Groundwater & Salinity Processes in Simmons Creek sub-catchment, Billabong Creek, NSW

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CSIRO Land and Water, Canberra
Technical Report 24/02, December 2002
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Front cover: Lower reach of Simmons Creek, NSW, intersecting a shallow watertable and functioning as a drain for highly saline groundwater inflow to Billabong Creek. View downstream, westward towards the Sugarloaf.
EXECUTIVE SUMMARY

Introduction

Simmons Creek sub-catchment is part of the upper Billabong Creek catchment in the NSW Riverine Plain. It represents a local-scale alluvial and weathered bedrock aquifer system. Distinctive features, in terms of groundwater and salinity processes, include a catchment-wide sub-surface basement high that greatly influences both groundwater flow and the location of major salt stores, and the significant depth of incision of Billabong Creek channel at the down-gradient end of the catchment. Both these natural geologic features govern hydrogeologic processes, particularly the accumulation and steady discharge of saline groundwater.

The Simmons Creek study was undertaken to:

1. Provide a conceptual understanding of groundwater systems in the catchment.
2. Define the patterns and processes of recharge, pathways of salt transport and groundwater discharge.
3. Contribute to an understanding of landscape processes in areas affected by, or at risk from, high watertables and salinity, including an understanding of the relative importance of salt transport via surface and near-surface wash-off processes versus baseflow.
4. Contribute to an understanding of the mechanisms controlling the generation and delivery of salt to streams in riverine landscapes generally.

These aims were directed towards the National Dryland Salinity Program (Land & Water Australia) Project CLW28: Generation and delivery of salt and water to streams. The investigation also interlinks with the Murray-Darling Basin Commission (MDBC)-CSIRO Heartlands Initiative by providing fundamental groundwater and salinity information towards the implementation of targeted tree planting for sustainable catchment management in the Riverine Plain.

Site description

Simmons Creek catchment is located at the eastern edge of the Riverine Plain, adjacent to the uplands of the Lachlan Fold Belt and immediately east of the township of Walbundrie. The mean annual rainfall is close to 550 mm, with most precipitation falling in the winter months. The catchment covers an area of 178 km² and is rimmed with low granite hills. Valley-fill alluvium over weathered granite is highly variable in thickness (0-100 m). Flat valley floors characterise the drainage system up-catchment from the floodplain. The southern part of the catchment is dominated by the low-gradient Billabong Creek floodplain. Billabong Creek is steeply incised into the floodplain sediments, with the creekbed at 10-12 m below the adjacent landscape surface.
All creeks are ephemeral, except Billabong Creek which rises in mountains in the higher rainfall zone to the east. The lower reach of Simmons Creek intersects the watertable in a clay-rich alluvial aquifer whereupon the channel functions as a groundwater drain that exports highly saline groundwater (half the salinity of sea-water) directly to Billabong Creek. The catchment is 90% cleared and now supports grain crops and sheep and cattle grazing.

**Groundwater system**

Simmons Creek catchment represents a local groundwater flow system, with relatively short groundwater flow paths in alluvium and underlying weathered bedrock. The upper aquifers, 0-20 m depth, are mainly poorly permeable clay-rich fluvial-lacustrine sediments of the Quaternary Cowra (or Shepparton) Formation. This shallow aquifer system includes subordinate shoestring sand lenses nearer Billabong Creek. The uppermost sediments include a blanket of silty-clay “parna” deposits that were originally aeolian dust accessions. Parna is believed to have brought substantial salt into the Riverine Plain from the arid Mallee district to the west. Significant latter-day salt accessions are now stored in these upper clay-rich strata, particularly where the drainage system is poorly developed.

Deep alluvial aquifers comprise sandy clays and subordinate gravels. Beneath Billabong Creek, where incised granite basement is at up to 100 m in depth, the deeper alluvium is probably correlative with the Late Tertiary Lachlan (or Calivil) Formation. Intensely weathered granite (“saprolite”) also functions as an aquifer beneath the lowlands, although where this material is dominated by kaolinite clay, such as underlying the mid-catchment swamp area, it tends to function more as a salt store and an aquitard.

The sub-surface basement architecture, or palaeotopography, greatly influences the hydrogeology of the catchment. Buried granite highs extend diagonally across the catchment and, to a substantial extent, partition the groundwater system. Dense palaeolacustrine or palaeo-swamp clay underlies present-day ephemeral swamps in the constricted mid-catchment area, immediately north of the zone of basement highs. Southwards groundwater flow from the northern two-thirds of the catchment is partially constricted both vertically and laterally by the basement barrier of intensely weathered granite and the adjacent plug of heavy clay, and by bedrock hills to the east and west. The occluded mid-catchment area functions as a sump where – additional to swamp sediments in the past – ancient salt stores have accumulated. Groundwater appears to pond up-gradient from the constricted area, resulting in high watertables in mid-catchment aquifers. For example, the watertable is at approximately 4 m depth beneath Wiesners Swamp in the lower-mid catchment area, and is also highly saline. The nature of any deeper aquifer system beneath this constricted mid-catchment area is unknown.

In the catchment as a whole, steep hydraulic gradients correspond with fresh groundwater and more readily flushed aquifers. Low hydraulic gradients correspond with saline to highly saline groundwaters because of sluggish or impeded throughflow. In the shallow aquifer system in general, there is an inverse relationship between hydraulic conductivities and groundwater EC.
Beneath much of the Billabong Creek floodplain the watertable is at 4-6 m depth, and salinities (electrical conductivity, EC) range from fresh to 32000 µS/cm. Hydraulic gradients and hydraulic conductivities are both low in this shallow aquifer system. Saline groundwater is discharging directly to the lower tract of Simmons Creek, to sparse topographic low areas, and via seepages in the bank of Billabong Creek. The hydraulic gradient here, at the southern edge of the system, does not seem to be a driving mechanism for groundwater discharge into Billabong Creek. Rather, it is the juxtaposition of the considerable depth of incision of Billabong Creek and the shallow depths of watertables in the adjacent floodplain aquifers that culminates in groundwater seepage into the creek. Catchments that are otherwise similar to Simmons Creek catchment may have creekbeds elevated above the level of the floodplain watertables by virtue of more shallow incision of the trunk drainage channel. In the latter scenarios, the delivery of saline groundwater directly to main streams may be much less of an issue.

The shallow aquifer system is not widespread in the northern half of the Simmons Creek catchment. Where present in the north, it appears to be perched groundwater in localised pockets underlying main creekbeds where the valley floor is broad and flat. For the most part, however, watertables in the north are at depths exceeding 40 m, and the associated groundwater is fresh to brackish, so the potential problems of waterlogging and salinity seem to mainly be an immediate concern in the southern half of the catchment.

Conclusions

Ground geophysical methods and shallow drilling have enabled identification of both saline groundwater and regolith units that contain appreciable salt stores in Simmons Creek catchment. Salt transport via baseflow – direct groundwater inflow to the stream – is far more important than transport via surface and near-surface wash-off processes. Salinity processes in the catchment are entirely groundwater driven.

Highly saline groundwater and major salt stores are largely confined to the uppermost 15 m of strata, particularly in the southern half of the catchment. Deeper aquifers contain relatively fresh groundwaters. Extensive areas of the upper strata in the lowlands are clay-rich and poorly transmissive and contain salt stores in the unsaturated zone as well as saline groundwater in the phreatic zone. The contribution of mobilised stored salt to increasing stream salt loads is an important component of salinisation processes in the region. Stored salts were originally sourced from accumulations of cyclic salts derived from rainfall, from rock weathering, and from former aeolian silty-clay accessions that were deposited in sheets (termed 'parna') across the landscape during windy periods of at least the past 50,000 years. Salt that was once entrained with fine-grained windborne clay aggregates would have been largely flushed from the system soon after the clays were deposited as parna blankets. Latter-day cyclic salt accessions, however, have subsequently accumulated in widespread reworked parna deposits. Salt sequestration in this case is a function of the distinctive crumbly texture and clay-rich composition of parna in much of the Riverine Plain. Structurally occluded, poorly transmissive saprolitic granite and palaeolacustrine clay bodies in the mid-catchment area also function as important near-surface salt reservoirs.
Salt exports from the catchment exceed present-day salt imports because of remobilisation of ancient salt stores under current hydrologic conditions, which involve high watertables and probably some excess recharge. This state of salt disequilibrium is expected to persist through future decades, possibly much longer. In the interim, the saline groundwater system needs to be monitored and managed to avoid further environmental degradation and depressed productivity of agricultural land.

Mitigation measures, if executed, need to be directed towards the catchment groundwater system. Further rises of watertables need to be averted because the higher the watertable, the greater the saline discharges to Simmons Creek, to topographic low areas in the floodplains and to Billabong Creek. Management options, including revegetation and modified farming systems, also need to be aimed at recovering soil health and at conserving or restoring habitats and biodiversity. Agronomic strategies are likely to be beneficial within a relatively short timeframe because the recharge and discharge areas are in close proximity to each other, because saline groundwater is largely restricted to the uppermost aquifers, and because land salinisation is not yet at an advanced stage. A high priority for catchment management in the future is to protect Wiesners Swamp Nature Reserve from environmental degradation (through stock grazing) and from potentially rising saline groundwaters that will imperil the woodland of ancient eucalypts and juvenile regrowth.

The findings and results of investigations in Simmons Creek catchment for the present study contribute to an understanding of mechanisms controlling the generation and delivery of salt to streams in eastern riverine landscapes generally, particularly in the 500-800 mm rainfall zone and where clearing of native vegetation commenced well over 100 years ago.

Drought conditions during 2001-2003 have hampered efforts to fully constrain hydrologic fluxes and to clearly define recharge zones and recharge dynamics for the catchment during the course of the present study. Accordingly, the network of piezometers that have been installed with automatic data capacitance loggers will continue to be monitored until well after the next substantially wet year, when more succinct and targeted management recommendations can be framed.
This technical report is a collation of information collected in late 2001 and 2002 for the groundwater components of Project CLW28 (National Dryland Salinity Program, Land & Water Australia) and the Murray-Darling Basin Commission (MDBC) – CSIRO Heartlands Project, for which Simmons Creek is one of the focus catchments. A background overview plus analysis of the available hydrogeological and geophysical data are presented here. The focus is on the shallow groundwater system. Preliminary interpretations are included to present our current understanding of the groundwater system and specific attributes of the study area relevant to the occurrences of high saline watertables and salinisation of Billabong Creek, the trunk drainage channel through the region. This compilation is aimed at facilitating integration of the groundwater information with terrain and soil/regolith analysis and salinity management planning for the catchment. This initial reporting will be supplemented after the present drought breaks, when greater responses are expected to be recorded in the network of monitored piezometers. Simmons Creek catchment has recently been covered by MDBC-funded Airborne Electromagnetic (AEM) survey (outlined in Section 1.1). This present work – which is based on conventional hydrogeological techniques – will serve as a base-line study for interpretation and assessment of the AEM data for the area.
ACKNOWLEDGEMENTS

The authors acknowledge funding from Land & Water Australia, Project CLW28: Generation and Delivery of Salt and Water to Streams, and from the Murray-Darling Basin Commission (MDBC) for the Heartlands Project. (MDBC Project D10003). CSIRO Land & Water colleagues involved in collaborative components of the Heartlands Project (Land and Soil Surveying, and Farm Systems Modelling): Hamish Cresswell, Zahra Paydar, John Gallant, Mark Glover, Linda Gregory, Neil McKenzie and Andrew McPherson, have supported the groundwater and salinity components of the research. Alma Park – Pleasant Hills Landcare Group representative, Bernie Coyle, provided support in the field. The landholders are thanked for their interest in and support of our work and for access to their properties. The NSW Department of Land and Water Conservation (DLWC) provided stream gauging and groundwater data and collaboration for the study. Geophysical imagery was provided by the MDBC; processing of the geophysical datasets was by Geoscience Australia and the Bureau of Rural Sciences (BRS). Glen Walker, CSIRO Land & Water, provided pertinent insight during the course of this project. Sincere thanks are extended to Ian Jolly, CSIRO Land & Water, Nimal Kulatunga, DLWC, and Peter Baker, BRS, for reviewing this report and for providing positive input and constructive comments.
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1 INTRODUCTION

1.1 Introduction

1.1.1 Stream salinity trends – Billabong Creek
The upper Billabong Creek catchment (Figure 1) is identified as a region of major concern in terms of stream salinisation. Billabong Creek at Walbundrie shows one of the highest significant rising stream salinity trends in the Murray-Darling Drainage Division (Williamson et al., 1997; Jolly et al., 1997a). The mean EC of Billabong Creek at Walbundrie is around 1300 µS/cm. For the period 1981-1991 there was an increasing EC trend of approximately 60 µS/cm/year (Jolly et al., 2001), although it is noted that rainfall was relatively low for some of this gauging period. The data represents an annual salinity increase of 4.7%. This is by far the greatest increase in streams of the Murrumbidgee-Riverina region. Within the whole Murray-Darling Basin, only two of the 87 gauging stations in 26 sub-basins analysed by Jolly et al. (2001) show EC trends greater than Billabong Creek. The latter sites are in the lower Loddon and lower Avoca Rivers in the semi-arid Mallee district (Figure 1) where an enormous legacy of widespread intense natural salinisation processes from the Quaternary has been inherited.

Salinity traverses of Billabong Creek conducted by the NSW Department of Land and Water Conservation (DLWC) in the late 1990s identified reaches of the creek where substantial inflows of saline groundwater occur. These include the ~17 km stretch of Billabong Creek that borders the Simmons Creek sub-catchment (Figure 2). A 380 µS/cm increase in stream salinity was measured between Morgans Lookout in the east and Walbundrie in the west (Alamgir, 1999). In particular, a 6 km tract of the creek near Morgans Lookout, between the Walla Walla and Brooklyn bridges (labelled in Figure 2), showed a 1000 µS/cm increase in salinity, from 2020 to 3130 µS/cm, attributed to groundwater inflow (Williams and Kulatunga, 2001). It has been suggested that direct adverse biological effects are likely to occur in Australian river stream and wetland ecosystems when salinity levels reach EC levels of 1560 µS/cm (NSW DLWC, 2000).

The average creekwater salinity at Walbundrie for 2001 was 1700 µS/cm (DLWC data). This high stream salinity reflects the low rainfall and low stream flow rates for the year which resulted in limited dilution of salt loads downstream from the main runoff areas of the upper Billabong Creek catchment in the eastern uplands. Drought conditions have persisted through to early 2003 and a very high salinity of 5876 µS/cm was recorded at Walbundrie on 22/02/2003, for example, when stream flow was low, representing a salt load of 7.6 tonne/day. Typical salinities of Billabong Creek for a major wet period have not yet been clearly identified.

1.1.2 Winter rainfall zone
The upper Billabong Creek area lies within the 500-800 mm/year rainfall zone of southeastern Australia (Figure 1) where 50% of the Murray-Darling tributaries have significantly rising stream salinity trends. In contrast, the change in salt balance has been minimal in areas of higher rainfall, >800 mm/year (Jolly et al., 2001). The latter is
a function of greater and more constant flushing and dilution of salt accessions through time from the topographically steep, higher rainfall zone and also because of less land clearing in the mountainous areas and greater distances from the major sources of aeolian saline dust. Much of the >800 mm rainfall zone is drained by rivers flowing directly to the southeastern seaboard, so the salts are more readily flushed to the ocean. Together, these factors tend to result in smaller salt stores compared to the plains and less perturbation and mobilisation of any resident salt.

Figure 1. Murray-Darling Basin with rainfall zones delineated. Billabong Creek is labelled and the upper Billabong catchment (upstream from Walbundrie) is outlined. Seasonal maximum rainfall subdivision based on median monthly rainfall (Summer: November - April; Winter: May - October).

In the <500 mm/year rainfall zone of the Riverine Plain, in comparison, low rainfall tends to implicate low or slow remobilisation of resident salt. In this zone, the relative lateness of changes in agricultural land use may imply that stream salinity trends and catchment salt imbalances have not yet peaked, except perhaps where the streams cross-cut the naturally-salinised parts of the Mallee where highly saline watertables have long been close to the landscape surface. In much of this semi-arid part of the country, the landscape was subject to widespread primary salinisation tens of thousands of years ago, so we have not witnessed as radical a change in the status quo in recent decades as in the 500-800 mm rainfall zone. Elsewhere in the <500 mm/year rainfall zone, in the Darling Basin, it has been predicted that salinity is likely to develop more slowly than in southern parts of the Murray-Darling Basin. This is because the character of the soils, land use and vegetation of the Darling Basin contribute to less severe salinisation compared to large parts of the Murray Basin (Jolly et al., 2001). Another factor is the effect of summer dominance of rainfall or a more uniform distribution of rainfall seasonality. For a given rainfall zone, a lower evaporation-precipitation ratio (E/P)
during the hottest months can offset evaporative water loss and the associated concentration of solutes.

For a given annual rainfall, catchment leakage rates – and potential groundwater recharge rates – tend to increase as rainfall becomes more winter-dominant. This is because plants use less water in winter than in summer (Silberstein et al., 2002). In the winter-dominated rainfall zone across the southern part of Australia (south of the red line in Figure 1), summers are dry and water deficit is at the maximum, with potential evaporation rates greatly exceeding precipitation rates. This favours evaporative concentration and salinisation as water vapour is lost to the atmosphere from near-surface watertables and from soil profiles, with solutes being cumulatively left in the landscape as efflorescent salt. Accordingly, management and mitigation works in the immediate future need to substantially focus on the southern 500-800 mm rainfall zone where land clearing has been extensive and dryland (or “rainfed”) agriculture is well-established, where there has been major perturbation of resident salt stores since the mid-1800s, and where the highest stream salinisation increases are being recorded.

1.1.3 Catchment salt balances
In their analysis of data from 101 Murray-Darling Basin gauging stations, Jolly et al. (1997b; 2001) calculated catchment salt balances from the ratio of salt output to salt input. This analysis pinpointed regions that are not in equilibrium. Salt output was based on catchment areas and on salt loads at stream outlets. Salt input data was sourced from Blackburn and McLeod (1983), based on catchment areas, annual rainfall and measurements of salt concentrations in rainfall across the basin. Salt output/input (O/I) ratios of >1 designate areas of the basin that are in salt disequilibrium, i.e., where accumulated salt is being mobilised and is contributing substantially to stream salt loads. Billabong Creek catchment upstream from Walbundrie has an O/I ratio of 3.7 (Jolly et al. 1997b; 2001), which is amongst the highest ratios in the Murrumbidgee-Riverina region. Catchment salt balance and stream salinity trends, together, demonstrate the consequences of mobilisation of accumulated salt stores in dryland areas, and the effect on stream salinity. The present study, accordingly, focuses on the nature of accumulated salt stores, to help explain processes contributing to the observed high salt loads in Billabong Creek.

At the synoptic scale, most of the stream flow in the main drainages that cross the low-gradient 500-800 mm/year rainfall zone – the River Murray, Billabong Creek, the Murrumbidgee and Lachlan rivers – is derived from further east, from the uplands in the >800 mm/year rainfall zone. Episodic runoff from the lower rainfall zone catchments themselves contributes little towards dilution of salt loads in the trunk drainages. Thus, the uplands contribute relatively large quantities of fresh surface water and the lowlands contribute relatively large quantities of saline groundwater to the main rivers.

1.1.4 Complementary research in Billabong Creek catchment
The National Land and Water Resources (NLWRA) Audit Dryland Salinity Theme assessed salinity management options for Billabong Creek. A rising trend in groundwater levels was noted and various modelling techniques were applied, involving postulated broad-scale land use change to reverse this trend (Baker et al., 2001).
The draft plan for the MDGC – CSIRO *Heartlands Initiative* selected upper Billabong Creek as one of the focus catchments for designing management strategies and implementing on-ground works towards sustainable land use in the Basin (Heartlands Core Group, 2000). Four catchments for *Heartlands* work, two in NSW, Billabong Creek and Kyeamba Creek, and two in Victoria, Honeysuckle – Sheep Pen creeks and the Mid-Ovens Basin, were selected in partnership with respective Catchment Management Authorities and Boards and local communities, because of pressing land management difficulties in these particular areas. Investigation of groundwater processes in Billabong Creek and Honeysuckle Creek forms Project 5 of the *Heartlands* research program and is directed at determining spatially explicit recharge targets to ameliorate salinisation.

CSIRO Land & Water Project CLW28, *Generation and Delivery of Salt and Water to Streams*, is a project within the National Dryland Salinity Program (Land & Water Australia). The goal of the project is to develop an understanding of landscape processes and ecosystem functions in areas affected by, or at risk from, high water tables and salinity. One such area is Simmons Creek sub-catchment in the upper Billabong drainage system. The underlying purpose of this project is to resolve the mechanisms that control the generation and delivery of salt to streams in riverine landscapes. This understanding, in turn, is aimed at informed management of salinity to improve farmer’s terms of trade and to restore biodiversity. Four reports for Project CLW28, submitted to Land & Water Australia in August 2002, complement the present report: Cresswell (2002), Hook *et al.* (2002), Gallant and Paydar (2002), and McKenzie *et al.* (2002).

In the Billabong system, the rising trend in stream salt load is correlated with rising groundwater levels. An understanding of groundwater processes is the starting point for research and mitigation measures that are applied to salinised areas in the region. Thus, both NDSP Project CLW28 and the *Heartlands Initiative* are underpinned by the need to understand groundwater and salinisation processes as a foundation for the more specific objectives of the respective projects. The present report on Groundwater Processes in Simmons Creek catchment aims to provide a thorough understanding of the hydrogeology of this focus catchment and succinct information about groundwater processes that are likely to be pertinent to other salinised catchments in the Riverine Plain of the Murray-Darling Basin. This report therefore provides a basis for subsequent reporting for *Heartlands* work in Simmons Creek catchment and for complementary research on landscape and ecological processes relevant to the generation and delivery of salt and water to streams (Project CLW28) in a much larger regional context.

The stream gauging station on Billabong Creek at Walbundrie has been monitored by DLWC since 1981. Two stream gauging stations were installed in the Simmons Creek study area in 2001 by DLWC and CSIRO for concurrent investigations: DLWC’s study of the feasibility of a salt interception scheme near Morgans Lookout (Williams and Kulatunga, 2001; see also Section 7.1, this report), and CSIRO’s CLW28 and *Heartlands* research. One of these new gauging stations is located on Billabong Creek, on Hillview property, between Brooklyn Bridge and Morgans Lookout. The second is located on Simons Creek 400 m upstream from the bridge on the Culcairn-Walbundrie Road.
Adjunct to the *Heartlands* commitment to the upper Billabong Creek catchment and under the auspices of the MDBC, airborne electromagnetic (AEM) data were acquired over the area in September 2001 (MDBC Project D2018). The survey area includes almost all of Simmons Creek sub-catchment. A fixed wing CASA 212-200 aircraft operated by Fugro Airborne Surveys and the high-resolution TEMPEST electromagnetic system were used for the survey. This broadband system involves a 25 Hz base-frequency square wave transmitter loop was mounted on the aircraft and a 75KHz streamed sampling three-component receiver towed 120 metres behind and 33 metres below the aircraft. Processing and transformation of the TEMPEST input measurements include Conductivity Depth Image (CDI) slices. The latter are generated from EMFlow software (Macnae *et al.*, 1998; Lane and Pracilio, 2000) that allows portrayal of sub-surface conductivity variations at discrete depths in plan view. The Bureau of Rural Sciences (BRS) is in the process of calibrating the TEMPEST AEM data, so the preliminary outputs from the survey were not utilised for the present investigations at Simmons Creek. The results from this additional information layer with respect to our investigations in the area and to planning of on-ground works to mitigate salinity are expected to be documented in 2003.

1.2 Aims of the Groundwater Investigation

- Provide a conceptual understanding of groundwater systems in the catchment, particularly the shallow aquifer system.
- Define the patterns and processes of recharge, pathways of salt transport and groundwater discharge.
- Contribute to an understanding of landscape processes in areas affected by, or at risk from, high watertables and salinity, including an understanding of the relative importance of salt transport via surface and near-surface wash-off processes versus baseflow.
- Contribute to an understanding of the mechanisms controlling the generation and delivery of salt to streams in riverine landscapes generally.

1.3 Catchment Description

Simmons Creek catchment covers an area of 17800 ha (178 km²). The study area and key localities are shown in Figure 2. Simmons Creek is one of several sub-catchments in the Upper Billabong drainage system characterised by shallow groundwater that, in places, is highly saline. The trunk drainage channel, Billabong Creek, is a sinuous perennial creek that maintains an east-west course for over 350 km between and sub-parallel to the Murrumbidgee and Murray rivers, NSW. Billabong Creek ultimately joins the Edward River near the western edge of the low-gradient Riverine Plain, and the Edward River joins the River Murray in the flat Mallee region (Figure 1). In the study area, Billabong Creek is deeply incised, typically to depths of 5-12 metres below the adjacent floodplain surfaces (Figure 3).
Simmons Creek sub-catchment is representative of catchments at the eastern margin of the Riverine Plain of the Murray-Darling Basin that border slopes and extensive bedrock exposures of the Lachlan Fold Belt uplands. Simmons Creek sub-catchment itself is rimmed with hills of granite and subordinate metasedimentary rocks. Elevation ranges from 345 m AHD at Mullemblah Hill to 180 m AHD at Billabong Creek, providing a total relief of 165 m. The drainage pattern is essentially north-to-south. Broad flat valley floors flanked by granite slopes are characteristic. The drainage system is constricted mid-catchment by the slopes of Mount Royal in the east and Mullemblah Hill in the west (labelled in Figure 2), where the valley floor narrows to a width of 3 km. South of the mid-catchment constriction, the low-gradient Billabong Creek floodplain forms a major landscape unit.

Figure 2. Simmons Creek sub-catchment and locations. Cross-section line A-A’ relates to block diagram, Figure 18.
Figure 3. Billabong Creek near Walla Walla bridge where the creek is incised into the Morgan’s Lookout granite outcrop. In 2001, creekwater EC here ranged from 470 to 1580 µS/cm.

Figure 4. Wiesners Swamp, supporting ancient eucalypts but limited juvenile regrowth due to grazing pressure prior to recent gazetting as a Nature Reserve. The swamp is underlain at shallow depth by intensely weathered granite (‘saprolite’) storing highly saline groundwaters, EC around 18000 µS/cm.

Apart from Billabong Creek – which rises in the eastern uplands, almost 100 km east of the study area, in a higher rainfall zone – all creeks in the catchment are intermittent,
and are usually dry. The only other exception is the lower reach of Simmons Creek that is commonly sustained by groundwater seepage. The incised channel functions as a groundwater drain (cover photo); typical flow rates here have been around 1 litre/second during the period of observation. Overland flow across the Billabong floodplain is hampered by the flat gradient. Numerous ephemeral swamps scattered across the floodplain attest to localised ponding of surface water and very limited surface flow to Billabong Creek.

Two swamps located south of the center of the catchment, Larundel Swamp and Wiesners Swamp (Figure 2), are ephemeral and only hold surface water once every few to several years. Wiesners Swamp is vegetated with large eucalypts (Figure 4), whereas Larundel Swamp is bare of trees and is vegetated with sedges. The Simmons Creek outlet from Wiesners Swamp is poorly integrated, as illustrated in Figure 2, although the outlet channel has been artificially excavated in the historic period. East of the swamps, in the topographically constricted mid-catchment area, Simmons Creek is a broad ephemeral swamp area that is densely vegetated with eucalypts and is subject to episodic flooding. The lowermost reach of Simmons Creek is a more clearly defined channel; this trends essentially southwestward across the Billabong floodplain towards Piney Range in the southwest corner of the catchment, near Walbundrie.

The catchment is predominantly cleared, with only minor areas of retained eucalypt, cypress pine and acacia vegetation. Most of the ringbarking was carried out in the mid-to late 1800s, with clearing completed around 1910. Land use in the area is dominantly dryland cropping (wheat and canola), with subordinate grazing. The catchment lies within the Alma Park-Pleasant Hills Landcare area.

The climate is temperate, with a mean annual rainfall of 546 mm (1956-2001), and high potential evaporation, exceeding 1300 mm. The annual evaporation-precipitation ratio (E/P) is 2.4. Water deficit is pronounced during the summer months. Rainfall for the year 2001 was below average, totalling 390 mm at Walbundrie and, apart from Billabong Creek, there has been very little surface water in the catchment since late 2000. Drought conditions have persisted through to early 2003. The area lies within the 86% of the Murray-Darling Basin where mean annual runoff is <25 mm.

1.4 Previous Investigations

The history of land clearing, present-day land usage and the problems of high groundwater levels and salinity in the Alma Park-Pleasant Hills Landcare area were comprehensively overviewed by Tuckson (1993; 1994). The NSW Department of Land and Water Conservation (DLWC) investigated saline groundwater inflows to Billabong Creek (Alamgir, 1999). Subsequent detailed investigation by DLWC has concentrated on a 2.5 km stretch of Billabong Creek near Morgans Lookout (Alamgir 1999, 2001; Williams and Kulatunga, 2001). A regional-scale groundwater study of the Eastern Murray region was compiled by DLWC (Kulatunga and Lucas, 2000). The local Landcare group has developed a catchment management plan (Alma Park-Pleasant Hills Landcare Group, 2001). The National Land and Water Resources Audit Dryland Salinity Theme included an assessment of salinity management options for Billabong Creek, focusing mainly upstream from Simmons Creek (Baker et al., 2001).
2 GEOLOGY

2.1 Introduction

Simmons Creek catchment is rimmed by hills of dominantly Upper Devonian Jindera Granite, with subordinate outcrops of Ordovician metasediments. The granite is generally pink and is variably coarse-grained to porphyritic to aplitic. The metasedimentary country rock comprises slates, phyllites, schists and gneisses. Outliers and low tors and domes of granite are scattered across the catchment. The NSW Geological Survey has mapped the regional geology at 1:250 000 scale (Tuckwell, 1975).

In July 2001, high resolution airborne magnetic, gamma-ray and elevation data for much of the upper Billabong Creek area – including Simmons Creek catchment – were acquired by Kevron Geophysics, under the auspices of the MDBC, the BRS and Geoscience Australia (GA). A fixed-wing Shrike Aerocommander aircraft was used for the 34,178 line-kilometer geophysical survey. The east–west survey lines were flown 100 metres apart, with north–south tie lines spaced 1000 metres apart, and terrain clearance was 60 metres above ground level. Instrumentation included a Geometrics G-822A Caesium vapour aircraft magnetometer and a Geometrics G856 proton precession base station magnetometer, an Exploranium GR820 gamma-ray spectrometer with 256 channels and a 50 litre NaI (T1) crystal, a Sperry AA-210 radio altimeter, a Rosemount barometer and thermometer, and a Fugro Omnistar virtual base station navigation system.

Airborne magnetics detect local variations in the earth’s magnetic field that are typically associated with different rock types. Airborne gamma-ray spectrometry (AGS), or radiometrics, detects variation in the natural radioactivity of the uppermost 30-40 cm of soil and regolith, potentially providing information about different types of sediments and soil materials and about drainage patterns in a survey area. The Total Magnetic Intensity (TMI) coverage of the Simmons Creek catchment is shown in Figure 5, and the AGS coverage of the area is shown in Figure 7.

2.2 Total Magnetic Intensity (TMI) Interpretation

Figure 6 is an interpretation of the surface and sub-surface bedrock geology based on the TMI image (Figure 5), outcrops and drill-hole data. Significantly, the magnetic image reveals granite extending diagonally beneath the catchment, from Mullemblah Hill in the northwest to Morgans Lookout in the southeast. The depth to this heterogeneous magnetic anomaly is no doubt variable but at least some of the represented granite is shallow, as indicated by outcropping domes, some of which are labelled in Figure 6. The presence of shallow basement corresponding with the TMI anomaly has further been confirmed by drilling beneath Wiesners Swamp for the present study (Piezometer CLW5), where intensely weathered kaolinitic 
\[\text{[Al}_2\text{Si}_2\text{O}_8(\text{OH})_4]\] granite was intersected at around 8 m depth.
Figure 5. Airborne Total Magnetic Intensity (TMI) image of Simmons Creek catchment.
Non-magnetic potassic bedrock outcrops (high K-gamma radiation) protruding granite domes palaeo-ana branch channels granite domes outcropping near-surface coarse pink magnetic granite (Devonian Jindera Granite) Deeper or leached portions of granite bodies underlying Cainozoic alluvium Buried non-magnetic granite and Ordovician metasediments and subordinate outcrops (slates, phyllites, schists, gneisses) 

Figure 6. Bedrock geology (Palaeozoic) interpreted from TMI imagery. Airborne Total Magnetic Intensity (TMI) image of Simmons Creek catchment.
The TMI image suggests that, although outcrops of Ordovician metasediments are subordinate to granite exposures, the metasediments may be much more extensive at depth, particularly beneath the northern depocentre of the catchment.

The NW-SE trend of Alma Park Creek (labelled in Figure 2) and the course of Simmons Creek east of the swamps closely follow the northeastern edge of the near-surface magnetic granite body for several kilometres. Apparently, the establishment of the original drainage pattern was constrained by the basement structure that diagonally crosses the whole catchment. Southward progradation of the lower reach of Simmons Creek was evidently impeded in early stages of the evolution of the area by the Morgans Lookout granite that extends for several kilometres beneath the southern alluvial plain. The course of Simmons Creek has consequently been deflected westward, away from near-surface extensions of this granite body, towards Wiesners Swamp then southwestward to the Piney Range granite outcrops (Figures 5 and 6). Protruding domes of granite on Beaver Rock and Glenara properties in the southeastern part of the catchment also influence the course of the lower reach of Simmons Creek.

Initial incision of the Simmons Creek drainage network into crystalline basement rocks in Pre-Cainozoic times was no doubt concurrent with deep incision of Billabong Creek into Palaeozoic bedrock during periods of high discharges from the Great Dividing Range to the east. The TMI image does not give any strong indication of the position of any deep channels incised into basement that may have linked the northern and southern parts of the Simmons Creek catchment. The structural architecture suggests that during much of the recent geologic evolution of the catchment, precursor lakes or swamps would probably have tended to pond approximately where the present-day swamps are located (dashed outline in Figure 6) because of the abutting granite highs to the east and west and also because of possibly limited conduits for southward flow down-gradient from this constricted area. Westward outflow from inferred dammed surface water bodies during lake-full conditions of humid times in the Late Tertiary - Quaternary would perhaps have been controlled by the configuration of the granite bodies to generate a stream course similar to that of the present-day lower reach of Simmons Creek.

The catchment architecture strongly indicates that this area to the north-northeast of the granite highs would have functioned as a sump for both surface water and infiltrated groundwater, and would have been at least a partial bottleneck for southwards overland flow and groundwater throughflow. This northern depocentre is at least 50 m deep (e.g., Bore GW027989, Hope View property, and GW054890, Royston, labelled in Figure 2). East of Wiesners Swamp, the depocentre is 55 m deep, overlying 17 m of weathered granite, with fresh granite at 72 m depth (Bore GW024612, Rowan Homestead, labelled in Figure 2). Similarly, immediately east of Larundel Swamp, saprolitic granite underlying alluvium was encountered at 65 m depth, during drilling by the BRS in February 2002 (G. Jones, BRS, pers. comm., 2002). The distinctive basement architecture is no doubt the combined legacy of widespread Early Permian glaciation across the southern part of Australia and the effects of rifting of the continent from Antarctica during the Late Cretaceous-Tertiary. The very long period of terrestrial weathering and differential erosion over the past 270 million years also accounts for the broad-scale morphology of the terrain. It is assumed that erosional and weathering
products from this prolonged terrestrial history have largely been lost from the regional landscape and that the present-day alluviation of the valleys relates only to the Tertiary-Quaternary timeframe.

Geological heterogeneity such as represented in the catchment is expected to profoundly affect the groundwater system, influencing the pattern of recharge, storage and discharge. In Simmons Creek catchment in particular, the lateral and vertical geometry of the sub-surface basement geology and overlying strata constrain the disposition and nature of aquifers. The distinctive geometry governs groundwater flow rates and flow directions within the catchment, as described and discussed further below.

2.3 Airborne Gamma-ray Spectrometric (AGS) Interpretation

The geophysical data, bedrock geology, topography and drainage configuration enable definition of the patterns of valley-infill and the distribution of aquifers in the catchment. Based on these data, the interpreted extent of the main alluvial aquifer system is outlined in Figure 7, overlain on the AGS image. Within some of this area, alluvium is a relatively thin cover. This is indicated by the presence of near-surface and scattered outcropping granite (Figures 5 and 6), described above. In the latter situations, fractured and weathered bedrock is taken to be a more important aquifer than is alluvium; this is probably particularly the case towards the catchment margins.

AGS data represent the natural radioactivity of potassium (K), thorium (Th) and uranium (U) in the landscape. The image for the study area (Figure 7) is dominated by high potassium (K) gamma-radiation (pink in the image) associated with outcrops of K-feldspar rich granite exposed on hills around the edges of the catchment. The Morgans Lookout and Piney Range granite outcrops register high K-Th-U gamma-ray signatures (white in the image), indicating high U-Th radioactivity, most likely from zircon in the granite, along with high K-feldspar. Surficial alluvium along Billabong Creek reflects the same high K-Th-U signatures indicating detrital sediments derived mainly from the abutting granite outcrops, from both within the present study area and from upstream, i.e., east of Morgans Lookout.

The upper catchment creeks – Alma Park, Ryan and Woodburne creeks and their tributaries, and Simmons Creek south of their confluence – are defined by low gamma-radiation in all three radioelements (black in the image). This indicates that quartz is the dominant sediment along the creek channels. Similarly, a quartz signature (black) is registered around the eastern edge of Larundel Swamp, corresponding with a subtle crescentic foredune or lunette landform. A bend in the Walla Walla-Alma Park Road (Figure 2) follows the crest of the northeastern portion of this low foredune. This subtle landform is relict from earlier periods in the environmental evolution of the area when the swamp would have been a perennial surface water body, when winnowed quartz was blown from beaches onto a low, near-shore foredune at the down-wind edge of the swamp. The correlative foredune existing along the eastern edge of Wiesners Swamp is less apparent in the AGS image.
Figure 7. Airborne gamma-ray spectrometric (AGS), or radiometrics, image of Simmons Creek sub-catchment. The yellow outline approximately delimits the extent of the main alluvial/colluvial aquifers, interpreted from topographic and AGS data and available stratigraphic information. These main aquifers are fringed with fractured/weathered bedrock and colluvium aquifers towards the catchment boundary (white dotted line); creeks/swamps = blue lines.
The AGS response across the alluviated northern two-thirds of the catchment is heterogeneous, with thorium well-represented (green in image), along with widespread quartz-rich sediment (black). The Th signature is taken to represent insoluble thorium ions complexed with iron oxides in the soil and possibly subordinate resistate mineral grains in the sediment sourced originally from the fringing granites and metamorphics. The relatively high Th AGS signatures across the lowlands may, in places, reflect the absence of K due to weathering and leaching of detrital feldspar during kaolinitisation of alluvium, and not necessarily intrinsically high concentrations of Th. Loss of K has no doubt occurred during weathering of bedrock and colluvium in the provenance areas as well as in situ in the alluvial deposits during clay formation and pedogenesis.

A considerable proportion of the surface and near-surface sediment across the catchment is taken to be aeolian in origin, namely ‘parna’ deposits, that were originally transported eastward during windy, and probably arid, periods from source areas in western parts of the Riverine Plain and the Mallee region further west (labelled in Figure 1). These reworked aeolian deposits now blanket the topographically low parts of the catchment and correspond with low gamma-responses. Parna is described and discussed further in Sections 2.4.3, 6.3.2 and 6.4. Where mottled U responses are seen in the lowlands (blue speckles), uranium complexed with soil carbonate is suggested, particularly in the floodplains of the main tributaries.

The importance of the gamma-spectrometry in terms of the hydrology of the catchment is that better-drained areas correspond with pink and white in the image and less well-drained soils correspond with the mottled green-blue to black signature across the lowlands.

2.4 Aquifers

2.4.1 Aquifers in Simmons Creek catchment

Weathered granite aquifers in the northern part of Simmons Creek catchment occur at depths of 40-90 m. These aquifers are confined, with SWLs of the order of 15-45 m below the ground surface. The aquifers are occasionally pumped by old farm bores, most of which were installed in the 1960s, and provide potable to moderately saline groundwaters, 1250-4500 µS/cm. Trends in SWLs over the years since bore construction are difficult to gauge because of pumping, however, it seems unlikely that watertables from these bedrock aquifers will rise to the landscape surface in the near future.

Alluvial sedimentation of the highly uneven Palaeozoic basement topography in Simmons Creek catchment probably spans the Tertiary and Quaternary, based on stratigraphic information from elsewhere in the Riverine Plain (e.g., Brown, 1989; Evans and Kellett, 1989). Up to 100 m of alluvial infill over deeply incised and weathered granite underlies Billabong Creek (DLWC Bore GW088535 and GW88537, located south of Morgans Lookout). In the northern part of the catchment, the thickness of alluvial strata over weathered granite and metasedimentary rocks appears to be considerably less than 100 m, although this is difficult to ascertain from bore logs because of the nature of the underlying weathered basement.
Southwest of Wiesners Swamp, near Brittas Reserve Road, recent drilling by the BRS intersected approximately 20 m of variable Lachlan Formation above weathered granite at 94 m depth (P. Baker, BRS, pers. comm., 2002). Similarly, on Glenara property (labelled in Figure 2) sands were encountered at 76-93 m depth (L. Kohlhogen, Glenara property, pers. comm., 2002). In Figure 6, this area in the southwestern part of the catchment, is mapped as Cainozoic (Tertiary-Quaternary) alluvium, adjacent to near-surface granite. Deep sands here probably represent an ancient palaeochannel that once fed Billabong Creek. Nearby, 300 m east of Brittas Reserve Road, the presence of a palaeochannel is indicated in a geophysical traverse carried out for the present study (EM-34 Traverse B, Figure 14).

Beneath the middle reach of Simmons Creek, east of Wiesners and Larundel swamps, 55 m of clayey sand and sandy clay overlie deeply weathered granite (Bore GW024612, Rowan). Tuckson (1993) reports 50-70 m of clay and sand alluvium infilling other parts of the catchment.

Beneath Wiesners Swamp, approximately 8 m of dense grey clay overlies intensely weathered granite (Piezometer CLW5). Similarly, heavy clay – including black clay – underlies Larundel Swamp (CLW3, and Tuckson 1993; also observed during dredging of dams on the swamp floor, December 2002). This clay is taken to be palaeolake or palaeo-swamp sediment deposited from standing water during wetter periods in the past. The grey to black colour is indicative of chemically reducing depositional settings such as anoxic lake bottom environments. This poorly permeable clay body, or series of bodies, located where the catchment is laterally constricted, is important to groundwater and salinisation processes in the catchment. Commonly, alluvium forms only a thin veneer on buried bedrock highs. Thus, the thickness of fluvial-lacustrine sediments in the catchment is highly variable, ranging from 100 m to a metre or less. Sandy clay generally dominates the upper facies, with clayey sand more abundant at greater depth, and gravels also represented in the lower facies beneath Billabong Creek (DLWC records, bores GW088535-GW088539). The deeper, coarser alluvium underlying Billabong Creek is no doubt a legacy from high fluvial discharges from uplands to the east during very wet periods of the Tertiary and early- to mid-Quaternary. The upper clay-rich alluvium is more locally sourced, from deeply weathered, kaolinitised bedrock, or remobilised from nearby silty-clay parna deposits, during periods of lower stream discharges.

High-resolution laser altimetry data covering Simmons Creek catchment and the adjacent area south of Billabong Creek suggests that the lowlands between Morgans Lookout and Piney Range comprise a low-gradient alluvial fan that spreads westward from the Billabong Creek debouchment point immediately south of Morgans Lookout (J. Gallant, CSIRO, pers. comm., 2002). This large, low-angle alluvial fan – the surface of which is bisected by the present-day Billabong Creek channel – must have covered a total area of at least 80 km², dropping 15 metres from apex to toe, east to west. The debouchment point, at the fan's proximal end, is a <2 km wide constriction. Here, Billabong Creek is bordered by granite, Morgans Lookout to the immediate north and near-surface granite to the south, the latter revealed in DLWC drill-hole data documented by Williams and Kulatunga (2001). This broad alluvial fan probably has a
Late Tertiary-Early Quaternary antiquity. The fan – and its overlying blanket of parna – has greatly influenced the course of the lower reach of Simmons Creek, which conforms to a “gutter drainage” line that borders the fan’s distal (i.e., northern and northwestern) edges. Thus it appears that the origins of Wiesners Swamp, located on this gutter drainage line, relate to ponding between the northern edge of the precursor alluvial fan and granite domes to the immediate north. This alluvial fan has implications for groundwater flow in uppermost aquifers of the floodplain (Section 4.2).

Shallow aquifers are not widespread in the northern half of the catchment. North of Wiesners Swamp, both existing piezometers and drill-holes sunk to depths of 15 m for the present study have almost invariably been dry, including beneath Larundel Swamp (CLW3). The only exception is Piezometer 287 (on Royston property, labelled in Figure 2), located in a broad, flat tract of Alma Park Creek where a shallow perched watertable of saline groundwater, to 13000 µS/cm, is present at approximately 6.5 m depth. This apparently localised groundwater body beneath the valley floor may not be permanent since the SWL has declined through the drought conditions of 2001-2003. Gleyed clays at shallow depth in some drill-holes in the north, beneath areas that can be regarded as chains of ephemeral swamps, further suggest the presence of transient perched groundwater beneath valley floors.

2.4.2 Regional alluvial aquifers in the Riverine Plain

The study area lies some 40 km east of the eastern edge of the so-called Murray Groundwater Basin where Cainozoic sediments are 200 to 600 m thick and major regional aquifer systems are present. In the upper Billabong catchment – immediately outside the Groundwater Basin proper, although part of the Murray-Darling Drainage Basin – Cainozoic sediments are typically less than 100 m thick and overlie variable bedrock types and heterogeneous basement topography of the Palaeozoic Lachlan Fold Belt.

Tertiary-Quaternary alluvium in the eastern Riverine Plain of NSW is commonly referred to as the Cowra and Lachlan Formations (Baker et al., 2001; Carter-O’Connell, 2001). The upper facies, the Cowra Formation, is typically clay-rich and is an aquifer system containing generally poor quality groundwater. Elsewhere in the eastern Murray Basin, the upper fluvial-lacustrine sediments, comprising clay, silt and sand, are named the Shepparton Formation, or the Shepparton Aquifer System (Brown, 1989; Evans and Kellett, 1989; Macumber, 1991). The lower facies in the Riverine Plain, the Lachlan Formation, is higher yielding and stores relatively fresh groundwater. The Lachlan Formation is correlative with the Calivil Formation, a widespread, important freshwater aquifer in the Murray-Darling Basin (Brown, 1989; Evans and Kellett, 1989).

The following notes pertaining to the Calivil Formation are cited from Evans and Kellett (1989). The Calivil Formation was deposited after the Middle Miocene in the ancestral Murray River drainage system. The sediments backfill upland valleys; base level was high because the sea had transgressed over the Mallee at that time. The relatively coarse-grained Calivil deposits are 20-50 m thick. In Victoria, these coarse sediments are termed the "deep leads". The Calivil Aquifer System generally contains substantial volumes of fresh groundwater in the Riverine area, including fresh recharge waters near the uplands. Beneath the NSW Riverine Plain, regional groundwater salinity
in the Calivil Aquifer System increases gradually from east to west over a flow path of 300 km.

The Cowra and Lachlan Formations, overall, exhibit vertical and lateral heterogeneity. Further north in the Riverine Plain, in the Liverpool Plains region, comparable alluvial facies are referred to as the Narrabri Formation, the upper clay-dominated unit, and the Gunnedah Formation, the lower, sand-dominated strata, although no clear boundary exists between the two units (Timms et al., 2001). The Shepparton Formation is a composite aquifer-aquitard system, characterised by variably discontinuous, confined-unconfined shoestring sand bodies. Commonly, the unit is so clayey that little horizontal connection between the layers exists, and vertical flow dominates (Evans and Kellett, 1989). The Shepparton Formation is typically 40-60 m thick (Macumber, 1991).

The uppermost alluvial deposits within the incised Billabong Creek channel are representative of the Latest Pleistocene-Holocene Coonambidgal Formation (Brown and Stephenson, 1991), which is generally mapped as ‘Quaternary alluvium’ (Qa). Typically inset into confined floodplains of the Shepparton (or Cowra) Formation, the Coonambidgal Formation channel sands can attain thicknesses of up to 20 m beneath the channel floors of modern river systems of the Riverine Plain (Brown and Stephenson, 1991).

Generally, the uppermost alluvial sequences of the Riverine Plain comprise Late Quaternary fluvial sediments that were deposited in single channel, anabranching and distributary channels and floodplains, and associated aeolian deposits (the latter described in Section 2.4.3). Distinct phases of fluvial and aeolian activity correspond with the Late Quaternary glacial and interglacial cycles (Bowler, 1990). In particular, sediments within 10-20 m of the surface of the Riverine Plain were deposited in the last 100,000 years (Page and Nanson, 1996). The resultant complex stratigraphic architecture consists of vertically and laterally accreted units in the form of sand stringers and sand sheets in palaeochannel beds, encased in overbank fines in prior floodplains. This complex alluvial aquifer system is further complicated at Simmons Creek by the mid-catchment bedrock constriction, up-gradient from which very dense, poorly permeable palaeo-swamp clays (dashed outline, Figure 6) have accumulated.

2.4.3 Parna
A blanket of aeolian silty clay commonly dominates the uppermost few metres of alluvium in the Riverine Plain. This loess-like parna unit was originally deposited gradually to form a sheet across the landscape, on hills and lowlands, bedrock and alluvium alike. In the Riverine Plain the unit was named the Widgelli Parna (or, the “Widgelli Pedoderm”) by Butler (1958). Brown and Stephenson (1991) assign the Widgelli Parna to the upper Shepparton Formation. The eastern Riverine Plain of NSW is located on the major dust path of southern Australia, down-wind from abundant sediment supplies of the playas and dunefields of the more arid Mallee landscape to the west. Long periods of wind-blown accession are indicated by the thickness of the sediment, which can exceed 1 m (Chen, 2001). Present-day annual average rates of aeolian dust deposition in eastern Australia exceed 30 tonne/km² (300 kg/ha) and dust activity is estimated to have been >50% greater during arid, windy periods of the Late Quaternary (McTainsh and Lynch, 1996).
The original proportions of this exotic aeolian material relative to the soil and sediment profiles that it is now part of are highly variable. In places, parna may make up to 50% of the soil profile (Gatehouse et al., 2001). Parna deposits have commonly been reworked, often washed from hills to thickly blanket the adjacent lowlands, and have also been subject to substantial post-depositional bioturbation. Where there is poorly developed drainage, parna deposits often persist in the landscape – as in the lowlands of Simmons Creek catchment. Where runoff is high and surface drainage is relatively efficient, the deposits have tended to have been mixed with alluvium and redistributed and are indistinguishable as a unique landscape unit.

Parna deposits are typically pigmented red because of high haematite (Fe₂O₃) contents inherited from hot, dry, oxidised inland provenance areas. Reddened clays containing a high percentage of silt-size quartz with characteristic ferric iron-rich kaolinitic cutans were most likely originally deflated from swales in the dunefields to the distant west (Bowler and Magee, 1978). Salt initially entrained with windborne clay aggregates would have been readily leached from the sediment soon after deposition as parna (Section 6.3.1).

Where water retention has occurred in situ in parna profiles, in poorly drained parts of the landscape, parna deposits tend to become yellow due to hydration and reduction of haematite to goethite (FeO.OH). Very commonly, A-horizons in parna profiles have been further leached of soluble components to form an end-product of poorly-structured grey sodic soil (Butler, 1958; N. McKenzie, CSIRO, pers. comm., 2002). Parna deposits in the Riverine Plain have the propensity to store appreciable quantities of cyclic salts. This tendency is a function of their clay-rich composition and crumbly, porous texture, as described in Section 6.3.2.

2.4.4 Simmons Creek aquifers in the regional context
Stratigraphic logs from recent DLWC borehole drilling adjacent to Billabong Creek near Morgans Lookout place the transition from the Cowra Formation to the underlying Lachlan Formation at 50-60 m depth (Bores GW088535-GW88539). The uppermost approximately 20 m of the Cowra strata are particularly clay-rich. Three superimposed aquifers are recognised in this area near Morgans Lookout: the shallowest at about 15 m depth (Cowra Formation), an intermediate aquifer at 30-40 m depth (Cowra Formation), and a deep confined aquifer system at 58-100 m depth (Lachlan Formation). A basal, one kilometer wide palaeochannel aquifer at >55 m depth near Morgans Lookout is tapped by production bores that supply over 570 ML/year of low salinity water (400-1600 µS/cm) to local towns such as Walla Walla (Williams and Kulatunga, 2001). The hydraulic head of the deepest aquifer is about 4 m above the watertable of the upper aquifer (N. Kulatunga, DLWC, pers. comm., 2002). This vertical distribution of aquifers is very comparable to that described in detail from the Murrumbidgee alluvial fan, 100 km north of Simmons Creek, by Timms and Acworth (2002).

High yields of potable groundwater were intersected in sands at 55 m depth in a recent borehole on Glenara property (noted above); the groundwater is under considerable hydraulic pressure, rising to a Standing Water Level (SWL) of only 3 m after drilling (L. Kohlhogen, Glenara, pers. comm., 2002). This aquifer is taken to represent the
Lachlan Formation. More saline groundwater was intersected in this bore in an overlying aquifer at 35 m depth, the latter taken as representing the Cowra Formation. This bore, close to scattered granite domes at Beaver Rock and Glenara, and to Sugarloaf Hill, indicates that there has been very deep incision of basement in the southwestern part of the catchment (to 100 m depths) and major but heterogeneous Tertiary-Quaternary sedimentation in the area.

The present study focuses on the upper <20 m of alluvium, i.e., the Cowra (or Shepparton) Formation. These sediments in Simmons Creek catchment are most important to the issues of shallow saline aquifers, salt sources, salt storage, waterlogging, soil structure deterioration, salt scalds in the landscape, and saline discharges into Billabong Creek. In particular, the very significant role of Late Quarternary palaeo-swamp clay bodies and parna in the upper 20 m of strata is emphasised in this report.
3 METHODS

The following methods were adopted for groundwater investigations in Simmons Creek catchment, aimed at developing an understanding of the generation and delivery of salt and water within the catchment and to Billabong Creek.

3.1 Piezometer Installation

In the early 1990s, the Alma Park-Pleasant Hills Landcare Group and DLWC installed a network of piezometers (Tuckson 1993, 1994). On DLWC bore location maps these piezometers are numbered with three digits and prefixed with GW400. In addition, older deep farm bores have historically been used for pumping groundwater, particularly during droughts.

CSIRO Land & Water installed 11 piezometers in 2001 and two additional ones in late 2002 (the latter after completion of Project CLW28). The new piezometer sites were based on major gaps in the distribution of data points with respect to depth to watertable and groundwater salinity measurements from the existing network of piezometers. Some locations were selected because of distinctive geographic features, such as in the Billabong Creek palaeo-anabranch channel (Figure 6) and ephemeral swamps. Some sites were based on information derived from our ground electromagnetic traverses (Sections 3.2 and 4.6, below). Sites are shown as red dots in Figures 8 and 9, with piezometer numbers prefixed by CLW.

A Proline solid flight auger drill-rig and a Jarrett hand auger were used for drilling; the drill-hole diameter is 0.90 m. No drilling fluids were used. The depth at which saturated sediments – i.e., aquifers, or free waters – were initially intersected during drilling of each piezometer was recorded for comparison with final water level measurements (Standing or Static Water Levels, SWLs). Aquifer confinement was indicated where the groundwater level rose after completion of drilling. PVC pipes, 50 mm diameter, were slotted over a 1 m long section at the base, open to the aquifer. The bottom 1.0 m of the drill-hole, around the PVC pipe, was backfilled with coarse river sand to ensure good movement of groundwater into the piezometer. The basal sandy back-fill was overlain by approximately 0.5 m of bentonite, and the remaining space around the pipe was backfilled with excavated soil and sediment. The uppermost 0.5 m was cemented. The length of PVC tube protruding above the ground surface (Top of Collar = TOC) was measured so that this length could be subtracted from the depth to watertable measured by a weighted tape measure dropped from the top of the tube, to calculate the depth below ground surface. The piezometer was capped. Steel casings with padlocks were cemented around the top of the piezometers, embedded 0.5 m below the ground surface.

Co-ordinates and elevations of all piezometers were accurately surveyed (Trimble Differential GPS) to enable measurement of the hydraulic gradients in the catchment and for terrain analysis.

Automated Data Flow Capacitance loggers were installed in 21 piezometers for intensive monitoring of water level fluctuations for the present study. Eighteen of these were installed in Simmons Creek catchment and one in CLW4, on the southern side of
Billabong Creek. Two additional loggers were installed in West Hume Landcare piezometers located in the floodplain south of Billabong Creek – between Burrumbuttock Creek and Billabong Creek, Piezometers BBB 14 (68) and BBB15 (67) – for the purpose of monitoring and comparing thresholds and fluxes on the southern and northern sides of Billabong Creek.

3.2 EM-34 Traverses

Five Electromagnetic Induction (EMI) traverses were carried out across sections of the catchment. The traverses were generally east-west, approximately perpendicular to the main groundwater flow direction, the objective being to detect possible preferred pathways of groundwater flow in shallow aquifers towards Billabong Creek. The EM-34 instrument (McNeil 1980; GEONICS EM-34/3 Technical Notes, undated), using 10 m coil spacing and coils aligned vertically (horizontal dipole), measures the aggregate electrical conductivity within approximately the top 7.5 m. These traverses complement EM-31 traverses conducted by Tuckson in 1994; the EM-31 device measures the conductivity of the top few metres. The units of measurement are conductivity units, milli Siemens per metre (mS/m).

3.3 EM-39 Profiling

Twelve piezometers were selected for down-hole EMI measurements: CLW 1, 2, 5, and Landcare piezometers: 263, 264, 265, 268, 269, 271, 278, 287 and 289. The GEONICS EM-39 probe (McNeill, 1986) measures the aggregate electrical conductivity of soil, sediment and rock and moisture immediately surrounding a given depth. The radial distance of the measurement at each sample point is approximately 0.9 m. Measurements (ECa) were taken at 20 cm intervals down each borehole, measured in mS/m.

3.4 Salinity Measurements

3.4.1 Surface water and groundwater salinity measurements

Surface water and groundwater salinities were determined by Electrical Conductivity (EC) measurements. Piezometers were bailed dry and allowed to refill prior to measuring to ensure that aquifer water is represented.

The following thresholds provide a baseline for gauging the severity of groundwater salinity: <800 µS/cm (EC units) - good drinking water, <2500 µS/cm - potable, >2500 µS/cm - not potable, >10000 µS/cm - saline, 50000 µS/cm - seawater.

3.4.2 Soil salinity measurements

Soil salinity was assessed by 1:5 soil:water extracts on sediment samples retrieved at 0.5 metre intervals down the drill-holes. The samples were dried in a fan-forced oven at 40° C for 3 weeks. The entire sample was then hand ground with an iron mortar and pestle to pass through a 2 mm aperture sieve. Each ground sample was thoroughly mixed and 5 g weighed into a plastic jar and 25 ml of deionized water added. The samples were shaken for 1 hour in a mechanical shaker then allowed to stand for ¾
hour. The EC\textsubscript{1:5} were measured using a TPS LC 81 conductivity meter, calibrated before use with a fresh standard 0.01M KCl (EC 1413 µS/cm).

Soil salinity measurements were made on samples from eight drill-holes: CLW 6, 7, 8, 9, 10, 11, 12 and 13.

Assessment of the severity of soil salinity, EC\textsubscript{1:5}, can be based on thresholds: low: <600 µS/cm, moderate: 600-1400 µS/cm, and high: >1400 µS/cm.
4 RESULTS AND INTERPRETATIONS

4.1 Depth to Watertable

Depth to watertable (Standing Water Level, SWL) is illustrated in Figure 8, overlain on the Digital Elevation Model (DEM) of the catchment, using groundwater depth measurements for winter 2001. Contours were initially generated by SURFER Version 7 based on a Kriging gridding method, and subsequently modified, based on qualitative information about the catchment. For areas outside the piezometer network, contouring was done by hand using the topography for guidance.

Data points are very sparse in the northern part of the catchment. Piezometer 287 provides the main datum for the north, where shallow aquifers appear to be either very localised or, more generally, non-existent. Piezometers CLW3 in Larundel Swamp and CLW10 beside Ryan Creek in the northeastern part of the catchment have remained dry since installation. Two additional drill-holes in the north failed to intersect groundwater within 15 m: in a creekline at the junction of Alma Park Road and Mullemblah Lane; and in Simmons Creek immediately south of the junction with Alma Park and Ryan Creeks (drilling conducted in December 2002, sites not included in Figure 8). These four new northern drill-holes, along with information from old farm bores, mentioned below, indicate that watertables are generally at depths greater than 40 m, and that Piezometer 287 is isolated and probably atypical for the north overall. Depth designations of >15 m evidently apply for most of the northern part of the catchment. Figure 8, thus, provides only a rough indication of the distribution of watertable depths at catchment scale and cannot be taken as factual except for the specific data points (red dots) for which actual measurements are available. Obviously, the addition or removal of any data points (i.e., of piezometers with measured depths to watertable) would significantly alter the contours. The depth to watertable contours must, accordingly, be taken as a schematic construction that is based on scattered data points.

The plotted data relate to the upper (shallow) aquifers. Excluded are deep SWLs, of 37-46 m, recorded in old farm bores by Tuckson (1993). These bores relate to the deep aquifer system where moderately fresh to slightly saline groundwaters are stored (described briefly in Section 2.4). This deeper groundwater system has not been the focus of investigations for the present study because it became evident early in the project that saline groundwaters and salt stores are concentrated in the uppermost 15 m of strata.

The watertable is generally deepest towards the catchment margins, particularly up-gradient in the north, shallowing to the south. Beneath the whole Billabong Creek floodplain the watertable is shallow, typically at 5-6 m depth. Very shallow watertables, <4 m depth, appear to be associated with occurrences of near-surface weathered bedrock or with alluvium overlying basement highs, particularly where these correspond with local topographic lows. Two such sites are located beneath Wiesners Swamp (CLW5) and in the nested piezometers 271/272 beside Glue Pot Road, towards the southeast corner of the catchment. This correspondence points to a causal relationship between elevated watertables and basement highs at these sites.
Both shallow and deeper aquifers are influenced by the proximity to sub-surface granite. Ponding of groundwater up-gradient from basement highs may be implicated. The fact that water-bearing material underlying Wiesners Swamp (CLW5) is intensely weathered granite complicates our understanding of the shallow aquifer system. Near this
weathered granite aquifer, shallow aquifers are clay-rich, taken to be palaeo-swamp clays, based on the general setting and composition of the sediments (e.g., Piezometers 271/272 and CLW1, CLW3, CLW11). To the south, intersected silty sands and gravels are associated with shallow shoestring sand aquifers. Thus, the shallow groundwater system is definitely not contained in a straightforward layer-cake alluvial stratigraphy, and the depth to watertable contours are inevitably masking complicated hydrogeologic relationships at finer scales.

Overall, the configuration of the SWL contours suggests a degree of partitioning of groundwater systems north and south of the mid-catchment swampy area and the adjacent/subjacent weathered granite body that extends diagonally beneath the catchment. Some of the basement rock that the TMI image (Figure 5) reveals as extending across the >10 km distance between outcrops at Morgans Lookout and the slopes of Mullemblah Hill must vertically constrict the groundwater system, since it is established that dense saprolitic granite underlies Wiesners Swamp at very shallow depth. Likewise, the heavy palaeo-swamp clay body to the adjacent north, in the topographically constricted mid-catchment area, is likely to function as a plug to southward groundwater flow to some degree. The impression is of partial segregation of groundwater bodies respectively within the northern and southern parts of the catchment. The watertable configuration reveals very shallow watertables over these complicated mid-catchment areas, indicative of a degree of obstruction of groundwater flow paths. This semi-partitioning of the groundwater system is pertinent to remedial measures aimed at lowering watertables in the catchment (Section 7).

4.2 Potentiometry and Groundwater flow directions

Potentiometric contours were generated by SURFER Version 7 based on a Kriging gridding method, extrapolated by hand outside the extent of the piezometer network, using topography as a guide. The potentiometric surface is illustrated in Figure 9, using Australian Height Datum (AHD) elevations. Piezometers CLW3 (Larundal Swamp) and CLW10 (Ryan Creek) were excluded from the contouring because the potentiometric surface at these localities can only be conjectured. As noted above with respect to the depth to watertable contouring, lateral facies changes greatly complicate groundwater flow, and the potentiometric map is representative only of groundwater flow at the broad, sub-catchment scale.

A moderately steep potentiometric gradient descends from the hills, particularly beneath the slopes of Mullemblah Hill in the west. The gradient flattens considerably towards the center of the catchment, especially further south, beneath the flat Billabong Creek floodplain. In aquifers underlyng most of the floodplain, the main groundwater flow direction is westward. Shallow aquifers beneath the floodplain are contiguous with creekwater in Billabong Creek. There is a 15 m fall in the elevation of the Billabong creekbed along its course from east to west, from Walla Walla Bridge to Walbundrie. Westward groundwater flow is therefore promoted beneath the adjacent catchment lowlands. This tendency no doubt relates to the facies configuration and slope of strata in the interpreted low-gradient alluvial fan (Section 2.4) that now forms the upper aquifer system beneath the floodplain.
Figure 9. Potentiometric surface and general groundwater flow directions for the upper (shallow) aquifer system (November 2001). Contours generated by SURFER software. Palaeo-anabranch channel of Billabong Creek near Morgans Lookout interpreted from the TMI image (Figure 5) and field observations; the palaeochannel now functions as an aquifer for fresh water.

The potentiometric surface flattens in the vicinity of Wiesners Swamp. In fact, the 2 m contour interval is masking a slight groundwater depression, with <1 m head differences, centred beneath the swamp (dotted outline in Figure 9). Detailed analysis of the December 2001 SWLs registers a shallow watertable depression in Piezometers 268 and CLW5 at Wiesners Swamp (SWL 183 m AHD). A measure of hydrologic closure is
represented here, with slight “internal” groundwater flow towards the depression beneath the swamp. Groundwater pumping by the large, ancient eucalypts in the swamp (Figure 4) may be the mechanism maintaining this depression. Otherwise, a slight “groundwater mound” might be expected beneath the swamp given that there is evidence that sporadic surface waters in the swamp recharge the underlying waterbody. The interpreted role of eucalypts is discussed further in Section 4.7. Hydraulic gradient reversal by eucalypts in shallow watertable areas – and the repercussions for the sustainability of trees – is described in detail by Heuperman (1999). The capacity of eucalypts to lower watertables by 1-3 m on both fresh and saline sites has been described by Schofield et al. (1989).

The present-day hydrodynamics in this mid-catchment area, in a sense, mimic the interpreted palaeo-regime, when permanent swamps and centripetal drainage were probably operating in the middle of the catchment, and pooling of water may have occurred upstream from obstructions afforded by basement highs and parna blankets. The potentiometry at the Wiesners Swamp locus implies a negligible hydraulic head difference and minimal capacity to drive groundwater flow down-catchment away from Wiesners Swamp and across what must have once been an encircling rim of weathered granite.

The weathered granite aquifer in the lower mid-catchment area is at least 17 m thick (Bore GW024612, a deep farm bore on Rowan property, labelled in Figure 2), although the saprolite profile beneath the catchment is no doubt highly variable in thickness, lateral extent, porosity and permeability. Nonetheless, at least 17 vertical metres of weathered granite aquifer abuts the down-gradient floodplain alluvial aquifers and these two aquifers are probably hydraulically connected even though the hydraulic gradient is low and southward groundwater flow rates are no doubt accordingly slow. Whether there is any greater hydraulic conductivity and higher rates of groundwater flow at depth, linking deep aquifers in the north to deep aquifers in the south, is not known.

An arcuate mound, or ridge, of shallow groundwater and corresponding lower EC values is revealed in the potentiometry for the eastern part of the Billabong Creek floodplain. The groundwater mound (labelled in Figure 9) approximately follows the Walbundrie Road from Piezometer CLW8 through CLW9, and then curves northwestward through Piezometer 263 towards CLW11. The elevated watertable along this zone, at 6-4 m depth below the ground surface, to some extent, reflects the influence of underlying basement beneath the shallow alluvial aquifer as revealed in the TMI image (Figure 5). The hydraulic head represented by the elongate mound is no doubt important to transmission of relatively fresh groundwaters along several kilometers of the northern bank of Billabong Creek to the adjacent south.

Horizontal groundwater flow directions – perpendicular to the potentiometric contours – are indicated with thick arrows in Figure 9 (summarised from vector analysis of the gradients in the SURFER program). Rates of lateral subsurface flow are probably very low overall, especially beneath the lowlands (cf. Gallant and Paydar, 2002), and may well be only ephemeral, occurring after major rainfall episodes, beneath the steeper slopes. Therefore, Figure 9 must be interpreted with some circumspection.
Figure 10. Simmons Creek sub-catchment Digital Elevation Model (DEM) and interpreted main groundwater flow directions indicated with thick white arrows, based on surface topography, TMI, potentiometry and supporting subsurface data. Main runoff zones indicated with thin white lines. Major saline discharge areas shown as pink hatched lines. Catchment boundary = white dotted line; creek/swamps = light blue; extent of palaeo-swamp clays = yellow dashed line; extent of magnetic highs, including near-surface basement = dark blue dashed lines (from Figures 4 & 5).
In general, the main flow directions follow the landscape topography, particularly the
creeklines. In the south the flow pattern is influenced by shallow shoestring sand
aquifers. Complications are encountered in the southeast where elevated watertables
intersected by Piezometers 271/272 and CLW1 present an uneven potentiometric
surface. These anomalies may be attributable to the presence of underlying near-surface granite (indicated in the TMI image, Figure 5) locally influencing the hydrodynamics, noted above. Also in the southeast, Piezometers CLW8 and 289 are located along a subtle topographic divide that extends east-west. From this subtle divide northward groundwater flow is towards the middle reach of Simmons Creek and Wiesners Swamp, and southward groundwater flow is towards the Brooklyn Bridge stretch of Billabong Creek. These flow paths are separated by the arcuate groundwater mound that underlies the eastern part of the Billabong floodplain, described above (and labelled in Figure 9).

The groundwater flow information derived from the potentiometric surface is
summarised in Figure 10, overlain on the DEM of the area. Additional flow directions
are interpreted south of Billabong Creek, based on the TMI image (Figure 5, and
continuation of the airborne magnetic coverage further south, not shown). The latter
suggests two NW-SE -striking conduits between basement highs. These separate
pathways probably direct groundwater flow northward to Billabong Creek, respectively, to near Morgans Lookout and to just east of Piney Range (white arrows south of Billabong Creek, Figure 10). This interpretation may be relevant to inputs of saline groundwater to Billabong Creek from the south and is discussed further below.

4.3 Surface Water Salinities

4.3.1 Simmons Creek catchment streams
EC measurements taken on ephemeral surface waters in creeks in the catchment in
November 2000 are shown in Figure 11. Surface waters, where present, throughout the
catchment are fresh (EC <600 µS/cm). The only exception is in the lower reach of Simmons Creek where the EC is >2000 µS/cm. This measurement is attributed to rare surface runoff mixing with saline groundwater in the creekbed and/or to dissolution of efflorescent salt on the creekbanks, relict from foregoing periods of saline groundwater discharge in the creek channel.

The data reveal that surface wash-off processes are not important in terms of salt
acquisition and that catchment-wide runoff waters are fresh. This invokes a history of infiltration of both past and contemporary salt accessions to the landscape surface. It implies that almost all lateral salt mobilisation occurs via baseflow – direct groundwater inflow – or interflow (lateral flow above the watertable), not via runoff waters.

These data suggest that salt accessions blown into the catchment and deposited onto the landscape surface and cyclic salts derived from rainfall have been – and continue to be – leached and infiltrated. The widespread presence of sodic soils in the catchment is, to a substantial extent, a legacy of such processes. Parna deposits in waterlogged areas, in particular, tend to have been further leached of soluble components – additional to early loss of soluble NaCl that may have once been entrained with the original dust (Section 2.4.3 – and form an end-product of poorly-structured grey sodic soil. As incoming, latter-day salt is washed down through the degraded soil profile, sodium is left behind,
binding to clay particles by occupying the main cation exchange sites, commonly displacing calcium. Build up of sodium contributes to soil dispersion and internal erosion once the profile is in contact with water. This increases the dispersive potential of the clay, with ultimate destruction of soil structure.

The key finding of the present study, that surface wash-off processes are not important to lateral salt mobilisation and that baseflow is the driving mechanism, may be important to understanding the generation and delivery of salt and water to streams in countless other catchments around the edges of the Riverine Plain. Surface wash-off processes no doubt increase in importance further west, where there is more primary salt in the landscape nearer the Quaternary salt lakes and regional dunefields.

Figure 11. Surface water sample points and EC readings.
4.3.2 Lower Simmons Creek
During 2001, salinity measurements taken in Simmons Creek at the bridge on the Culcairn-Walbundrie Road ranged from 17000 µS/cm (August 2001) to 27000 µS/cm (December 2001).

Salinity measurements taken in July 2001 at approximately 100 m intervals along the lower reach of Simmons Creek, from its confluence with Billabong Creek upstream for 1.5 km, range from 15600 to 22140 µS/cm. These data reveal that the whole lower reach of the creek channel intersects the watertable and functions as a groundwater drain for highly saline groundwater most of the time, and seldom as a surface drainage line for fresh runoff water. Fresh water, 925 µS/cm, however, was recorded in Simmons Creek in September 1999 (Baker et al, 2001), during a 600 mm rainfall year.

4.3.3 Billabong Creek
The average creekwater salinity at Walbundrie for 2001 was 1600 µS/cm (DLWC data). Typical salinities of Billabong Creek waters are included in Figure 11 to illustrate the steadily increasing salt loads down the creek, from EC values <900 µS/cm in the east to >1000 µS/cm at Walbundrie (for November 2001). Measurements taken at other times along Billabong Creek for the present study gave wide-ranging EC values, for example, a low of 470 µS/cm at Walla Walla Bridge in September 2001, to a high of 2500 µS/cm at Walbundrie in February 2002. As noted above (Section 1.1.1), two years of persistent drought conditions resulted in a very high salinity of 5876 µS/cm being recorded at Walbundrie in early 2003 when stream flow was particularly low. Regardless of the time of year, periodicity of rainfall events, and the absolute values at each site, the trend of increasing salinity from east to west is maintained, with the increase commonly embracing an EC range of 200-300 µS/cm. Clearly, this increase relates to inflows of shallow saline groundwater (Section 6.4).

4.4 Groundwater Salinities

Figure 12 shows the groundwater salinity gradient for the upper (shallow) aquifers within the catchment, contoured using SURFER Version 7 and a Krigging gridding technique. The piezometer data established that highly saline aquifers (apart from minor scattered break-of-slope occurrences) are contained beneath the lowlands, laterally constrained between the bases of bordering slopes. Accordingly, the initial SURFER-generated contours were manually adjusted to the topography, particularly the valley floors defined by DEM analysis as described by Gallant and Dowling (submitted), and Gallant and Paydar (2002).

It is tacit that salinity increases with distance along groundwater flow paths, water from recharge areas being generally fresh and water approaching discharge areas being more saline. Lengths of flow paths, residence times and rates of groundwater flow, the nature of salt stores intercepting the flow paths, and various other hydrogeologic factors contribute to increasing salinity down-gradient. The salinity gradient depicted in Figure 12, therefore, reveals considerable information about the groundwater hydrology of the catchment.
Figure 12. Groundwater salinity gradient for shallow aquifers in Simmons Creek catchment, November 2001. Contours generated initially by SURFER software, then modified in accordance with terrain analysis from the DEM (see text).

A large, irregularly-shaped ‘hot spot’, in which groundwater salinities exceed EC 14000 µS/cm, is prominent (shaded pink, Figure 12). This underlies much of the lowland area in the southern part of the catchment and the central, topographically constricted area. This broad hot spot, in turn, encompasses two discrete areas containing highly saline groundwaters with ECs ranging from 18000 to 32000 µS/cm. The latter areas are: (a) in the lower reach of Simmons Creek and surrounding area, and, (b) beneath the southern part of Glue Pot Road and extending to encompass the area underlying Wiesners Swamp. South of the saline groundwater concentrations, the
gradient of progressively fresh groundwater is steep leading to scattered shoestring sand aquifers. Many of these probably flow directly to Billabong Creek.

Data points are sparse within the northern two-thirds of the catchment although the overall salinity gradient is evidently gentle from the hills to the lowlands. Local break-of-slope salinity outcrops are not represented because these are take to be transient features related to ephemeral processes at distinctive topographic-hydrologic intersections, and possibly to intermittent interflow rather than to stored groundwater of the main aquifers.

An inverse relationship is observed catchment-wide between the potentiometry and the salinity contours. Steep hydraulic gradients correspond with fresh groundwater and more readily flushed aquifers. Low hydraulic gradients correspond with saline groundwaters where throughflow is much more sluggish or impeded.

Relatively fresh groundwater, EC <2000 μS/cm, is present in the southeastern part of the catchment (Piezometers 263, 289, CLW6, 7, 8 and 9). Importantly, no major salt contributions to Billabong Creek are derived from this part of Simmons Creek catchment. The floodplain aquifer system here is apparently well-flushed of salt. High stream salinities noted for this stretch of Billabong Creek, near Morgans Lookout (Alamgir, 1999), must, accordingly, be sourced from either the southern side of Billabong Creek and/or from Kangaroo Creek sub-catchment to the northeast of Morgans Lookout, rather than from the southeastern corner of Simmons Creek catchment. On the southern side, a possible source of saline groundwater may be in shallow palaeolacustrine clays underlying Gum Swamp, near Walla Walla. In the case of Kangaroo Creek, stream EC measurements are highly variable, but are up to 11000 μS/cm. An interpreted NW-striking structural conduit leading to Billabong Creek from the southeast (illustrated in the lower right corner of Figure 5, and the contiguous part of the TMI image further to the south, not shown) may be responsible for bringing some saline inflows to this tract of Billabong Creek near Morgans Lookout. This possibility, indicated with a white arrow in the lower right corner of Figure 10, tends to be supported by potentiometric contours and groundwater flow directions mapped by Alamgir (1999) in this southeastern corner, south of Billabong Creek. Saline groundwater inflows to Billabong Creek near Morgans Lookout are presently being investigated in detail by DLWC (Williams and Kulatunga, 2001).

The salinity contours in Figure 12 represent only the uppermost aquifers in Simmons Creek catchment, i.e., the upper Cowra Formation (uppermost Shepparton Formation equivalent). Generally, the underlying aquifers contain less saline groundwater. For example, stratification of groundwater salinities is well-represented in five deep bores drilled by DLWC to total depths of 45-101 m in the vicinity of Morgans Lookout. Upper aquifers at around 10-14 m deep contain groundwaters with variable salinities, EC 1210-11400 μS/cm. Underlying aquifers, located at between 33-94 m depths, yield generally fresh groundwaters, EC <1800 μS/cm, although with one moderately saline aquifer intersected between 34-42 m depth, EC around 4500 μS/cm (N. Kulatunga, DLWC, written comm., 2001). Thus, for the most part, saline groundwater is associated with shallow aquifers within the upper 15 m of sediments. Deeper aquifers intersected by these drill-holes, at 58-94 m, contain relatively fresh groundwater, 670-1780 μS/cm.
The deep aquifers are probably representative of the Lachlan Formation (Calivil Formation equivalent), overlying granite basement and infilling the ancestral Billabong Creek palaeovalley. Recent pump testing of one of these new DLWC bores for a period of one week yielded 700 µS/cm groundwater at a yield of 70 L/sec. (N. Kulatunga, DLWC, pers. comm., 2002).

The salinity of groundwaters sampled from a weathered granite aquifer at 60-75 m depth at Rowan homestead, on Simmons Creek east of the swamps (GW024612), is variable: 1400 µS/cm in 1994, and 6100 µS/cm in 1997 (not represented in Figure 12 which plots only the upper aquifers). This variability may reflect the periodic influence of creekwaters penetrating into this deep sump immediately north of the interpreted basement barrier. Runoff waters from the nearby slopes of Mt Royal and creek waters from the northern tributaries of Simmons Creek infiltrating beneath this mid-catchment location may be concentrated during episodic events, and deep percolation into basal sediments and weathered granite may be favoured merely because down-gradient overland flow is so poorly-promoted across the flat landscape southwards beyond this point.

Figure 12 indicates that, in addition to saline groundwaters in shallow aquifers being exposed to the northern bank of Billabong Creek, relatively fresh groundwaters are no doubt also seeping into the creek, at least along the tract from Morgans Lookout to around Brittas Reserve. This zone of relatively fresh water and well-leached regolith above the watertable corresponds closely with a low ECa conductivity area (<100 mS/m) defined by Tuckson (1994) from EM31 traverses. This fresh groundwater inflow from the southeastern corner of Simmons Creek catchment is regarded as important towards dilution of salt loads that Billabong Creek sequesters from somewhere east of Morgans Lookout, from the adjacent Kangaroo Creek catchment, or from the south, from beneath Gum Swamp area, for example.

Major ion chemistry of groundwaters from aquifers at <14 m depth near Morgans Lookout, i.e., the “watertable aquifer” indicates NaCl type waters, lying on mixing paths between seawater and local rainfall (Williams and Kulatunga, 2001).

4.5 Hydraulic Conductivities

It has been emphasised in the literature that hydraulic conductivities (K) of the Shepparton Formation of the Murray-Darling Basin are highly variable (e.g., Evans and Kellett, 1989). This is to be expected given the highly varied depositional history – including complex fluvial sedimentation, lacustrine and aeolian deposits – that is represented in the uppermost strata of the basin. An average regional hydraulic conductivity of 2-3 m/day is estimated for the Shepparton Formation (Evans and Kellett, 1989).

Hydraulic conductivities for representative shallow aquifers in the Simmons Creek catchment were estimated for the present study from recovery rates following bailing of the piezometers and relating K to time (Freeze and Cherry, 1979, p. 339-341).
Sandy-gravelly aquifers give $K$ values of around 7.7 m/day at CLW7, Brooklyn Road, in the interpreted palaeo-anabranch channel, and 4.2 m/day at CLW6, close to Billabong Creek, near Brooklyn Bridge. Much lower $K$ values are calculated elsewhere: 0.024 m/day for sandy clay at Piezometer 278, near Simmons Creek upstream from (east of) Wiesners Swamp, and 0.1 m/day for CLW11, west of Wiesners Swamp.

Typical clay aquifers give $K$ values of less than 1 mm/day (e.g., 0.00005 m/day for CLW5 in Wiesners Swamp and 0.00004 m/day for CLW1 in southern Glue Pot Road). In the case of CLW1, full recovery of the prior water level after bailing took some months and in CLW5, Wiesners Swamp, recovery took several weeks, indicative of the extremely limited capacity of these clayey materials to transmit groundwater.

In kaolinised granite beneath Wiesners Swamp (Piezometer CLW5), groundwater is substantially bound up in very heavy clay. Here, the saprolite is dominantly clay presumably because there has been limited opportunity through geologic time for clays to be flushed out of this topographic sump. Elsewhere, saprolitic granite is highly variable in texture and porosity and permeability properties. Away from the sump area, the sub-surface weathered granite is expected to provide moderately transmissive conduits for groundwater flow, albeit curtailed by the low hydraulic gradient.

For the most part, the catchment-wide $K$ values in the upper aquifers are very low, reflecting the flat hydraulic gradient and poorly permeable clay-rich aquifer material. Groundwater is transmitted slowly from the main recharge areas around the perimeter of the alluvial infill to the lowland aquifers and discharge areas. In general, $K$ values and groundwater ECs in the shallow aquifers reflect an inverse relationship, and hydraulic conductivities can be roughly predicted from groundwater EC.

The $K$ values imply that groundwater transmission from the northern half of the catchment to the southern floodplains appears to be limited, supporting the interpretation, above, that the groundwater system is segregated to some degree. This impression was initially interpreted from the TMI image (Figure 5) and discussed above with respect to the partially bifurcated structural framework of the catchment. There may be only limited opportunity for groundwaters – except those that can percolate through coarser-grained saprolite and through the uppermost metres of blanketing alluvium – to be transmitted southward beyond the constricted swamp area.

4.6 EM-34 Traverses

Properties contributing to the bulk electrical conductivity of the ground beneath the EM-34 instrument include porosity, degree of saturation with groundwater, the amount of electrolytes (salt) in the saturating fluids, and the amount of clay in the substrate. Thus, EMI aggregates or bulks all properties together to measure apparent conductivity (ECa) of the terrain at the measured locality. Highly conductive ground and/or moisture induce a stronger signal than material that is less conductive. Only in the case of homogeneous saturated substrate material would ECa variation provide an indication of salinity variation. The EMI measurement at each site is therefore a combination of conductivities influenced by varied factors. Low conductivity readings are obtained from dry, sandy soils or rocks that contain very little clay or salt. High conductivity
readings are typical for a site with dense clay that is waterlogged, particularly if the groundwater is saline. Lateral variations in conductivity represent changes in landscape components and properties. It is the variations that are relevant to interpretation of the underlying ground, rather than the absolute measurements. Changes in ECa are generally dominated by variation in soluble salts and clay content. Thus, EMI is only an indirect method for detecting salt and saline groundwater.

A map of the five EM-34 traverses is given in Figure 13, and graphs of the conductivity readings along each traverse (ECa in mS/m versus kilometers) are shown in Figures 14 and 15. The y-axes for all traverses have the same range, 0-200 mS/m, so that catchment-wide bulk electrical conductivities can be compared. Information about each traverse and interpretations are annotated on the graphs.

**Traverse A**, along the Walbundrie-Culcairn Road, across the Billabong Creek floodplain, from west of Simmons Creek to near Morgans Lookout (Figure 14) was hampered by the presence of powerlines and occasional buried metals in the roadside ditches, so some interpretations of the readings are provisional. Relatively high EMI readings (>130 mS/m) identify salinised sediment and saline groundwater at Simmons Creek. Other interpreted saline pathways crossing the Billabong Creek floodplain are pinpointed by conductivities exceeding 100 mS/m. Importantly, palaeochannels or shoestring sand lenses carrying fresh groundwater are identified by low EMI readings, <40 mS/m. Piezometer CLW9 was installed at Merry Vale on the strength of the low EMI reading at this locality (<25 mS/m), representing an aquifer of coarse sand containing fresh groundwater, 319 µS/cm, at 5 m depth. Granite is identified by low EMI readings towards the eastern end of the traverse. Low conductivities towards the eastern and western catchment edges may also relate to relatively fresh groundwater in recharge zones.

![Figure 13. EM-34 traverses: (A) Simmons Creek to Morgans Lookout, (B) Brittas Reserve Road to East Walkyrie Road, (C) Glenara to Glue Pot Road, (D) Wiesners Swamp, (E) Larundel Swamp.](image-url)
**Traverse B**, from Brittas Reserve Road, immediately south of Wiesners Swamp, to the eastern end of Walkyrie Road, crossed the northern part of the Billabong Creek floodplain (Figure 14). Widespread swamps across this traverse gave relatively high EMI readings, commonly to 150 mS/m. One palaeochannel (<50 mS/m) was crossed between Brittas Reserve Road and the swamps SW of Wiesners Swamp. The palaeochannel, presumably containing sand and relatively fresh groundwater, is located at the western edge of a magnetic high in the TMI image (Figure 5), parts of which are interpreted to be near-surface granite. This palaeochannel may have once been an outlet conduit from Wiesners Swamp. Relatively low readings across a 1 km stretch near the Lindavale ruins, immediately south of Wiesners Swamp, were followed-up by drilling (CLW12; no piezometer installed), where granitic gravel was intersected at a few meters depth. The location of the latter EMI low corresponds with near-surface granite interpreted from the TMI image (Figures 5 and 6). Dense clays and associated highly saline groundwater in the vicinity of Glue Pot Road gave high readings, to >160 mS/m, although with occasional sandier, more resistive palaeochannels suggested within this topographically low area. Granite underlies the gentle slope east of Glue Pot Road and outcrops on the hillcrest near the end of East Walkyrie Road.

**Traverse C**, from Glenara property in the west to Brittas Reserve Road, then along the west-east road between Wiesners and Larundel swamps to Glue Pot Road, gave very heterogeneous readings (Figure 15). The variable ECa responses here may reflect the occurrences of both near-surface granites (lows), based on the TMI data (Figures 5 and 6), plus swamps (highs) and sandy palaeochannels (lows). Swamp clays in the broad middle reach of Simmons Creek at Rowan homestead (ECa measurements to 150 mS/m) are closely bounded to the east by granite slopes of Mount Royal, corresponding with lower ECa measurements, <100 mS/m.

**Traverse D**, across Wiesners Swamp, and **Traverse E**, across part of Larundel Swamp (Figure 15), reveal variable ECa readings dominated by clays, >120 mS/m, although with some heterogeneity possibly indicating the subsurface presence of sandier palaeochannels and/or uneven distributions of alluvial clay horizons and underlying shallow saprolite and granite.
Figure 14. EM-34 readings: A. Simmons Creek to Morgans Lookout; B. Brittas Reserve Road to East Walkyrie Road.
Figure 15. EM-34 readings: C. Glenara to Glue Pot Road; D. Wiesners Swamp; E. Larundel Swamp.
4.7 EM-39 Profiles

Down-hole EM-39 readings are shown in Figure 16 (a) to (l). The x-axis scale (ECa) range is the same for the 12 plots, 0 to 600 mS/m, in order to compare substrate conductivities catchment-wide.

The EM profiles are annotated with stratigraphic information and interpretations. Many of the profiles show increasing conductivities with depth towards the bottom of each piezometer. The highest ECa readings relate to verified saline groundwater. Salinised capillary fringes above watertables commonly depict a pronounced “EC bulge”. Additional EC bulges are associated with clay layers, both above and below the watertables, suggesting salt retention and accumulation in poorly permeable clay strata. In contrast, sandier layers are depicted with lower ECa readings, reflecting greater permeabilities and the likelihood that salts are readily flushed out of such layers. Split (two) EC bulges down a profile (e.g., Piezometer 278, Figure 16j), may represent relatively recent shallow aquifer development through watertable rise following clearing of native vegetation. Alternatively, multiple EC bulges may indicate that salt is accumulated in clayey strata.

The highest readings overall, 400 - 500 mS/m, are associated with salinised clays and highly saline groundwaters in the southern Glue Pot Road discharge area (CLW1, Figure 16a) and swampy substrate near Simmons Creek south of Rowan (Piezometer 278, Figure 16j).

A pronounced EC bulge in the capillary fringe underlying Wiesners Swamp, CLW5 (Figure 15c), may be reflecting salt concentration by the large eucalypts as they pump groundwater from the shallow aquifer. This behaviour tends to be supported by the EC1.5 profile for CLW13, also in Wiesners Swamp (Figure 17h), as noted below, and by the potentiometry, described in Section 4.2. The mechanism for the build-up of soil salinity beneath eucalypts in shallow watertable areas is described by Heuperman (1999). Future seasonal EM39 measurements down Piezometer CLW5 are warranted, in order to monitor the magnitude of salt accumulation in the root zone and the behaviour of the watertable in response to continued utilisation of groundwater by the eucalypts. It seems likely that salts may be leached from the surface down to the watertable following intermittent inundation of the swamp. It will therefore be of interest to monitor both the substrate and watertable here following major rainfall events and an episode of flooding of the swamp to observe whether the soil profile is flushed and built-up salt stores are leached to the watertable.

Sandy aquifers, such as shoestring sands, show low ECa readings <200 mS/m and uncomplicated down-hole conductivity trends that are approximately vertical. These are taken to represent ‘recharge profiles’, e.g., Piezometer 263, Figure 16d; Piezometer 289, Figure 16l. More pronounced recharge fronts are suggested where the down-hole conductivity gradients are gently increasing from the ground surface to the watertable, indicative of progressive leaching of salts downwards through the unsaturated zone. These interpretations only relate to vertical processes in the given profiles. It is noted
that the suite of ECa values at each site are also the result of lateral dynamics and of variable processes through time.

Figure 16. Down-hole EM-39 readings. Piezometer locations shown in Figure 13.
Figure 16 (contd.). Down-hole EM-39 readings.
4.8 Soil:Water 1:5 Extracts

The patterns of distribution of salt stores within the profiles, EC_{1:5} (µS/cm), are illustrated in Figure 17 (a) to (h). The x-axis scale range is the same for the eight plots, 0 to 1800 µS/cm, in order to compare soil salinities catchment-wide.

CLW6 at Brooklyn Bridge: these soils and floodplain sediments have low EC_{1:5} values, <200 µS/cm, particularly around the watertable where lateral infusion of fresh water from Billabong Creek nearby is indicated. The latter is supported by logger data from the piezometer that point to discrete “recharge pulses” that follow rainfall events in the region and consequent increased stream flows (Section 6.1.3; Appendix, CLW6 hydrograph).

CLW7 on Brooklyn Road is sited in an interpreted palaeo-anabranch channel of Billabong Creek (labelled in Figures 6 and 9). EC_{1:5} values are very low, <50 µS/cm, and represent the highly permeable coarse sand and gravel of the palaeochannel and fresh recharge water that is most likely sourced from Billabong Creek and Morgans Lookout.

CLW8 auger hole at the corner of Glue Pot Road and Walbundrie Road gave generally low EC_{1:5} values, <200 µS/cm. However, a pronounced “salt bulge”, to 300 µS/cm, is present at 2-3 m depth in the unsaturated upper profile. This may be a legacy of a palaeo-watertable or palaeo-root zone, or a combination of both, or a panna layer with adhered salt. The aquifer here is a clayey sand layer at around 9 m deep. Post-depositional chemical alteration of the sediments is apparent, with mottling in the form of gleyed and oxidized material, including segregations or ‘peds’ of iron-oxide cemented sand. Groundwater EC in this aquifer is low, 913 µS/cm, suggesting possible direct, localised recharge through the overlying sediment in this slightly elevated area at the edge of the Billabong Creek floodplain, and possibly runoff from the gentle slope to the east, on Aden Vale property (labelled in Figure 2). CLW8 site is situated on a subtle groundwater ridge, depicted in the potentiometric contours (Figure 9).

The contrast is extreme between fresh groundwater in CLW8 and the occurrence of salt scalds, only 0.5 km to the north (labelled in Figures 10 and 13), and of highly saline groundwater, to EC 34000 µS/cm, in dense clay in CLW1, 1 km to the north. Two possible explanations are suggested. Partitioning of fresh and saline groundwater in the near-surface alluvial system may be indicated, with fresh waters stored in sandier units along the groundwater mound that arcs across the floodplain (represented by CLW8), and highly saline groundwater in dense clays beneath the low-lying swampy area to the immediate north, represented by CLW1 and the nearby salt scalds. Alternatively, the contrast may represent intense evaporative concentration of exposed groundwater in the topographic low area where the capillary fringe intersects the ground surface, where both shallow saline groundwater and the salt scalds occur. Solute accumulation in this case may be a largely in situ process that is exacerbated by the limited flushing capacity of the low-lying, swampy area and a high salt storage capacity of the underlying dense clays, and impeded throughflow because of adjacent near-surface granites, the latter as suggested from the TMI data (Figure 5). “Outcrops” of salt crusts at the landscape
surface are most prevalent during summer months because of intensified evaporative processes and infrequent dissolution due to limited summer rainfall (e.g., Figure 25). The latter scenario is probably the most likely explanation because the watertable within the overall area remains close to 202 m (AHD) and the CLW8 setting evidently does not represent a perched aquifer.

**CLW9**, in a shoestring sand palaeochannel at Merry Vale (see EM-34 Traverse A, Figure 14, described above), gave very low EC values of <50 µS/cm, typical of fresh groundwater in a sandy aquifer.

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**Figure 17.** Down-hole 1:5 soil:water extract EC measurements. Site locations shown in Figure 13.

**CLW10**, beside Ryan Creek in the northern part of the catchment, presents heterogeneous EC trends, indicating layered sediments. The watertable was not intersected during drilling of this 15 m deep hole, and the piezometer has remained dry.
since installation. High conductivities in the unsaturated zone generally relate to clayey layers and high soil carbonate contents, since silicified calcrete segregations were very commonly intersected during drilling here. Salt bulges (to 800 µS/cm, above threshold values of 300 µS/cm) are conspicuous in the profile. These intercalated high conductive layers probably relate to stored salts that may have been flushed to the valley floors from the surrounding hill flanks. Accumulated cyclic salts thus derived are likely to have illuviated through the coarse creek channel sands to underlying clay layers.

**CLW11**, adjacent to swamps in the lower reach of Simmons Creek near Brittas Reserve Road and west of Wiesners Swamp, presents very high EC\(_{1:5}\) values, to >1200 µS/cm. The profile relates to heavy palaeo-swamp clays – encountered when drilling – and retained salt therein. The slope of the EC\(_{1:5}\) profile above the watertable is consistent with dilution or flushing of the substrate via floodwaters from the adjacent swampy reach of the creek. At 5 m depth, a salt bulge corresponds with the capillary fringe above the watertable. Below the watertable, substantial salt bulges are apparent in the heavy grey clay aquifer/aquitard material.

**CLW12**, near Lindavale ruins south of Wiesners Swamp, drilled through a low EM-34 anomaly on Traverse B (Figure 14, described above), corresponds with shallow granitic gravels. Decreasing EC\(_{1:5}\) values below a gravel layer that was intersected at >2 m depth indicates flushing of this permeable material. A salt bulge (EC\(_{1:5}\)) at 6-7 m depth corresponds with heavy clay and retained salt therein.

**CLW13** drill-hole in Wiesners Swamp, gave high EC\(_{1:5}\) values (800-1600 µS/cm) from 2.5 to 9 m depth. The EC\(_{1:5}\) value of the intensely weathered granite saprolite at around 8 m depth is >1600 µS/cm. This is the highest EC\(_{1:5}\) measured in the catchment and substantiates that clay-rich saprolitic granite has a high salt store capacity and, in places, is a very major salt store in the catchment. This seems particularly the case where groundwater flow is blocked in structurally or topographically constricted areas. The groundwater EC in this aquifer/aquitard is similarly high, >19000 µS/cm. In the unsaturated profile, EC\(_{1:5}\) values range from 200 to 800 µS/cm. Two major processes are suggested. The trend may reflect flushing of the uppermost clays with infiltrated swamp waters following inundation of the swamp once every few years. Large, deep desiccation cracks observed in the swamp floor would tend to function as preferred pathways for this episodic infiltration. Alternatively, the high EC\(_{1:5}\) values in the profile above the watertable may reflect salt concentration due to groundwater pumping by the large eucalypts, a process discussed above (Sections 4.2 and 4.7).
Figure 17 (contd.). Down-hole 1:5 soil:water extract EC measurements.
5 CONCEPTUAL MODEL OF THE GROUNDWATER SYSTEM

The geology and groundwater hydrology of Simmons Creek catchment, integrating information collected and interpreted for the present study and DLWC data, is conceptualised schematically in Figure 18.

In the Groundwater Flow System (GFS) classification scheme of Coram et al. (2000), Simmons Creek catchment is a Local Flow System, with recharge and discharge areas being less than 5 km apart. Local Flow Systems respond rapidly to increased groundwater recharge. Watertables rise rapidly and saline discharge typically occurs within 20-30 years of agricultural development (Coram et al., 2000).

Deep alluvium underlying Billabong Creek (Lachlan Formation), in contrast, is no doubt hydraulically connected laterally with contiguous alluvial deposits extending to the east and the west, beyond Simmons Creek catchment. So, this deep aquifer conduit is part of a Regional Flow System in Alluvial Aquifers in the GFS scheme. Regional Flow Systems typically have a greater storage capacity and higher permeability than local or intermediate flow systems. In the case of this deeper regional flow system beneath the southern part of Simmons Creek catchment, i.e., underlying Billabong Creek and its immediately adjacent floodplain, resident groundwater tends to be fresh. The deeper system is therefore not a concern in terms of discharging saline groundwater and associated management issues.

Simmons Creek catchment is a hybrid hydrogeological province comprising local groundwater flow paths in both deeply weathered Palaeozoic rock and overlying Cainozoic sediments. Connectivity between bedrock and alluvial aquifers is variable. Beneath the lowland mid-catchment area subjacent alluvium and basal weathered bedrock are both saturated with saline groundwater. There is a high degree of hydraulic continuity even through transmissivities are poor. In the latter case, connectivity is probably augmented by upward groundwater flow paths enforced by the interpreted adjacent hydrological barrier, as illustrated diagrammatically in Figure 18. This mid-catchment bottleneck area is constricted laterally, east-west (not conveyed in Figure 18), as well as vertically. Convergence of groundwater flow paths is therefore perceived as being three-dimensional. Elsewhere, superimposed aquifers are unconnected, particularly where the alluvium is thick, such as in strata intersected by deep DLWC drill-holes near Morgans Lookout.

Representative salinities for catchment sub-environments are presented in Figure 19 to illustrate the distribution of salt and saline groundwaters. Up-catchment bedrock and basal alluvial aquifers tend to contain fresh to brackish groundwaters. An isolated exception is in Piezometer 287 in Alma Park Creek where a localised shallow aquifer underlying the broad flat valley floor contains 13000 µS/cm groundwater, apparently perched above a moderately fresh aquifer system at >40 m depth.

Shallow shoestring sand lenses within the floodplains contain fresh groundwaters although it is likely that residence times are transient in these permeable lenses, with water readily lost to downward infiltration or via lateral transmission to Billabong
Figure 18. Conceptual model of Simmons Creek sub-catchment and key processes in the groundwater system. Cross-section line A - A’ shown on Figure 2.

Figure 19. Typical salinities of groundwaters in Simmons Creek sub-catchment (data from the present investigation, DLWC bore records and Tuckson, 1993).
Creek. Clayey upper aquifers – correlative with the widespread Cowra Formation, the Upper Shepparton Formation and the Narrabri Formation of the Riverine Plain – and intensely weathered near-surface granites commonly contain highly saline groundwaters.

The relatively small area of the Simmons Creek catchment, 178 km², and the short groundwater flow paths, combined with the fact that the saline aquifers are contained within the uppermost 15 m, suggest that this catchment would be responsive to management strategies aimed at averting salinity. Two fundamental characteristics of this particular catchment, however, limit the likelihood of full effectiveness of future management measures to regain catchment health.

Firstly, the depth of incision of Billabong Creek across the southern edge of the catchment augments delivery of saline groundwaters from shallow aquifers directly into the stream, in spite of the low hydraulic gradient. This depth is of the order of 10 m below the surface of the adjacent floodplain, whereas the watertables are typically 5-7 m below the landscape surface (Figure 8). Catchments that are otherwise similar to Simmons Creek catchment may have creekbeds at levels above the adjacent floodplain watertables by virtue of more shallow incision of the trunk drainage channel.

Secondly, the mid-catchment palaeo-swamp clay body and adjacent basement high of saprolitic granite, together, greatly complicate and impede groundwater flow and function as a major salt store from which highly saline groundwater flows southward. These features are completely obscured beneath the flat to undulating lowlands. The composite structural-stratigraphic barrier, combined with the flat hydraulic gradient down-catchment from the sub-surface constriction, has promoted salt accumulation in this sump for probably many tens of thousands of years. Perhaps only subordinate amounts of this salt store have been flushed from the system through time and only relatively slow leaching of the salt down-gradient proceeds under present conditions. This characteristic is distinctive to Simmons Creek and may not be typical for other Local Flow System catchments in the region that are otherwise very similar in extent and hydrogeological character and that may appear analogous from the ground surface. These factors are considered further below with respect to management implications (Section 7).
6 GROUNDWATER PROCESSES

6.1 Recharge Processes

6.1.1 Regional recharge processes
In Riverine Plain catchments adjacent to the eastern uplands recharge typically occurs in local areas of high relief. Bare bedrock hills promote relatively high runoff rates with consequent infiltration on the slopes, particularly where there is thin sandy soil and/or where the rock is fractured and weathered. Porous colluvial aprons fringing hills and scattered granite domes are likely to be important recharge or interflow zones.

Permeable sandy-gravelly creekbeds generally provide major preferential pathways for vertical leakage of surface waters to underlying alluvial aquifers. In the ~550 mm average annual rainfall zone, however, recharge waters tend to be transient in the creeks, apart from the trunk drainage channels that inherit most of their streamflow from higher rainfall zones.

On a regional scale in the dryland agriculture belt, recharge also occurs beyond the root zone of annual crops and pastures during most years. Annuals only utilise water when the plants are growing and cannot use excess water from high magnitude rainfall events or prolonged rainfall periods. In the case of annual crops, recharge is enhanced where tillage is deep.

6.1.2 Local recharge processes
The inferred main runoff zones and potential recharge zones in Simmons Creek catchment are indicated in Figure 10 (white dashed arrows), based on available topographic, geophysical and potentiometric information. It should be borne in mind that persistent drought conditions in the catchment throughout the period of investigation, from late 2000 to early 2003, has precluded accurate definition of recharge zones and processes.

Localised direct recharge across the cleared alluvial plains is no doubt favoured where the regolith comprises permeable material, such as porous alluvial and aeolian sands. Several down-hole EM-39 profiles (Figure 16) and 1:5 soil:water profiles (Figure 17) suggest direct, vertical infiltration of fresh recharging waters that may be flushing salts from the soil profile en route down to the watertable. Such trends appear to be disrupted where poorly permeable heavy clay layers are intersected. However, there is not always a one-to-one correlation, and these down-hole profiles are only two-dimensional and do not represent lateral processes or temporal variation in trends.

Climatic factors tend to govern whether such diffuse recharge occurs across the flat lowlands. Infiltration and recharge is promoted when rainfall events are intense, extreme or prolonged – or when precipitation is above average – and when evaporation is offset by cool or cloudy conditions (e.g., in winter, late autumn or early spring). Further, recharge is most likely to occur when the soils are already moist from precursor rainfall events. Conversely, recharge is inhibited following dry periods when parched soils and dehydrated vegetation tend to absorb all available moisture rather than
permitting downward infiltration. Lastly, the nature of vegetation and the depth of the root zone are crucial to whether deep drainage – diffuse recharge – proceeds to the watertable.

Aerial photographs and high-resolution imagery derived from laser altimetry reveal numerous small ephemeral swamp landforms scattered across the broad Billabong floodplain. The presence of the swamps indicates that surface water tends to pond on the lowlands, rather than infiltrate to underlying aquifers. This is no doubt a function of poorly developed drainage-lines across the floodplain, the flat topographic gradient and limited permeability of clayey soils on the floodplain. The latter includes a degree of surface sealing in the topographic depressions. These swamp landforms suggest that, locally, there is little direct recharge through the soils of the floodplains. The propensity for waterlogging here is no doubt enhanced by parna sheets because the clay-dominant composition and crumbly, aggregated texture enhance the retention of both salt and water (Section 6.3.2).

In the case of Wiesners Swamp, infiltration of episodic surface waters – following inundation of the swamp once every few years – is probably promoted because of the nature of the swamp floor, with large desiccation cracks attesting to likely preferential recharge pathways to the near-surface watertable. The Wiesners Swamp profile in Figure 17(h) suggests freshwater recharge through the uppermost 6 metres of clayey substrate that overlies the saturated kaolinitic body and its capillary fringe.

Most of the ~550 mm of rain falling on the Simmons Creek catchment in a typical year appears to either evaporate or be utilised by vegetation, with a relatively small fraction infiltrating to the groundwater system. Little groundwater from the large northern part of the catchment appears to be transmitted southwards beyond the extensive mid-catchment barrier. This implies that most rainfall in the north is utilised within that part of the catchment. Maintenance of maximum storage in northern basal aquifers (i.e., Lower Cowra, or Shepparton, Formation and underlying weathered bedrock) is inferred.

The shallow alluvial aquifer system in the southern half of the catchment south of the interpreted basement highs extends over a relatively small proportion of the total catchment area. It is assumed that the underlying deep alluvial aquifer (Lachlan, or Calivil, Formation) beneath Billabong Creek is largely recharged from upstream, by waters originally sourced from the higher rainfall zone in the uplands to the east. The available hydrogeologic information indicates that the shallow aquifers (uppermost Cowra, or Shepparton, Formation) in the southern part of the catchment receive recharge mostly from local sources, via limited or only sporadic runoff from bordering hillslopes and possibly episodic diffuse recharge (‘deep drainage’) from overlying soils and strata, and only limited lateral throughflow from further up-gradient.

6.1.3 Piezometer responses 1990s
Monitoring of Landcare piezometers sunk in 1994 involved almost monthly water level measurements from early 1994 to late 1995, and only a few measurements taken subsequently up to the end of 1999. Several of the piezometers were recorded as remaining dry since construction (Pepper, 2000). The latter include three piezometers
The following observations are made from unpublished hydrographs prepared by DLWC from these data in 2001. Piezometers 263 and 265 are responsive to rainfall events. In the case of Piezometer 263, this is in an interpreted shallow shoestring sand aquifer and such aquifers tend to drain readily after recharging. Pepper (2000) first noted that Piezometer 263 appears to follow seasonal rainfall fluctuations. Piezometer 265, on Osocosy property, is close to an interpreted substantial recharge zone on the granitic slopes of Mullemblah Hill. The hydrograph supports the expectation that this area is responsive to runoff and to possible interflow from nearby slopes. The storage capacity of shallow aquifers over bedrock, however, tends to be limited and Piezometer 265 is observed to be periodically dry.

Water levels in Piezometer 289, adjacent to the Culcairn-Walbundrie Road, and located on the arcuate groundwater mound identified in the potentiometric map generated from the present study (Figure 9), is moderately responsive to rainfall. Pepper (2000) noted that this piezometer appeared to follow seasonal fluctuations. The watertable here has declined during recent dry years although occasional pumping from the adjacent windmill may be the cause in this case.

Piezometers 267, 268, 269, 271 and 278, scattered across the catchment lowlands north of Billabong Creek floodplain, maintained fairly steady water levels up to 2001 but have recently declined (Section 6.1.4). These piezometers all penetrate clayey aquifers and appear not to be particularly responsive to rainfall events. The hydrograph for the shallow Piezometer 272 (which is nested with the deeper Piezometer, 271, at the corner of Glue Pot and Walkyrie roads; location shown in Figure 13) is slightly more responsive. This is possibly because the watertable here is very shallow, at 3.5-1.5 m depth, and the piezometer is located in a low-lying natural swampy area where dams have been constructed and where the setting is periodically damp. Accordingly, the underlying watertable may receive some vertical recharge from overlying ephemeral surface water, when present. Large eucalypts here may also play a role in watertable behaviour during summer (described in Section 6.1.4).

**6.1.4 Hydrographs 2001-2003**

Hydrographs for 18 piezometers being monitored for the present investigation are shown in the Appendix. Not included are two monitored piezometers in Burrumbuttock area, south of Billabong Creek, and no hydrograph has been generated for Piezometer 265 on the slopes of Mullemblah Hill (Osocosy property), because this has commonly been dry. The limited time-span covered by the datasets, for the period late 2001 to mid-2003, reflect drought conditions that have persisted in the catchment since the beginning of the present monitoring period. Thus, the hydrographs are representative of catchment behaviour for dry years. Typical trends for wet years and decadal timescales are unknown.

Watertable decline has been the prevalent trend for the past two years. The main positive responses in the network of monitored piezometers were recorded in aquifers adjacent or subjacent to Billabong Creek, attributable to lateral infiltration of creekwater.
through porous alluvium adjacent to the creek channel (e.g., CLW6, described below, and CLW4).

Very rapid watertable fluctuations recorded in most of the automatically logged piezometers during the observation period correspond inversely with atmospheric pressure fluctuations, not with rainfall events. Changes in atmospheric pressure can produce readily discerned fluctuations in piezometers penetrating confined aquifers (Freeze and Cherry, 1979). In the case of parts of the Simmons Creek alluvial strata, clay layers function as aquicludes and serve to confine even shallow aquifers. In particular, overburden pressure is a recognised phenomenon in swelling clays, where the clay is not capable of sustaining its own weight but transfers some of this stress to the water surface (Timms et al., 2001). Thus, preliminary logger data from Simmons Creek show water columns falling in the piezometers in response to increases in barometric pressure and future data analysis must take this tendency into account.

Lateral infiltration of creekwater into adjacent floodplain aquifer layers occurs along the banks of Billabong Creek, as suggested in the vertical profiles, Figures 16(d) and 17(a). Watertable data from Piezometer CLW6, near Brooklyn Bridge, reveals “recharge pulses” following rainfall events. For example, the small “recharge spike”, or throughflow pulse, was observed a few days after a rainfall event in February 2002. This flux relates to increased streamflow following rainfall, with much of the adjacent creekwater arriving from the mountains upstream. Generally, however, the water level trend in CLW6 was steadily declining during this period (CLW6 hydrograph, Appendix), commensurate with a falling creekwater level. Alamgir (1999; 2001) notes that variable recharge and discharge flows occur beneath Billabong Creek, from and to underlying aquifers, depending upon the reach of the creek and seasonal conditions. The influence of pressure heads from the underlying (Lachlan Formation) aquifers is an additional factor.

6.1.5 Hydrologic equilibrium
A state of dynamic discharge-recharge equilibrium appears to have been attained in Simmons Creek catchment some time since clearing. Both the deep and shallow aquifer systems give the impression of being full, i.e., near their maximum capacity for storage. It is predicted that major recharging seasons are balanced by increased discharges down-gradient. What is not yet established is whether there are substantial time lags between recharge and discharge episodes. Given that the flow paths in the system are short (Figure 10), the time lag is probably not lengthy. This should easily be assessed following a wet year or a series of wet years, after the present drought has broken.

The apparent new hydrologic equilibrium differs fundamentally from the water balance of 150 years ago when the amount of water lost through evapotranspiration from native trees would have closely approximated that received through rainfall, leaving little excess water for groundwater recharge. Thus, although recharge would have approximately equaled discharge in pre-clearing times, the amounts of water involved were probably very small. As soon as the landscape was cleared, much lower water losses via evapotranspiration became the status quo, resulting in greatly increased recharge (possibly up to an order of magnitude greater than the pre-clearing rates). Filling up of aquifers and the rise of watertables may have initially occurred many
decades ago, given that most of the ringbarking in the catchment took place between the 1860s and 1890s. Filling up of the aquifers – or, development of new shallow aquifers in previously unsaturated strata – would perhaps have been augmented by the poor capacity of the catchment lowlands to promote surface flow to remove excess runoff from the system. It is probably only since a threshold of maximum storativity of the groundwater system has been attained that the new hydrologic regime, in which recharge and discharge appear to roughly balance each other, could have become established. The actual amounts of water involved in this new equilibrium are evidently very dependent upon the contemporary rainfall regime and, during dry years at least, are generally very low (Section 6.4).

It should be emphasised that, even though hydrologic equilibrium appears to be established in the catchment, the system nonetheless is in a state of salt disequilibrium, described in Section 6.4.
6.2 Discharge Processes

Groundwater discharge settings in the catchment are represented diagrammatically in Figure 18; typical salinities at the respective sites are given in Figure 19. Four main groundwater-influenced scenarios linked to salinity in the catchment are summarised in Figure 20. A potential fifth scenario is also described below.

A. Valley floor baseflow discharge of highly saline groundwater where the dissected creekbed intercepts the shallow watertable. Subsurface extensions of granite of Pinny Range and the Sugarloaf, which outcrop between Wallumbrie and Simmons Creek, may also influence upward groundwater flow in this vicinity.

B. Salt scalds in topographic lows overlying near-surface granite highs (the latter evident in airborne magnetic data). The hydraulic gradient is fairly flat, the groundwater is highly saline, and the elevated SWL from both shallow and pressured deeper aquifers intersects low points in the landscape in an ephemeral creeklime around the southern part of Glue Pot Road. Evaporative concentration of solutes from the capillary fringe is intense.

C. Groundwater seepage occurs where there is a sharp decrease in surface slope (gradient), particularly where the available area for groundwater to move down-slope is restricted. Topography is more influential in these settings than hydrologic factors. Weathered bedrock and/or shallow colluvial aquifers are typical. Efflorescent salt precipitates at the landscape surface during evaporation of the exposed groundwater.

D. Discharge of saline groundwater from clay-rich aquifers of the alluvial plains to the banks of Billabong Creek enhanced by the combination of high watertables and the depth of incision of the Billabong Creek channel. Saline discharge to the banks of Billabong Creek occurs from both the northern and southern alluvial plains.

Figure 20. Four major groundwater-influenced scenarios linked to salinity in the Simmons Creek catchment, based on geological, geomorphological and hydrological characteristics.
6.2.1 Lower Simmons Creek
In the lower reach of Simmons Creek the elevated watertable intersects the creekbed and, consequently, highly saline groundwater is discharging into the creek (Figure 20a). For much of the year, the creek channel functions as a groundwater drain (cover photo; Figures 21 and 23) that exports saline groundwater directly into Billabong Creek at the confluence, adjacent to the steep granite slopes of Piney Range.

![Figure 21. Dead trees in the lower reach of Simmons Creek where highly saline groundwater (>16000 µS/cm) is actively discharging. Efflorescent salt encrusts the bases of the tree trucks. Salinised clays of the creek banks are severely eroded.](image)

In the case of the lower reach of Simmons Creek, salinities of discharging groundwater reach EC levels of 15000-27000 µS/cm. Young eucalypts along this stretch of the creek have died and the roots and trunks now function as wicks for saline groundwater, with salt efflorescing around the trunk bases (Figure 21). Fine-grained sediment in the creekbank is salinised and, as a consequence, is highly eroded and rilled. Saline indicator species such as sea barley grass (*Hordeum marinum*), annual beard grass (*Polypogon monspeliensis*) and couch grass (*Cynodon dactylon*) are established in the creekbed. Side-gullies additionally serve as discharge sites for highly saline groundwater seepage (Figure 22).

The high solute load in groundwater in the lower part of Simmons Creek promotes complex chemical reactions upon exposure of these waters to the atmosphere and to biological activity. For example, the seepages are commonly encrusted, not only with efflorescent salt, but also with iron precipitates. The latter include black iron sulphides beneath the creekbed, grey gleyed clays, and orange iron oxides at the interface with the atmosphere (Figures 23 and 24). The iron precipitates indicate that dissolved iron makes up part of the solute composition of the groundwater. The iron was probably originally sourced from weathered iron silicate minerals in bedrock and transported as dissolved ferrous iron (Fe^{2+}) in the groundwater.
Oxidation (addition of $O_2$) or hydrolysis (addition of $H_2O$) of the dissolved $Fe^{2+}$ upon exposure at the discharge sites produces $Fe^{3+}$ and rapid precipitation of ferrihydrite ($Fe_2$H$_4$O$_8$ 4$H_2$O), an amorphous, reddish-brown iron oxide (Figure 24b). Black iron sulphide ($FeS_2$) forms from dissolved sulphur in the saline groundwater and through reduction of iron oxides. The dissolved sulphur was probably originally derived from windborne calcium sulphate (gypsum) or, less likely, from weathering of possible pyrite in metasedimentary rocks in the upper parts of the catchment. Dissolved $SO_4$ concentrations in the shallow aquifers are 84-1300 mgL$^{-1}$ (five major ion analyses from Williams and Kulatunga, 2001).

In the anaerobic environment beneath the creekbed, $Fe^{3+}$ oxides are reductively dissolved by micro-organisms in decomposing biomass, and iron-rich gelatinous precipitates result (Figure 24a). It is the continuous supply of Fe and S from discharging solute-laden groundwaters from which Fe and S reducing/oxidising bacteria derive their energy that promotes the accumulation of organic matter. The phenomena of microbiological encrustation, caused by the accumulation of microbes (bacteria), extracellular polymeric substances and inorganic precipitates (usually iron or manganese oxides) are not uncommon in association with saline groundwaters at discharge zones. Potentially significant is the oxidation of ferrous iron which reaction produces hydrogen ions in addition to ferric hydroxide. Excess hydrogen ions displace...
exchangeable cations in the soils and sediments and promote an acidic environment. The lower reach of Simmons Creek, thus, is a potential acid sulphate site, such as described by Fitzpatrick et al. (2001). Likewise, the lower reach of Kangaroo Creek to the immediate east shows a similar propensity for acid sulphate development where black FeS$_2$ mud thickly underlies the creekbed.

Figure 23. Yellow gelatinous ‘biofilms’ in discharged saline groundwater in lower Simmons Creek. The creekbed is underlain by black sulphide mud, and halite is efflorescing on the creek banks. The organic-inorganic mats are by-products of biochemical reactions in solute-laden groundwater.

Figure 24(a). Close up of gelatinous mats in saline groundwater which overlies black sulphidic mud (field of view 0.5 m wide).
Secondary gypsum is not being precipitated \textit{in situ} from sulphur-bearing groundwaters at Simmons Creek, as is known from some saline groundwater discharge areas where evaporation rates are considerable. This appears to be attributable to the fact that available calcium in the near-surface system is sequestered by bicarbonate ($\text{HCO}_3^-$) in the soil profile to form secondary calcium carbonate, or \textit{calcrete}, leaving little excess Ca for formation of calcium sulphate from dissolved sulphur. In five major ion analyses of groundwaters from shallow aquifers near Morgans Lookout (Williams and Kulatunga, 2001), $\text{HCO}_3^-$ concentrations (60-710 mgL$^{-1}$) consistently exceed Ca concentrations (55-240 mgL$^{-1}$). This indicates that, in the saturated zone at least, there is excess bicarbonate, with Ca the limiting factor for calcrete and gypsum formation. Horizontal layers of silicified calcrete are exposed in the banks of Billabong Creek in Brittas Reserve, approximately 5 m above the creekbed. This suggests that $\text{SiO}_2$ precipitates \textit{in situ} from discharging silica-saturated groundwater, as well as forming from silica-saturated pore waters in the soil zone (Section 6.3.1). Silica precipitation appears to be governed by evaporative concentration of dissolved $\text{SiO}_2$, either in the soil profile or, in the case of the horizontal layers at Brittas Reserve, upon exposure of discharging groundwaters at the creekbank. The silica is typically cherty.
(cryptocrystalline quartz) and replaces host CaCO₃ nodules or lenses. Calcrete is obviously the preferred host for silica precipitation. This is presumably because, in its absence, secondary clay minerals are likely to form from surplus aqueous silica upon contact with aluminous, cation-rich material, rather than pure SiO₂ precipitating directly from solution. Active silicification of calcrete in groundwater discharge environments in the semi-arid zone is described by English (2001). Given the inferred high concentrations of dissolved silica in Simmons Creek groundwaters, it is likely that silica is adsorbed onto amorphous ferrihydrite in the discharge zone of the lower creek channel, where gelatinous iron oxide masses are abundant (described above).

6.2.2 Glue Pot Road salt scalds

In the southern Glue Pot Road area the watertable of the upper clay-rich aquifer intersects the topographically low parts of the landscape (Figure 20b). Evaporative concentration of solutes is intense, resulting in ECs up to 34000 µS/cm and precipitation of efflorescent salts at the ground surface (Figure 25; locality labelled in Figures 10 and 13). Progressive concentration of additional solutes in the underlying shallow aquifer and in exposed or near-surface groundwater is promoted seasonally when winter rainfall flushes the summer salt crust to the watertable. Patches of the ground surface have become bare of vegetation because of toxic concentrations of salt. These areas have been prone to removal of soil through deflation and become “salt scalds”, as illustrated in Figure 25. The situation here may be exacerbated by impeded through-drainage because of damming caused by the Glue Pot Road embankment. Salt scalds are a very minor occurrence in the catchment.

Figure 25. Salt scald, southern Glue Pot Road (locality labelled in Figures 10 and 13).
6.2.3 Break-of-Slope seeps
Localised break-of-slope salt efflorescence occurs seasonally in groundwater recharge-discharge subsystems on some hillslopes (Tuckson, 1993; 1994). Because of tree clearing of the uplands, recharge in these areas has become high and volumes of shallow groundwater or interflow water beneath the slopes have increased. The hydraulic permeability and gradient do not always allow the increased volume of groundwater to drain downslope, resulting in a rise in water level. Typically, break-of-slope salt efflorescence tends to occur in the vicinity of the maximum concave curvature of the ground surface (e.g., Figure 20c), and can be a seasonal or ephemeral phenomenon.

6.2.4 Direct Discharge to Billabong Creek
Along the northern bank of Billabong Creek an important mechanism for salt entering the creek is through baseflow from shallow saline aquifers via springs and seepages in the incised creekbank. Southward flow and consequent discharge to Billabong Creek is governed by the low hydraulic gradient although it is probable that discharge is increased following major or protracted recharge events. It is also possible that major salinity increases are seasonal. The potential for salt leaching from shallow saline aquifers in the southern end of the catchment through the steeply entrenched bank of Billabong Creek is probably high most of the time (as conveyed in Figure 20d). Likely saline groundwater discharge sites are indicated by scattered occurrences of black sulphidic mud and/or orange iron oxides along the creekbed. Additionally, Williams and Kulatunga (2001) noted that saline inflow from the watertable aquifer is represented by a wetted area well above the stream level when creek flows are less than 5000 ML/day. Those authors also note that the groundwater salinity signal appears to be lost for flows exceeding 6500 ML/day.

Near Morgans Lookout, saline groundwater inflow (2000 – 15000 µS/cm) to Billabong Creek is attributed to the fact that the alluvium narrows here due to shallow bedrock on the creek flanks. An additional factor is the presence of a permeable, low salinity sand aquifer (<1600 µS/cm) in the underlying palaeochannel at depths exceeding 60 m which provides a driving head to the creek (Williams and Kulatunga, 2001).

6.2.5 Potential saline discharge to Wiesners Swamp
Additional to the four main groundwater-influenced scenarios represented in Figure 20, a potential fifth scenario may arise in the future if highly saline groundwater stored in kaolinitic granite at shallow depth beneath Wiesners Swamp rises above the present SWL of <5 m (SWL 3.7 m in late 2002, two years into a severe drought). Discharge of this groundwater (EC >18000 µS/cm) to the swamp floor – or intersection of the capillary fringe with the ground surface – would have an adverse effect on the eucalypt forest (Figure 4) and would greatly impede juvenile regrowth in this recently gazetted Nature Reserve.

Presently it appears that groundwater pumping by the eucalypts is serving to slightly lower the watertable as well as to build up salt stores in the unsaturated substrate in the root zone. If salinity here increases it seems likely that these ancient trees will be killed. If this occurs, there may be little to prevent the already shallow watertable from rising to the ground surface and the area consequently becoming a large saline discharge zone.
6.3 Salt Sources and Stores

6.3.1 Salt sources
Salt accumulations residing today within eastern Riverine Plain landscapes and waterways have, for the most part, been derived over many thousands of years. The salt accumulations have two main origins: rainfall deposited “cyclic salts”, and aeolian accessions sourced from more saline Late Quaternary environments in western parts of the Riverine Plain and the Mallee region further west (Figure 1). The importance of cyclic salts derived from rainfall is emphasised for the Mallee region in particular by Allison and Hughes (1983). Windblown silt and clay has been mobilised from upwind regions during intermittent high wind events of the glacial cycles of at least the last 50,000 years, including present-day dust activity.

Parna deposits in the Riverine and highland landscapes (described in Section 2.4) and some of the salt in the underlying groundwater systems are legacies of periods of intense aeolian activity in the past. The intensity of aeolian activity is a function of abundant sediment sources in the arid west and the reduced vegetation cover – or destabilisation of plants – and possibly also stronger Westerly winds during the ice ages. Much of the original salt entrained in clay aggregates would have been readily leached from the parna layers soon after deposition. Notwithstanding, it is the combination of the clay-rich composition – with kaolinite commonly being the second most abundant mineral after silt-size quartz – and crumbly texture of the parna blankets that predispose these upper strata to latter-day sequestration and storage of any incoming salts at Simmons Creek (Section 6.3.2).

Additional to cyclic salts from rainfall and windborne salt, a third potential salt source is through mineral weathering in the local environment (“indigenous solutes”). The presence of abundant secondary silica precipitates in the catchment suggests that active weathering of local granites contributes to at least some of the solutes, as discussed further below.

The most common mobile salt in the atmosphere – and entrained with dust particles in southern Australia – is sodium chloride, NaCl (halite, or “table salt”), with calcium sulphate, CaSO₄·2H₂O (gypsum) occurring in subordinate proportions. Calcium carbonate (CaCO₃), “lime”, is also ubiquitous in semi-arid Australian landscapes. Terrestrial forms of CaCO₃ are commonly called calcrete and the marine form is limestone. The latter makes up the substrate geology of much of the Mallee, relict from major Tertiary marine incursions onto the continent. Vast areas of limestone were also exposed on the southern Australian continental shelf during periods of low sea-levels of the Late Quaternary glacial extremes. Large quantities of this exposed CaCO₃ were transported onshore and across considerable distances inland by wind activity during glacial times. Powdered CaCO₃ blown eastward from western regions has no doubt contributed considerably to the solute loads in Riverine catchments. This seems particularly the case in granitic geologic provinces, where little of the resident calcium is likely to be indigenous. Aeolian accessions of CaCO₃ dust are readily reworked in the upper landscape and reprecipitated in situ as nodules and lenses or layers of calcrete. Much of this is associated with parna deposits. The widespread occurrence of a
calcareous substrate near the base of parna profiles was highlighted in the earliest literature on the subject (e.g., Butler, 1956; 1958).

Salt has accumulated at or near the land surface through evaporative concentration of rainfall. These salts are prone to percolation into soils and into fractured and/or porous weathered bedrock outcrops and have progressively accumulated over tens to hundreds of thousands of years.

Parna deposits in the eastern Riverine Plain of NSW, once concentrated on windward western and southwestern aspects, have substantially been eroded and washed into lower landscape positions throughout the Late Quaternary. It is implicit that salt entrained with windborne dust would have readily been leached by rainfall upon deposition of the aeolian sediment. Initial remobilisation of such salts in the landscape has probably been from hillslopes to valley floors where they have been admixed with other sediments and soils.

Even in the present-day climate, saline dustfall (dry particulate grains of resuspended terrestrial dust with some entrained salt sourced substantially from salt lakes and dunefields in the Mallee and western Riverine Plain) and dissolved salts in rainfall (principally sourced from the ocean) can be considerable. Modern dust may contain up to 50% by weight of salts (Kiefert, 1995; Timms and Acworth, 2002). Dust transport during the arid last glacial maximum (ca 25,000 – 15,000 years ago) was at least double the present aeolian deposition rates (McTainsh and Lynch, 1996). These salts, particularly chloride, have arrived and continue to arrive in the eastern Riverine Plain from western parts of the Murray-Darling Basin that were naturally salinised long ago. Based on solute concentrations in rainwater in the Murray-Darling Basin for 1974-75, Blackburn and McLeod (1983) calculated present-day salt accession volumes from rainwater of 23-30 kg/ha/year (3.8 - 4.5 mgL⁻¹ concentrations) for the Wagga Wagga area and 38 kg/ha/year (5.1 mgL⁻¹) for Albury. Accessions of these ‘cyclic salts’ have no doubt been very much greater during arid periods of the past and it is inferred that some of the earlier salt acquisitions have remained stored in the regolith – in weathered bedrock and fine-grained alluvium in particular – of the eastern Riverine Plain catchments. Present-day salt accessions contribute considerably to ancient salt stores (see Section 6.3.1, above).

Subordinate quantities of solutes have, throughout geologic time, been locally sourced through in situ weathering of bedrock within the catchment. These solutes – cations and dissolved silica in particular – are readily taken into the groundwater system during clay formation and pedogenic processes. In many exposures of weathered bedrock, solutes were leached long ago and the rock has become intensely kaolinised, composed of aluminium and silica clays plus inert quartz, although the original igneous textures are retained. A case in point is a large exposure of weathered granite in a road cutting at the Walla Walla turnoff on the Culcairn-Walbundrie Road, near Morgans Lookout. Here, solutes such as sodium, potassium, calcium and excess silica have been leached and the material is dominantly kaolinite and quartz plus secondary iron oxides, although the original granite textures and large corestones, developed during early phases of weathering, are intact. Material from this site was analysed by Gunn et al. (1979) and contains comparable sodium and chloride contents and negligible other soluble cations.
and anions (apart from bicarbonate which is a product of weathering reactions and the flux of CO₂ in the subaerial profile). Chloride is an insignificant component of fresh granite and sodium is the most readily leached common cation in weathering crystalline rocks. Exotic inputs of halite (NaCl) such as cyclic sources are therefore indicated by the presence of equal contents of Cl and Na in this saprolite outcrop and the pervasive kaolinitisation of original Na-bearing minerals. The analyses are consistent with influxes of salt from rainfall and/or dryfall dust onto the outcrop and infiltration into the porous profile probably long after most of the weathering and leaching of the original rock.

Silicified carbonate nodules and layers are very common in the unsaturated zone of the catchment (Section 6.2.1). Excess silica is a product of the weathering of feldspars and micas to kaolinite clay. The abundance of both weathering granite and secondary silica in the catchment implies that pore waters and groundwaters are commonly saturated with respect to dissolved silica (H₄SiO₄) and suggests that the source of this solute is indigenous, rather than originating from outside the catchment.

Mineral weathering due to weak acids, particularly in the soil unsaturated zone, is regarded as a major contributor to stream salt loads in the Murray Darling Basin by White and Wasson (in prep.). Those authors note that the contribution of salts from mineral weathering is particularly important for locations more than 1400 km upstream of the River Murray mouth and may, in fact, be the principal source of dissolved salts in upland catchments. Whilst cyclic salts dominate in the lower Murray-Darling Basin, the contributions of weathering products such as Ca, Mg and HCO₃, to stream salt loads in the upper catchments may be equal to those from cyclic salt (White and Wasson, in prep.). The present study suggests that H₄SiO₄ is also potentially an important indigenous solute in the eastern Riverine Plain.

Hydrogeochemical studies of groundwaters in Kyeamba Valley, near Wagga Wagga, reveal that the increase in salinity in the shallow groundwater system is associated with the discharge of saline groundwaters from Ordovician metasediments that are of marine origin. The stable isotopes of deuterium and oxygen-18 do not support evaporative concentration in these shallow groundwaters but rather to a genesis involving water-rock interaction (Jankowski et al., 1998). Simmons Creek catchment, located less than 60 km from Kyeamba Creek, shares many characteristics with the latter catchment, including bedrock geology, although metasediments are subordinate to granite here. This may imply that minor quantities of the salts at Simmons Creek owe their origin to connate salts in metasedimentary rocks in the catchment.

Notwithstanding the White and Wasson (in prep) and Jankowski et al., (1998) studies, NaCl contributions from regional Palaeozoic rocks appear to be negligible on the basis of ³⁶Cl analyses of groundwaters from the Boorowa area, in the Lachlan River catchment, some 200 km northeast of Simmons Creek (Evans, 1998). The fact that the ³⁶Cl radiogenic isotope half-life is 300,000 years and that ³⁶Cl/Cl ratios are greater than zero indicate that chloride, in that catchment at least, is very much younger than the bedrock and is most likely sourced from relatively recent atmospheric salts, including cyclic salts introduced to the landscape via rainfall, and dust fluxes (Evans, 1998).
Importantly, low abundances of Cl in Lachlan Fold Belt bedrock types preclude rock weathering as a major source of chloride.

6.3.2 Salt stores

Substantial salt stores in the upper alluvial sediments correspond with clayey-silt layers above the watertable. The mode of occurrence suggests downward dispersion, or illuviation, of either cyclic salt from rainfall and/or salt that was once entrained within aeolian sediments that were originally deposited on the landscape surface (e.g., Figure 17e, see also notes above, Section 4.8). Salt storage in analogous clayey-silt units that include substantial aeolian components, in the unsaturated upper 15 metres of the Lower Murrumbidgee alluvial fan, is 10 kg/m², or 102 tonnes/ha, calculated per square metre of surface area (Timms and Acworth, 2002).

Some of the salt now stored in the uppermost soil layers may be attributable to pre-clearing accumulation of solutes in the root zone of pre-existing forests. This salt would be residual from the uptake of groundwater by trees over long periods of time, accumulated progressively as the trees pumped groundwater and as solutes were excluded and left in the soil profile.

The distinctive structural architecture of Simmons Creek catchment, characterised by the mid-catchment basement barrier that “plugs” the system to some extent (Figures 18 to 20), probably predisposed this catchment, in particular, to concentrated accumulation of solutes. The Wiesners Swamp area may have once been the depocentre of a small closed hydrologic system and, as such, the terminus for most of the solutes flushed from the northern sub-catchments. During wet periods of the Late Quaternary climatic cycles (the interglacial periods), high rainfall rates would have readily flushed the upper parts of the catchment. Parna-derived and other salts deposited on the hills during preceding dry glacial periods would have been mobilised at least as far south as the mid-catchment swamps. Overflow of these surface water bodies may have been impeded because of fringing granite highs (Figures 5 and 6) and/or because watertables and swamp water levels were kept sufficiently low (below approximately 180 m AHD) through efficient utilisation of runoff waters by the pre-existing forest vegetation. Salt loads mobilised from the northern two-thirds of the catchment may not have been readily flushed further south to Billabong Creek and to the River Murray during those times. Rather, salt accessions from the northern part of the catchment may have tended to accumulate immediately up-gradient from the basement barrier and subsequently remained in storage in dense swamp clays and weathered bedrock until relatively recent remobilisation by the rising watertable.

Cyclic salt accessions have accumulated in widespread reworked parna deposits where salt sequestration is a function of the distinctive crumbly texture and clay-rich composition of the parna. The porous texture, comprising multi-scale ‘polyhedral clay peds’, promotes water retention in the near-surface profile whereupon solutes can be concentrated through evaporation as water molecules are lost to the atmosphere and salts are left behind. This soil (micro)structure favours adsorption of residual solutes. In places, elevated watertables are now in contact with the shallow saline parna blanket, or with fine-grained alluvium sourced from former parna deposits.
The observed accumulation of highly saline groundwaters in clay-rich upper aquifers and in intensely weathered near-surface granite is enhanced by poor transmissivities of the fine-grained substrates. Storage of salts in heavy palaeo-lacustrine or palaeo-swamp clays may also be the case beneath Gum Swamp, 3 km southeast of Morgans Lookout, near Walla Walla. The groundwater flow direction from beneath Gum Swamp is north-northwestward to Billabong Creek near Morgans Lookout. Groundwater salinities near the swamp are up to 12700 µS/cm (DLWC Piezometer 40, Alamgir, 1999; Williams and Kulatunga, 2001).

Salinisation of soils can occur due to past high watertables that brought the salt closer to the surface during Quaternary aridification cycles, particularly during the more arid times of the last 50,000 years, particularly if tree cover was reduced due to aridity. Saline aquifers and substantial salt stores in saprolitic granite and palaeo-swamp clay deposits no doubt accumulated long before clearing of the landscape in the late 1800s and early 1900s. The appearance of high saline watertables in the present landscape and saline discharges to the streams is the consequence of widespread tree clearing and European agricultural practices of the past 140 years. The respective processes, ancient and contemporary, are similar insofar as deep-rooted native vegetation is lost – on the one hand in response to protracted aridity, and on the other to wholesale land clearing for agriculture – with watertables consequently forced to rise in both cases. Resident salt in the substrate is subsequently mobilised by groundwaters to discharge at the landscape surface and into end-of-valley streams. The fundamental difference is the rates of these processes, with the current trends occurring over decadal time scales compared to natural Quaternary climatic fluctuations occurring with a periodicity of tens of thousands of years.

The substantial salt stores, residual from past conditions, along with contemporary accessions, are currently being remobilised in response to relatively recent and present-day land use practices. Past high watertables and associated high salt loads and evaporative concentration of solutes in the near-surface substrate may have been part of the evolution of Simmons Creek catchment. Evidence for this might be suggested, for example, in “EC bulges” or “salt bulges” in the profiles above the present watertables, such as illustrated in Figures 16(a) and 17(c). If these relict features relate to past high, saline watertables, it can not be known whether they are the consequence of natural Late Quaternary processes or represent early responses to tree-clearing this century. The observed salt bulges in the profiles may equally represent downward percolation of cyclic salts that were initially concentrated nearer the landscape surface through evaporative concentration and subsequently infiltrated down to and retained by clay-rich strata.

6.4 Salt loads and salt balances

The groundwater system cannot be regarded as a well-integrated one. It essentially functions as two full buckets with perhaps only localised lateral leakage between them. In the larger, northern part of the catchment, up-gradient from the mid-catchment obstacles, the amount of discharge probably approximates the amount of recharge. The northern ‘bucket’ overflows slowly through the uppermost part of the basement high of salinised weathered granite and the associated dense, salinised palaeo-swamp clay body.
Saline groundwater trickles down-gradient into the smaller bucket to the adjacent south, *i.e.*, to the floodplain aquifers, and possibly also to the deeper Calivil system where this is present at depth nearer Billabong Creek. Considerable inertia is represented in the shallow system because of the low hydraulic gradient and the slight groundwater depression beneath Wiesners Swamp. Although the weathered granite at several metres depth here is storing substantial amounts of saline groundwater, the negligible hydraulic head cannot readily promote southward flow (Figure 9). The limited amount of throughflow to the south trickles out of the catchment via Simmons Creek outlet and scattered springs along the northern bank of Billabong Creek. Groundwater flow in the floodplain aquifers is, for the most part, hampered by the low hydraulic gradient and poor transmissivities. The overall salt store in the catchment – in the subsurface palaeo-swamp clays and abutting weathered granite and in near-surface parna deposits (Figure 26) – is probably substantial, however, this store is only poorly mobilised because of the low rates of recharge and limited throughflow.

Stream flow (Q) in Simmons Creek was measured periodically during 2001 using a RBC flume in the creek at the bridge on the Culcairn-Walbundrie Road to estimate the volume of baseflow water flowing through the flume per unit time. This was multiplied by the creekwater salinity (EC measurements converted to mgL⁻¹ concentrations using a conversion factor of 0.640) to calculate the salt load of Simmons Creek and gauge its salt contribution to Billabong Creek.

Simmons Creek flow during drought conditions is less than 1 litre/sec; our measurements at the bridge during 2001 range from 0.16 l/sec to 1.0 l/sec. Measured ECs in the creek have ranged from 17000 µS/cm (August 2001) to 26900 µS/cm (December 2001). These EC measurements, coupled with the observation that surface water flow is very rare in any of the catchment drainages and that, when it does occur, the surface waters are fresh (Figure 11), indicate that all of the above measurements were of baseflow. Salt load measurements vary widely, ranging from 180 to 930 kg/day, with a mean of 450 kg/day. This represents approximately 164 tonnes of salt per year entering Billabong Creek directly from the Simmons Creek channel “groundwater drain”. Additional salt is discharged from Simmons Creek catchment via seepages and springs along the northern bank of Billabong Creek east of the Simmons Creek outlet; the latter quantities are estimated separately below.

Salt loads were calculated for Billabong Creek at Walbundrie using flux values obtained from the DLWC web site:

17/12/2001, Q 25 ML/day, EC 2610 µS/cm, Salt load 39 t/day;
20/12/2001, Q 31 ML/day, EC 2700 µS/cm, Salt load 50 t/day;
21/12/2001, Q 45 ML/day, EC 2730 µS/cm, Salt load 74 t/day.

Corresponding salt loads for Simmons Creek were 0.39, 0.36, 0.45 t/day, which were 1%, 0.7%, and 0.6% of the salt load of Billabong Creek. This indicates that groundwater being exported down Simmons Creek alone was a minor contributor of salt to Billabong Creek in 2001.
Rainfall at Walbundrie for the year 2001 was 390 mm. Assuming Simmons Creek flow averages 1 L/sec, this is equivalent to 31.5 ML/year. If this baseflow is generated for the southern half of catchment (~85 km²), the amount of output from the Simmons Creek channel alone suggests a negligible recharge rate (<1 mm/year) during a very dry year. This excludes consideration of additional baseflow from seepages elsewhere along Billabong Creek, which is expected to be several times this amount.

Using a mean salt concentration of rainwater of 4.5 mgL⁻¹ (Blackburn and McLeod, 1983; Jolly et al. 1997), 390 mm of rain in 2001 brought approximately 149 tonnes of salt into the southern half of catchment. Salt leaving by Simmons Creek baseflow (i.e., the ‘groundwater drain’ alone) was 164 tonnes/year, using the mean daily value of 450 kg/day. Additional salt exports to Billabong Creek, from widespread scattered discharge points east of Simmons Creek channel are roughly estimated below.

Periodic measurements of EC along Billabong Creek taken for the present study between Brooklyn Bridge and Walbundrie indicate that appreciable amounts of salt are entering the creek from groundwater accessions, additional to direct exports from Simmons Creek. For example, on 21/2/2002 the EC at Brooklyn Bridge was 2064 µS/cm, while at Walbundrie it was 2730 µS/cm, a difference of 666 µS/cm, or around 18 tonnes of salt entered Billabong Creek on that day (24% of the salt load). This is equivalent to approximately 3.8 ML/day (1387 ML/year) along the meandering 17 km reach of the creek, although it is already established that salt loads vary enormously (Section 4.3.2, and data presented above). Assuming an aquifer depth of 8 m, an average hydraulic conductivity value of 0.5 m/day, and an average hydraulic gradient of 1.5/1000, groundwater flow into Billabong Creek is 0.1 ML/day (36.5 ML/year) from the Simmons Creek catchment. If it is assumed that the average EC of groundwater entering the creek from the floodplain aquifers is 10000 µS/cm (~6000 mgL⁻¹), approximately 210 tonnes/year of salt are exported from the catchment to Billabong Creek, additional to that from the Simmons Creek channel itself (164 tonnes, calculated above). This ignores salt contributions from south of Billabong Creek. Whilst these estimates may perhaps not be generalised for wet years, the overall recharge and discharge rates appear to be very low. Flow records for Billabong Creek from the new Hillview gauging station near Brooklyn Bridge and the Walbundrie station reveal a net gain of just over 4000 ML/year from the north and south sides of Billabong Creek combined, or, around 2000 ML/year from Simmons Creek catchment (Paydar and Gallant, 2002), although these values, again, may not be representative of more ‘average’ years, least of all for wet periods.

Looking again at the salt balance for 2001, salt lost from the catchment via groundwater inflows to Billabong Creek was approximately 210 tonnes, based on the above estimated average groundwater EC. Adding the estimated salt losses together (164 tonnes from Simmons Creek outlet and 210 tonnes from additional seepages to the east), 374 tonnes were exported whilst 149 tonnes arrived in rainfall in the southern half of the catchment (Figure 26). The salt O/I ratio is 2.5, representing moderate salt disequilibrium. Jolly et al. (2001) noted that a salt O/I ratio of >1 represents existing or impending salinisation of a catchment or of end-of-valley streams.
Thus, Simmons Creek catchment lost salt to Billabong Creek last year, whilst it probably transmitted little more groundwater than that gained through recharge from rainfall. In a more typical year, with a rainfall approaching the average of 550 mm, over 200 tonnes of salt/year would be imported to the southern half of the catchment. Salt outputs during an ‘average year’ cannot readily be estimated. If it is assumed that hydrologic balance is more-or-less maintained, and if recharge and discharge are equitable, a commensurate increase in the amounts of salt sequestered from the catchment salt stores would be expected. It follows that, in a more typical year, more salt would be exported to Billabong Creek than that estimated for 2001. Salt O/I ratios during wet years are predicted to significantly exceed the ratio of 2.5 estimated for 2001, and may closely approach the ratio of 3.7 estimated by Jolly et al. (2001) for the whole upper Billabong Creek system upstream of Walbundrie for an aggregate of 10 years.

Thus, wet years are likely to reveal that all catchments, including Simmons Creek, export much greater quantities of salt than dry years. Whilst a new dynamic hydrologic equilibrium has apparently been attained within Simmons Creek catchment sometime since land clearing, a new salt equilibrium with a salt O/I = 1, will take much longer to be established. Under the present hydrologic regime, and given the geologic and geomorphologic complications, it may take many decades for existing salt stores to be flushed from the catchment. Management implications of this status quo are discussed in Section 7.

Figure 26. Salt balance estimates for Simmons Creek catchment, in a dry year, 390 mm rainfall (2001). Normal rainfall years (~550 mm) and wetter years are predicted to cause sequestering of greater volumes of salt from the salt stores and greater discharges of saline groundwater down-gradient.
7 MANAGEMENT IMPLICATIONS

7.1 Lowering the watertable and associated considerations

In response to ringbarking of native trees 140-80 years ago, increased recharge caused watertables to progressively rise over the ensuing decades. The watertables may have risen several meters or even >10 metres above their pre-clearing levels and are now maintained at these elevated levels. The increased recharge and increased hydraulic heads following clearing have promoted greater discharges down gradient, the latter encumbered with salts acquired from the regolith between the recharge and discharge zones. A new equilibrium between discharge and recharge has been attained. This dynamic discharge-recharge equilibrium engenders salt disequilibrium and will continue to do so as long as salt is being leached from pre-existing – possibly ancient – salt stores (Section 6.4).

More salt is leaving the upper Billabong catchments than is currently being added to existing repositories. It should be reiterated, however, that the total amount of salt exported from the catchment is small, relative to the overall salt load of Billabong Creek. In this post-clearing hydrologic regime, the system is expected to flush itself of much of the resident salt. The process, however, is very slow and is complicated by the nature of salt storage beneath the mid-catchment area. Flushing of salt stores from the catchment may take many decades under contemporary dynamics. In the interim, an awareness of the processes in operation and potential fluxes in these processes, foresight, and informed management of the catchment is required to preserve its agricultural productivity and restore its environmental integrity.

The calculations in Section 6.4 are best guesses to gain an idea of the magnitude of the salinisation problem in Simmons Creek catchment. They indicate that this catchment, alone, is a minor contributor to the Billabong Creek salt load although it must be acknowledged that the rising trend in stream salt load correlates with rising groundwater levels in the up-gradient sub-catchments generally.

Lowering groundwater levels in the southern half of Simmons Creek catchment would decrease salt exports to Billabong Creek. Discharge volumes appear to equal recharge volumes, and any reduction of recharge through modified land use will result in commensurate reduction of saline discharge volumes down-gradient, albeit with an unknown time lag between action and result.

It may be unlikely however, that watertables could be lowered sufficiently to below the level of the Billabong creekbed altogether, along all reaches of the creek. Therefore, at least some saline accessions to the trunk drainage seem inevitable given the degree of incision of Billabong Creek to below the watertable levels of the adjacent saline floodplain aquifers, and given the existence of the substantial mid-catchment salt store, beneath the swamps and in the adjacent saprolitic material. If groundwater levels in the lower aquifers rise further, it is obvious that the Billabong creekbed will gain more saline groundwater and the stream salt load will increase further. Off-site effects, accordingly, will increase, to ultimately impinge on downstream aquatic ecosystems and the River Murray.
Clearly, the export of saline groundwater to Billabong Creek, high saline watertables and salt outcrop in the landscape are groundwater-driven processes. Salts are not being derived from surface wash processes in this catchment (Section 4.3). The contribution of mobilised stored salt – from former para deposits in the upper strata that the elevated watertables are now in contact with, and from structurally occluded, poorly transmissive shallow aquifers – to increasing stream salt loads underscores our understanding of salinisation processes in the region. Mitigation measures must be directed towards the groundwater system. Importantly, further rises of watertables should be prevented because the higher the watertable, the greater the discharge to Simmons Creek, to the topographic low areas in the floodplains and to the banks of Billabong Creek.

A simple dilemma is presented: on the one hand, the considerable depth of incision of Billabong Creek tends to entail that this ‘natural’, pre-existing outlet bordering the down-gradient end of the catchment should offset further rises of up-gradient watertables. On the other hand, the low hydraulic gradient and poor transmissivities of the lowland aquifers implicate sluggish delivery of groundwater through the catchment to this main outlet. It is therefore likely that, following periods of high recharge, transient watertable rises may occur, in the process, potentially salinising overlying soils and outcropping in topographic low areas en route to the outlets along Billabong Creek. Thus, although there appears to be an overall recharge-discharge equilibrium in operation, the dynamics may involve lag times during which considerable damage and salinisation may occur when and where there are perturbations between recharge and discharge.

Management scenarios adopted for Simmons Creek catchment need to be directed toward mitigating the salinity problem – saline groundwater discharge to Billabong Creek, potential salinisation of Wiesners Swamp, waterlogging in parts of the catchment lowlands and accompanying soil degradation and salinisation in topographic low areas – and towards improving the overall health of the catchment, its biodiversity and its agricultural productivity. Management aimed at stemming salt exports to the regional trunk drainage entirely may be unrealistic given the available hydrogeologic information for the area. Other sub-catchments of the upper Billabong system, where Billabong Creek is less deeply incised and where accumulated salt stores are smaller or more tractable because the sub-catchment architectures are less complicated and greater throughflow and greater flushing of salts have naturally been promoted, may present better opportunities for substantially lowering the salt load in Billabong Creek.

For the upper Billabong Creek catchment near Holbrook (east of Simmons Creek catchment) and for both the Cowra and Lachlan Formations in this area, groundwater simulations using the FLOWTUBE modelling tool predicted that, under current recharge conditions, waterlevels will rise to or near the surface by 2050 (Baker et al., 2001). A 50% reduction of current recharge levels can delay the rise by up to 50 years and if a 90% reduction in recharge can be achieved, then the groundwater levels are unlikely to reach the surface at all (Baker et al., 2001).
Similar groundwater modelling has been carried out for Kyeamba Creek catchment near Wagga Wagga. Kyeamba catchment is an alluvial-bedrock groundwater flow system analogous to Simmons Creek. The similarity includes the presence of bedrock highs that influence groundwater dynamics in local scale alluvial aquifers, and the fact that land salinisation is less of a problem than stream salinisation – in the latter case, of the Murrumbidgee River. FLOWTUBE simulations for Kyeamba Creek catchment reveal rapid responses of watertables to modelled recharge reduction scenarios. The estimated 10 mm/year of excess recharge in the Kyeamba catchment can readily be absorbed by the use of perennial pastures, without the need for widespread reafforestation (Cresswell et al., 2002). Successful planting of trees and perennials within the Kyeamba catchment to date indicate rapid response of water levels and encourage more widespread use of this management strategy (Cresswell et al., 2002). Similar modelling cannot readily be applied to Simmons Creek catchment because of heterogeneity of hydraulic conductivities in the alluvial and weathered bedrock aquifers and because recharge rates appear to be very low (Section 6.4). Nonetheless, using the modelling of Kyeamba catchment as a guide, it is predicted that revegetation in Simmons Creek catchment would generate positive responses is a relatively short timeframe.

The subsurface saline plug that substantially segregates the northern two-thirds of Simmons Creek catchment from the lowlands of the Billabong floodplain is pertinent to management plans for the catchment. Any land use changes put into place within the northern part of the catchment might not influence groundwater processes in the southern, salinised area. Therefore, the southern half of the catchment is the priority for future land use planning and should be the prime target if modified management practices are deemed advisable for the catchment. In the north, break-of-slope treebelts should be maintained and additional belts planted if salinisation occurs in the footslopes.

The approximate salt load and salt balance estimates in Section 6.4 suggest that any reduction of recharge would curtail a commensurate amount of discharging groundwater. Given the local scale of the groundwater flow system and the relatively short flow paths, revegetation strategies are likely to be effective in lowering the watertables in Simmons Creek catchment through use of rainwater where it falls, thereby curtailing deep drainage beyond plant root zones and infiltration to the watertable.

Agronomic solutions, involving revegetation and a mixture of agriculture and forestry (“agroforestry”), are preferable over engineering options. Pumping of saline groundwater from the uppermost 15 m of poorly transmissive, low-gradient aquifers would be very difficult. Also problematic would be the disposal of any extracted saline water in a setting such as Simmons Creek where further salinisation of Billabong Creek must be averted. Engineering drains, such as tile drainage in the lower reach of Simmons Creek, would have a local effect but would not curb saline discharges to Billabong Creek from seepages elsewhere.

It should be noted that, regardless of what salinity management measures are instigated, salts residing in the upper, unsaturated alluvial profile, with its blanketing parna component and illuviated saline clay-silt layers, are unlikely to be readily flushed from
the catchment. These salts in the regolith above the watertable tend to be flushed downwards by infiltrating rain although substantial time would be required for complete leaching. It should be borne in mind that the latter process has been constant and has continuously flushed cyclic salts to the watertable, however, that new salts are always being added to the soil profile by rainfall and dust accessions. Detailed profiling for the present study also confirms that there are layers in the uppermost several metres of soil in which salt stores are particularly concentrated and which appear relatively resilient to further downwards leaching.

Wherever the watertables are shallow, efflorescent salts will continue to accumulate in the capillary fringe due to evaporative concentration in the present climate with its high E/P ratio. These limitations apply to other salinised catchments in the region as well as Simmons Creek. Distinctive to Simmons Creek catchment is the substantial – and possibly ancient – salt store residing in palaeo-swamp clays and adjacent saprolite that forms a major mid-catchment plug. This can neither be ignored nor eliminated, and management strategies must be designed around this relatively intractable salt store.

The recommendations for revegetation strategies in Section 7.2 are based solely on groundwater information contained in this report. These guidelines need to be fine-tuned with respect to soil conditions, terrain analysis, present-day farm practices and the potential for planning and implementation of new farming systems in the nominated areas. It is noted that some break-of-slope tree planting was undertaken in the catchment by the Landcare Group several years ago to alleviate localised efflorescent salt outbreaks on the hillsides (Tuckson, 1993; 1994).

The feasibility of a saline groundwater interception scheme near Morgans Lookout, possibly to be conducted in conjunction with pumping of recently drilled production bores, is presently being evaluated by DLWC (Williams and Kulatunga, 2001). It is envisaged that pumping from the Lachlan Formation would depressurize the deeper aquifers. It is postulated that the resultant head difference could be manipulated to induce vertical leakage from the watertable to a level below Billabong Creek streambed, thereby stemming groundwater inflows to the creek. It has further been proposed that disposal of pumped groundwater for irrigation appears to be a viable option (Williams and Kulatunga, 2001). It is not known whether soil resources in the floodplains are capable of sustaining potential commercial uses from deeper groundwater extractions. Pumped fresh groundwater from the Lachlan Formation might be better utilised to bolster environmental flows in Billabong Creek rather than for irrigated agriculture.

Of possible relevance to the Morgans Lookout Salt Interception Scheme are other feasibility studies of pumping from the Lachlan, or Calivil, Formation to avert salinity risk in the Riverine Plain. For example, in the dryland riverine plains of the Loddon and Campaspe valleys of Victoria, feasibility studies of expanded groundwater pumping from the “Deep Lead Aquifer” (mainly the Calivil Formation) have been conducted with a view to salinity mitigation whilst providing opportunities for further regional development based upon irrigated agriculture (Dyson et al., 1999). In the case of the Campaspe valley, where groundwater pressure trends have been steadily rising in both the Shepparton and Calivil Formations through the 1980s and 90s, the extent of groundwater pumping since 1982 for irrigation appears to have prevented regional
groundwater discharge occurring in its northern plains (Dyson et al., 1999). Whilst the Lodddon Deep Lead system affords substantial quantities of available groundwater, caution needs to be exercised with continued long-term use of moderately saline groundwater in the region. In particular, irrigation waters high in sodium have the potential to cause a decline in soil structure (Dyson et al., 1999).

This principle of pumping from the Calivil Formation aquifer to induce vertical leakage from the overlying saline Shepparton Formation and tempering high watertable levels has been tested in irrigation areas in the Victorian Riverine Plain by Brownbill (1997). It is thought that if lower groundwater pressures in the deeper system (and hence head difference) are maintained, high watertables in the Shepparton Formation may be exacerbated. Mixed results were reported from these northern Victorian pumping tests. Vertical groundwater leakage downward into the Calivil aquifer by means of groundwater pumping was promoted mainly from the lowest layers of the Shepparton Formation whilst the shallowest piezometers showed negligible drawdown and a lack of watertable response (Brownbill, 1997). The latter is assumed to be because of recharge from applied water.

7.2 Revegetation Options

Lowering of the watertable is not desirable for the whole southern half of Simmons Creek catchment because groundwater in the eastern part of the floodplain aquifer system is relatively fresh (Figure 12). These waters, inflowing to the northern bank of Billabong Creek between Morgans Lookout and Brittas Reserve, are probably contributing favourably to environmental flows in Billabong Creek and serve to dilute salt loads in the creekwater. The arcuate mound, or ridge, of shallower groundwater levels and corresponding lower EC values that extends along the Walbundrie Road from Piezometers CLW8 through CLW9 and 263 towards CLW11 (labelled in Figures 9 and 27) should, ideally, be retained.

Mitigation measures should, rather, be directed towards the lower-middle and southwestern parts of the catchment, where groundwaters are both shallow and very saline (Figures 8 and 12). Perennial vegetation is the most promising means of lowering the watertable and curtailing saline groundwater inflows to Billabong Creek.

Planting of deep-rooted perennial grasses/legumes in the lowlands would promote moisture utilization at depth, and lower the near-surface watertable that underlies the adjacent swamps. The Billabong Creek floodplain and the area between Wiesners and Larundal swamps, as well as north of the saline discharge area in Simmons Creek itself, would benefit from the establishment of perennial herbaceous plants. The objective would be to provide some protection for the eucalypt woodland in the mid-catchment area, particularly Wiesners Swamp itself, from the shallow, highly saline groundwater body. The introduction of extended periods of summer-active lucerne (e.g., *Medicago sativa*) into crop rotation and/or perennial phalaris (*Phalaris aquatica*) pasture, combined with minimum tillage and shortened fallow periods in the areas delineated in pale orange in Figure 27, would cut down deep drainage and diffuse recharge in lowland zones surrounding the wooded swamps.
In <600 mm/year rainfall areas of the Victorian uplands, for example, phalaris and lucerne are clear salinity control winners in various dryland salinity trials, lowering the potential to ‘top-up’ the watertable from seasonal recharge from rainfall and/or flooding, and improving both on-site soil conditions and downstream environmental impacts (Reid et al., 1997). These trials demonstrated that watertable reductions of the order of 2 m relative to the control sites were achieved and that lucerne can remove more soil-water to depths of 6 m than any other adaptable crop (Reid et al., 1997). This magnitude of watertable control would be very positive for the lowlands of Simmons Creek catchment where watertables are presently at 4-6 m depth (Figure 8).

In the low-lying salinised areas along the lower reach of Simmons Creek and around the southern part of Glue Pot Road, halophytic plants such as Old Man Salt Bush (*Atriplex nummularia*) and tall wheat grass (*Agropyron elongatum*) would remedy the salinity damage that has already occurred in these areas (red hatched areas in Figure 27). These halophytes would also mitigate erosion and arrest further deterioration, and improve soil drainage. A stand of Old Man Salt Bush planted 10 years ago immediately south of Wiesners Swamp, near the Lindavale ruins on Clare property, is presently flourishing. This indicates that, when fenced off from stock, saltbush can grow well in the area. Saltbush can also periodically serve as fodder. Tall wheat grass is a palatable and productive summer-active perennial grass species that grows on saline and poorly drained soils. It has the potential to restore salt-affected land and improve agricultural

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Figure 27. Suggested areas for revegetation (diagrammatic), based on groundwater information.
productivity, and to increase the summer/autumn drawdown of the watertable in discharge areas to lessen the impact of winter recharge (Reid et al., 1997). The degraded lower reach of Simmons Creek would greatly benefit from being fenced off from stock.

Fostering regeneration of remnant native vegetation along the roads throughout the catchment, in Wiesners Swamp and the low-lying areas surrounding both the swamp and Simmons Creek to the east would further serve to lower elevated watertables. This would also provide needed habitat for nature conservation. These areas are delineated in yellow in Figure 27. Regeneration of native vegetation is already well advanced along some roads, e.g., Brittas Reserve Road, providing interconnected habitat corridors without impinging on agricultural land. At present, Wiesners Swamp contains large ancient eucalypts, with only minimal and localised juvenile regrowth. Recent gazetting of the swamp as a Nature Reserve, and exclusion of grazing stock from the reserve, should restore biodiversity and protect this ecosystem in the years ahead. Importantly, further rises in the level of the highly saline groundwater body that closely underlies the swap areas must be averted, and regeneration of eucalypts here would greatly help this objective.

Promotion of regeneration of native vegetation on the eastern slopes of the hills occupying the southwestern part of the catchment, Sugarloaf Hill to Beaver Rock-Glenara area and the lower slopes further northeastward to Golden Valley, should effectively reduce recharge and lower the down-gradient watertable that the southern reach of Simmons Creek presently intersects. Cypress pine (Callitris sp.) is the dominant native tree on these hillslopes and is presently readily self-propagating on granitic areas in the catchment. Abatement of rabbit pressures has no doubt helped regeneration of the pine seedlings in recent decades, and exclusion of grazing stock should foster natural regeneration in additional areas. Natural regeneration of native trees on these slopes could be supplemented with complementary tree planting to maximise recharge decline. This area is shown in mauve in Figure 27.

The hillslopes around Morgans Lookout no doubt supply fresh runoff and interflow waters directly to Billabong Creek, as do the southern slopes of Piney Range, near Walbundrie. Episodic runoff and interflow on these hillsides are regarded as important to contributing to stream flow in Billabong Creek and dilution of salt loads therein. These slopes should therefore not be extensively reforested except where severe soil erosion is manifest, as on the eastern slopes of Morgans Lookout.

In the 1990s, the local Landcare Group carried out break-of-slope revegetation in scattered saline outbreaks (Tuckson, 1993). Establishment of timberbelts at breaks-of-slope, specifically along the upper margin of colluvial aprons, has the potential to draw on the uppermost edges of the groundwater system before it is able to cause higher groundwater pressures and salinity lower in the landscape.

Recommended tree planting on the cleared southeastern hillslopes, as initially proposed by Tuckson (1994), is reiterated here. Nominated areas are delineated in green in Figure 27. Strategic farm forestry and commercial tree plantations have the potential of reaping both productivity and environmental benefits. The capacity of eucalypts to lower watertables by 1-3 m on both fresh and saline sites has been noted above (Section
4.2; Schofield et al., 1989). Additional tree planting could be extended on the slopes between the two green areas (Figure 27). It has been estimated by Gallant and Paydar (2002) that planting 10% of uphill parts of the catchment to trees, as well as increased pasture in the lower lying lands, would reduce recharge by about 0.4 m, with more substantial decreases in the watertable level if larger areas were planted with trees.

Groundwater in aquifers underlying the gentle slopes that flank the flat lowlands is relatively fresh. Therefore, tree planting on the hillsides is likely to be a highly effective proposition. Given the local scale of groundwater flow paths in the catchment, the time lag between establishment of perennial vegetation and trees and when the groundwater should start to fall may be of the order of only a few to several years. It is very possible that positive effects of revegetation and of modified land management systems will begin to be registered in the next few years during the course of Heartlands monitoring of the catchment.

These types of long-term interventions and management measures to protect the agricultural and environmental resources of the area need to be instigated, not only in Simmons Creek catchment, but also on comparable cleared land on the southern side of Billabong Creek from where saline groundwater is also discharging into Billabong Creek.

Land use management proposals and farm-based strategies to lower the watertables in Simmons Creek catchment will be pursued further and refined through collaborative Heartlands projects during 2003.
8 SUMMARY

- A groundwater monitoring network has been established across the study area, including installation of 11 new piezometers in 2001-early 2002. Automatic water level loggers have been installed in most of these piezometers.

- Recently, in December 2002, two new piezometers were installed in the northern part of Simmons Creek catchment for future monitoring to ensure that groundwater levels and salinities remain safe.

- Ground geophysical methods and shallow drilling have enabled identification of both saline groundwater and regolith units that contain appreciable salt stores, and have elucidated the distribution of salt in the catchment.

- Airborne magnetic imagery has proven valuable in mapping the distribution of near-surface basement highs that influence the hydrogeology of the catchment.

- Patterns and processes of salt transport and discharge to the catchment lowlands and salt export to Billabong Creek have been identified through the combination of hydrogeological and conventional ground geophysical methods.

- A conceptual model of the groundwater system has been developed and an understanding of landscape processes in areas affected by, or at risk from, high watertables and salinity has been formulated.

- The major salt sources are taken to be cyclic atmospheric salts delivered via rainfall and dustfall. These cyclic salts have progressively accumulated in the regolith over many thousands of years. Solutes actively being sourced from weathering bedrock are probably a subordinate contemporary salt source.

- The importance of parna in the landscape is recognised. In the first instance, the original airborne dust sourced from the west no doubt brought entrained salt into the eastern Riverine Plain. Such salts would have readily been leached from parna deposits soon after deposition. The parna deposits themselves have evidently been reworked from higher landscape positions, such as hillslopes, and now blanket local valley floors. Beneath the valley bottoms, clay-rich layers in the reworked parna deposits, in turn, have tended to sequester newer salt loads that have been illuviated down from the ground surface from contemporary cyclic salt inputs.

- Further research on the role of parna as both an original salt source and a latter-day salt store, and post-depositional processes involved in the remobilisation of salt from the deposits is warranted. These propensities and processes no doubt have wide application over very broad regions of the Riverine Plain.

- Salt is presently stored in clay-rich strata – alluvial and aeolian deposits – in both the unsaturated and saturated zones. Intensely weathered bedrock,
particularly near-surface basement highs of saprolitic granite, is another important salt store. Additionally, dense palaeo-swamp or palaeolacustrine clays represent a significant salt store in the mid- to lower catchment area.

- Salt transport via baseflow is far more important than transport via surface and near-surface wash-off processes. There is no history of primary salinisation in the region. Therefore, we are dealing with secondary salinity that is not an overprint to primary salinity processes that were climatically driven over very long periods of time in the Quaternary, as in the western Riverine Plain and the Mallee region.

- Salinity processes in the catchment are groundwater driven. Evidently, surface salts are flushed downwards relatively efficiently into the soil profile and, in places, into shallow aquifers. This is probably typical of much more extensive areas at the edges of the Riverine Plain, in the 500-800 mm/year rainfall zone, where there is hilly, rocky terrain that promotes periodic runoff that may exceed the regional mean annual average of <25 mm.

- This finding, that surface wash-off processes are not a driver in the generation and delivery of salt to streams in the study area, probably applies to comparable areas in the eastern edge of the Riverine Plain, where relatively higher rates of rainfall promote the flushing of surface salts downwards into the soil profile.

- Highly saline groundwater, 14000-32000 µS/cm underlies much of the lowland area of the southern half of the catchment. Watertables associated with these saline aquifers are 4-6 m below the ground surface in the lowlands (Billabong Creek floodplain).

- Highly saline groundwater and major salt stores are confined to the uppermost 15 m of strata beneath the catchment lowlands, whilst deeper aquifers typically contain relatively fresh, or, at worst, brackish, groundwaters. The upper strata are generally clay-rich and poorly transmissive and contain salt stores in the unsaturated zone as well as saline groundwater in the phreatic zone.

- The lower reach of Simmons Creek intersects the saline watertable whereupon the creek channel functions as a groundwater drain that exports saline groundwater directly to Billabong Creek. The flow rate of groundwater in the channel during dry years (2001-2003) is typically no more than 1 L/sec.

- Saline groundwater is also discharged from the floodplain aquifers via seepages in the bank of Billabong Creek. The substantial depth of incision of Billabong Creek augments these discharges from adjacent aquifers.

- The contribution of mobilised stored salt – from accumulated cyclic salt, from former parna deposits in the upper strata that the elevated watertables are now in contact with, and from structurally occluded, poorly transmissive saprolitic and palaeolacustrine clay bodies – to increasing stream salt loads underscores our understanding of salinisation processes in the region.
• A dynamic hydrologic equilibrium appears to now be established, with discharge volumes approximately equal to recharge volumes, although the duration of likely time lags between major recharge and discharge episodes is not yet established.

• Salt exports from the catchment exceed present-day salt imports because of a history of sequestering and remobilisation of ancient salt stores. This state of salt disequilibrium will persist through future decades, possibly longer. In the interim, the saline groundwater system needs to be monitored and managed to avoid further environmental degradation and decreased productivity of agricultural land.

• Salt exports from Simmons Creek catchment are minor compared to the overall salt load of Billabong Creek, particularly during low rainfall years.

• Mitigation measures need to be directed towards the groundwater system. Importantly, further rises of watertables need to be prevented because the higher the watertable, the greater the saline discharge to Simmons Creek, to topographic low areas in the floodplains, and to Billabong Creek.

• Management options, including revegetation and modified farming systems, additionally need to be aimed at restoring soil health and at conserving or restoring biodiversity and habitats.

• Regular monitoring of groundwater fluctuations and salinities in the piezometer network is well underway, along with monitoring of stream flow and salinities in both Simmons and Billabong creeks. Drought conditions during 2001-2003 have restricted efforts to fully constrain hydrologic fluxes and to clearly define recharge zones for the catchment during the course of the present study. Accordingly, piezometers with automatic data capacitance loggers installed for the present project, will continue to be monitored until well after the next substantially wet year.

• Continued seasonal monitoring of the soil salinity beneath Wiesners Swamp, including future EM39 measurements down Piezometer CLW5, are planned, to assess the magnitude of the build-up of soil salinity, of groundwater salinity, and watertables in response to groundwater pumping by the potentially vulnerable eucalypt woodland.

• This report is aimed at providing a foundation for the development of terrain-based farming system models suitable for practical catchment planning and salinity management.

• The findings and results of intensive fieldwork and laboratory analysis in Simmons Creek catchment for the present study contribute to an understanding of mechanisms controlling the generation and delivery of salt to streams in riverine landscapes generally. Ongoing monitoring of the catchment following
instigation of on-ground words and initiation of new land management practices will provide a yardstick for the appropriateness of these strategies for analogous catchments in the region.
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APPENDIX - Hydrographs
Ground water hydrographs
Ground water hydrographs
Ground water hydrographs