltration) or aquitard (retarded infiltration).

Peck et al. (1980) reviewed the hydraulic conductivity, measured by the slug test method, for unconsolidated, deeply weathered material at sites including the 'upper Helena River' (the Helena subcatchment) and nearby Bakers Hill areas. Within the zone 0–3 m above hard bedrock, values for hydraulic conductivity were low to moderately low and relatively uniform on the broad scale, with the highest value of 0.12 m/d obtained from the Helena subcatchment and a value of 0.0082 m/d from the Bakers Hill area. A hydraulic conductivity as high as 1 m/d (moderate) is unusual for these materials (George 1992; Clarke et al. 2000).

Bedrock structure shows a north-westerly trend that clearly affects surface drainage, but bedrock inhomogeneities, such as faulting, are much less likely than are topography and the composition of the weathered profile to influence groundwater movement. The north-west and east-trending faulting form fractured rock aquifers beneath the weathered saprock aquifers. The most prominent of these is the Dumbleyung Fault that passes near Yetar Spring and the Flynn plantation (Figs 1.1 & 2.5). Fractured rock aquifers outside major fault zones may extend no more than 10 m below the weathered profile (De Silva 2003). Groundwater yields from these fractured rock aquifers are dependent on the intensity of jointing and fracturing in the bedrock, openness of fractures and joints, the lithology of the rock, access to a recharge area, and the amount of recharge.

Groundwater flow within the weathered and/or fractured rock aquifers is mainly in short, low-volume flow systems originating close to the local surface water divide and discharging at points of expression, such as breaks-of-slope and the nearest drainage line (Appendix A2.1, Photos 19–22). Recharge to these aquifers is mainly by direct infiltration of rainfall or runoff and there may be some leakage or throughflow from surficial and sedimentary aquifers higher in the landscape. Groundwater discharges from the weathered and/or fractured rock aquifers to watercourses and wetlands, and into surficial and Tertiary sediments that occupy lower slopes and valleys, and from shallow watertables by evapotranspiration.

2.6.4 Minor weathered and/or fractured rock aquifers

Dolerite dykes (d), within the Yilgarn South-west Groundwater Province, are not as scattered in the Mundaring catchment as mapped (Wilde & Low 1978, 1980). The fine-grained structure of dolerite dykes tends to weather to a dark grey to grey clay or sandy clay with a low effective porosity. These units commonly form impermeable or semi-permeable barriers to groundwater movement. When a dyke is located obliquely across a slope, groundwater is commonly found at the upslope contact between the dyke and bedrock and moves downslope along this boundary.

2.6.5 Fractured rock aquifers

Quartz veins (q) and quartzite, due to their brittle nature, have a higher density of joints and fractures than surrounding bedrock and can store significant volumes of groundwater. They yield up to 500 m^3/d of low salinity groundwater near Manjimup (Prangley 1994) but have not been found in this catchment.

2.7 Vegetation and cleared areas

2.7.1 Vegetation complexes

Mattiske & Havel (1998) described the vegetation complexes in the catchment prior to European settlement (Fig. 2.8). The vegetation patterns reflect the influences of landforms, soils and climate as recognised by early workers (Heddle et al. 1980). Nearly all of the catchment has tree cover – mostly native forest with some plantations in the west (Figs 2.9–11; Appendix A2.3). The plantations are mostly pine and none is in the Ngangaguringuring or Darkin Swamp management unit. The canopy cover decreases from about 75% in the west of the catchment, where jarrah (*Eucalyptus marginata* Sm.) is the main species (Ward 1977), to about 20% in the east, where wandoo (*E. wandoo* Blakely) is the main species. Marri (*C. calophylla*) and powderbark wandoo (*E. accedens*) respectively are minor species in the west and east (Stokes & Batini 1986).

2.7.2 Clearing history

The first major removal of forest canopy in the catchment was in 1903 just after the Mundaring Weir was completed. In response to a succession of dry years when the reservoir did not fill, approximately 80 km^2 of forest was ringbarked. This area included about 48 km^2 with high rainfall close to the Weir and about 18 km^2 of the Helena subcatchment immediately to the east. This treatment appeared to increase runoff, although the effect was partially masked by a wetter-than-average year in 1907. Streams were found to be saltier than before the clearing, and there was a rise in the total amount of salt flowing into the reservoir. The maximum recorded stream salinity was 1540 mg/L TDS (Dixon 1996, for TDS see Glossary). To remedy the situation, regrowth forest was allowed to replace the original stand and some pines were planted on parts of the ringbarked areas (Fig. 2.10) in the second and third decades (Dixon 1996). Salinity in effect drove revegetation and preservation of vegetation within the catchment thereafter. The salinity of Mundaring Reservoir reached 550 mg/L (Stokes & Batini 1985, 1986) before subsiding. However, since 1960 the salinity in the reservoir has been increasing again with even higher stream salinities, largely due to clearing in the east of the catchment (Batini & Selkirk 1978).

The second major removal of native forest was post-World War II clearing of private property from 1948 (Fig. 2.11) for grazing and grain growing (Dixon 1996). This recommencement of the clearing–salinity cycle, after the completion of soil surveys in 1947 (Bennett & McPherson 1983), coincided with the advent of suitable fertilisers and machinery for this marginal and hilly land, mostly in the medium or low-rainfall areas (Ward 1977). Such episodic clearing and development was common in Western Australia, and Conochie (1979) indicates some of the factors. The link between clearing and salinity was already established in the Mundaring catchment and now scientists observed elsewhere that farmed catchments were much greater exporters of chloride than forested catchments (Peck et al. 1973) and explained the vertical salt profile using transects south of the Mundaring catchment (Johnston 1981).

This second major removal of forest continued into the late 1960s and may also have raised reservoir salinities. The Public Works Department (PWD), after taking over from the Goldfields Water Supply (GWS), planned a major new dam just upstream of the present reservoir, (on Allen Road below Jones Crossing on Gorrie Road) about 1 km into the Helena West

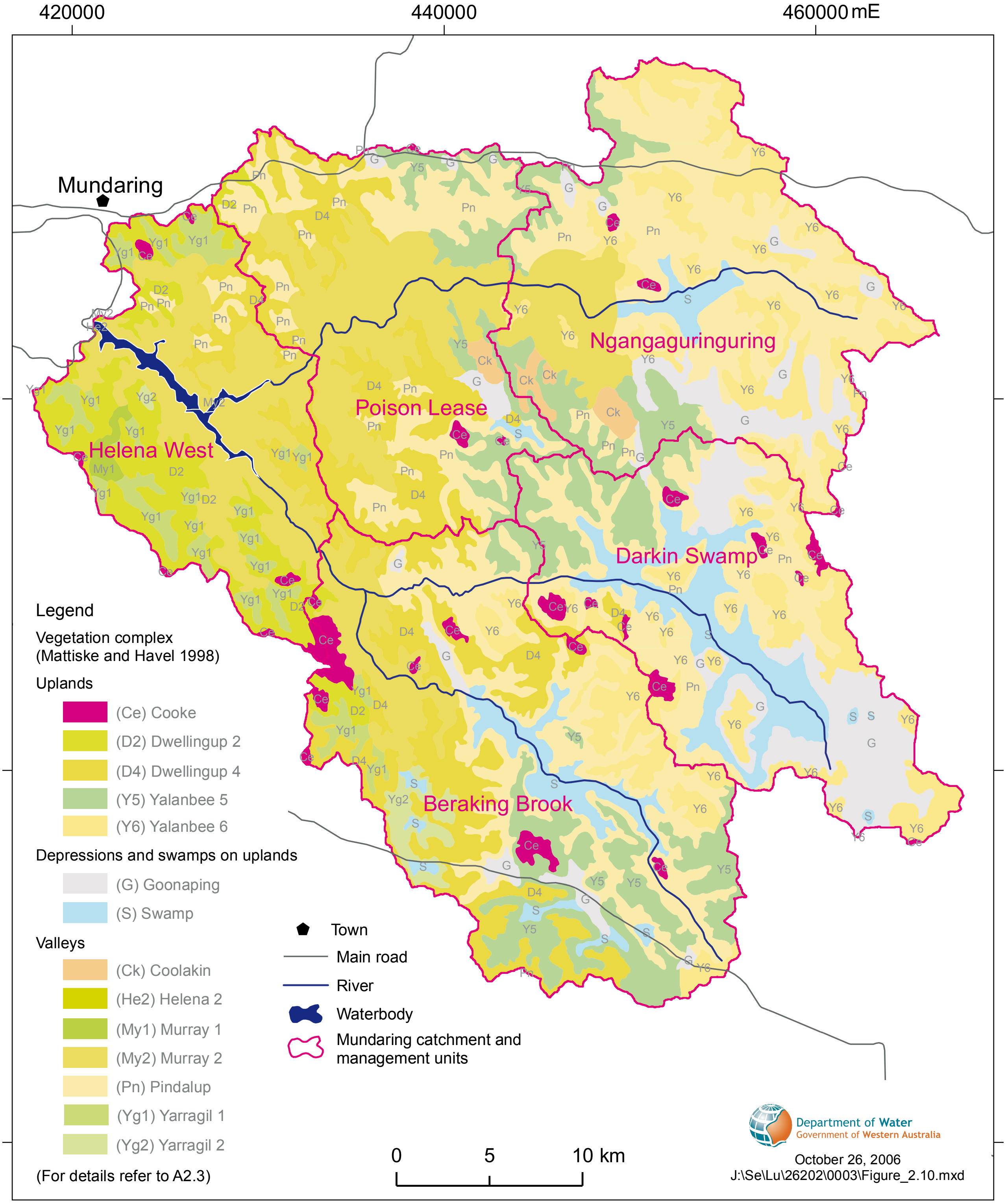


Figure 2.8 Vegetation complexes (pre-European)

management unit. The site was selected, an exploratory trench dug across the valley and the then Forests Department, instructed to clean-cut the proposed dam site to the high-water mark, removed all saleable timber (Underwood pers. comm.). The PWD subsequently cancelled the proposed reservoir, as new streamflow data suggested that it would never fill. The Forests Department regenerated the area by burning it in a seed year, then fully protected it until new saplings were established. Today this area on Nockine Brook and Nockine Road is prime, but uniform, wandoo regrowth with jarrah. The Gorrie pine plantations along the Helena River and Helena Brook are upstream of this proposed dam site.

In addition to large clearing events, virtually all the native forest in the catchment has been logged, with the western quarter logged prior to 1950 and the balance logged in the period 1950–75 to provide firewood for the Wundowie charcoal–iron plant (Batini & Selkirk 1978) and for the GAWS pumps. As the eastern two-thirds of the catchment lies within the low-rainfall zone, the likelihood that this contributed to the rising salinities since the 1960s (Batini & Selkirk 1978) can now also be assessed from the modelled scenarios (Sections 4 & 5), but intuitively, the impact would be more rapid if more trees per hectare were cut. The transient removal of vegetation by logging, wildfires and prescribed burning is not depicted on Figure 2.11.

Commercial pine plantations were established in the period 1967–80 (Fig. 2.10). These were targeted on sandy areas especially in the Poison Lease and Beraking Brook management units, including, Wellbucket and Christmas Tree Well (Fig. 2.5). The pines used more water than the native bush they replaced. The percentage areas remaining cleared are quantified by the graphs in Section 3.3.3.

2.7.3 Salinity management and revegetation

Schofield et al. (1989) judged the banning of Crown land releases and the introduction of clearing controls for water resource catchments as the first serious measures to control salinity. The State prevented further land release in the Wellington, and south to the Denmark, catchment in 1961 and 1978. The Public Works Department supported the practice of maintaining Crown ownership of catchment areas for the city water supply (Power 1963, p.34). To prevent further clearing, the Department purchased 126 km^2 of mainly uncleared farmland, mostly between 1956 and 1965 (Batini & Selkirk 1978; Public Works Department 1979). Subsequently, the partially cleared Chambers' and Flynn's farms were purchased in 1971 and 1972 and reforestation trials (Appendix A2.1, Photo 24) left only 0.60 km^2 of pastured land in the east of the Flynn plantation and predominantly pines on the (Chambers' farm) Wellbucket plantation. Revegetation programs were also undertaken on some of the land cleared for agriculture (Croton & Dalton 1999). Reasons for Crown ownership apart from stopping clearing included the exclusion of agricultural superphosphate, trace elements, chemicals and pollutants that would affect the water quality. Recently, further farm buy-back was recommended by Kabay (2001) to manage downslope saline seeps (Appendix A2.1, Photos 18–22). The Water Corporation purchased 3 km^2 on Abercorn Road in 2002 and 2005.

To further reduce dryland salinity, the Western Australian Government introduced clearing control legislation in the Wellington Dam catchment in 1976 (Public Works Department 1979). Additional catchments were proclaimed under the *Country Areas Water Supply Act 1947* in 1978 to control the clearing of native vegetation and so protect water resources in the Mundaring Weir catchment and three other catchments near the south coast (Public Works Department 1979;

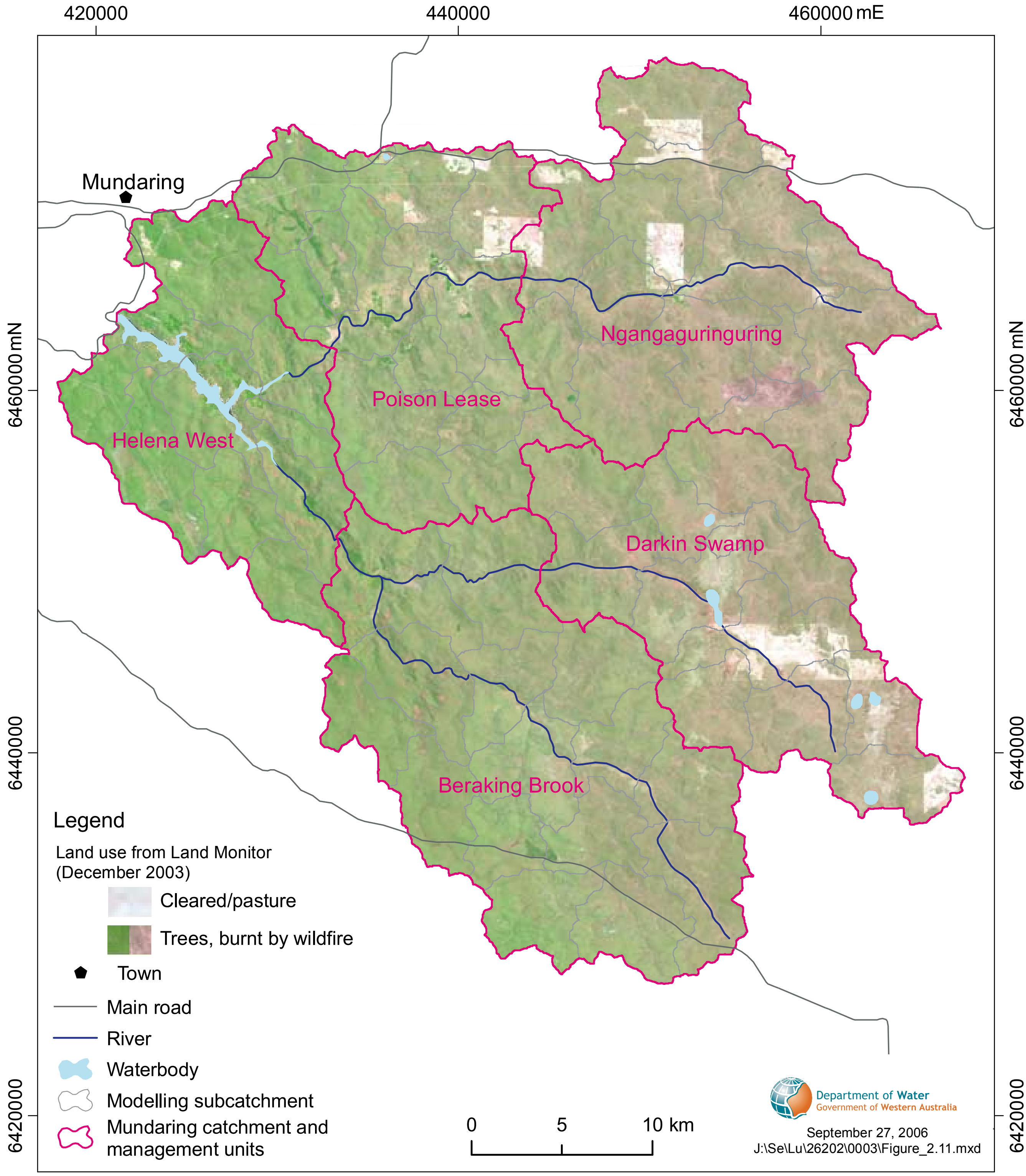


Figure 2.9 Tree cover, cleared and burnt areas (Landsat December 2003)

Sadler & Williams 1981). As this legislation affected silviculture as well as broadacre clearing, clearing licence policy and guidelines were developed to allow continuation of operations that did not permanently remove vegetation. Bosch and Hewlett (1982) found little was known worldwide about the effects of vegetation changes on water yield and evapotranspiration. At the time the clearing controls were imposed, the WAWRC (Western Australian Water Resources Council) predicted that the Mundaring Reservoir salinity could have risen from 360 to 700 mg/L (cf. 1500 by this study) if all private land was cleared (Public Works Department 1979).

The Water Authority of Western Australia (1987a) reported that forest thinning could be used to significantly increase water yield from the high-rainfall areas of the northern jarrah forest. These areas, based on papers by Stokes and Batini (1985, 1986) and earlier by Batini and Selkirk (1978) that supported forestry within the catchment, could be extended to forest with more than 1000 mm/yr rainfall without affecting water quality. Stokes and Batini (1985) concluded that heavy logging (the reduction by 31% of basal area, 42–56% of crown density and 80% of volume of trees suitable for firewood) had little permanent effect on increasing streamflow, saline baseflow and the quality of streamflow where the rainfall is less than 700 mm/yr (this is within the low-rainfall zone, see Glossary). This supports the findings of the Water Authority of Western Australia (1987b) that, on average, regions in the low-rainfall zone display much smaller groundwater responses to logging and regeneration (when allowed to recover naturally) than regions of higher rainfall. The Water Authority of Western Australia (1987b) also observed that the intermediate-rainfall zone was potentially the most affected by logging, with large but temporary increases in stream salinity (Bari & Ruprecht 2003). This was consistent with generalisations much earlier by the PWD (Power 1963, p. 26) that:

- Forested, high-rainfall areas (>1100 mm/yr in Schofield et al. 1988) yield high volumes of excellent low-salinity water and low-rainfall areas (< 900 mm/yr) can yield low volumes of water of acceptable salinity.
- When permanently cleared, low-rainfall areas show large increases in salinity of runoff. The further into the low-rainfall, salt-prone areas that a stream commences, the higher its salinity. Logging together with regeneration does not appear to have this effect (Underwood pers. comm. 2006).
- High-rainfall areas, after clearing, yield larger volumes of runoff that tend to offset the trend for rising salinity to exceed the 'acceptable limits' for domestic supply as more of the forests are cleared. For example, the Jane Brook catchment (that, like the whole Mundaring catchment, falls outside the high-rainfall zone) reached 600 mg/L after clearing for suburban development.

2.7.4 Presently cleared areas

The latest phase of Crown land releases for private purposes, which extended from 1948 (Dixon 1996, p. 2) to the 1960s (Schofield et al. 1989), was partially reversed by the Crown repurchasing land in the 1970s. Batini and Selkirk (1978, p. 3) show the extent of logging, ringbarking and dieback, in response to concerns of Havel (1976). Significant clearing along the internally draining far south-eastern reaches of the Darkin River MU in the 1980s, and a similar clearing event on the eastern edge of the Ngangaguringuring MU prior to the 1970s (Appendix A2.1, Photos 33–34), preceded the redefinition of the Helena hydrological catchment boundary using new elevation data in 2004.

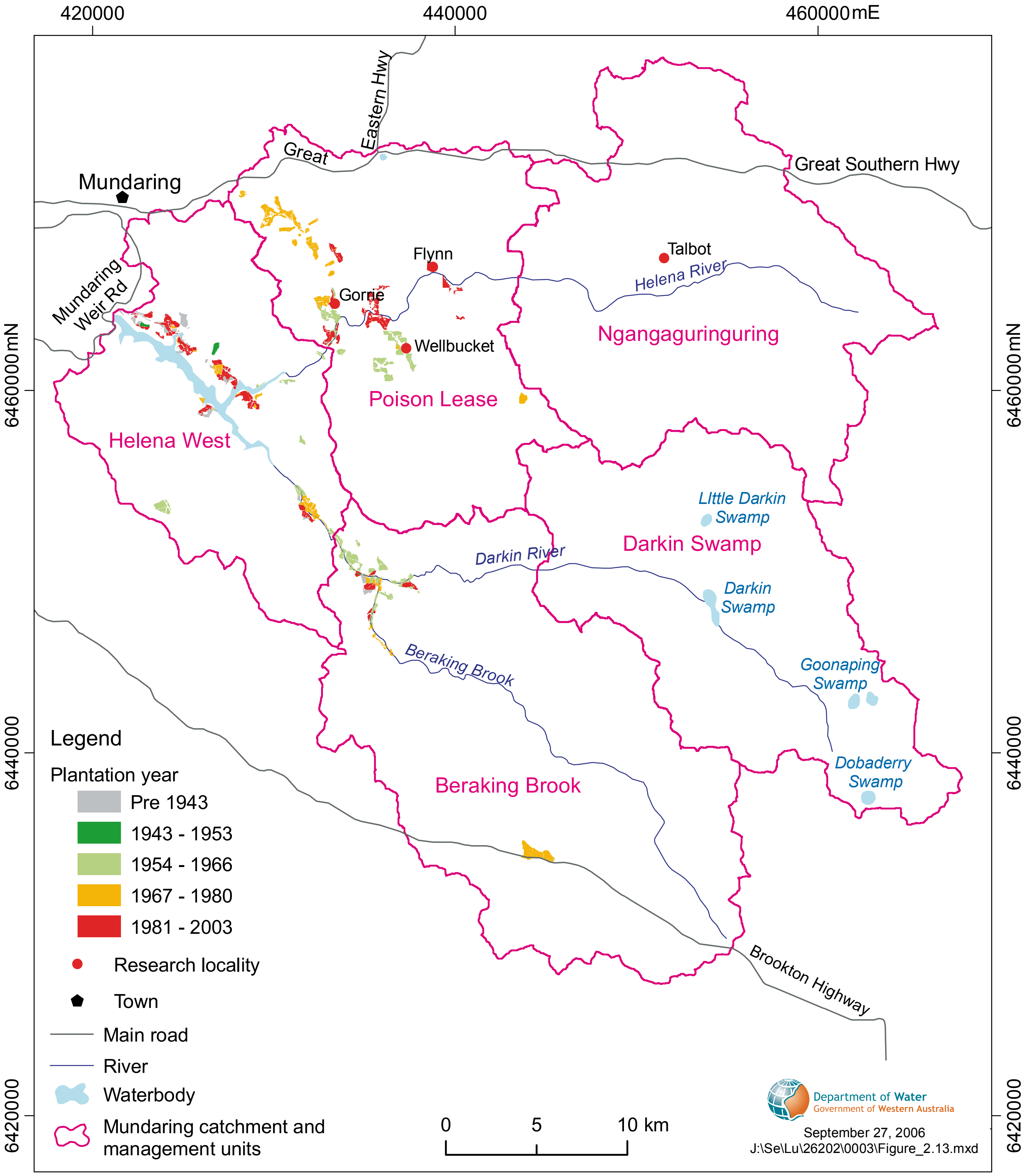


Figure 2.10 Plantation history mosaic

The essentially private-tenure lands permanently cleared of vegetation (Figs 2.9, 2.11 & Table 2.5) now comprise 15.2 km^2 (A & E) in the Darkin subcatchment, 22.8 km^2 (B, C, D, F, G & H) in the Helena subcatchment and 0.5 km^2 (I) in the Helena West management unit (excluding the 6.2 km^2 of reservoir area). Despite there being less than 5% of the catchment in private ownership and only two-thirds of this permanently cleared, highly saline groundwater is discharging to the Helena River at some of these sites (Appendix A2.1, Photo 22). Stokes and Batini (1986) state that this clearing in the low-rainfall zone was particularly responsible for reservoir salinities increasing to a mean of 400 mg/L from the 1960s.

Table 2.5 Areas remaining cleared of tree canopy

Location and extent of clearing (Figs 2.9 & 2.11) (Omits 0.60 km^2 on Flynn not planted and 6 km^2 on Wellbucket recently logged)	**Label**	**Area** (km^2)
Qualen Road farm south of Darkin Swamp – 40% of the 28.49 km^2 that is in the catchment	A	11.8
Abercorn Road and Goods Road – 85% of farms nearby	B	7.2
Great Southern Highway and Wundabiniring Road north-west – 80% of various Lots	C	6.2
Talbot Road West – 90% of Lots 3 & 4 and 80% of a block to the east on Helena Road	D	5.6
Crown lease east of Dobaderry Swamp – 85% of the 4 km^2 that is in the catchment	E	3.4
Mt Observation – 60% of Location 27700 that is now inside the catchment boundary	F	1.4
Great Southern Highway from Manaring Lake to Talbot Road West – 10% of 3 groups of Lots	G	1.2
Farms on Flynn Road north of the Flynn plantation – 65% of 4 Lots	H	1.2
Lake CY O'Connor – several small blocks north of the Reservoir	I	0.5
Total clearing (2.6% of 1480 km^2 catchment and 55% of 71 km^2 (5%) freehold land)		39.0

In 1978, 196 km^2 of the 1480 km^2 catchment was land held as either private or government free/leasehold. Since the establishment of clearing controls in 1978, significant permanent clearing within the catchment has stopped. Only 71 km^2 is now private free/leasehold land. Of this area, 32 km^2 is timbered and compensation has been paid to retain the vegetation on 27 km^2 of native vegetation near Qualen Road, Great Southern Highway and Abercorn-Goods Road (in Localities A, G & B). The rest consists of small areas elsewhere that aggregate to at least 3 km^2 and are uncompensated (Fig. 2.11; Appendix A2.1, Photo 9; Phil Roberts pers. comm. 2006). Only minor attrition and parkland clearing of private land beyond that shown in Figure 2.11 is evident at Flynn Road (in the north-west of Locality H) and just east of there in the sand quarries (Land Monitor 2002). Of the 39 km^2 cleared on private free/leasehold land, 23 km^2 is annual pasture in the flowing part of the catchment and 15 km^2 is above the Darkin Swamp, past which there is little flow. There is also about 3 km^2 outside the CAWSA catchment boundary, near both Dobaderry Swamp and Mt Observation (Fig. 2.11, Localities F & E). In addition, there are for various reasons at least 4 km^2 cleared on government freehold land.

Dieback disease, caused by *Phytophthora cinnamomi*, is not rampant in the catchment and is likely to have affected only small portions of forest in the western quarter of the catchment (Batini & Selkirk 1978, Fig. 2). Fires, both prescribed burns and wildfires, have only short-term localised impacts on flow and salinity but longer-term impacts on erosion and siltation.

The occurrence of Wandoo Crown Death and Decline (WCDD) has the potential to reduce vegetation cover in the eastern parts of the catchment where wandoo is the dominant tree species (Appendix A2.1, Photos 16, 19, 20 & 24). Smith (2003b) examined the effects of reduced rainfall on groundwater levels under wandoo vegetation and in the Flynn plantation catchment (Bari 1998). Water levels (and hence saline groundwater discharge) were found to be stable or declining beneath both pasture and tree plantations. A proportion of these plantations are pines with potentially higher water use than native reforestation.

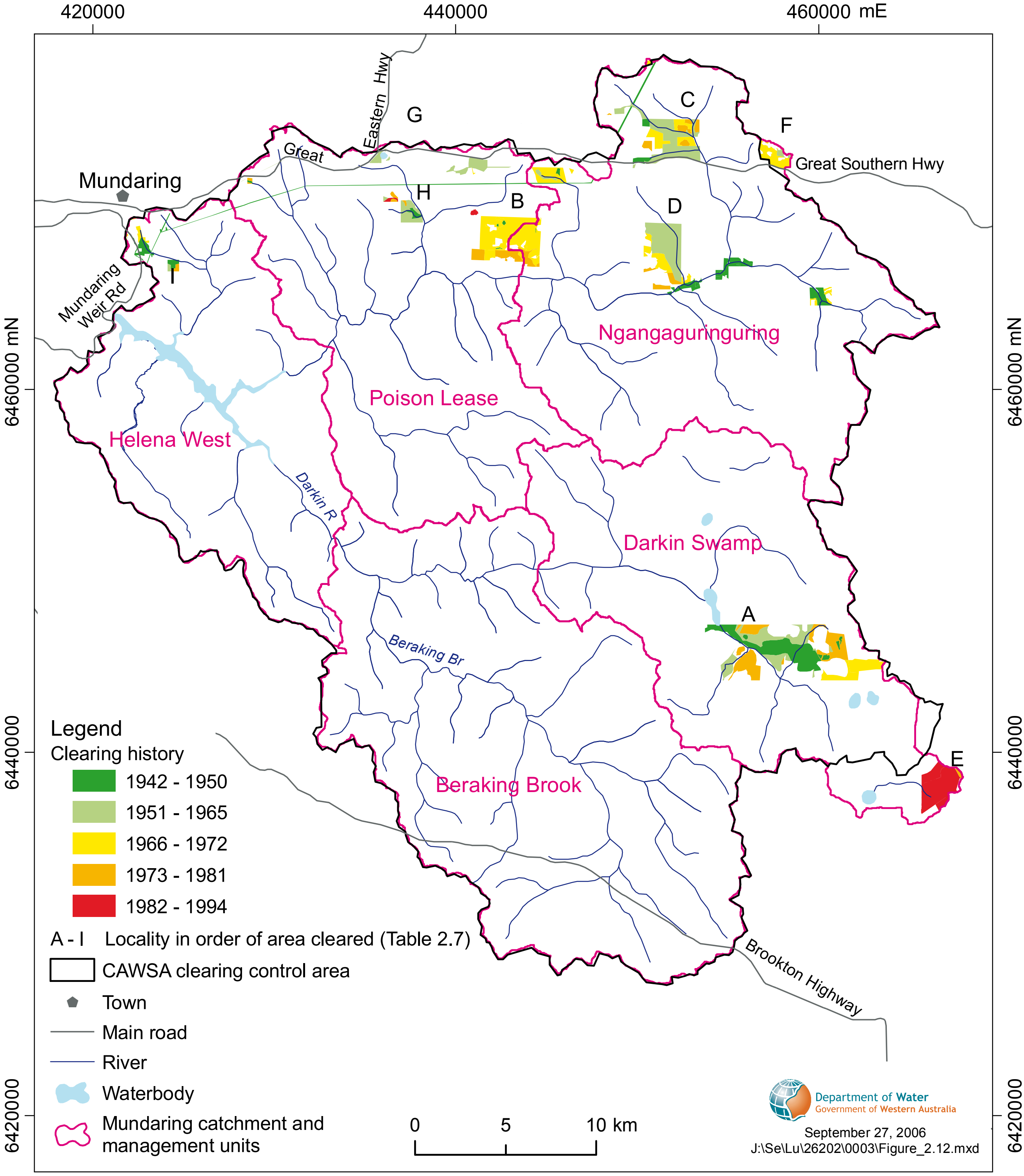


Figure 2.11 Permanent clearing history mosaic 1942-2003

3 Flow and salinity characteristics

The largest flows, from the high-rainfall, highly-incised Helena West MU, in combination with the fresh Darkin River flows, help to maintain low reservoir salinities by offsetting the saline Helena River flows. Yet from 1990–2002 the 593 km^2 Helena subcatchment provided 1.4 times more flow than the slightly larger 665 km^2 Darkin subcatchment (areas bolded in Table 2.1) – down from double the flow in earlier years (Stokes & Batini 1985). The Helena subcatchment has a greater proportion of cleared private land (Fig. 2.10, 2.11 & Table 2.1) than the Darkin subcatchment (Appendix A2.1, Photos 9, 11, 18, 33, 34, & 36), but its more incised landscape probably accounts for their different average annual salinities: 1300 and 190 mg/L respectively (Table 3.1 on p. 49). Most significantly, almost no flow in the Darkin River originates above Darkin Swamp, where the sedimentary aquifer may therefore be retaining and accumulating salt. The Darkin Swamp overflowed in summer 1996 and contributed tannin colouring to the reservoir (Barrett pers. comm. 2006). All salinities in this Section are in mg/L TDS (Total Dissolved Solids), abbreviated to mg/L.

The tendency for groundwater levels in cleared areas to rise, causing groundwater to dissolve and mobilise salt in the subsoil, and for this salty water to degrade nearby vegetation and waterways is not disputed. Groundwater quality ranges from fresh to saline and shows both a regional trend of increasing to the NNE and local patterns of increasing downslope. Where detailed data are available, such as at Flynn plantation (and Wellbucket, Figs 1.1 & 2.5), local-scale patterns (in the weathered bedrock aquifer) are revealed to be more complex and involve more factors (Batini et al. 1977) than just topography, land use and variable rainfall. Salt input ('load') to the Helena Reservoir is nearly all from inherently salty groundwater, either discharging to streams or contaminating surface soils and surface runoff.

3.1 Rainfall

Rainfall directly affects streamflow and groundwater recharge, and has the potential to both increase and decrease stream salinities. As rainfall since the 1970s has been lower than the long-term average (Fig. 2.3), those presented are for 1990–2002 unless otherwise stated (Table 2.1). The rainfall was extrapolated to all the subcatchments (Fig. 2.2) with bias according to distances from the nearer rain gauges (Dean & Snyder 1977). The derived rainfall is the area-weighted mean of the subcatchments upstream of each gauging station and decreases from west to east across the catchment and, to a lesser extent, from south to north, being lower in the Darkin River (640 mm/yr) and Ngangaguringuring (598 mm/yr) subcatchments compared to the 902 mm/yr for the remainder (the Helena West subcatchments). Figures 3.1b–3.4b and A3.2b–A3.5b show the rainfall histories at the northern and southern stream gauging stations and for the high-rainfall western stream gauges.

Typically only 10–20% of rainfall becomes streamflow in the wetter areas and merely 1–2% in drier parts (Ruprecht et al. 1996). There is a disproportionately large decrease in streamflow for a small decrease in rainfall. Large variations in streamflow, particularly in the west, reflect annual fluctuations in rainfall. A long-term 10% reduction in winter rainfall since the early 1970s has reduced streamflow by 30–50% (Ruprecht et al. 1996) in the jarrah forest that extends

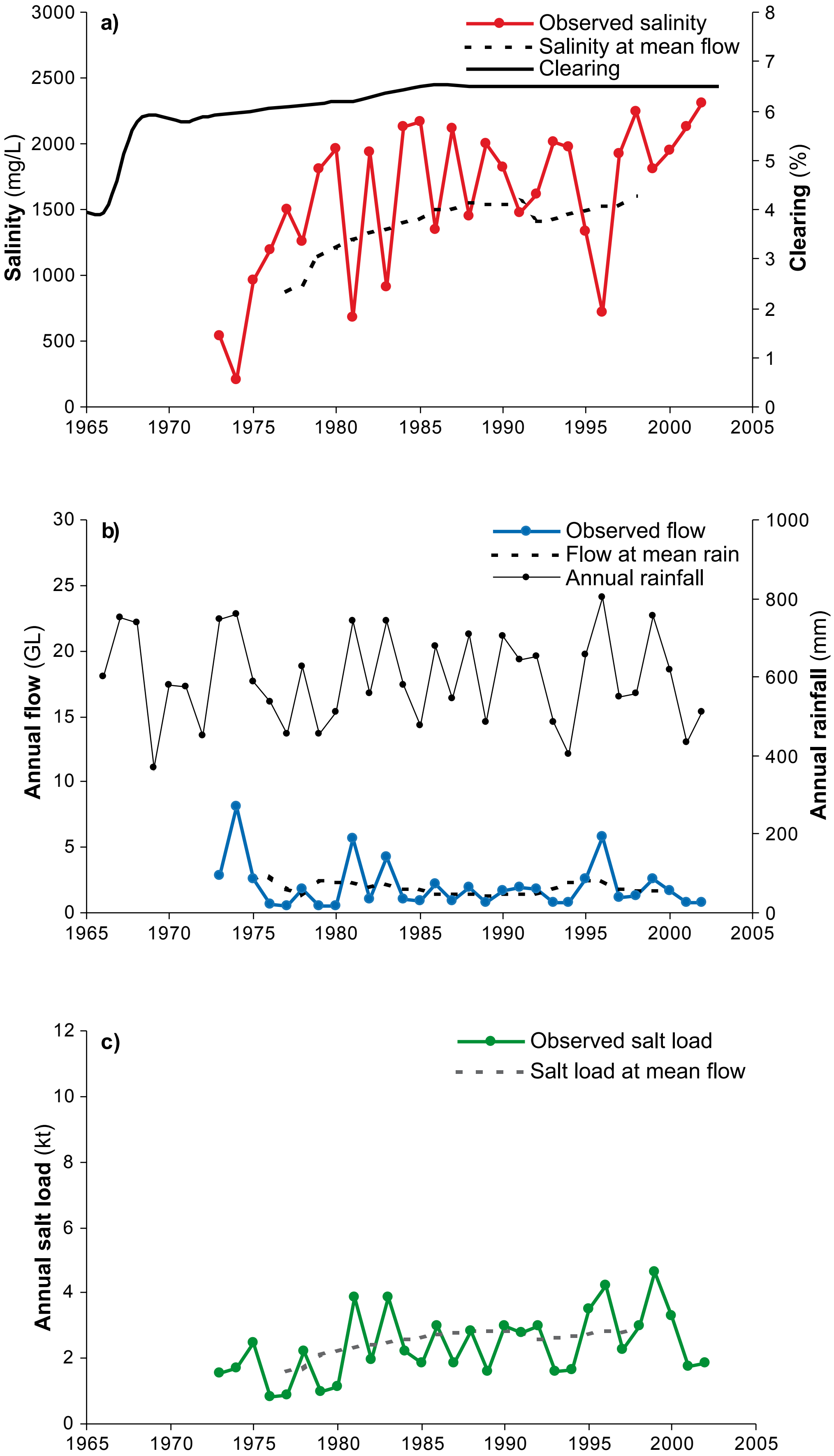
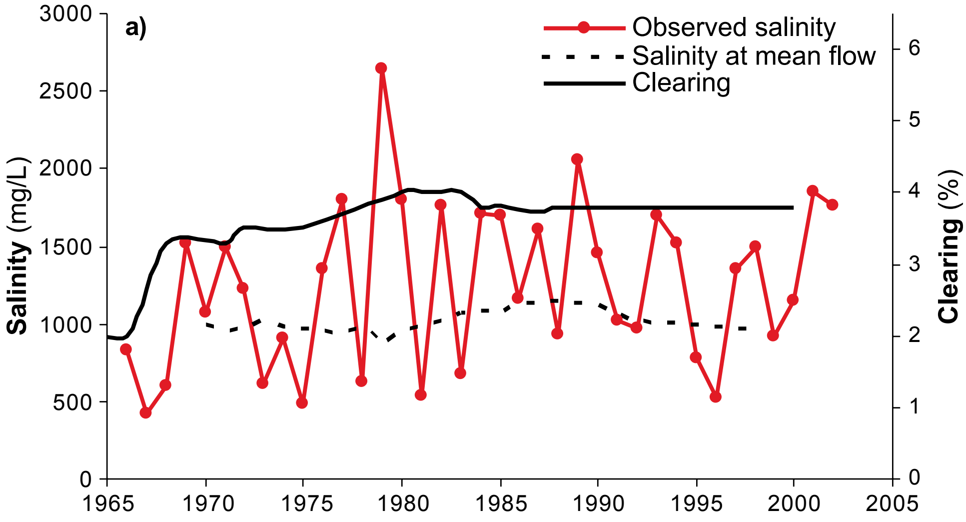
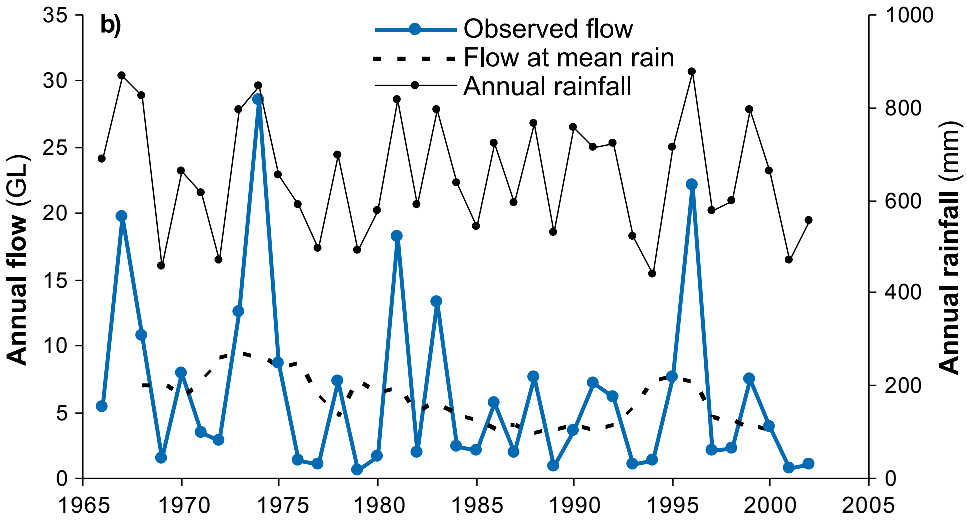


Figure 3.1 a) Salinity b) flow and c) salt load for Ngangaguringuring gauging station





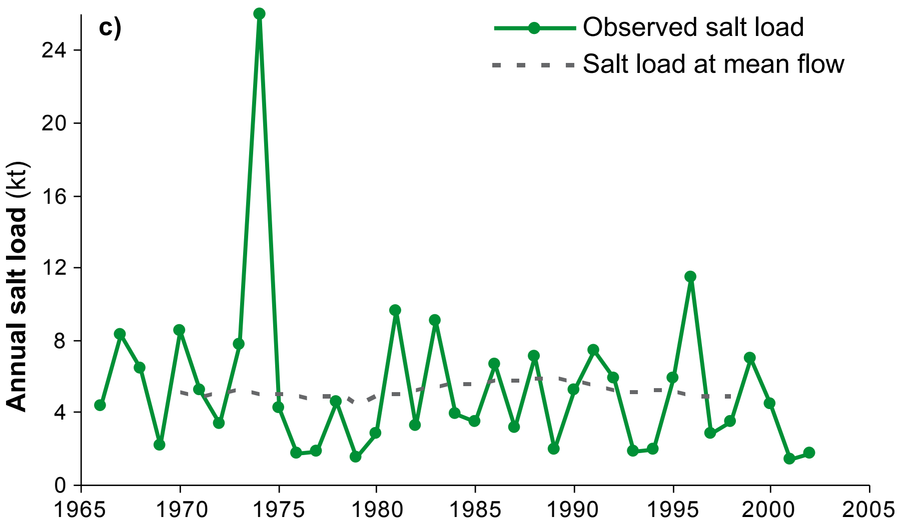


Figure 3.2 a) Salinity b) flow and c) salt load for Poison Lease gauging station

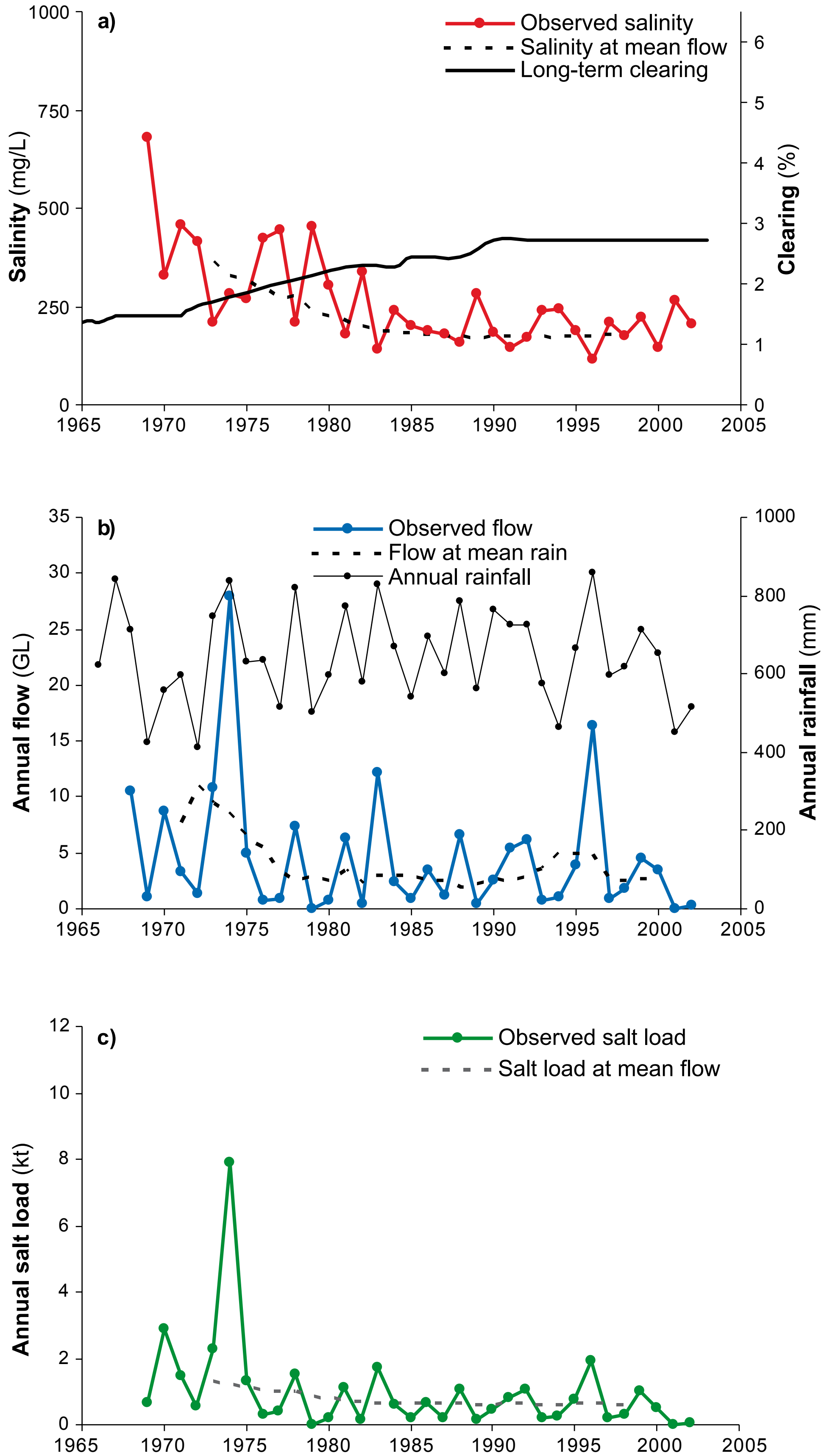


Figure 3.3 a) Salinity b) flow and c) salt load for Darkin River gauging station

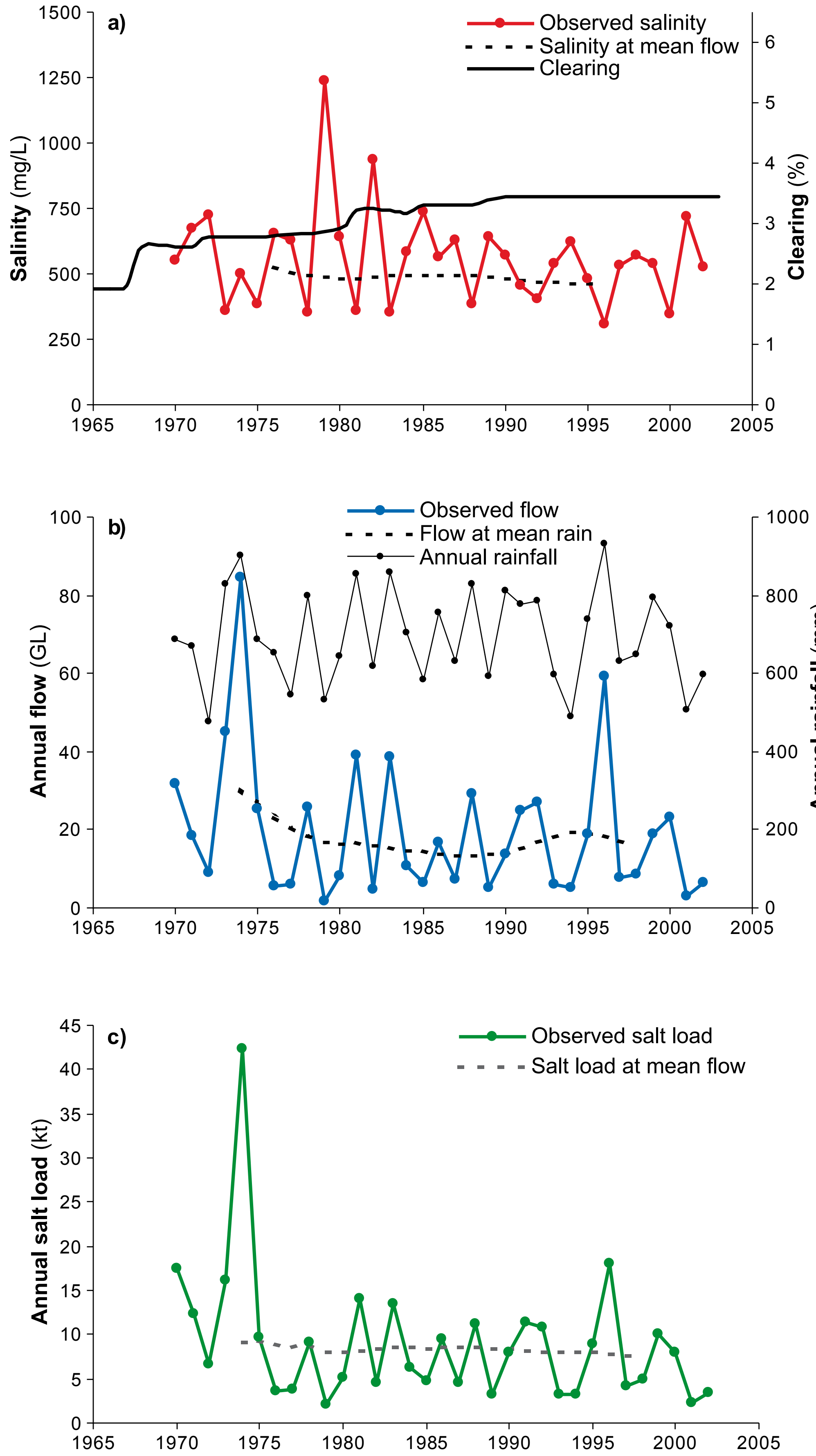


Figure 3.4 a) Salinity b) flow and c) salt load for Mundaring Reservoir inflow

through the wetter (but 50% ungauged) west of the catchment. While the interplay between rainfall and streamflow influences the dilution and flushing of salt from the catchment, it can have more complex effects on groundwater and saline groundwater discharges (discussed further in Section 4).

Figure 3.5 highlights the most recent significant shifts in rainfall, with respect to season, for a station south of the Beraking Brook MU in the south of the catchment. Pluviometers in the east and west of the catchment showed the same pattern of more summer rainfall and less winter rainfall (Appendix 3.1). Summer rainfall, with the exception of extreme cyclonic events, rarely generates streamflow to the reservoir due to the very high evapotranspiration rate and the dryness of soil. Thus increases in summer rainfall do not in any way offset the 10–20% decreases in winter rainfall seen across the catchment. Annual rainfall for 1975–2003 was 5, 10 and 13% less respectively than the long-term average immediately east of the Ngangaguringuring MU, south of the Beraking MU and west of the Helena West MU.

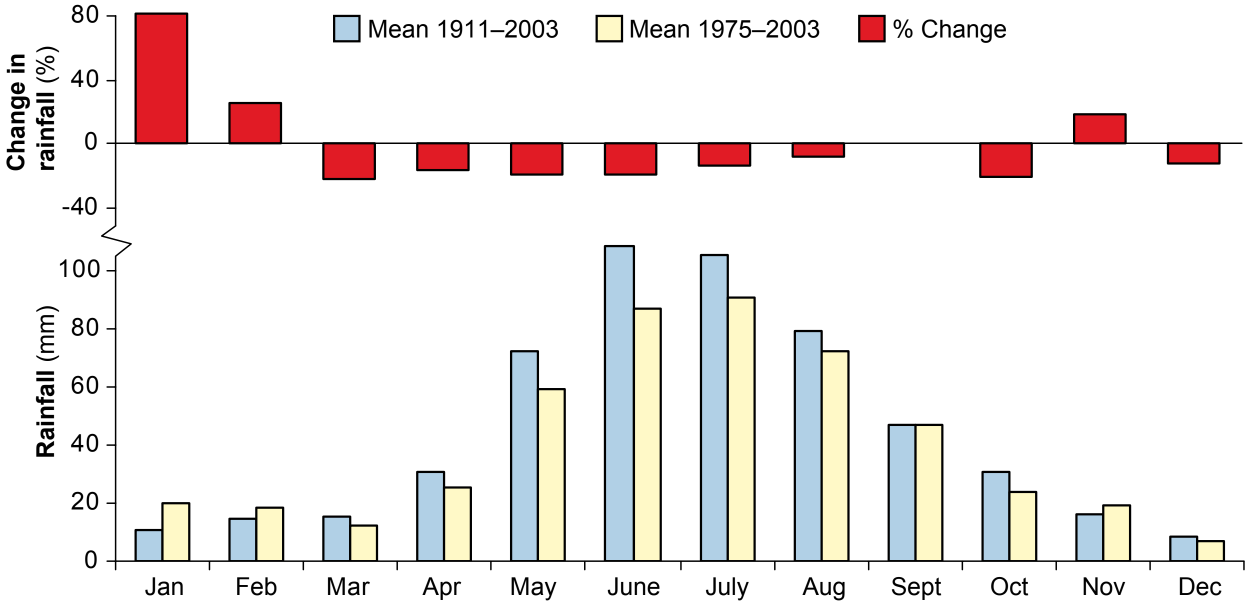


Figure 3.5 Seasonal rainfall shift at a station south of the Beraking Brook MU

3.2 Groundwater

Salt stored in the soil profile is mobilised by groundwater, especially when groundwater levels rise, and then concentrated through evaporative discharge or, less commonly, diluted by additional recharge. So groundwater salinity normally increases along a groundwater flow path (Fig. 2.7), whether from the weathered rock aquifer to the sedimentary and surficial aquifers or just within the sedimentary and surficial aquifers. Groundwater is fresh where recharged high in the landscape and saline beneath the flats. For example, Christmas Tree Well in a surficial sand aquifer near Brookton Highway had an end-of-winter 2004 salinity of 240 mg/L indicating local recharge. Flows to the Darkin River from swamps including Darkin Swamp, all 70–80 mg/L at the end of winters 2004 and 2005 and up to 130 mg/L in late spring 2005 (Appendix 3.4), clearly had no baseflow component.

The most environmentally significant baseflow occurs near the border between the Poison Lease and Ngangaguringuring MUs, just south and downslope from the large Abercorn Road clearing. Here saline discharge from palaeochannel sediments sustains the summer flow of the Helena River beyond the Ngangaguringuring stream gauging station (Smith & Smith 2005).

In contrast, the Darkin Swamp and the nearby swamps are poorly connected to the Darkin River because of their lower elevation, insignificant relief and lack of incision (by the Darkin River), and behave mainly as a recharge regime (Figs 3.6a–c & 3.7). These swamps are within what is interpreted to be an extensive section of palaeochannel about 25 km long. The groundwater (presumably saline at depth) lacks the hydraulic head to discharge to the Darkin River even though the water level is near the surface. The occasional winter outflow from these swamps appears to be small and to comprise fresh runoff after intense rainfall. The Darkin Swamp is then behaving as an overflowing sponge rather than a groundwater flow system. Consequently the clearing in the far south-east has not had a lasting or significant impact on reservoir inflow salinity although, as for clearing in the north-east, it has the potential to do so.

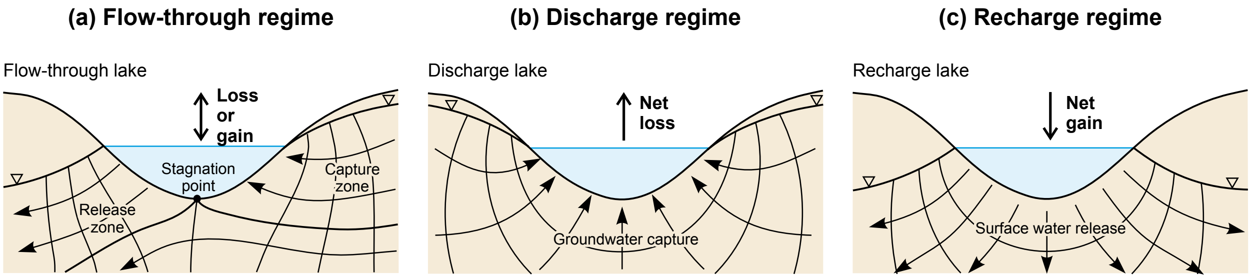


Figure 3.6a—c Diagrams of groundwater movement at wetlands

3.2.1 Groundwater salinity

There are clearly high groundwater salinities (2000–15 000 mg/L) in the northern half of the Ngangaguringuring management unit, drained by Wundabiniring Brook (Fig. 2.2). A second cluster (2000–4000 mg/L) in the Poison Lease management unit includes Wariin Brook north of Flynn plantation and saline seeps high in the landscape south of Abercorn Road (Fig. 1.1). This second area extends east from the Mundaring Reservoir to both east and south of Flynn and includes the Wellbucket plantation (Figs 1.1 & 2.5). A few salinities of less than 500 mg/L and the lowest at 120 mg/L indicate recent rainfall recharge. The typical depth to bedrock is 7–20 m, with one bore (2133-1-SE-0001 in the WIN database) located on a dyke and several in Cainozoic deposits.

Groundwater salinities range from 140 to 2000 mg/L and possibly as high as 4000 mg/L near discharge points along Wariin Brook, north-west of Yarra Road (Figs 2.7 & 3.7, 2000 & 3600 mg/L) and also at Horans Brook Reserve east of the catchment boundary (Fig. 2.2). Discharge from a spring west of the Goods Road sand extraction quarry contains about 3000 mg/L (Appendix A2.1, Photo 16). Sediments in this region discharge saline water to the Helena River, maintaining summer flow of approximately 2000 mg/L at Ngangaguringuring increasing to almost 3000 mg/L downstream (Fig. 3.7; Appendix A2.1, Photos 23 & 25–27).

The most intensive groundwater monitoring is of the more than 40 bores (Appendix A2.1, Photo 24) at Flynn where reforestation and rainfall reduction in the 1970s have gradually lowered water levels and largely disconnected the saline watertable from surface water

(Figs. 1.1 & 2.5). Water levels were shallow initially but, with declines of 2–6 m revealed by 25 years of monitoring, many of the bores are now dry (Bari & Schofield 1991, Bari 1998). Groundwater in the very shallow bores was fresh (less than 500 mg/L), but in most bores salinity was 3000–5000 mg/L and in some was 10 000–18 000 mg/L, revealing no pattern but varying widely even over short distances.

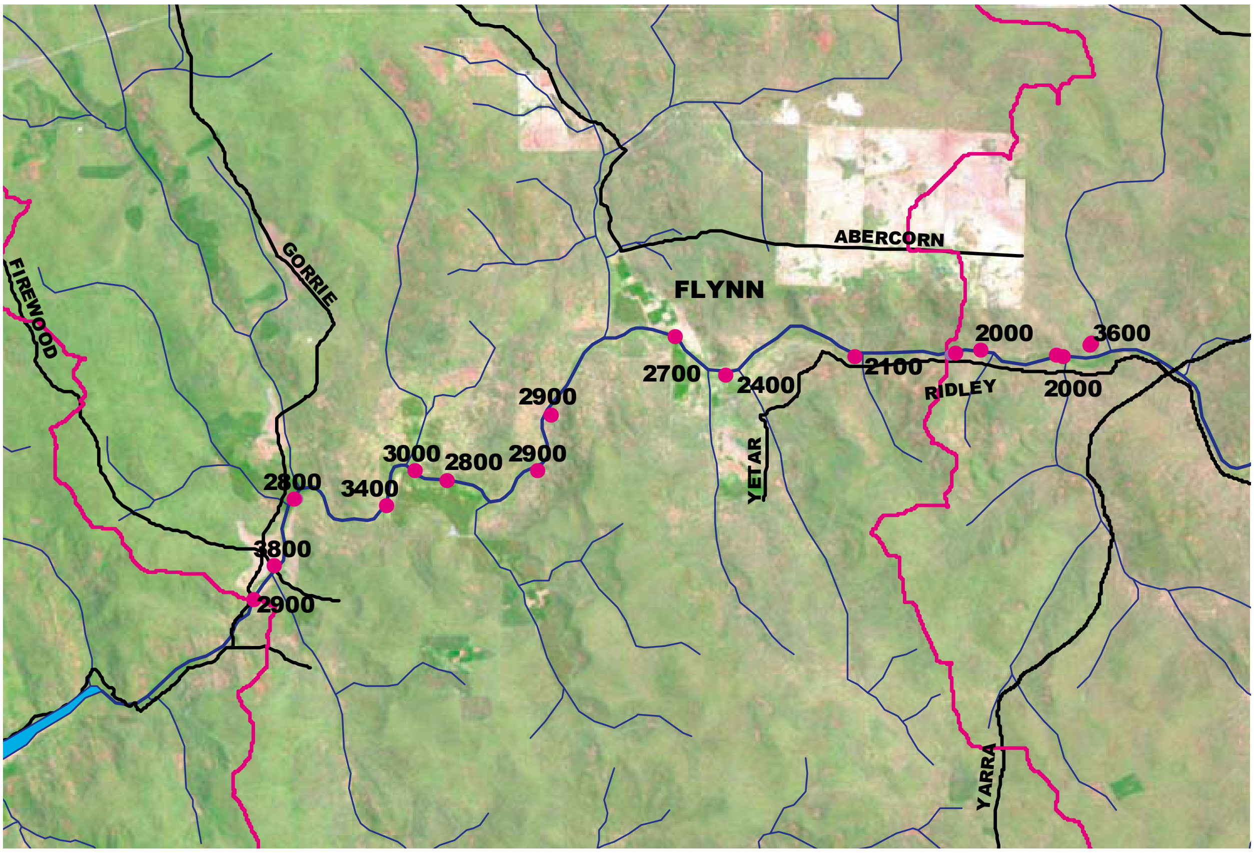


Figure 3.7 Summer salinities (mg/L) near the Ngangaguringuring and Poison Lease boundaries (red)

3.2.2 Rising watertable and land salinisation

Rain and surface water readily infiltrate the soil over much of the catchment and recharge the various aquifers (Fig. 2.7). Increased recharge follows land clearing (for agriculture), alters the water level and salinity according to the landscape setting, and causes dryland salinity. Most groundwater discharge, controlled by the slope, is near streamlines. Significant volumes of groundwater are intercepted and transpired by vegetation, particularly in swamps and wetlands where residence times are large, leaving behind the salts and raising salinities.

Where water levels rise, groundwater may dissolve salt within the unsaturated zone and, once within about 2 m of the ground surface, be drawn up by capillary action, evaporate and leave salt concentrated in the soil (Appendix A2.1, Photos 9, 15, 16, 17, 19–22 & 28). The increased soil salinity reduces agricultural production and in severe cases forms salt scalding at the surface, especially in combination with waterlogging. The land becomes unproductive and eventually trees and pasture die. Salt accumulated on the surface and within the (shallow) soil profile raises stream salinity when mobilised by runoff.

With rising water levels and groundwater discharge, intermittent swamps or wetlands may become more saline and permanently inundated/waterlogged. The broad flats and lower slopes that contain wetlands such as the Darkin Swamp and the Goods Road spring (Appendix A2.1, Photos 37 & 16) have the highest risk of land salinisation, potentially combining poor surface and groundwater drainage with saline shallow groundwater (Figs 2.7, 3.6 & 3.7, detailed in Section 4.1 & Fig. 4.2).

Rising groundwater levels can be controlled by measures that include revegetation, agroforestry, high-water-use crops and pastures, shallow and deep drains and groundwater pumping. Biological options such as revegetation can be considered as long-term strategies for controlling groundwater recharge. Several revegetation strategies (Bari 1998; Bari & Boyd 1994; Bari & Schofield 1991; Bell 1989; Bell et al. 1990) succeeded in disconnecting saline groundwater from surface water at the Flynn experimental site (Fig. 1.1; Appendix A2.1, Photo 24). Batini (2004) has recently observed water level declines of 5–9 m even in the forest east of Flynn.

Engineering options for managing groundwater discharge, such as interception by small dams, evaporation and removal, may be needed in the short- to medium-term. Long-term monitoring of the watertable, deeper groundwater levels and salinities between the water bodies and their recharge areas will be needed to evaluate the effects of management changes on what are three-dimensional aquifer systems.

3.2.3 Baseflow at Ngangaguringuring

The groundwater volumes and salinities sustaining sustaining year-round saline flow at Ngangaguringuring are of concern as 37% of the reservoir salt load passes this gauging station (Section 3.4.4). Baseflow discharge has both commenced soon after and increased since flow gauging began at this gauging station in 1972 (Fig. 3.8). Baseflow began in 1975 (Fig. 3.8), 8 years after clearing (for agriculture) at Abercorn Road (Appendix A2.1 & Photo 20) directly upslope of the gauging station. Groundwater discharge from hillslopes below half the 7.6 km^2 Abercorn Road clearing has persisted each summer, in contrast to areas cleared further upstream at Talbot Road West and at Wundabiniring Brook north of the Great Southern Highway (Fig. 2.11, Localities D & C). Flow beneath Yarra Road ceases in summer as it disconnects from upstream pools (Fig. 1.1, Appendix A2.1 & Photos 29–32) and by early summer is sourced from immediately upstream of Yarra Road. Baseflow rose quickly to about 500 kL/d in the late 1970s then steadily increased to 1200 kL/d in the late 1990s (Fig. 3.8). This increase is in response to rising watertables around Abercorn Road following land clearing and associated reduced tree water use. The present baseflow of 1200 kL/d indicates that, for approximately 3.8 km^2 of the Abercorn Road clearing that lies upstream of Ngangaguringuring (Fig. 2.11, Locality B), the recharge to groundwater is 19% of the local 600 mm/yr rainfall. This rate contrasts sharply with the 1% recharge rate typical of the surrounding weathered bedrock.

Baseflow salinity rose steadily from the initial 1450 mg/L in 1975 until 1981 when it began a gradual decline from about 2500 to less than 2000 mg/L (Fig. 3.9). The rise in salinity corresponds to the first 7 years of baseflow discharge resulting from elevated groundwater levels and the dissolution of large salt stores within the regolith. It is followed by a decline in salinity as baseflow continues to rise but is reducing stored salt within the profile. It is conceivable that this discharge may eventually become fresh, but this process could take many decades. In 1995, a typical rainfall year, the salt contribution from the groundwater baseflow, using the Lyne and Hollick (1979) method, was estimated to be 60% of the total salt load at the gauging station. The remainder was from interflow and surface runoff.

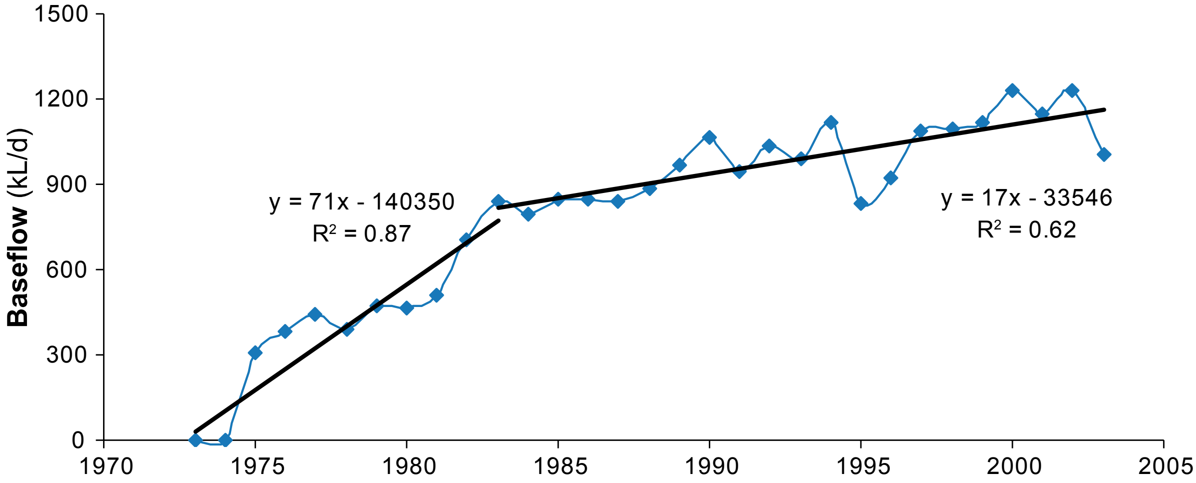


Figure 3.8 Late summer to early autumn baseflow at Ngangaguringuring

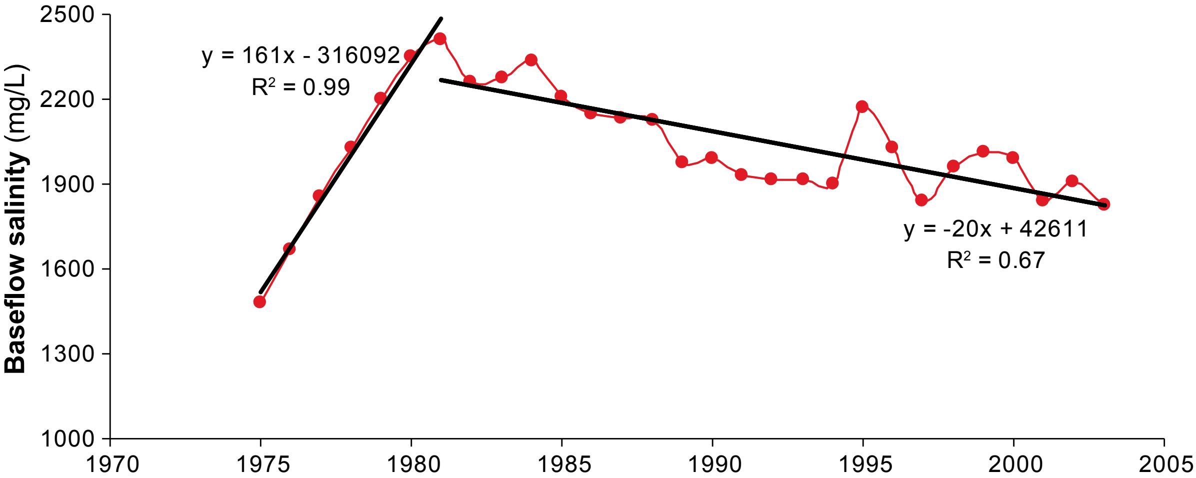


Figure 3.9 Late summer to early autumn baseflow salinity at Ngangaguringuring

In normal or wet years (Fig. 3.10) salinity drops off steeply with winter rainfall, occasionally increasing briefly as a result of salt flushing in the first rains. In these years, winter rainfall significantly dilutes and flushes salt from the surface soil resulting in fresh runoff that overwhelms the comparatively small volume of saline groundwater discharge. In dry years, there is not the initial pulse of salinity followed by freshening with the onset of winter rains seen at all the other gauges in the catchment. This indicates that in dry years there is insufficient flushing of catchment soils for surface runoff to become fresh. Winter peaks in salinity during dry years (Fig. 3.11) are the result of the little runoff dissolving so much salt at the soil surface that runoff is even more saline than the baseflow.

3.2.4 Salinity risk, salt store, distribution and balances

The risk of land salinisation due to shallow watertables varies from no risk to high risk depending mainly on the geology, topography (drainage) and distribution of rainfall. A salinity-risk map, an outcome of the current investigations, integrates data on depth-to-watertable, topography, slope and landforms to identify areas at risk of developing a shallow watertable or salinity (Fig. 4.2).

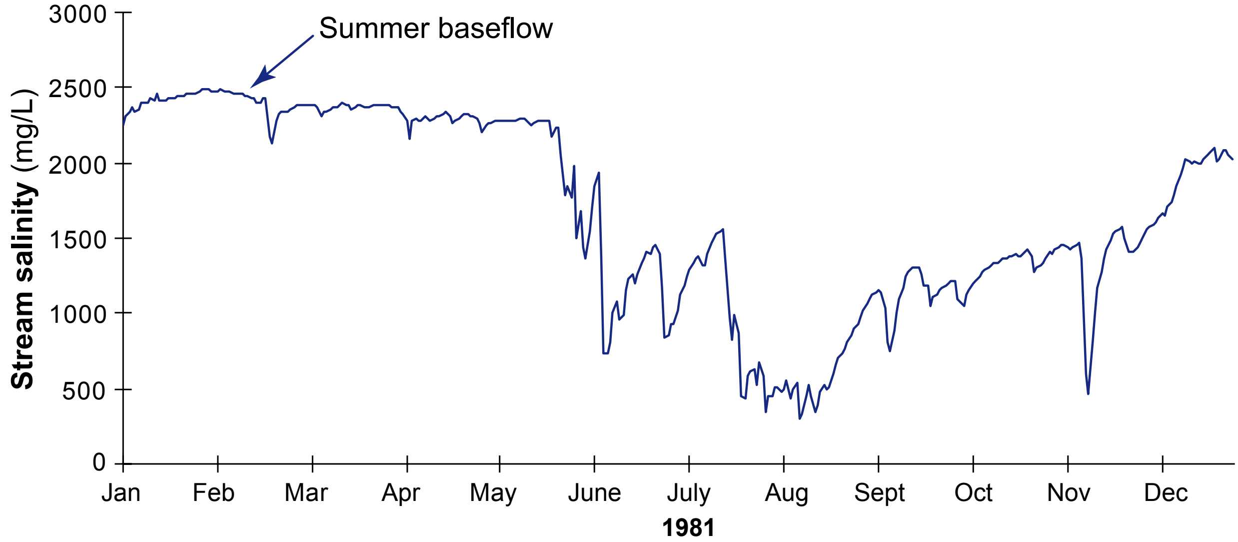


Figure 3.10 Typical winter freshening of baseflow at Ngangaguringuring in early years

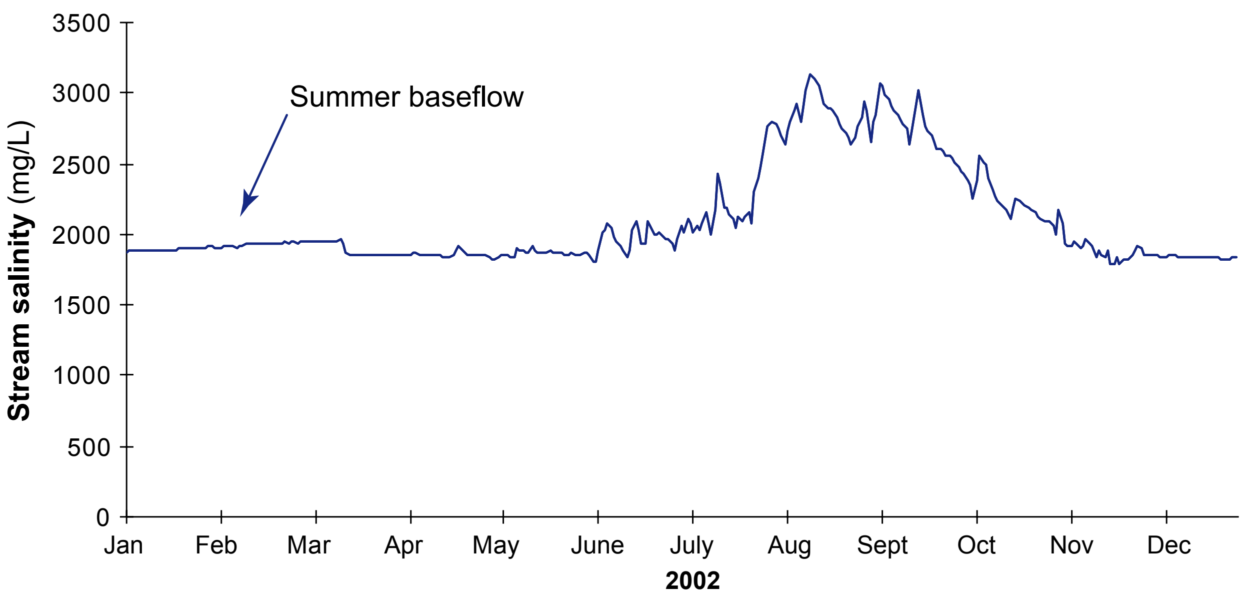


Figure 3.11 Typical winter salinising of baseflow at Ngangaguringuring in recent years

Clayey weathered-rock profiles beneath lateritic subsoils invariably have soil solute concentrations above 2000, some in excess of 10 000 mg/L, in areas where the average annual rainfall is less than 900 mm (Stokes et al. 1980). High salt stores were accumulated over thousands of years of limited flushing as deep-rooted vegetation transpired infiltrating water and mostly kept the weathered profile unsaturated. This salt storage in the weathered bedrock profile increases to the east as rainfall decreases (Fig. 2.2). Thus the eastern catchment in the moderate-rainfall zone (where rainfall is as low as 540 mm/yr) has a greater risk of land salinisation than the wetter western catchment. This is so particularly in the Helena subcatchment but also to a lesser degree in the generally forested and partially waterlogged Darkin subcatchment.

The further the catchment extends inland the lower the rainfall, the higher the salt storage in the landscape (see Section 2.2 & Appendix A4.1.4 for saltfall), and the more likely that the river drains at least some cleared agricultural land (rather than the State Forest to the west). Water draining from forested basins will remain fresh as long as these State Forests maintain enough transpiration in sensitive areas, such as the north-east of the catchment, to prevent mobilisation of salt. Early panic over salinity in the west may have misjudged the nature of the source, for although the salt was quickly released there was little salt stored. The pines replanted may now be using more water than desired and native vegetation could be considered in the west to increase runoff.

3.3 Surface water

The term 'salt load', the product of streamflow and salinity, is used regularly in the following sections and is defined as the mass of salt transported by streamflow, as distinct from salinity which is the concentration of salt in that water body. More than thirty years of streamflow and salinity data are available for seven gauging stations (since 1966–72, Section 2, Fig. 2.2, Table 2.1 & Appendix 3). The determination of flow and salinity trends, based on that used for the Kent Salinity Situation Statement (De Silva et al. 2007) is described in Appendix 3. The salinity and salt load analysis commences from the earliest time at which both salinity and flow records exist and is graphed together with the permanent clearing, i.e. without short-term variations such as due to fire and silviculture (Figs 3.1–3.4 & A3.2–A3.5). Significantly, for management and remediation of the catchment, this reveals:

- higher rainfall and runoff in the Helena West management unit (Section 3.3.1)
- most salt load comes from the north of the catchment (along the Helena River) as Darkin Swamp acts as a sink for cleared areas in the Darkin River subcatchment (Section 3.3.2)
- with the exception of the Helena River (Ngangaguringuring and Poison Lease), no strong flow or salinity trends exist between 1977 and 2002 and most of the catchment is fresh (Section 3.3.3).

3.3.1 Higher rainfall and runoff in the western subcatchments

The mean rainfalls, flows and flow-weighted salinities for all seven gauging stations are in Tables 2.1 & 3.1. Due to higher rainfall and a more incised landscape, the small tributaries in the Helena West MU contribute nearly as much flow (8.4 GL/yr) as both of the significantly larger subcatchments above the Darkin River (3.6 GL/yr) and Poison Lease (5.1 GL/yr) gauging stations. Approximately 6% of rainfall becomes runoff in Helena West, compared with less than 1% for the rest of the catchment.

The annual rainfall and flow, which are strongly correlated, dilute the salt discharging from the catchment (Figs 3.1b–3.4b). High and low annual rainfalls have an exaggerated effect on streamflow volumes. In most high-rainfall years the increased flushing of salt from soils and the dilution of saline groundwater discharges result in reduced annual stream salinities. The converse is true for low-rainfall years. While streamflows at mean rainfall generally declined up to the late 1980s, they have increased only slightly since 1990 (Table 3.1, column 6) and may be temporarily suppressing salinity. Improvement in mean streamflows for the 1990s has been due to the very good annual rainfalls in 1996 and 1999.

Table 3.1 Flow and salt trends in the Mundaring catchment

Gauging station	Mean annual salinity and flow (1977–89) 1990–2002[a]			Annual trend (1977–89) 1990–2002		
	Arithmetic mean salinity (mg/L)	**Flow** (GL)	**Salt output/ input ratio**	**Salinity** (mg/L)	**Flow** (GL)	**Salt load** (t)
Ngangaguringuring	(1700) 1700	(1.7) 1.8	(1.4) 1.7	(50) 9[b]	(-0.1) 0.1 b	(90) 20[b]
Helena Brook	(510) 410	(0.7) 0.8	(1.2) 1.3	(-20) 4	(0) 0 b	(-10) 5
Poison Lease	(1500) 1300	(5.0) 5.1	(1.3) 1.3	(20) -20	(-0.3) 0.2[b]	(100) -90
Darkin River	(250) **190**	(3.3) 3.6	(0.2) 0.2	(-9) 0[b]	(-0.1) 0.1[b]	(-30) 0[b]
Little Darkin River[c]	(250) **220**	(0.7) 0.9	(0.5) 0.5	(-9) 2	(0) 0.1	(-6) -1[b]
Pickering Brook[c]	(240) **240**	(1.5) 2.0	(1.2) 1.4	(-5) 5	(0 b) 0	(-7) 10
Rushy Creek[c]	(450) **440**	(1.2) 1.2	(1.2) 1.2	(-2) -8	(-0.1) 0.1	(-2 b) -10
Whole reservoir	**(620) 510**	(15) 17.1	(0.8) 0.8	(-0.1 b) -5	(-0.5) -0.3[b]	(6 b) -75

[a] Period used in modelling
[b] Denotes trend not statistically significant at 95% confidence level
[c] Due to station closure, 1999–2002 flow figures in mean are from LUCICAT modelling

3.3.2 Most salt load is from the Helena River

Salt output/input ratios greater than 1 (Table 3.1) indicate that salt is being flushed from five northern gauged subcatchments faster than it is being deposited from the atmosphere. Only the Darkin and Little Darkin subcatchments are clearly accumulating salt – even the Helena West management unit is exporting salt. Salt export is the normal flow-generation process, very common in the high-rainfall zone of the south-west. The bulk of the salt load to the Mundaring Reservoir comes from the north of the Helena subcatchment. Discharge, or baseflow, from sediments near the Ngangaguringuring gauging station is large enough to sustain summer flow of the Helena River and has a salinity of almost 2000 mg/L, although this increases downstream to almost 3000 mg/L (Fig. 3.7). The onset of permanent baseflows at Ngangaguringuring in 1975, due to about half the 7.2 km^2 cleared near Abercorn Road (Table 2.5 & Fig. 2.11, Locality B), corresponds with a steep rise in salinity, to above 2000 mg/L, from previously potable levels (Fig. 3.1a).

The monthly breakdown of flow in a typical year (1995) shows that baseflow contributes nearly all the flow except in the wettest 5 months (Fig. 3.12). With salt concentration higher than in surface flow, baseflow usually contributes more than 80% of the salt load apart from in the wettest months. October 1995 was uncharacteristically wet, exaggerating the total flow relative to baseflow.

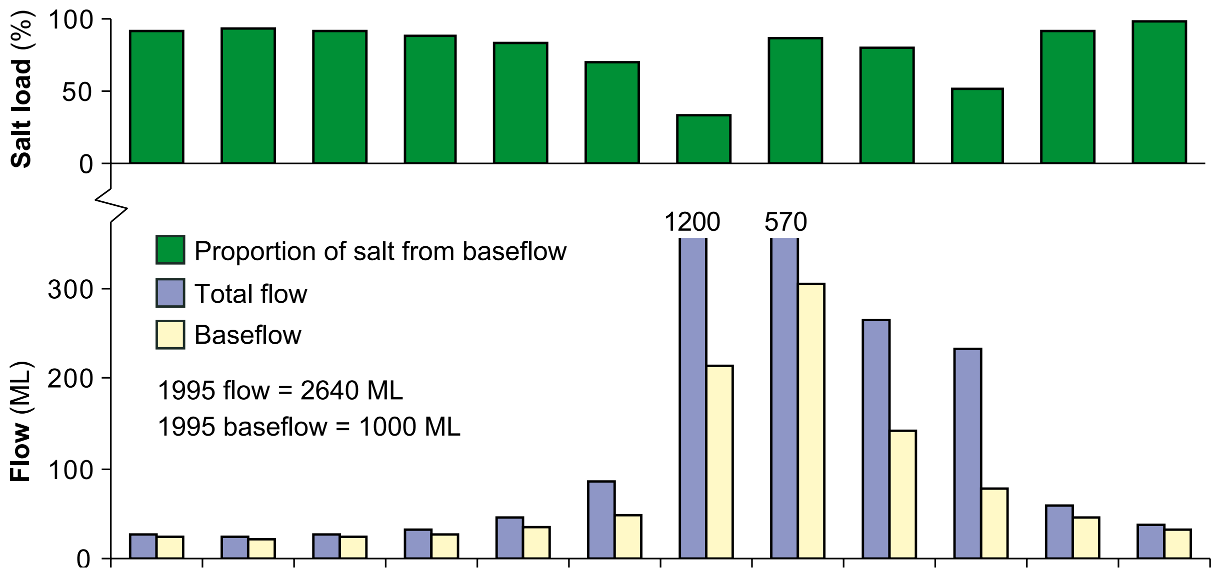


Figure 3.12 Monthly salt load in baseflow at Ngangaguringuring for a typical year (1995)

Fluctuations in water quality at Ngangaguringuring (Fig. 3.1) directly influence water quality at Poison Lease (Fig. 3.2). This is best observed from the matching salinities and salt loads at these two gauging stations for the 1980–90 period. Salt load at mean flow from Ngangaguringuring and Poison Lease peaked in 1988 at 2.9 and 5.9 kt/yr respectively; 0.6 and 1 kt/yr higher than their 1980 levels. Approximately half of the Abercorn Road clearing is generating saline groundwater discharge upstream of Ngangaguringuring, while half is generating flow that enters downstream via Wariin Brook. This accounts for the discrepancy between the Ngangaguringuring and the Poison Lease increases in salt load, and further implicates land use at Abercorn Road in the fluctuations of salt load at Poison Lease. From 1980, salinity at mean flow for Ngangaguringuring increased from 1200 to 1500 mg/L by 1989. Correspondingly, salinity at mean flow downstream at Poison Lease increased from a previously stable 950 mg/L in 1980 to peak at 1100 mg/L in 1988. The salt load at Poison Lease and Ngangaguringuring increased during 1977–89 (by 100 and 90 t/yr respectively), but has stabilised and is now declining at Poison Lease (by 90 t/yr). These decreases in salinity and salt load at Poison Lease highlight that significant freshening of runoff from the MU must be occurring to counter the increase in salt load from Ngangaguringuring. The future salinity will depend on whether the salt load continues to rise at Ngangaguringuring and whether runoff at Poison Lease continues to freshen and counteract it. The high salinities of the Poison Lease and Ngangaguringuring MUs (1300 and 1700 mg/L respectively) combined with their significant flow contribution to the reservoir (5.1 GL/yr), make the Helena subcatchment the dominant source of salt to the reservoir. The Poison Lease GS provides the end quality of water from the Helena subcatchment, and reveals significant dilution of the saline flow from the Ngangaguringuring subcatchment. This dilution is consistent with a lower extent of land clearing west of Ngangaguringuring, and thus a lower risk of saline groundwater discharge. Increased rainfall, and thus flushing, is also a major factor in reduced salinity to the west of Ngangaguringuring. Diversion of the saline summer flow at Ngangaguringuring (Fig. 3.10) to an evaporation point will be considered later.

Summer rainfall has the potential to increase the salt load to the reservoir, particularly from the north-east of the catchment. Although summer rainfall events rarely induce flow to the reservoir from the Helena or Darkin rivers, they do generate flows (in excess of baseflow) upstream at Ngangaguringuring. Like the first heavy rains of winter these flows flush some of the salt accumulated over the dry season from the surface soil to the streambed, but are too short to become fresh. In most cases the salt will remain in the streambed until flushed by winter rains to the reservoir. The 4 years of highest inflow salinity (1979, 1982, 1985 & 2001) had some of the lowest annual rainfalls (Figure 3.4, also Fig. 5.1 in Section 5 & Fig. A3.6 in Appendix 3). Croton and Dalton (1999) discuss such correlations and patterns in more detail. Statistical analysis (Table 3.1) for the data graphed (Figs 3.1–3.4 & A3.2–A3.5), with the exceptions of Ngangaguringuring and Poison Lease, reveals only small differences between the period 1990–2002 and the preceding 12-year period of 1977–89.

3.3.3 The Helena River is becoming more salty but elsewhere remains fresh

Except at Ngangaguringuring, annual flow-weighted stream salinity has stabilised across the catchment since the early 1980s, concluding a declining trend that began before stream gauging. The post-1990 trend at Ngangaguringuring would be statistically significant increases by 31 mg/L per year were it not for the dip in 1990–91. Streamflows remain fresh and well below the 500 mg/L threshold for drinking water quality except in the Helena River. Substantial clearing at the eastern extremity of the Darkin subcatchment is upstream of Darkin Swamp, where salinities remain low, and overflow is rare (Appendix A2.1, Photos 35–37). Flows from the Darkin subcatchment are 190 mg/L at the Darkin River gauging station (Table 3.1). Similarly, streamflows from the small western subcatchments contain 220–440 mg/L.

The salinity, flow and salt load for the Darkin River and all the fresh, gauged tributaries in the Helena catchment decreased from the beginning of records in the late 1960s and stabilised in the early 1980s (Figs 3.3 & A3.2–A3.5). (Note that for Helena Brook (Fig. A3.2) the salinity upswing from 1995 is the expected short-term response to large hot wildfires in the south of the subcatchment in 1993 and in the north of the subcatchment in 1996.) At the Darkin River gauging station, annual salinity that was highest (680 mg/L) at the start of records in 1969 (and may have previously been much higher) has stabilised at less than 200 mg/L since the mid 1980s. With flow simultaneously stabilising at around 2.6–3.6 GL/yr, the salt load contribution to the reservoir has remained very low at 0.6 kt/yr in both most of 1977–89 and 1990–2002. The decreasing flow in the mid to late 1970s, at all gauging stations except Ngangaguringuring (as explained in Section 3.2.3), indicates progressive drying of soils and reduced runoff due to the decreasing rainfall (Fig. 2.3) and the regrowth from the 1950–75 logging (Batini & Selkirk 1978) that previously doubled yield (Batini pers. comm. 2006).

The accumulation of salt (salt output/input ratio < 1) in the regolith in the south of the catchment may be attributable to extensive palaeochannel sediments (Fig. 2.5) behaving as a salt sink, storing saline water and preventing it from discharging to the Darkin River. The steep decrease in salinity from 680 mg/L, at the start of the Darkin River gauging station records, leaves open the possibility that there was an initial flush of salt following the clearing in the east of the subcatchment in the late 1940s. The declining salinity would thus indicate progress towards a new equilibrium as the rising groundwater flushed salt from the soil. Salt and flow discharge, if occurring, may now be low enough to be completely absorbed by the palaeochannel sediments (Section 2.6.2). Alternatively, but also speculative, the high salinities at all gauging stations at the start of recording could be due to timber harvesting of 1950–75 (Section 2.7.2, Batini & Selkirk 1978). The decline in trend at the start of many of the records (Figs 3.3, A3.2–A3.5) might be the tail end of a response to the preceding widespread logging.

3.4 Reservoir

The salinity of the water supply is currently maintained below the drinking water standard by pumping fresh water from the pumpback dam into the reservoir above the outlet. So it is important to distinguish between the salinity of reservoir inflows, discussed in this Section, and the salinity in the reservoir itself. The salinity of reservoir inflows, and thus the amount of low-salinity pumpback and mixing required, fluctuates from year to year depending on rainfall, vegetation cover and land use. Reservoir salinity, inflow, and salt load all decreased slightly between 1990 and 2002. These small reductions have persisted since the late 1970s, with salinity at mean flow gradually declining from 510 to 460 mg/L (Fig. 3.4a). Thus the 1970s appear to mark the end of the second of three clearing episodes that each pushed the inflow salinity over 500 mg/L.

3.4.1 Salinity

Reservoir inflow salinities fluctuate (largely between 350 and 650 mg/L) and frequently exceed the 500 mg/L drinking water standard. The mean and median salinities for 1990 to 2002 are 510 and 530 mg/L respectively, with fresh inflows in only 5 of the 13 years. In the low-flow years the annual salinity has not been as high as in 1979 (even in 2001), reducing the degree to which the drinking water threshold is exceeded.

The 2001 and 1979 peaks in salinity were in response to the two lowest inflow years (Sections 3.3.1 & 3.3.2). Surface runoff in these low-flow years flushed some salt from soil into the river but did not persist long enough to really lower stream salinity or eventually dilute saline groundwater discharges. Low flows from the north-east of the catchment in 2001 kept the salinity at mean flow and the salinity trend in decline, despite a higher annual salinity. This is because the reduction in saline flow from the Helena River was greater, in terms of salt load contribution, than the reduction in the fresh flow from the rest of the catchment. A string of lower flow years would result in increased salinity of runoff, in the short term, from soils that have accumulated salt through capillary action and evapotranspiration, while eventually reducing groundwater levels, salinity of runoff and saline groundwater discharge. Predictions for the salinity of the reservoir inflow with respect to this balance can only be modelled (see Section 4).

3.4.2 Inflow

Total reservoir inflows have fluctuated greatly from lows of 1.7, 4.9 and 3.2 GL in 1979, 1982 and 2001, to highs of 85 and 59 GL in 1974 and 1996 respectively (Fig. 3.4b). The mean annual reservoir inflow is 17.1 GL (Table 3.1). Variation in flow partially reflects changes in annual rainfall (Fig. 3.4b) and vegetation cover (Section 3.2.3). Streamflow shows a declining trend of 0.5 GL per year from 1977 to 1989, but not from 1990 to 2002, largely due to the very wet 1996. If such wet years become less frequent, streamflow will decline further.

The 1994 catchment-wide annual rainfall (490 mm) was the lowest since 1972 (470 mm) but large forest fires may have boosted annual streamflow slightly relative to other low-rainfall years. The burnt areas were about 5, 10 and 6 km^2 respectively just east of Ngangaguringuring, just south of Little Darkin River and just north of Rushy Creek gauging stations.

3.4.3 Load

The mean annual salt load to the reservoir is 7.4 kt and varies less between years than the inflow (Table A3.1). The 10th and 90th percentile salt loads are 3.2 and 11.3 kt respectively.

3.4.4 Relative contributions

The high runoff from the relatively small Helena West MU dominates the inflow to the reservoir, with the Helena River (Poison Lease) and Darkin River gauging stations recording the remainder (Fig. 3.13). The relative volumes of fresh flow from the Helena West MU and the Darkin River and the saline flow from the Helena River determine the overall salinity of the water entering the reservoir.

Table 3.2 Relative flow and salt contributions to the reservoir 1990–2002

Management unit	Gauge site	Runoff (% rainfall)	Annual flow GL	Annual flow (%)	Annual salt load kt	Annual salt load (%)
Ngangaguringuring and Poison Lease	Ngangaguringuring	0.9	1.8	(11)	2.8	(37)
	Helena Brook	3.9	0.8	(5)	0.3	(4)
	Poison Lease	1.8[a]	3.3	(19)[b]	1.9	(26)[b]
	Both MUs	1.3	5.1	(30)	4.7	(63)
Darkin Swamp and NW Beraking Brook	Darkin River	0.8	3.6	(21)	0.6	(8)
Helena West[a]	Little Darkin River	2.6	0.9	(5)	0.2	(2)
	Pickering Brook	6.9	2.0	(12)	0.4	(6)
	Rushy Creek	3.5	1.2	(7)	0.4	(6)
	Not gauged	6.0[b]	4.4	(25)[c]	1.1	(15)[c]
	Whole MU	6.0	8.4	(49)	2.2	(29)
Whole catchment	Mundaring Reservoir	1.8	**17.1**	(100)	7.4	(100)

[a] No data after 1998 due to station closures, 1999–2002 figures taken from LUCICAT modelling
[b] Below Ngangaguringuring and Helena Brook gauging stations
[c] Average of data from the Little Darkin River, Pickering Brook and Rushy Creek gauging stations

For 1990–2002, the reservoir annual inflow and salt load respectively were 17.1 GL and 7.4 kt (Table 3.2), with an arithmetic mean inflow salinity of 510 mg/L (Table 3.1). The southern and western tributaries of the reservoir, within the Darkin Swamp, Beraking Brook and Helena West management units, collectively contributed 70% of the inflow but only 37% of the salt load (Fig. 3.13). The Ngangaguringuring and Poison Lease MUs, despite a much lower flow of 30%, contributed the remaining 63% of salt load. Of these, the Ngangaguringuring MU is estimated to provide 11% of the flow and 37% of the salt load. These figures highlight the Helena subcatchment (especially the Ngangaguringuring management unit) as the focus for salt remediation. Full diversion of saline water by damming the Helena River near the Poison Lease gauging station would reduce mean annual salinity and inflow to 230 mg/L and 12.0 GL (from 17.1, Table 3.2). Full diversion at the Ngangaguringuring gauging station would reduce the mean annual salinity and inflow to 300 mg/L and 15.3 GL (Table A3.7).

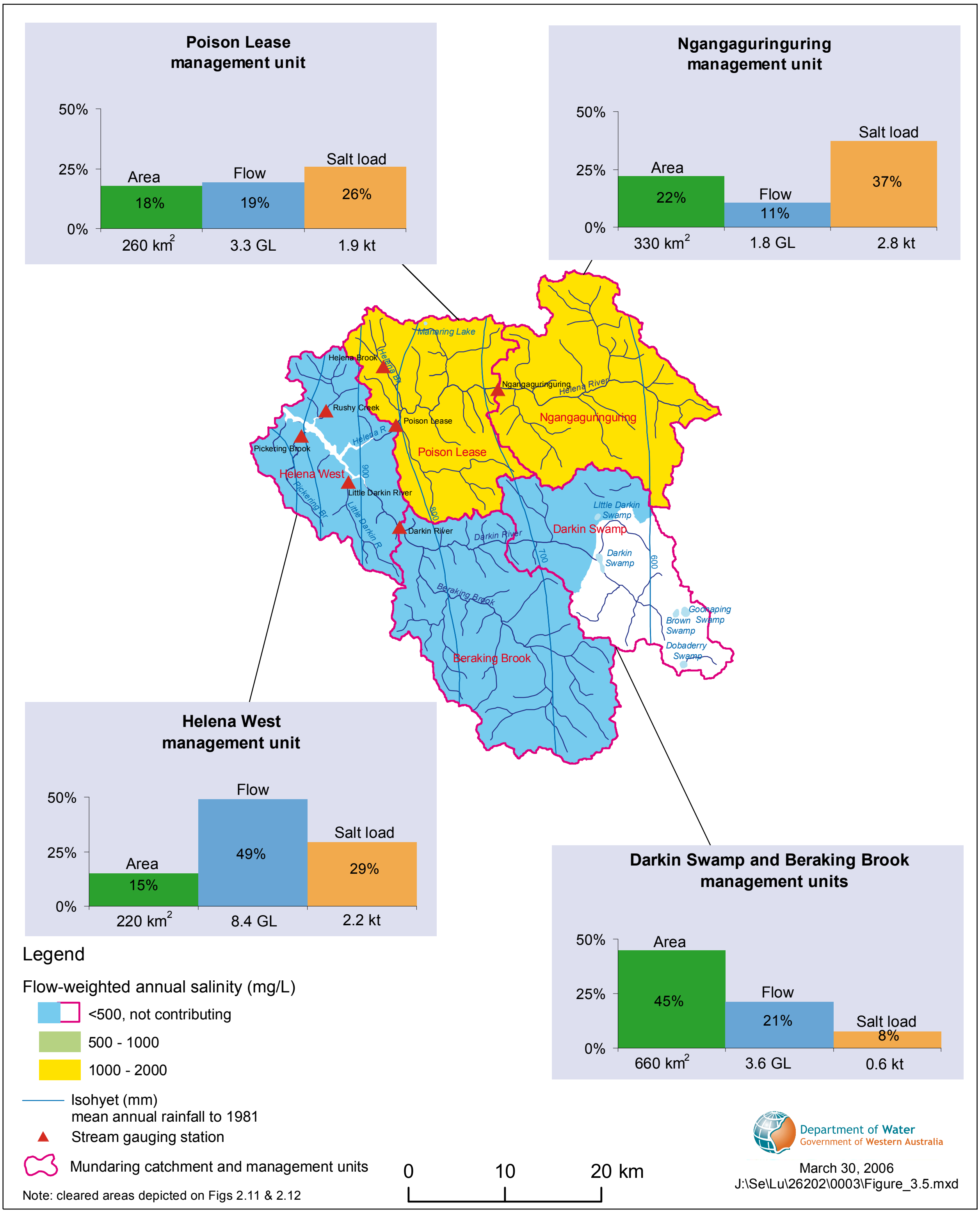


Figure 3.13 Flow and load contributions to the reservoir

4 Modelling

What effects will changed catchment conditions have on the salinity and inflow to the Mundaring Reservoir? Two models designed to handle the specific conditions of catchments peculiar to Western Australia – LUCICAT and MAGIC – were applied to simulate these changes under different land-use and rainfall scenarios and to answer management questions in Section 5. The MAGIC model is a steady-state model and assumes that the same land use has been applied to a catchment for many years and the salinity processes are at equilibrium. LUCICAT is a dynamic model that uses daily rainfall. Section 4 describes the formulation, calibration and verification of both models for the area upstream of the Mundaring Weir (Fig. 2.2), while more details of these processes are in Appendix 4.

4.1 MAGIC model

The MAGIC model is a steady-state model that uses specified, unchanging land covers and rainfall, runs monthly time-steps and gives annual outputs once the soil moisture of the catchment is calculated for equilibrium conditions. It has the advantage of being able to incorporate detailed catchment characteristics, since it has GIS capabilities and subdivides each subcatchment into 25 by 25 m cells.

The MAGIC model has been used for all of the Water Resource Recovery Catchments – Collie, Denmark, Warren and Kent (Mauger et al. 2001; Bari et al. 2004; Smith et al. 2006; De Silva et al. 2007). Initially used in the Mundaring catchment (Dixon 1996), it was updated for this study with both the latest advances in the model and recent catchment information.

4.1.1 Model formulation

The MAGIC model was formulated based on the most recent application, except for using the greenness ratio used to estimate evapotranspiration (ET) in the Kent Catchment (De Silva et al. 2007). The potential transpiration (PT) per unit LAI (Leaf Area Index) equation used by the WEC-C physical-process water-balance model in the North Jarrah Forest (Boniecka & Croton 2004; Croton et al. 2005) was used to estimate ET. The LAI was derived from the adjusted normalised-difference vegetation index (adjusted NDVI) from the 2002 Landsat scene (Land Monitor 2002; Mauger 2003). See Appendix 4 for details.

Rainfall and saltfall used in the model are described in Appendix 4.1.4. As the observed streamflow varies from less than 1% of the rainfall in the east of the catchment to 7% in the west, the estimated evapotranspiration is key to the hydrological simulation. During the calibration process, the transpiration equation had to be adjusted by a non-linear factor that varied from 1 in the west to 5.5 in the east of the catchment (Appendix 4, Fig. A4.1).

The water use of the swampy vegetation in the catchment was estimated by assuming it was perennial pasture (with a rooting depth of 5 m and with an LAI that varied with annual average rainfall, Equations A4.1 to A4.4). In the Darkin Swamp management unit, streamflow from the Darkin Swamp was set to zero. Possible small infrequent flows and salt output from this swamp during the period 1986–2002 are not significant to the model (Section 2.6.2 & Section 3).

Each subcatchment had three subsurface layers. The geology information and hydraulic conductivities used in the bottom two layers are outlined in Section 2.6. The surface layer was related to the subsystems/phase level in the soil–landscape systems (Western Australia Department of Agriculture 2004) described in Section 2.5.2. Their properties of thickness, (saturated) permeability, ratio of voids, field capacity, and wilting point were used to estimate the amount of water in the (soil) top layer that cannot drain away and that plant roots cannot extract.

4.1.2 Model calibration and verification

The 2002 Landsat scene was used to capture the land use of the catchment since it best represented the vegetation during the calibration period. The rainfall record for the period 1986–98 was chosen as this best represents the catchment at steady state and all the stream gauging stations in the Helena West management unit were closed in early 1999. Further, most of the clearing ended in 1981 (Fig. 2.11), except in the Darkin Swamp management unit, and by 1986 the rise in salt load caused by clearing had stabilised at Ngangaguringuring (Fig. 3.1). The estimated reservoir inflow, salt load and flow-weighted salinity were used.

The predictions of MAGIC and LUCICAT were compared using the most recent 13-year period with rainfall records, 1990–2002. As land use in the catchment hardly changed during this period, the 2002 Landsat scene was again used to calculate the LAI of the forest and the extent of pasture. The streamflow and salt load trends at the gauging stations were very small or not statistically significant (Table 3.1). The mean streamflows and salt loads at the gauges during this period were compared with the model results. The salinity, streamflow and salt load for the non-gauged half of the Helena West management unit were estimated (Section 3).

The average rainfall year of 1995 (for the period 1990–2002) was used to test a (dynamic) run of the model. The rainfall and pan evaporation were applied in monthly time-steps. The same land-use and modelling parameters were applied to the catchment as in the calibration (Appendix A4.1.6).

4.1.3 Results and discussion

The predicted and measured streamflows and salt loads matched well, within 5% and 4% respectively in the calibrations (Fig. 4.1). Chiew and McMahon (1993) suggested that if the ratio of the mean simulated flow to the mean recorded flow is in the range 0.90–1.1 and the R^2 (coefficient of determination) is above 0.8 then the model calibration and predictions are 'always acceptable'. The results for the major gauging stations at Poison Lease and Darkin River, and for the reservoir inflow are shown in Table 4.1, being for the three periods (1995, 1986–98 & 1990–2002) run in the calibration and verification. The same modelling parameters were used for all three cases. Predicted streamflows, salt loads, and groundwater discharge areas relevant to the management units and gauging stations for the calibration and verifications cases are detailed in Tables A4.4 & A4.5.

The predicted streamflow at Poison Lease for the period 1986–98 was 2.2 GL higher than the measured flow (bold numbers in Table 4.1), which might seem significant but equates to 0.6% of rainfall, of which only 1.4% becomes streamflow. It is very difficult to increase the accuracy of any catchment model at such low runoff coefficients, especially for the MAGIC model where the rainfall, averaged over the 13-year period, was applied in monthly steps. The modelled streamflow matched measured flow better in the higher runoff Helena West management unit where 50% of the inflow to Mundaring Reservoir is generated, including the Pickering Brook subcatchment with the highest runoff coefficient (7%).

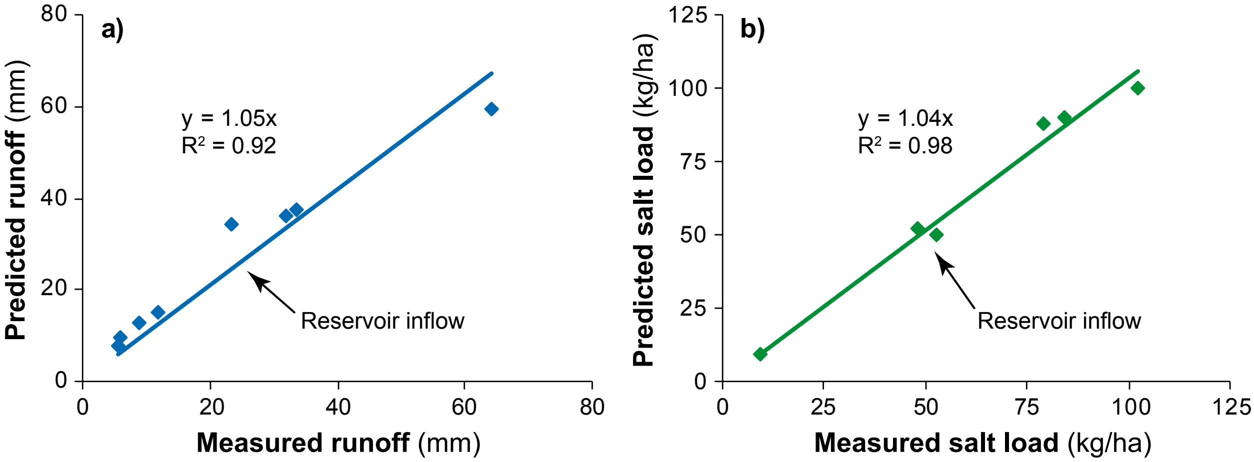


Figure 4.1 MAGIC calibration of a) runoff and b) salt load to Mundaring Reservoir

Table 4.1 MAGIC model calibration and validation at the major gauging stations and for the reservoir inflow

Model calibration		Poison Lease			Darkin River			Reservoir inflow		
		1995	'86–'98	'90–'02	1995	'86–'98	'90–'02	1995	'86–'98	'90–'02
Salinity (mg/L)	Measured[a]	780	930	910	190	160	160	480[b]	440[b]	430[b]
	Modelled	510	700	960	90	100	140	310	330	415
Streamflow (GL)	Measured	7.7	**5.4**	5.1	4.0	3.9	3.6	18.7[b]	17.6[b]	17.1[b]
	Modelled	9.5	**7.6**	5.7	6.5	6.3	4.1	22.4	22.3	18.2
Salt load (kt)	Measured	4.8	5.0	4.7	0.74	0.61	0.57	9.0[b]	7.8[b]	7.4[b]
	Modelled	5.1	5.3	5.5	0.60	0.60	0.59	6.9	7.4	7.5

[a] Flow-weighted (not arithmetic mean)
[b] Estimated

The model performed better for the 1990–2002 period, the period used in Section 5 to apply the catchment management scenarios. The accuracy of the predicted reservoir inflows for the management scenarios within 10% for streamflow and salt load, and within 20% for salinity.

The model predicted the areas with saline discharge and shallow watertable (Fig. 4.2), the latter within 2 m of the ground surface. The cleared areas in the Darkin Swamp management unit had little discharge, being modelled as sedimentary units with high horizontal and vertical conductivity, but have relatively low elevation, insignificant relief and lack of incision. In contrast, the cleared areas in the north-east of the catchment, north of the Great Southern Highway, provide more discharge: they have more weathered and/or fractured rock aquifers (Section 2.6.3) together with higher elevation and relief.

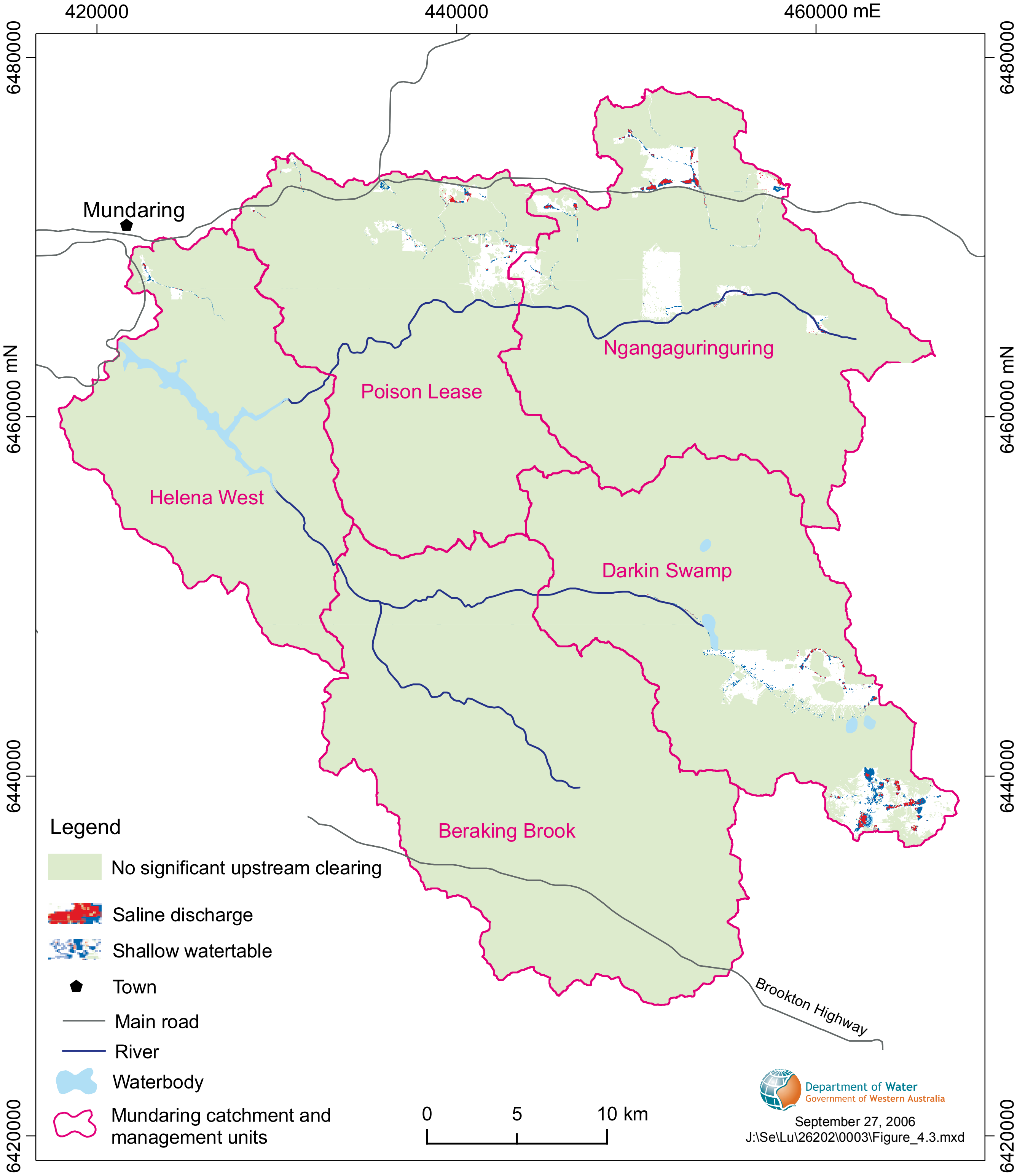


Figure 4.2 Salinity risk - predicted shallow watertable and saline discharge areas from the base case

4.2 LUCICAT model

The LUCICAT model generates daily streamflows and salt loads from the 66 surface-water subcatchments (Fig 2.2) that take into account the distribution of rainfall, pan evaporation, soil salt storage and land use, and incorporate attributes like soil depth, groundwater level and change in land use (Bari et al. 2003; Bari & Smettem 2003, 2004, 2005, 2006; Beverley et al. 2005). The model sums daily streamflows and salt loads for monthly and annual comparison. Subcatchments are also incorporated and form building-blocks in the model, consisting of (i) Dry, Wet and Subsurface Stores (ii) saturated Groundwater Store and (iii) a transient Streamzone Store (Fig. A4.2). The physical processes that the model emulates are listed below:

- *Evapotranspiration* comprises three components: interception, transpiration by vegetation and evaporation from soil. Interception is represented by a canopy store, which is dependent on the Leaf Area Index of the vegetation. The rest of the rainfall reaches the soil surface and either infiltrates or creates runoff. Some of the rainfall salt is intercepted on the plant leaves but then washed onto the soil in subsequent events. Transpiration is modelled as a function of the LAI, the relative root volume in all five stores (Fig. A4.2), the moisture content and the potential energy (pan evaporation). Evaporation takes place from the Dry and Wet Stores and (where they exist) the Streamzone Stores.
- *Surface runoff* is generated from the variably contributing saturated areas along the Streamzone and is dependent upon the water content of the Wet Store (Fig. A4.2). Where part of the Streamzone is saturated by the presence of the permanent groundwater system, additional surface runoff is generated.
- *Interflow* is the contribution of shallow, intermittent groundwater after rainfall recharge. If the permanent groundwater system does not discharge to the stream, interflow controls the recession limb of the streamflow hydrograph. It is a function of the lateral hydraulic conductivity of the topsoil, and the water content of the Wet Store (Fig. A4.2).
- *Percolation* is the amount of vertical water flow between the highly conductive topsoil to the less conductive Subsurface Store (Fig. A4.2). It is controlled by the vertical conductivity, the water content in the Wet Store and the soil moisture deficit in the Subsurface Store. Most of the percolated water is transpired by the deep-rooted trees and very little reaches the Groundwater Store. Recharge to the Groundwater Store comprises both matrix and preferential flow.
- *Baseflow* is the contribution of the (permanent) groundwater system to streamflow. It ensues where the Groundwater Store connects to the streambed to form the Streamzone Store (Fig. A4.2). It is a function of the lateral hydraulic conductivity of the aquifer, hydraulic gradient and discharge area along the stream.

Generated streamflow from each of the subcatchments is routed downstream based on open channel hydraulics through a detailed channel and stream network (Fig. 2.2). A particular segment of the channel may lose water through evaporation and also infiltration and become dry if the groundwater system does not contribute to the stream. The model is capable of reporting streamflow and salinity at any nominated point in the network.

4.2.1 Calibration and verification

The LUCICAT model was calibrated and verified for the Mundaring catchment to represent daily streamflow and salinity generation processes for the period 1979–2003. The predicted and measured daily streamflow, salt load and salinity graphs matched very well for all gauged subcatchments. The calibrated model was used for predicting the effects of management scenarios on salinity reduction.

Most of the parameters of this model do not change between applications in different catchments (Bari et al. 2003; Bari & Smettem 2004). The seven parameters that may vary between subcatchments (Table A4.3) can be correlated with physical field parameters. Details of calibration and verification are given in Appendix A4.2.2. Because the groundwater level rose and flows were unstable following clearing in 1970s, streamflow and salinity data up to 1990 were used for calibration and the rest of the data to 2003 used for verification. Once satisfactory matching of the observed and predicted daily flows was achieved, the next step was to calibrate the daily stream salinity and salt load. The lateral hydraulic conductivity of the Groundwater Store (K_{ll}) and the parameter (C_u), which controls the stability of the salts stored in the topsoil, were also adjusted to give the most satisfactory matching of the observed and predicted flows, salinities, salt loads (Fig. A4.2) and groundwater trends (Fig. A4.3).

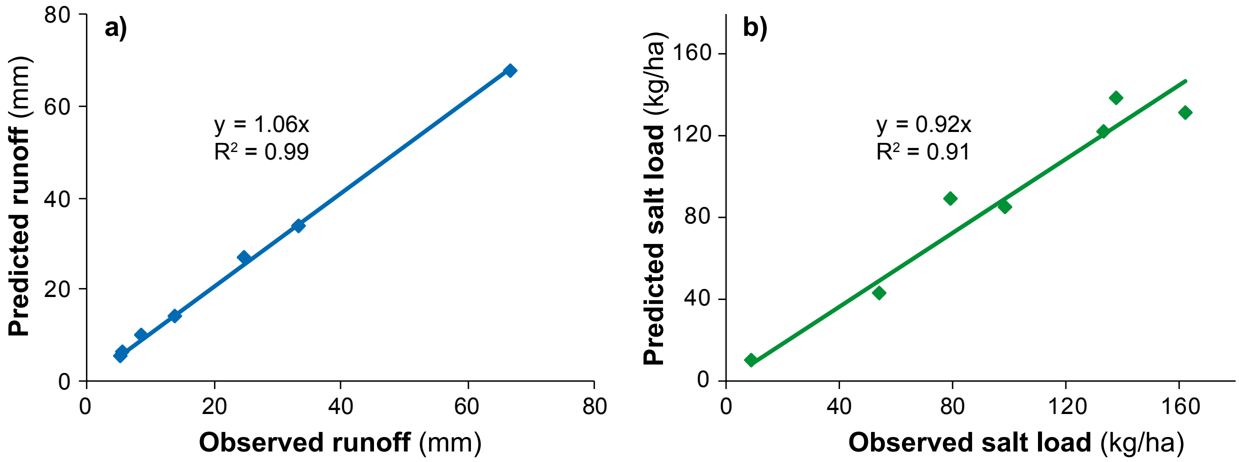


Figure 4.3 LUCICAT calibration of mean annual a) runoff and b) salt load at the seven gauging stations

Daily simulated and observed streamflow hydrographs matched reasonably well for most of the gauging stations, except during some peaks and recessions. Surface runoff and interflow components dominate the daily streamflow from May to October. Only the Helena River at the Ngangaguringuring gauging station flows all year, due to local hydrogeology. Here the baseflow salinity of 2000–3000 mg/L was occasionally overpredicted by the model. Daily predicted stream salinities at the Poison Lease gauging station (Fig. A4.6) were less than observed ones for the representative year 2000 (chosen for its midrange rainfall and runoff) but the daily salt loads matched well. Daily observed and predicted salinities of the Rushy Creek subcatchment exceeded 500 mg/L at the onset and end of the flow period. Daily observed salinities at the other gauging stations (Darkin River, Pickering Brook (Figs A4.7 & A4.8), Little Darkin River and Helena Brook) were less than 500 mg/L during the 1979–2003 period and were reasonably predicted by the model.

Monthly observed and predicted runoffs for the seven gauging stations for the whole simulation period show good agreement (e.g. Poison Lease Fig. A4.5). The coefficients of determination (R^2) between the observed and predicted monthly runoffs ranged from 0.78 to 0.93. The model overpredicted runoff for months with very high streamflow. Monthly salt load was overpredicted for Poison Lease GS when there was very little streamflow (Fig. A4.5b).

Annual mean simulated and observed runoffs (1990–2002) for all gauging stations (Fig. 4.3a) match within -2.7 to +0.4 mm. The model tends to underpredict the low-flow years for most of the gauging stations (Fig. 4.4). The predicted annual lows (10th percentile) were generally less and the predicted highs (90th percentile) were generally more than observed flows (Tables 4.2 & 4.3). As a result the coefficient of variation (CV) of the predicted annual flow was generally greater than that of the observed data; however, the coefficient of determination (R^2) was better with annual than monthly data. Chiew and McMahon (1993) suggested that if the ratio of the mean simulated flow to the mean recorded flow is in the range 0.90–1.1 and the R^2 is above 0.8 then the model calibration and predictions are 'always acceptable'. Annual mean predicted and observed salt loads (1990–2002) also matched well (Fig. 4.3b). At Poison Lease the annual salinities predicted, particularly for the low-flow years, were greater than those observed. Annual predicted and observed Rushy Creek, Little Darkin River and Pickering Brook salinities generally matched well (Fig. A4.4).

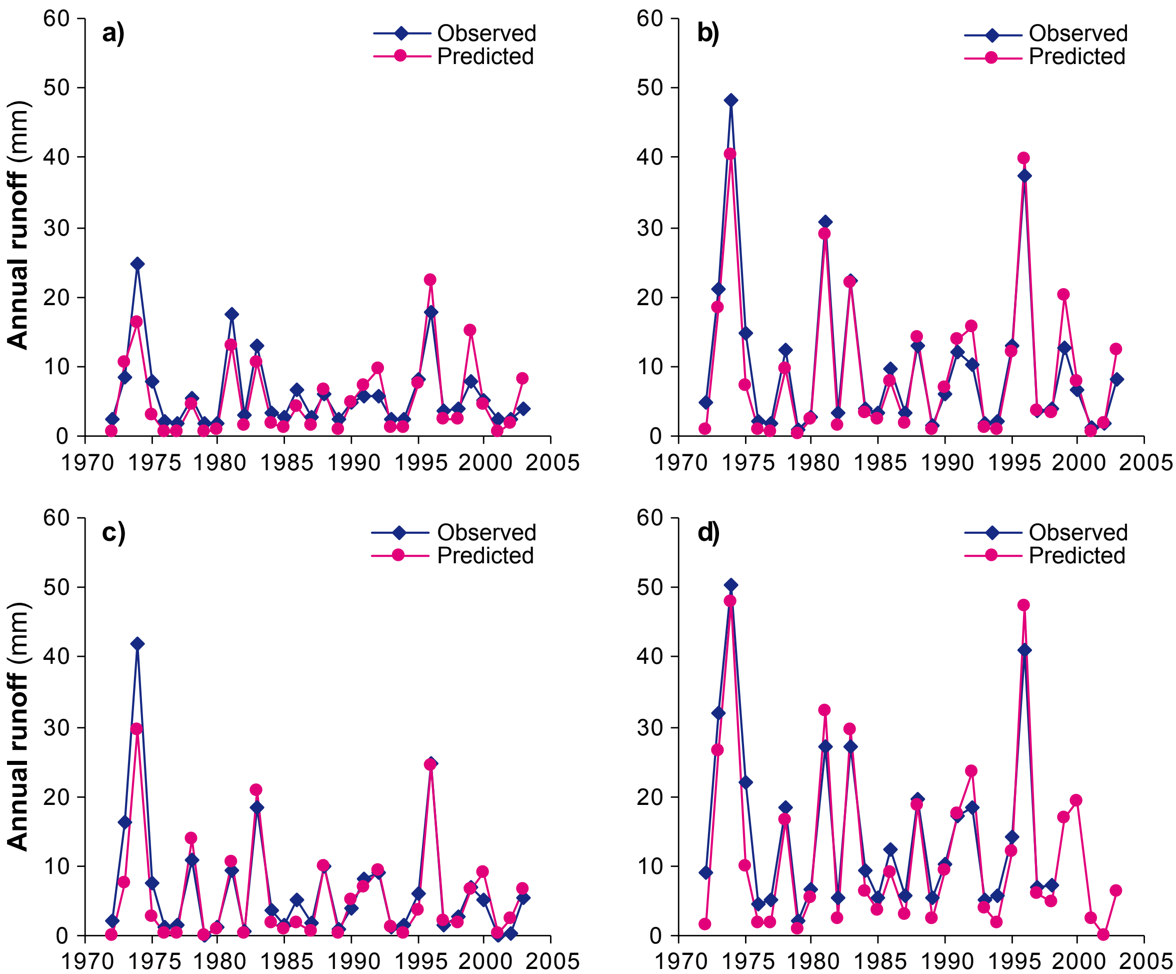


Figure 4.4 Annual observed and predicted runoffs at a) Ngangaguringuring b) Poison Lease c) Darkin River gauging stations and d) into the reservoir

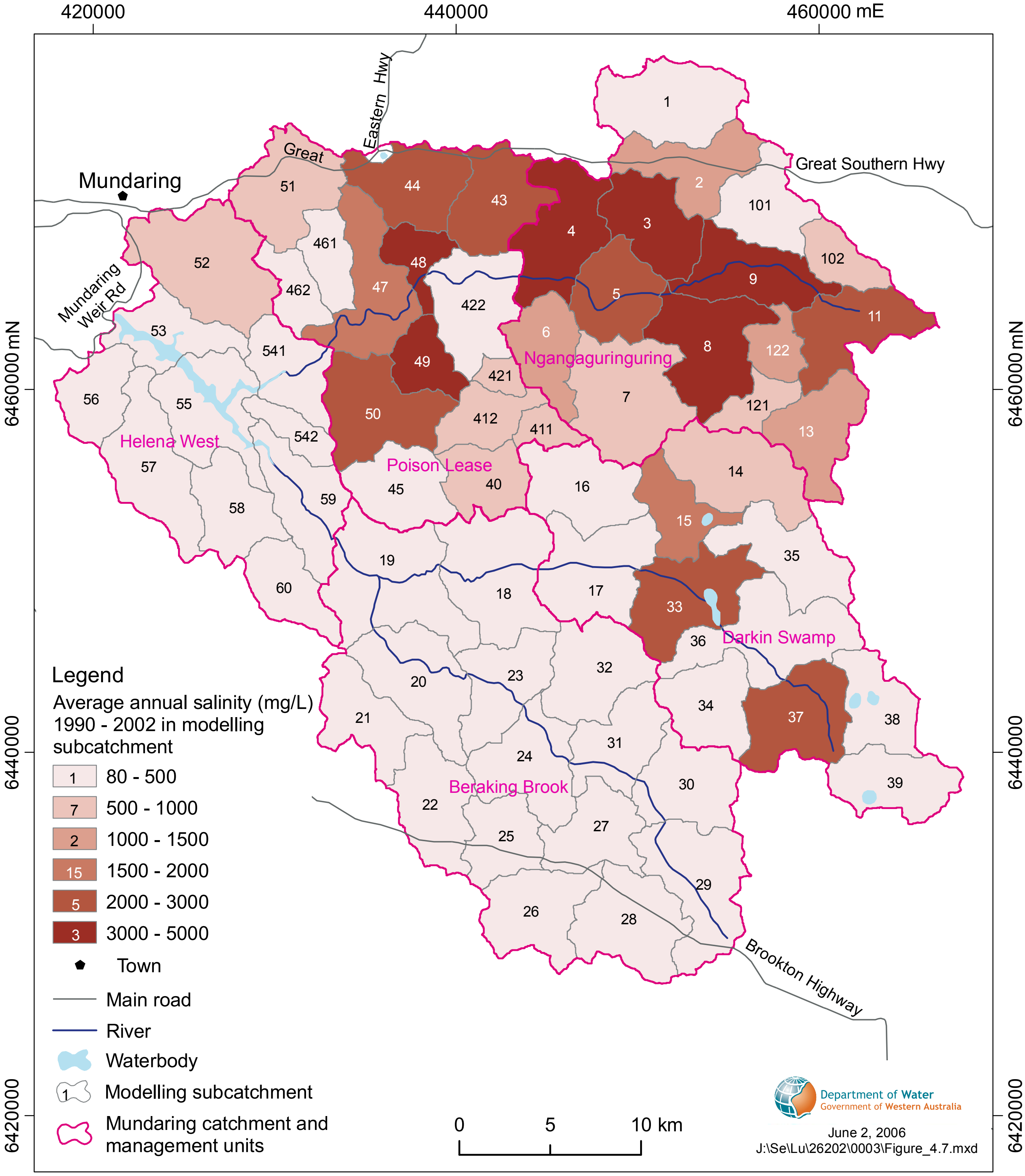


Figure 4.5 Predicted mean annual stream salinity (LUCICAT 1990–2002)

The predicted means of salinity (Fig. 4.5), runoff (Fig. A4.9) and salt load (Fig. A4.10) during 1990–2002 indicate their spatial distribution and origins. Stream salinity in the Mundaring catchment ranges widely, from 80 to 4500 mg/L (Fig. 4.5). Higher salinity was generally associated with lower rainfall and a relatively larger proportion of cleared catchment. The distribution of annual runoff generally reflects the distribution of rainfall (Fig. 2.2), proportion of cleared land (Figs 2.9–2.11), and to a lesser extent catchment hydraulics. The western, wetter parts provided the greatest runoff while the eastern drier forested parts of the catchment shed less than 1 mm/yr (Fig. A4.9). In contrast, subcatchments with a higher percentage of cleared area tended to generate higher salt loads than their uncleared counterparts. The salt yield from the drier uncleared eastern part of the catchment mostly ranged from 1 to 50 kg/ha (Fig. A4.10).

Table 4.2 Observed annual runoff (mm) statistics 1990—2002

Gauging station	10th Percentile	Median	Mean	90th Percentile	CV
Ngangaguringuring	2.4	5.0	5.6	8.0	0.7
Helena Brook	9.7	22.2	30.6	56.6	0.9
Poison Lease	1.7	6.0	8.6	12.9	1.1
Darkin River	0.5	3.8	5.4	9.0	1.2
Little Darkin River	10.1	19.8	24.9	49.8	0.8
Pickering Brook	34.5	51.9	66.7	121.7	0.6
Rushy Creek	11.4	23.5	33.2	62.8	0.8
Dam inflow	5.2	10.3	12.6	18.4	0.8

Table 4.3 LUCICAT-predicted annual runoff (mm) statistics 1990—2002

Gauging station	10th Percentile	Median	Mean	90th Percentile	CV
Ngangaguringuring	1.2	4.7	6.2	14.0	1.0
Helena Brook	5.5	23.3	31.0	54.4	1.1
Poison Lease	1.0	7.1	9.8	19.3	1.1
Darkin River	0.5	3.2	5.1	8.5	1.2
Little Darkin River	5.7	15.8	27.1	50.6	1.0
Pickering Brook	25.9	44.7	67.9	143.5	0.8
Rushy Creek	5.3	15.4	33.7	55.4	1.0
Dam inflow	2.6	9.2	12.6	21.9	0.9

4.3 Base case — the present management scenario

The base case is the equilibrium hydrological condition, calculated using the MAGIC and LUCICAT models, under the current climate and land use (2002 Landsat scene). For the Mundaring Reservoir during the period 1990–2002 the estimates were annual inflow of 18.7 GL, annual salt load of 7.1 kt and flow-weighted salinity of 490 mg/L (Table A4.6). Some parameters used in the modelling affected the final estimates for the Mundaring Reservoir inflow. The LUCICAT model was run for an extra period (2004–27) with only the 2003 land use (Appendix 5). Not varying the Landsat scene raises mean annual inflow to Mundaring Reservoir by 1.4 GL, compared to the simulation for the years 1990–2002 where the LAI is varied between years (Tables A5.8 & A4.6). Also, compared to these the (2014–26 arithmetic mean of the flow-weighted annual) salinity of the reservoir inflow increased to 500 mg/L (Table 5.1).

More scenarios were run using the LUCICAT model as it is considered better suited for the dynamic forest management options. Hence the LUCICAT results are reported for all of the modelled management options. Comparison with this base is used to assess the modelling-derived equilibrium characteristics for land-use or rainfall change scenarios.

5 Management options and scenarios

This Section sets out the range of yields, salinities and salt loads for likely conditions (scenarios) both controlled (e.g. vegetation changes, tenure, and forest mass) and uncontrolled (e.g. rainfall, climate, wildfire). It presents two main groups of vegetation management scenarios – farming and forestry and resulting equilibrium inflow salinities (Fig. 5.1 & Table 5.1). No attempt has been made to evaluate combinations or to exhaust the spectrum of forestry activities and fire intensities.

The introduction of clearing controls in 1978 and revegetation of repurchased farmland have averted the rise of inflow salinity to about 1500 mg/L (Table 5.1 Present clearing risk…) The arithmetic mean of the flow-weighted annual inflow salinity to the reservoir is 510 mg/L (1990–2002, Table A3.6). While not rising, this is just above the desired 500 mg/L limit for potable water, a level that has been exceeded in 7 of the 10 years up to 2002 (Fig. 5.1). This low residence-time reservoir can only tolerate a few dry, high-salinity inflow years without significant pumpback. The volume stored is only a few years' supply and the annual withdrawal and inflow are similar.

Modelling to hydrological equilibrium, for a range of specific management actions, allows comparison with the equilibrium for 'no change in land use' (base case). The base case estimates for the period 1990–2002 are annual inflow of 20.1 GL to Mundaring Reservoir, annual salt load of 7.7 kt and flow-weighted salinity of 500 mg/L (Table A5.8) – coincident with the target salinity. If no further action is taken (Fig. 5.1), the target salinity will be exceeded in 7 out of 10 years.

The most effective management options are:

- Farming: Replanting the 23 km^2 of annual pasture in the flowing part of the catchment (Nganguringuring and Poison Lease MUs) with deep-rooted perennial pasture or (commercial) trees would greatly lower salinity, to 270 and 230 mg/L respectively.
- Forestry fire: A 12-year cycle of prescribed burning to limit fuel in the forest has the least impact on salinity. More frequent burning (on a 4-year cycle) in the Helena West MU could lower the reservoir inflow salinity to 440 mg/L. Hot wildfires leave areas of unburnt, medium and totally burnt forest and temporarily increase runoff, but generate more from the western than the eastern part of the catchment. Hot wildfires appear to result in very vigorous regrowth with reduced runoff after a number of years.
- Forestry silviculture: The specified silvicultural treatments of gap creation, shelter wood and thinning (considered in this report) would lower reservoir salinity and generate additional water, most of which would be from the western part of the catchment.

5.1 Historic cases — a catastrophe averted

Sufficient similar scenarios were modelled to confirm the dramatic reported impacts of earlier episodes of ringbarking and land clearing, and the mobilisation of salt even in the wetter western part of the catchment. Due to data quality issues, rather than simulations of historic water analyses, clearing and ringbarking, modelling is based on present climate data.

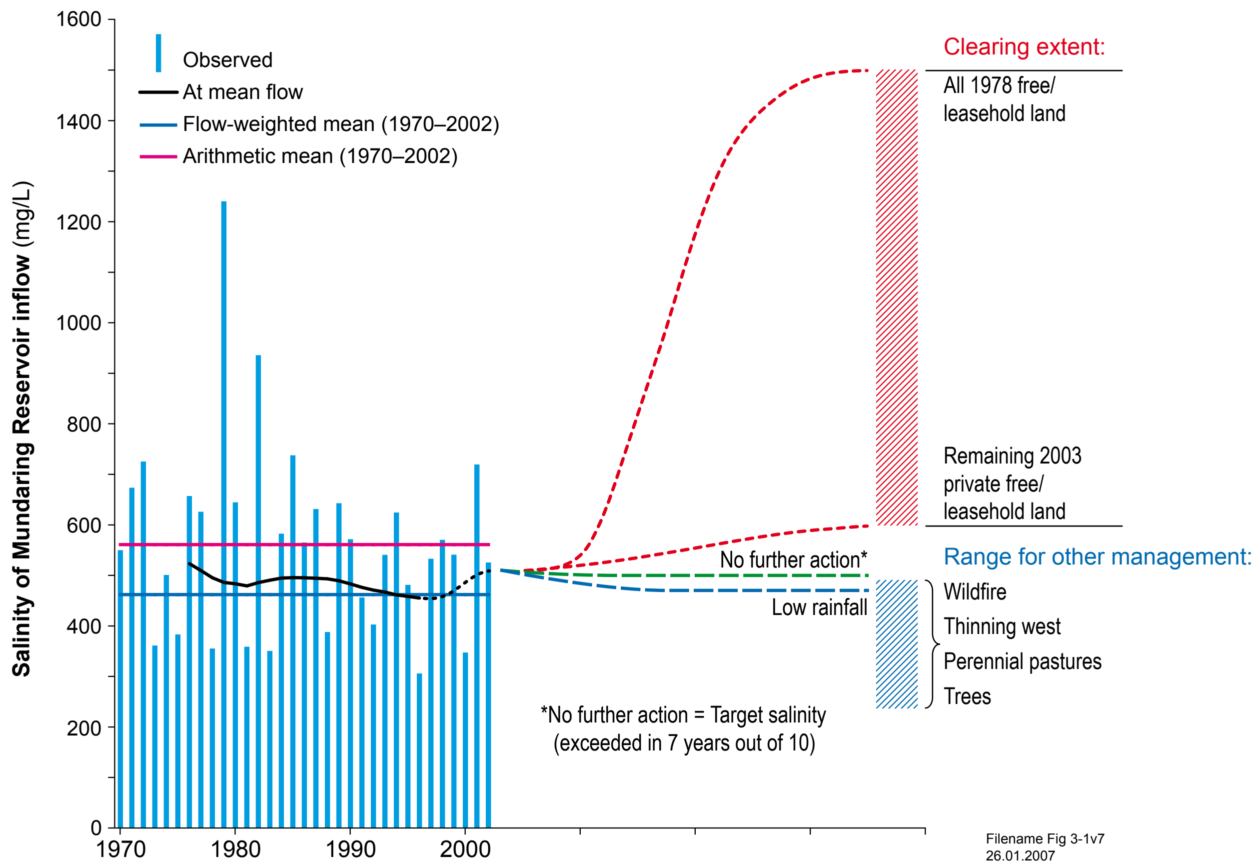


Figure 5.1 Salinity of inflow to Mundaring Reservoir

5.1.1 Present clearing risk (all 1978 freehold and private leasehold land cleared for annual pastures)

The land tenure in the catchment is shown in Figs 2.4 & 5.2 and the private tenure of 1978 is still recognisable. To reveal how successful the clearing controls and land acquisitions of the 1970s were, the clearing of 1978 private leasehold, private freehold and government freehold land (196 km^2) was simulated from 2003 (an additional 157 km^2 of clearing). The mean annual inflow and salinity to the reservoir could rise to 31.4 GL and 1500 mg/L respectively (Table A5.10). Salinity at the outlets of the Ngangaguringuring and Poison Lease management units would have been around 2900 and 2800 mg/L respectively. The clearing controls and land acquisition of the 1970s were significantly more beneficial than estimated by the Western Australian Water Resources Council (Public Works Department 1979, Fig. 9, 700 mg/L).

5.1.2 Decreased rainfall

The most recent mean whole-of-catchment annual rainfall, 660 mm for 1997–2003, is 4% below the 690 mm for 1975–2003 (Appendix 5). This longer period commences a year earlier than the shift to a new lower rainfall phase noted by the Indian Ocean Climate Initiative Panel (2004). If this 1997–2003 rainfall regime continues, the inflow to the reservoir would decrease from 20 to 16 GL, the load from 7.1 to 6.0 kt (Appendix 5) and the mean annual inflow salinity from 500 to 470 mg/L (Table 5.1). This predicted reduction in salinity might be attributed to less groundwater discharge to the streamzone and the small numbers used to calculate the arithmetic mean; as the salt load has been increasing at Ngangaguringuring despite the decreased rainfall.

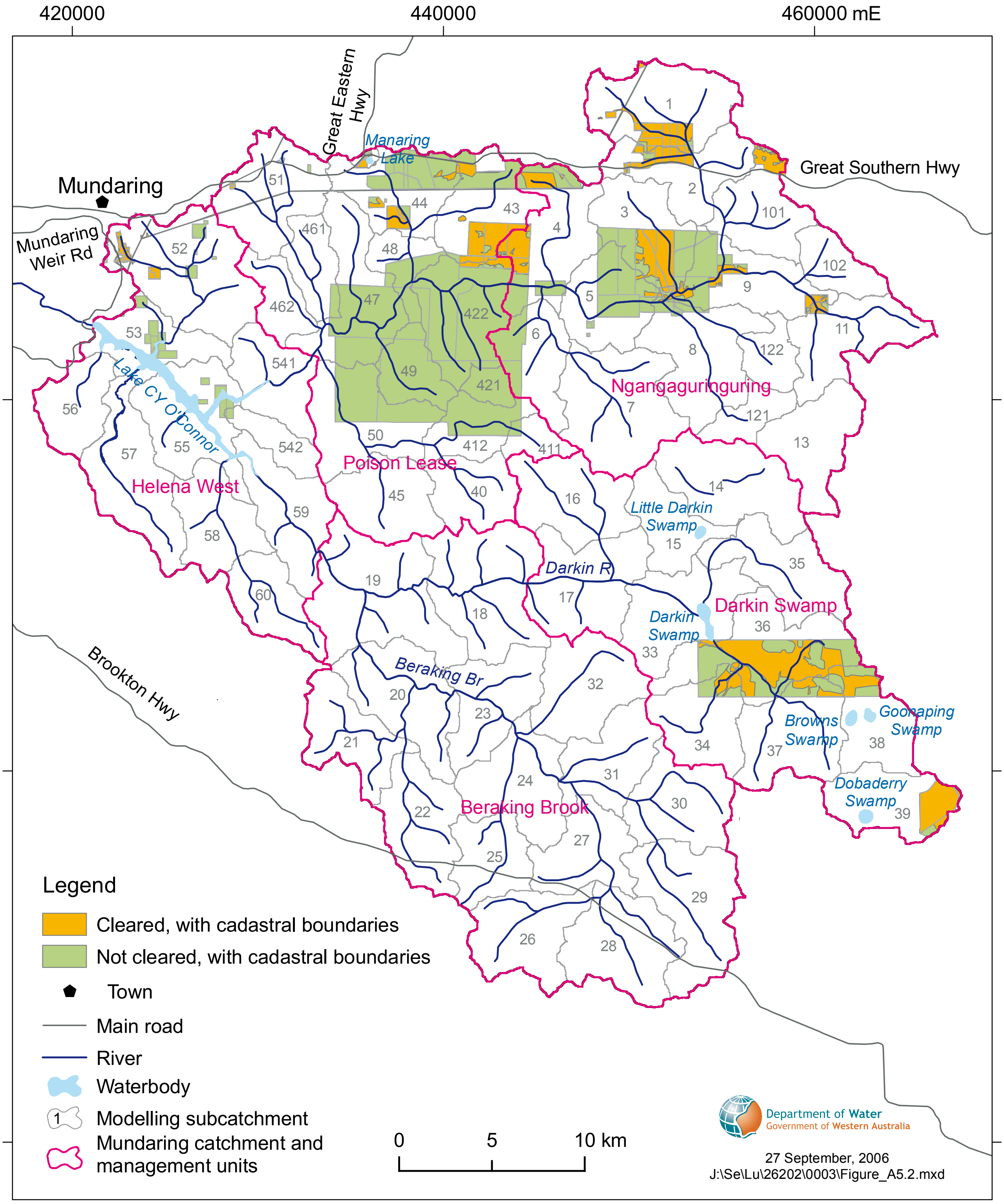


Figure 5.2 Spatial distribution of free/leasehold land for modelled scenarios

Table 5.1 Projected reservoir inflow for key management scenarios

Scenarios	Area affected (km^2)	Reservoir annual inflow		
		Salinity (mg/L)	Streamflow (GL) [a]	Salt load (kt)
No change				
Base case (Section 5.1)	0 [b]	500	20.1	7.7
Present clearing risk (all 1978 free/leasehold land cleared for annual pasture)	157 [c]	1500	31.4	30.5
Decreased rainfall	1480 [b]	470	15.9	6.9
Farm management (Section 5.2)				
Cleared areas				
Continue with annual pastures as for base case	39 [b]	500	20.1	7.7
Change to deep-rooted perennial pastures [d & e]	23	270	19.7	5.4
Change to (commercial) trees [d]	23	230	18.6	4.1
Timbered areas				
All 2003 scene cleared for annual pasture	30 [f]	600	24.5	10.9
Forest management (Section 5.3)				
Silviculture (thinning by 30%, transient effects)				
In the east (Ngangaguringuring MU)	328	480	20.7	7.8
In the west (Helena West MU)	221	460	22.7	7.9
Prescribed burns (transient effects)				
In the east (Ngangaguringuring MU)				
On a 4-year cycle	328	460	20.6	7.8
On a 12-year cycle	328	500	20.2	7.7
In the west (Helena West MU)				
On a 4-year cycle	221	440	22.4	8.0
On a 12-year cycle	221	480	20.8	7.8
Hot wildfire (transient effects) [g]				
In the east (Ngangaguringuring MU)	328	490	20.5	7.7
In the west (Helena West MU)	221	470	22.6	7.9

[a] Flows are elsewhere rounded to 2 significant figures
[b] Within the 1480 km^2 catchment, 39 km^2 (2.6%) remains cleared on private free/leasehold land (Section 2.7.4)
[c] The area cleared increases by 157 from 39 to 196 km^2
[d] Replace the 23 km^2 of annual pasture currently on farms in Poison Lease and Ngangaguringuring MUs
[e] MAGIC results scaled to LUCICAT base
[f] The area cleared increases by 30 from 39 to 69 km^2
[g] Adopts the composition of the January 2005 wildfire (Higgs 2005): 31% hot, 60% medium and 9% unburnt

5.2 Farm management

The scenarios – maintaining annual pastures at the 2003 level, planting deep-rooted perennials or (commercial) trees in place of pastures and, if the clearing controls were lifted, the effects of completely clearing the farmland for annual pastures – are described below.

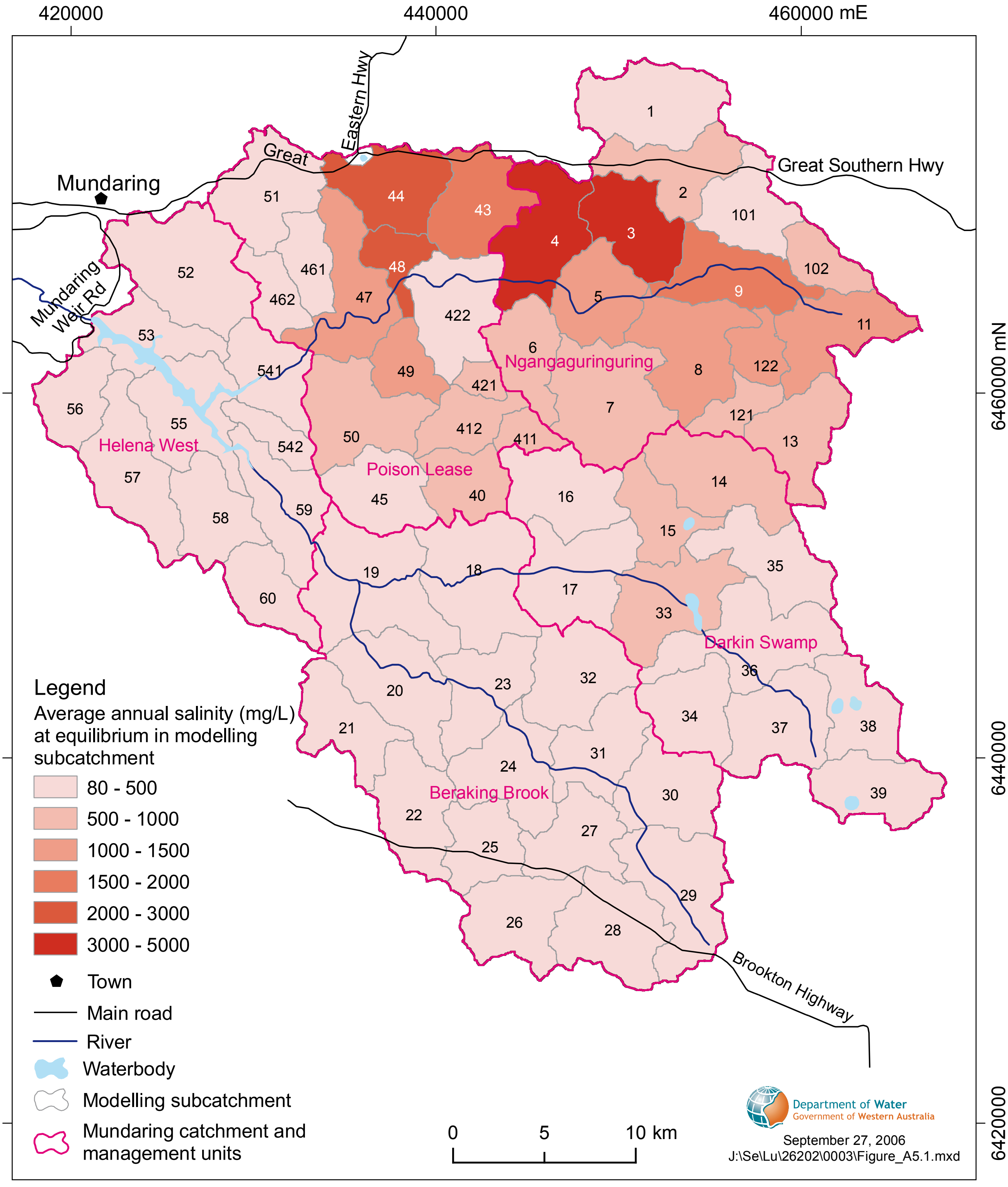


Figure 5.3 Distribution of salinity for all cleared private land planted with trees

5.2.1 Maintain annual pastures (the base case)

The cleared farmland is mostly covered with annual pastures, and comprises 17, 6 and 15 km^2 respectively in the Ngangaguringuring, Poison Lease and Darkin Swamp MUs in 2003. This current land use equates to the base case (Table 5.1). The Darkin River is currently fresh and its salinity does not seem to be affected by the clearing on the farms upstream of the Darkin Swamp.

5.2.2 Replace annual pastures with deep-rooted perennial pastures

The mean annual salinity of the reservoir inflow would be 270 mg/L (230 lower than the 500 of the base case) if the 23 km^2 of annual pasture were replaced with high-density deep-rooted (3 m effective rooting depth) perennials on farms in the Poison Lease and Ngangaguringuring management units. The salinities of the Ngangaguringuring, Poison Lease and Darkin Swamp management units are predicted to decrease to below 1000 mg/L (Table A5.6). (Note that for Darkin Swamp the mean annual salinity is for the whole MU even though south-eastern half provides little flow).

The density of deep-rooted perennial pastures was represented by keeping LAI at maximum (equivalent to the winter maximum LAI for annual pasture) for the whole year, even though, in reality this would not be feasible. If the perennials are too heavily grazed (leaving 80 to 50% winter maximum LAI), then they have the same value as annual pastures in terms of salinity reduction in the streams (De Silva et al. 2007).

Deep-rooted perennials were simulated using MAGIC only (Table A5.6) and the results adjusted at the reservoir inflow for comparison with LUCICAT results (Appendix 5.1.4).

5.2.3 Replace annual pastures with (presumably) commercial trees

LUCICAT predicts that the (arithmetic) mean (of the flow-weighted) annual (1990–2002) salinity of the reservoir inflow would be 230 mg/L (270 lower than the base case) if the priority areas for maximum impact – the areas with annual pasture in the Poison Lease and Ngangaguringuring management units, were replaced with tree plantations (Table 5.1). The mean annual salinity remained above 500 mg/L in the eastern section of the catchment, where lower rainfall, higher evaporation and low runoff limit flushing of accumulated salts from the streamzone (Fig. 5.3). The mean annual stream salinity at the Poison Lease gauging station will fall from 2100 to 380 mg/L (Table A5.11).

Figure 5.4 shows the generalised relationships of annual reservoir inflow salinity, streamflow and salt load to the area of land to be reforested by using the results of (i) the base case (39 km^2 cleared), (ii) all free/leasehold including government land as at 1978 (196 km^2 cleared), (iii) 2003 (69 km^2 cleared), and (iv) replacing the annual pastures with trees (0 km^2 cleared). Mean annual inflow to the Mundaring Reservoir is predicted to decline approximately linearly to 18.6 GL (Table A5.11) if all the cleared areas were planted. The relationships of the cleared areas replanted to mean stream salt load and salinity reductions are also approximately linear. The reservoir mean annual incoming salinity, streamlow and salt load would fall at the rate of 0.066 GL, 3.7 mg/L and 137 t per km^2 revegetated. These results are similar to the corresponding exercises in the Denmark and Kent Water Resource Recovery Catchments (Bari et al. 2004; De Silva et al. 2007).

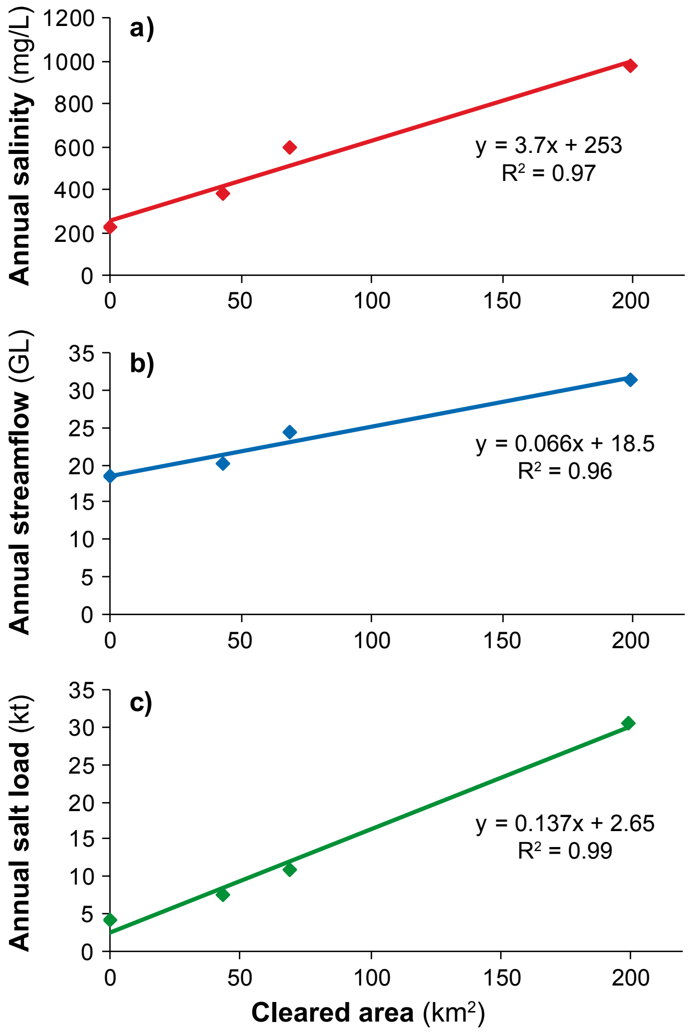


Figure 5.4 The LUCICAT-predicted Mundaring Reservoir inflow a) salinity b) volume and c) salt load relationships to cleared area

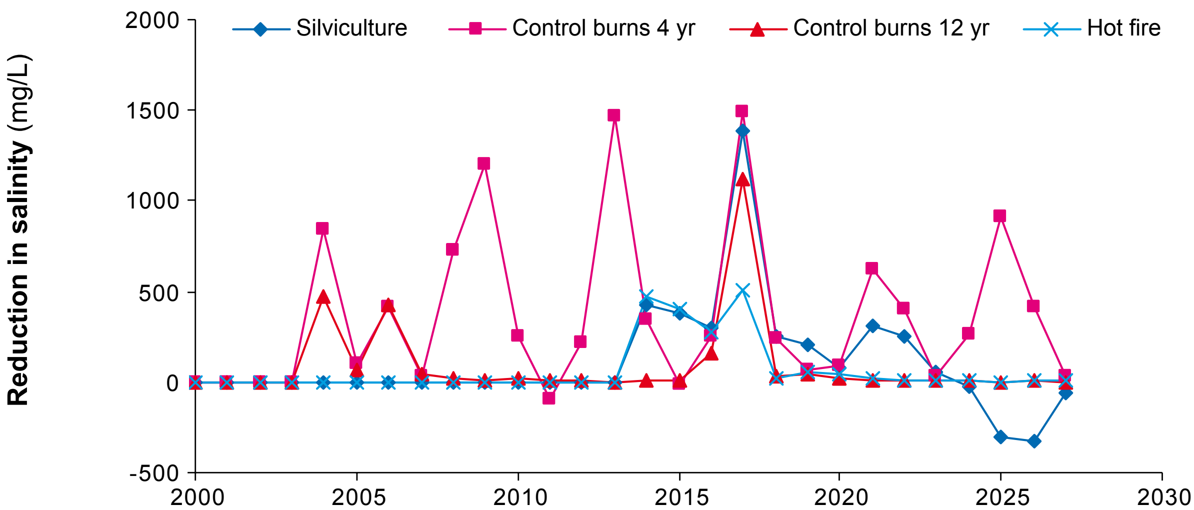


Figure 5.5 Salinity changes predicted for silviculture and forest fire in the Ngangaguringuring MU

5.2.4 Completely clear 2003 free/leasehold land for annual pastures

If all 30 km^2 of timber on the free/leasehold land as at 2003 (Fig. 5.2) were cleared for agricultural development then mean annual stream salinities at most of the gauging stations would rise (Appendix 5). Mean annual inflow and salinity to the Mundaring Reservoir are predicted to increase from 20.1 to 24.5 GL and from 500 to 600 mg/L respectively (Table 5.1). Such clearing is however regulated by the CAWS Act clearing controls (Public Works Department 1979; Sadler & Williams 1981) and, since July 2004, the *Environmental Protection Act 1986*.

5.3 Forest management

For simplicity, to simulate forest management practices and compare effects between east and west, LUCICAT was applied to only the Ngangaguringuring and Helena West MUs (Appendix 5). These practices, described below, apply to all of the catchment except that in the Conservation and National parks, that form about 38% of the Mundaring catchment, commercial timber operations are not practised. To this extent, recent and proposed expansions of Conservation and National park area will limit the application of forestry for salinity and water yield management e.g. by silvicultural thinning.

5.3.1 Silviculture

Early in the cycle of thinning (a 30% reduction in LAI) there are large transient reductions in the annual salinity – as much as 1500 mg/L depending on annual rainfall (Fig. 5.5). Mean streamflow from the Ngangaguringuring MU increases from 2.3 to 2.7 GL (Tables A5.13 & A5.8), and the mean annual inflow to the reservoir by 3%, from 20.1 to 20.7 GL, decreasing the mean annual inflow salinity by 20 to 480 mg/L (Table 5.1).

The effects of silviculture would be greater in the Helena West than in the Ngangaguringuring MU (Tables A5.13 & A5.8). The mean inflow to the reservoir would increase to 22.7 GL and mean salinity would reduce to 460 mg/L (Table 5.1). Even in this high-runoff MU the extra 14% yield is only 1 GL per km^2, which is one-seventh of the increase observed after more severe basal (tree stem) area and LAI reduction in experimental catchments in the high-rainfall zone (Robinson et al. 1997, Fig. 15).

High-water-use trees, such as pines and some native vegetation with high stand density, are appropriate on the sedimentary aquifer (Fig. 2.7) to rapidly reduce recharge and hence saline discharge. On the other hand, the stand density of pines should be managed, particularly in the western half of the catchment and near streams, so their water use does not reduce yield (runoff). For the pine plantations in the Helena West MU, where salt stores are smaller, forest management – thinner stands of pines and possibly native vegetation – could be used to increase yield without increasing salinity.

5.3.2 Prescribed burns

Prescribed low–medium intensity burning is undertaken by the Department of Environment and Conservation mainly to reduce forest litter that could fuel a hot fire with resultant intense forest damage (Sneeuwjagt & Higgs 2005) and erosion, and to promote forest health. The simulated effects of prescribed burning, on 4- and 12-year cycles, in the Ngangaguringuring and Helena West MUs (representing the east and west of the catchment) are, as for silviculture, transient (Appendix 5). The 4-year cycle has the larger impact on streamflow and salinity (Fig. 5.5) – in the Ngangaguringuring MU the mean annual inflow to the reservoir increases to 20.6 GL and salinity decreases by 40, to 460 mg/L (Table 5.1), compared with minimal benefits (only 0.1 GL increase in inflow and 2 mg/L reduction in salinity) with a 12-year cycle.

Most of the increase in streamflow is expected to come from the Helena West MU (Tables A5.14, A5.15 & A5.8). On a 4-year cycle, reservoir inflow would increase to 22.4 GL and salinity decrease from 500 to 440 mg/L, and for a 12-year burning cycle, the additional streamflow would be 0.7 GL and the reservoir salinity reduction would be only 20 mg/L (Table 5.1). Prescribed burning repeated on a 4-year cycle has effects on streamflow similar to a single round of thinning (see Glossary).

5.3.3 Hot wildfires

The transient effects of a hot wildfire (CALM 2005) were estimated by simulating fires in the west and east, again using the Ngangaguringuring and Helena West MUs (Fig. 5.6). The distribution of burning intensity was based on an actual fire in January 2005 that encroached on the south-east end of the reservoir (Higgs 2005), killed more than one million trees and was subsequently reflected in the data of the Little Darkin gauging station. The simulated fire is similar to the Mt Cooke hot wildfire south of the catchment in January 2003, estimated to have killed millions of trees on 18 000 ha (Burrows 2005). Hot wildfires sometimes have other hydrological effects such as erosion and siltation not detailed in this report.

A hot fire in the Ngangaguringuring MU would have little lasting effect on the inflow salinity to Mundaring Reservoir, mainly because runoff there is normally very low, averaging 1% of the annual rainfall (Fig. 5.5). If the hot fire was restricted to the Ngangaguringuring MU, mean reservoir inflow salinity is predicted to decrease by 10 mg/L while the inflow is predicted to increase by 0.4 GL. A hot fire in the Helena West MU would decrease mean reservoir inflow salinity by 30 mg/L and increase streamflow by 2.5 GL (Table 5.1 & Fig. 5.1).

Barrett (pers. comm. 2006) advises that for Little Darkin the yield for the year following the January 2005 hot wildfire was 1 GL, and, by reference to the Pickering Brook control station record, was some 2.2 times the yield expected if the wildfire had not occurred. Modelling indicated a doubling of yield in the year after the hot-fire scenario in this subcatchment (Fig. 5.6). Due to vigorous regrowth triggered by the wildfire the runoff in a few years time could be less than before the wildfire. Over this longer (5-year) period the modelling indicates a 50% yield increase at Pickering Brook and only a 10% increase at Ngangaguringuring.

5.4 Engineering changes

This study was confined to the Mundaring catchment and did not explore the effects on salinity of mixing water piped from the pumpback dam and/or the dams and groundwater supplying metropolitan Perth and Mandurah, or water removed by draining, pumping or diversion from the catchment. In this Section we consider several engineering scenarios (options) particularly in relation to the sedimentary aquifer.

5.4.1 Drains — not an option here

Both deep and shallow drains expedite discharge and flow to the reservoir, so increase streamflow and salt load. They are most likely to be considered for the wetlands in the Darkin Swamp MU to overcome waterlogging or to harvest additional fresh water, but are unlikely to be used for saline groundwater in the sediments or bedrock near Ngangaguringuring. Construction and maintenance costs may make this option unappealing. For Darkin Swamp this might add 0.4 GL runoff to the 0.4 GL from below the swamp.

5.4.2 Groundwater pumping — an option requiring more investigation

The sedimentary aquifer has, since clearing, maintained saline-to-brackish summer flow in the Helena River almost to the Reservoir (Smith & Smith 2005). Groundwater pumped from bores in the sedimentary aquifer may reduce salinity, especially north of the Ngangaguringuring MU, without change to the existing plantations and native vegetation. The discharge points, whether inside or outside the catchment, would need to be environmentally compatible with (constant) brackish-to-saline discharge. Alternatively, use of the water (e.g. for agriculture, sand mining or even desalination) within the catchment could leave salt disposal as a problem. Simply pumping the groundwater to the Helena River would expedite discharge and increase the river flow, while reducing evaporative concentration, lowering the groundwater levels and reducing if not eliminating the mobilisation of salt from the regolith. A reduction of 100 mg/L is based on the graphs of baseflow salinity and volumes, doubled to allow for similar discharge to Wariin Brook to the north (Mauger pers. comm. 2006). Any investigation and monitoring of the sedimentary aquifer should include Ngangaguringuring and Darkin Swamp – the latter in case it begins to discharge water and possibly salt.

5.4.3 Surface water diversion — probably not an option

Full diversion of saline water by damming the Helena River near the Poison Lease gauging station would reduce the actual 1990–2002 mean annual salinity and inflow to 230 mg/L and 12.0 GL (from 17.1, Table 3.2). Full diversion at the Ngangaguringuring gauging station would reduce the mean annual salinity and inflow to 300 mg/L and 15.3 GL. Such large reductions in inflow would not be acceptable and would require at least a sump or dam and disposal to an evaporation basin.

5.4.4 Pumpback

The pumpback of fresh water from west of the Mundaring Weir is already lowering salinity in the reservoir, especially in critical periods (Itzstein-Davey & Conacher 2001). This western catchment area was not included in this study but modelling could be extended to incorporate it. The availability of mixing to lower the reservoir salinity below 500 mg/L reduces the need to stem saline inflow and therefore significantly reduce the overall water resource.

5.4.5 Combinations of the above

Management using combinations of the scenarios has not been considered as each scenario has quite a small impact.

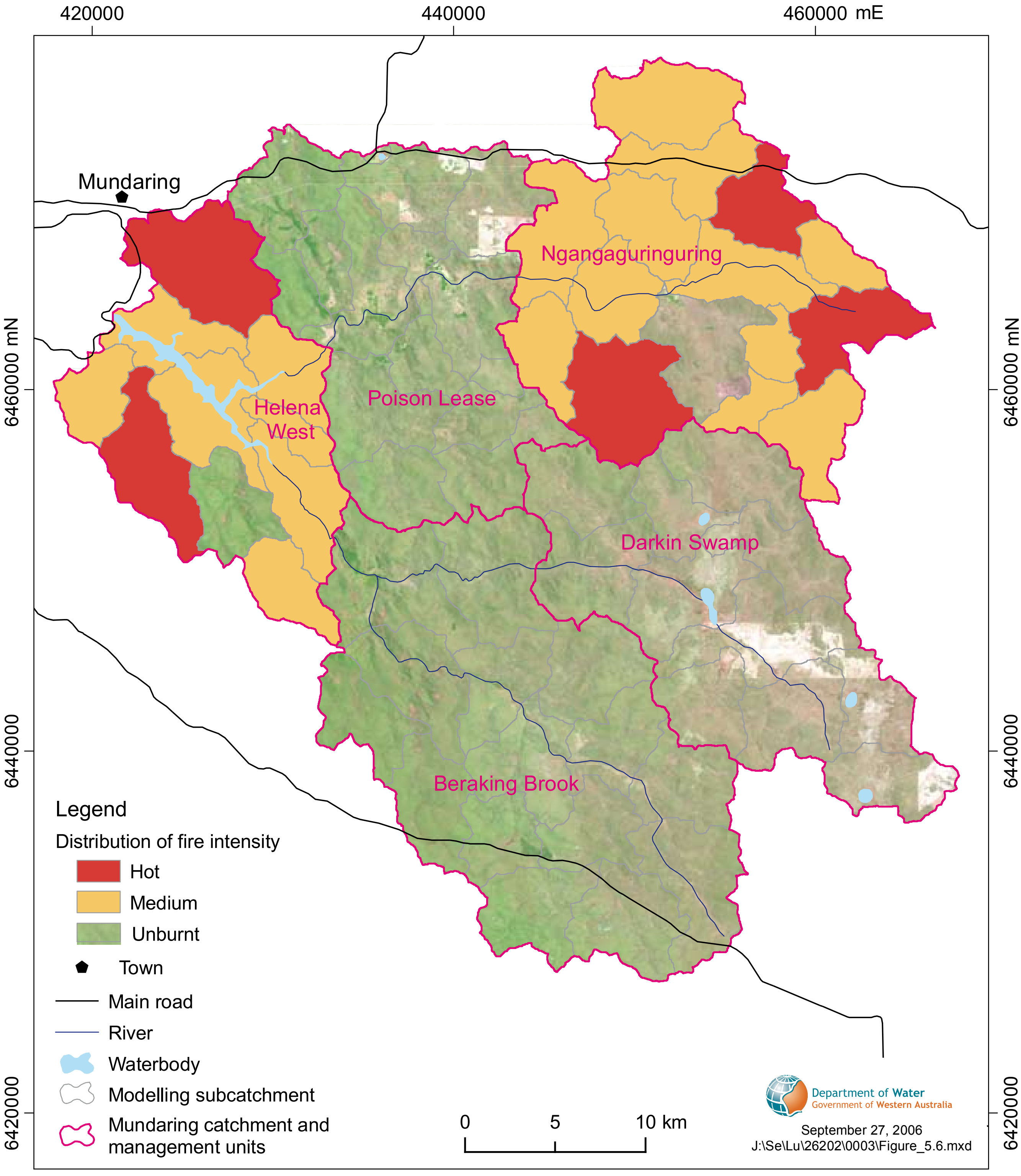


Figure 5.6 Distribution of burning intensity in a hot wildfire scenario

6 Conclusions

The Mundaring Reservoir inflow salinity, with a mean of 510 mg/L, has exceeded 500 mg/L in 7 of the 10 years up to 2002. This low-residence-time reservoir has 25–30% of its capacity pumped out each year and can only tolerate a few dry, high-salinity inflow years without significant pumpback. The volume stored is only a few years' supply and the annual withdrawal and inflow are similar. The three inflow contributors to the Mundaring Reservoir are the Helena River (30%), Darkin River (21%) and the area flanking the reservoir itself (49%). In wet years the proportion of flow contributed by the two main rivers falls below 50%. Most salt (53%) comes from the Helena River and very little from the Darkin River.

Clearing for agriculture is regulated throughout the 1480 km^2 mostly forested catchment. Only 71 km^2 (5%) is privately owned with just 39 km^2 (3%) of this cleared. Because vegetation management has previously contained or reversed clearing-related salinisation of the Helena River it remains the focus for future management (Appendix 6). Salinities have not yet risen (nor are they predicted to rise) to levels at which engineering solutions additional to the pumpback pipeline need be considered. (Such measures have necessarily been considered in the other, more southerly Water Resource Recovery Catchments). The pumpback is used mainly to increase the resource but also to modify its quality; in particular, to lower its salinity.

6.1 At present

With overall low rainfall and high salt stores in the regolith, the Mundaring catchment forms the northern limit of potential surface water resource catchments in the Darling Plateau. Rainfall decreases eastward from about 1050 to 500 mm/yr.

Rainfall has decreased significantly (13% in this catchment) since the 1970s and modelling has shown that this reduction most reduces runoff near the reservoir and hence the dilution of saline inflow from the Helena River. The highest inflow salinities (750–1250 mg/L) were in the low-rainfall years of 1979, 1982, 1985 and 2001; yet sustained decreased rainfall slightly lowers the inflow salinity.

Even with only minor residual clearing since the 1970s the mobilisation of salt from storage in the regolith, particularly in the Ngangaguringuring MU, has gradually raised the inflow salinity of Lake CY O'Connor above the desired limit for drinking (500 mg/L). Also, with such little clearing, runoff remains a very low 1–6% of rainfall with both runoff and rainfall declining steeply to the east. There remains a risk of Darkin Swamp, currently non-flowing, also exporting water and salt. Further investigation may reveal the need for reforestation at Qualen Road (Locality A).

The catchment is currently showing little change in salinity or salt load and there has been no dramatic change in vegetation since the 1970s to affect the current mean annual inflow to Lake CY O'Connor of 17.1 GL with 7.4 tonnes of salt, giving a salinity of 510 mg/L. Modelling shows that at hydrological equilibrium the corresponding mean annual reservoir inflow, load and salinity would be 20.1 GL, 7.7 kt and 500 mg/L respectively.

The recognition of (palaeochannel) sedimentary aquifers explains the perennial saline groundwater discharge near the Ngangaguringuring gauging station. Just a small cleared area high on the slopes east of the Flynn plantation is maintaining saline-to-brackish discharge, drawing the salt from adjoining bedrock. Since its onset after clearing in the 1970s, groundwater discharge has contributed about 60% of the salt load to the nearby Ngangaguringuring gauging station. Key differences in elevation and dissection probably account for the lack of discharge from the same aquifer at Darkin Swamp. Investigation and monitoring with bores north of both Darkin Swamp and the Ngangaguringuring gauging station would confirm salinity and water levels.

The key for managing salinity in the Mundaring catchment is to disconnect groundwater discharge from surface water flow in the Helena River at Ngangaguringuring and prevent groundwater connection to the Darkin Swamp. This has been demonstrated at Flynn, where substantial reforestation coincident with decreased rainfall lowered the watertable and significantly reduced saline groundwater discharge. This salinity management will require reforestation and maintenance of forest over the local recharge areas, such as the 3 km^2 of land purchased by the Water Corporation in 2003 and 2005 and comprising about half of the recharge area on Abercorn Road near the Ngangaguringuring gauging station. At the same time, the western higher rainfall catchments would benefit from silvicultural treatments to maintain or enhance runoff.

6.2 Even less rainfall

The most recent mean whole-of-catchment annual rainfall, for the period 1997–2003, is 660 mm and is 6% below that for 1975–2003 of 690 mm. If this 1997–2003 rainfall regime continues, the average annual inflow to the reservoir would decrease from 20 to 16 GL and the load from 7.1 to 6.5 kt. The mean annual inflow salinity would decrease from 500 to 470 mg/L due to a reduction in groundwater discharge to the streamzone.

6.3 Farm management

6.3.1 Perennial pastures

Planting deep-rooted perennial pastures on 23 km^2 of private freehold land in the Ngangaguringuring and Poison Lease management units could reduce the salinity at the reservoir (by 230) to 270 mg/L. This is for pastures with an effective rooting depth of 3 m and an LAI kept throughout the year at that of annual pastures in winter. This extent of vegetation change is unlikely to be feasible.

6.3.2 Tree plantations

Establishing (commercial) trees in the **suitable** areas (23 km^2 of the 39 km^2 currently cleared excluding the Darkin Swamp MU that does not flow significantly) could reduce the mean annual salinity, streamflow and salt load to the reservoir to 230 mg/L, 18.6 GL and 4.1 kt. The conclusion is simplistic in that salt storage characteristics are quite different among MUs and the costs and politics of planting may be unattractive.

6.3.3 Further clearing

If the clearing on private land were increased (hypothetically, as this is regulated) to 100%, the impacts are projected to vary with position in the catchment, probably increasing toward the north-east. Modelling indicates that if the remaining timbered, private freehold land were to be cleared (30 km^2) the mean annual salinity and inflow to the reservoir would increase to 600 mg/L and 24.5 GL respectively. This is substantially better than clearing all the free/leasehold land of 1978 for which modelling indicates the mean annual salinity and inflow to the reservoir would increase to 1500 mg/L and 31 GL. These numbers provide the measures of success of the land management of the 1970s in maintaining this as a WRRC.

6.4 Forest (and plantation) management

Forest management is clearly the first alternative to 'do nothing'. Revegetation since the 1970s, together with land (re)purchases and clearing controls, has recovered and restricted the rise of salinity in the Mundaring catchment. Just to be clear, some of this forest (and plantation) is on Government managed (previously private) freehold land. Nearly all of the catchment is forested and forest management (of fire, thinning, harvesting and reforestation) is compatible with maintaining and recovering salinity of surface water resources.

Conservation Reserve management may be of concern. Silviculture improves salinity and yield slightly in the west only, so thinning for water yield should be practised (in addition to prescribed burning) in the Helena West MU. Throughout the catchment the forest is already younger and possibly more limiting of runoff than before logging.

The effects of thinning and burning are beneficial but transient, unless regrowth is regularly controlled. Modelling shows that thinning to increase water yield should only be considered near Mundaring Weir within the higher rainfall Helena West MU. Modelling also shows that large hot fires increase flow in the Helena West MU for a period and have little effect in the Ngangaguringuring MU to the east.

High-water-use stands, dense pines or even some native species could be used on the sedimentary aquifer to reduce recharge and hence saline discharge such as near the Ngangaguringuring gauging station. Conversely, management of pines is needed in the western half of the catchment and near streams where their high water use could reduce yield (runoff). In these areas native vegetation could be used to increase yield without increasing salinity. Pine plantations managed at less than 100% cover also could increase runoff in the higher rainfall west of the catchment where salt stores are smaller.

Vegetation reduction from fire, (jarrah) dieback, wandoo crown decline or death, drought death, or age-related death have only transient effects on salinity, flow and salt load. The most significant of these effects follow from large intense fires and sustained widespread logging.

7 Recommendations

7.1 Management options

Communicate results to all major stakeholders (Department of Environment and Conservation, Forestry Products Commission, Water Corporation) so that they can action or have input into any subsequent or ongoing work.

Maintain clearing controls. Since July 2004, clearing applications in these areas have been regulated under the Environmental Protection Act 1986 and no clearing should be permitted.

Specifically retain the options for silviculture (thinning), on government freehold land and of wandoo, throughout the catchment. Reforest government freehold land, especially that near Abercorn Road, to the appropriate density; so, to allow management of density by thinning/burning/logging, do not include in a National or Conservation park. Map the areas where, to increase runoff, pines could be less than maximum density. Negotiate with the Forest Products Commission (FPC).

Manage the remaining cleared areas forming 3% of the catchment. Advise landholders near Mt Observation and Dobaderry Swamp (Localities F & E) that they are within the Mundaring catchment and brief them regarding land use. Consider more land purchases at Abercorn and Goods roads, Wundabiniring Road, Talbot Road West, Mt Observation and Flynn Road (Localities B, C, D, F & H) in no priority order, and monitor the areas near Qualen Road and Dobaderry Swamp (Localities A & E) in case they discharge into the Darkin River.

Focus on management of the subcatchments with highest salinities under the 1990–2003 rainfall.

Examine in more detail the impacts of prescribed burning regimes and forest fires on hydrology and salt load by extending the results of this study's modelling. Investigate whether silviculture, specifically burning and thinning for enhanced water yield, is desirable in the area that may for increased security against clearing-related salinity, be added to the Helena National Park. Thinning, in addition to just prescribed burning, should be a management option.

Investigate the hydrogeology, flow or discharge from Darkin Swamp to determine the risk of it beginning to discharge water and salt.

Establish targets and standards against which management progress can be measured.

Examine the status of the catchment area below Mundaring Weir and its effects on management of the Helena Water Resource Recovery Catchment.

Consider pumping and draining the sedimentary aquifer near Ngangaguringuring and diversion of the Helena River there or at Poison Lease to reduce runoff from the east.

Prepare a catchment management plan from this Salinity Situation Statement, detailing actions, timelines and responsibilities.

7.2 Monitoring and evaluation

Continue streamflow and salinity monitoring at the gauging stations to determine whether recent trends, particularly runoff decline, continue. Continue monitoring to assess for rainfall trends. In particular, revise the saltfall data and examine the chemistry for changes in NO_2 and S-SO_4 as they both pre-date the 30-year-old rainfall change.

Expand monitoring of groundwater levels and salinity beyond a few representative bores in Flynn plantation by constructing multi-level investigation bores in sedimentary aquifers north of Darkin Swamp and Ngangaguringuring.

Continue Landsat monitoring to assess changes in forested land, the impacts of fires of different intensity and vegetation recovery after fire, especially in Darkin Swamp where vegetation reduction could lead to export of water and salt.

7.3 Where to from here?

This study focuses on conceptual salinity reduction options — to understand the extent of the land-use changes needed to reach the salinity target. It is the first step in the recovery approach.

The next step will be the evaluation of the management options from this study. For this the water quality objectives will be defined and, in consultation with key stakeholders (considering social, economic and environment aspects) scenarios to meet these objectives will be evaluated. Additional and more detailed modelling will be used. In the recovery plan step the major components of management options to be implemented will be identified, an implementation strategy developed and funding sources identified (Appendix 7).

The final step will be to implement this plan and to recover this catchment from salinity.

Glossary, acronyms and units

a	Annum, 1 year (see yr)
acre (ac)	Imperial area 22 yards by 220 yards, 0.4047 hectares, 0.004047 square kilometres
alienated land	Former Crown land released for private ownership (freehold) or control (leasehold)
analysed chlorine (mg/L)	Used as a measure of salinity in the 1900s and equivalent to 1.6 mg/L TSS
aquifer	A geological formation or group of formations able to receive, store and transmit significant quantities of water
AQWAbase	The Water and Rivers Commission groundwater point source database for Western Australia, now incorporated in the WIN database
basal area	Cumulative area occupied by tree stems expressed in m^2/ha, e.g. 20 m^2/ha in the Mundaring catchment
base case	The equilibrium hydrological condition, calculated using each of the MAGIC and LUCICAT models, under the current climate and land use (Land Monitor 2002)
baseflow	Streamflow sustained by groundwater discharge and not attributable to direct runoff from precipitation (Jackson 1997)
bore	A hole drilled from the ground surface e.g. to obtain groundwater information
brackish water	See saline water
bulge profile	A soil profile that has maximum salinity at an intermediate depth (Schofield et al. 1988)
calibration	Modifying model parameters for best fit of output to observations in a chosen calibration period (Schofield et al. 1988, p. 67)
CALM	(Western Australia) Department of Conservation and Land Management, merged with the Department of Environment in 2006 to form the Department of Environment and Conservation
catchment	The surface area providing runoff to a waterbody, reservoir or point of interest
CAWS	Country Areas Water Supply
CAWS Act	The *Western Australian Country Areas Water Supply Act 1947* legislation
centimetre (cm)	A length of 0.01 metres

clearing	Removal of deep-rooted native vegetation for agricultural land use especially shallow-rooted perennials
clearing controls	Procedures controlling clearing of native vegetation under the CAWS Act 1947
craton	Generally Precambrian continental crust that has attained stability and has been little deformed for a long period (Jackson 1997)
cubic metre (m^3)	The volume of a 1 metre cube = 1000 litres (1 kL)
CV(s)	Statistical coefficient(s) of variation, equals standard deviation divided by mean, not related to R^2 (see below)
dam	A barrier to streamflow that creates a water storage for diversion or controlled release (Stokes et al. 1995, p. 9-5)
Darkin subcatchment	Used interchangeably with Darkin River subcatchment for the area above the Darkin River gauging station (rather than strictly above the junction with the Helena River)
DEM	Digital Elevation Model – automatically analyzed digital gridded elevation data
diversion	Diversion of the June, July and November flows that were saline would reduce the amount of salt entering the reservoir and therefore reduce the salinity levels
DoE	(Western Australia) Department of Environment
DoW	(Western Australia) Department of Water
evaporation	The vaporisation of water from a free-water surface above or below ground level, normally measured in millimetres of thickness daily, monthly and annually
evapotranspiration	A collective term for evaporation and transpiration, measured as pan evaporation (mm/yr) by the Bureau of Meteorology
fire intensity	Expression of heat release (Sneeuwjagt & Higgs 2005), influenced by the speed of the fire and the amount of fuel consumed
flowpath	A 3-dimensional route taken by groundwater moving from recharge to discharge
foot (ft)	A length of 0.3048 metres
forestry	The art and science of managing the forests to meet the objectives of the owner – firefighting, burning, logging, regenerating and replanting (Underwood pers. comm. 2006)
fresh water	Water of salinity less than 500 mg/L TSS (Map in Mayer et al. 2005)
gallon	A volume of 1 (Imperial/UK) gallon = 4.546 litres = 1.2 (US) gallons
GAWS(S)	Goldfields and Agricultural Water Supply (Scheme 1956) expanded on the 1902 service to the Coolgardie Goldfields and eastern Wheatbelt towns

gigalitre (GL)	A volume of 1 000 000 000 litres, 1 billion litres, 1000 megalitres (1000 ML), 1 million cubic metres (1 Mm^3), 220 million gallons (220 MG)
GIS	Geographical Information System, used to store, view, and analyse digital geographical information
grains per gallon (gpg)	Superseded unit of salinity equivalent to 14.3 mg/L TDS (14.2 in Schofield et al. 1988, p. 68)
greenness	The percentage of a pixel in a Landsat image that has sunlit green leaves
groundwater	Water that occupies the pores and crevices of rock or soil
groundwater level	An imaginary surface representing the total head of groundwater and defined by the level to which water will rise in a piezometer.
GS	Gauging station
GWS(A)	Goldfields Water Supply (Administration) managed the GAWS until 1912 when replaced by the PWD
hectare (ha)	Metric area 100 metres by 100 m, 10 000 square metres (10 000 m^2), 0.01 square kilometres, about 2.47 acres
Helena/Helena catchment	Could (by shortening Helena WRRC to Helena with or without catchment) come to be used interchangeably (but hopefully not in this report) for the catchment area of the Mundaring Reservoir that is here termed the Mundaring catchment
Helena Reservoir	Rarely used, inadvertently, for Mundaring Reservoir as the only reservoir on the Helena River
Helena River catchment	Strictly the area drained by the Helena River and its tributaries above the confluence with the Swan River and abbreviates to Helena catchment (caution, see Helena catchment)
Helena subcatchment	Used interchangeably with Helena River subcatchment for the area above the Poison Lease gauging station (rather than strictly above the junction with the Darkin River)
Helena (River) WRRC	That part of the Helena River catchment draining to the Mundaring Weir, hence the Mundaring Weir catchment (Mundaring catchment) as used in the SSS – the WRRC boundary was neither drawn nor specified at that time
high-rainfall zone	Above the 1100 mm/yr isohyet in the south-west jarrah forest, see low-rainfall zone
hydraulic conductivity	Volume of fluid that will flow through a porous medium in unit time under a unit hydraulic gradient at right angles to a unit area, depending upon kinematic viscosity
hydraulic gradient	The rate of change of total head per unit distance of flow at a given point and in a given direction (Jackson 1997)

interflow	Runoff infiltrating the surface and moving toward streams as ephemeral shallow groundwater – also known as storm seepage (Jackson 1997)
intermediate-rainfall zone	Between the 900 and 1100 mm/yr isohyets in the south-west jarrah forest, see low-rainfall zone
isohyet	A line on a map indicating places of equal rainfall
kilogram (kg)	A mass of 1000 grams (g), 0.001 tonnes
kilolitre (kL)	A volume of 1000 litres, 1 cubic metre (1 m^3) or 220 (approx) gallons
kilometre	A length of 1000 metres
kilotonne (kt)	A mass of 1000 tonnes = 1 000 000 kilograms
km^2	An area of one square kilometre = 100 hectares = 247 acres
LAA (Fig. 2.4)	*Land Administration Act 1997*
Leaf Area Index (LAI)	The total (single-sided) area of leaves on plants divided by the area of land occupied by the plants. This measure of leaf area coverage is a proxy for water use.
litre (L)	A volume of 1000 cubic centimetres (cm^3), 0.001 cubic metres (m^3)
logging	The mechanical process of removing logs from the forest
low-rainfall zone	Below the 900 mm/yr isohyet in the south-west jarrah forest, not a fixed area, but together with high and intermediate zones reflects an increasing potential for salt release upon clearing
m AHD	Height in metres above Australian Height Datum taken as Mean Sea Level +0.026 m at Fremantle
management unit(s) (MU, MUs)	Land areas predominantly based on surface water drainage (with some variations possibly defined by the local community to account for social boundaries)
marginal water	See saline water
megagallons (MG)	A volume of 1 000 000 gallons, 1 million gallons
megalitre (ML)	A volume of 1 000 000 litres, 1 million litres, 1 thousand cubic metres (1000 m^3), 220 thousand gallons
metre (m)	Metric unit of length
middle Helena catchment	The area drained by the Helena River above the pumpback dam and below Mundaring Weir
mile (Imperial)	A length of 1.609 kilometres, 1609 metres
millimetre	A length of 0.1 centimetres
MU(s)	See management unit(s)
Mundaring catchment	Used in this report for the area draining to Mundaring Weir (and Reservoir), see Mundaring Weir Catchment Area

Mundaring Weir Catchment Area	Area proclaimed under the CAWS Act comprising a watershed boundary drawn in 1978, not entirely coincident with the more accurately defined boundary used in this report for the Mundaring catchment
Mundaring Reservoir	Used in this report for Lake CY O'Connor, the body of water held by Mundaring Weir
MWS	Metropolitan Water Supply (Department)
NRM	Natural Resource Management
outcrop	Geological unit (e.g. bedrock) exposed at the surface
overland flow	Surface runoff after rainfall
piezometer	A pipe or narrow bore to measure water pressure (Jackson 1997)
pipehead	A small dam allowing diversion of some streamflow into a water supply pipe (Stokes et al. 1995, p.9–4)
potable water	Water both fresh and suitable for human consumption
precipitation	The deposition of water in solid or liquid form on the Earth's surface from atmospheric sources (Schofield et al. 1988, p. 69)
prescribed burn	A planned and carefully timed burn carried out to a prescription for the area by CALM (2005) mainly to reduce forest litter that could fuel a hot fire with extensive forest damage
pumpback	Water pumped into the Mundaring Reservoir
PWD	(Western Australia) Public Works Department
R (for r)	Statistical 'correlation coefficient', see also R^2
R^2 (for r^2)	Statistical coefficient of determination, see also CV and R
rainfall recharge	Recharge to groundwater directly from rainfall with no consideration of overland flow
recharge	The downward movement and addition of water to the groundwater system
recharge area	Where water recharges an aquifer, whether by direct infiltration (where unconfined) or leakage (where confined)
reforestation	Planting trees on land cleared of native forest
regolith	Geological material from fresh rock to fresh air and includes weathered bedrock, sediments and soil
residence time (years)	Surface storage volume-to-inflow ratio (also used for time taken for groundwater to move from recharge to discharge, in other reports)
resumption	Compulsory acquisition of private land by Government (Schofield et al. 1988, p. 69)
ringbarking	Killing trees by cutting around the trunk to sever all active pathways for sap movement

runoff	The portion of rainwater discharged over the surface and in streams, expressed as mm of rainfall. Flow in streams is streamflow.
saline water	Water of salinity above 500 mg/L, qualified as marginal below 1000 or 1500, brackish 1000 to 2000 or 3000, hypersaline or brine above 35 000 mg/L (Mayer et al. 2005)
salinisation	The accumulation or concentration of salt in soil or water
salinity (specific)	The concentration of total dissolved salts in water
salinity (general)	Effects on land and in water of the build up of salt on or near the surface as a result of rising groundwater (prefer salinisation)
salt content	See soil salt 1
salt load	Salt transported to the reservoir in streamflow, measured in tonnes
salt storage	See soil salt 2
saprock	Compact, slightly weathered bedrock with low porosity; defined as having less than 20% of weatherable minerals altered but generally requiring a hammer blow to break (Eggleton 2001)
saprolite	Weathered bedrock in which the fabric of the parent rock, originally expressed by the arrangement of the primary mineral constituents (e.g. crystals), is retained (Eggleton 2001)
saturated thickness	The thickness of the saturated zone
saturated zone	Below the watertable all the interstices are filled with water under pressure greater than atmospheric (Jackson 1997)
scouring	Release of denser saltier stored water (through a valve deep inside the base of the dam) so that coincident fresher reservoir inflows are retained and lower the reservoir salinity
silviculture	Everything to do with the operation of the forest (equivalence with agriculture) but, in this report, specifically removal by three types of (current) silvicultural treatments – gap creation, thinning (30% reduction in LAI) and shelter wood
soil moisture deficit	Difference between the maximum (field capacity) and actual moisture content of soil
(soil) salt	1. Salt content, mass of soluble salt in a volume of soil (kg/m^3) 2. Salt storage, mass of soluble salt integrated down a soil profile (kg/m^2) 3. Salt concentration, mass of soluble salt in the soil divided by the volumetric water content (mg/L) (Stokes et al. 1980)
square kilometre (km^2)	An area of 100 hectares, equivalent to that of a 1 km square
square metre (m^2)	An area equivalent to that of a 1 m square
SSS	State Salinity Strategy, preceded by the SAP (Salinity Action Plan)
storage reservoir	A major reservoir of water created in a river valley by constructing a dam

streamflow	Flow in streams expressed as volume (ML or GL) or rate (ML/yr or GL/yr) cf. runoff
surface water	Water flowing or held in streams, rivers, and other wetlands (Stokes et al. 1995) p. 9–6
TDS (mg/L)	Total Dissolved Solids expressed as milligrams per litre. Usually used for the salinity of groundwater as this may have significant silica and bicarbonate. Can be calculated from 1) Total Soluble Salts by adding analysed silica (SiO_2) and adjusting carbonate for bicarbonate lost during evaporation 2) measured conductivity 3) measured resistivity, or read from a calibrated refractometer.
thinning	Selective removal of stems, most commonly from an even-aged forest stand
tonne (t)	A mass of 1000 kilograms (1000 kg)
TSS (mg/L)	Total Soluble Salts expressed as milligrams per litre and formerly used for surface water salinity determined by evaporation.
transpiration	Process by which water is released as vapour from the stomata (pores) of leaves, effectively removing water from the soil
unalienated land	Crown land not opened up for private ownership, see alienated land
unsaturated zone	Between the land surface and watertable where water is at less than atmospheric pressure, including capillary water containing gases generally at atmospheric pressure (Jackson 1997)
upper Helena River catchment	The catchment of the Helena River above Mundaring Weir, mostly drained by the Helena River and its tributaries such as the Darkin River – a confusing term firstly because the junction of the Helena and Darkin rivers is inundated by the reservoir and so is ill-defined, and secondly the term ‘upper Helena dam’ was used for a proposed dam site near Poison Lease gauging station to control most of the Helena subcatchment and none of the Darkin subcatchment
watertable	The surface of unconfined groundwater at which the pressure is equal to that of the atmosphere (Jackson 1997)
WAWA	Water Authority of Western Australia
WAWRC	Western Australian Water Resources Council
weir	A dam built across a stream to raise, divert, measure and/or control its flow
Wheatbelt	Grain and sheep growing area of south-west Western Australia north and east of the State Forest
WIN	Water Information database maintained by the Department of Water
WRRC	Water Resource Recovery Catchment
yr	Year (used rather than ‘a’ for annum)

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Appendix 1
Contacts and technical referees

Robin Smith convened and Tim Sparks facilitated a half-day, 28 April 2005 presentation at Mundaring Weir covering:
1. Current knowledge, what we had done and how
2. Feedback on resource/technical issues, including other management scenarios

Table A1.1 Contacts

Name	Organisation	Contact numbers
Blake, Graeme	DoW, GIS	6364 7802
Congdon, Karina	Water Corporation, Darkin River sampling	
Crean, Annette	DoW, GIS	6364 6817
Duncan, Nick	(former) DoE, information officer	
Gorton, Jade	DoW, SGA	6250 8012
*Goh, Jerome	MRD	
Hearn, Roger	DEC Manjimup	9771 7936
Jeevaraj, Charles	Water Corporation, inflows to reservoir	9420 2285
*Mauger, Geoff	Geographic Information Analysis Pty Ltd	9401 3516
*McGrath, John	Manager Technical Services Branch	9475 8837, 0417 995 100
Meinema, Mike	DEC District Manager Mundaring	9295 9100
Pollock, Kevin	DEC Mundaring	9295 9100
*Revell, Martin	DoW, SGA Region	9690 2621
*Roberts, Phil	DoW, program manager	6364 6671
*Sparks, Tim	DoW, salinity program coordinator	6364 7819
Rakich, Paul	DoW contact re grab samples in Mundaring catchment, at Welshpool with Paul Earp	9231 8336
Rose, Emma	Water Corporation, Darkin River sampling	
Rowlands, David	DoW, hydrology and vegetation data capture	6364 7816
*Terry, Colin	(former) Water Corporation, Planning Engineer	
Underwood, Roger	Forestry Consultant	9339 4055
Van Beelen, Richard	Action Sand Quarry	9257 1100
Waterhouse, Alex	DoW, salinity publication	6364 7821
White, Marion	Program Manager, Environmental Water	6364 7138
Wood, Scott	FPC Bunbury	9725 5267, 0427 904 634
Wreford, Nicole	DEC, Librarian	6467 5165
Ye, Lin	DoW, GIS	6364 7441

*Potential Technical Advisory Group members

Table A1.2 Invitees to Workshop 2005 and Technical Review Panel (TRP)

Name	Affiliation, role	Contact	Address
Barrett, Keith	Retired engineer	9457 2105	45 Acanthus Road WILLETON WA 6155
Bartle, John	DEC 1st representative	DEC	
Batini, Frank	Retired catchment researcher	9457 1952	36 Juniper Way WILLETON WA 6155
Clarke, Christopher	Geologist	0409 942 185	13 Ranson Street SUBIACO WA 6008
George, Richard	DAFWA, proxy if unavailable	9780 6100, 0404 819 532	Department of Agriculture and Food PO Box 1231 BUNBURY WA 6231
Goh, Jerome	MRWA	9323 4461	PO Box 6202 EAST PERTH WA 6892
Harper, Richard	FPC 2nd representative, proxy if unavailable	FPC	
Manning, Liz	Secretary Wandoo Response Group (proxy Frank Batini or Colin Terry)	9641 2292, 0427 441 482	PO Box 254 YORK WA 6302
Mauger, Geoff	Geographic Information Analysis Pty Ltd	9401 3516	
McFarlane, Don	CSIRO, 1st representative	9333 6215	Private Bag 5 WEMBLEY WA 6913
McGrath, John	FPC, 1st Representative, proxy if unavailable, Manager Technical Services Branch	9475 8837, 0417 995 100	Locked Bag 104 Bentley Delivery Centre WA 6983
Read, Viv	Viv Read & Associates	9358 5630	Suite 2, 105 Broadway NEDLANDS WA 6009
Reynolds, David	UWA		
Silberstein, Richie	CSIRO, 2nd representative	9333 6334	Private Bag 5 WEMBLEY WA 6913
Smettem, Keith	Associate Professor, School of Environmental Systems Engineering CWR, UWA	6488 1692	The University of Western Australia 35 Stirling Highway, CRAWLEY, WA 6009
Terry, Colin	Formerly Water Corporation, Planning Engineer		
Underwood, Roger	Consultant	9339 4055	
Wallace, Ken	DEC, 2nd representative, proxy if unavailable	9334 0341	Locked Bag 104 Bentley Delivery Centre WA 6983
DoW participants:			
Bari, Mohammed	Program Manager	6364 7801	
Dixon, Renee	Supervising Water Resource Officer	6364 7805	
* Revell, Martin	Acting Operations Manager for the Swan-Avon Catchment, link to Avon-Upper Swan NAP and Avon NHT	6250 8010	
Roberts, Phil	Program Manager, Land and CAWS Act Clearing Management	6364 7815	
Rowlands, David	Environmental Officer	6364 7816	
* Ruprecht, John	Director of Water Resource Management Division	6364 6602	
* Sparks, Tim	Acting Manager, Salinity and Water Resource Recovery Branch	6364 7819	
Waterhouse, Alex	Communications Officer	6364 7821	
DoW staff not present:			
Boniecka, Lidia	Engineer	6364 6650	
De Silva, Jayath	Hydrogeologist	6364 7807	
Smith, Robin	Supervising Hydrogeologist	6364 7818	

Appendix 2
Catchment photographs and soil classification

A2.1 Catchment photographs

This photographic tour takes the viewer from the lowest to the highest points in the Mundaring catchment (Fig. A2.1). Follow the Helena River, with a zigzag to the Wariin Brook, Flynn plantation, and as far as Wundabiniring Road. Then head south via the Little Darkin and Darkin swamps and zigzag down the Darkin River and up Mount Dale. Photos by M Smith (2), R Smith (28) and Salinity and Water Resource Recovery Branch (10).

1 Mundaring Weir from the south (RIMG_0669)

2 Pumping station beside Helena River from Weir (IMG_0003)

3 Mundaring Reservoir (Lake CY O'Connor) east from Weir (IMG_0004)

4 Mundaring Reservoir (Lake CY O'Connor) SW to junction of Helena with Darkin River (IMG 3896)

5 *Waterfall north of Lake CY O'Connor after heavy rain* *(IMG 3887)*

6 *Final gauging station before the Helena River enters Lake CY O'Connor* *(IMG 3946)*

7 *Firewood Road Bridge on the Helena River*
(Firewood Rd Bridge-2)

9 *Motorbike jumps on Wellbucket south-east of Gorrie*
(Jump ramps Gorrie)

8 *Helena River 1 km above Firewood Road Bridge*
(Helena River site 3-2)

10 *Mt Gorrie west across the Helena River*
(Mt Gorrie and grasstrees Helena R – 2)

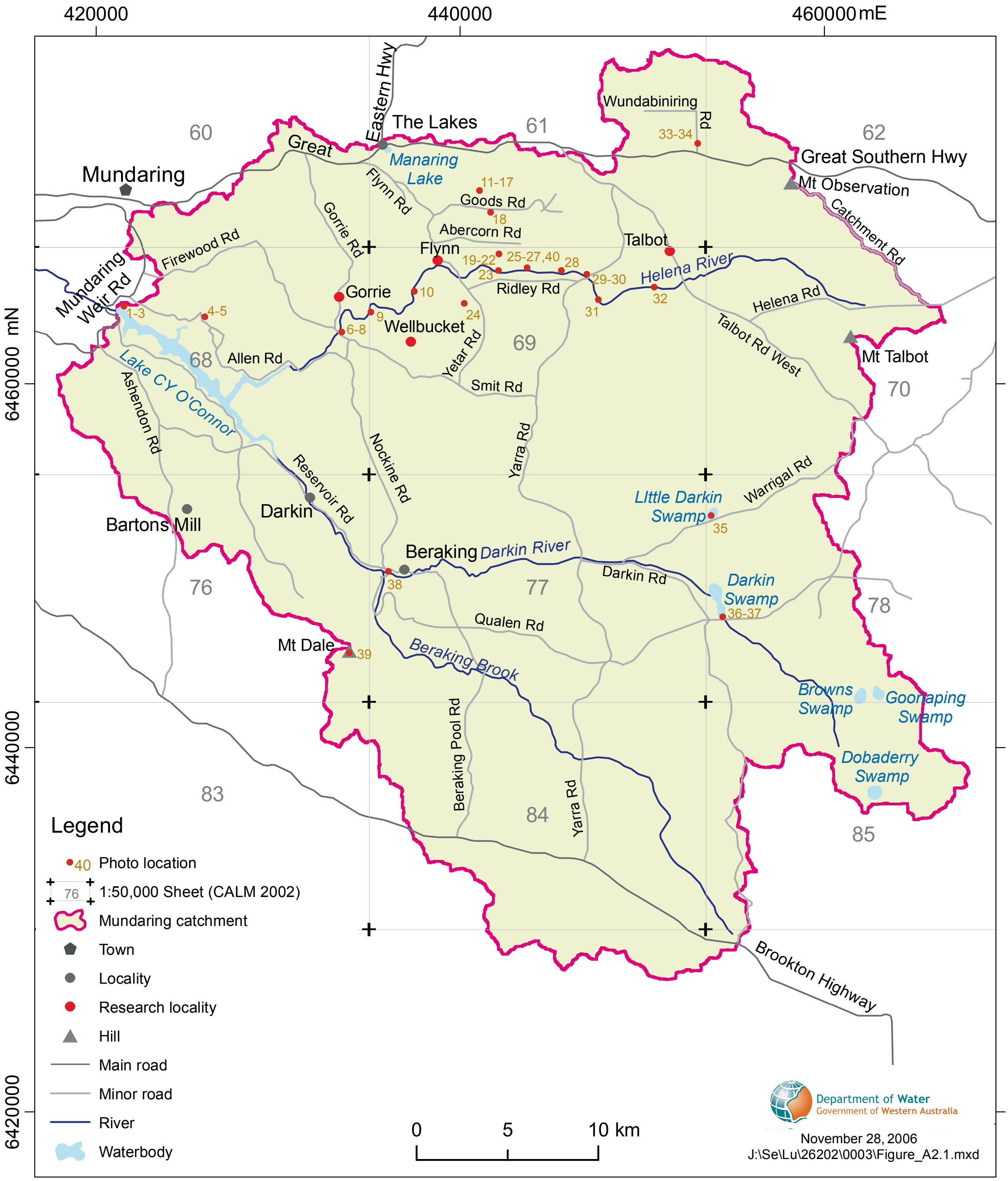


Figure A2.1 Mundaring catchment photograph locations

11 Sand quarry between Goods Road and Wariin Brook (Action-3)

12 Bulldozer above sand pit face (Action-18)

13 Red and white sand capped by ferruginous gravel (Action-8)

14 Red and yellow cross-bedded sand (Action-13)

15 Groundwater exposed by sand mining (Action-17)

16 Spring with stressed wandoo west of western sandmining lease (Action-21)

17 Wariin Brook pool N of Goods Road
(Pool Wariin Bk N of old sand quarry)

18 Farm south from Goods Road
(Farm in Helena catchment-2)

19 Easternmost hillside seep S of Abercorn Road
(15 Saline seep eastern-2)

20 Westernmost seep S of Abercorn Road
(14 Saline seep vehicle)

21 Boulders at westernmost seep S of Abercorn Road (20 Saline seep boulder)

22 Saline seepage above the Helena River
(Ironstained creek S of Abercorn Rd-2)

23 Rock crossing Helena River S of hillside seeps
(Crossing on Helena River south of hillside seeps No 2)

24 Wandoo plantation on Flynn (9 Flynns Hillslope wandoo-2)

25 Ngangaguringuring gauging station and motorbike crossing (Ngangaguringuring gauging station-2)

26 Conductivity at Ngangaguringuring gauging station
(Ngangag V-notch)

27 Rock crossing Helena River 400 m upstream of Ngangaguringuring gauging station (Rock crossing Helena River2)

28 Waterpoint N of Helena River 1 km W of Yarra Road
(CALM watering hole in subcatchment 4)

29 Helena River upstream from Yarra Road Bridge — winter (Helena River - 2)

30 Helena River upstream from Yarra Road Bridge — summer (Yarra Road Crossing - dry looking upstream)

31 Helena River above Yarra Road (Helena R 1500 m SE Yarra Rd)

32 Helena River pool at Cliffords 2 km below Talbot Road West (Cliffords Helena R pool SW Talbot Rd West)

33 Farmland and salt source in the NE Mundaring catchment (Cattle and stubble SW of Wundabiniring Rd-2)

34 Farmland and salt source in the NE Mundaring catchment (Rock and crop SW from Wundabiniring Rd-2)

35 Little Darkin Swamp from the north
(Top of Little Darkin Swamp – 2)

36 Darkin River draining off farmland after heavy rain
(IMG 969)

37 Darkin River entering Swamp below Qualen Road
(Darkin River on DS side of road near farm)

38 Darkin River at Nockine Road Bridge
(Darkin River Nockine Rd crossing-2)

39 Darling Plateau horizon west from Mt Dale to Perth CBD (View from top of Mt Dale_1)

40 Flower (Rose-tipped mulla mulla Ngangaguringuring GS)

A2.2 Soil classification

Table A2.1 Soil—landscape subsystem and phase descriptions

The subsystems are shown in Figure 2.6.

Symbol	System	Subsystem / phase	Thickness (m)	Permeability (mm/hr)	Summary description
HE	Murray Valley	Helena S.	0.640	0.130	The most deeply entrenched valleys in the Helena, often with > 30% slope and 200 m relief. Soils are mainly red and yellow earths but there are some duplex soils all of which overly rocky basements.
HR	Murray Valley	Hester S.	0.982	0.280	Ridges and hill crests on laterite and gneiss, relief 5–40 m, slopes 5–15%. Soils are sandy gravels, loamy gravels and loamy earths.
MY	Murray Valley	Murray S.	0.938	0.237	Deeply incised valley of the Murray River; red and yellow earths and minor duplex soils; occasional rock outcrops; narrow sandy terrace.
MY2	Murray Valley	Murray 2 ph.	0.970	0.190	Gentle to moderately inclined sideslopes (3–25%) and narrow valley floors with few areas of rock outcrop. Variable moderately well to well drained duplex and gradational soils.
MY3	Murray Valley	Murray 3 ph.	0.950	0.250	Very gentle to moderately inclined sideslopes and lower slopes (< 15%) with very few areas of rock outcrop. Variable moderately well to well drained duplex and gradational soils.
MY4	Murray Valley	Murray 4 ph.	0.720	0.165	Very gently inclined valley floors with sideslopes < 20%), with very few areas of rock outcrop and poorly drained and commonly saline soils.
CO	Darling Plateau	Cooke S.	0.680	0.127	Crests and upper slopes dominated by granite outcrop and very shallow yellow duplex soils, and yellow and brown massive earths.
DW	Darling Plateau	Dwellingup S.	0.971	0.288	Divides, lower to upper slopes and hillcrests. Duplex sandy gravels and loamy gravels with minor areas of shallow gravels, deep sandy gravels, yellow deep sands and yellow and pale deep sands, often gravelly.
DW2	Darling Plateau	Dwellingup 2 ph.	0.810	0.260	Very gently to gently undulating terrain (< 10%) with well drained, shallow to moderately deep gravelly brownish sands, pale brown sands and earthy sands overlying lateritic duricrust.
DW3	Darling Plateau	Dwellingup 3 ph.	0.530	0.208	Gentle to moderately inclined slopes (3–20%) with well drained shallow to moderately deep gravelly brownish sands, pale brown sands and earthy sands overlying lateritic duricrust.
GO	Darling Plateau	Goonaping S.	1.225	0.384	Level to gently sloping imperfectly drained swampy margins with deep grey, yellowish brown or brown siliceous or bleached sands.
PN	Darling Plateau	Pindalup S.	0.877	0.247	Shallow minor valleys (5–20 m) with gentle sideslopes (3–10%) and broad swampy floors. Soils are loamy gravels, and deep sands, and non-saline wet soils on the valley floors.
YG	Darling Plateau	Yarragil S.	0.885	0.240	Shallow, narrow, upper valleys of the deeply dissected Murray, Bindoon and Helena units. Alluvial, clay and loam soils, moderately well drained, often gravelly, with some sands and loams. Salt prone. Woodland of *E. wandoo*, *E. accedens.*
YG1	Darling Plateau	Yarragil 1 ph.	0.970	0.229	Very gentle to moderately inclined concave sideslopes. Moderately well drained yellow duplex soils and yellow and brown massive earths. Woodland of *E. wandoo*, *E. marginata*, *E. accedens*. Casuarina obesa on salt affected areas.

Table A2.1 continues

Symbol	System	Subsystem / phase	Thickness (m)	Permeability (mm/hr)	Summary description
YGh	Darling Plateau	Yarragil DpYGh	0.930	0.235	Very gentle to moderately inclined (< 20%) concave valley sideslopes. Moderately well drained yellow duplex soils and yellow and brown massive earths.
YGsw	Darling Plateau	Swamp	0.820	0.154	Level to very gently inclined valley floors. Swampy river flats and terraces in granitic rocks; loamy and sandy duplex, wet soils, non-cracking clays and loams.
CO	Wundowie	Wundowie CO	0.600	0.166	Residual granite, laterite and duricrust crests above Yalanbee, Pindalup and Michibin. Shallow clayey sands and loams derived from granite and gneiss. Low shrublands, heath, sedges and some low *E. wandoo* and *marginata* and *acacia* spp.
GO	Wundowie	Goonaping S.	1.225	0.384	Level to gently sloping imperfectly drained swampy margins with deep grey, yellowish brown or brown siliceous or bleached sands.
LV	Wundowie	Leaver S.	1.082	0.348	Gravelly slopes and ridges found in the western part of the study area where streams and rivers have dissected the Darling Plateau.
PN	Wundowie	Pindalup S.	0.575	0.143	Shallow upper gently to sloping valleys. Alluvial red and yellow duplex and uniform fine soils which are often gravelly. Salinity prone especially in upper reaches. *E. wandoo* woodland with some *E. rudis* and *camaldulensis*, acacia and titree.
PN3	Wundowie	Pindalup 3 ph.	1.230	0.362	Very gently to gently inclined (< 10%) valley headwaters with moderately well drained shallow to moderately deep sands underlain by mottled clay.
PNh	Wundowie	Pindalup hillslope ph.	1.080	0.369	Very gently to gently inclined sideslopes (< 10%) with well drained gravelly brownish sands, pale brown sands and earthy sands.
PNsw	Wundowie	Pindalup swampy valley floor ph.	1.030	0.192	Swampy floors of minor valleys.
YA	Wundowie	Yalanbee S.	1.139	0.381	Residual plateau at the top of the landscape shallowly dissected by Pindalup valleys. Pisolitic gravelly, yellowish brown soils that vary in texture from loamy sands to clays, with pockets of pale sands and areas of outcropping laterite.
YA5	Wundowie	Wundowie YA5	0.994	0.304	Very gentle to gentle hill slopes (< 10%). Shallow pisolitic gravelly loams and clay loams over laterite. Mixed woodland and low woodland. Dominated by mixed *E. wandoo*, *E. loxophylla* associated with *E. marginata* and *E. accedens*.
LV	Clackline	Clackline Leaver S.	0.967	0.294	Gravelly slopes and ridges of the dissected western Darling Plateau.Yellow gravelly sand and loams with pockets of pisolitic gravel and sandy loam over pink clay below upper slopes. *E.wandoo* on clay, *E. marginata* and calophylla and dryandra.
MN	Clackline	Michibin S.	0.934	0.255	Gentle to moderate hill slopes of freshly weathered soils. Red and yellowish brown loams and clays, often gravelly with rocky areas and lateritic crests. *E. loxophleba* and wandoo. Casuarina on rock and *E. marginata* and accedens on gravel.
PN	Clackline	Pindalup S.	0.575	0.143	Shallow upper gently to sloping valleys. Alluvial red and yellow duplex and uniform fine soils which are often gravelly. Salinity prone especially in upper reaches.

Table A2.1 continues

Symbol	System	Subsystem/ phase	Thickness (m)	Permeability (mm/hr)	Summary description
R1	Clackline	Clackline Steep Rocky Hills 1	0.710	0.192	Areas of rock outcrop and steep rocky hills.
YA	Clackline	Yalanbee S.	1.142	0.383	Undulating, Darling Range upland which contains predominantly 'buckshot gravel' soils.
CK	Boyagin	Coolakin S.	0.912	0.230	Minor Valleys bounded by Dwellingup or Norrinee units; moderate slopes with gravelly and sandy yellow duplex soils; a minor valley floor with sandy alluvium; occasional rock outcrops and laterite spur.
CO	Boyagin	Cooke S.	0.540	0.143	Residual granite, laterite and duricrust crests above the Yalanbee, Pindalup and Michibin units. Shallow to very shallow sandy to clayey sands derived from granite and gneiss.
KO	Boyagin	Kokeby S.	1.274	0.437	Very gentle sloping areas located in small pockets on summits and at breaks of slope. White and deeply bleached sand over laterite at greater than a metre depth.
LV	Boyagin	Leaver S.	1.082	0.348	Gravelly slopes and ridges of the western Darling Plateau. Gravelly yellow and red duplexes, gravelly deep clayey sands and sandy loams over laterite and clay. *E. calophylla, dryandra* spp., *Adenanthos* with *E. wandoo* and *E. marginata* on clay.
MN	Boyagin	Michabin S.	0.934	0.255	Hillslopes formed from weathering fresh rock and rock outcrop. Red and yellow loams and clays, often with gravelly and saline areas. *E loxophleba*, wandoo are common with casuarinas on rocky and *E. marginata* and *E. accedens* on gravelly clays.
PN	Boyagin	Pindalup S.	0.575	0.143	Shallow upper gently to sloping valleys. Alluvial red and yellow duplex and uniform fine soils which are often gravelly. *E. wandoo* but with some and *E. marginata* and small areas of *E. accedens, E. loxophleba*, acacias and casuarinas on salt.
YA	Boyagin	Yalanbee S.	1.142	0.383	Undulating, Darling Range upland. Pisolitic gravelly, yellowish brown soils that vary from loamy sands to clays, with pockets of pale sands and rock. *E. marginata* & calophylla and dryandra on sand, *E. wandoo* on clays and *E. accedens* on crests.
DA	Dale	Dale S.	1.127	0.320	Broad valley floors in the West Kokeby and Dale River areas containing sand over clay soils and pale sands.
KO	Dale	Kokeby S.	1.274	0.437	Very gently sloping areas located in small pockets on summits and at breaks of slope. White and deeply bleached sand over laterite at greater than one metre depth.
KOlat	Dale	Kokeby laterite ph.	0.760	0.260	Lateritised ridges and crests with shallow gravels and sandy gravels under proteaceous heath.
MA	Dale	Dale Maitland S.	0.410	0.116	Swamps found on the broad valley floors in the West Kokeby-Dale area.
SH	Dale	Sheahan S.	1.459	0.575	Pockets of deep, pale sand common on hillslopes.

A2.3 Vegetation descriptions

The 14 vegetation complexes (pre-European) shown in Figure 2.8 and Tables A2.2–A2.4 occupy three geomorphic settings within the Darling Plateau system (Mattiske & Havel 1998).

Table A2.2 Uplands	
Cooke (Ce)	Mosaic of open forest of *Eucalyptus marginata* subsp. *marginata-Corymbia calophylla* (subhumid zone) and open forest of *Eucalyptus marginata* subsp. *thalassica-Corymbia calophylla* (semiarid and arid zones) and on deeper soils adjacent to outcrops, closed heath of Myrtaceae-Proteaceae species and lithic complex on granite rocks and associated soils in all climate zones, with some *Eucalyptus laeliae* (semiarid), and *Allocasuarina huegeliana* and *Eucalyptus wandoo* (mainly semiarid to perarid zones).
Dwellingup 2 (D2)	Open forest of *Eucalyptus marginata* subsp. *marginata-Corymbia calophylla* on lateritic uplands in subhumid and semiarid zones.
Dwellingup 4 (D4)	Open forest to woodland of *Eucalyptus marginata* subsp. *thalassica-Corymbia calophylla* on lateritic uplands in semiarid and arid zones.
Yalanbee (Y5)	Mixture of open forest of *Eucalyptus marginata* subsp. *thalassica-Corymbia calophylla* and woodland of *Eucalyptus wandoo* on lateritic uplands in semiarid to perarid zones.
Yalanbee (Y6)	Woodland of *Eucalyptus wandoo-Eucalyptus accedens*, less consistently open forest of *Eucalyptus marginata* subsp. *thalassica-Corymbia calophylla* on lateritic uplands and breakaway landscapes in arid and perarid zones.

Table A2.3 Depressions and Swamps on Uplands	
Goonaping (G)	Mosaic of open forest of *Eucalyptus marginata* subsp. *marginata* (humid zones) and *Eucalyptus marginata* subsp. *thalassica* (semiarid to perarid zones) on the sandy-gravels, low woodland of *Banksia attenuata* on the drier sandier sites (humid to perarid zones) with some *Banksia menziesii* (northern arid and perarid zones) and low open woodland of *Melaleuca preissiana-Banksia littoralis* on the moister sandy soils (humid to perarid zones).
Swamp (S)	Mosaic of low open woodland of *Melaleuca preissiana-Banksia littoralis*, closed scrub of Myrtaceae spp., closed heath of Myrtaceae spp. and sedgelands of *Baumea* and *Leptocarpus* spp. on seasonally wet or moist sand, peat and clay soils on valley floors in all climatic zones.

Table A2.4 Valleys	
Coolakin (Ck)	Woodland of *Eucalyptus wandoo* with mixtures of *Eucalyptus patens, Eucalyptus marginata* subsp. *thalassica and Corymbia calophylla* on the valley slopes in arid and perarid zones.
Helena 2 (He2)	Mosaic of open forest of *Eucalyptus marginata* subsp. *thalassica-Corymbia calophylla* and woodland of *Eucalyptus wandoo* with some *Eucalyptus accedens* and *Eucalyptus rudis* on the deeper soils ranging to closed heaths and lithic complex on shallow soils associated with granite on steep slopes of valleys in semiarid and arid zones.
Murray 1 (My1)	Open forest of *Eucalyptus marginata* subsp. *marginata-Corymbia calophylla-Eucalyptus patens* on valley slopes to woodland of *Eucalyptus rudis-Melaleuca rhaphiophylla* on the valley floors in humid and subhumid zones.
Murray 2 (My2)	Open forest of *Eucalyptus marginata* subsp. *thalassica-Corymbia calophylla-Eucalyptus patens* and woodland of *Eucalyptus wandoo* with some *Eucalyptus accedens* on valley slopes to woodland of *Eucalyptus rudis-Melaleuca rhaphiophylla* on the valley floors in semiarid and arid zones.
Pindalup (Pn)	Open forest of *Eucalyptus marginata* subsp. *thalassica-Corymbia calophylla* on slopes and open woodland of *Eucalyptus wandoo* with some Eucalyptus patens on the lower slopes in semiarid and arid zones.
Yarragil 1 (Yg1)	Open forest of *Eucalyptus marginata* subsp. *marginata-Corymbia calophylla* on slopes with mixtures of *Eucalyptus patens* and *Eucalyptus megacarpa* on the valley floors in humid and subhumid zones.
Yarragil 2 (Yg2)	Open forest of *Eucalyptus marginata* subsp. *thalassica-Corymbia calophylla* on slopes, woodland of *Eucalyptus patens-Eucalyptus rudis* with *Hakea prostrata* and *Melaleuca viminea* on valley floors in subhumid and semiarid zones.

Appendix 3 — Salinity and flow analysis

A3.1 Rainfall

The average monthly rainfalls at three pluviometers, representative of the south, east and west of the catchment (Met. Stations 10620, 10144 and 9031 respectively), over the periods 1911–2003 and 1975–2003 (Figs 3.5, A3.1a & b) show large reductions in winter rainfall and increased summer rainfall. Winter rainfall in the west of the catchment is approximately double that of the south and the east, the difference being less dramatic for spring and autumn, while summer rainfall is only slightly higher.

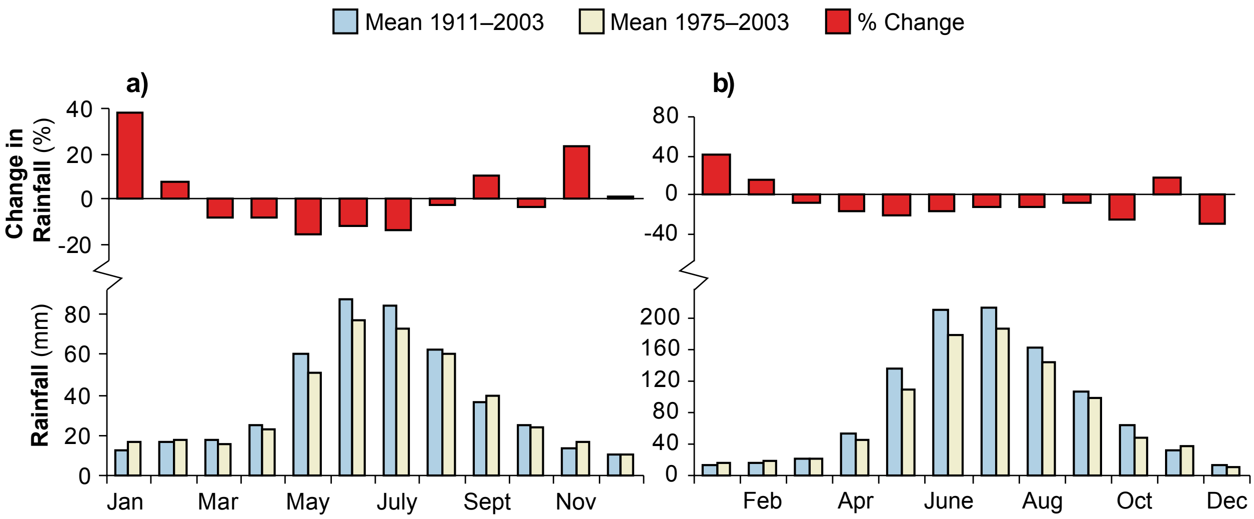


Figure A3.1 Seasonal rainfall trends in the a) Ngangaguringuring and b) Helena West MUs

A3.2 Groundwater

A3.2.1 Baseflows at Ngangaguringuring

Baseflows were calculated by averaging the January–March gauged streamflows at Ngangaguringuring using the Lyne and Hollick algorithm (1979). Although not illustrated in this report, baseflow increases slightly in the winter months. The summer period salinity data, except during peak flow events, was used to calculate the salinity of baseflow. Salinity data were not continuous until 2000 so daily time-series data were extrapolated according to the surface water data analysis methodology (Section A3.3). Insufficient samples were available in late-1974 to early-1975 to give baseflow salinity for the first year of persistent annual flow, so December baseflows were used.

A3.2.2 Salt storage and distribution

Schofield et al. (1988) summarized the geographic distribution of salt in soils and groundwater, based on the work of Dimmock et al. (1974), Stokes et al. (1980), Slessar et al. (1983) and Tsykin and Slessar (1985). Soil cores of some 40 laterite profiles to 40 m depth and covering a rainfall range of 560–1350 mm/yr were analysed for salt content. The sites included Bakers Hill to the north of and similar to the eastern Mundaring catchment. Slessar et al. (1983) identified a site within the Mundaring catchment near the former Yarra Road gauging station. Salt **storage** increases inversely proportional to annual rainfall, ranging from an average of **17 kg/m^2** above 1000 mm/yr to 95 kg/m^2 at 600 mm/yr. This could be accumulated in 17 000 years at the rate of 56 kg/ha/yr and certainly post-dates the lateritisation. Stokes and Batini (1985, 1986) summarized the salt storage determinations in Wellbucket and Yarra catchments by Batini (1976). Soil chloride storage averaged 1.35 × 10^5 kg/ha with a range from 0.08 to 4.9 × 10^5 kg/ha (consistent with the figures above, divide by 10^4 and multiply by 58/35 to convert to salt kg/m^2 of 1.3 to 81). Bore logs revealed salt bulges between 3 and 1 m depth in valley floors and in finer textured soil beneath sandier surfaces. Methods to interpret Cl^- concentrations in soil profiles were developed by Peck et al. (1981).

As well as (soil) salt storage, the average (soil) salt content and average (soil) solute concentration both increased with decreasing rainfall. A low salt content zone extends east from the Darling Scarp to approximately the 1100 mm rainfall isohyet. In this area the average salt **content** was **0.16 kg/m^3.** (This converts to 1.6 kg/m^2 for a 10 m thick regolith.) The salt content increased in a near exponential manner with distance inland from the Darling Scarp to at least the 750 mm rainfall isohyet. The average soil salt content in the 750–1100 mm/yr rainfall zone was 0.79 kg/m^3. (This converts to 7.9 kg/m^2 for a 10 m thick regolith.) Both distance from the Scarp and mean annual rainfall were strongly correlated with average soil salt content. However, there was also high local variability of soil salt content. The peak salinity is located near the bottom of the 'soil' (weathered) profile, but is closest to the surface in profiles towards the valley floor (discharge point). The lowest pH (3.5–4) corresponds roughly with the highest salt content (Dimmock et al. 1974).

Salt is accumulating in low-rainfall forested areas but discharging from areas cleared for agriculture (Schofield et al. 1988). Salinity in streams in these areas will fall to potable levels in the order of several hundreds of years (Dimmock et al. 1974). Tsykin and Slessar (1985) derived 'a non-linear regression equation (r [sic] = 0.96)' to estimate average soil salinity for the Darling Plateau immediately south of the Mundaring catchment. So for the major cleared areas in the catchment, namely Qualen, Wundabiniring, Helena and Goods roads (Table 2.5), the estimated soil salt storages are nearer 95 than 15 kg/m^2 and the saltfall about 8 mg/L.

A3.3 Surface water

A3.3.1 Surface water data analysis methodology

Salinity grab samples were collected for all of the gauging stations. Darkin River, Poison Lease and Ngangaguringuring gauging stations have continuous daily data since conductivity meters were installed in 2000, 1992 and 2000 respectively. Before calculating trends in annual stream salinity, daily salinity records for all the gauging stations were interpolated from point samples based on the following method.

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

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

In Equation A3.1 the values of the two parameters (a', b') were determined using an interpolation process. Five point samples at a time were used to develop the relationship. As the relationship between the salinity and streamflow changes due to significant changes in land use, the values of these two parameters also change. Using parameters (a', b') for the most recent salinity sample at the gauging station, the daily salinity in the period without continuous record was calculated from Equation A3.1.

The daily salinity, salt load and streamflow records were then summed to get the annual flow (F), salinity (S) and salt load (L) at each gauging station. The annual rainfall (R_a) for each subcatchment was also calculated.

Next, the annual relationships between (i) streamflow and salinity and (ii) streamflow and rainfall for each gauging station were developed. In the first case, a nine-point centred moving-regression was used to calculate the parameters a'' and b'' (Equation A3.2). Similarly, in the streamflow/rainfall case nine years of data were used each time to determine the values of parameters c and d (Equation A3.3). The values of these parameters also changed with time due to changes in land use. The annual relationships can be described as:

$$S = a'' F^{b''} \qquad \textit{Equation A3.2}$$

$$F = c + dR_a \qquad \textit{Equation A3.3}$$

Based on Equation A3.3, values of annual streamflow F_r under mean annual rainfall (R_a) conditions for the period of the trend analyses (1979–2002) were determined:

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

The annual stream salinities (S_f) at mean annual streamflow ($\overline{F}$) were also calculated for the analysis period (Figs 3.1a–3.4a & A3.2a–A3.5a):

$$S_f = a'' \overline{F}^{b''} \qquad \textit{Equation A3.5}$$

The annual salt loads at mean flow (L_f) were calculated (Figs 3.1c–3.4c & A3.2c–A3.5c):

$$L_f = S_f\overline{F} \qquad \textit{Equation A3.6}$$

The annual stream salinity at mean flow (S_f) for each gauging station (Equation A3.5) was then plotted against an annual time-step. As the nine-point moving-regression was centred, output of the regression could only be obtained between four years after the first year of data and four years before the last year of data (1983–98).

A linear regression equation was developed for the periods 1979–89 and 1990–2002. The slope of the regression equation is taken as the rate of change in annual stream salinity, and is referred to as the trend. 1990 was chosen as the dividing year between the two periods of comparison, as a distinct change in salinity at mean flow is observed at the major gauging stations.

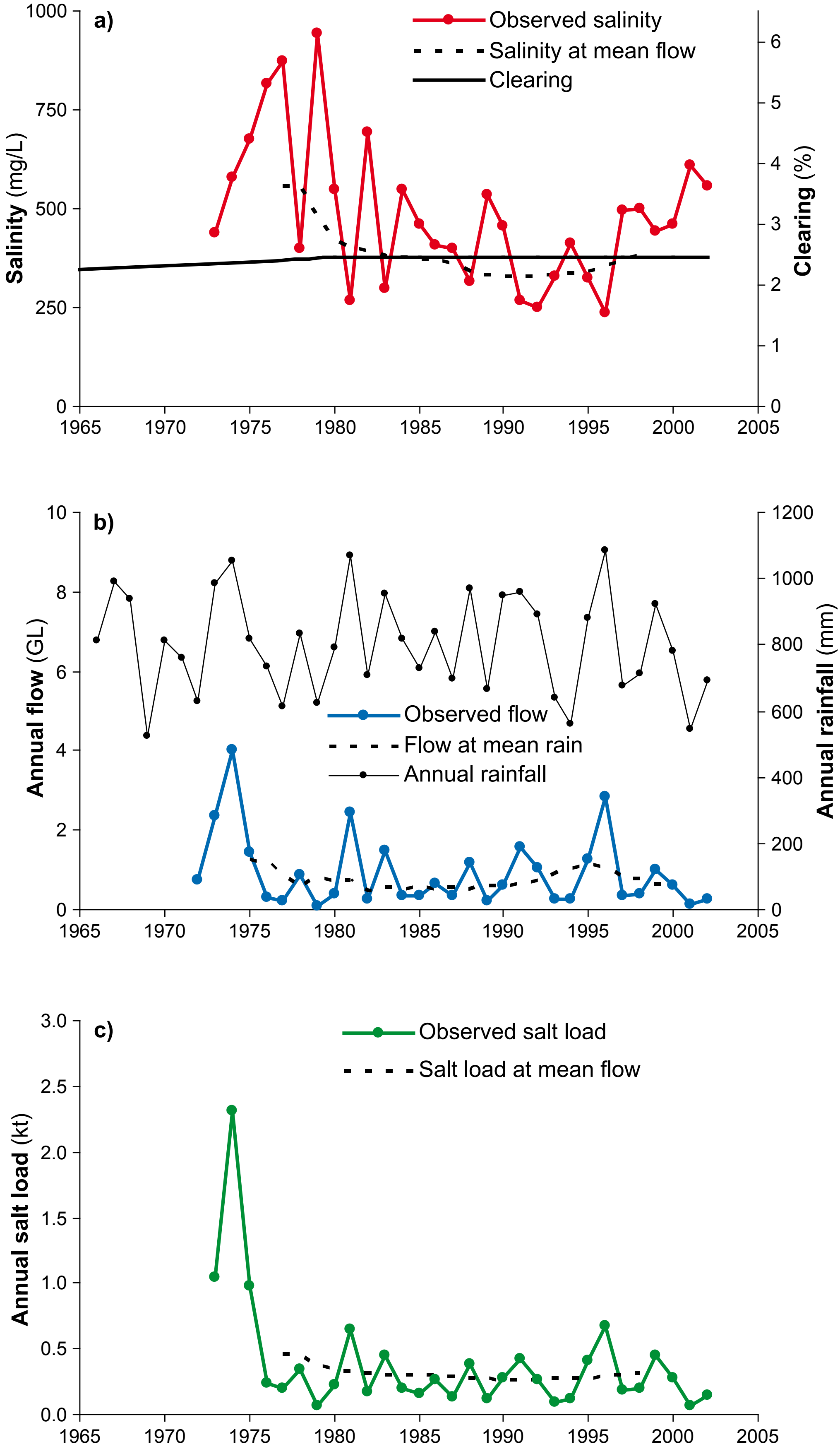


Figure A3.2 (a) Salinity (b) flow and (c) salt load for Helena Brook gauging station

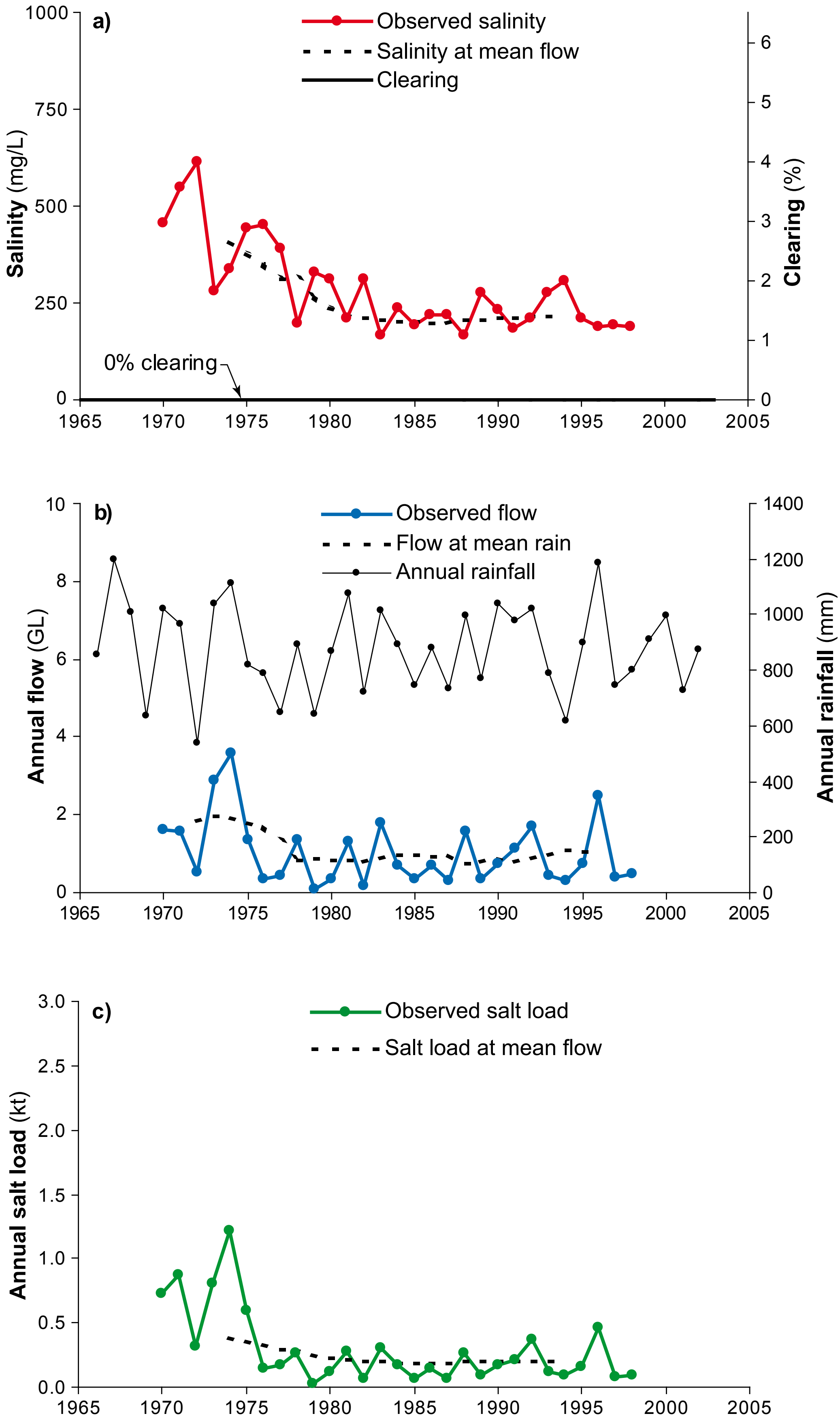


Figure A3.3 (a) Salinity (b) flow and (c) salt load for Little Darkin River gauging station

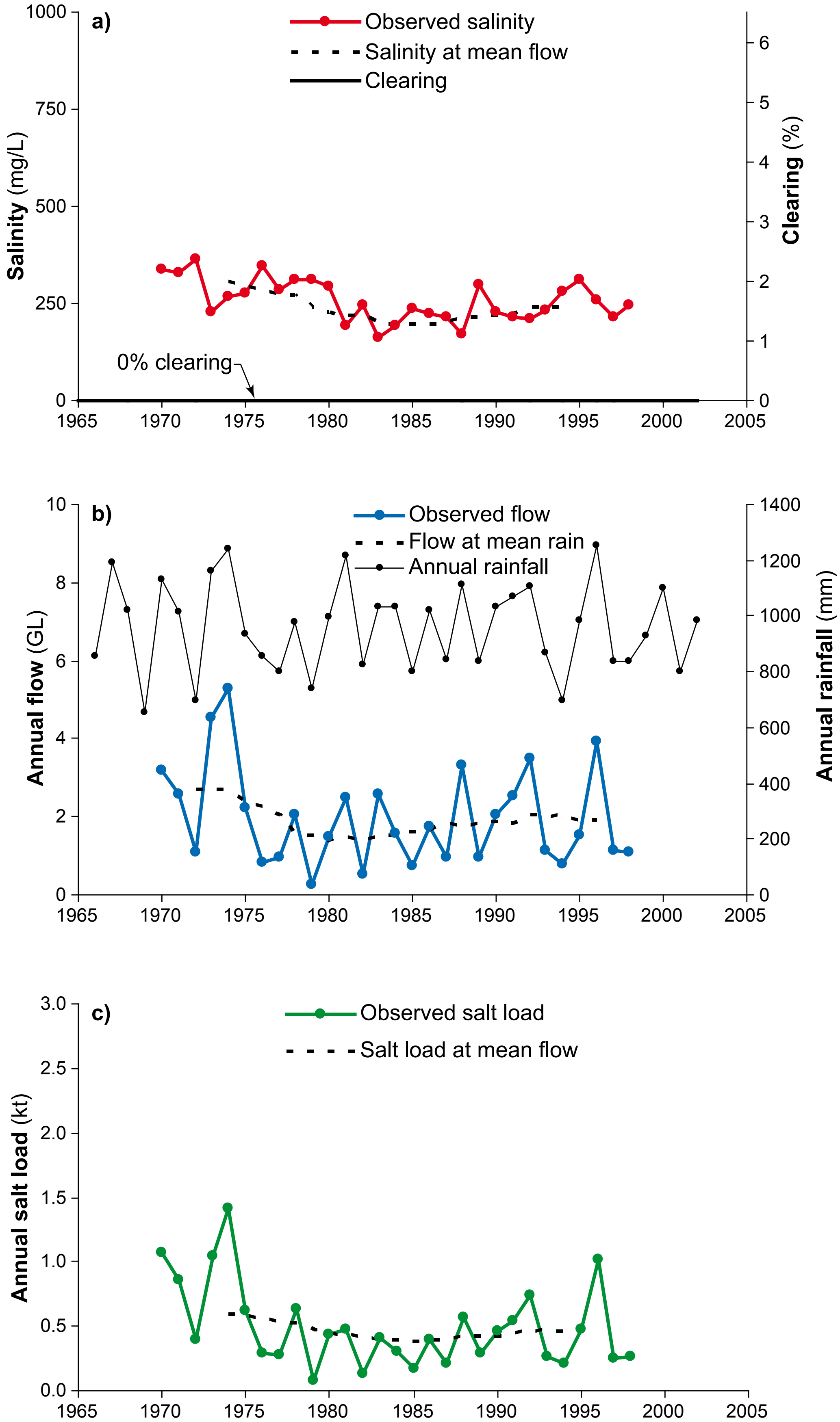


Figure A3.4 (a) Salinity (b) flow and (c) salt load for Pickering Brook gauging station

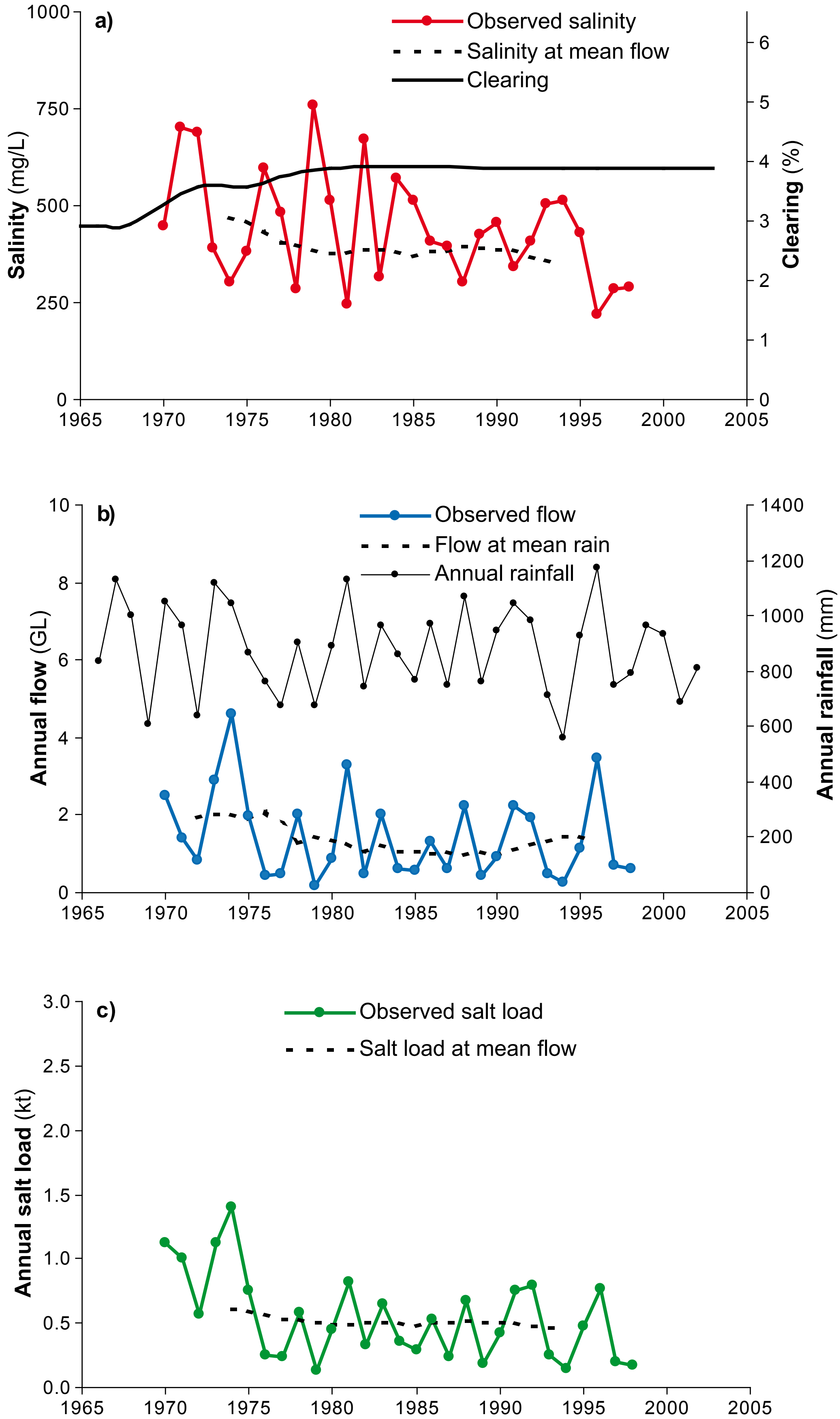


Figure A3.5 (a) Salinity (b) flow and (c) salt load for Rushy Creek gauging station

The trends were then tested for significance using a t-distribution analysis (Watts & Halliwell 1996). Taking the correlation coefficient (R) that was obtained from each regression the following equation was used:

$$t = \frac{R\sqrt{n-2}}{\sqrt{1-R^2}}$$ *Equation A3.7*

where n is the number of samples. Comparing the calculated value of t with that listed at the 95% confidence limit confirmed if the trend was significant.

A3.3.2 Surface water analysis

Salt load trends corroborate salinity trends by combining the variability of inversely-related salinity and flow data. This makes them useful in determining long-term changes in salt output of a catchment. Although salinities decrease in years of high flow, the total volume of streamflow becomes the most significant variable affecting salt loads (Figs 3.1c–3.4c & A3.2c–A3.5c). The increased flushing in wet years reduces the stream salinities (Figs 3.1a–3.4a & A3.2a–A3.5a). Nevertheless, the higher flows in these good rainfall years still result in higher than average transportation of salt to the reservoir. High salinities tend to occur during periods of low flow, with little impact on the salt load. Since the inverse relationship between salinity and flow helps to smooth the effects of high salinity years on the reservoir inflow, the load graphs closely resemble the flow graphs.

A3.4 Reservoir inflow

Annual inflow and salt load to Mundaring Reservoir were calculated by summing the gauged flow contributions from the Helena subcatchment, the Darkin subcatchment, and an estimated flow from the partly gauged Helena West management unit based on its three gauging stations. Just less than 50% of the area of the Helena West management unit is gauged and the annual flow and load from the ungauged part were estimated from similarity analysis. The gauged and ungauged portions (including the reservoir area) of Helena West are likely to generate similar flow and salt load (per unit of area), so flow and salt load were scaled up by the ratio of the total area of Helena West to the gauged area (This scaling factor is close to 2). The LUCICAT model output (see Section 4 & Appendix 4 for details) was used for 1999–2002 when the three gauging stations in the Helena West were inoperative (Fig. A3.6). Mean salinities for each year are calculated from the annual load and flow. The arithmetic mean of these annual salinities is used when comparing periods, such as 1977–89 and 1990–2002.

The Water Corporation calculates inflow to the reservoir based on dam levels, reservoir bathymetry and estimates of losses such as evaporation and pumping. A scatter plot of the flows obtained by the gauging and the storage methods (Fig. A3.7) has a slope of almost 1 and an intercept that suggests the storage calculations give about 3 GL/yr more inflow than the gauging based calculations. This may be related to runoff in lower rainfall years from the ungauged subcatchments of the Helena West MU, where the average runoff is 8.4 GL/yr (with only 4.1 GL/yr gauged). The good agreement between the two methods of reservoir inflow calculation generally supports the estimations of flow from the ungauged parts of the catchment.

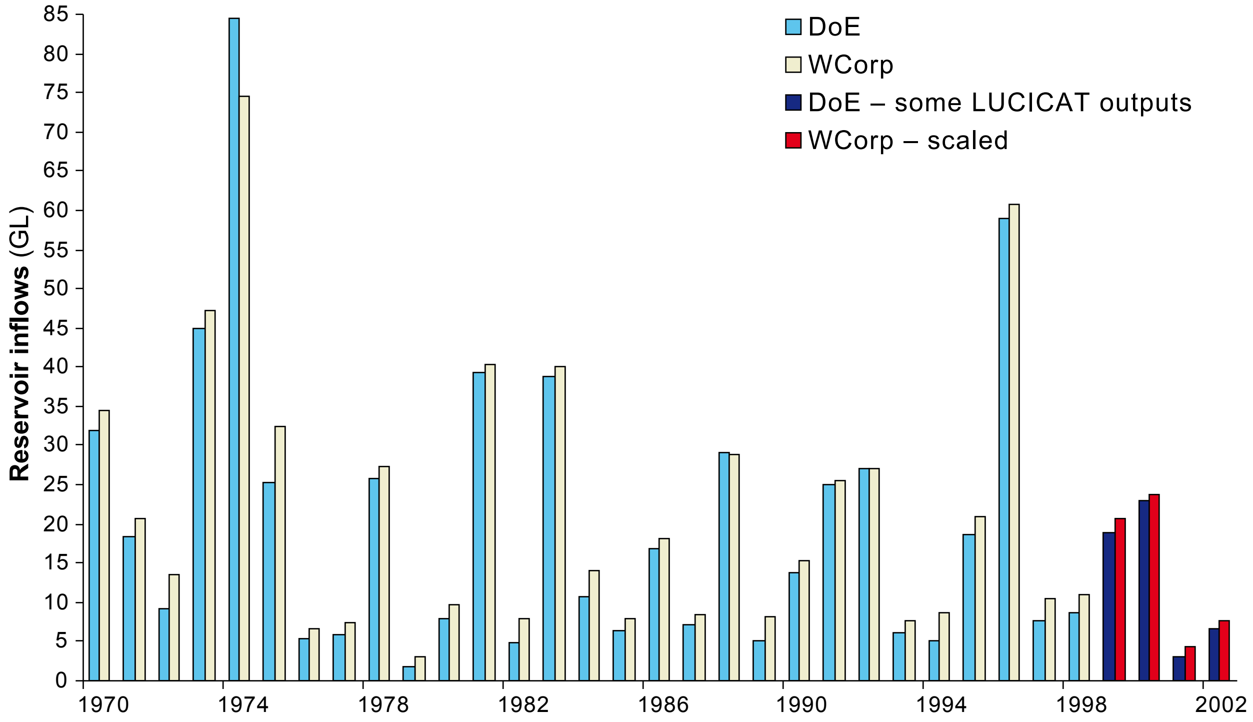


Figure A3.6 Reservoir annual inflow estimates

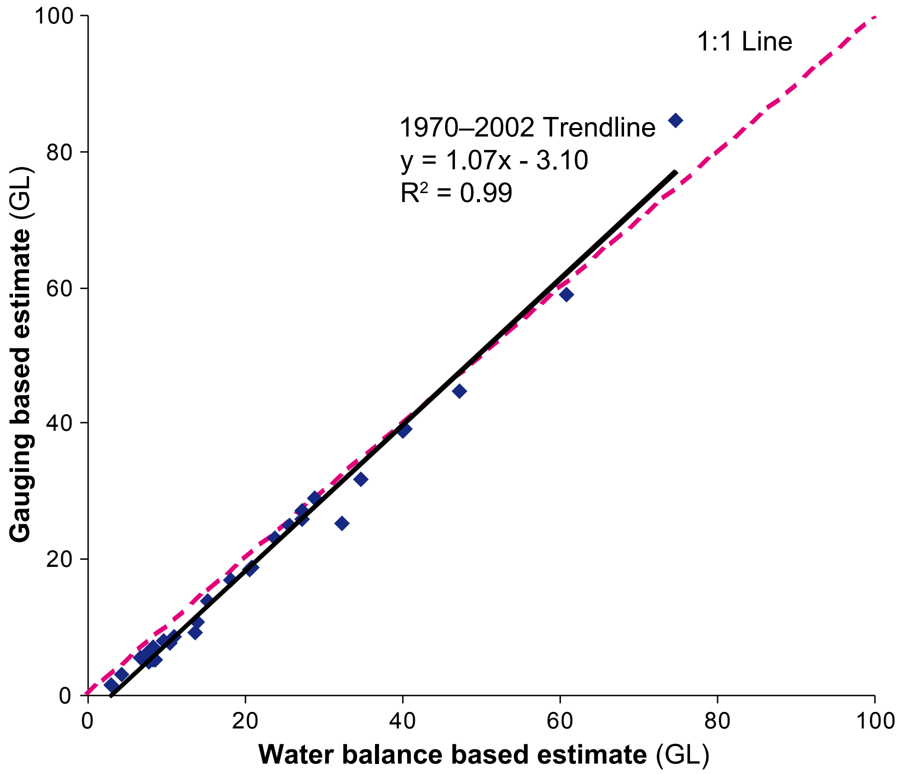


Figure A3.7 Scatter plot comparison of reservoir inflow estimates 1970—2002

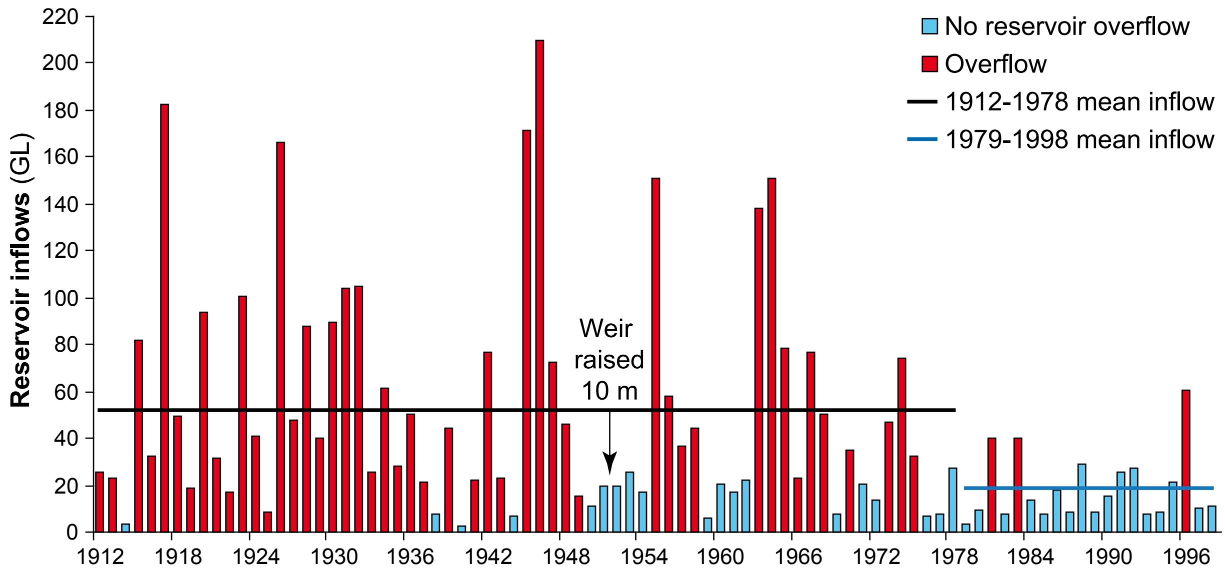


Figure A3.8 Reservoir annual inflow estimates and years of overflow

Overflow at the Weir has been less frequent since 1951, when the Weir was raised 10 m, and less frequent still since the 1970s when rainfall and inflow decreased (Fig. A3.8).

A3.4.1 Reservoir inflow salinity

Reservoir inflow, salt load and salinity data vary widely from year to year with high coefficients of variation (Table A3.1). The salinity distributions have negligible skew with salinity fairly evenly distributed around the mean value. Salt loads were moderately positively skewed indicating that most annual salt loads were below the mean, which was biased by a few high load years. This is further indicated by the 10th percentile value being closer to the mean than the 90th. Inflow to the reservoir was highly positively skewed because flows were generally below the mean value, which was biased by less frequent but very high flow years. The high coefficient of variation for inflow is a result of the infrequent large flow events that bias the data.

Table A3.1 1990—2002 inflow and salinity statistics for the reservoir

	Salinity (mg/L)	**Inflow** (GL)	**Salt load** (kt)
Mean	510 [a]	17.1	7.4
Median	530	13.8	7.9
10th percentile	360	5.3	3.2
90th percentile	610	26.7	11.3
Coefficient of variation	0.22	0.88	0.61
Skew	-0.19	1.95	0.98

[a] Arithmetic mean

Arithmetic, rather than flow-weighted, means are stated throughout this report (Table A3.2), because of the low residence time of supply in the reservoir (approximately 3 years based on the storage to inflow ratio). Reservoirs with high residence times allow greater mixing of both higher fresh and lower saline inflows. A low residence time reservoir can quickly become saline in response to extended low flow conditions. In these reservoirs, flow-weighted mean inflows are falsely fresh, being heavily biased towards infrequent high-flow years such as 1996 (Figs 3.1–3.4). These high flow events may even occur less frequently than the residence time during drought.

Table A3.2 Flow-weighted salinities and flows

Gauging station	Mean annual flow-weighted salinity and flow (1977–89) 1990–2002 [a]	
	(mg/L)	(GL)
Ngangaguringuring	(1300) 1500	(1.7) 1.8
Helena Brook	(380) 340	(0.7) 0.8
Poison Lease	(920) 910	(5.0) 5.1
Darkin River	(190) 160	(3.3) 3.6
Little Darkin River [b]	(210) 200	(0.7) 0.9
Pickering Brook [b]	(220) 220	(1.5) 2.0
Rushy Creek [b]	(360) 360	(1.2) 1.2
Whole reservoir	(460) 430	(15) 17

[a] Period used in modelling

[b] Due to station closure, 1999–2002 flow figures in the mean are from LUCICAT modelling

A3.5 Non-regular salinity and flow measurement sites visited 9 September 2004 to 23 October 2006

The only regular monitoring of water quality is at the gauging stations. In addition to these a nucleus of 38 sites for irregular monitoring was established by the occasional visits (described below) to 119 points, (mostly in 2005 as shaded in Table A3.3). These 38 core sites are italicised (to distinguish them among the 119 points comprising 64 unique sites) in Tables A3.4–A3.14, consolidated in Table A3.13 and shown on Fig. A3.9. The MGA (AGD94) coordinates have been amended to match the January 2000 orthomosaic features using the departmental geographical information system.

Table A3.3 Catchment field visits 2003—06

Date	Area	Purpose	Comments
30.08.2004	Most	Initial catchment tour with whole Branch	Followed heavy rain, all rivers and waterfalls flowing, Darkin Swamp overflow (Table A3.4)
06.09.2004	Reservoir, Helena Brook	Stream salinities near reservoir	Low salinity inflow to reservoir except in Helena River (Table A3.5)
15.12.2004	Helena	Source of summer flows at Ngangaguringuring GS	Found pools and groundwater discharge to above Ngangaguringuring GS (Table A3.6)
08.03.2005	Helena	Follow-up summer flows at Ngangaguringuring GS	Found pools and groundwater discharge sustained at end of summer (Table A3.7)
30.03.2005	Flynn and Helena	Batini bores and follow-up summer flows at Ngangaguringuring GS	Deep groundwater levels except near Ngangaguringuring GS (Table A3.8)
19.09.2005	Darkin Swamp	Joint visit with Water Corporation	Darkin Swamp discharging after heavy rain (Table A3.9)
11.11.2005	Upper Darkin and Helena rivers	Check end-of-winter flows without entering Telstra Rally area	Slightly higher salinities and one saline puddle in non-flowing Darkin River, but Helena River flowing saline at Yarra Road (Table A3.10)
12.12.2005	Helena	Hydrogeology tour to sites of salinity, palaeochannel sediments, groundwater discharge to pools and early summer flows mostly above Ngangaguringuring GS	Salinisation on north-east boundary, both fresh and saline groundwater pools above Ngangaguringuring GS with groundwater discharge as on 15.12.2004 (Table A3.11)
13.02.2006	Darkin Swamp	Introduction for Honours candidate	Dry despite recent thunderstorms, groundwater sustained pools fresh near Darkin Swamp (Table A3.12)
31.03.2006	Western half	Check coordinates (in Table A3.13)	Few are more than 5 m (up to 30), inaccurate
23.10.2006	Helena	Palaeochannel and geophysics	Palaeochannel 400 m along Yarra Road (Table A3.12)

Visits to the Helena River aimed to find the source of summer flows recorded at the Ngangaguringuring gauging station and to find where they disappear upstream of the Poison Lease gauging station. The expected explanation was that groundwater seepage was causing the flow at the Ngangaguringuring gauging station in summer while transpiration by streamzone vegetation and evaporation from the pools caused water loss upstream of the Poison Lease gauging station. The field investigation of 15 December 2004 started at the Poison Lease gauging station, progressed upstream beyond the Ngangaguringuring gauging station (Table A3.1, Fig. 3.7d shows key locations & salinities). It was followed by visits on 8 March, 30 March and 12 December 2005 (Tables A3.7, A3.8 & A3.11). Later visits found groundwater sustaining Clifford's Pool above Yarra Road and a saline tributary to Wariin Brook.

Visits to the Darkin subcatchment (mainly) were made on 30 August 2004 (Table A3.4, Branch tour), 19 September 2005 (with Water Corporation staff, Table A3.9), 11 November 2005 (Table A3.10) and 13 February 2006 (Table A3.12) to seek indications of salt entering the Darkin River or within the sediments; accompanied by Water Corporation staff and a University of Western Australia Honours student.

Figure A3.9 Sites for irregularly testing water

A3.5.1 Sites visited on the initial tour on 30 August 2004

Table A3.4 Various sites and sampling 30 August 2004

Site no.	Feature	ID no.	Flow	Meter Multiline P4			Location
			m^3/d	mS/cm	°C	mg/L	MGA GDA94
1	*Rushy Creek gauging station waterfall*	*616007*	*2.0*	*0.535*	*17*	*330*	*425 739 mE 6463 849 mN*
2	*Helena River at Allen Road bridge*	*6161284*	*Yes*	*2.45*	*9.5*	*1900*	*431 155 mE 6460 760 mN*
3	*Poison Lease gauging station*	*616216*	*Yes*	*2.5*	*9.5*	*2000*	*432 948 mE 6462 327 mN*
4	*Darkin River at Beraking*	*6162952*	*Yes*	*0.189*	*9.1*	*130*	*435 960 mE 6449 665 mN*
5	Christmas Tree Well Pool	6161374	No	0.264	12.5	180	445 600 mE 6434 150 mN
6	*Christmas Tree Well*	*6161375*	*No*	*0.492*	*11.5*	*360*	*445 600 mE 6434 200 mN*
7	*Darkin River at Piggery Road*	*6161423*	*Yes*	*0.148*	*10.9*	*120*	*452 510 mE 6449 260 mN*
8	*Darkin R. on Qualen Rd Darkin Swamp*	*6161040*	*Yes*	*0.149*	*18.1*	*90*	*454 410 mE 6447 066 mN*
9	*Little Darkin Swamp east side*	*6161424*	*Yes*	*0.126*	*15.0*	*80*	*454 005 mE 6453 020 mN*
10	Warrigal Rd below Little Darkin Swamp	6161425	Yes	0.151	15.0	110	451 327 mE 6451 221 mN
11	*Darkin River culvert, Warrigal Road*	*6161426*	*Yes*	*0.156*	*9.5*	*120*	*448 885 mE 6450 158 mN*
12	*Helena River at Yarra Road*	*6161038*	*Yes*	*4.62*	*10.1*	*3800*	*446 910 mE 6465 845 mN*
13	*Wariin Brook at Flynn Road*	*6161266*	*0.5*	*2.11*	*12.0*	*1600*	*438 589 mE 6469 207 mN*
14	Hillside seep N of Helena River	6161427	Yes	6.5	14.7	4800	441 600 mE 6467 120 mN
15	*Helena River at Yetar Road*	*6161287*	*0.1*	*4.22*	*10.3*	*3500*	*440 075 mE 6465 730 mN*
16	Helena River crossing SW of Mt Gorrie	6160284	0.5	3.32	10.1	2700	435 860 mE 6464 170 mN

A3.5.2 Sites visited near the reservoir and Helena Brook 6 September 2004

Table A3.5 Various sites and sampling 6 September 2004 to complement 30 August 2004

Site no.	Feature	ID no.	Time	Flow	Meter Multiline P4			Comments
			hour		mS/cm	°C	mg/L	MGA GDA94
17	Creek, Reservoir Road	616008	1122	Yes	0.256	12.8	160	421 290 mE 6462 880 mN
18	Hay Creek, culvert	6161072	1130	Yes	0.359	15.2	220	421 410 mE 6462 155 mN
19	Pickering Brook	6161009	1139	Yes	0.294	13.8	180	423 235 mE 6461 410 mN
20	Small creek culvert	6161474	1149	Yes	0.150	13.6	90	424 399nE 6461 081 mN
21	Helena pines	6161428	1205	Yes	0.440	13.6	280	426 134 mE 6459 148 mN
22	Small creek	6161475	1217	Yes	0.142	14.2	80	427 641 mE 6457 615 mN
23	*Little Darkin River GS 10.50 m*	*6161010*	*1227*	*Gs*	*0.254*	*13.6*	*160*	*428 080 mE 6456 470 mN*
24	Small creek	6161429	1240	Yes	0.128	14.6	80	428 754 mE 6456 597 mN
25	Small pool	6161444	1247	Yes	0.153	16.3	90	429 666 mE 6455 991 mN
26	*Darkin River, Darkin*	*6161445*	*1255*	*Yes*	*0.291*	*11.8*	*180*	*431 089 mE 6454 792 mN*
27	*Bridge, Darkin River*	*6161476*	*1305*	*Yes*	*0.280*	*11.4*	*170*	*431 506 mE 6453 927 mN*
28	*Darkin River GS 10.15 m*	*6161002*	*1320*	*GS*	*0.300*	*11.7*	*200*	*433 245 mE 6451 765 mN*
29	*Beraking Brook, Old Dale Rd*	*6162951*	*1330*	*Yes*	*0.257*	*12.1*	*160*	*435 800 mE 6449 375 mN*
30	Nockine River rockpools	6161477	1400	Yes	0.182	13.2	120	434 028 mE 6461 018 mN
31	Nockine River crossing	6161478	1410	Yes	0.191	13.9	120	433 750 mE 6461 570 mN
32	*Helena River, Firewood Rd*	*6160280*	*1420*	*Yes*	*1.93*	*12.5*	*1400*	*433 253 mE 6462 843 mN*
33	*Helena Brook, Oak Gorge Rd*	*6161480*	*1430*	*Yes*	*0.531*	*13.3*	*350*	*433 265 mE 6465 422 mN*
34	*Helena Brook GS 10.48 m*	*6161012*	*1445*	*GS*	*0.460*	*12.2*	*320*	*431 585 mE 6468 475 mN*
35	*Tributary of Helena Brook*	*6161446*	*1505*	*Yes*	*0.342*	*15.2*	*220*	*431 724 mE 6471 280 mN*

A3.5.3 Sites visited along the Helena River 15 December 2004

At the Poison Lease gauging station (Table A3.1, Site 3) the channel was full of water, the stage level was 10.01 m and 265 m^3/d was trickling over the flat weir. The flow increased upriver and at the Ngangaguringuring gauging station (Site 43) the stage level was 10.16 m and the flow through the v-notch weir was 1356 m^3/d. Investigations were then concentrated in model-subcatchment 4 (Fig. A4.9) and found where groundwater was seeping almost directly into the Helena River from sandy sediments above an interpreted palaeochannel. A swamp at the border of model-subcatchments 4 and 5, some 2.7 km upstream from the Ngangaguringuring gauging station and 0.7 km downstream from Yarra Road (Fig. 1.1), was completely dry, as was the Helena River upstream in model-subcatchment 5.

Table A3.6 Helena River sites and sampling 15 December 2004

Site no.	Feature	ID no.	Time	Flow est.	Meter LF320			Comments
			hour		mS/cm	°C	mg/L	MGA GDA94
3	*Poison Lease GS*	*616216*	*0940*	*Trickle, 265 m^3/d*	*4.50*	*20.6*	*2900*	*432 948 mE 6462 327 mN*
32	*Firewood Rd bridge*	*6160280*	*1018*	*Trickle*	*5.67*	*20.7*	*3800*	*433 253 mE 6462 843 mN*
36	1600 m above GS	6160281	1028	Still channel	4.31	20.7	2800	433 539 mE 6463 864 mN
37	Upstream further	6160282	1050	Still channel	5.35	22.3	3400	434 947 mE 6463 762 mN
38	Crossing 3100 m	6160283	1104	Trickle	4.76	22.4	3000	435 388 mE 6464 305 mN
16	Crossing SW Mt Gorrie	6160284	1115	?	4.70	25.9	2800	435 860 mE 6464 170 mN
39	Swamp	6160285	1130	?	4.64	25.6	2900	437 241 mE 6464 303 mN
40	Helena River	6160286	1140	?	4.57	22.7	2900	437 447 mE 6465 155 mN
41	Flynn pines	6160287	1155	Slow	4.19	21.8	2700	439 341 mE 6466 351 mN
15	*Helena River Yetar Road*	*6161287*	*1202*	*?*	*3.83*	*23.2*	*2400*	*440 075 mE 6465 730 mN*
42	*Rock bar, deep pool*	*6160289*	*1218*	*Flowing*	*3.48*	*23.7*	*2100*	*442 055 mE 6466 035 mN*
43	*Ngangaguringuring GS*	*616013*	*1232*	*1356 m^3/d*	*3.38*	*24.5*	*2000*	*443 592 mE 6466 110 mN*
44	*Rock bar, shallow*	*6160291*	*1241*	*Flowing*	*3.35*	*24.0*	*2000*	*444 007 mE 6466 132 mN*
45	Track seep	6160292	1340	Trickle	2.15	26.4	1200	445 668 mE 6466 250 mN
46	*Water point*	*6160290*	*1341*	*Nil*	*6.29, 6.48, 5.65, 6.57*	*26.9, 20.0, 27.8, 19.2*	*3600, 4400, 3300, 4500*	*445 644 mE 6466 229 mN*
47	*Big pool in Helena River*	*6160293*	*1404*	*Low*	*3.20*	*21.7*	*2000*	*445 238 mE 6466 028 mN*
48	*Collapsed culvert below swamp*	*6160294*	*1425*	*Flowing*	*3.25*	*22.6*	*2000*	*445 145 mE 6466 065 mN*

All tributaries were dry except for the tributary north in model-subcatchment 4, which was swampy with pools of groundwater seepage, but was not apparently flowing. It contained a thickly-vegetated water hole (Table A3.6, Site 46) with a layering of salinity up to 4500 mg/L, the highest recorded all day and possibly indicative of concentration by evapotranspiration rather than the salinity of the baseflow. A big pool (20 by 40 and 2 m deep) was found on the Helena

River nearby (Site 47) some 1.64 km upstream of Ngangaguringuring GS with a salinity of 2000 mg/L, the second lowest recorded for the trip. The lowest, 1200 mg/L for seepage from the sand (Site 45), was probably diluted with recent rainwater.

The water flow at the Ngangaguringuring gauging station (Site 43) must be from groundwater seepage into the main channel (upstream of the red subcatchment boundary in Fig. 3.7d) as it had the same concentration of 2000 mg/L as the baseflow in the upstream channel at Sites 44 and 48. Possibly a lot of seepage with up to 2000 mg/L occurs near the big pool (Site 47). Access to suspected pools in the Helena River immediately upstream of this point was not located. As the streamflow decreased downstream of the Ngangaguringuring gauging station, the salinity increased through Sites 42, 15 and 41 to 2900 mg/L at Site 40 (Table A3.6). This was then almost steady through Sites 39 and 16. Then by Site 38 salinity increased to 3000 mg/L, peaking at 3800 mg/L at Site 32 just 600 m upstream of the Poison Lease gauging station where it was 2900 mg/L. Site 32 had the only salinity (3800 mg/L) significantly different from 2900 mg/L.

Most likely, transpiration by the vegetation close to the stream, especially pine plantations on Gorrie, Wellbucket and Flynn, increased the salinity of the river. At one point (Site 38) this section of the Helena River had no culvert and no apparent flow. Follow-up visits were needed to check for sediments and seeps on the north tributary upstream of Site 44 at the end of summer, to check the dry swamp and also any pools/wetlands up to Yarra Road.

A3.5.4 Sites visited along the Helena River 8 March 2005

Table A3.7 Helena River sites and sampling 8 March 2005

Site no.	Feature	ID no.	Time	Flow estimated	Meter LF320		
			hour		mS/cm	°C	mg/L
46	*Water point*	*6160290*	*1335*	*Nil*	*6.40*	*18.8*	*4400*
47	*Big pool*	*6160293*	*1400*	*Low*	*3.22*	*20.0*	*2000*
48	*Collapsed culvert*	*6160294*	*----*	*Not visited*			
44	*Rock bar, shallow*	*6160291*	*1405*	*0.03 m^3/s, ~2600 m^3/d*	*3.09*	*21.1*	*2100*
43	*Ngangaguringuring GS*	*616013*	*1420*	*Staff 10.149 m, 1160 m^3/d*	*3.14*	*21.8*	*2000*
42	*Rock bar, deep pool*	*6160289*	*1430*	*Bit less*	*3.42*	*23.0*	*2100*
15	*Helena River Yetar Road*	*6161287*	*1440*	*Trickle*	*3.81*	*21.0*	*2400*

A3.5.5 Sites visited along the Helena River 30 March 2005

Phil Roberts, David Rowlands, Frank Batini (consultant for BGC) and Bob Huston (CALM Mundaring) visited the Flynn plantation (Site 15, Table A3.8) and then bores at 441 395 mE 6461 596 mN drilled in the 1970s by Frank Batini to monitor response to 50% thinning of the canopy. The eastern shallow bore had fresh water or bottom-of-hole at 3.3 m while the western deeper bore had salt water at 17.7 m at 14:26 hours. During the return from this site DoE staff revisited sites on the Helena River.

Table A3.8 Helena River sites and sampling 30 March 2005

Site no.	Feature	ID no.	Time	Flow est.	Meter LF320			Meter3401comp.to25 °C		
			hour		mS/cm	°C	mg/L	mS/cm	°C	mg/L
46	*Water point*	*6160290*	*1510*	*Nil*	*5.83* *5.84* *6.08*	*21.3* *20.3* *21.5*	*3800* *3900* *4000*	*6.55* *6.66*	*20.7* *20.4*	*4000* *4000*
47	*Big pool*	*6160293*	*1520*	*Low*	*2.99*	*19.3*	*2000*	*3.40*	*19.5*	*2000*
48	*Collapsed culvert*	*6160294*	*1530*	*Trickle*	*3.00*	*19.4*	*2000*	*3.39*	*19.6*	*2000*
44	*Rock bar, shallow*	*6160291*	*1540*	*0.03 m^3/s, ~2600 m^3/d*	*3.79*	*20.9*	*2400*	*3.43*	*20.7*	*2000*
43	*Ngangaguringuring GS*	*616013*	*1550*	*Staff 10.149 m, 1160 m^3/d*	*3.48*	*20.7*	*2300*	*3.84*	*20.7*	*2300*
42	*Rock bar, deep pool*	*6160289*	*1600*	*Bit less*	*3.29*	*21.4*	*2100*	--	--	--
15	*Helena R. Yetar Rd*	*6161287*	*1610*	*Trickle*	*3.61*	*20.6*	*2300*	--	--	--

These salinities are very similar to those measured on 15 December 2004 and 8 March 2005.

A3.5.6 Darkin Swamp, Darkin and Helena rivers at Yarra Road 19 September 2005

The Darkin Swamp visit of 19 September 2005, timed to follow a wet period, found no indication of salt (entering the Darkin River or discharging from the sediments). Water Corporation staff participated in this trip to discuss the nature and extent of surface flow from upstream of Darkin Swamp. Flow through Darkin Swamp is restricted to runoff from intense rainfall events, when the catchment is wet and the swamp is full. A follow-up on 11 November 2005 in drier conditions found very little more salt in the water.

The Darkin River rises among swamps found mostly in the south-east of the catchment. It drains the southern 665 km^2 of the Mundaring catchment but gains most flow downstream of the Darkin Swamp. Its average yearly flow-weighted salinity is now estimated to be about 200 mg/L rather than 400 mg/L (Stokes & Batini 1985). While the Helena River drains an 11% smaller area, its flow is about 1.5 times greater than the flow from the Darkin River. These differences in the two subcatchments are not attributable to differences in clearing but in their relief and the associated groundwater discharge, demonstrated by the minimal flow through the Darkin Swamp. In contrast, well-developed summer flow has been recorded for the past 40 years in the Helena River. The current detailed assessment of the salinity situation is the first to examine and interpret saline groundwater discharge and salinity trends along the rivers.

The unconfined to semi-confined sedimentary aquifers are now recognised as significant sources of saline water in the Mundaring catchment. The sediments were deposited in palaeovalleys and topographic depressions in fresh or weathered bedrock and are suspected to be Late Eocene in age. The irregular occurrences appear to have been connected with ancestral drainages from the east (Salama 1997; Commander et al. 2001), possibly equivalent to the Werillup Formation (mainly exposed overlying bedrock in the onshore western Eucla Basin (Clarke et al. 2003)). Extending NW for about 50 km these sediments are found in the east of the water supply catchment (about half in the each of the Darkin River and Helena River subcatchments).

It is becoming clear that swamps and springs north of the Helena River are discharging groundwater from the sedimentary aquifer because they adjoin land cleared of deep-rooted native vegetation. At least one major spring east of Yetar Spring (Figs 2.2 & 3.7d) continuously discharges water with a salinity of 2000 mg/L to the Helena River, that increases downstream to almost 3000 mg/L. A nearby swamp with no apparent outflow has salinity of up to 4500 mg/L. Eventually all salt discharged to the surface is carried to the reservoir in runoff.

In contrast, groundwater from the same type of sedimentary aquifers in the Darkin River subcatchment may contribute to streamflow only during wet years, thus the mean weighted salinity of the river is 400 mg/L. Clearing in this subcatchment will have already enhanced recharge to the groundwater but it is uncertain whether this will result in groundwater discharge and raise the salinity of the Darkin River. Unlike the Helena subcatchment that is exporting salt, the Darkin subcatchment is receiving more saltfall than it is discharging and so is less a concern for salinity management.

The sedimentary aquifer is more extensive in the Darkin River subcatchment but currently either does not contribute to river flow or contributes only in very wet years.

Table A3.9 Darkin Swamp, Darkin River and Helena River sites and sampling 19 September 2005

Site no.	Feature	ID no.	Node no.	Flow est.	W/Corp meter		DoE meter		Location
					mS/cm	°C	mS/cm	mg/L	MGA AGD94
8	*Darkin River on Qualen Road at Darkin Swamp*	*6161040*	*367*	*Yes*	*0.148*	*21.1*	*0.140*	*~80*	*454 410 mE 6447 066 mN*
49	*Darkin River 1st tributary E of Korner Road*	*6161447*	*376*	*No*	*0.106*	*15.9, 15.5*	*0.120*	*~70*	*454 669 mE 6443 960 mN*
50	*Darkin River 2nd tributary E of Korner Road*	*6161448*	*394*	*No*	*0.218*	*21.8, 21.7*	*0.212*	*~120*	*458 000 mE 6443 960 mN*
7	*Darkin River at Piggery Road*	*6161423*		*Slight*	*0.138*	*16.8*	*0.121*	*~80*	*452 510 mE 6449 260 mN*
51	Little Darkin Swamp outflow at Roberts and Warrigal Roads	6161449	325 pre-322	To drain	0.125	25.5, 25.4	0.133	~70	450 321 mE 6450 724 mN
52	*Darkin River at Yarra Road*	*6161039*	*340*	*Yes*	*0.118*	*14.5*	*0.098*	*~70*	*446 720 mE 6450 460 mN*
12	*Helena River at Yarra Road*	*6161038*	*92–97 (outlet)*	*Strong*	*3.77*	*14*	*3.06*	*~2100*	*446 910 mE 6465 845 mN*

A3.5.7 Sites visited in the south, east and north of the catchment 11 November 2005

This visit located saline streamflow into Wariin Brook.

Table A3.10 Darkin and Helena rivers sampling 11 November 2005

Site no.	Feature	ID no.	Flow est.	Branch meter			Comments
				mS/cm	°C	mg/L	
6	*Christmas Tree Well at Brookton Hwy*	*6161375*	*0.8 m depth*	*0.0943*	*15.2*	*95*	*445 600 mE 6434 200 mN*
53	*Small pool N of Browns Swamp, Korner Rd, dam overflow/seepage*	*6161631*	*No*	*5.7*	*25*	*3500*	*462 432 mE 6443 990 mN*
8	*Darkin River at Qualen Road*	*6161040*	*No*	*0.274*	*14.2*	*170*	*454 410 mE 6447 066 mN*
7	*Darkin River Piggery Road*	*6161423*	*No*	*0.035*	*25.2*	*180*	*452 510 mE 6449 260 mN*
9	*Little Darkin Swamp E side access*	*6161424*	*Almost full*	*0.174*	*26.7*	*100*	*454 005 mE 6453 020 mN*
11	*Darkin River culvert, Warrigal Road*	*6161426*	*No*	*0.255*	*22*	*130*	*448 885 mE 6450 158 mN*
52	*Darkin River at Yarra Road*	*6161039*	*No*	*0.238*	*18.9*	*130*	*446 720 mE 6450 460 mN*
12	*Helena River at Yarra Road*	*6161038*	*0.5 m^3/min*	*3.69*	*20.1*	*2400*	*446 910 mE 6465 845 mN*
54	*Tributary of Wariin Brook*	*6161632*	*Trickle*	*6.27*	*26.5*	*3700*	*439 428 mE 6471 669 mN*

A3.5.8 Sites visited in the Helena River subcatchment 12 December 2005

Robin Smith, Jayath De Silva and Margaret Smith inspected cleared areas, saline seeps, Wariin Brook baseflow and, following up from December 2004, flow in the Helena River. Spring 2005 was mild and showery so again flow was sustained in the Helena River through Site 3 (Table A3.11) to the reservoir.

The starting point, the cleared farmland west of Wundabiniring Road and north of Great Southern Highway, had hay-growing and streamzone cropping that may be nutrient sources for the Helena River. Waterlogging is evident in the streamlines, and abandoned windmills indicate that groundwater is now saline. The area to the south has stressed wandoo indicative of a shallow saline watertable.

The area north of the Great Southern Highway and now recognised to be inside the north-eastern Helena subcatchment boundary appears salt-affected, especially in the west, and has sandy swamps to the east.

The 5500 mg/L (Table A3.11, Site 55) pool below Talbot Road West and the adjoining large area of cleared farmland, is similar to salinities on record. The farm is likely to be a source of the nutrients indicated by the prevalence of algae downstream, e.g. at Site 43.

Cliffords Pool (Site 56) and other pools were full but there was no flow at the next stop, 5500 m upstream of Yarra Road. The small flow at Yarra Road originated from this 5500 m reach, but flow increased between Sites 46 and 44 to an estimated 800 m^3/d and then possibly further increased in the 400 m above Ngangaguringuring gauging station (Site 43) where it was 1600 m^3/d. Flow diminished downstream by Site 15 on Yetar Road and remained small at Sites 2 and 3, possibly indicating some additional groundwater input to sustain flow to the reservoir.

Table A3.11 Helena subcatchment sites and sampling 12 December 2005

Site no.	Feature	ID	Time	Flow	Meter LF320			Comments
			hour	m³/d	mS/cm	°C	mg/L	Not all MGAs repeated
--	Wundabiniring farm streams	Gt Sthn Hwy		0				Shallow saline WT, stock, hay, crop, old windmills
--	Boundary farm streams	Ditto		0				Sandy, salt affected in west
55	*Helena pool, Talbot Road West*	*6160175*	*1100*	*0*	*7.7*	*18.7*	*5500*	*Iron stains in seepage, 452 270 mE 6465 630 mN*
56	*Cliffords Pool, Helena R.*	*6161289*	*1110*	*0*	*1.17*	*19.2*	*740*	*Big waterhole 450 425 mE 6465 264 mN*
--	Helena River bed	None		Dry				Vegetated, 5500m Yarra Rd
57	Pool, pigs digging	6161627	1120	0	2.51	17.1	1700	1500m to Yarra Road, 447 573 mE 6464 472 mN
58	Helena at old bridge site	6161628	1130	Small	2.87	17.4	1900	100m to Yarra Rd, 446 981 mE 6465 759 mN
12	*Helena at Yarra Road*	*6161038*	*1140*	*Slight*	*3.08*	*19.9*	*2000*	*Iron in seepage*
46	Water point	6160290	1150	No	4.45	22.9	2800	Dog and pig tracks
45	Track seep	6160292	1155	Seep	1.5	24.1	850	Seep down track
47	*Big pool (in Helena)*	*6160293*	*1210*	*Gentle*	*2.85*	*18.2*	*1900*	*Lots fish and marron*
48	*Collapsed culvert*	*6160294*	*1220*	*Small*	*2.83*	*17.6*	*2000*	*Swamp outlet below 11*
44	*Rock bar, shallow*	*6160291*	*1230*	*~800*	*2.9*	*17.8*	*2000*	*400 m to Ngangaguringuring*
43	*Ngangaguringuring GS*	*616013*	*1310*	*1572*	*2.97*	*18.5*	*2000*	*Some algae (nutrients)*
42	*Rock bar, deep pool*	*6160289*	*1320*	*~1500*	*3.18*	*20.6*	*2000*	*Access to hillside seeps*
59	Creeklet halfway up hill	6161629	1335	Small	11.07	27.3	6700	Iron staining, 441 960 mE 6466 885 mN
14	Hillside seep N of Helena	6161427	1350	Seep	27	30	16000	Small puddles, iron stained
13	*Wariin Brook at Flynn*	*6161266*	*1410*	*Small*	*2.72*	*25.9*	*1500*	*Road junction to Flynn*
60	Seep near Wariin Brook	6160459	1430	Small	2.27	23.6	1400	NW of old sand pit, 440 600 mE 6469 990 mN
61	Wariin pools	6161630	1440	0	2.74	23.8	1700	Soupy orange stagnant deep, 441 310 mE 6470 110 mN
15	*Helena River Yetar Road*	*6161287*	*1500*	*Small*	*3.19*	*18.3*	*2100*	*440 075 mE 6465 730 mN*
--	Mt Gorrie	None		---				Photos of grasstrees
2	*Helena R Allen Rd bridge*	*6161284*	*1530*	*Slight*	*3.84*	*23*	*2400*	*Steep access*
3	*Poison Lease GS*	*616216*	*1600*	*660*	*3.54*	*17.7*	*2500*	*Orange muddy colour*

These salinities are very similar to those measured in December 2004 and March 2005.

At Site 60, seeps had 1400 mg/L flow beneath the old sand pit but Wariin Brook was stagnant upstream (Site 61) and contained 1500 mg/L downstream at Site 13.

Site 14, the hillside seep closest to the hillside boulders, had a series of puddles with concentrations by evaporation to 1600 mg/L. Further down the hill on an adjoining creeklet the small flow contained 6700 mg/L (Site 59).

A3.5.9 Sites visited in the catchment 13 February 2006

Catchment and Darkin Swamp tour for new Water Corporation staff and UWA Honours student.

Table A3.12 Darkin and Helena rivers sampling 13 February 2006

Site no.	Feature	ID no.	Flow est.	Branch meter			Comments
				mS/cm	°C	mg/L	
1	*Rushy Creek GS*	*616007*	*Dry*				*425 739 mE 6463 849 mN*
62	*Jones Crossing, Gorrie Rd*	*6161998*	*Dry*				*432 629 mE 6461 732 mN*
3	*Poison Lease GS*	*616216*	*Stagnant*				*432 948 mE 6462 327 mN*
4	*Darkin River at Beraking*	*6162952*	*Dry*				*435 960 mE 6449 665 mN*
28	*Darkin River GS*	*616002*	*Dry*				*433 245 mE 6451 765 mN*
8	*Darkin River on Qualen Road at Darkin Swamp*	*6161040*	*No*				*454 410 mE 6447 066 mN*
63	*Darkin Swamp waterpoint off Qualen Rd*	*6161996*	*No*				*454 183 mE 6447 142 mN*
64	*Piggery Rd crossing puddle E side*	*6161997*	*No*	*0.940*	*36*	*350*	*452 573 mE 6449 448 mN*
52	*Darkin River at Yarra Road*	*6161039*	*No*				*446 720 mE 6450 460 mN*
56	*Cliffords Pool, Helena R. above Yarra Rd*	*6161289*		*0.988*	*25*	*530*	*450 425 mE 6465 264 mN*
44	*Rock bar, shallow crossing*	*6160291*	*Small*	*3.28*	*28*	*1900*	*440 007 mE 6466 132 mN*
43	*Ngangaguringuring GS*	*616013*	*10.15 m, 1160 m^3/d*	*6.27*	*26.5*	*3700*	*443 592 mE 6466 110 mN*
14	Saline hillside seep	6161427					441 600 mE 6467 120 mN

A3.5.10 Sites for irregular water testing

Table A3.13 Sites (38) recommended for testing on irregular visits, with their initial conductivities from earlier tables

Site no.	Feature	ID no.	Fig. A3.9	Conductivity & salinity			Location
			no.	mS/cm	°C	mg/L	MGA GDA94
55	*Helena pool, Talbot Road West*	*6160175*	*1*	*7.7*	*18.7*	*5500*	*452 270 mE 6465 630 mN*
56	*Cliffords Pool on Helena River*	*6161289*	*2*	*1.17*	*19.2*	*740*	*450 425 mE 6465 264 mN*
12	*Helena River at Yarra Road*	*6161038*	*3*	*4.62*	*10.1*	*3800*	*446 910 mE 6465 845 mN*
46	*Water point*	*6160290*	*4*	*6.29*	*26.9*	*3600*	*445 644 mE 6466 229 mN*
47	*Big pool in Helena River*	*6160293*	*5*	*3.20*	*21.7*	*2000*	*445 238 mE 6466 028 mN*
48	*Collapsed culvert below swamp*	*6160294*	*6*	*3.25*	*22.6*	*2000*	*445 145 mE 6466 065 mN*
44	*Rock bar, shallow*	*6160291*	*7*	*3.35*	*24.0*	*2000*	*444 007 mE 6466 132 mN*
43	*Ngangaguringuring GS*	*616013*	*8*	*3.38*	*24.5*	*2000*	*443 592 mE 6466 110 mN*
42	*Rock bar, deep pool*	*6160289*	*9*	*3.48*	*23.7*	*2100*	*442 055 mE 6466 035 mN*
15	*Helena River at Yetar Road*	*6161287*	*10*	*4.22*	*10.3*	*3500*	*440 075 mE 6465 730 mN*
54	*Tributary of Wariin Brook*	*6161632*	*11*	*6.27*	*26.5*	*3700*	*439 428 mE 6471 669 mN*
13	*Wariin Brook at Flynn Road*	*6161266*	*12*	*2.11*	*12*	*1600*	*438 589 mE 6469 207 mN*
35	*Tributary of Helena Brook*	*6161446*	*13*	*0.342*	*15.2*	*220*	*431 724 mE 6471 280 mN*
34	*Helena Brook GS*	*6161012*	*14*	*0.460*	*12.2*	*320*	*431 585 mE 6468 475 mN*
33	*Helena Brook, Oak Gorge Rd*	*6161480*	*15*	*0.531*	*13.3*	*350*	*433 265 mE 6465 422 mN*
32	*Helena River, Firewood Rd*	*6160280*	*16*	*1.93*	*12.5*	*1400*	*433 253 mE 6462 843 mN*
3	*Poison Lease gauging station*	*616216*	*17*	*2.5*	*9.5*	*2000*	*432 948 mE 6462 327 mN*
62	*Jones Crossing, Gorrie Rd*	*6161998*	*18*	*--*	*--*	*dry*	*432 629 mE 6461 732 mN*
2	*Helena River at Allen Road bridge*	*6161284*	*19*	*2.45*	*9.5*	*1900*	*431 155 mE 6460 760 mN*
53	*Small pool N of Browns Swamp, Korner Rd*	*6161631*	*20*	*5.7*	*25*	*3500*	*462 432 mE 6443 990 mN*
50	*Darkin R. 2nd tributary E of Korner Rd*	*6161448*	*21*	*0.212*	*21.8*	*~120*	*458 000 mE 6443 960 mN*
49	*Darkin R. 1st tributary E of Korner Rd*	*6161447*	*22*	*0.120*	*15.9*	*~70*	*454 669 mE 6443 960 mN*

Table A3.13 continues

Site no.	Feature	ID no.	Fig. A3.9 no.	Conductivity & salinity mS/cm	°C	mg/L	Location MGA GDA94
8	*Darkin R. on Qualen Rd Darkin Swamp*	*6161040*	*23*	*0.149*	*18.1*	*90*	*454 410 mE 6447 066 mN*
63	*Darkin Swamp waterpoint off Qualen Rd*	*6161996*	*24*				*454 183 mE 6447 142 mN*
64	*Piggery Road crossing puddle E side*	*6161997*	*25*	*0.940*	*36*	*350*	*452 573 mE 6449 448 mN*
7	*Darkin River at Piggery Road*	*6161423*	*26*	*0.148*	*10.9*	*120*	*452 510 mE 6449 260 mN*
9	*Little Darkin Swamp east side*	*6161424*	*27*	*0.126*	*15*	*80*	*454 005 mE 6453 020 mN*
51	*Little Darkin Swamp outflow at Roberts and Warrigal Roads*	*6161449*	*28*	*0.133*	*25.5*	*~70*	*450 321 mE 6450 724 mN*
11	*Darkin River at Warrigal Road*	*6161426*	*29*	*0.156*	*9.5*	*120*	*448 885 mE 6450 158 mN*
52	*Darkin River at Yarra Rd*	*6161039*	*30*	*0.098*	*14.5*	*~70*	*446 720 mE 6450 460 mN*
4	*Darkin River at Beraking*	*6162952*	*31*	*0.189*	*9.1*	*130*	*435 960 mE 6449 665 mN*
6	*Christmas Tree Well*	*6161375*	*32*	*0.492*	*11.5*	*360*	*445600 mE 6434 200 mN*
29	*Beraking Brook, Old Dale Rd*	*6162951*	*33*	*0.257*	*12.1*	*160*	*435 800 mE 6449 375 mN*
28	*Darkin River GS*	*6161002*	*34*	*0.300*	*11.7*	*200*	*433 245 mE 6451 765 mN*
27	*Bridge, Darkin River*	*6161476*	*35*	*0.280*	*11.4*	*170*	*431 506 mE 6453 927 mN*
26	*Darkin River, Darkin*	*6161445*	*36*	*0.291*	*11.8*	*180*	*431 089 mE 6454 792 mN*
23	*Little Darkin River GS*	*6161010*	*37*	*0.254*	*13.6*	*160*	*428 080 mE 6456 470 mN*
1	*Rushy Creek GS*	*616007*	*38*	*0.535*	*17*	*330*	*425 739 mE 6463 849 mN*

A3.5.11 Hydrogeology in the Ngangaguringuring subcatchment 23 October 2006

Robin Smith, Jayath De Silva, Natti Hundi, Philip Commander, Richard Lindsay and Margaret Smith inspected lineaments, sand quarries, cleared areas, saline seeps, Wariin Brook and Helena River baseflows and sites for potential geophysical traverses. Winter 2006 had the lowest rainfall on record and spring was mild and showery so groundwater levels and seeps were at their peaks. Flow was sustained in the Helena River from both above and below Yarra Road and probably through to the reservoir. The river was losing and gaining flow respectively upstream and downstream of Big Pool. The salinities were not much different from those previously measured.

A VLF (very low frequency) geophysical survey for 500 m along Yarra Road indicated a 400 m crossing of the palaeochannel between bedrock with anomalies at the river and the bedrock contact to the south-west, both oblique rather than vertical.

Table A3.14 Ngangaguringuring subcatchment sites and field salinities 23 October 2006

Site no.	Feature	ID	Time	Flow	Conductivity meter		Comments
			hour	m^3/d	mS/cm	mg/L	Site nos, coords from WRT 34
13	*Wariin Bk at Flynn Rd*	*6161266*	*0915*	*Small*	-	-	*438 589mE 6469 207mN*
60	Seep near Wariin Brook	6160459	1045	Small	2	1200	NW of old sand pit 440 600mE 6469 990mN
61w	Wariin Bk pools, west		1100	Small	5	3000	440 640mE 6470 087mN
60s	Swamp S of Wariin Bk		1130	Small	11	6600	W of old sand pit, 440 576mE 6469 940mN
14	Hillside seep N of Helena River	6161427	1215	Seep	-	-	Small flow, iron stained 441 600mE 6467 120mN
59	Creeklet halfway up hill	6161629	1345	Small	-	-	441 960mE 6466 885mN
42	*Rock bar, deep pool*	*6160289*	*1315*	*~1500*	*3.5*	*2000*	*442 055mE 6466 035mM*
43	*Ngangaguringuring GS*	*616013*	*1325*	*1572*	-	-	*0.20m stage, ~30L/s 443 592mE 6466 110mN*
48	*Collapsed culvert*	*6160294*	*1335*	*Small*	-	-	*Swamp outlet, less flow 445 145mE 6466 065m*
47	*Big pool (in Helena)*	*6160293*	*1340*	*Gentle*	-	-	*Fish and mattress 445 238mE 6466 028mN*
46	Water point	6160290	1400	No	-	-	Very wet track to east 445 644mE 6466 229mN
45	Track seep	6160292	1415	Seep	1.3 to 1.7	900	Very wet track 445 668mE 6466 250mN
12	*Helena at Yarra Road*	*6161038*	*1445*	*Small*	*4.3*	*2500*	*Higher than downstream 446 910mE 6465 845mN*

Appendix 4 — Modelling

A4.1 MAGIC model formulation

A4.1.1 Ground surface

The ground surface was represented by the digital elevation model (DEM) prepared in 2004 for the Water Corporation of Western Australia IWSS (Integrated Water Supply Scheme) GIS model for Surface Water Resources (Fig. 2.1). Most of the DEM was derived originally from 5 m contours in forested areas. In the farm areas a more detailed DEM, available from DOLA in 2002 for the Land Monitor Project, was merged with the original DEM. Slope, aspect, plan curvature and drainage directions were computed from the DEM using the MAGIC System. In areas where drainage lines were not strongly defined by the topography, and mapping of streams was available from DOLA topographic maps, drainage was constrained to follow the mapped streams.

A4.1.2 Evapotranspiration equations

The tree evapotranspiration demand function initially used was similar to that used by the WEC-C physical balance model used in the Northern Jarrah Forest (Boniecka & Croton 2004; Croton et al. 2005).

$$PT_{day} = LAI \times [A \times \ln(E) + B] \qquad \text{if } 0 < E < 1 \qquad \textit{Equation A4.1a}$$

$$PT_{day} = LAI \times E \times B \qquad \text{if } 0 < E < 1 \qquad \textit{Equation A4.1b}$$

Where: PT_{day} = daily potential evapotranspiration
E = daily pan evaporation (without bird guard) in mm
A = 0.7
B = 0.6 (constants A and B are the same as used in Yarragil 4X catchment)
LAI = Leaf Area Index

Average annual potential evapotranspiration was calculated by applying Equation A4.1 to the daily pan-evaporation records at Dwellingup from 1942 to 2002. For sites other than Dwellingup, the Dwellingup daily record was factored by the ratio of the average annual pan evaporation at the site to that at Dwellingup, based on the map of isopleths published in Luke et al. (1988). By evaluating a number of hypothetical sites, Equation A4.2 was developed by fitting an equation to the graph of annual potential evapotranspiration versus annual pan evaporation. (The derivation of Equation A4.2 is in a spreadsheet called Standard_Evap_1942_2002.xls.) This provided a simpler calculation of annual potential evapotranspiration, which was then applied to every cell of a gridded map of annual pan evaporation that had been prepared by interpolating the map of isopleths published in Luke et al. (1988).

$$PT_{year} = \alpha \times LAI \times [194 \ln(AE/1560) + 354] \qquad \textit{Equation A4.2}$$

Where: PT_{year} = annual potential evapotranspiration
AE = annual pan evaporation (with bird guard) in mm
α = factor set by model calibration

After the initial calibration runs of the model, it was necessary to multiply the potential evapotranspiration equation by a non-linear factor (α) that varied from 1 in the west of the catchment to 5.5 in the east (Fig. A4.1). The vegetation in the east had LAI as low as 0.4, while the LAI of forested catchments in the west could be as high as 2.2. This is because the vegetation in the west is predominantly jarrah with 75% canopy cover, while in the east it is predominantly wandoo with 20% canopy cover (Section 2.7.1) The pine plantations in the west of the Mundaring catchment had LAI as high as 3.0. Even though the LAI in the east is very low, it still has mean annual runoff as low as 1% of the rainfall. The non-linear factor was necessary to give realistic evapotranspiration of the forest in the east. The non-linear evapotranspiration parameter (α) was calibrated to a value of 1.1 for five subcatchments with mean annual rainfall 725–800 mm, probably due to the occurrence of pine plantations with a higher LAI in these catchments.

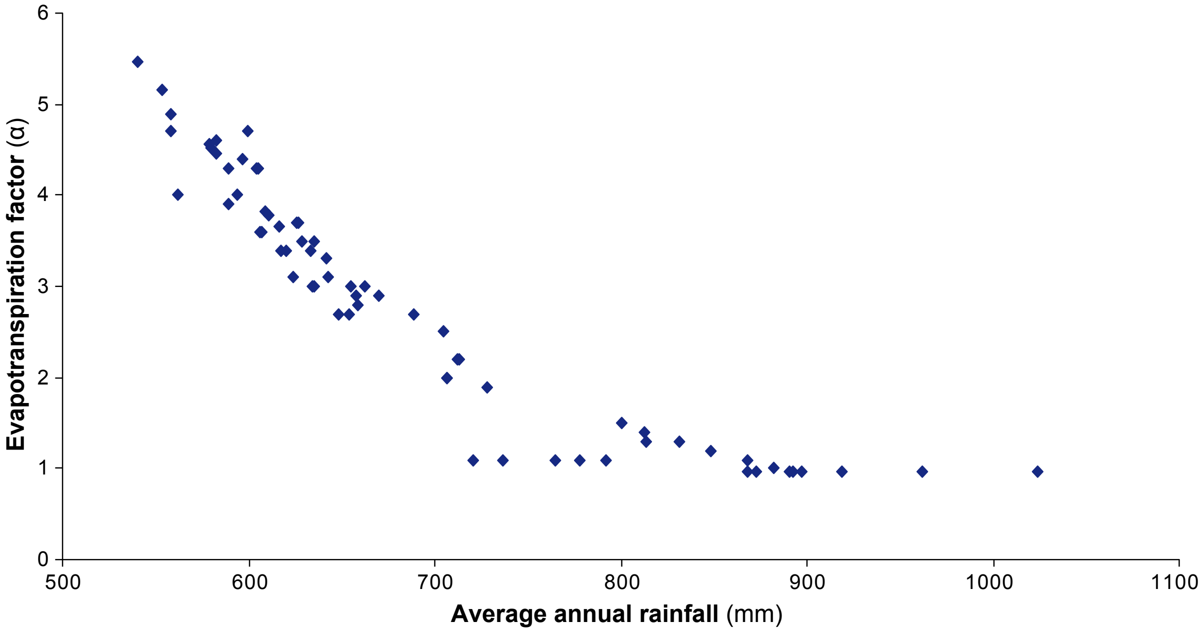


Figure A4.1 Non-linear evapotranspiration factor (α) varying with average annual rainfall across the Mundaring catchment

A4.1.3 Leaf Area Index (LAI)

The normalised mid-summer Landsat satellite scene for 2002 (from the Land Monitor Project) was used to estimate the LAI in the Mundaring catchment, not the summer 2003 scene that had a large burnt area in the east. The LAI is necessary for estimating the evapotranspiration of the forest. An adjusted normalised difference vegetation index (adjusted NDVI) was used to estimate the LAI. The standard NDVI index formula is given in Equation A4.3.

NDVI = (TM Band 4 – TM Band 3)/(TM B and 4 + TM Band 3) *Equation A4.3*

Where: TM Bands 3 and 4 are reflectance values from the Landsat Thematic Mapper for the mid-summer 2002 normalised scene.

It is assumed in the standard formula that total shade occurs where ‘TM Band 4’ = ‘TM Band 3’ = 0, that zero vegetation occurs where ‘TM Band 4’ = ‘TM Band 3’, and 100% green vegetation occurs where 'TM Band 3' = 0 (% vegetation is undetermined where 'TM Band 4' = 0, but is assumed zero). When the actual TM data have values for total shade and zero vegetation that differ from those assumed in the standard formula, an equivalent formula, called the 'adjusted NDVI' that effectively linearly transforms the actual values to comply with the standard assumptions, can be prepared. In the formula for LAI (Equation A4.4), the adjusted NDVI had the shade point at 'TM Band 4' = 20 and 'TM Band 3' = 16, and the point 'TM Band 4' = 143 and 'TM Band 3' = 149 was assumed to lie on the line of zero vegetation. These values were determined by examination of the scatter diagram of TM Band 3 versus TM Band 4 (Boniecka 2002). The formula for LAI was established by regression of NDVI against LAI measured using hemispherical photographs at a number of sites in the Northern Jarrah Forest (Wallace 1996), with a further correction factor (0.96) to account for imperfect standardisation of the Landsat TM data from 2002 to 1996 (Equation A4.4). This process is more fully documented in (Mauger 2003).

$$LAI_{2002} = 0.048 \times (Adjusted\ NDVI_{2002})/0.96 – 0.74 \qquad \textit{Equation A4.4}$$

A4.1.4 Pasture evapotranspiration equations

Annual pasture

Annual Transpiration of pasture was set by assuming for each month a growth cycle represented by a coefficient proportional to a nominated peak LAI. The appropriate peak LAI was derived from calibration of the runoff against streamflow (Mauger 1996, p. 7). The monthly transpiration of pasture ($MT_{(P)}$) is defined by Equation A4.5.

$$MT_{(P)} = 0.352 \times EP_{(M)} \times LAI \qquad \textit{Equation A4.5}$$

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

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

LAI is the area of leaf surface area within a unit area on the ground. The maximum pasture LAI (LAI(max)) was set during calibration to be 1.95

Extensive work on annual pasture has allowed a good understanding on how the LAI parameter changes during the growth cycle (Nulsen & Baxter 1986). The LAI of annual pasture is set to change monthly to represent its annual growth cycle. The LAI of annual pasture is zero in summer and reaches a maximum of 1 in winter (Table A4.1).

Table A4.1 Growth factors for annual pasture

Month	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Growth factor	0	0	0	0.2	0.5	1	1	1	1	0.8	0.4	0.3

Deep-rooted perennial pasture

Deep-rooted perennial pasture was assigned a constant monthly value for LAI of 1.95, which is the same as the maximum annual pasture LAI in winter. In practice, the plants may wither if soil moisture is depleted, but the model assumes that once soil moisture is available they can quickly re-establish. The deep-rooted perennials were assumed to have a rooting depth of 5 m, which means that, when the upper layer is dry, they can draw water from the clay layer if it is available within the nominated depth. Water use from the clay layer was assumed to be at 60% of the rate in the upper layer to account for the stress of drawing it from depth.

A4.1.5 Rainfall and saltfall

A total of 37 pluviometers within and around the catchment was selected for creating long-term daily rainfall series for each subcatchment. The daily rainfall series at the centroid of each subcatchment was calculated on its distance from the nearest three pluviometers (Dean & Snyder 1977) and used to calculate the average monthly rainfall for 1986–98, 1995 and 1990–2002. Saltfall (dry fallout and salt precipitated in rainfall) was estimated using the relationship of Hingston & Gailitis (1976) between salt concentration in rain and distance from the coast in Western Australia, and converted to TDS (Mayer et al. 2005, p. 92). It varied from 11.1 in the west to 7.9 mg/L in the east of the catchment. The salt input from the salt concentration was estimated by using the average annual rainfall at the centroid of the subcatchment and the subcatchment area.

A4.1.6 MAGIC parameters

The parameters used in the calibration of the Helena catchment and used in all modelled scenarios are outlined below. They maybe useful for future MAGIC modelling of this or a similar catchment.

1. The maximum annual pasture LAI (parameter *CLAI*) was set to 1.95.
2. The swampy areas with low LAI were assumed to behave like perennial pastures with an LAI = 0.00363 × annual mean rainfall (parameter *DPLAI*) with a rooting depth of 5 m. LAI varied from 1.9 to 3.7. The swampy areas tended to correspond to the areas identified as pasture inside the forested areas and were derived from the 2002 Landsat scene.
3. Potential tree transpiration was calculated using *Equation A4.2*. The non-linear α varied from 1 in the west to 5.5 in the east (Fig. A4.1).
4. The soil–landscape system mapping and database (Department of Agriculture 2004) were used to set the top layer parameters of permeability (K), thickness (*depth*), and moisture content between field capacity and wilting point (*Dry*). At field capacity, water will not drain through the soil but is still available for plant use. At wilting point, there is no more water for plants to use. The database gave the percentages of each soil group within a soil–landscape system mapping unit, and the properties of the soil groups in the A and B horizons. The top layer was taken as the sum of the A and B horizons. The values of properties to use within a mapping unit were calculated as area-weighted averages of the thickness-weighted averages of the top layer, using the spreadsheet *MUWASoilGrps_Helena.xls*. K varied from 0.12 to 0.44 m/month. *Depth* varied from 0.4 to 1.27 m. *Dry* is on average 20 m^3 (i.e. about 32 mm over the 625 m^2 cell).
5. The transmissivity of the bottom layer including the clay and saprolite layers (*KD* m^2/yr), the vertical permeability of the middle layer (*VC* m/yr), the water storage capacity of the clay layer (*CLAYVOL* m^3) and the parameter *minclay* (m^3) varied according to the rock

type. (The significance of *minclay* is that water deficit in the middle layer in excess of *minclay* may be made up by water from the bottom layer to the extent that such water is available.) All of these parameters were calculated in maps in Rascal project *heltopo.ras* by using the command file *setmapsnew.dat*. A map was used to distinguish between surficial, sedimentary and weathered bedrock (Section 2.6). The porosity used was 0.2. The minimum depth of clay used for the parameter *minclay* was 10 m for clay and 0 m for sedimentary units.

6. The limiting rate at which the top layer will recharge the clay layer when the clay is unsaturated (*Clayinf* m^3/month per cell) was set to 18, i.e. 29 mm/month. *Clayinf* is not usually varied during calibration. It has low sensitivity because most of the time the water available to move would be less than *Clayinf*.
7. When the clay is saturated, water from the top layer passes through the clay (by preferred pathways) to the bottom layer at a maximum rate given by parameter *Claytrans*. *Claytrans* was 0.7 m^3/month (11 mm/month) for weathered bedrock units and 18 m^3/month (29 mm/month), the same as *Clayinf*, for surficial units.
8. The salt load in the streams from cleared areas is estimated to be the salt from rain that reaches the stream plus the salt output from groundwater discharge. The salt load parameters used for subcatchments in each gauged catchment are shown in Table A4.2. The salt output/input ratio for the Darkin River gauging station was taken from Table 3.1 since there was no clearing in this catchment downstream of Darkin Swamp. It was assumed that Darkin Swamp held any salt output from the farm upstream.

Table A4.2 MAGIC salt load parameters

Gauging station	**Salt from rain multiplier**	**Groundwater salinity** (mg/L)
Ngangaguringuring	0.57	5000
Helena Brook	0.75	5000
Poison Lease	0.75	5000
Darkin River	0.2	3000
Little Darkin River	0.57	2000
Pickering Brook	0.75	2000
Rushy Creek	0.75	3000

A4.2 The LUCICAT model

LUCICAT is a distributed conceptual catchment hydrology model. A large catchment is divided into subcatchments that incorporate the spatial distribution of rainfall, pan evaporation, soil salt storage and land use. Each subcatchment is represented by the ‘open book’ approach and a fundamental building-block model is applied. Catchment attributes such as soil depth, rainfall, pan evaporation, land-use change, groundwater level, salt storage are incorporated into the fundamental model (Bari & Smettem 2004, 2005, 2006; Beverley et al. 2005). The fundamental building-block model consists of (i) unsaturated soil module (Dry, Wet and Subsurface unsaturated stores), (ii) saturated groundwater module, and (iii) a streamzone module (Fig. A4.2).

Flow generated from each subcatchment is routed downstream based on open channel hydraulics through a detailed channel and stream network (Fig. 2.2). A particular segment of the channel may lose water through evaporation and infiltration and become dry if the groundwater system does not contribute to the stream. The model can report streamflow and salinity at any of the nominated channel nodes.

The Mundaring catchment was divided into 66 subcatchments ranging from 4.7 to 41 km^2 (Fig. 4.5). All the spatially variable attributes of the catchment are incorporated into the model.

A4.2.1 Data preparation and LUCICAT model set up

A4.2.1.1 Rainfall and saltfall

The average (1975–2002) annual rainfall ranged from 1035 mm in the west to 550 mm in the east. Spatial average salt concentration of the rainfall was estimated to be 7.5 mg/L, which is lower than the 7.9–11.1 mg/L used by MAGIC (A4.1.4) based on Mayer et al. (2005, p. 92).

A4.2.1.2 Pan evaporation

With no pan evaporation data recorded within the Mundaring catchment, data at the centroid of each subcatchment was adopted from Luke et al. (1988) and ranged from 1940 to 1770 mm. Annual pan evaporation was converted to daily using a harmonic function.

A4.2.1.3 Salt storage

A strong correlation of increasing soil salt storage with decreasing rainfall has been well-established for the south-west of WA (Johnston 1987; Stokes et al. 1980). The salt storage of the highly conductive topsoil (generally 2–3 m thick) is very low in the south-west, and generally in the order of 0.5 to 1.2 kg/m^3. Most of the salt is stored in the unsaturated clay profile. In the Mundaring catchment, a number of soil salt storage measurements were undertaken from the experimental catchments (Stokes & Batini 1985). Given the limited data, the salt content and mean annual relationship developed for the Collie River catchment was used.

A4.2.1.4 Land-use history

When the CAWS Act was legislated in 1978, about 3% of the catchment area had been already cleared for agricultural development (Fig. 3.4a). The land-use history for the subcatchments for the whole period of simulation (1964–2003) was consolidated as a 'land-use history' file. If part of a subcatchment was cleared, a concept of land-use fractions was used to reflect the changes.

A4.2.2 LUCICAT model calibration

The LUCICAT model is easy to calibrate (Bari & Smettem 2003, 2004) as most of the parameters remain 'fixed' once calibrated in one catchment with exception of 7 physically meaningful parameters which may vary between catchments. The range of these parameter values and their ranking in terms of sensitivity are shown in Table A4.3. The most sensitive parameter (ia) – the relationship between the catchment-wide lateral conductivity of the topsoil and moisture content – ranged from 2 to 3.15 (Table A4.3). The second most sensitive parameter vertical conductivity of the upper layer (K_{uv}) which controls the percolation to the deep unsaturated profile, ranged between 15.29 and 27.185 mm day^{-1} for other applications. The other 'variable' parameters are the topsoil depth (d) and its spatial distribution of water holding capacity (b,c), and the average lateral conductivity (K_{ll}) of the aquifer (Table A4.3). The model was transferred with same parameter set from its successful application to the Kent River catchment (De Silva et al. 2007). A few of the parameters were then adjusted for best fit. However, one parameter (α_t) controlling the evapotranspiration and initially set at 1, was varied to 1.5–5.5 across the catchment.

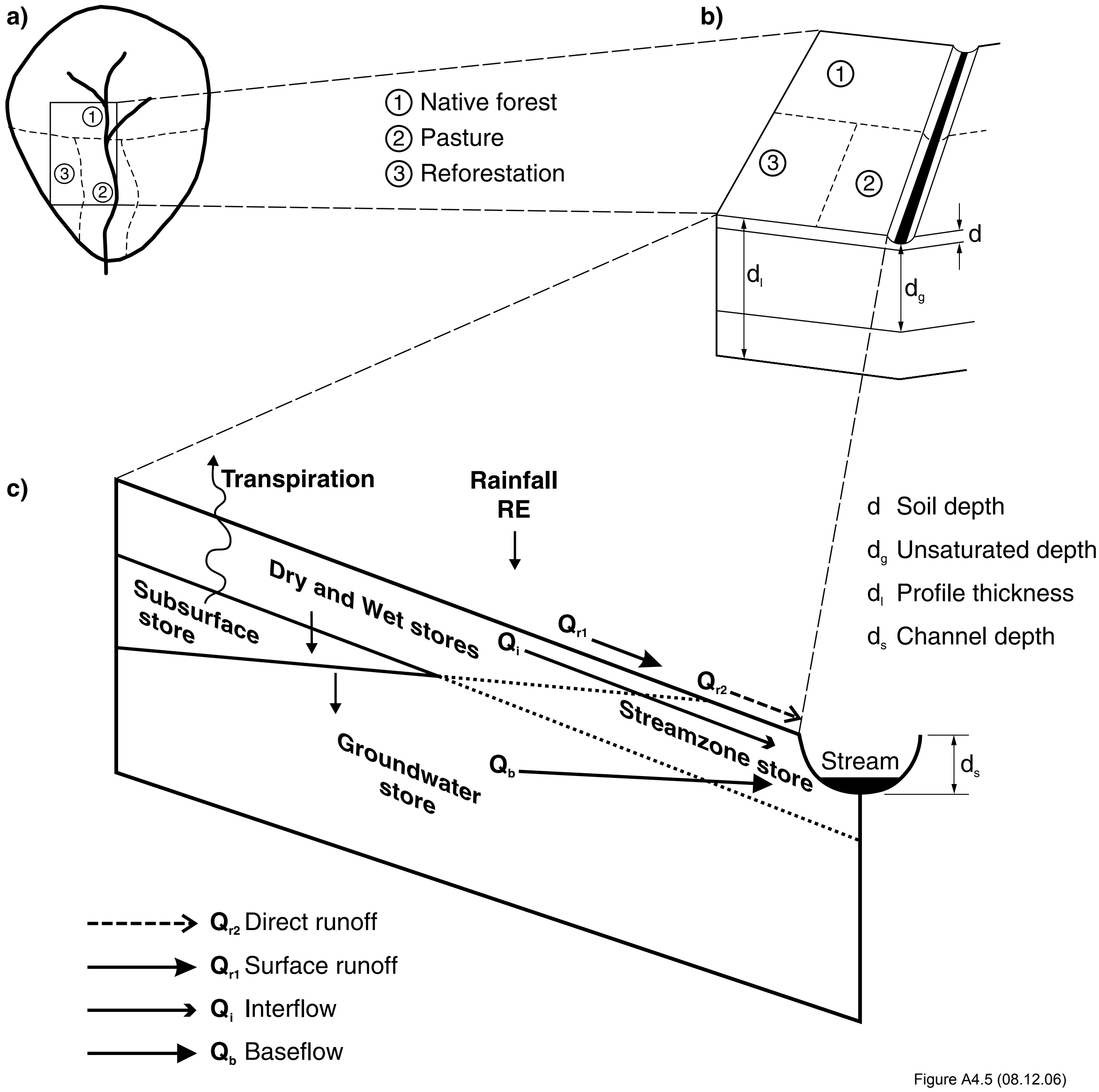


Figure A4.2 Schematic of a) subcatchment b) 'open book' representation c) hydrological processes

Table A4.3 Initial adopted and final values of the 'variable' parameter set

Parameter	Unit	Range	Rank	Most likely	Upper Kent	Mundaring
ia	-	2.0–3.15	1	2.3	2.0	1.8
K_{uv}	(mm/day)	15.29–27.185	2	27.185	27.185	27.185
c	-	0.256–0.56	3	0.256	0.125	0.125
d	(mm)	1900–2500	4	2500	1550–2500	1650–2450
K_{ll}	(mm/day)	400–1500	5	500	350	350
b	-	0.123–0.625	6	0.256	0.125	0.125
C_u	-	0.0042–0.0263	7	0.0163	0.0063	0.0063

After satisfactory matching of the observed and predicted daily flows, the daily stream salinity and salt load were calibrated. It was not possible to estimate the initial salt storage of the streamzone from observed data. Therefore, the model was run a few times and the final value of the streamzone salt store was taken as the initial value for each of the runs. Then the lateral hydraulic conductivity of the deep aquifer (K_{ll}) was adjusted for most satisfactory matching of the observed and predicted flows, salinities, salt loads and groundwater trends. The 'final' parameters and a comparison of the parameters for the Kent River and Mundaring catchments are given in Table A4.3.

A4.2.2.1 Groundwater system

Groundwater in the south-west of Western Australia is well-connected to the stream channel in the high-rainfall zone, but about 15–20 m below the stream channel in the low-rainfall zone (unless dryland salinity has developed, in which case it will be connected to the stream channel). Initial groundwater levels for each of the forested subcatchments were developed based on the records and regional trend. Estimation of the initial groundwater levels beneath the cleared areas was difficult. There were some studies of trends in groundwater level, particularly in the cleared areas of the Mundaring catchment (Bari & Boyd 1993). There is experimental evidence elsewhere in the south-west showing the rate of change in groundwater level following land-use changes (Mauger et al. 2001; Bari 1998). Based on those data and land-use history, initial groundwater levels beneath the cleared areas were estimated and incorporated into the model. Typical examples of the predicted groundwater levels under native forest (21, 11) and cleared (43) subcatchments are shown in Figure A4.3.

A4.2.2.2 Annual streamflow, salinity and load

The LUCICAT-predicted daily streamflows and salinities (summed to give monthly and annual yields, salt loads and flow-weighted annual salinities) showed good agreement to the data from all gauging stations. Annual observed and predicted runoffs for three selected gauging stations are shown in Figure 4.4. There are three high-flow years during the period of study. At the Poison Lease gauging station the predicted annual flow was slightly higher than observed in 1996 and 1999 (Fig. 4.4a). LUCICAT generally underpredicted the low-flow years, which resulted in the 10th percentile annual flow lower than observed in most cases

(Tables 4.2 & 4.3). The observed and predicted annual salt loads were 77 and 80 kg/ha respectively. At Poison Lease, the observed and predicted mean annual runoffs were 8.6 and 9.8 mm respectively, resulting in an underprediction of 14%. For the Darkin River, observed and predicted runoffs were very similar. The model grossly overpredicted the high and low flow years at Ngangaguringuring (Fig. 4.4c). The coefficient of variation of the predicted annual runoff was greater than of the observed (Tables 4.2 & 4.3). At the Mundaring Weir, the predicted annual inflow compared very well with the data from the reverse water-balance calculation for the reservoir (Fig. 4.4d). At the dam wall, the mean (1992–98) predicted and observed annual runoffs were 12.8 and 12.6 mm respectively (Tables 4.2 & 4.3).

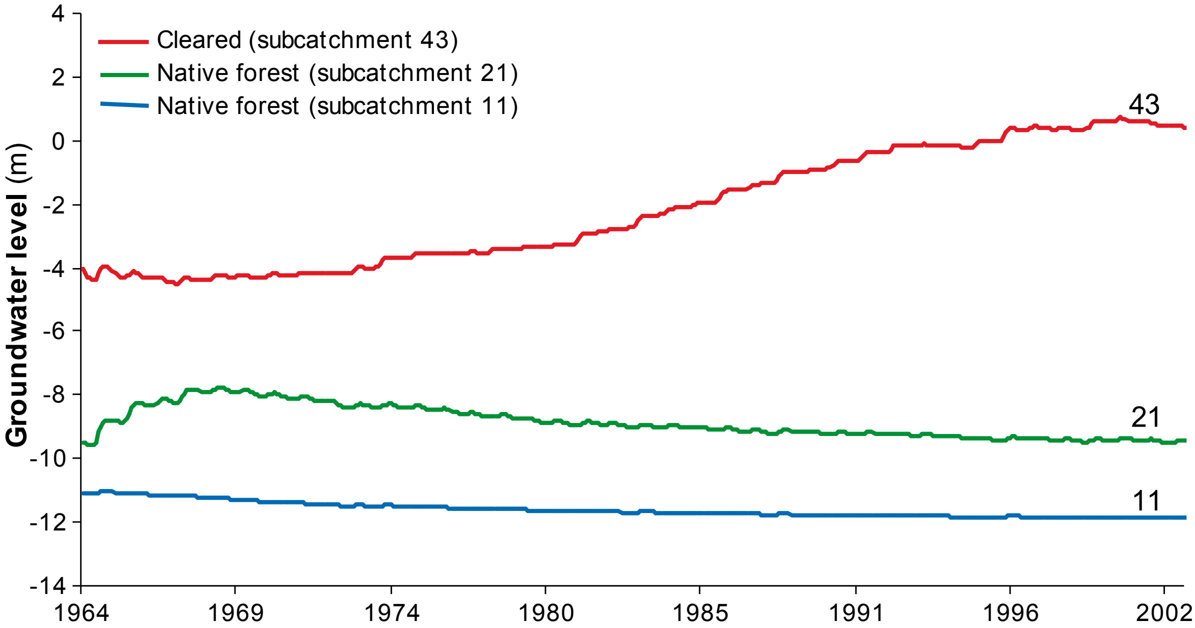


Figure A4.3 Predicted groundwater levels in cleared and forested subcatchments

The simulated mean annual streamflows (1990–2002) for all gauging stations were up to 13% greater than the observed flows (Fig. 4.3). The predicted annual low (10th percentile) flows were generally lower and the predicted high (90th percentile) flows were generally greater than observed. As a result, the coefficients of variation (CVs) of the predicted annual streamflow were generally greater (Tables 4.2 & 4.3). However, the coefficients of determination (R^2) between all the gauging stations ranged from 0.7 to 0.94. Chiew and McMahon (1993) suggested that if the ratio of the mean simulated flow to the mean recorded flow ranges 90–110% and the R^2 is above 0.8 then the model calibration and predictions are 'always acceptable'.

At all the gauging stations, the observed and predicted annual salinities and salt loads matched well (Fig. 4.3b). The predicted annual salinities were compared, for most of the gauging stations, to the sampled salinities. For the Rushy Creek gauging station, there appears to be a declining trend in annual salinity which was generally predicted well (Fig. A4.4a). The predicted annual salinities, particularly for the low-flow years, were greater than observed at Poison Lease. However, during the period of continuous stream salinity record (1993–2003), mean annual observed and predicted salt discharges at Poison Lease were 73 and 87 kg/ha respectively. The mean annual observed salinity at the Little Darkin River was approximately 225 mg/L and matched the predicted salinity reasonably well (Fig. A4.4c). The mean annual observed salinity at the Pickering Brook gauging station was about 250 mg/L and predicted and recorded annual salinities generally matched well (Fig. A4.4d). Due to local geology, the Ngangaguringuring gauging station flows the whole year. The baseflow salinity was 2000–3000 mg/L and was occasionally overpredicted by LUCICAT.

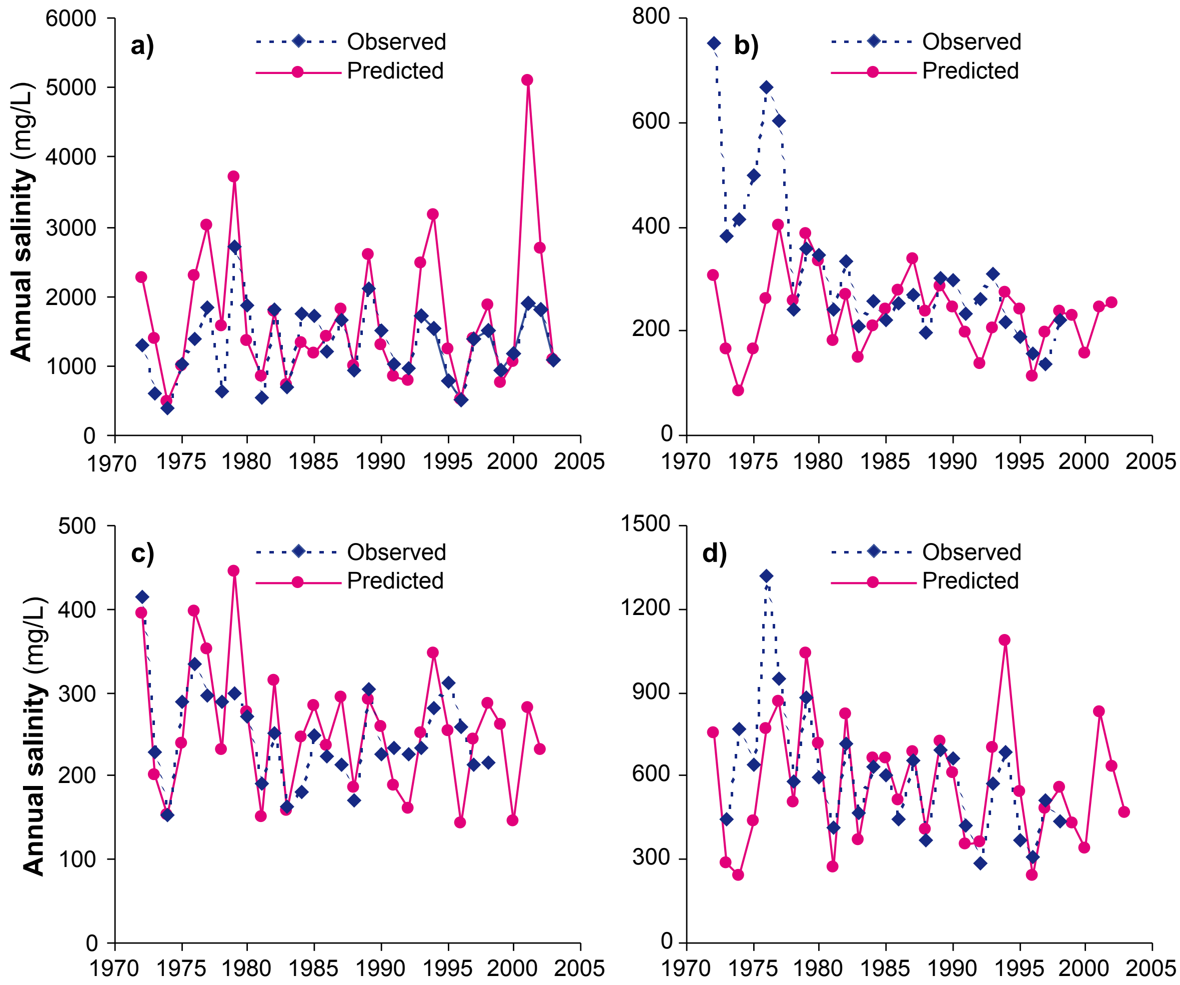


Figure A4.4 Annual observed and predicted stream salinities at a) Poison Lease b) Little Darkin River c) Pickering Brook and d) Rushy Creek

A4.2.2.3 Monthly flow and salt load

For the whole simulation period the relationships between observed and predicted monthly streamflows and salt loads for most of the gauging stations are very strong. The LUCICAT model sometimes overpredicted monthly streamflow for the months with very high streamflow. This overprediction was consistent at most of the gauging stations. At Poison Lease, the monthly salt load was overpredicted when there was very little streamflow (Fig. A4.5). A constrained linear relationship between the monthly observed and modelled streamflows gives a R^2 of 0.87. Overall, the coefficients of determination (R^2) between the observed and predicted monthly streamflows for all the gauging stations ranged from 0.78 to 0.93. Similar monthly relationships were also obtained when LUCICAT and LASCAM models were applied to other catchments in Western Australia (Sivapalan et al. 1996; Berti et al. 2004; Bari & Senatherajah 2005; De Silva et al. 2007).

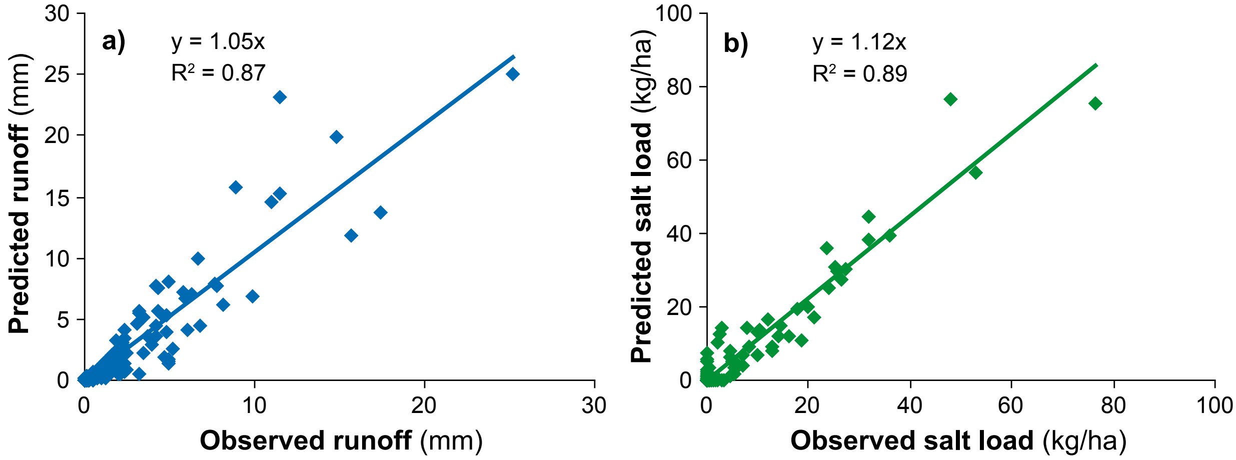


Figure A4.5 Monthly observed and predicted a) runoff and b) salt load at Poison Lease

A4.2.2.4 Daily runoff, salinity and load

Daily simulated and observed streamflow hydrographs matched reasonably well for most of the gauging stations. In the average-flow year of 2000, the spatial average rainfall at Poison Lease was 590 mm. Daily streamflow was dominated by surface runoff and interflow during October to May (Fig. A4.6a). Daily stream salinity was in the range 5–6000 mg/L (Fig. A4.6b). The model predicted the flow very well, but the early and late predicted daily salinities were higher than observed ones. Daily observed stream salinity increased to 10 000 mg/L in April–June when the upper part of the catchment began flushing salts left on the soil surface by the evaporation of groundwater. The model slightly underpredicted the daily salinity, but matches the observed salinity (Fig. A4.6b). The model also slightly overpredicted the maximum daily (peak) flow within the year 2000. The predicted and observed maximum runoffs were 0.0.42 and 0.39 mm respectively. The daily observed and predicted runoffs for the other gauging stations were also well matched except for some peaks and recessions.

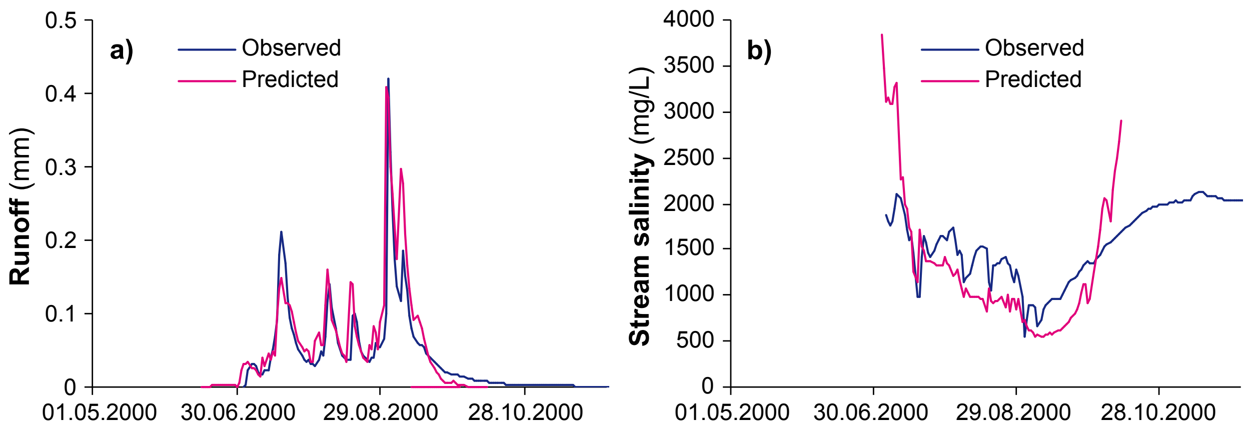


Figure A4.6 Daily observed and predicted a) runoff and b) salinity at Poison Lease

The Darkin River gauging station is in the eastern drier part of the catchment. The mean annual runoff rate is 5.2 mm or only 0.82% of rainfall. The predicted and observed daily runoffs and salinities generally matched well. For one of the lowest annual runoffs recorded – in (August to October) 1997 – the predicted and observed daily runoffs matched very well in terms of flow duration, peaks and recessions (Fig. A4.7a) as did predicted daily stream salinities with salinity sample data (Fig. A4.7b).

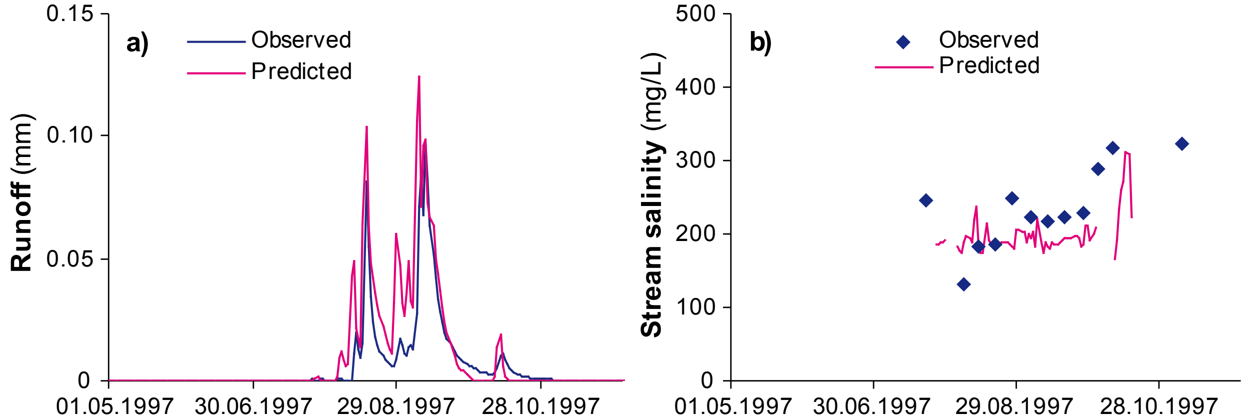


Figure A4.7 Daily observed and predicted a) runoff and b) salinity at Darkin River

The Pickering Brook gauging station is in the western part of the catchment where the runoff rate is high. The daily salinity of the Rushy Creek catchment was more than 500 mg/L at the onset of winter and summer. The LUCICAT predictions matched the daily salinity of Rushy Creek. The observed daily salinities of the other gauging stations (e.g. Darkin River, Pickering Brook and Helena Brook) were potable and reasonably predicted by the LUCICAT model for 1979–2003 (Figs A4.7 & A4.8). The predicted daily stream salinities at Poison Lease were less than observed for the representative year 2000 (Fig. A4.6) but the daily streamflows and salt loads matched well. The representative year was chosen because it had a mid-range rainfall and runoff.

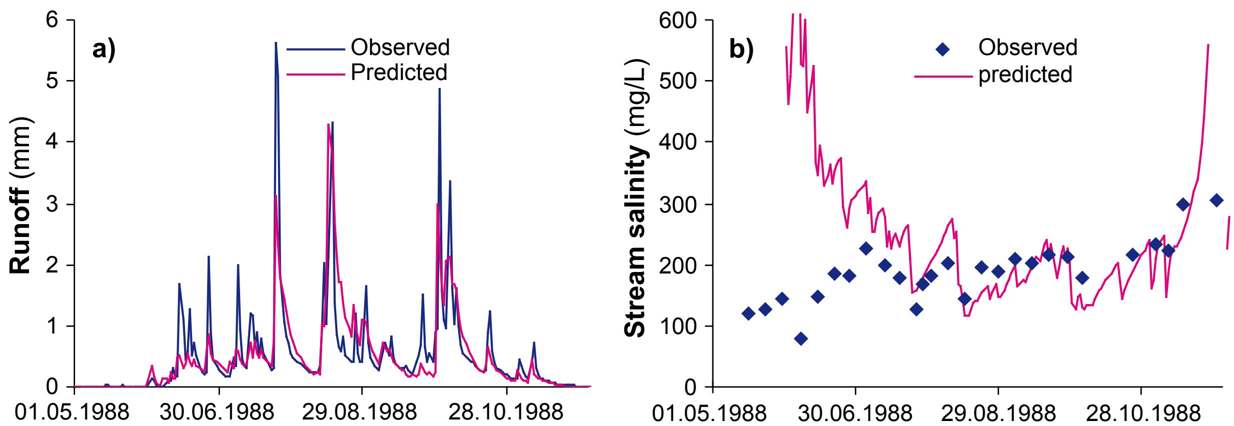


Figure A4.8 Daily observed and predicted a) runoff and b) salinity at Pickering Brook

A4.2.2.5 Spatial distribution of runoff salinity and load

The distribution and sources of runoff, salt load and salinity predicted mean for the period 1990–2002 (Figs 4.5, A4.9 & A4.10). The annual runoff generally reflects the distribution of rainfall, land cover (Fig. 2.9), and to a lesser extent slope. Subcatchments with greater proportions of cleared areas generate more runoff than their uncleared or less cleared counterparts. The sources of highest runoff, more than 110 mm/yr, were the western, wetter parts of the catchment, while the eastern drier part of the catchment with insignificant clearing had runoff less of than 1 mm/yr (Fig. A4.9).

Mean annual stream salinities across the catchment varied from 90 to 4500 mg/L (Fig. 4.5). Higher salinity was generally associated with lower rainfall and a relatively larger proportion of the catchment area cleared. For example, the mean annual salinity of subcatchment 51, with no significant clearing, was 900 mg/L, whereas the salinity of subcatchment 44 with 15% clearing was 2300 mg/L (Fig. 4.5).

The sources of salt load varied with the proportion of the catchment area cleared and the annual rainfall. Subcatchments with more cleared areas tended to generate bigger salt loads (Fig. A4.10). Predicted mean annual salt loads were between 1500 and 300 kg/ha for the eastern, low-rainfall subcatchments with greater proportions of cleared areas, but only from 1 to 100 kg/ha for the drier uncleared eastern parts of the catchment (Fig. A4.10).

Table A4.4 Calibration case for MAGIC model — 2002 land use with average rainfall for 1986—98

	Management unit					Gauging station						Reservoir inflow	
	Ngangagur-inguring	Poison Lease	Darkin Swamp	Beraking Brook	Helena West	Helena Brook	Poison Lease [a]	Darkin River	Little Darkin River	Pickering Brook	Rushy Creek	Total the MUs not the GSs	Measured [b] comparison
Total area (km^2)	328	265	274	392	221	27	593	665	37	30	39	1480	
Total cleared area in 2002 (km^2) *	16.5	6.4	15.2	0	0.5	0.1	22.8	15.2	0	0	0.5	38.5	
Total cleared in 2002 (%)	5	2	6	0	0	0	4	2	0	0	1	3	
Average rainfall (mm/yr) (1986–98)	605	714	633	731	903	810	654	541	881	962	880	648	
Streamflow (GL)	2.5	5.1	2.4	3.9	8.4	1.0	7.6	6.3	1.3	1.8	1.5	22.3	17.6
Runoff (mm)	7.7	19	8.7	10	38	36	13	9	34	60	38	15	12
Salt load (kt)	2.9	2.4	0.1	0.5	1.4	0.3	5.3	0.6	0.2	0.2	0.4	7.4	7.8
Stream salinity (mg/L)	1144	480	34	133	171	276	700	96	152	134	259	330	440
Groundwater discharge (GL) *	0.38	0.22	-	-	0.03	0.02	0.60	0	0	0	0.03	0.64	
Groundwater discharge (mm)	1.17	0.82	-	-	0.16	0.77	1.01	0	0	0	0.89	0.43	
Shallow watertable (km^2)	2.4	0.8	1.3	0	0.1	0.04	3.16	1.34	0	0	0.14	4.63	
Shallow watertable (% of total area) *	0.7	0.3	0.5	0	0.1	0.2	0.5	0.2	0	0	0.3	0.3	
Discharge area (km^2) *	1.3	0.3	0.4	0	0	0.02	1.63	0.38	0	0	0.03	2.15	
Modelled discharge area (% of total)	0.4	0.1	0.1	0	0	0.1	0.3	0.1	0	0	0.1	0.1	

[a] Includes Ngangaguringuring GS & MU, and Helena Brook GS

[b] Includes estimated values of streamflow and salt load for some ungauged subcatchments in Helena West MU (Section A3.4)

* Cleared areas on private free/leasehold land only, excluding at least 4 km^2 on government free/leasehold land in Poison Lease MU

Table A4.5 Verification of MAGIC model — 1995 actual rainfall

	Management unit					Gauging station						Reservoir inflow	
	Ngangagur-inguring	Poison Lease	Darkin Swamp	Beraking Brook	Helena West	Helena Brook	Poison Lease [a]	Darkin River	Little Darkin River	Pickering Brook	Rushy Creek	Total the MUs not the GSs	Measured [b] comparison
Total area (km^2)	328	265	274	392	221	27	593	665	37	30	39	1480	
Total cleared area in 2002 (km^2)	16.5	6.4	15.2	0	0.5	0.1	22.8	15.2	0	0	0.5	38.5	
Total cleared in 2002 (%)	5	2	6	0	0	0	4	2	0	0	1	3	
Actual rainfall for 1995 (mm/yr)	657	770	637	729	937	881	707	560	900	982	930	675	
Streamflow (GL)	2.9	6.6	2.8	3.7	6.4	1.0	9.5	6.5	1.1	1.7	1.2	22.4	18.7
Runoff (mm)	8.8	25.0	10.3	9.4	29.1	36.9	16.0	9.7	30.7	57.8	29.7	15.1	12.3
Salt load (kt)	2.7	2.1	0.1	0.5	1.4	0.2	4.8	0.6	0.2	0.2	0.3	6.9	9.0
Stream salinity (mg/L)	954	312	29	142	224	233	506	93	172	141	300	306	481
Groundwater discharge (GL) *	0.34	0.19	-	-	0.02	0.01	0.54	0	0	0	0.02	0.55	
Groundwater discharge (mm)	1.04	0.74	-	-	0.08	0.37	0.90	0	0	0	0.48	0.37	
Shallow watertable (km^2)	2.0	0.6	3.1	0	0.08	0.03	2.63	3.05	0	0	0.08	5.76	
Shallow watertable (% of total area) *	0.6	0.2	1.1	0	0	0.1	0.4	0.5	0	0	0.2	0.4	
Discharge area (km^2) *	0.9	0.6	0.9	0	0	0.01	1.51	0.95	0	0	0.01	2.54	
Modelled discharge area (% of total)	0.3	0.2	0.3	0	0	0	0.3	0.1	0	0	0	0.2	

[a] Includes Ngangaguringuring GS & MU, and Helena Brook GS

[b] Includes estimated values of streamflow and salt load for some ungauged subcatchments in Helena West MU (Section A3.4)

* Cleared areas on private free/leasehold land only, excluding at least 4 km^2 on government free/leasehold land in Poison Lease MU

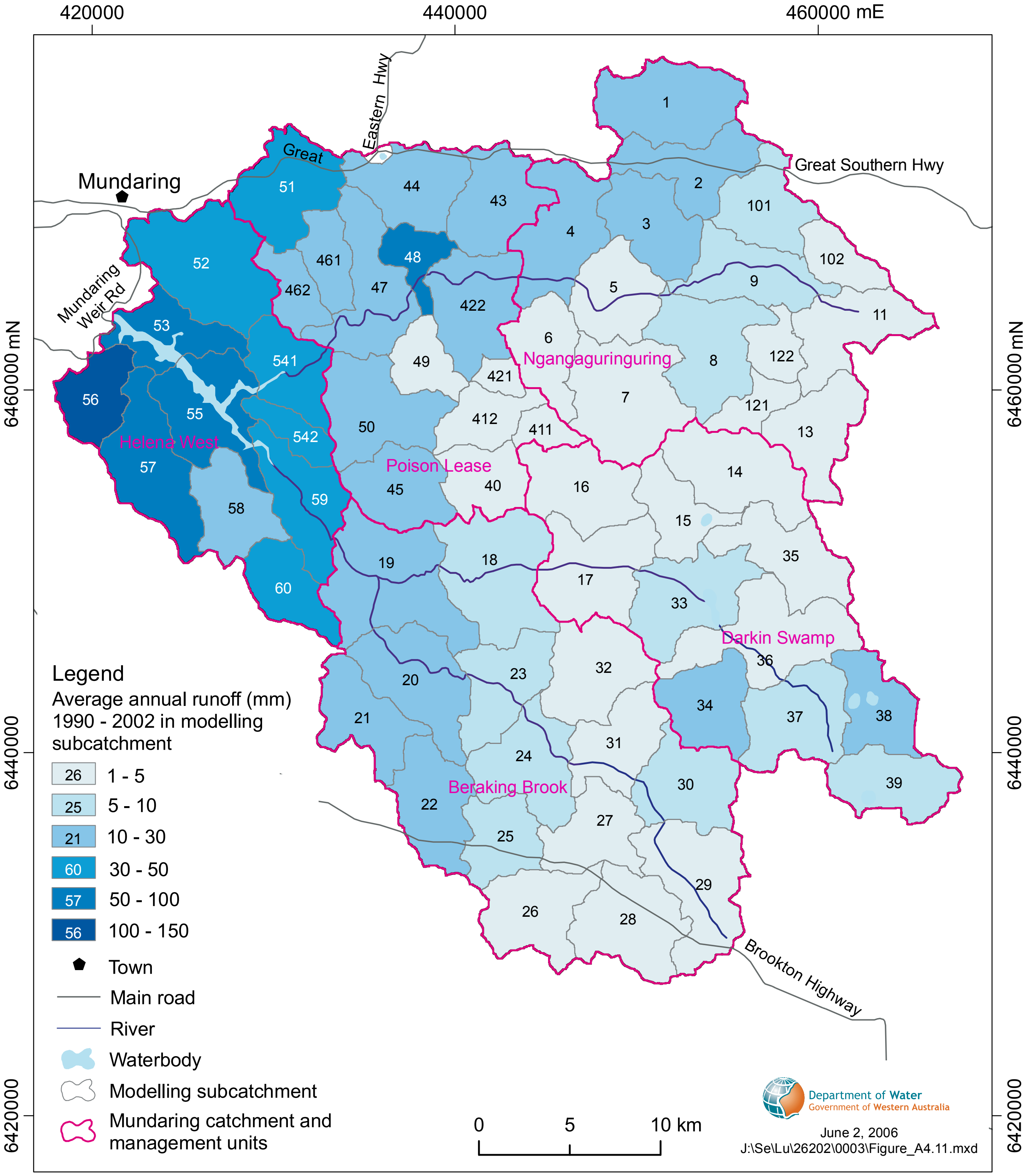


Figure A4.9 Annual subcatchment runoffs

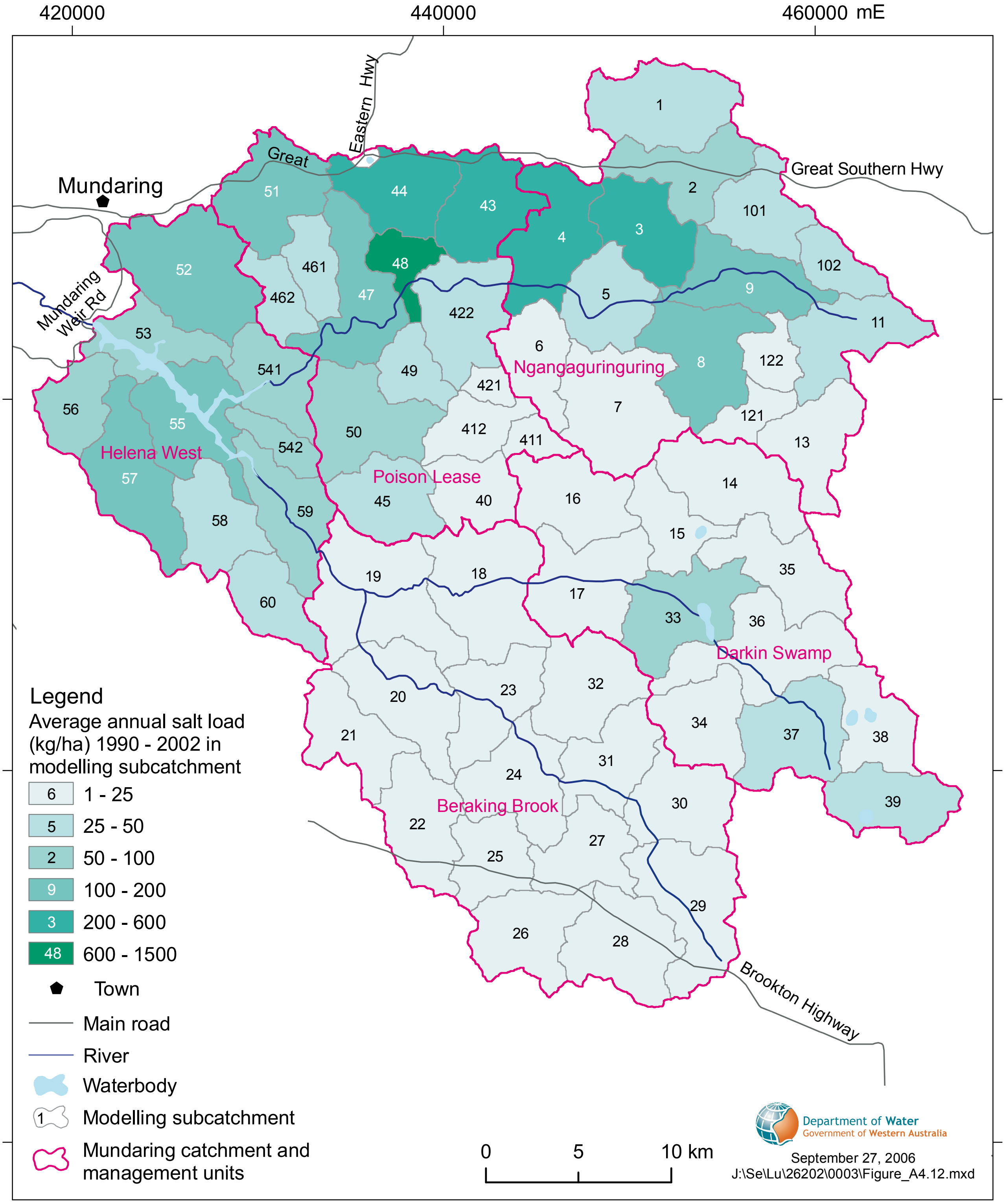


Figure A4.10 Annual subcatchment salt loads

Table A4.6 Calibration case for LUCICAT model

	Management unit					Gauging station						Reservoir inflow
	Ngangagur-inguring	**Poison Lease**	**Darkin Swamp**	**Beraking Brook**	**Helena West**	**Helena Brook**	**Poison Lease [a]**	**Darkin River**	**Little Darkin River**	**Pickering Brook**	**Rushy Creek**	**Total the MUs not the GSs**
Total area (km^2)	328	265	274	392	221	27	593	665	37	30	39	1480
Total cleared area in 2002 (km^2)	16.5	6.4	15.2	0	0.5	0.1	22.8	15.2	0	0	0.5	38.5
Total cleared in 2002 (%)	5	2	6	0	0	0	4	2	0	0	1	3
Rainfall period at equilibrium [b]												
Annual rainfall (mm)	598	707	597	714	905	792	868	962	892	666	647	694
Streamflow (GL)	1.84	3.23	0.32	3.27	10.00	0.80	1.15	1.87	0.86	3.58	5.06	**18.65**
Runoff (mm)	5.6	12.2	1.2	8.3	45.3	29.8	29.6	62.3	23.3	5.4	8.5	12.6
Salt load (kt)	2.61	2.03	0.13	0.54	1.80	0.35	0.45	0.38	0.15	0.67	4.64	**7.11**
Mean salinity (mg/L)	2371	3459	1120	184	219	769	565	245	221	202	1893	**487**
Groundwater discharge to streamzone (mm)	1.4	0	0	0	0	1.3	1.1	0.6	0	0	0.1	0
Baseflow (mm)	0.5	0	0	0	0	0	0	0	0	0	0	0
Representative year at equilibrium [c]												
Annual rainfall (mm)	620	720	578	753	1005	783	936	1100	997	681	665	723
Streamflow (GL)	1.36	2.44	0.04	5.57	17.91	0.62	1.59	4.08	1.42	5.61	3.80	27.32
Runoff (mm)	4.1	9.2	0.1	14.2	81.1	23.0	40.7	135.9	38.5	8.4	6.4	18.5
Salt load (kt)	2.22	2.01	0.02	0.56	2.58	0.32	0.56	0.61	0.24	0.59	4.22	7.39
Mean salinity (mg/L)	1630	822	679	101	144	513	354	150	169	105	1111	270
Groundwater discharge to streamzone (mm)	1.3	0	0	0	0	1.2	1.1	0.5	0	0	0.1	0
Baseflow (mm)	0.5	0	0	0	0	0	0	0	0	0	0	0

[a] Includes Ngangaguringuring GS & MU, and Helena Brook GS
[b] Annual mean for the period 1990–2002
[c] Annual rainfall of 2000

Appendix 5
Management options

A5.1 Application of the MAGIC model to management options

Only Tables A5.1 and A5.2 are positioned within the following text and, for ease of comparison, the remainder are grouped at the end.

A5.1.1 Base case

A base case of the model prepared using the 2002 Landsat scene (Land Monitor 2002) to define tree water-use and to identify areas of annual pasture had a total cleared area of 39 km^2 on private free/leasehold land, a mean reservoir inflow of 18.2 GL/yr with an average annual salinity of 414 mg/L (numbers cited are bolded in the summary of results Table A5.3, but are not rounded in the Appendices as in the main report). The 2002 Landsat scene showed at least 4 km^2 of additional cleared government freehold land in the Poison Lease management unit. This was due to normal forestry activities including the logging of pine plantations.

A5.1.2 Decreased rainfall scenario

This scenario representing a drier climate used the mean rainfall from 1997 to 2003, which was 96% of the mean rainfall (1990–2002) used in the base case. Reservoir inflow reduced to 17.8 GL/yr with salinity 387 mg/L (bolded in the summary of results Table A5.4).

A5.1.3 All 1978 free/leasehold land cleared for annual pasture

In this scenario, all private freehold and leasehold land (196 km^2) was assumed to have been totally cleared and used for annual pasture. Streamflow increased to 21.7 GL/yr and average annual salinity increased to 706 mg/L (bolded in the summary of results Table A5.5).

A5.1.4 Use of deep-rooted perennial pasture

The areas of annual pasture in the base case were assumed to be capable of growing a deep-rooted perennial crop such as lucerne; its LAI was set at the peak LAI of the annual pasture it replaced and kept constant throughout the year. It was assumed that water could be extracted from the soil to 3 m depth, and that stress when drawing water from below the surface layer (about 1.5 m thick) would reduce the potential transpiration by 40%. If the soil within the depth limit dried out, transpiration stopped, but resumed immediately when water became available again. Reservoir inflow reduced to 17.5 GL/yr with salinity 307 mg/L (bolded in the summary of results Table A5.6).

These MAGIC results were adjusted to match the LUCICAT 'base' and 'all change to commercial trees' scenarios (Table 5.1) because the LUCICAT model did not run this scenario. The differences in the results for the MAGIC and LUCICAT models are discussed in Appendix A5.3. The adjustments resulted in a reservoir inflow of 19.7 GL/yr with a salinity of 274 mg/L (bolded in Table A5.1).

A5.1.4.1 Adjusting MAGIC results to match LUCICAT base case

The MAGIC modelling results were adjusted for LUCICAT by:

1. Making a flow adjustment = 'LUCICAT base' streamflow minus the reduction in 'MAGIC perennial' streamflow from 'MAGIC base' multiplied by 0.54
2. Making a salt adjustment = 'LUCICAT base' salt load minus the reduction in 'MAGIC perennial' salt load from 'MAGIC base' multiplied by 1.09
3. Making a salinity adjustment = adjusted salt load divided by adjusted streamflow.

The above adjustments were justified by calculating the decrease in streamflow and salt load between 'all cleared area planted with commercial trees' and the 'base case' for each model for the reservoir inflow. The streamflow reduction was 1.5 GL for LUCICAT and 2.8 GL for MAGIC and was re-scaled by a factor of 1.5/2.8 = 0.54. The salt load reduction was 3.6 kt for LUCICAT and 3.3 kt for MAGIC and was re-scaled by a factor of 3.6/3.3 = 1.09.

Table A5.1 Adjusting MAGIC perennial options to LUCICAT base case

Management option	Streamflow (GL)	Salt load (kt)	Decrease in streamflow scaled (GL)	Adjusted streamflow (GL)	Decrease in salt load scaled (kt)	Adjusted salt load (kt)	Original salinity (mg/L)	Adjusted salinity (mg/L)
LUCICAT								
Base	20.1	7.7	-	-	-	-	499	-
All cleared area planted with commercial trees	18.6	4.1	-	-	-	-	233	-
MAGIC								
Base	18.2	7.5	-	-	-	-	414	-
Deep-rooted perennial pastures	**17.5**	5.4	0.4	**19.7**	2.3	5.4	**307**	**274**
All cleared area planted with commercial trees	15.4	4.2	-	-	-	-	275	-

A5.1.5 Reforestation

To simulate planting trees on all cleared land, any cell that had contained annual pasture or had been assigned some ephemeral grasses within forest was assigned the average LAI for the remaining forested areas in its subcatchment. Reservoir inflow reduced to 15.4 GL/yr with salinity 275 mg/L (Table A5.7).

A5.2 Application of the LUCICAT model to management options

Daily rainfall and pan evaporation data for the period 1980–2003 were repeated for the period 2004–27, taking 1980 as 2004. In the native forest LAI was kept constant using the Landsat satellite 2003 scene (Land Monitor 2003). Except for burning and silvicultural treatment, all the management options were 'implemented' on 1 January 2004. Plant-rooting depth and Leaf Area Index were increased gradually to represent normal plant growth and reached mature forest levels in year 10. The model was run on a daily time-step and then the output was summed to annual for comparison with records. Figure A5.1 shows the annual inflow, salt load and salinity into the Mundaring Reservoir under different land-use management options. If all the cleared area of the catchment was planted with trees, annual inflow salinity to the Mundaring Reservoir would reduce to approximately 230 mg/L by 2025. So, the annual mean for the period 2014–26, which corresponds to the annual rainfall of 1990–2002, was taken for comparison of different management options.

When quoting annual results, the average of mean salinity for each year is used, rather than total load divided by total flow, because it indicates the likely quality available for supply from the reservoir, which uses most of each annual inflow. The average annual salinity is the sum of the annual salinities divided by the number of years.

A5.2.1 Maintain annual pastures (the base case, see 5.2.1)

The LUCICAT model was run to 2027 to predict the streamflow and salinity at equilibrium. Retaining the same subcatchment fractions of pasture and forest, and allowing all recent plantations to grow to maturity built a picture of the catchment at equilibrium with no further action. Daily streamflows, peak flows, salinities and salt loads were similar to the calibration period. Average annual figures also remained similar to the calibration period (Fig. A5.1), with inflow and salinity to the Mundaring Reservoir being 20.1 GL and 500 mg/L respectively. At the Poison Lease gauging station, mean (2014–26 arithmetic mean of the flow-weighted annual) stream salinity is predicted to increase slightly, from 1893 to 2091 mg/L. Predicted mean annual streamflows and salt loads at equilibrium for different management units are detailed in Table A5.8.

A5.2.2 Decreased rainfall (see 5.1.2)

Mean annual rainfall for the entire catchment during 1997–2003 was 660 mm, 4% lower than the 1975–2003 mean of 690 mm. There is speculation that the south-west rainfall regime may be declining further, as there has been no high-rainfall year since 1996 (Fig. 2.3). To estimate the effects of lower rainfall in future, observed rainfall for 1997–2003 was repeated for 2004–27 period, taking 2004 as 1997 rainfall. All other parameters were unchanged.

If the low-rainfall regime continues, the inflow to the Mundaring Reservoir is predicted to decrease from 20.1 to 15.9 GL. The average annual inflow salinity would decrease by 30 to 470 mg/L (Table 5.1) as streamflow from the high-runoff management units would decrease proportionally (Table A5.9).

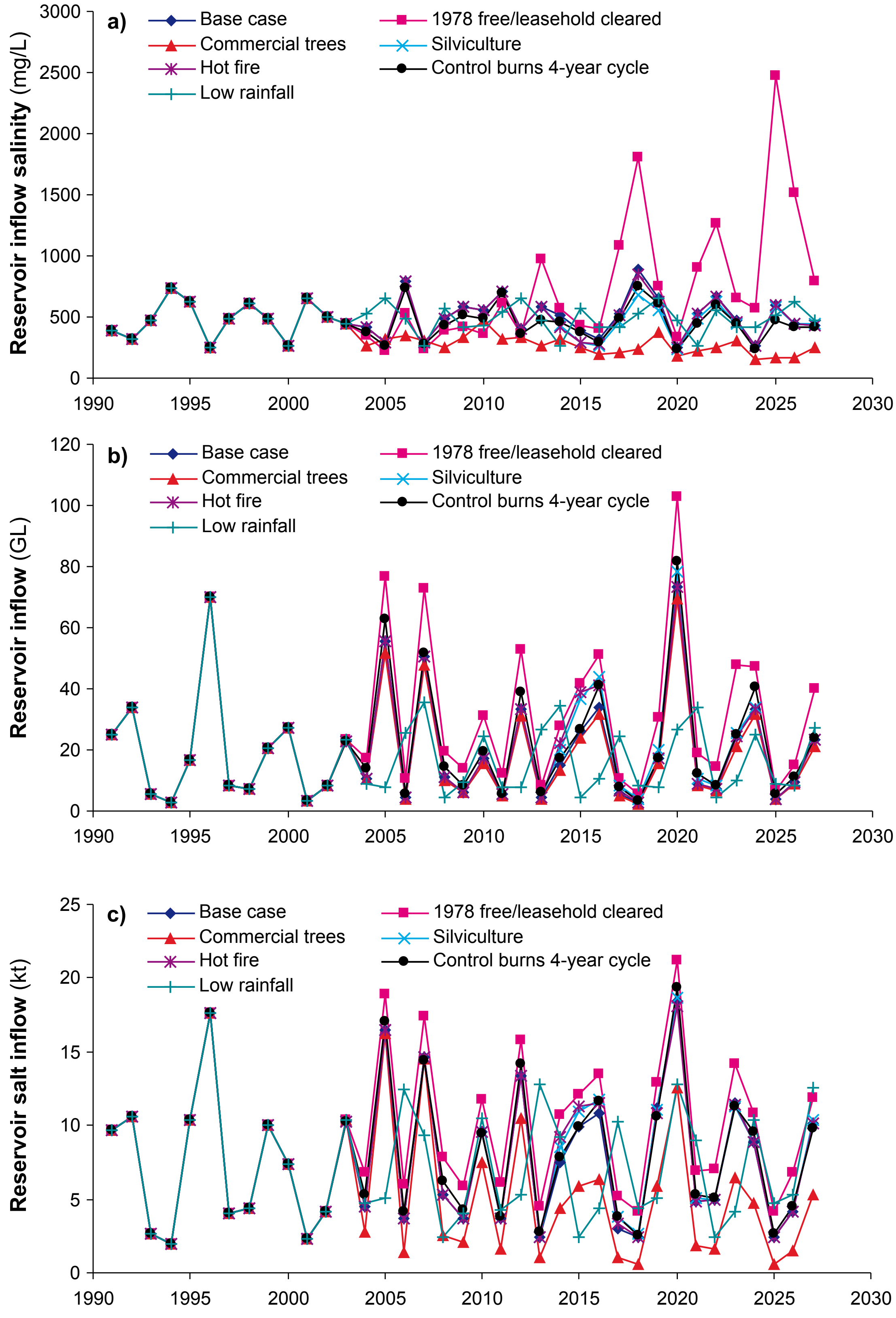


Figure A5.1 LUCICAT-predicted annual reservoir a) inflow salinity b) inflow and c) salt load

A5.2.3 All cleared area planted with (presumably) commercial trees (see 5.2.3)

Replanting 100% of the cleared catchment area with (commercial) trees would reduce mean annual stream salinity at the Poison Lease gauging station from 2091 to 382 mg/L and flow from 5.47 to 4.74 GL (bolded in Table A5.10). The average inflow salinity to the Mundaring Reservoir is predicted to decrease to 233 mg/L (Table 5.1). The conceptual groundwater levels below the replanted areas fall substantially over time, with further reductions possible beyond the modelling time frame. Beneath native forest the groundwater level was practically stable for the whole simulation period. In terms of within-year variations, the peak flow, recession and flow duration all reduced. The groundwater contribution to the streamzone falls to nearly zero and the mean annual salinities of all management units, except Ngangaguringuring, fall below 1000 mg/L (Table A5.10). (About 135 ML or 7% of the 1 ML/d summer flow at Ngangaguringuring does not reach Poison Lease. This leads to a negative salinity shown only as a dash in Table A5.10.) Figure 5.3 shows as the mean annual salinities (2014–26) of the subcatchments under 100% tree planting. The average salinity of subcatchment 4 was the highest (3490 mg/L) because, due to local geology, groundwater discharges to the streamzone throughout the year. The highest salinities (above 500 mg/L) remained in the eastern section of the catchment, where lower rainfall, higher evaporation and low runoff limit flushing of accumulated salts from the streamzone. These areas may need more time to reach their steady-state salinity value.

A5.2.4 All 1978 free/leasehold land cleared for annual pastures (see 5.1.1)

If all the free/leasehold land (in 1978) in the Mundaring catchment was cleared then mean annual stream salinity at the Poison Lease gauging station is predicted to increase to 2777 mg/L (bolded in Table A5.11). (These free/leasehold areas are shown as private freehold, private leasehold and government freehold in Figure 2.4 and coloured on Figure 5.2.) Mean annual inflow and salinity to the Mundaring Reservoir would increase from 20.1 to 31.4 GL and from 500 to 1500 mg/L respectively. Except for Ngangaguringuring, mean annual salinity increases at the other gauging stations will not be significant (Table A5.11). For the Ngangaguringuring, Poison Lease and Darkin Swamp management units, mean salinity is predicted to exceed 1000 mg/L.

A5.2.5 All 2003 free/leasehold land cleared for annual pastures (see 5.2.4)

Some free/leasehold land of 2003 is still forested (dark green in Fig. 5.2) but if it was all cleared for agriculture the mean annual stream salinity at most of the gauging stations would increase (bolded in the summary of results Table A5.12). Mean annual inflow and salinity to the Mundaring Reservoir are predicted to increase from 20.1 to 24.5 GL and from 500 to 600 mg/L respectively. The mean annual stream salinities at the Ngangaguringuring and Poison Lease gauging stations are predicted to decrease slightly while the streamflows and salt loads are predicted to increase (Table A5.12). Figure 5.2 is based on the 2002 Landsat scene and in contrast to permanent clearing shown on Figs 2.9–2.11 shows the logged plantations on Wellbucket and the remaining 0.60 km^2 of pasture on Flynn.

A5.2.6 Characteristics curves

Plotting the proportions of the cleared area planted with trees against mean annual streamflow, salinity and salt load at equilibrium (Fig. 5.4) reveals some interesting facts. This could be used for estimating the effects of tree planting and harvesting on the inflow, salinity and salt load to the Reservoir. Mean annual inflow to the Mundaring Reservoir is predicted to decline approximately linearly to 18.5 GL if all the cleared areas are planted. The relationships between the cleared areas planted to mean stream salt load and salinity reductions are also approximately linear. The mean annual inflow and salt load to the Mundaring Reservoir would fall at the rate of 0.65 GL and 134 tonnes per square kilometre of cleared area planted. The mean annual inflow salinity is predicted to decrease roughly 3.7 mg/L per square kilometre of cleared area planted. Similar results were also obtained from the LUCICAT and MAGIC modelling in the Kent and Denmark River catchments for predicting catchment management options (Bari et al. 2004; De Silva et al. 2007).

A5.2.7 Silviculture (see 5.3.1)

Although logging takes place within the whole Mundaring catchment, most of it within State Forest, only logging in the Ngangaguringuring and Helena West management units was studied (Fig. 5.6). This allows comparison of silviculture from west to east and, since it is about half the catchment, also allows scaling up for the whole catchment without running another scenario. Modelling allowed for the gradual regrowth that follows silviculture so the maximum impacts are in the year following treatment. The Leaf Area Index for each of the subcatchments was reduced to 70%. In LUCICAT, logging took place in 2014 and LAI was linearly increased to its pre-treatment value by 2024. No other input variables were changed.

The average annual inflow to the Mundaring Reservoir is predicted to increase from 20.1 to 23.2 GL, or 16%. Average annual inflow salinity would decrease by 55 to 444 mg/L (bolded in the summary of results Table A5.13). Streamflow from the Ngangaguringuring MU is predicted to increase from 2.3 to 2.9 GL and average annual stream salinity to decrease by approximately 230 mg/L. However, in the early years of treatment annual salinity would decrease by as much as approximately 1500 mg/L (Fig. 5.5). If silvicultural treatment is implemented in the Ngangaguringuring MU alone, the mean inflow salinity to the Mundaring Reservoir is predicted to decrease to 480 mg/L (Table 5.1).

There would be a relatively large increase in streamflow from the Helena West MU. The largest increase (approximately 50%) was from the Little Darkin River gauging station, with average stream salinities at the Pickering Brook and Rushy Creek predicted to decrease by 33 and 66 mg/L respectively. If the silvicultural treatment takes place in the Helena West management unit alone then the reservoir inflow and salt load would increase to 7.9 kt and 22.7 GL respectively and the mean annual inflow salinity would decrease to 460 mg/L (Table 5.1).

A5.2.8 Prescribed burns (see 5.3.2)

As part of forest management in the Mundaring catchment the Department of Environment and Conservation undertakes prescribed burning, generally in 4-, 8- or 12-year cycles (Frank Batini pers. comm. 2005). Prescribed burning in 4- and 12-year cycles, starting only in 2004, was simulated in just the Ngangaguringuring and Helena West MUs. Leaf Area Index was reduced to 70% of the pretreatment value and then increased linearly to the pretreatment values 3 years later.

The 4-year cycle has larger effects on streamflow and salinity than the 12-year cycle (Fig. 5.5) – with a (4-year cycle) in the Ngangaguringuring MU alone, average annual inflow to the Mundaring Reservoir is predicted to increase to 20.6 GL and salinity to decrease to 460 mg/L (Table 5.1). From the Ngangaguringuring MU streamflow is predicted to increase from 2.4 to 2.8 GL, with a salinity reduction by 394 from 2177 to 1783 mg/L (bolded in the summary of results Table A5.14). A 12-year cycle would have only negligibly increased inflow and salinity reduction.

Most of the additional water would be generated from the Helena West MU (Table A5.14): on a 4-year cycle streamflow from the Helena West MU would increase to 12.9 GL. Inflow and salinity to the reservoir are predicted to be 22.4 GL and 440 mg/L respectively (Table 5.1). On a 12-year cycle, the streamflow from the management unit would be 11.3 GL and salinity would reduce to 195 mg/L (bolded in the summary of results Table A5.15).

A5.2.9 Hot wildfires (see 5.3.3)

The simulation of occasional hot wildfires was based on the recent large fire of 15–25 January 2005 at Beraking Brook and Pickering Brook (Higgs 2005). Thermal imaging, used by CALM to estimate the scale of biomass change after the fire, was used to estimate the intensities of the vegetation damage (that is, reduced LAI): 31% of the burnt area was simulated as ‘burnt hot’ in both the east and west of the catchment, with 60% medium and 9% undisturbed.

For an area burnt hot, the assumptions used were that the LAI of the forest (including trees, understorey and litter) would be 20% of the pre-fire LAI in the first year after the fire (Table A5.2). This roughly assumes that 80% of the trees were burned, that the forest would take 5 years to recover (return to its original LAI, and that the forest would have 70% of its original LAI immediately after the fire, and take 4 years to recover. In both the Helena West and Ngangaguringuring MUs the areas burnt hot, medium and unburnt were considered to be 31, 60 and 9% respectively (Fig. 5.6). In LUCICAT the wildfire was in 2014. Streamflow from both the management units is predicted to increase:

- *Wildfire in the Ngangaguringuring MU only:* inflow to the reservoir increases from 20.1 to 20.5 GL, and salinity decreases by 8 to 490 mg/L (Table 5.1). The mean annual stream salinity would decrease from 2177 to 1997 mg/L (bolded in Table A5.16).
- *Wildfire in the Helena West MU:* streamflow increases by approximately 2.5 GL, mostly generated from the ‘burnt hot’ Rushy Creek and Pickering Brook subcatchments (Fig. 5.6, Table A5.16), and decreases the reservoir inflow salinity to 470 mg/L.

Table A5.2 Reduction in LAI and recovery period due to wildfire

	Fire intensity		
	Hot	**Medium**	**Unburnt**
LAI reduced to	20%	70%	No change
Recovery period	5 years	4 years	No change

A5.3 Comparison of the MAGIC and LUCICAT models

The two models are fundamentally quite different. The MAGIC model is a steady-state model and assumes that the same land use has been applied to a catchment for many years and the salinity processes are at equilibrium. It was used to take a ‘snapshot’ of the catchment for a particular land use in an average year. Various management options were then applied using the same rainfall. LUCICAT is a dynamic model that uses daily rainfall.

The MAGIC model was calibrated first to the catchment under the 2002 land use and for the period 1986–88, using records that represented the catchment in its full expression of salinity. In the LUCICAT model the daily rainfall and pan evaporation data for the period 1971–2002 was repeated after 2002, taking 1971 as 2003. All the management options were implemented on 1 January 2003. Plant rooting depth and Leaf Area Index were increased gradually to represent normal plant growth and reached mature forest values in year 10. By the year 2024, the catchment was in equilibrium. The average annual figures for the years 2024–34 were compared to the MAGIC base case and reported as ‘Rainfall period at equilibrium’ in the Tables A5.3–A5.7. The MAGIC base case used average monthly rainfall for the period 1990–2002 with the 2002 land use.

The differences between the two models for different areas of trees planted are shown in Fig. A5.2. The MAGIC results are for the ‘base’ case (Table A5.3), the ‘all 1978 free/leasehold land cleared’ scenario (Table A5.5), and the ‘all cleared free/leasehold land planted with trees’ scenario (Table A5.7). The LUCICAT results are for ‘all the 1978 free/leasehold land cleared’ case (Table A5.11), the ‘base’ case (Table A5.8), ‘all cleared land planted’ case and ‘all 2003 free/leasehold land cleared’ case (Table A5.12) and ‘all cleared area planted’ case (Table A5.10). Differences in cleared areas in the ‘base’ cases for the two models are principally due to different methods of calculation.

A5.3.1 Salinity

The differences in salinity reflect the differences in streamflow and salt load outputs of the two models.

A5.3.2 Streamflow

The streamflows generated by the models were similar for the ‘base’ case (private free/leasehold land cleared 39 km^2) and agreed with the records of inflow to the Mundaring Reservoir (Fig. A5.2b). The MAGIC streamflows for other options tended to be lower than from LUCICAT, particularly ‘for all 196 km^2 of free/leasehold land cleared’ (Fig. A5.2b).

MAGIC uses 25-m square geographically-based cells to register the land use and from the average LAI of forest in good condition within each subcatchment estimates the water use of the added plantations. This may lead to some overestimation of water use if the land was not all able to support the better-conditioned forest.

LUCICAT used a simpler method to input land-use information. It assumed the LAI of the plantations to be the same as the existing native forest and the LAI for the added plantations to be a constant with a percentage of the catchment planted. The water use of the trees (native forest or plantations) was adjusted during the calibration process to match records.

A5.3.3 Salt loads

In MAGIC, the stream salt load is the sum of the salt loads in rainfall that does not enter the groundwater (75% of the total salt in rain) and in the groundwater discharging into the shallow top layer. The 'discharge into the shallow top layer' output from the MAGIC model and the 'groundwater discharge to streamzone' output in the LUCICAT model should be similar because they both represent discharge to the shallow top layer. The 'baseflow' output from LUCICAT is the estimated average annual discharge that reaches the stream. The MAGIC model does not separate this groundwater flow component from the total streamflow.

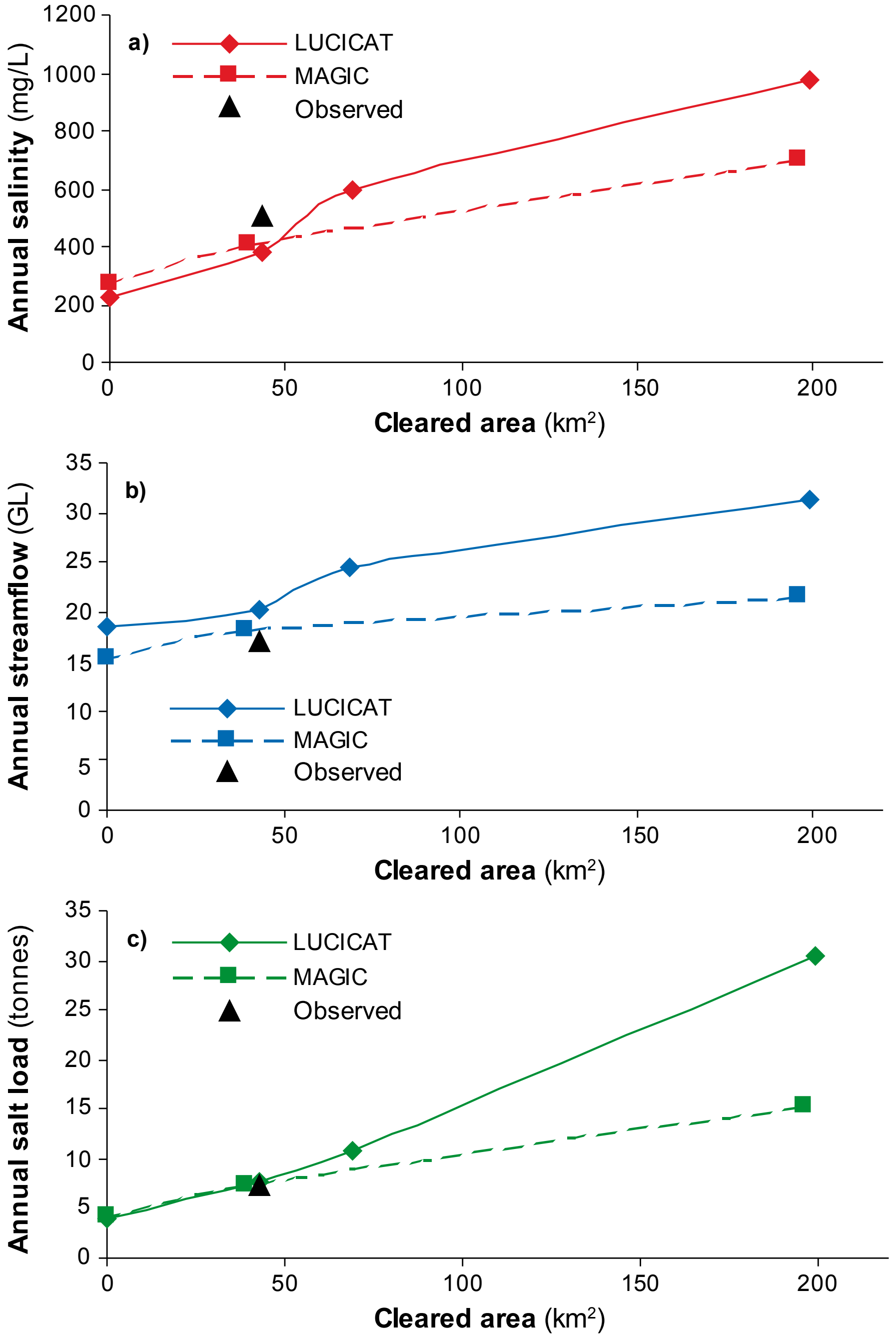


Figure A5.2 Comparison of modelled a) salinity b) volume and c) salt load (for area cleared see Fig. 5.4)

The MAGIC model represents the catchment in steady state, and hence it assumes that the salt entering the top layer and the salt entering the stream are the same for the average year in equilibrium. However, in the dynamic situation simulated by LUCICAT, in many locations salt may accumulate for several years before there is enough rainfall to flush the salt in interflow (lateral flow of water in the top layer) to the surface and the stream. So the smaller salt loads of LUCICAT represent retention in soil; partly the time delay of the salt discharged into the soil that does not reach the stream in one year.

A small component of the differences in salt loads in the models might be partly due to the MAGIC model not reaching equilibrium after 3 years. The MAGIC model was run for 3 years using a repeat of the average monthly rainfall for the period 1990–2002 and the land use of the catchment constant for all management options. It took LUCICAT a run of 24 years with the base case vegetation applied to the catchment for salinity to stabilise (Fig. A5.2b). It took LUCICAT a run of 50 years for the 1978 free/leasehold land cleared scenario for the salinity to stabilise.

Table A5.3 MAGIC 'base case'

	Management unit					Gauging station						Reservoir inflow	
	Ngangagur-inguring	Poison Lease	Darkin Swamp	Beraking Brook	Helena West	Helena Brook	Poison Lease [a]	Darkin River	Little Darkin River	Pickering Brook	Rushy Creek	Total of the MUs not the GSs	Measured [b] comparison
Total area (km^2)	328	265	274	392	221	27	593	665	37	30	39	1480	
Total cleared area in 2002 (km^2) *	16.5	6.4	15.2	0	0.5	0.1	22.8	15.2	0	0	0.5	38.5	
Total cleared in 2002 (%)	5	2	6	0	0	0	4	2	0	0	1	3	
Average rainfall (mm/yr) (1990–2002)	598	707	597	714	906	792	647	541	892	962	868	638	
Streamflow (GL)	2.3	3.4	0.4	3.8	8.3	0.9	5.7	4.1	0.6	1.9	1.5	**18.2**	17.1
Runoff (mm)	6.9	13	1.4	10	38	35	10	6	16	63	37	12	12
Salt load (kt)	3.0	2.5	0.1	0.5	1.5	0.3	5.5	0.6	0.2	0.2	0.4	7.5	7.4
Stream salinity (mg/L)	1313	724	211	135	177	290	959	142	327	126	283	**414**	430
Groundwater discharge (GL) *	0.4	0.2	-	-	0	0	0.6	0	0	0	0	0.7	
Groundwater discharge (mm)	1.2	0.8	-	-	0.2	0.8	1.1	0	0	0	1.2	0.5	
Shallow watertable (km^2) *	2.4	0.8	3.0	0	0.1	0.04	3.1	3.0	0	0	0.13	6.2	
Shallow watertable (% of total area)	0.7	0.3	1.1	0	0.1	0.1	0.5	0.4	0	0	0.3	0.4	
Discharge area (km^2) *	1.3	0.3	1.1	0	0	0.02	1.6	1.1	0	0	0.03	2.8	
Modelled discharge area (% of total)	0.4	0.1	0.4	0	0	0.1	0.3	0.2	0	0	0.1	0.2	

[a] Includes Ngangaguringuring GS & MU, and Helena Brook GS

[b] Includes estimated values of streamflow and salt load for some ungauged subcatchments in Helena West MU (Appendix A3.4)

* Cleared areas on private free/leasehold land only, excluding at least 4 km^2 on government free/leasehold land in Poison Lease MU

Table A5.4 MAGIC 'low-rainfall' scenario

	Management unit					Gauging station						Reservoir inflow
	Ngangagur-inguring	Poison Lease	Darkin Swamp	Beraking Brook	Helena West	Helena Brook	Poison Lease [a]	Darkin River	Little Darkin River	Pickering Brook	Rushy Creek	Total of the MUs not the GSs
Total area (km^2)	328	265	274	392	221	27	593	665	37	30	39	1480
Total cleared area in 2002 (km^2) *	16.5	6.4	15.2	0	0.5	0.1	22.8	15.2	0	0	0.5	38.5
Total cleared in 2002 (%)	5	2	6	0	0	0	4	2	0	0	1	3
Average rainfall for 1997–2003 (mm/yr)	583	669	542	676	882	739	622	512	868	943	840	611
Streamflow (GL)	2.3	3.4	0.4	3.8	8.0	0.9	5.7	4.1	0.6	1.9	1.5	**17.8**
Runoff (mm)	6.9	13	1.4	10	36	35	10	6	16	63	37	12
Salt load (kt)	3.0	2.0	0.1	0.5	1.4	0.3	4.9	0.6	0.2	0.2	0.4	6.9
Stream salinity (mg/L)	1303	583	204	128	175	278	870	135	319	124	245	**387**
Groundwater discharge (GL) *	0.41	0.23	-	-	0.05	0.02	0.63	0	0	0	0.05	0.68
Groundwater discharge (mm)	1.2	0.85	-	-	0.21	0.79	1.1	0	0	0	1.2	0.46
Shallow watertable (km^2) *	2.4	0.8	1.1	0	0.1	0.04	3.1	1.1	0	0	0.13	4.4
Shallow watertable (% of total area)	0.7	0.3	0.4	0	0.1	0.1	0.5	0.2	0	0	0.3	0.3
Discharge area (km^2) *	1.3	0.3	0.3	0	0	0.02	1.6	0.32	0	0	0.03	2.1
Modelled discharge area (% of total)	0.4	0.1	0.1	0	0	0.1	0.3	0	0	0	0.1	0.1

[a] Includes Ngangaguringuring GS & MU, and Helena Brook GS

* Cleared areas on private free/leasehold land only, excluding at least 4 km^2 on government free/leasehold land in Poison Lease MU

Table A5.5 MAGIC 'all 1978 free/leasehold land cleared'

	Management unit					**Gauging station**						**Reservoir inflow**
	Ngangagur-inguring	Poison Lease	Darkin Swamp	Beraking Brook	Helena West	Helena Brook	Poison Lease [a]	Darkin River	Little Darkin River	Pickering Brook	Rushy Creek	Total of the MUs not the GSs
Total area (km^2)	328	265	274	392	221	27	593	665	37	30	39	1480
Total cleared area (km^2)	56	102	33	0	6	0.6	158	33	0	0	2	196
Total cleared area (%)	17	38	12	0	3	2	27	5	0	0	6	13
Average rainfall for 1990–2002 (mm/yr)	598	707	597	714	906	792	647	541	892	962	868	638
Streamflow (GL)	2.4	5.2	0.4	3.8	9.9	0.9	7.6	4.1	1.5	1.8	1.7	**21.7**
Runoff (mm)	7.4	20	1.3	10	45	34	13	6	40	62	42	15
Salt load (kt)	4.8	8.3	0.1	0.5	1.6	0.3	13.1	0.6	0.2	0.2	0.5	15.3
Stream salinity (mg/L)	1990	1591	212	135	165	284	1718	142	132	128	278	**706**
Groundwater discharge (GL) *	0.8	1.4	-	-	0.1	0	2.2	0	0	0	0.1	2.3
Groundwater discharge (mm)	2.4	5.2	-	-	0.7	0.7	3.6	0	0	0	2.4	1.6
Shallow watertable (km^2) *	4.1	6.8	0.8	0	0.8	0.04	11	0.8	0	0	0.4	12
Shallow watertable (% of total area)	1.3	2.5	0.3	0	0.4	0.1	1.8	0.1	0	0	1.1	0.8
Discharge area (km^2) *	1.7	2.7	0.1	0	0.5	0.02	4.4	0.1	0	0	0.2	5.3
Modelled discharge area (% of total)	0.5	1.0	0	0	0.2	0.1	0.7	0.0	0	0	0.4	0.4

[a] Includes Ngangaguringuring GS & MU, and Helena Brook GS

* In cleared areas only

Table A5.6 MAGIC 'all cleared free/leasehold land planted with deep-rooted perennials'

	Management unit					Gauging station						Reservoir inflow
	Ngangagur-inguring	Poison Lease	Darkin Swamp	Beraking Brook	Helena West	Helena Brook	Poison Lease [a]	Darkin River	Little Darkin River	Pickering Brook	Rushy Creek	Total of the MUs not the GSs
Total area (km²)	328	265	274	392	221	27	593	665	37	30	39	1480
Total planted area (km²)	16.5	6.4	15.2	0	0.5	0.1	22.8	15.2	0	0	0.5	38.5
Total planted (%)	5	2	6	0	0	0	4	2	0	0	1	3
Average rainfall for 1990–2002 (mm/yr)	598	707	597	714	906	792	647	541	892	962	868	638
Streamflow (GL)	1.8	3.2	0.4	3.8	8.4	0.9	5.0	4.1	0.6	1.8	1.5	**17.5**
Runoff (mm)	5.5	12	1.4	10	38	33	8	6	16	62	39	12
Salt load (kt)	1.6	1.7	0.1	0.5	1.4	0.2	3.4	0.6	0.2	0.2	0.3	5.4
Stream salinity (mg/L)	**914**	**550**	**211**	135	167	217	682	142	327	128	221	**307**
Groundwater discharge (GL) *	0.14	0.08	-	-	0.03	0.01	0.22	0	0	0	0.03	0.25
Groundwater discharge (mm)	0.42	0.30	-	-	0.15	0.24	0.37	0	0	0	0.87	0.17
Shallow watertable (km²) *	1.3	0.4	0.5	0	0.1	0.04	1.7	0.48	0	0	0.13	2.3
Shallow watertable (% of total area)	0.4	0.2	0.2	0	0.1	0.1	0.3	0.1	0	0	0.3	0.2
Discharge area (km²) *	0.5	0.1	0	0	0	0.01	0.61	0.01	0	0	0.03	0.75
Modelled discharge area (% of total)	0.1	0.0	0	0	0	0.1	0.1	0	0	0	0.1	0.1

[a] Includes Ngangaguringuring GS & MU, and Helena Brook GS
* In cleared areas only

Table A5.7 MAGIC 'all cleared free/leasehold land planted with trees'

	Management unit					Gauging station						Reservoir inflow
	Ngangagur-inguring	Poison Lease	Darkin Swamp	Beraking Brook	Helena West	Helena Brook	Poison Lease [a]	Darkin River	Little Darkin River	Pickering Brook	Rushy Creek	Total of the MUs not the GSs
Total area (km²)	328	265	274	392	221	27	593	665	37	30	39	1480
Total planted area (km²)	16.5	6.4	15.2	0	0.5	0.1	22.8	15.2	0	0	0.5	38.5
Total planted (%)	5	2	6	0	0	0	4	2	0	0	1	3
Average rainfall for 1990–2002 (mm/yr)	598	707	597	714	906	792	647	541	892	962	868	638
Streamflow (GL)	0.8	2.8	0.4	3.8	7.6	0.7	3.6	4.1	0.6	1.5	1.2	**15.4**
Runoff (mm)	2.3	11	1.4	10	34	27	6	6	16	51	30	10
Salt load (kt)	0.9	1.3	0.1	0.5	1.3	0.2	2.3	0.6	0.2	0.2	0.3	4.2
Stream salinity (mg/L)	1224	479	211	135	176	224	639	142	327	157	232	**275**
Groundwater discharge (GL) *	0.07	0.06	-	-	0.03	0.01	0.13	0	0	0	0.03	0.16
Groundwater discharge (mm)	0.21	0.22	-	-	0.13	0.32	0.21	0	0	0	0.73	0.10
Shallow watertable (km²) *	0.8	0.4	0.3	0	0.1	0.04	1.2	0.35	0	0	0.11	1.6
Shallow watertable (% of total area)	0.2	0.1	0.1	0	0	0.1	0.2	0.1	0	0	0.3	0.1
Discharge area (km²) *	0.2	0.1	0	0	0	0.01	0.36	0	0	0	0.01	0.47
Modelled discharge area (% of total)	0.1	0	0	0	0	0.1	0.1	0	0	0	0	0

[a] Includes Ngangaguringuring GS & MU, and Helena Brook GS
* In cleared areas only

Table A5.8 LUCICAT 'base case'

	Management unit					Gauging station						Reservoir inflow
	Ngangaguringuring	Poison Lease	Darkin Swamp	Beraking Brook	Helena West	Helena Brook	Poison Lease [a]	Darkin River	Little Darkin River	Pickering Brook	Rushy Creek	Total of the MUs not the GSs
Area (km^2)	328	265	274	392	221	27	593	665	37	30	39	1480
Cleared private area in 2002 (km^2)	17	7	17	0	1	1	25	17	0	0	1	43
Cleared private area in 2002 (%)	5.3	2.8	6.2	0	0.6	5.6	4.2	2.6	0	0	3.2	2.9
Rainfall period at equilibrium [b]												
Annual rainfall (mm)	598	707	597	714	905	792	647	666	892	962	868	694
Streamflow (GL)	**2.29**	3.18	0.41	3.57	10.64	0.80	**5.47**	3.98	1.01	1.86	1.27	**20.1**
Runoff (mm)	7.0	12.0	1.5	9.1	48.2	29.5	9.2	6.0	27.2	62.2	32.5	13.6
Salt load (kt)	2.77	2.45	0.14	0.56	1.78	0.32	5.21	0.70	0.16	0.36	0.43	**7.69**
Average annual salinity (mg/L)	**2177**	**1956**	**1035** [c]	176	203	708	**2091**	193	203	237	495	**500**
Groundwater discharge to streamzone (mm)	1.5	0	0	0	0	1.3	0.1	0	0	0.6	1.1	0
Baseflow (mm)	0.5	0	0	0	0	0	0	0	0	0	0	0
Representative year at equilibrium [d]												
Annual rainfall (mm)	620	720	578	753	1005	783	665	681	997	1100	936	723
Streamflow (GL)	2.62	2.97	0.29	7.25	20.16	0.67	5.60	7.54	1.86	4.07	1.93	33.29
Runoff (mm)	8.0	11.2	1.0	18.5	91.2	24.7	9.4	11.3	50.3	135.8	49.5	22.5
Salt load (kt)	2.84	2.60	0.11	0.70	2.62	0.30	5.44	0.81	0.27	0.59	0.57	8.87
Average annual salinity (mg/L)	1082	872	397	96	130	453	971	107	144	145	293	266
Groundwater discharge to streamzone (mm)	1.5	0	0	0	0	1.2	0.1	0	0	0.5	1.1	0
Baseflow (mm)	0.5	0	0	0	0	0	0	0	0	0	0	0

[a] Includes Ngangaguringuring GS & MU, and Helena Brook GS
[b] Annual mean for the period 1990–2002
[c] Due to low flow 0.41 GL, half the catchment is not contributing salt for any of the land-use changes
[d] Annual rainfall of 2000

Table A5.9 LUCICAT 'decreased rainfall'

	Management unit					Gauging station						Reservoir inflow
	Ngangaguringuring	Poison Lease	Darkin Swamp	Beraking Brook	Helena West	Helena Brook	Poison Lease [a]	Darkin River	Little Darkin River	Pickering Brook	Rushy Creek	Total of the MUs not the GSs
Area (km^2)	328	265	274	392	221	27	593	665	37	30	39	1480
Cleared area in 2002 (km^2)	17	7	17	0	1	1	25	17	0	0	1	43
Cleared area in 2002 (%)	5.3	2.8	6.2	0	0.6	5.6	4.2	2.6	0	0	3.2	2.9
Rainfall period at equilibrium [b]												
Annual rainfall (mm)	583	678	541	675	880	738	625	620	867	943	839	661
Streamflow (GL)	1.62	2.60	0.18	2.75	8.77	0.45	4.22	2.93	0.76	1.74	0.86	**15.9**
Runoff (mm)	4.9	9.8	0.7	7.0	39.7	16.7	7.1	4.4	20.5	57.9	22.0	10.8
Salt load (kt)	2.43	1.93	0.09	0.43	1.61	0.25	4.35	0.53	0.14	0.34	0.36	6.49
Average annual salinity (mg/L)	2484	726	1469	194	211	830	1490	212	209	234	498	**470**
Groundwater discharge to streamzone (mm)	1.7	0.9	0.2	0	0.6	1.1	1.3	0.1	0	0.5	1.1	0.7
Baseflow (mm)	0.6	0	0.1	0	0	0	0.3	0	0	0	0	0.1
Representative year at equilibrium [c]												
Annual rainfall (mm)	620	720	578	753	1005	783	665	681	997	1100	936	723
Streamflow (GL)	2.53	4.68	0.24	4.31	13.12	0.78	7.21	4.55	1.26	2.86	1.17	24.88
Runoff (mm)	7.7	17.7	0.9	11.0	59.4	28.9	12.2	6.8	33.9	95.4	30.1	16.8
Salt load (kt)	3.15	4.19	0.13	0.65	2.22	0.40	7.33	0.78	0.22	0.49	0.51	10.33
Average annual salinity (mg/L)	1246	894	549	151	169	509	1018	172	173	170	433	415
Groundwater discharge to streamzone (mm)	1.7	0.8	0.2	0	0.6	1.1	1.3	0.1	0	0.5	1.1	0.6
Baseflow (mm)	0.6	0	0.1	0	0	0	0.3	0	0	0	0	0.1

[a] Includes Ngangaguringuring GS & MU, and Helena Brook GS
[b] Annual mean for the period 1990–2002
[c] Annual rainfall of 2000

Table A5.10 LUCICAT 'all cleared area planted with commercial trees'

	Management unit					Gauging station						Reservoir inflow
	Ngangaguringuring	Poison Lease	Darkin Swamp	Beraking Brook	Helena West	Helena Brook	Poison Lease [a]	Darkin River	Little Darkin River	Pickering Brook	Rushy Creek	Totalof the MUs not the GSs
Area (km^2)	328	265	274	392	221	27	593	665	37	30	39	1480
Cleared area after planting (km^2)	0	0	0	0	0	0	0	0	0	0	0	0
Cleared area after planting (%)	0	0	0	0	0	0	0	0	0	0	0	0
Planted area (km^2)	17	7	17	0	1	1	25	17	0	0	1	43
Planted area (%)	5.3	2.8	6.2	0	0.6	5.6	4.2	2.6	0	0	3.2	2.9
Rainfall period at equilibrium [b]												
Annual rainfall (mm)	598	707	597	714	905	792	647	666	892	962	868	694
Streamflow (GL)	1.57	3.17	0.39	3.57	9.86	0.63	**4.74**	3.95	1.01	1.74	1.10	**18.6**
Runoff (mm)	4.8	12.0	1.4	9.1	44.6	23.5	8.0	5.9	27.2	58.0	28.2	12.5
Salt load (kt)	1.68	0.28	0.12	0.56	1.45	0.18	1.96	0.68	0.16	0.30	0.32	4.10
Average annual salinity (mg/L)	2244	–	352	177	175	424	**382**	188	203	212	426	**233**
Groundwater discharge to streamzone (mm)	1.6	0	0	0	0.1	0	0.9	0	0	0.1	0.2	0.4
Baseflow (mm)	0.5	0	0	0	0	0	0.3	0	0	0	0	0.1
Representative year at equilibrium [c]												
Annual rainfall (mm)	620	720	578	753	1005	783	665	681	997	1100	936	723
Streamflow (GL)	1.73	3.11	0.26	7.25	19.20	0.49	4.84	7.52	1.86	3.95	1.71	31.56
Runoff (mm)	5.3	11.7	1.0	18.5	86.9	18.1	8.2	11.3	50.3	131.6	43.7	21.3
Salt load (kt)	1.60	0.22	0.09	0.70	2.09	0.16	1.81	0.79	0.27	0.50	0.42	4.69
Average annual salinity (mg/L)	922	70	332	96	109	321	375	105	144	127	245	149
Groundwater discharge to streamzone (mm)	1.6	0	0	0	0	0	0.9	0	0	0.1	0	0.4
Baseflow (mm)	0.5	0	0	0	0	0	0.3	0	0	0	0	0.1

[a] Includes Ngangaguringuring GS & MU, and Helena Brook GS
[b] Annual mean for the period 1990–2002
[c] Annual rainfall of 2000
– *Represents a negative salinity in modelling due to loss of salt between Ngangaguringuring and Poison Lease gauging stations*

Table A5.11 LUCICAT 'all 1978 free/leasehold land cleared'

	Management unit					Gauging station						Reservoir inflow
	Ngangaguringuring	Poison Lease	Darkin Swamp	Beraking Brook	Helena West	Helena Brook	Poison Lease [a]	Darkin River	Little Darkin River	Pickering Brook	Rushy Creek	Total of the MUs not the GSs
Area (km^2)	328	265	274	392	221	27	593	665	37	30	39	1480
Cleared area (km^2)	54.1	106.3	31.1	0	7.9	0.6	155	31	0	60	1.6	199
Cleared area (%)	16.5	40.1	11.4	0	3.6	2.3	26.2	4.7	0	0	4.0	13.4
Rainfall period at equilibrium [b]												
Annual rainfall (mm)	598	707	597	714	905	792	647	666	892	962	868	694
Streamflow (GL)	2.79	13.52	0.69	3.62	10.74	0.80	16.30	4.30	1.02	1.88	1.28	**31.4**
Runoff (mm)	8.5	51.0	2.5	9.2	48.6	29.7	27.5	6.5	27.6	62.7	32.8	21.2
Salt load (kt)	4.34	23.62	0.33	0.61	1.58	0.28	27.95	0.94	0.17	0.34	0.39	30.47
Average annual salinity (mg/L)	**2924**	**2762**	1041	190	171	614	2777	218	206	222	438	**1500**
Groundwater discharge to streamzone (mm)	1.6	6.3	0.7	0	0.6	1.2	3.7	0.3	0	0.6	1.1	1.7
Baseflow (mm)	1	0.3	0.1	0	0	0	0.5	0	0	0	0	0.2
Representative year at equilibrium [c]												
Annual rainfall (mm)	620	720	578	753	1005	783	665	681	997	1100	936	723
Streamflow (GL)	3.22	14.46	0.28	7.38	20.18	0.67	17.68	7.66	1.89	4.06	1.92	45.52
Runoff (mm)	9.8	54.6	1.0	18.8	91.3	24.7	29.8	11.5	51.2	135.2	49.3	30.8
Salt load (kt)	4.55	23.19	0.12	0.76	2.39	0.26	27.74	0.87	0.28	0.55	0.51	31.00
Average annual salinity (mg/L)	1412	1603	413	103	119	394	1569	114	146	136	264	681
Groundwater discharge to streamzone (mm)	1.7	6.6	0.8	0	0.6	1.3	3.9	0.3	0	0.6	1.1	1.8
Baseflow (mm)	1	0.3	0.1	0	0	0	0.5	0	0	0	0	0.2

[a] Includes Ngangaguringuring GS & MU, and Helena Brook GS
[b] Annual mean for the period 1990–2002
[c] Annual rainfall of 2000

Table A5.12 LUCICAT 'all 2003 private free/leasehold land cleared for annual pasture'

	Management unit					Gauging station						Reservoir inflow
	Ngangaguringuring	Poison Lease	Darkin Swamp	Beraking Brook	Helena West	Helena Brook	Poison Lease [a]	Darkin River	Little Darkin River	Pickering Brook	Rushy Creek	Total of the MUs not the GSs
Area (km^2)	328	265	274	392	221	27	593	665	37	30	39	1480
Cleared private free/leasehold area (km^2)	24.6	17.5	30.8	0	1.5	1.5	37.2	30.8	0	0	1.3	69.4
Cleared area (%)	7.5	4.8	11.2	0	0.7	5.6	6.5	4.6	0	0	3.4	4.7
Rainfall period at equilibrium [b]												
Annual rainfall (mm)	598	707	597	714	905	792	647	666	892	962	868	694
Streamflow (GL)	3.77	4.47	1.31	3.61	11.35	0.80	8.23	4.92	1.02	1.88	1.72	**24.50**
Runoff (mm)	11.5	16.9	4.8	9.2	51.4	29.7	13.9	7.4	27.6	62.7	44.1	16.6
Salt load (kt)	4.26	2.72	1.15	0.60	2.15	0.28	6.98	1.75	0.17	0.34	0.76	10.88
Average annual salinity (mg/L)	1860	841	2013	182	238	614	1599	288	206	222	645	**597**
Groundwater discharge to streamzone (mm)	1.8	1	0	0	0.7	1	1.4	0	0	0.5	1.6	0.7
Baseflow (mm)	0.6	0	0	0	0	0	0.3	0	0	0	0	0.1
Representative year at equilibrium [c]												
Annual rainfall (mm)	620	720	578	753	1005	783	665	681	997	1100	936	723
Streamflow (GL)	4.37	4.31	0.31	7.38	20.97	0.67	8.68	7.69	1.89	4.06	2.51	37.34
Runoff (mm)	13.3	16.3	1.1	18.8	94.9	24.7	14.6	11.6	51.2	135.2	64.4	25.2
Salt load (kt)	5.12	2.77	0.17	0.75	2.98	0.26	7.89	0.92	0.28	0.55	0.89	11.79
Average annual salinity (mg/L)	1172	643	547	102	142	394	909	120	146	136	355	316
Groundwater discharge to streamzone (mm)	1.8	1	0	0	1	1	1.5	0	0	0.6	2	0.8
Baseflow (mm)	0.6	0	0	0	0	0	0.3	0	0	0	0	0.1

[a] Includes Ngangaguringuring GS & MU, and Helena Brook GS
[b] Annual mean for the period 1990–2002
[c] Annual rainfall of 2000

Table A5.13 LUCICAT 'silvicultural thinning'

	Management unit					Gauging station						Reservoir inflow
	Ngangaguringuring	Poison Lease	Darkin Swamp	Beraking Brook	Helena West	Helena Brook	Poison Lease [a]	Darkin River	Little Darkin River	Pickering Brook	Rushy Creek	Total of the MUs not the GSs
Area (km^2)	328	265	274	392	221	27	593	665	37	30	39	1480
Cleared thinned in east (km^2)	328	0	0	0	0	0	0	0	0	0	0	328
Cleared thinned in west (km^2)	0	0	0	0	221	0	0	0	0	0	0	221
Rainfall period at equilibrium [b]												
Annual rainfall (mm)	598	707	597	714	905	792	647	666	892	962	868	694
Streamflow (GL)	**2.74**	3.18	0.41	3.57	13.34	0.80	5.92	3.98	1.45	2.36	1.60	**23.2**
Runoff (mm)	8.3	12.0	1.5	9.1	60.4	29.5	10.0	6.0	39.1	78.8	40.9	15.7
Salt load (kt)	2.86	2.49	0.14	0.56	1.97	0.32	5.35	0.70	0.19	0.41	0.48	8.02
Average annual salinity (mg/L)	1946	744	1035	176	181	708	2011	193	167	209	436	**444**
Groundwater discharge to streamzone (mm)	1.5	0	0	0	0	1.2	0.1	0	0	0.5	1.1	0
Baseflow (mm)	0.5	0	0	0	0	0	0	0	0	0	0	0
Representative year at equilibrium [c]												
Annual rainfall (mm)	620	720	578	753	1005	783	665	681	997	1100	936	723
Streamflow (GL)	2.66	2.97	0.29	7.25	20.49	0.67	5.63	7.54	1.93	4.16	1.97	33.66
Runoff (mm)	8.1	11.2	1.0	18.5	92.7	24.7	9.5	11.3	52.3	138.8	50.4	**22.7**
Salt load (kt)	2.94	2.57	0.11	0.70	2.60	0.30	5.50	0.81	0.26	0.59	0.56	8.92
Average annual salinity (mg/L)	1105	863	397	96	127	453	977	107	136	141	286	265
Groundwater discharge to streamzone (mm)	1.5	0	0	0	0	1.3	0.1	0	0	0.6	1.1	0
Baseflow (mm)	0.5	0	0	0	0	0	0	0	0	0	0	0

[a] Includes Ngangaguringuring GS & MU, and Helena Brook GS
[b] Annual mean for the period 1990–2002
[c] Annual rainfall of 2000

Table A5.14 LUCICAT 'prescribed burning (4-year cycle)'

	Management unit					Gauging station						Reservoir inflow
	Ngangaguringuring	**Poison Lease**	**Darkin Swamp**	**Beraking Brook**	**Helena West**	**Helena Brook**	**Poison Lease [a]**	**Darkin River**	**Little Darkin River**	**Pickering Brook**	**Rushy Creek**	**Total of the MUs not the GSs**
Area (km^2)	328	265	274	392	221	27	593	665	37	30	39	1480
Burn in east (km^2)	328	0	0	0	0	0	0	0	0	0	0	328
Burn in west (km^2)	0	0	0	0	221	0	0	0	0	0	0	221
Rainfall period at equilibrium [b]												
Annual rainfall (mm)	598	707	597	714	905	792	647	666	892	962	868	694
Streamflow (GL)	**2.79**	3.18	0.41	3.57	12.93	0.80	5.97	3.98	1.39	2.24	1.53	**22.9**
Runoff (mm)	8.5	12.0	1.5	9.1	58.5	29.5	10.1	6.0	37.5	74.7	39.2	15.5
Salt load (kt)	2.85	2.53	0.14	0.56	1.93	0.32	5.37	0.70	0.18	0.39	0.47	8.01
Average annual salinity (mg/L)	**1783**	–	1035	176	181	708	1996	193	165	211	435	**447**
Groundwater discharge to streamzone (mm)	1.7	0.9	0.3	0	0.6	1.2	1.4	0.1	0	0.5	1.1	0.7
Baseflow (mm)	0.6	0	0.1	0	0	0	0.3	0	0	0	0	0.1
Representative year at equilibrium [c]												
Annual rainfall (mm)	620	720	578	753	1005	783	665	681	997	1100	936	723
Streamflow (GL)	3.74	2.97	0.29	7.25	26.20	0.67	6.71	7.54	3.08	4.78	2.77	40.45
Runoff (mm)	11.4	11.2	1.0	18.5	118.6	24.7	11.3	11.3	83.3	159.3	71.1	27.3
Salt load (kt)	3.05	2.68	0.11	0.70	3.01	0.30	5.72	0.81	0.33	0.65	0.67	9.55
Average annual salinity (mg/L)	814	901	397	96	115	453	853	107	108	136	242	236
Groundwater discharge to streamzone (mm)	1.8	1.0	0.3	0	0.6	1.3	1.4	0.1	0	0.6	1.1	0.7
Baseflow (mm)	0.6	0	0.1	0	0	0	0.3	0	0	0	0	0.1

[a] Includes Ngangaguringuring GS & MU, and Helena Brook GS
[b] Annual mean for the period 1990–2002
[c] Annual rainfall of 2000
– Represents a negative salinity in modelling due to loss of salt between Ngangaguringuring and Poison Lease gauging stations

Table A5.15 LUCICAT 'prescribed burning (12-year cycle)'

	Management unit					Gauging station						Reservoir inflow
	Ngangaguringuring	Poison Lease	Darkin Swamp	Beraking Brook	Helena West	Helena Brook	Poison Lease [a]	Darkin River	Little Darkin River	Pickering Brook	Rushy Creek	Total of the MUs not the GSs
Area (km^2)	328	265	274	392	221	27	593	665	37	30	39	1480
Burn in east (km^2)	328	0	0	0	0	0	0	0	0	0	0	328
Burn in west (km^2)	0	0	0	0	221	0	0	0	0	0	0	221
Rainfall period at equilibrium [b]												
Annual rainfall (mm)	598	707	597	714	905	792	647	666	892	962	868	694
Streamflow (GL)	2.38	3.18	0.41	3.57	**11.30**	0.80	5.56	3.98	1.12	1.97	1.35	**20.84**
Runoff (mm)	7.2	12.0	1.5	9.1	51.2	29.5	9.4	6.0	30.1	65.7	34.5	14.1
Salt load (kt)	2.78	2.46	0.14	0.56	1.82	0.32	5.24	0.70	0.17	0.37	0.45	7.77
Average annual salinity (mg/L)	2068	2264	1035	176	**195**	708	2065	193	190	229	470	**481**
Groundwater discharge to streamzone (mm)	1.8	0.9	0.3	0	0.6	1.2	1.4	0.1	0	0.5	1.1	0.7
Baseflow (mm)	0.6	0	0.1	0	0	0	0.3	0	0	0	0	0.1
Representative year at equilibrium [c]												
Annual rainfall (mm)	620	720	578	753	1005	783	665	681	997	1100	936	723
Streamflow (GL)	2.63	2.97	0.29	7.25	20.18	0.67	5.60	7.54	1.86	4.08	1.93	33.31
Runoff (mm)	8.0	11.2	1.0	18.5	91.3	24.7	9.4	11.3	50.3	136.0	49.5	22.5
Salt load (kt)	2.83	2.60	0.11	0.70	2.62	0.30	5.43	0.81	0.27	0.59	0.57	8.86
Average annual salinity (mg/L)	1078	873	397	96	130	453	969	107	144	144	293	266
Groundwater discharge to streamzone (mm)	1.8	1.0	0.3	0	0.6	1.3	1.5	0.1	0	0.6	1.1	0.7
Baseflow (mm)	0.6	0	0.1	0	0	0	0.3	0	0	0	0	0.1

[a] Includes Ngangaguringuring GS & MU, and Helena Brook GS

[b] Annual mean for the period 1990–2002

[c] Annual rainfall of 2000

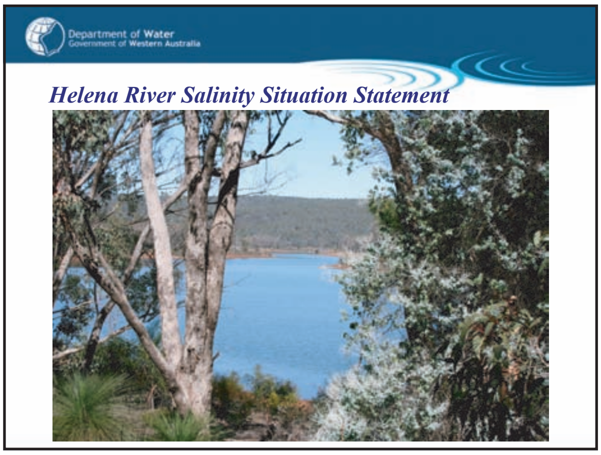
Table A5.16 LUCICAT analysis of 'hot wildfires'

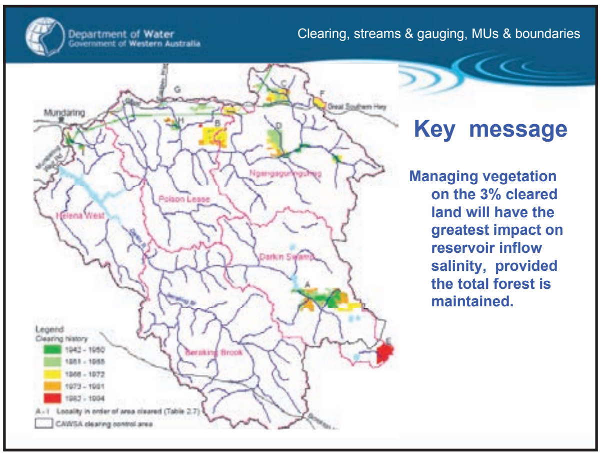
	Management unit					Gauging station						Reservoir inflow
	Ngangaguringuring	**Poison Lease**	**Darkin Swamp**	**Beraking Brook**	**Helena West**	**Helena Brook**	**Poison Lease [a]**	**Darkin River**	**Little Darkin River**	**Pickering Brook**	**Rushy Creek**	**Total of the MUs not the GSs**
Area (km^2)	328	265	274	392	221	27	593	665	37	30	39	1480
Totally burnt (km^2)	102	0	0	0	68	0	0	0	0	0	0	0
Medium burn (%)	197	0	0	0	133	0	0	0	0	0	0	0
Unburnt (%)	29	0	0	0	20	0	0	0	0	0	0	0
Rainfall period at equilibrium [b]												
Annual rainfall (mm)	598	707	597	714	905	792	647	666	892	962	868	694
Streamflow (GL)	2.67	3.18	0.41	3.57	13.12	0.80	5.85	3.98	1.13	2.78	2.10	**23.0**
Runoff (mm)	8.1	12.0	1.5	9.1	59.4	29.5	9.9	6.0	30.4	92.7	53.7	15.5
Salt load (kt)	2.78	2.48	0.14	0.56	1.96	0.32	5.26	0.70	0.17	0.43	0.52	7.91
Average annual salinity (mg/L)	**1997**	2122	1035	176	188	708	2033	193	191	204	420	**465**
Groundwater discharge to streamzone (mm)	1.8	0.9	0.3	0	0.6	1.2	1.4	0.1	0	0.5	1.1	0.7
Baseflow (mm)	0.6	0	0.1	0	0	0	0.3	0	0	0	0	0.1
Representative year at equilibrium [c]												
Annual rainfall (mm)	620	720	578	753	1005	783	665	681	997	1100	936	723
Streamflow (GL)	2.63	2.97	0.29	7.25	20.25	0.67	5.60	7.54	1.86	4.14	1.94	33.39
Runoff (mm)	8.0	11.2	1.0	18.5	91.6	24.7	9.4	11.3	50.3	138.0	49.8	22.6
Salt load (kt)	2.82	2.60	0.11	0.70	2.61	0.30	5.42	0.81	0.27	0.58	0.56	8.84
Average annual salinity (mg/L)	1072	873	397	96	129	453	967	107	144	141	289	265
Groundwater discharge to streamzone (mm)	1.8	1.0	0.3	0	0.6	1.3	1.5	0.1	0	0.6	1.1	0.7
Baseflow (mm)	0.6	0	0.1	0	0	0	0.3	0	0	0	0	0.1

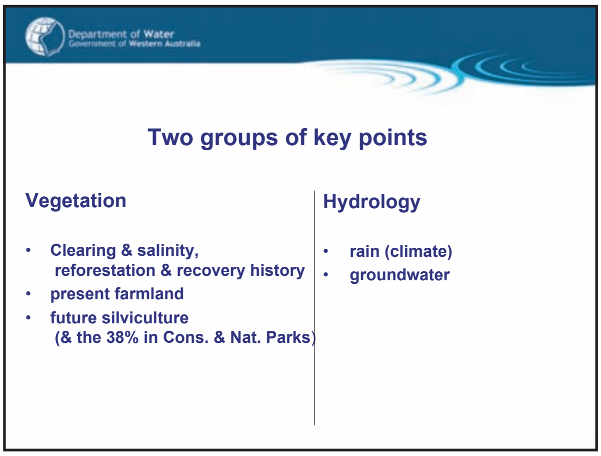
[a] Includes Ngangaguringuring GS & MU, and Helena Brook GS
[b] Annual mean for the period 1990–2002
[c] Annual rainfall of 2000

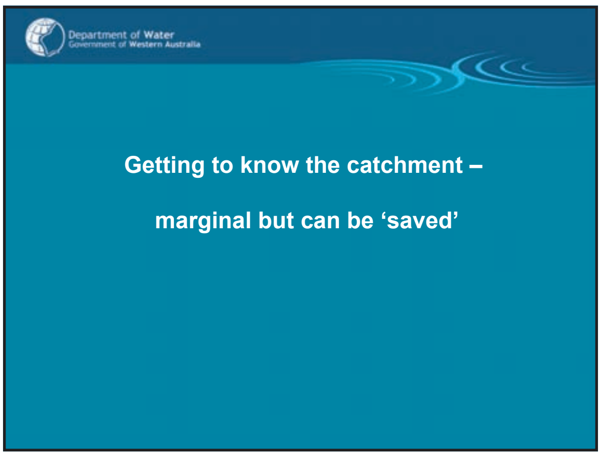
Appendix 6 — Presentation on the Helena River Salinity Situation Statement

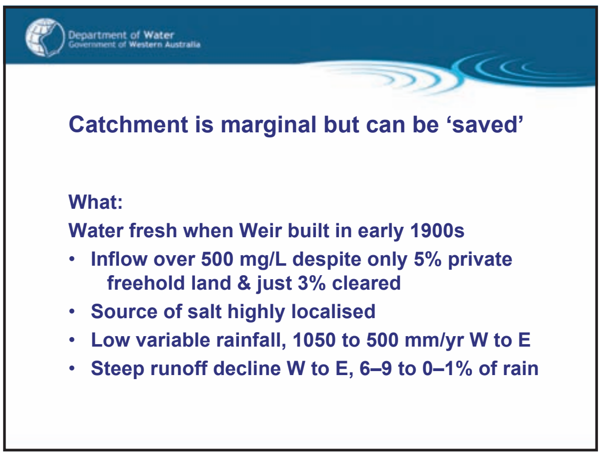
The following is an overview of a marginal catchment that, by asking 'why?' and 'so what?', covers some 26 key points.











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Water fresh when Weir built in early 1900s

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Inflow over 500 mg/L despite only 5% private freehold land & just 3% cleared

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Helena, part of Darkin & West, gauging stations, rainfall

Source of salt highly localised

Rainfall low and variable (1050 to 500 mm/yr W to E)

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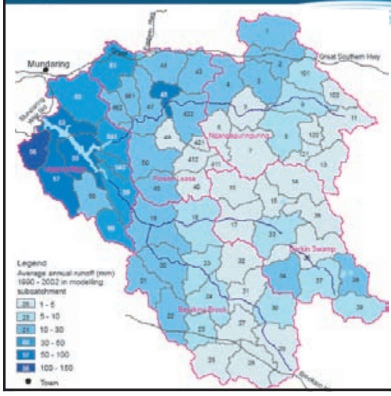
Modelling subcatchments



Runoff declines W to E, steeply, from 6--9% of rain to 0--1%

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Catchment marginal but can be 'saved'

Requires active management to maintain as a Water Resource Catchment

Total area	1480 km^2				
Gov. freehold cleared	4				
Private freehold	71				
TIMBERED	32	plus CLEARED	39		
Compensated	27	Non-flowing	15	in CAWSA	10
Uncompensated	3 to 5	Flowing	23	in CAWSA	18

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Decrease in rainfall (IOCI)

What

- **At Mundaring 1910–2003 = 1053 mm/yr, 1997–2003 = 860, 1975–2003 = 921 mm/yr**
- **13% this catchment since 1975, less from 1997**

So

- **Less yield to reservoir, but lower salinity**
- **Continue to monitor for trends**

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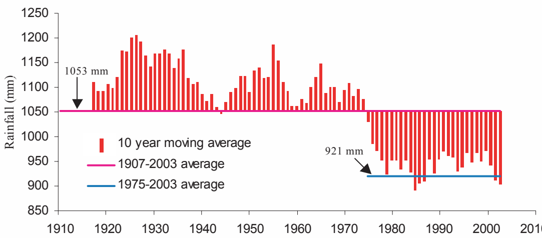
10-year moving average 1053 to 921 mm from 1970s

13% less rainfall at Mundaring since 1975



Consequence: less inflow to the reservoir, but lower salinity

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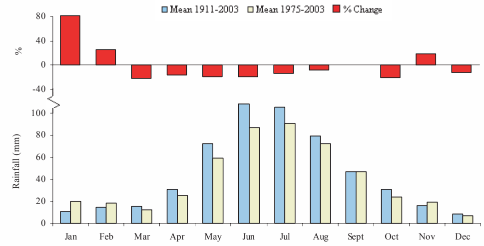
Most recent 29 of 93 years



Seasonal rainfall shift -- a station south of the Beraking Brook MU

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The reservoir has low residence time

- Volume pumped is similar to 17 GL annual inflow
- Reservoir holds 64 GL, only a few years inflow

So

- Tolerates only a few dry, high salinity inflow years without significant pumpback
- No capacity to meet more demand

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Need to reduce reservoir inflow salinity

What

- In 7 of the 10 years up to 2002 exceeded 500 mg/L
- Highest in low rainfall years ’79, 82, 85, 01
- Yet drops slightly if rainfall decreases long-term

So

- Need to further reduce runoff from east and/or increase runoff from west

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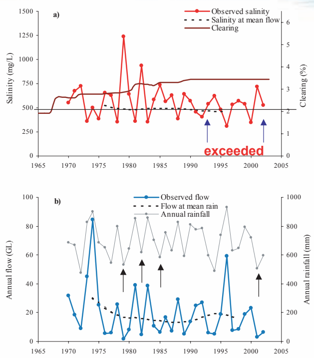

Salinity

500 mg/L exceeded in 7 of 10 years up to 2002

Salinity highest in low rainfall years (’79, 82, 85, 01)

Flow

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To reduce reservoir inflow salinity

Reduce runoff in the east

AND/OR

Increase runoff in the west

Continue pumpback,
to lower reservoir salinity

Why

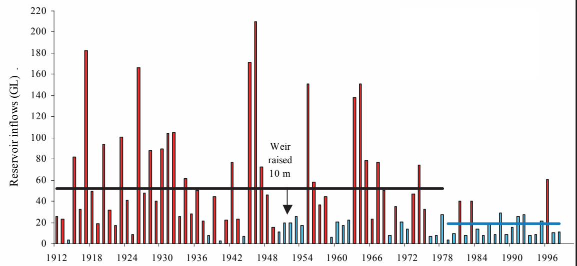
- Since 1970s MWS pumpback has increased yield and kept salinity below 500 mg/L

So

- There are limits to this option for management

Mean inflow dropped & only 3 overflows since 1970s

Since 1970s MWS pumpback has increased yield & kept salinity below 500 mg/L



But there are limits to this option for management

Poison Lease, the last gauging station before the Helena River enters Lake CY O'Connor

Monitoring comprises

1. Vegetation – Landsat since 1977 – good
2. Rainfall – adequate stations
3. Streamflow and salinity – good (gauges, grab)
4. Groundwater salinity and water level – short, focussed at Flynn, inadequate
5. Swamps – inadequate

So continue 1, 2 & 3, increase 4 & 5

Groundwater

Why most salt is from the NE of the catchment

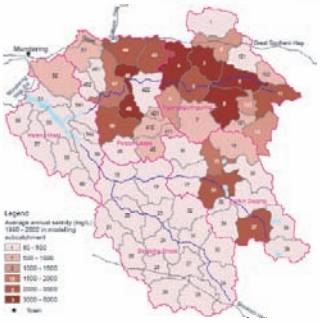
Exceptional geology and local clearing cause
year-round flow and
53% salt from the Helena River for 30% of flow
cf little salt and 21% flow from the Darkin River

So

- Need to reforest to reduce recharge OR
- Pump to stop the discharge

Modelled in runoff

Why most salt is from the NE - salinity

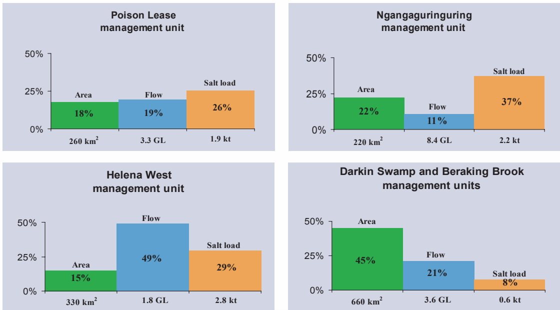


Modelled in runoff

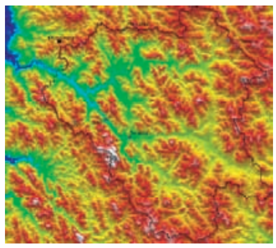
Why most salt is from the NE - salt load is localised

Note orange boxes

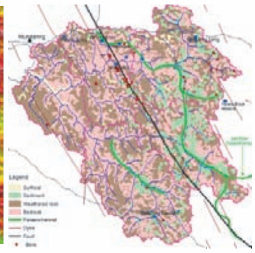
63% salt in 30% flow, Helena River – 8% salt in 21% flow, Darkin River



Exceptional geology, local clearing, year-round flow



DEM, NW trend, rejuvenated, boundary



Fault, bores, springs, channel sediments

To reduce salt from the NE of the catchment

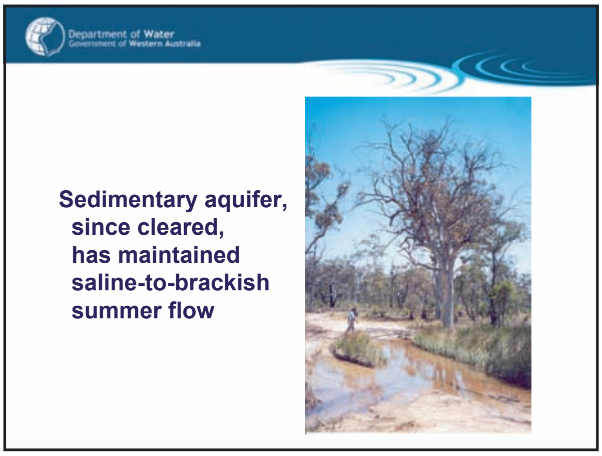
- **Reforest to reduce recharge**

OR

- **Pump to stop the discharge**

Sedimentary aquifer since cleared has maintained saline-to-brackish summer flow

What
- **Interpreted palaeochannel/inset valley**
- **High hydraulic conductivity**
- **Increased recharge after clearing**
- **Salt from bedrock higher in landscape**
- **60% salt load to Ngangaguringuring in baseflow**
- **Different from Darkin River swamps**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Government of Western Australia
Sedimentary aquifer, since cleared, has maintained saline-to-brackish summer flow


Department of Water
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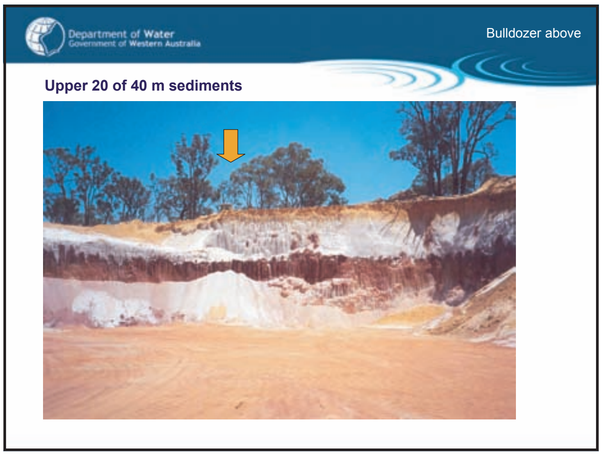
ABERCORN
GORRIE
FIREWOOD
2000
3600
2700
2400
2100
RIDLEY
2000
2900
3000
2800
2900
2800
3400
YETAR
3800
2900
YARRA
Summer salinities (mg/L) near Ngangaguringuring & Poison Lease gauging stations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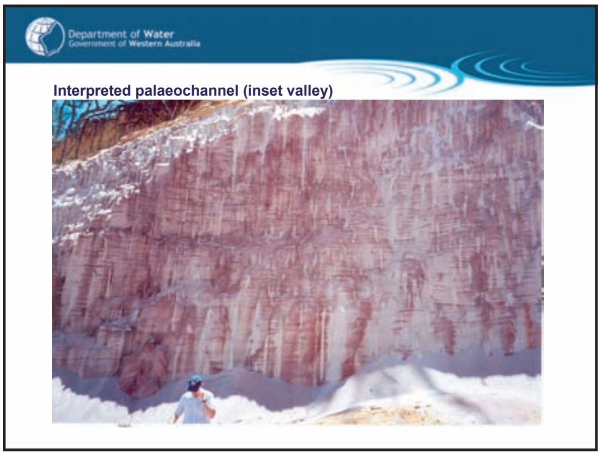
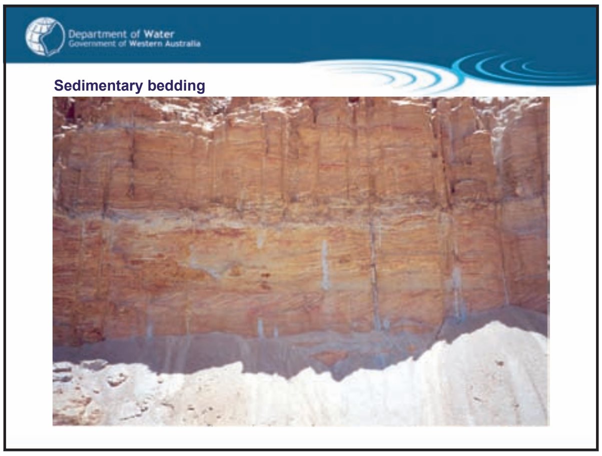
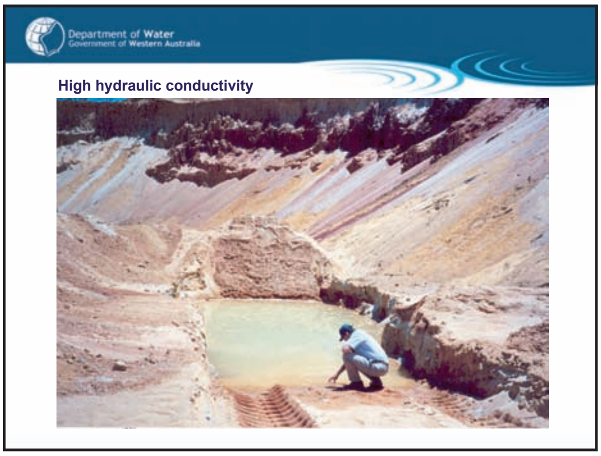
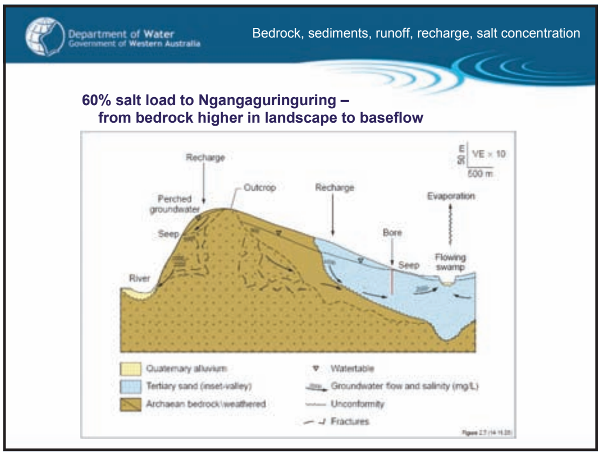
Government of Western Australia
Bulldozer above
Upper 20 of 40 m sediments

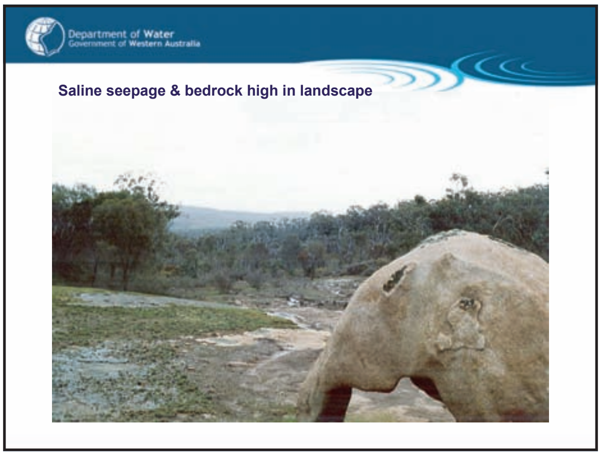

Department of Water
Government of Western Australia
Interpreted palaeochannel (inset valley)

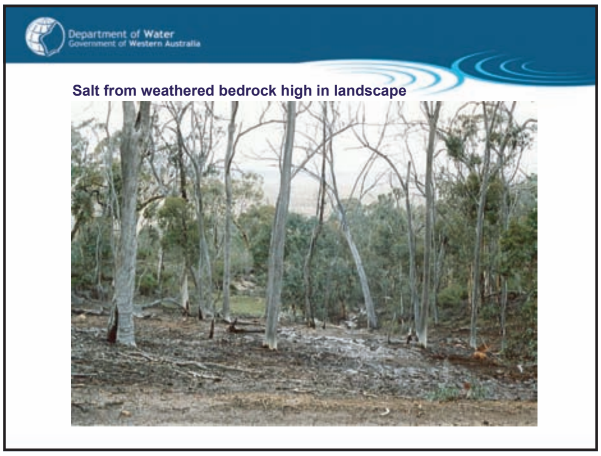

Department of Water
Government of Western Australia
Sedimentary bedding


Department of Water
Government of Western Australia
High hydraulic conductivity


Department of Water
Government of Western Australia
Increased recharge after clearing


Department of Water
Government of Western Australia
Bedrock, sediments, runoff, recharge, salt concentration
60% salt load to Ngangaguringuring –
from bedrock higher in landscape to baseflow
Recharge
Outcrop
Recharge
Perched groundwater
Evaporation
Seep
Bore
Seep
Flowing swamp
River
50 m
VE × 10
500 m
Quaternary alluvium
Tertiary sand (inset-valley)
Archaean bedrock\weathered
Watertable
Groundwater flow and salinity (mg/L)
Unconformity
Fractures


Department of Water
Government of Western Australia
Saline seepage & bedrock high in landscape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Government of Western Australia
Salt from weathered bedrock high in landscape


Department of Water
Government of Western Australia
Saline mineralised water high in the landscape


Department of Water
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Saline seep near cleared hilltop

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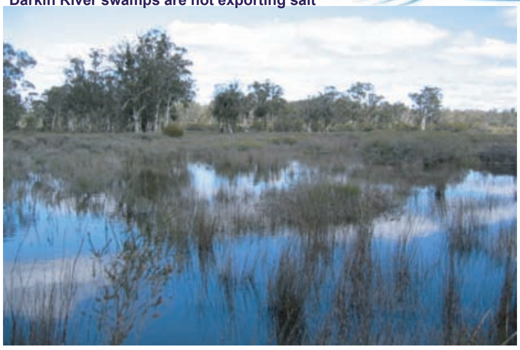
Mostly very shallow

Darkin River swamps are not exporting salt



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Sedimentary aquifer since cleared has maintained saline-to-brackish summer flow

What

- Flow & salinity monitoring at Ngangaguringuring
- Baseflow increasing
- Baseflow salinity now decreasing slightly

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Continue flow & salinity monitoring, Ngangaguringuring

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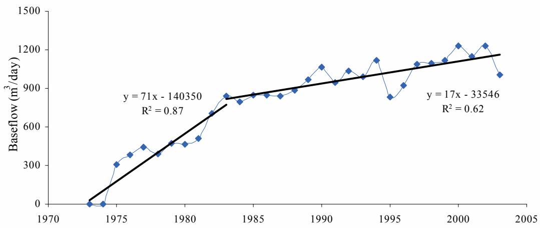
After onset and steep rise

Ngangaguringuring baseflow increasing



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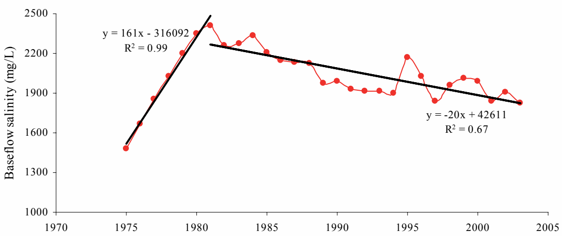
Well above 500 mg/L though

Ngangaguringuring baseflow salinity decreasing



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Key for managing salinity is to disconnect groundwater from surface water flow in the NE and prevent their connection in the SE

Why

- Demonstrated at Flynn by reforestation together with decreased rainfall

So consider

- Reforest WaterCorp 3 km² near Abercorn Road
- Change vegetation on private farms after that

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Pumping (or draining) the sedimentary aquifer near Ngangaguringuring would lower salt concentration

Why
- ET concentrates salt in perennial discharge since clearing near Ngangaguringuring

So
- Reduce ET by pumping or draining to streamline (same load, more yield, less saline, some cost)

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For the 2 MUs on the Helena River

Diverting the (saline-to-brackish) flow, to lower the salinity, reduces yield

What
- Diversion at NG or PL reduces both flow & salinity

So
- Requires disposal outside catchment
- Lowers yield from total 17.1 to 15.3 or 12.0 GL/yr
- Lowers salinity from mean 510 to 300 or 230 mg/L

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Salt may be accumulating in the sediments beneath Darkin Swamp where flow passes only during intense rainfall

Why
- Summer 1996 flow (high colour, indicating nutrients not salt)
- Overflows as trickles after high rainfall events in sustained wet winters (Aug 2003 & 4)
- Brackish surface water on upstream farm but no salt passes Darkin Swamp
- Not flowing because lacks dissection and relief of Ngangaguringuring

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Salt may be accumulating in the sediments beneath Darkin Swamp

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Salt … accumulating … Darkin Swamp … flow passes only during intense rainfall

So
- Preserve vegetation & low-flow status to contain salt
- Could be a problem if discharge commences & vegetation is lost, allowing watertable rise
- Watch for increase in vegetation and soil stress
- Monitor WL and TDS (Hons student)

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Vegetation management - past

Repeated cycles of clearing & salinity, reforestation & recovery

- 1900s to 1970s
- Fires & thinning

So

- Do not want clearing or alienation
- May not want burning or thinning in some areas
- Vegetation management (and reforestation) can maintain as WR catchment

1970s management was very successful

- Repurchased and reforested to leave only 5% private, 3% cleared
- Salinity of 1500 mg/L averted
- Now just over 500 mg/L, not changing drastically

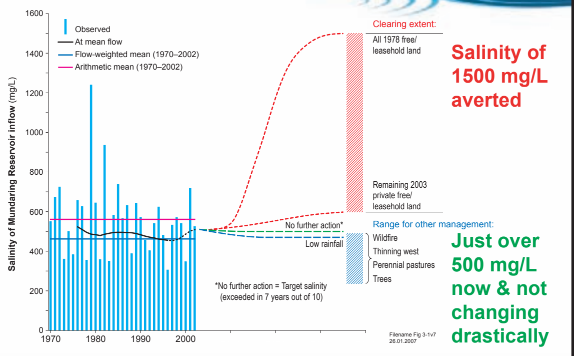
So

- Continue management and reduce cleared area
- Maintain clearing controls and forest

Repurchased & reforested leaving only

5% private 3% cleared

Mean values - so could go higher

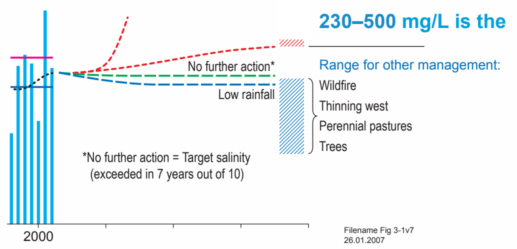


Vegetation management for potable inflow

Why

- Modelling shows 230–500 mg/L for a range from commercial trees, perennials, thinning and burning

Vegetation management for potable inflow



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How vegetation management can deliver potable inflow

- Priority to manage (change or reforest) remaining cleared areas, possibly purchasing more land
- Continue silviculture

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Vegetation management - farmland

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No more clearing on private land

Why

- Repeated cycles of salinity after clearing
- Reservoir inflow exceeds 500 mg/L
- Land clearing remains the major risk

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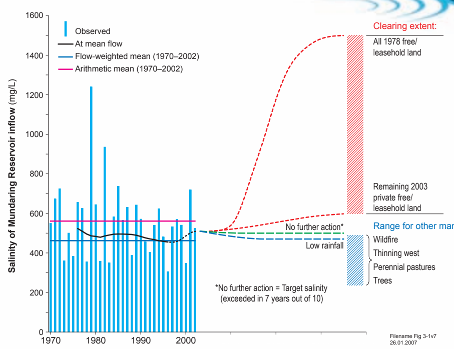

Land clearing still the major risk

cf 1978 threat of 1500 mg/L, clearing 2003 private land gives 600 mg/L

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Manage the small cleared farmland areas

Why

- Only 3% but still 500 mg/L
- Some outside the CAWS clearing control boundary where it does not correspond to the catchment boundary

So

- Deep-rooted perennials or commercial trees in 23 km^2 flowing part to gives 270 or 230 mg/L
- Best options
- Target catchment boundary, mainly NE as SE very low flow

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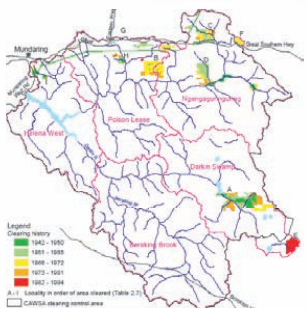
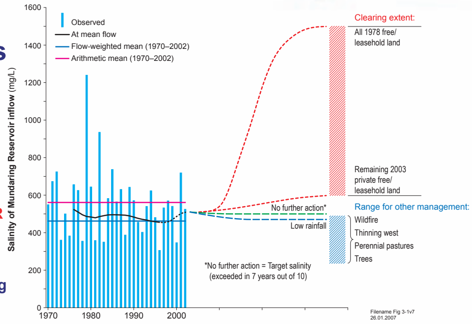
Manage the small existing cleared farmland areas



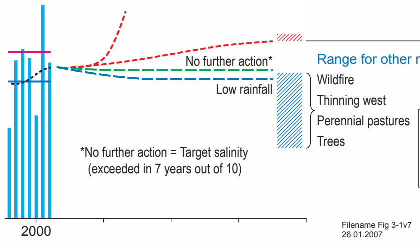
Especially outside the CAWS clearing control boundary in the NE (the SE flows to swamps)

Best options



270 mg/L for deep-rooted perennials OR 230 mg/L for commercial trees - in the 23 km² flowing

Best options



270 mg/L OR 230 mg/L - in the 23 km² flowing

No more clearing on private land

- Reforest and if necessary purchase priority (if not all) cleared land
- No more clearing as this will increase salinity e.g. even the 2003 scenario gives 600 mg/L
- Reforest government freehold land near Abercorn Road
- Maintain clearing controls

Further actions & priorities to consider

- Reforest and if necessary purchase priority (if not all) cleared land
- Reforest government freehold land near Abercorn Road
- Maintain clearing controls

Priority areas to reforest are in the Ngangaguringuring and Poison Lease MUs

A significant area of cleared farmland is actually within the catchment

- CAWS boundary is not the hydraulic boundary
- NE flow is saline, SE flow is to swamps

So

- Influence land use in NE
- Watch the swamps

Priority areas to reforest are in the Ngangaguringuring and Poison Lease MUs

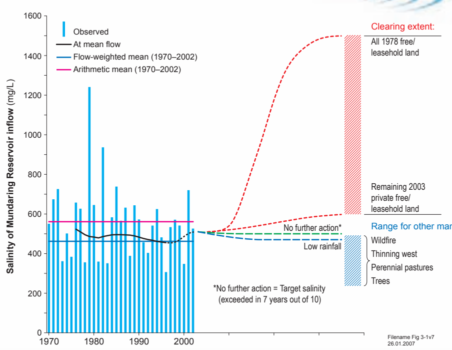
- If not reforesting, use deep-rooted perennials

Vegetation management - forest

Silviculture improves salinity and yield - only slightly and only in the west

- Modelled gap creation, thinning and shelter wood in west and east
- Much larger areas than farmed, for less effect
- Not possible in the 38% that is National/Conservation Parks
- No concern at Flynn, low rainfall (700–800 mm/yr)

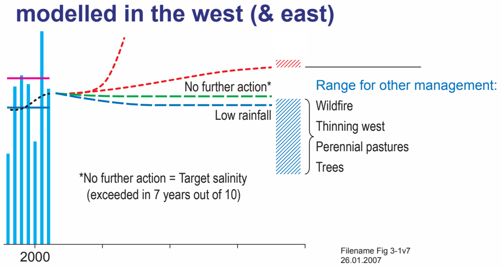
Silviculture improves salinity and yield - only slightly, only in the west



Gap creation, thinning & shelter wood

modelled in west (& east)

Gap creation, thinning & shelter wood modelled in the west (& east)



Forest areas much larger than farmed, but less effect

Not possible in the 38% National or Conservation Parks

Manage existing plantations with hydrogeology and yield in mind

- 1900–40s planted high water use (HWU) trees in west
- Sedimentary aquifer not fully forested

So

- Thin/change HWU trees in west and on streamlines to increase runoff
- Plant HWU trees on sedimentary aquifer to reduce discharge

Manage existing plantations with hydrogeology and yield in mind

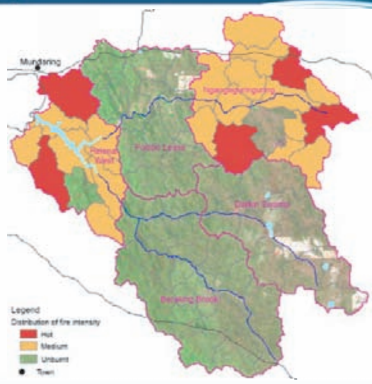
- West - thin
- Riparian - thin
- Aquifers - HWU

Burning and wildfire only temporarily increase runoff and slightly lower salinity

- Initial dramatic change but then vegetation thickens to use even more water e.g. Helena Brook in late 1990s, now watching Jan 2005 Little Darkin fire recovery

So

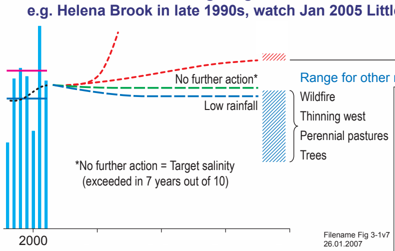
- Only of benefit in west
- Must be ongoing and frequent e.g. 4 yearly gives 440 mg/L
- Control dense regrowth in higher rainfall areas to increase low salinity runoff



Burning and wildfire only temporarily increase runoff and slightly lower salinity

Burning and wildfire only temporarily increase runoff and slightly lower salinity

After Initial dramatic change vegetation thickens to use even more water e.g. Helena Brook in late 1990s, watch Jan 2005 Little Darkin fire recovery



- Only of benefit in west
- Must be ongoing, frequent e.g. 4 yearly gives 440 mg/L
- Control dense regrowth in higher rainfall areas to increase low salinity runoff

Control of dense regrowth in higher rainfall areas would increase runoff of relatively low salinity & decrease the overall inflow salinity

Why

- Demonstrated by modelling
- Little Darkin fire in 2005

So

- Manage native vegetation and pines

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Conclusion

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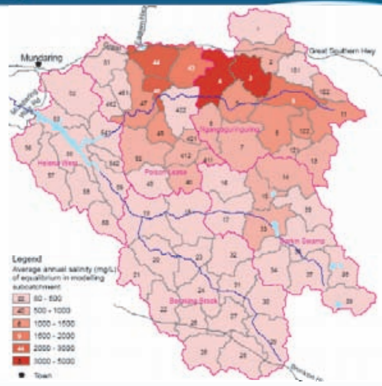

Average annual salinity at equilibrium for all cleared private land planted with trees

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The most impact on inflow salinity will come from vegetation management on the 3% cleared farmland but maintenance of the total forest underpins this

So

- **Manage cleared areas as top priority, then forests**

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The most impact on reservoir inflow salinity will come from vegetation management on the 3% cleared farmland - underpinned by maintenance of the forest

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Rose-tipped mulla mulla

Appendix 7 — ‘A fresh future for water’ brochure

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A fresh future for water

Helena River — Salinity Situation Statement

What is this Salinity Situation Statement?

Revegetation and forest management may, without further engineering, reduce the salinity of the Mundaring Reservoir inflow to below 500 mg/L (the potable limit). The Helena River Salinity Situation Statement is a major review of the Helena (River) Water Resource Recovery Catchment (WRRC) above the Mundaring Weir. It describes the effects of past changes and of future management scenarios.

Salinity recovery of the Helena River for the third time — the way forward

The Mundaring Reservoir supplies the Goldfields and Agricultural areas and is one of the larger surface water resources in the south-west of Western Australia, with a capacity of 63.6 GL and a mean annual flow of 17.1 GL.

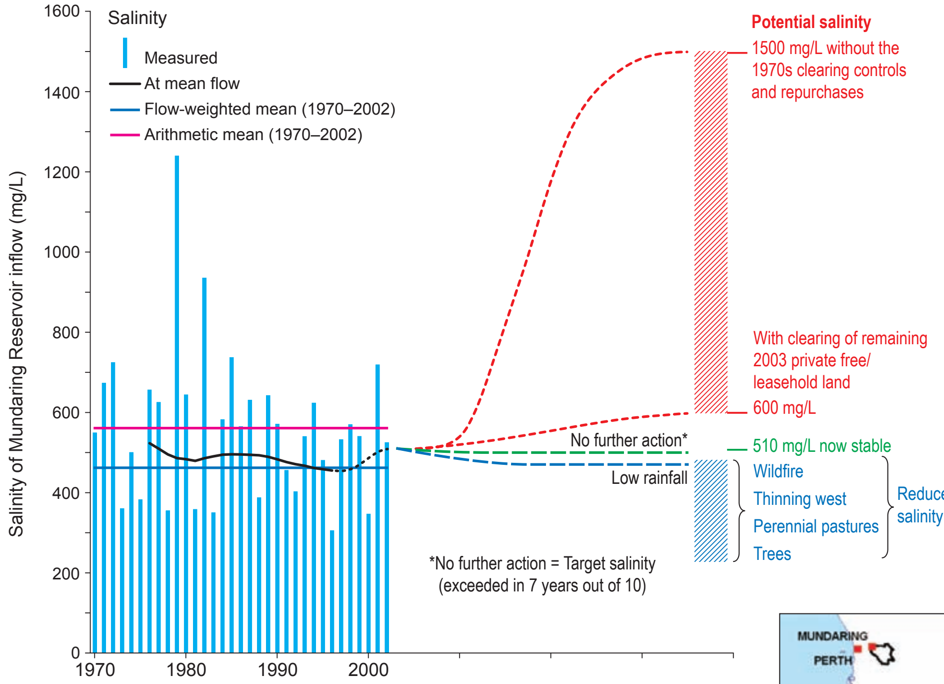

Figure 1 Salinity of inflow to Mundaring Reservoir

www.water.wa.gov.au

1

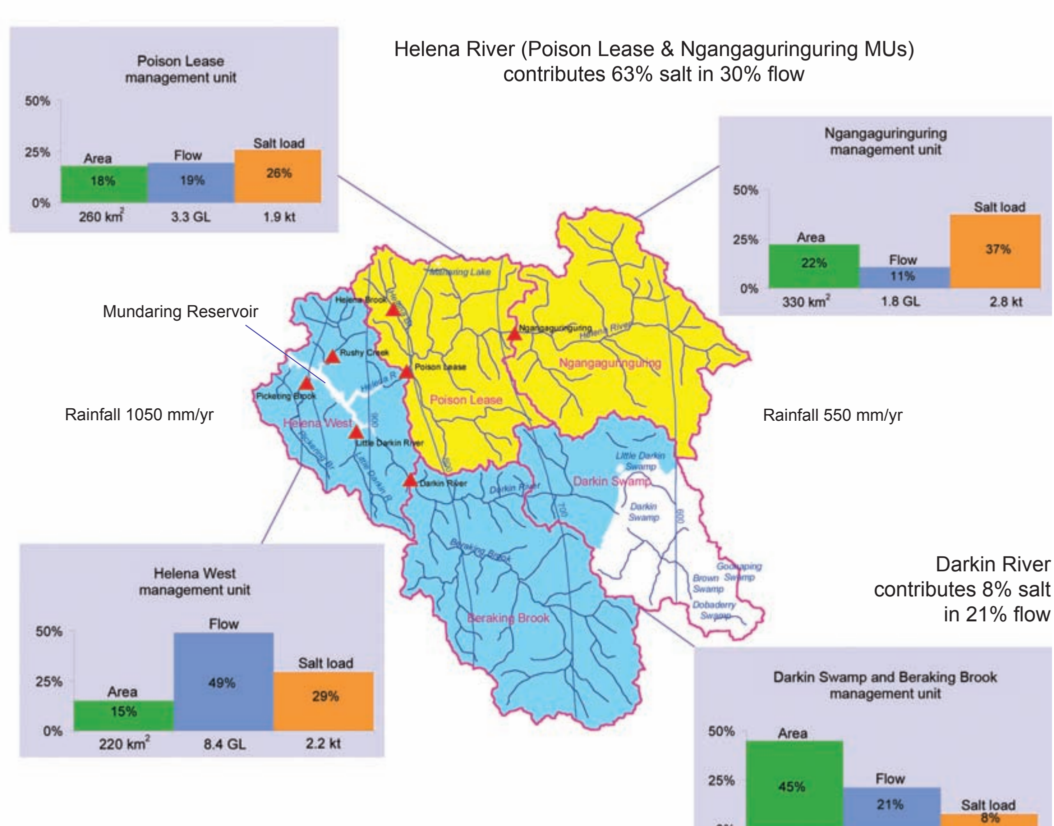

Figure 2 Flow and salt load contributions to the reservoir

This water resource has always been sensitive to even small areas of clearing, and recovery to potable salinity has required revegetation from 1908 and for a second time from the 1960s to 1980s, followed by clearing controls from 1978. Even so, since 1981 low-salinity pumpback, from downstream and from dams and groundwater supplying metropolitan Perth and Mandurah, has provided up to 60% of the annual abstraction. From 1996, the Salinity Action Plan tasked the Department of Water, formerly the Water and Rivers Commission, to work with the community and to investigate how salinity could for a third time be recovered to potable levels.

Key findings of the study include:

- Reduction of inflow salinity to potable levels would follow a) replacement of up to half of the current annual pasture with commercial trees or deep-rooted perennial pastures (Fig. 1), b) pumping to intercept groundwater seepage, or c) diverting saline flow out of the Helena River.
- The flow-weighted inflow salinity (1990–2002) is 510 mg/L with a range 305–719 mg/L (Fig. 1).
- The salinity of the inflow is projected to decrease to 470 mg/L if rainfall remains below average.
- The Helena River contributes 63% of the reservoir's salt load and only 30% of the inflow (Fig. 2), including substantial discharge from recently recognised palaeochannel sediments.
- Only 3% of the catchment is cleared but less than half of this, within the northern Ngangaguringuring and Poison Lease Management Units (MUs), contributes most of the salt.
- Before the Mundaring Weir was constructed in the early 1900s, the Helena River was fresh — about 290–370 mg/L Total Dissolved Solids (TDS) — but after nearby ringbarking the reservoir salinity rose to 550 mg/L.

Salinity trends in the Helena River

In the period 1990–2002, the average annual salinity of reservoir inflow was 510 mg/L and steady. Most of the salt load (63%) came from the Helena River with only 30% of the inflow.

2

In the 1960s, the flow-weighted annual inflow salinity was above 500 mg/L following post-war land releases and clearing. The pumpback dam constructed in 1971 provides up to 60% of the water supply in dry years. From 1956 to 1978 concerns that this potable water source might be lost led the State to repurchase some land and to extend the powers of the *Country Areas Water Supply Act 1947* to regulate any further loss of native vegetation. (The State did not preclude further Crown land release in this catchment as it had in the Wellington Dam to Denmark River catchments).

Because the north-east and south-east catchment boundaries were not then accurate, there was significant further clearing — legally. Despite this, and with the clearing controls effectively in place from 1978 and extensive plantations established in the period 1967–80, the cleared area of the 1480 km^2 Helena (River) WRRC has not risen significantly beyond 3% (~39 km^2).

With tree planting mostly in the higher rainfall western half, and also along the main rivers and on isolated sand patches, 97% of the catchment is now covered with either native forest or plantation timber. The remaining 3% cleared land, in the lower rainfall north-east and south-east, has mainly annual pasture. Only half of the cleared land (in the north-east) regularly contributes flows to the reservoir, as the other half drains to Darkin Swamp which retains surface water from the south-east except in prolonged high-rainfall periods.

Management options

Despite the beneficial effects of the clearing controls and the tree plantations, further land-use changes or engineering works will be required to meet the target salinity (Fig. 1). The salinity of the Mundaring Reservoir inflow is predicted to remain at 510 mg/L TDS — just above the 500 mg/L target — unless there is additional work or the low rainfall continues beyond 2003 (the end of the study period). Options that could achieve the target salinity include:

Replanting most of the cleared area with trees

Planting trees on at least half of the currently cleared land (Fig. 1) is predicted to lower salinity to 230 mg/L. The trees reduce groundwater recharge and saline discharge to the Helena River. Revegetation with commercial trees is more effective than a) changing to deep-rooted perennial pastures, or the changes that follow b) thinning of forest, c) prescribed burning or d) wildfire, in that order.

Establishing a groundwater pumping scheme

Groundwater pumping would not reduce the salt load but, by reducing water loss, would decrease the Helena River salinity by an estimated 200 mg/L and lower the reservoir inflow salinity below 500 mg/L.

Diverting the full flow of saline water from the Helena River

While diverting the full flow out of the Helena River at either of its two upstream gauging stations would lower salinity to well below 500 mg/L, both would greatly reduce inflow to the Reservoir.

How effective are the revegetation options?

Only half of the currently pastured land needs to be planted immediately with commercial trees or perennial pastures (Fig. 3, F), especially over the aquifers (Fig. 4, Flynn). The remaining pastured land, not continuously contributing flow, should be monitored and if feasible also planted with trees or deep-rooted perennial pastures.

Maintain the existing forest on 97% of the catchment, especially over the sedimentary aquifers but consider thinning for increased water yield in the high-rainfall west and in the riparian zone (Fig. 4).

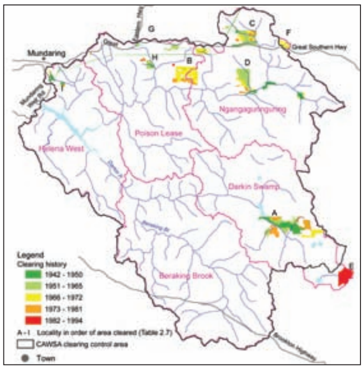

Figure 3 Manage the small existing cleared farmland areas — especially outside the north-east boundary (F) but also the south-east boundary (E) where flows are into swamps

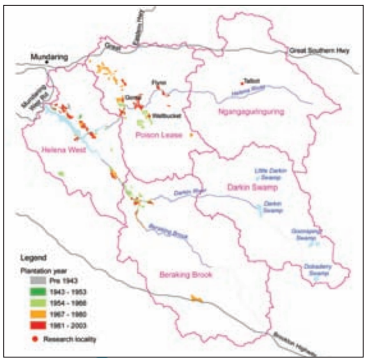

Figure 4 Manage existing plantations with hydrogeology and yield in mind — thin trees in the west and in riparian areas, but plant high-water-use trees above sedimentary aquifers near Flynn

3

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Table 1 Projected reservoir inflow for key management scenarios

Scenarios		Area affected (km²)	Reservoir annual inflow Salinity (mg/L)	Streamflow (GL)	Salt load (kt)
Base case	*No change*	0	500	20.1	7.7
Decreased rainfall		1480	470	15.9	6.9
Present clearing risk (1978 free/ leasehold land to annual pasture)		157	1500	31.4	30.5
Cleared areas	*Farm management*				
Continue with annual pastures as for base case		39	500	20.1	7.7
Change to deep-rooted perennial pastures		23	270	19.7	5.4
Change to (commercial) trees in Poison Lease and Ngangaguringuring MUs		23	230	18.6	4.1
Timbered areas					
All 2003 scene cleared for annual pasture		30	600	24.5	10.9
Thinning by 30% (transient effects)	*Forest management*				
In the east (Ngangaguringuring MU)		328	480	20.7	7.8
In the west (Helena West MU)		221	460	22.7	7.9
Prescribed burning (transient effects)					
In the east (Ngangaguringuring MU)					
On a 4-year cycle		328	460	20.6	7.8
On a 12-year cycle		328	500	20.2	7.7
In the west (Helena West MU)					
On a 4-year cycle		221	440	22.4	8.0
On a 12-year cycle		221	480	20.8	7.8
Hot wildfire (transient effects) based on January 2005 wildfire					
In the east (Ngangaguringuring MU)		328	490	20.5	7.7
In the west (Helena West MU)		221	470	22.6	7.9

A partnership approach

In April 2005 the State Government convened a workshop about meeting the water-quality target in the Mundaring catchment, to brief stakeholders, and to foster partnerships between state government agencies, NRM groups, local government, industry, research institutions, local community groups and consultants.

From April 2006 most of these participants reviewed and provided further input to the 'near-final draft' Helena River Salinity Situation Statement.

Where to from here?

This study focuses on conceptual salinity reduction options — to understand the extent of the land-use changes needed to reach the salinity target. It is the first step in the recovery approach illustrated in Figure 5.

The next step will be the evaluation of the management options from this study in consultation with key stakeholders. Scenarios to meet defined water quality objectives will be evaluated, considering social, economic and environmental aspects, and using more detailed modelling.

The recovery plan step will identify the major components of management options to be implemented, develop an implementation strategy and identify funding sources.

The final step will be to implement this plan and to recover this catchment from salinity.

Figure 5 The recovery approach

Where can you go for more information?

For more information contact Robin Smith, Department of Water, on (08) 6364 7818 or email salinity@water.wa.gov.au.

For copies of the Salinity Situation Statement report (WRT 34) contact the Department of Water (08) 6364 6500.

Copies of this brochure and the complete report *Helena River Salinity Situation Statement (WRT 34)* are also available from www.water.wa.gov.au at Water management> Salinity> Water Resource Recovery Catchments> The Helena River.

May 2007. Written by Robin Smith

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