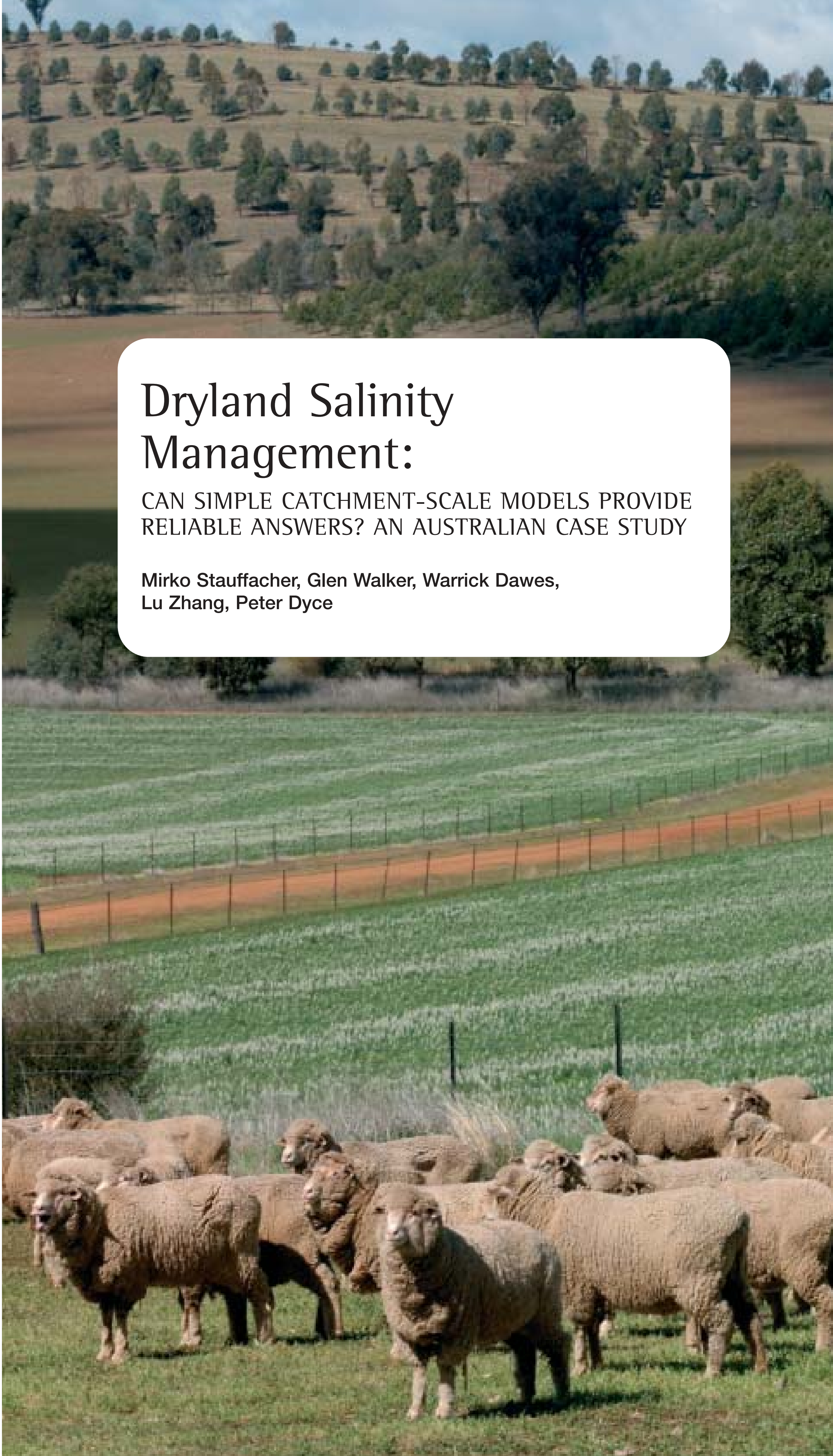

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CAN SIMPLE CATCHMENT-SCALE MODELS PROVIDE RELIABLE ANSWERS? AN AUSTRALIAN CASE STUDY

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CSIRO Land and Water Technical Report 27/03
MDBC Publication 13/03

Published by: Murray-Darling Basin Commission

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ISBN: 1 876830 53 0

Cover photo: Arthur Mostead *Margin photo: Mal Brown*

Acknowledgements

The writing of this report was funded through Murray-Darling Basin Commission Strategic Investigations and Education Program Grant Number D9004: ‘Catchment characterisation and hydrogeological modelling to assess salinisation risk and effectiveness of management options’.

The original case-study was funded through NRMS-LWRRDC Grant D6026 ‘Improving Dryland Salinity Management through Integrated Catchment Scale Management’. We thank all the team involved in this complex project for their valuable input; and the Liverpool Plains community for their help and support.

Executive summary

Introduction

Prior to this study, there was no clear understanding of the salinisation processes, their cause and extent in the Liverpool Plains catchment. For this work, we did a first-cut whole catchment analysis and then, based on the outcomes of this first appraisal, focused the research down to the areas that are extensively affected by salinity. For these two salt affected subcatchments, we developed a conceptualisation of the salinisation processes; developed some simple models that capture this conceptualisation and illustrated how these models were calibrated and applied for different scenarios. From the scenario modelling, we suggest the impacts of different options for this catchment with some assessment of confidence.

The Liverpool Plains catchment is on the western edge of the Great Dividing Range in northern New South Wales. The dominant aquifer in the catchment is a semi-confined intermediate to regional scale alluvial aquifer, with recharge beds located at the upstream end at the foot of hills and more rugged country. This report represents a broadscale scoping study with the following aims:

1. to define the processes leading to high watertables and land salinisation in the Liverpool Plains
2. to develop a conceptual model of the water and salt sources and sinks within the catchment
3. to apply a range of simple analytical tools to both surface and groundwater data
4. to simulate future groundwater trends in the catchment with a variety of recharge reduction targets.

Site description

The Liverpool Plains catchment lies within the Namoi River catchment in northern New South Wales. The study area covers 11,728 km^2 south of the town of Gunnedah. Ephemeral drainage occurs within the subcatchments of the Liverpool Plains, with ephemeral streams of the Mooki River and Cox's Creek draining to the Namoi River, and into the Murray-Darling River system. Mean annual rainfall varies from just over 1000 mm/yr at the top of the Liverpool Ranges in the south, to around 550 mm/yr on the plains proper. Rainfall is summer dominant and highly variable, with high intensity thunderstorms causing flooding on the plains. Sheep and cattle grazing were the dominant land use in the mid-1800s; this changed to cropping on the red soil of the foot-slopes of the ranges early in the century until the 1970s. In the early 1960s, advances in technology allowed the heavy-textured clay plains to become the main agricultural area, supporting a range of dryland annual crops. The steeper hills and ridges of the Liverpool Plains have never been cleared and thus remain covered by native eucalypts.

Groundwater system and salinity

The Liverpool Plains aquifer is an Intermediate to Regional flow system in Alluvial Deposits (Cainozoic/Mesozoic Volcanics) (Coram et al. 2000). The hydraulic gradient of groundwater flow follows the general topography, from the foothills of the Liverpool Ranges across the plains towards the Mooki River. The main aquifer is made up of gravel and sand and is locally called the Gunnedah Formation, while the semi-confining heavy clay layer over the top is called the Narrabri Formation. The Liverpool Plains catchment can be conceptualised as five almost independent groundwater systems, separated by bedrock highs.

There are two main complicating factors to groundwater flow in the aquifer. The first is that the permeable sediments of the Gunnedah Formation that provide lateral groundwater flow are contained in a much less permeable basalt bedrock structure. This results in the aquifer becoming both thinner and narrower in the direction of groundwater flow. The result is a greatly reduced capacity to transmit water and thus

the pressure increases and the water level rises. The second factor is the presence of shoe-string aquifers of sand in the Narrabri Formation, laid down as the bed of a prior water course. These provide partial hydraulic connection with the Gunnedah Formation, and may provide a conduit for upward movement of pressured groundwater.

Recharge to the Gunnedah Formation is at the southern upstream end of the aquifer, where extensive alluvial fans have been deposited by the upland creeks. As these creeks flow and flood they cut through the soil layers on the hills and allow water to percolate through the alluvial fans to the Gunnedah Formation directly. There is probably no diffuse recharge over the plain that contributes to the Gunnedah Formation, but recharge below the root-zone of crops in the Narrabri Formation will contribute to local watertables pushed up by the high potentiometric heads below. Since flooding is present in the catchment, it provides a pathway for a large amount of water to exit the catchment, bypassing both soil and groundwater. The actual amount of recharge to the Gunnedah Formation annually is only around 5 mm/yr.

There are few signs of surface salinity in the subcatchments of the Liverpool Plains. Only two subcatchments are showing signs of dryland salinity, Pine Ridge and Lake Goran and very salty creeks drain the areas, and groundwater is as high as 35 dS/m.

The conceptualisation of the salinisation processes on the Liverpool Plains identified two subcatchments (Pine Ridge, Lake Goran) as being affected by salinity and therefore, this study focused on those two subcatchments.

Surface and groundwater analyses

Groundwater trends of the Pine Ridge and Lake Goran catchments were fitted using the FLOWTUBE model. It is a simple groundwater model based on Darcy's Law and water mass balance. Comparison of available water and the capacity of the aquifer to transmit these volumes suggest that, even prior to land clearing and consequent recharge increases, some shallow water levels may have been typical for the catchment. The native grass was adapted to ephemeral water logging, and the swampy floodplain may have exhibited some signs of salinity even with native vegetation cover.

Modelling a no-change scenario, there are steady but small increases in groundwater heads mainly in the upper parts of the catchments, and certainly only minor rises near the outlet. This latter result is consistent with data collected by Timms (1996, 1998). Recharge reduction to the Gunnedah Formation is likely to be difficult given the location and size of the potential recharge beds. No recharge reduction scenario was modelled.

Stream flow and salinity in the nearby Big Jacks Creek subcatchment was analysed. Results indicate that stream flow is low unless flooding occurs, when a substantial volume of water can be mobilized. In the years with average or less rainfall, salt is stored in the catchment in the Narrabri Formation, and when a flooding event occurs this salt is remobilised and appears in the stream.

Portability of conceptual model, tools and results

The alluvial Groundwater Flows System of the Pine Ridge and Lake Goran aquifers is common in much of the western rim of the Great Dividing Range through New South Wales and Victoria. Similarly, the aquifer configuration is found in many parts of these two States. The management of recharge to the aquifer is likely best solved with engineering controls of flood events, while on the plains it is best to minimize water loss beneath the root-zone of crops to control local water levels using deep-rooted perennials. The buffer zone (unsaturated) generated by deep-rooted perennials would provide an effective store for floodwaters. In other parts of the Basin water is pumped from the relatively fresh lower aquifer and used as a water resource. Pumping in other subcatchments of the Liverpool Plains causes water levels to decline in an unsustainable manner, although salinity management in this way could be recommended in the Pine Ridge and Lake Goran subcatchments. In those

subcatchments, the groundwater of the Gunnedah Formation is fresh and could be used or disposed of easily. The pumping rates should be established as not to draw the highly saline shallow watertables of the Narrabri Formation down into the Gunnedah Formation. Pumping from the Narrabri Formation or the shoe-string sands presents a serious disposal problem due to high salinity. Coram et al. (2000) suggests that regional scale alluvial aquifers present major problems to biological recharge control due mainly to scale issues (magnitude of intervention needed). Pumping is recommended for sufficiently fresh water, along with living with salt if saline areas are small. Modelling and observations in the Pine Ridge and Lake Goran subcatchments support these recommendations.

From the results of other studies it is clear that management options are highly transferable between catchments of this type. Locally, groundwater and surface water salinity will dictate the mix of biological and pumping management of recharge and discharge areas.

Conclusions

- The Groundwater flow systems in the Pine Ridge and Lake Goran catchments are similar to many along the western rim of the Great Dividing Range, and are likely to share similar management strategies for saline outbreaks.
- In the Pine Ridge and Lake Goran catchments, recharge to the Gunnedah Formation is quite different from water loss below the root-zone of crops to the Narrabri Formation, and must be managed separately.
- Localised recharge to the Gunnedah Formation through the lower hillslope alluvial fans can be controlled by reafforestation and erosion control to prevent the perennial creeks from deeply incising the fans. On the plains themselves (Narrabri Formation), using appropriate deep-rooted perennials, the deepest possible unsaturated buffer in the root-zone must be developed and maintained so that the size of flood events can be minimised (increased water storage), and salt discharge to streams reduced.

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1. Introduction

In Australia, dryland salinity causes degradation to infrastructure, land and streams estimated to be worth $350 million annually. It also causes the loss of invaluable biodiversity. European style agricultural practices brought upon by the early settlers in the 1800s profoundly altered Australia's catchment water balances. This has resulted in the rising groundwater tables and salt remobilisation that lead to dryland and stream salinisation. If changes are not undertaken soon, the cost of salinity is estimated to increase at least five-fold in the coming decades.

The changes required for managing salinity fall into three broad categories. Since dryland salinity is caused by increased recharge under current agronomic practices, it is often assumed that biological recharge reduction will reverse the situation. Biological recharge reduction includes the use of perennials such as lucerne (alfalfa), agro-forestry or forestry plantation or incorporation of perennials in cropping rotations. Where these may not be effective on a reasonable time-scale, groundwater pumping or drainage may be used to protect important assets. In many cases, it is expected that neither of the former two options will be appropriate and that there could be a large increase in the area of saline land. We need to adapt to this or find opportunities for saline water usage. To implement changes, decisions will need to be made about which of the above options are appropriate, the degree of intervention required the spatial targeting of these options and incentives for the adoption of these options.

The Australian scientific community has thus been given an unprecedented challenge in providing the technical information to support these decisions over large areas of Australia. There is unlikely to be the time or money to conduct large-scale field investigations everywhere. It is therefore likely that such decisions will be made in a framework going from scoping to design stages. Each design stage is conducted at more detail, usually requiring more data and methods of greater complexity and sophistication. However, because of the constraints on time and money, it is likely that at each stage, much less area will be covered so that options become highly targeted. At the scoping stage, decisions need to be over large areas with only sparse data. We need to be able to predict with sufficient confidence and accuracy to distinguish the different options as to where they are clearly nonsensical; where they are clearly appropriate; and where further work is required (and hence move to the next stage). In this paper, we concentrate on this broadscale scoping stage and tools to support this process.

At this stage, it is important to understand and communicate the salinisation processes that are operating in a given catchment and predict the future costs of salinity for a range of scenarios, including the status quo. The data will often need to be appropriate for economic analysis. The basis of any technical analysis is the conceptualisation of the salinisation processes. While increased recharge is the cause of dryland salinity, there is a large variation in the way groundwater systems respond to increased recharge and hence how they will respond to management changes. Prediction of impacts under different scenarios implies that this conceptualisation needs to be captured in process-based models. There are a number of sophisticated groundwater and catchment models that can predict catchment response under different scenarios e.g. MIKE-SHE, TOPOG, MODFLOW and AQUIFEM-N. However, the general lack of available data makes it difficult to properly calibrate these models. Under these circumstances, the models can not provide the confidence in outputs as would normally be expected for such sophisticated models. The more complex the model, the greater the time to initiate and calibrate the model, the more training required to run the model and the more difficult to follow the information trail that leads from data and assumptions to the conclusions. Therefore, at the scoping stages, there would be advantages in using simpler models more appropriate to the

availability of data. Top-down modelling approaches usually have the simplicity being sought, but often are stochastic in nature and hence difficult to use in a predictive fashion. They can be used in a predictive fashion provided they capture the key processes associated with dryland salinity or are calibrated on data that incorporate appropriate processes.

We illustrate a suite of top-down analyses that provide the predictive capability. This is applied to assist salinity management in an important agricultural catchment in eastern Australia, relying on commonly available data. The study area is the Liverpool Plains catchment (1,172,800 ha) in northern New South Wales, Australia. It is a highly productive farming region, for which it was predicted in the early 1990s that 195,000 ha may become salt affected in the next ten years. Land use changes such as tree clearing, agricultural expansion and increased infrastructure have modified the catchment's hydrology over the last 30 years, leading in some areas to rising groundwater levels and consequently soil salinisation.

Prior to this study, there was no clear understanding of the salinisation processes, their cause and extent in the Liverpool Plains catchment. For this work, we did a first-cut whole catchment analysis and then, based on the outcomes of this first appraisal, focused the research down to the areas that are extensively affected by salinity. For these two salt affected subcatchments, we developed a conceptualisation of the salinisation processes; developed some simple models that capture this conceptualisation and illustrated how these models were calibrated and applied for different scenarios. From the scenario modelling, we suggest the impacts of different options for this catchment with some assessment of confidence. Some fieldwork is required as part of developing the conceptualisation, but does not involve much time or cost.

2. Site description

The study area is situated in the upper parts of the Liverpool Plains catchment, in eastern Australia (**Figure 1**). These plains encompass an area of 11,728 km^2 and are limited to the south by the Liverpool Ranges (which form part of the Great Dividing Range), to the east by the Melville Ranges and to the west by the Warrumbungle Range and Pilliga Scrub. Two rivers, Mooki River and Cox's Creek, drain northwards into the Namoi River, which is part of the Murray-Darling Basin.

The geological history of the catchment is characterised by a succession of erosional and depositional episodes (Gates 1980, Timms 1996), resulting in a geologically complex pre-Tertiary bedrock surface. The Permian basalts and shale basement is overlain by patches of Triassic conglomerates and remnants of Jurassic basalts (Garawilla) and sandstones (Pilliga). During the Eocene, the northern Liverpool Plains were covered by extensive basaltic flows of the Liverpool Shield volcano, which was heavily eroded during the Pliocene, receding to its current position, the Liverpool Ranges.

These form the basement bedrock. Late Tertiary and Quaternary thinning-upward alluvial deposits filled the landscape's palaeo-valleys, with thicknesses of up to 110 m. The deeper layer of alluvium, the Gunnedah Formation, contains gravels and sands, while the overlying layer, the Narrabri Formation, contains mostly clays and silts. These two formations are in partial hydraulic contact, the Narrabri Formation acting as a semi-confining layer. Poorly connected sand and gravel palaeo-channels described as 'shoe-string aquifers' (Broughton 1994a) can be found throughout the Narrabri Formation. Over the lower half of the salt affected subcatchments, the Narrabri groundwater system is saline with electrical conductivity (EC) values up to 35 dS/m, while the Gunnedah is uniformly fresh (EC<2 dS/m).

The hill slopes of the upper parts of those catchments expressing salinity, Pine Ridge and Lake Goran, are made out of basalts overlain by shallow colluvium and alluvium. On the flats, the alluvium uncomfortably overlays different

Figure 1. *Liverpool Plains catchment.*

lithologies windowed out by the erosion of the Tertiary basaltic cap. In these subcatchments, ephemeral creeks lose their channels on the change of surface gradient in going from the upland areas to the Plains and form extensive alluvial fans. In the last 50 years (R Banks pers. comm.), run-off on the ranges has increased and these creeks have deeply incised the soil layer on the hill-slopes, reactivating buried palaeo-channels. The groundwater flow in the alluvial aquifers is constricted at the outlet of these catchments by basement highs consisting of highly cemented Triassic sandstone and conglomerate outcrops. The constrictions and the semi-confining Narrabri Formation choke the groundwater system, resulting in high potentiometric heads that are currently two metres below ground level in the lower parts of the catchment.

The underlying deeper basement aquifers (Tertiary basalts, Triassic conglomerates, Permian basalts and limestone) have saturated hydraulic conductivity values comprised between 10^{-4} m/d and 0.8 m/d with *EC* values ranging from 1 to 2 dS/m. According to the University of New South Wales (UNSW) water quality studies (Broughton 1994a) and CSIRO Land and Water (Andrew Herczeg pers. comm. June 1997), there is only minor mixing between the basement and alluvial aquifers. Bore records indicate deeply weathered fronts on the basement, decreasing transmissivity (Gates 1980).

The rainfall decreases from over 1000 mm/yr at the top of the Liverpool Ranges (elevation up to 1000 m) in the south east to 550 mm/yr on the flats near Pine Ridge (elevation: 310 m). It is slightly summer dominated, when it is often short duration, high intensity rain or thunderstorms. Rainfall is extremely variable between years and seasons, resulting in drought, low river flows or flood conditions. The monthly maximum temperature in the study area is highest between November and March (up to 43°C) and lowest during July and August (0°C). Temperature varies mostly with altitude and shows some large diurnal variation. Frosts are common, and occasional snowfalls are experienced the ranges. Annual average potential evaporation of the area is 1900 mm, with a maximum of 275 mm in December and a minimum of 65 mm in June. Gates (1980) reported a predominance of potential evaporation over rainfall, varying from 3.1/1 to 1.2/1 for summer and winter respectively.

European settlement began in the 1830s and the land was predominantly used for sheep and cattle grazing until the 1880s. Then cropping became an important land use on the lighter textured red soils on the foot-slopes, resulting in extensive tree clearing. In the early 1950s, the heavy clays of the low lying alluvial flats became the main agricultural areas, replacing the deep rooted native plains grass (*Stipa aristiglumis*) with a range of annual crops (barley, sorghum, wheat). Cropping on the foot-slopes was progressively abandoned and replaced with pastures used for grazing. The steep ridges of the ranges are covered by various species of eucalypts.

3. Methods

3.1 Unique Mapping Areas

The land surface has been divided into a number of so-called Unique Mapping Areas (UMAs) based on slope classed derived from a digital elevation model, as shown in **Figure 2**. These areas represent geologically and geomorphologically consistent landscape units used as a framework for research and management within the catchment. Initially, eleven UMAs were defined for the Liverpool Plains (Johnston et al. 1995). For the purpose of this study, they were redefined according to their relevance to catchment-scale water balance processes and some were consequently lumped, resulting in three units. UMA 1 comprises the Liverpool Ranges and Hills, encompassing the non-alluvial component of the land surface. These are the higher rainfall zones and the soils are mainly shallow red-brown earths. Because of the low conductivity of the underlying basement groundwater systems, any water not evaporated or transpired is conceptualised as moving laterally as surface run-off or subsurface flow. UMA 2 comprises the colluvial/alluvial rims, defined as those Quaternary alluvial systems with slopes greater than one per cent. These are conceptualised as the recharge area to the semi-confined Gunnedah Formation. UMA 3 is the component of the Tertiary and Quaternary alluvial system with slope less than one per cent. These are considered to be the areas of diffuse recharge for the Narrabri Formation. The soil type consists mainly of Black Earths. A summary of their characteristics is presented in **Table 1**.

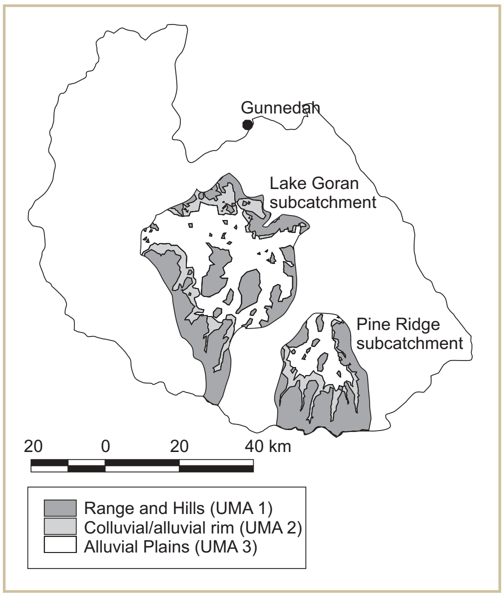


Figure 2. *UMAs in the Pine Ridge and Lake Goran subcatchments.*

3.2 Conceptual understanding of the groundwater system

The conceptual model for the groundwater system is detailed in Stauffacher et al. (1997), and follows an extensive review of available reports on the Liverpool Plains hydrogeology (Bradd et al. 1994, Broughton 1994a, 1994b, 1994c, Debashish et al. 1996, Gates 1980, Hamilton 1992, Tadros 1993) and analysis of borehole data. The main features of the model are shown in **Figure 3**. The late Tertiary-Quaternary unconsolidated alluvial deposits overlying the bedrock have a high transmissivity relative to the bedrock and are therefore considered to be the major contributor to the salinity process.

TABLE 1. Unique Mapping Areas description.

UMA	Description	Hydrological significance
UMA 1	Ranges and hills, thin soils, low permeability basement aquifer, high rainfall	High run-off generation area
UMA 2	Colluvial/alluvial rims and fans on the lower slopes. Ephemeral creek beds deeply incising the alluvium/colluvium.	Localised recharge to the Gunnedah aquifer through the deeply incised creek beds
UMA 3	Alluvial plains	Diffuse recharge into the Narrabri Formation

The conceptual model consists of seven key points:

1. The alluvial groundwater system has poor hydraulic connection to the other groundwater systems of the Liverpool Plains. Based on work by Broughton (1994a, 1994b, 1994c) who found the bedrock system to have very low permeabilities and on groundwater dating undertaken for this study, it has been assumed that the bedrock aquifers (mainly basalts in the salt affected areas) do not transport much water compared to the unconsolidated alluvial systems (gravels, sands). The subcatchment groundwater boundaries are therefore defined by bedrock highs and outcrops.
2. The Liverpool Plains catchment can be conceptualised as five almost independent groundwater systems. The five subcatchments are separated by bedrock highs as described above (**Figure 4**).
3. The most transmissive groundwater system is the semi-confined Gunnedah Formation (gravels and sands). This assumption is justified by the hydraulic conductivity in the Gunnedah Formation being up to 1000 times higher and the specific yield being up to 100 times lower than the Narrabri Formation (clays and silts) (Broughton 1994a). Flow to the Narrabri occurs through vertical leakage from the pressurised Gunnedah aquifer.
4. Only two subcatchments are affected by dryland salinity. There are characterised by bedrock highs constricting the alluvial groundwater flow at the outlets of the subcatchments. This, together with low topographic and potentiometric gradients and the lower hydraulic conductivity (higher clay content) at catchment outlets, limit the groundwater flow. These flow restrictions in the Gunnedah aquifer cause groundwater to discharge through the overlying Narrabri Formation to the soil surface. It is this discharge that results in land salinisation.
5. Groundwater recharge to the Gunnedah Formation consists of two components: localised recharge where the Gunnedah Formation outcrops in the colluvial/alluvial fans on the lower hill-slopes of the Liverpool Ranges; and downward leakage from the Narrabri Formation. The latter can only occur in the upper parts of the salt affected catchments, where groundwater gradients are downward. In the lower parts of the catchments, vertical gradients reverse and there will be some discharge from the Gunnedah Formation to the Narrabri Formation.
6. Groundwater recharge to the Narrabri from the land surface can only occur in the upper parts of the salt affected catchments. In the lower parts of the catchment, there is no storage in the aquifer for recharge to occur. Evidence of this is the higher salinities in shallow groundwater. Rainfall and floods can recharge the aquifer in the short-term but recharged water is evaporated or transpired afterwards. Floods on the land surface occur with a recurrence interval of about two years and probably dominate the ephemeral recharge. Removal of the deeper-rooted perennial vegetation on the Plains may have led to more shallow watertables and decreased available storage in the Narrabri Formation. This may have contributed to the increased land salinity.
7. Much of the salt discharge from the catchments occurs during the floods. Recharge from flood water causes discharge of saline water.

The elements of the conceptual model for the salinised subcatchments are schematically represented in **Figure 3**. This study will focus on the two catchments affected by dryland salinity, the Pine Ridge and Lake Goran catchments highlighted in **Figure 4**. These catchments are characterised by poor surface drainage and their groundwater outlets are laterally and vertically constricted by bedrock highs, leading to groundwater discharge and evaporative concentration of salt in the lower reaches.

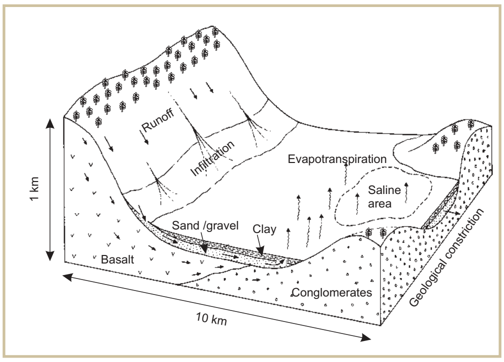


Figure 3. *Block diagram presenting the conceptual model for the hydrogeological processes on the salt affected catchments on the Liverpool Plains: recharge occurs at the break of slope and due to the bedrock highs at the outlet of the groundwater catchment, discharge to the surface occurs resulting in a saline area.*

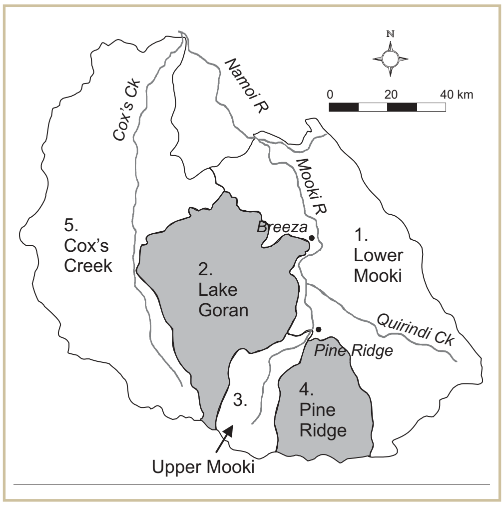


Figure 4. *Subcatchments of the Liverpool Plains. The catchments highlighted in grey are salt affected.*

3.3 Recharge estimation

3.3.1 Localised recharge

Much of the localised recharge into the Gunnedah Formation (Stauffacher et al. 1997) is thought to occur in the transition zone (UMA 2: alluvial fans on the lower hill-slopes) between the Ranges and Plains, by direct run-off interflow from UMA 1 (Ranges & Hills, **Figure 2**, **Table 1**). Our approach involves two steps, the first to provide estimates of run-off interflow from UMA 1 and the second to estimate, through groundwater modelling, the fraction of this 'lost' water from the uplands that effectively recharges the alluvial aquifer (Gunnedah Formation) locally through the incised stream bead on the colluvial-alluvial lower slopes.

Given high rainfall in the Ranges (over 1000 mm/yr), the localised recharge may become significant part of the overall catchment water balance. The major land use change that could impact on the upper catchment water yield would be either clearance of forests or reafforestation. In the choice of approach there were three considerations:

1. The methodology has to be based upon available data at a similar temporal (long-term groundwater processes, years) and spatial scale (catchment) as required for this project
2. Since the key driving variable is rainfall and in the lack of other daily or monthly meteorological information in the Ranges, the methodology should be based on mean annual rainfall
3. The methodology must be able to provide answers for different levels of afforestation on the Ranges.

A relationship derived by Holmes and Sinclair (1986) is of the appropriate form. They found that, for 17 catchments within Victoria, there were clear differences between evapotranspiration rates for forested and grassland catchments. Zhang et al. (2001) demonstrated with data from over 250 catchments worldwide that the Holmes-Sinclair relationship can be modified to provide a robust relationship between long-term average evapotranspiration and rainfall for a given forest cover (**Figure 5**). Hence, the modified Holmes-Sinclair relationship provides us with an appropriate predictor of the impacts on water yield of reafforestation or clearance of trees from the upland areas.

Zhang et al. (1997) used this relationship to estimate the amount of run-off interflow water that contributes to the water balance for the Pine Ridge and Lake Goran catchments. One fraction of the run-off interflow can contribute to localised recharge to the Gunnedah

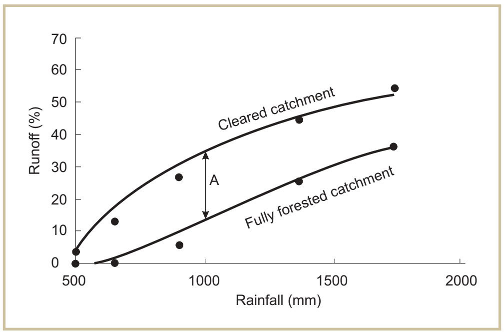


Figure 5. *Relationship between rainfall and runoff adapted from Holmes and Sinclair (1986) (—); obtained from the WAVES model (•).*

Formation, where it outcrops in UMA 2. A second fraction of the latter exits the catchment mainly in floods. A third fraction evaporates directly or from the shallow groundwater. A fourth fraction recharges the Narrabri Formation (diffuse recharge).

3.3.2 Estimation of diffuse recharge

Steady state deep drainage estimates were made on the Liverpool Plains by Kalma and Gordon using a soil properties model (SaLF) (Shaw & Thorburn 1985). The calculations indicate that 55% of the 92 sampled sites would have recharge values less that 20 mm/yr (**Table 3**). This is consistent with rainfall-fed recharge estimates from crop simulation models (Greiner 1997, Abbs & Littleboy 1998). Based on these results and as well as general experience on similar kind of soils and land use, an estimate of 20 mm/yr seems reasonable. For simplicity, we have chosen a constant value in spite of spatial land use and soils characteristics variability to provide some insight into the relativity of diffuse to localised recharge. If the diffuse recharge component in the overall recharge becomes an important driver for the groundwater modelling, we would then refine the estimates.

3.4 ^{14}C dating

^{14}C dating (using a direct absorption method and measurement made by liquid scintillation counting) were undertaken to test the conceptual model used as framework for the groundwater modelling. The percentages of modern carbon are expected to give some insight into the relativity of the groundwater travel times in the bedrock and alluvium aquifers. Groundwater was sampled in the Pine Ridge catchment at the top, middle and bottom of catchments, in three different aquifers: the bedrock, the lower alluvium (Gunnedah Formation) and the upper alluvium (Narrabri Formation) (**Figure 6**).

Due to the scarcity of bores in the Lake Goran catchment, no groundwater samples were collected. Nevertheless, due to its geographical proximity to the Pine Ridge catchment and their very similar geological, geomorphological and hydrogeological characteristics (Dyce and Richardson 1997), the results are expected to be applicable to both catchments.

3.5 Groundwater modelling

3.5.1 The FLOWTUBE model

The FLOWTUBE groundwater model was developed for the Liverpool Plains work to:

- be as simple as possible
- require the fewest number of parameters
- require the least amount of input data
- incorporate all the key processes of groundwater movement in alluvial systems.

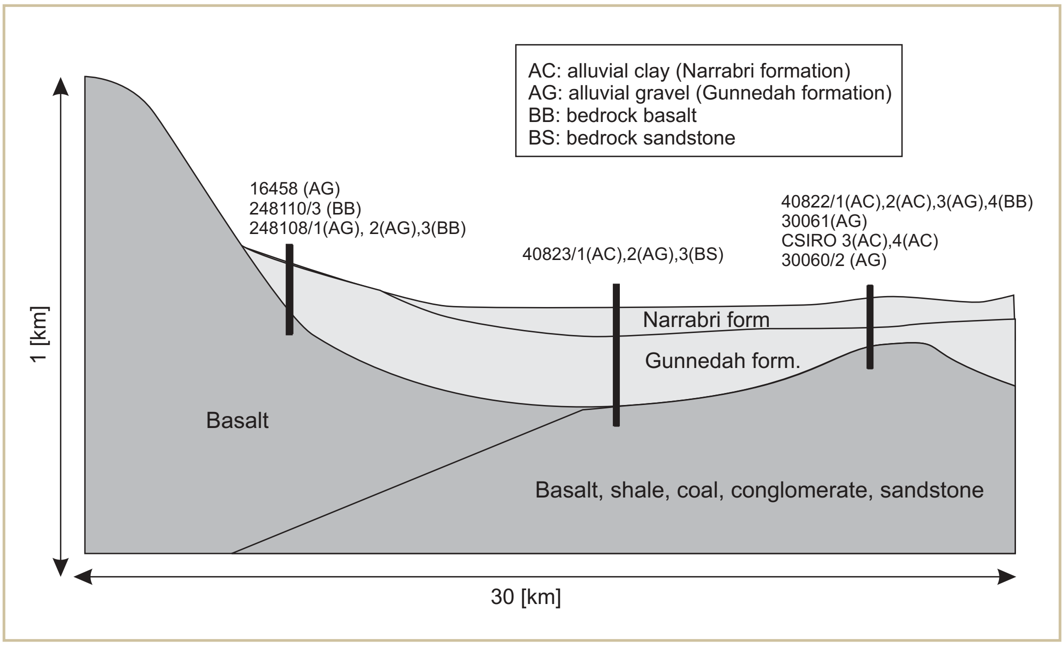


Figure 6. *Bore numbers, locations and lithology in the Pine Ridge catchment.*

The basis of the method is a groundwater budget of the catchment. The catchment is first described as a segmented tube and a groundwater balance is calculated for each cell. Inflows to each cell are vertical recharge over the cell, and lateral movement of water from higher up in the catchment. Outflows from each cell are surface discharge out of the cell, and lateral movement of groundwater to parts lower down in the catchment. The difference between inputs and output will cause a rising or lowering of the groundwater. All lateral fluxes are calculated using Darcy's Law, which can be written as:

$$q = k\ d\ i\ w \qquad (1)$$

where q is the flux (L^3/T), K is hydraulic conductivity of the aquifer (L/T), d is saturated depth of flow (L), i is hydraulic gradient (L/L), and w is saturated width of flow (L).

Figures 7 to 9 show the segmentation for the three subcatchments of the Pine Ridge catchment, and **Figures 10 and 11** show the long and cross sections for the three arms and trunk section of the Lake Goran catchment. The West arm feeds into the western end of the main trunk, the Central arm feeds in at the next cross-section down gradient, and the East arm feeds in at the second last cross-section down gradient.

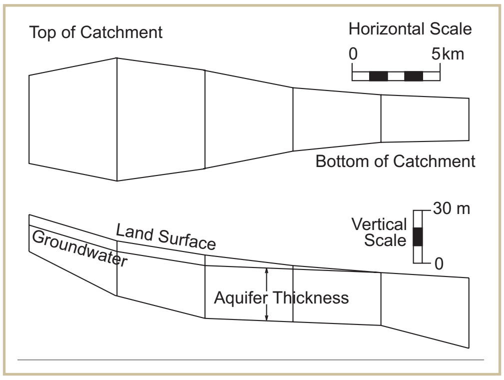


Figure 7. *Plan view and cross section of Big Jacks Creek catchment, as discretised from available bore lithology information presented in Dyce and Richardson (1997). Note that aquifer thickness does not indicate the depth below surface of the aquifer, only the average thickness of material.*

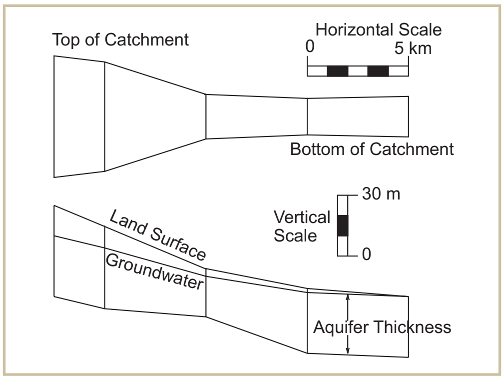


Figure 8. *Plan view and cross section of Yarramanbah Creek catchment, as discretised from available bore lithology information presented in Dyce and Richardson (1997). Note that aquifer thickness does not indicate the depth below surface of the aquifer, only the average thickness of material.*

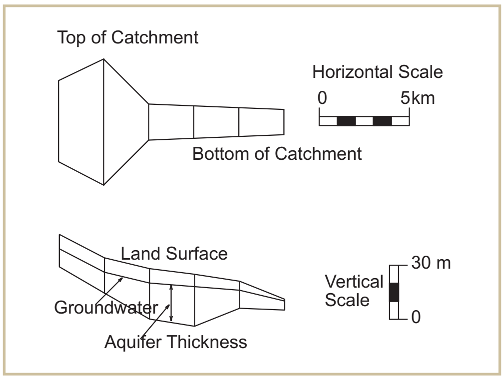


Figure 9. *Plan view and cross section of Pump Station Creek catchment, as discretised from available bore lithology information presented in Dyce and Richardson (1997). Note that aquifer thickness does not indicate the depth below surface of the aquifer, only the average thickness of material.*

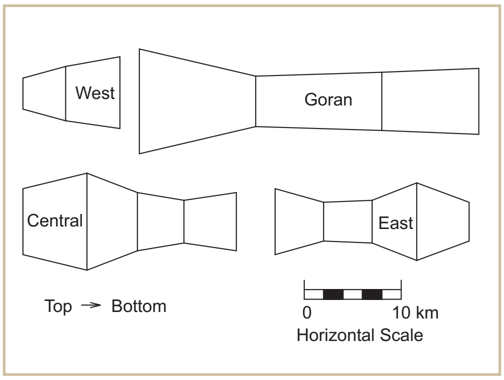


Figure 10. *Plan view for three arms and main trunk of the Lake Goran catchment, as discretised from bore lithology information presented in Dyce and Richardson (1997).*

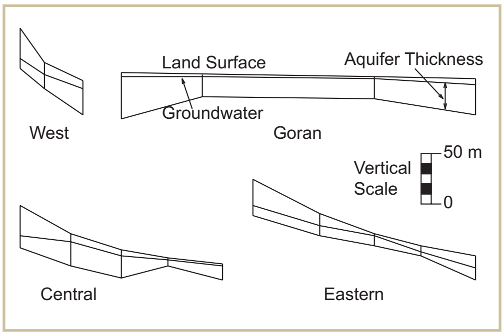


Figure 11. *Cross sections for three arms and main trunk of the Lake Goran catchment, as discretised from bore lithology information presented in Dyce and Richardson (1997). Note that aquifer thickness does not indicate the depth below surface of the aquifer, only the average thickness of material.*

Examining the conceptual model of Stauffacher et al. (1997) summarised in **Section 3.2**, all the factors affecting groundwater flow and rising watertables in the Liverpool Plains are present in Darcy's Law. Firstly the material making up the aquifer grades from boulders, to gravel, to sand, to sand and clay beds. The order of these materials means that the hydraulic conductivity of the aquifer material is decreasing from the hills-plains interface to the catchment outlet, and the flow of water can be expected to be restricted. Secondly, the slope of the land and the groundwater surfaces decrease moving from the hills and ranges to the catchment outlet, which again will slow down any water movement. Finally the saturated thickness and width of the aquifer, due to the intruded sandstone hills and bedrock topography, is reduced toward the catchment outlet further restricting flow. Application of Darcy's Law should be useful in various analyses of the water-balance and parameter estimation in the subcatchments of the Liverpool Plains. It forms the basis of the numerical model, and is used in the estimation of aquifer physical properties, such as hydraulic conductivity.

The FLOWTUBE groundwater model is a solution of 1D Darcy's Law for saturated flow, with variable properties along a tube. There are special conditions however for the conceptual model we are using that affect the equations. Reiterating, they are:

- The groundwater system consists of three layers (the semi-confining Narrabri Formation the highly conductive Gunnedah Formation, and some bedrock material).
- Underlying the region of interest is some basement material which plays no role in groundwater movement or storage (in effect this simply provides a lower limit to the extent of the aquifer).
- The middle layer is a highly conductive aquifer, and the water in this layer is assumed to always be under pressure, i.e. the heads are above the top of the aquifer, and so this layer contributes to water movement only.
- At the surface is a semi-confining layer with low conductivity; this layer contributes to storage of water under pressure but not to any lateral movement of water.

The mass in the tube at any time *t* is:

$$V(t) = \rho_1 A_1(t) + \rho_2 A_2(t) \qquad (2)$$

where *V* is volume of water per unit length (m^3/m), ρ is porosity (m^3/m^3), *A* is saturated cross-section area (equal to *d*i*; m^2), *t* is the time coordinate (days), and the subscripts *1* and *2* refer to the conducting (Gunnedah Formation) and confining (Narrabri Formation) layers respectively.

The flux within the tube at any point x as described by Darcy's Law is:

$$q(x) = -A_1(x)K(x)\frac{\partial h}{\partial x} \qquad (3)$$

where *q* is flux (m^3/d), *K* is hydraulic conductivity of the conducting layer (m/d), *h* is hydraulic head (m), and *x* is the space coordinate (m).

Mass balance demands that the rate of change of volume in the tube ($\delta V/\delta t$) is equal to the rate of change of water flux along the tube ($\delta q/\delta x$). Differentiating (2) with respect to time (and storage in the conducting layer is constant), (3) with respect to distance (and no flux carried by the confining layer), equating them and dropping the time and space ordinates for clarity, we get:

$$\rho_2 \frac{\partial A_2}{\partial t} = \frac{\partial}{\partial x}\left(-A_1 K \frac{\partial h}{\partial x}\right) + R \qquad (4)$$

where *R* is the diffuse recharge per unit length of tube ($m^3/d/m$).

Equation (3) can be expressed in finite-difference form between nodes *i* and *i+1* as:

$$q_i^j = \frac{A_{1,i}K_i + A_{1,i+1}K_{i+1}}{2} \cdot \frac{h_i^j - h_{i+1}^j}{\Delta x_i} \qquad (5)$$

where Δxi is the distance between node *i* and *i+1* (m).

Equation (4) can be rearranged and expressed as a fully-explicit finite-difference solution at node *i* and time *j* as:

$$A_{2,i}^{j+1} = \left(\frac{q_{i-1}^j - q_i^j}{\Delta x_i} + R_i^j \right) \frac{\Delta t^j}{\rho_{2,i}} + A_{2,i}^j \qquad (6)$$

where Δtj is the length of time step *j* (d).

The head at each node can be updated by:

$$h_i^{j+1} = h_i^j + \frac{A_{2,i}^{j+1} - A_{2,i}^j}{w_i} \qquad (7)$$

where w_i is width of the aquifer at node *i* (m).

The numerical solution of this problem is analogous to a diffusion equation, which has been extensively studied and is well understood. According to Crank (1975), the forward-difference solution is stable if the following condition is met:

$$\frac{D\,\Delta t}{\Delta x^2} < 1 \qquad (8)$$

where *D* is the diffusion coefficient (m^2/d), which in our case is the product of hydraulic conductivity and aquifer width, divided by the specific yield. Equation (8) can be rearranged to give a Δt for any desired aquifer properties.

This model has been implemented with a tree structure of tubes, reflecting the network of streams, which form the alluvial groundwater system. Each branch of the tree follows the above equations, while at the junctions of the branch, continuity of head and fluxes is maintained. This only requires trivial modifications to the conceptual and numerical model.

In the discharge areas, the amount of discharge can be estimated in two ways. In the first, discharge occurs when the aquifer can no longer transmit all of the water. The amount of discharge is equated from differences in the amount of water carried by the aquifer at different distances down the flowtube. In the second mode, a maximum discharge rate is specified.

3.5.2 Calibration

Within the alluvial aquifers, there is a need to estimate the distribution of hydraulic conductivity, porosity, and groundwater head along the flowtube. **Table 4** shows how the bore data is distributed across the catchments, and includes the number of bores and frequency of measurement. The simple conclusion is that there is insufficient groundwater head data to calibrate simulations with transient inputs over any reasonable time frame. For calibration purposes, only long-term steady state simulations will be performed, by using constant input conditions and running the model until calculated groundwater heads do not change over a single year.

TABLE 4. Available bore, lithology, hydrograph, and physical data for dryland salinity affected catchments in the Liverpool Plains. The section for long-term Hydrographs indicates the number of piezometer nests and the length of time regular reading have been taken for, and the Pump Test section indicates the number of pumping tests performed along with the estimated hydraulic conductivity.

	Yarramanbah Creek	**Big Jacks Creek**	**Pump Station Creek**	**Lake Goran catchment**
Number of bores	70	122	53	674
Valid depth to water	60	90	30	431
Lithology & >5 readings	11	14	10	23
Long-term hydrograph	1, 8 years	1, 10 years	0	7, 24 years
Pump tests and results	0	1, 10-20 m/d	0	0
Hills/ranges area, km^2	102	213	118	354
Contact area, km^2	33	54	42	138
Plains area, km^2	55	110	35	605

Hydraulic conductivity is the most critical parameter and was estimated by calibration. A range of hydraulic conductivity was chosen to constrain the calibration. Freeze and Cherry (1979) suggests that for gravel, the conductivity is between ten and 1000 m/d. Alluvial systems in eastern Australia similar to the Gunnedah Formation are in the range of ten to 100 m/d (WR Evans pers. comm. 1997). Salotti (1997) fitted both hydraulic conductivity and porosity to an aquifer system in the adjacent Borambil Creek catchment, where there was 17 years worth of good quality bore hydrographs, with irrigation and pumping data for the last ten years. The results suggested a range of conductivity from one to 30 m/d and a range of porosity of 0.05 to 0.3, for a single layer, combined sand and clay aquifer, of similar dimensions to those in Pine Ridge. Given that the modelled aquifer contained gravel, sand, and clay, the cleaner aquifer systems modelled in the Liverpool Plains catchments would have a higher conductivity than fitted by Salotti. The New South Wales Department of Land and Water Conservation (NSW DLWC) keeps an extensive database of bore lithological logs and hydraulic properties, and have developed a system where these properties can be estimated for any site where only a lithology log is available. Using profiles typical of those used in the cross-sections to estimate aquifer size in Dyce and Richardson (1997), the NSW DLWC procedure gave a conductivity range of five to 100 m/d, and a porosity range of 0.1 to 0.3. There has been a single pumping test carried out in the Pine Ridge catchment, near the outlet of the Yarramanbah Creek subcatchment (W Timms, pers. comm. 1997). This test indicated that the hydraulic conductivity within the most constricted part of the catchment was between ten and 20 m/d. The most consistent overlapping range of conductivity values from all the different data sources for the Liverpool Plains sites is ten to 100 m/d over the catchments; the data and selected range is shown in **Figure 12**.

Due to lack of transient data, it is difficult to calibrate the porosity. Hence, the porosity was assigned a constant value over all the subcatchments of 0.2. It is also notable that the various estimated porosity ranges all bracket the constant value chosen.

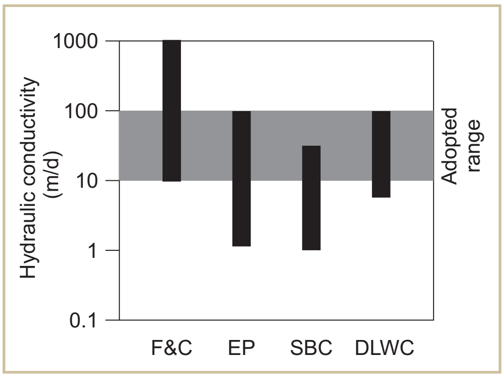


***Figure 12.** The ranges of hydraulic conductivity estimated from various sources, along with the adopted range for the study. F&C is Freeze and Cherry (1979), EP are the expert partners in the work, SBC is the Salotti (1997) study in Borambil Creek, and DLWC are estimates from NSW Department of Land and Water Conservation database.*

Since the physical shape and extent of the aquifer and confining layer, the physical properties of the aquifer and the current water levels were defined by borelogs (Dyce & Richardson 1997); and diffuse recharge was held as constant at 20 mm/yr, the only parameters that require fitting are the hydraulic conductivity of the aquifer and the proportion of run-off interflow that becomes localised recharge to the aquifer. These parameters are co-dependent and the combination must fit within all the constraints implicit in the observed data. The proportion of run-off that becomes localised recharge constant is constrained to be the same for each of the three subcatchments of the Pine Ridge catchment, as we would expect the erosion history of each of these to be similar, and therefore the processes and rates of flows to be similar. While this condition does not necessarily apply to the Lake Goran catchment, we assumed it did.

The FLOWTUBE model is a combination of Darcy's Law and a mass balance equation. It is possible to establish a relationship between the amount of localised recharge and the hydraulic conductivity at the hills/plains interface, thus:

$$\frac{K}{f} = \frac{RO}{d\,i\,w} \qquad (9)$$

where *RO* is the average rate of run-off from the hills and ranges (m^3/d), and *f* is the proportion of that run-off that becomes localised recharge. In calibrating the FLOWTUBE model in steady state mode, the ratio of conductivity and f is actually fitted. At this stage, we fix *f* and then calibrate the conductivity. In doing so, the amount of localised recharge must satisfy several constraints. First it should be an amount, that when taken on an annual average basis, does balance reasonable recharge rates in the alluvial fans of the catchments and discharge rates in the lower parts of the catchment and produce a conductivity estimate from (9) in the recharge area at the top of the catchment that is consistent with the *a priori* range determined in **Figure 12**, i.e. between ten and 100 m/d. On the basis of these limiting factors, we propose that five per cent of the run-off interflow from the hills becomes localised recharge in each subcatchment.

Using the area of alluvial fans in **Table 4** and the volumes of run-off interflow water from **Table 5**, an estimate of the annual average recharge rate in the alluvial fans can be made. In the subcatchments of the Pine Ridge catchment, the average rate varies between 0.06 and 0.07 mm/d, and in the Lake Goran catchment the average rate is 0.05 mm/d. Since the average rate for each of the three subcatchments in Pine Ridge are almost the same, it gives credence to the assumption that these subcatchments evolved together, and have similar hydrogeological behaviour. The fact that the rate is also very similar in the Lake Goran catchment, with different annual rainfall amounts, adds weight to the assumption of a fixed proportion of run-off interflow water becoming localised recharge.

Steady state calibration

With a fixed aquifer geometry and any given amount of localised recharge, we can calculate what the conductivity will be with any distribution of hydraulic heads using Equation (9). An inferred conductivity distribution that is relatively constant, or that is monotonically increasing or decreasing along the tube, will provide further confidence in the physical structure and conceptual model. If the distribution is random or chaotic however, then without significant geological changes along the tube this would indicate a poorly constructed model. Additional to calculating conductivity within the flow tube, using the results of the pump test at the catchment outlet from **Table 4**, we can infer the hydraulic gradient at the outlet and fix this as a boundary condition for the model.

Big Jacks Creek, a small area five kilometres from the outlet, showed high conductivity estimates outside the prescribed range. It is a simple conclusion that this area is likely to suffer from rising water levels (so that the steady state assumptions may no longer be valid) or is part of a discharge area. In the model runs, this area was set to have the maximum hydraulic conductivity (100 m/d) within the prescribed range, and showed the greatest rates of rise with transient simulations. Yarramanbah Creek had well behaved conductivity estimates throughout except right at the outlet, where salinity is expected to be expressed. Pump Station Creek required a high conductivity across the entire catchment due to its very thin lower section. This also inferred a high hydraulic gradient at the outlet of five per cent. A similar large drop in water level was reported by Timms (1998) who measured groundwater depth along transects passing through the outlet of the Pine Ridge catchment, so this model inference can be accepted as real. In the Lake Goran catchment, conductivity estimates were uniformly low, near the bottom of the range, except in the main trunk. Here a significant area required much higher conductivity to transmit the input water. Since this area contains the lake this was not seen as unusual, but conductivity was lowered to be consistent with the other fitted values; water levels here were modelled at the ground surface.

Conductivity estimates were rounded to multiples of five and some manual modifications performed to allow for this rounding. **Figures 13 to 16** show the fitted steady-state hydraulic heads for Big Jacks Creek, Yarramanbah Creek, Pump Station Creek and Lake Goran, respectively. The fits are excellent, as would be expected from calculating conductivity based on the heads to be fitted. All the catchments showed conductivity distributions that were well behaved, and thus we can be more confident in the structure of the aquifers and the conceptual model.

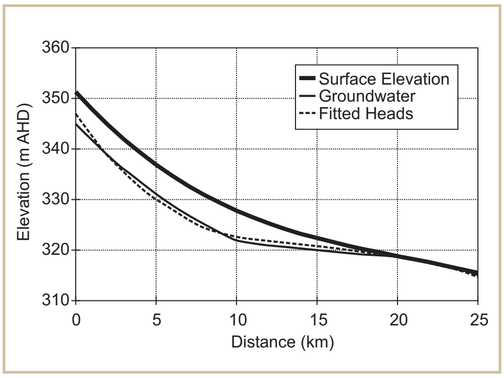


Figure 13. *Measured and fitted steady state groundwater heads in the Gunnedah Formation for Big Jacks Creek catchment. The root mean square error (RMSE) between the observed and calculated heads is 0.69 m.*

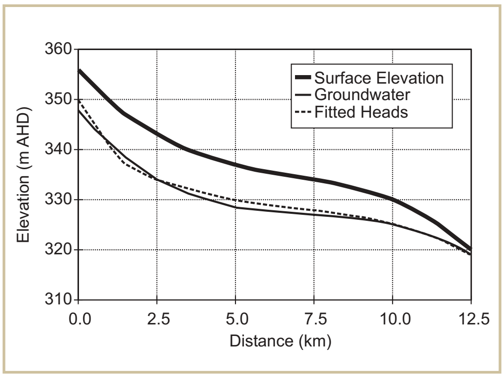


Figure 15. *Measured and fitted steady state groundwater heads in the Gunnedah Formation for Pump Station Creek catchment. The RMSE between the observed and calculated heads is 0.85 m.*

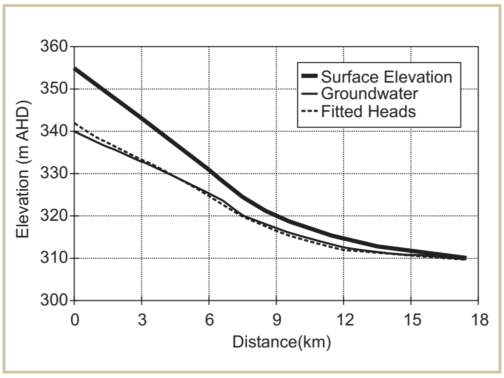


Figure 14. *Measured and fitted steady state groundwater heads in the Gunnedah Formation for Yarramanbah Creek catchment. The RMSE between the observed and calculated heads is 0.70 m.*

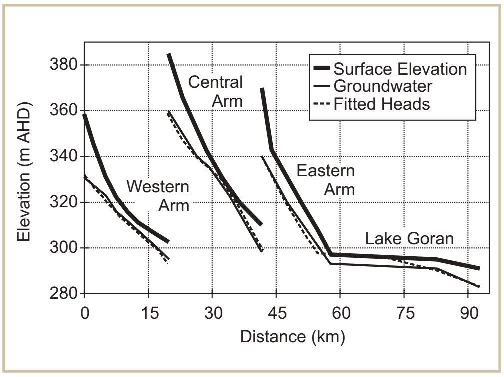


Figure 16. *Measured and fitted steady state groundwater heads in the Gunnedah Formation for the Lake Goran catchment. The RMSE between the observed and calculated heads for each of the three arms and trunk varied between 1.17 and 2.71 m, and is 1.78 m overall.*

4. Results

4.1 Run-off interflow

The run-off interflow for the Liverpool Ranges and hill slopes was calculated using the method described in **Section 3.1**. **Table 5** lists the run-off interflow and diffuse recharge values from Zhang et al. (1997).

In the Big Jacks Creek subcatchment, a gauging station was installed and has good records for 1996 to 1998. The data from this three year period indicates that between three per cent and five per cent of the rain falling in the hills and ranges leaves the catchment during floods.

4.2 ^{14}C groundwater dating

The ^{14}C dating results are summarised in **Table 6**.

In the **alluvium**, the trend is an ageing of the water down the flow-path. On the top of the catchment (dark shade), the water contains 96% modern carbon, in the middle (light shade), 50% and at the outlet 18.5% (no shade). For the bedrock, the ageing trend is the same, but due to a much lower permeability, the percentage of modern carbon is respectively 55, 11 and less than two from the top to the bottom of the catchment. At the outlet of the catchments, the deepest bores in the alluvium (just above the bedrock) also contain less than two per cent modern carbon, probably due to the very low flux of groundwater in the deepest alluvium layers. The alluvium aquifers are clearly the more dynamic systems on the Liverpool Plains and have therefore the largest water carrying capacity.

TABLE 5. Annual water inputs for dryland salinity affected catchments in the Liverpool Plains, estimated by Zhang et al. (1997). Run-off interflow is the volume of water coming from the hills and ranges above each catchment annually that may become Localised Recharge, and the Diffuse Recharge is a volume of water over the whole plains based on an annual leakage rate below the root-zone of 20 mm/yr. The later in considered as an upper boundary.

Catchment	Run-off interflow $10^6 m^3/yr$	Diffuse recharge $10^6 m^3/yr$
Big Jacks	27.8	1.1
Yarramanbah	15.5	0.6
Pump Station	21.4	0.35
Lake Goran	29.9	6

TABLE 6. ^{14}C dating results.

Sample	Lithology	$\delta^{13}C$ ‰ PDB	^{14}C pMC±1σ
16458	Alluvium: gravel, sand	-11.7	96.5 ± 1.5
248108/3	Bedrock: basalt	-13.7	55.3 ± 1.9
40823/2	Alluvium: gravel/sand	-10.4	49.9 ± 1.1
40823/3	Bedrock: sandstone	-11.6	11.7 ± 0.9
30061	Alluvium: gravel/sand	-13.7	BG < 2PMC
40822/3	Alluvium: gravel/sand	-14.1	BG < 2PMC
40822/4	Bedrock: basalt	-10.6	BG < 2PMC
30060/2	Alluvium: gravel, sand	-12.2	18.5 ± 1.0

4.3 Scenario modelling results

Scenarios to be considered are historical conditions, and future conditions under current and poor management practices. Problems with estimating prior conditions in these and other catchments are a general lack of historical water levels, difficulty estimating the spatial distributions of conductivity and porosity for groundwater models, and estimating temporal water inputs. Of these, the latter is often the most difficult, and particularly in the Liverpool Plains. The current modified conceptual model using a fixed proportion of run-off interflow water as recharge to the Gunnedah Formation may not apply uniformly from year to year, and may also depend on the erosion history of the catchments. It is likely that infiltration to the Gunnedah Formation is limited by available storage in the upper parts of the catchment, so size and timing of individual events will be important to the actual amount.

Zhang et al. (1997) have estimated the average annual run-off interflow volume for the catchments of the Liverpool Plains, as reported in **Table 5**, but how these values are modified to become Localised Recharge by historical circumstances is unknown. For the purposes of estimating a pre-European settlement situation, we can use the run-off interflow values from Zhang et al. for fully forested hills and uplands and assume that the same proportion as today infiltrates. This is run until a steady state is reached then used as the starting condition for scenario modelling. From 1950 to 2000 the run-off interflow for the current amount of clearing is used, then from 2000 to 2050 the run-off interflow value for fully cleared land is used. **Figures 17 to 22** show the historical initial groundwater level and modelled water level rise for Big Jacks Creek, Yarramanbah Creek, Pump Station Creek, and Lake Goran catchments. It is these simulations that will test the assumed value of porosity. If water levels rise much faster or slower than measured then the value used must be wrong, as well as the assumption of a uniform distribution. Bore hydrographs reported by Timms (1998) indicate water level rises of between one and five centimetres per year near the catchment outlets, which are consistent with the trends presented in **Figures 17 to 22**.

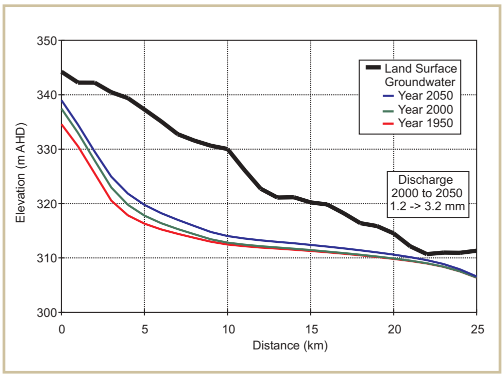


Figure 17. Transient water level simulation for estimated historical and future conditions in the Big Jacks Creek catchment.

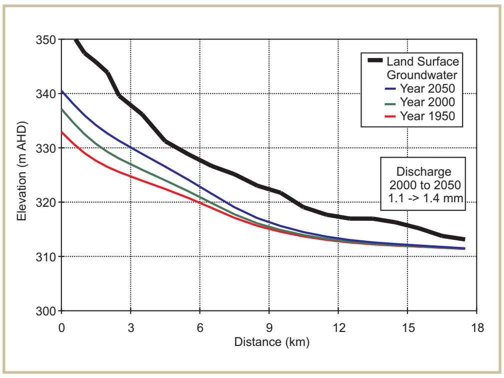


Figure 18. Transient water level simulation for estimated historical and future conditions in the Yarramanbah Creek catchment.

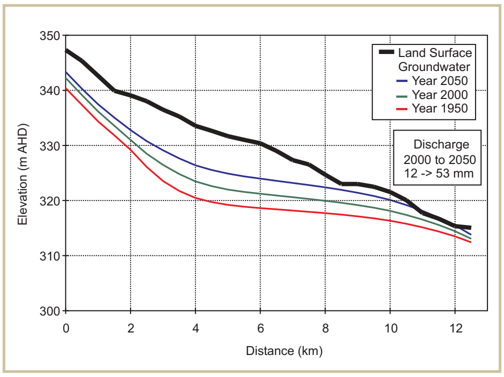


Figure 19. Transient water level simulation for estimated historical and future in the Pump Station Creek catchment

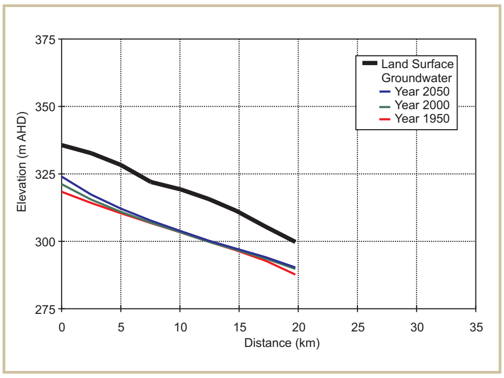


Figure 20. Transient water level simulation for estimated historical and future conditions in the Eastern valley within the Lake Goran catchment.

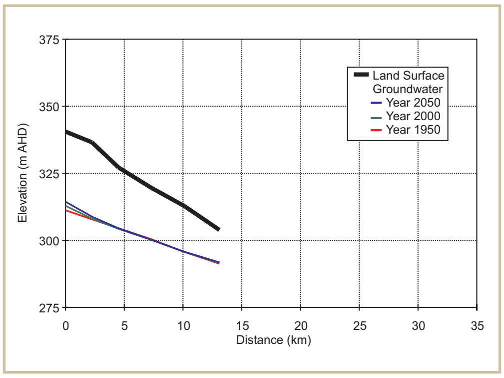


Figure 21. *Transient water level simulation for estimated historical and future conditions in the Western valley within the Lake Goran catchment.*

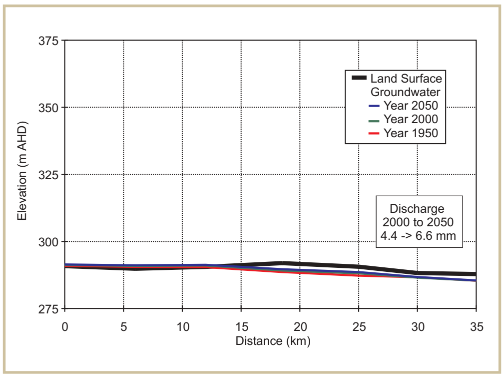


Figure 22. *Transient water level simulation for estimated historical and future conditions in the Lake Goran basin.*

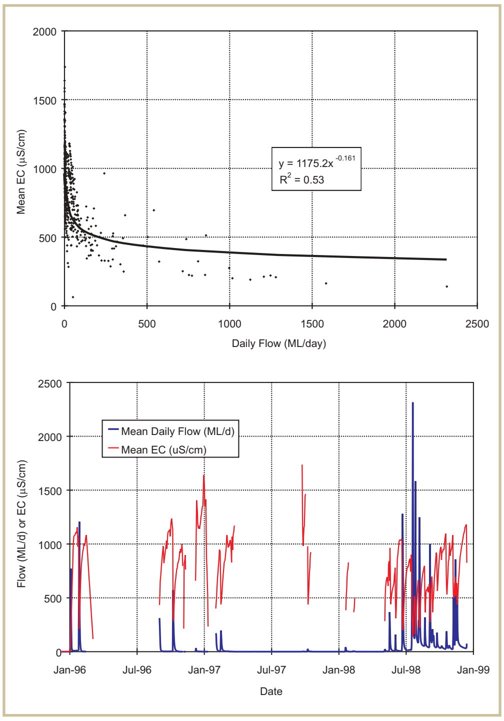
5. Discussion

5.1 Extent of land salinity

We estimate that over the next 20 years, the area at risk of salinity in the two salt affected catchments will show only a minor increase. The area at risk corresponds roughly to those areas with shallow saline groundwater in the lowest parts of the subcatchments, close to the outlets. The highly saline shallow watertables themselves are evidences that these areas have been historically saline and would have expressed some salinity in the past.

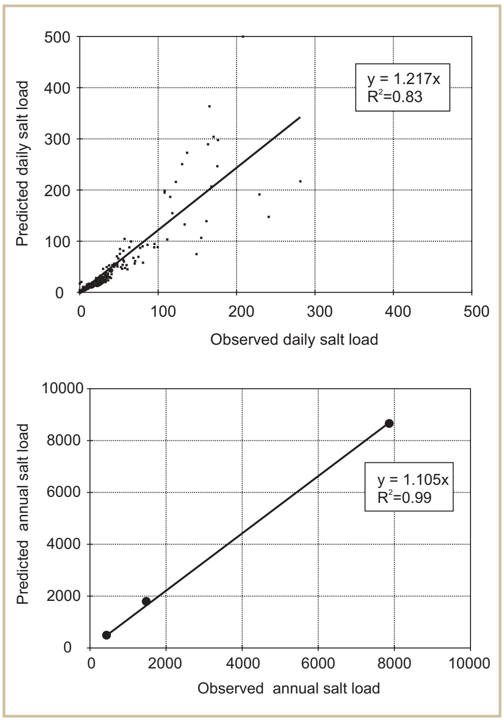
5.2 Salt loads to streams

Rainfall, daily stream flow and EC data from Big Jacks Creek for 1996 to 1998 have been analysed. The raw data of stream flow and stream electrical conductivity are shown in **Figures 23a and 23b**. A clear observation from **Figure 23a** is that for any significant flows, above say 500 ML/d, the stream *EC* is approximately constant. This strongly indicates a system that is not limited by salt availability, but rather the capacity to mobilise and shift the salt store. **Figure 23b** reinforces this observation, with *EC* varying within a clear band during the major event in 1998.



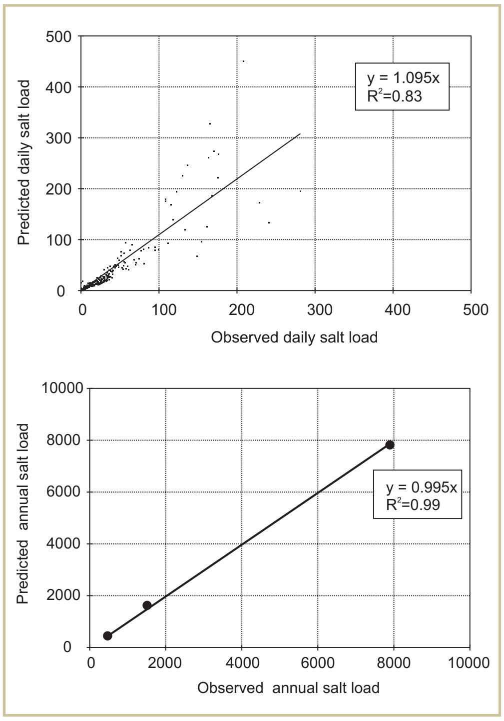
Figures 23a and 23b. *Daily flow versus daily mean EC, and the time series of flow and EC for Big Jacks Creek, for the three year period 1996 to 1998.*

Figure 23a also shows a power curve fitted to the flow-*EC* data. This appears to overestimate *EC* under the highest flows, which would have a corresponding effect on infilling *EC* from flow data alone. **Figures 24a and 24b** show the observed and predicted saltload (flow multiplied by *EC* and converted to tonnes) on a daily and annual basis using the curve fitted in **Figure 23a**. The observation of over-prediction is borne out with the best-fit linear regression passing through the origin having a slope greater than one in both **Figures 24a and 24b**. It is clear, however, that several points dominate the daily saltload graph where the scatter is greatest. The annual saltload appears to have enough compensating higher and lower flows such that the observed and predicted results show a much stronger linear relationship.



Figures 24a and 24b. *Observed versus predicted (a) daily and (b) annual saltload from Big Jacks Creek, based on a simple power regression.*

To compensate the annual saltload figures, a second regression for flow-EC was conceived where the multiplier in the equation was reduced by ten per cent, this being the approximate annual overestimate based on **Figure 24b**. The effect of this change is shown by the dotted line in **Figure 23a**. The changed daily and annual saltload figures are shown in **Figures 25a and 25b**. On a daily basis the best-fit slope through the origin is now closer to one, and the annual load fits a 1:1 line as required.



***Figures 25a and 25b.** Observed versus predicted (a) daily and (b) annual saltload from Big Jacks Creek, based on a modified power regression.*

Moving on to annual salt load versus rainfall input, **Table 7** includes all the relevant figures for the three years 1996 to 1998. The annual saltfall is based on a catchment area of 380 km^2 and an average rainfall salt concentration of 3.3 mg/L as measured at Gunnedah.

There are a number of inferences that can be drawn from the figures in **Table 7**. The first is that the catchment does not yield a large amount of stream flow, except under flood conditions, when there is a much larger but short-lived response. Another interpretation is that during average and below-average rainfall years, the catchment will store salt that is not removed by surface water flows. Then during large flood events the near surface salt store is mobilised and a great amount of salt is flushed from the system.

The average ratio of salt output to salt input (SO:SI) for the three years shown is 2.32, while total salt output divided by salt input is 2.77. From Jolly et al. (1997), the average SO:SI ratio is 1.03 for Cox's Creek at Boggabri which is a stream to the west (4040 km^2). The Mooki River is an adjacent catchment to the east, and has average SO:SI of 3.26 at Caroona (area 2540 km^2), and 2.75 at Breeza (area 3630 km^2). The latter values are similar to those found for Big Jacks Creek, and appear in the upper reaches of the Mooki River system. Further downstream in the Mooki there is groundwater pumping for irrigation and falling water levels, which may artificially alter any simple salt and water balance analysis.

5.3 Importance of localised recharge

Unlike many of the other reported areas of Australia, the recharge to the main aquifer relevant to salinity (Gunnedah Formation) has not increased by one or two orders of magnitude, but more likely about 1.5 to two times. This is because of the importance of localised recharge in the colluvial fan areas both prior to and after changing from native vegetation to agriculture. This localised recharge results from the lateral flow both

TABLE 7. Annual salt and water balance components for Big Jacks Creek.

Year	Rainfall (mm)	Saltfall (t)	Streamflow (mm)	Observed Saltload (t)	Modelled Saltload (t)
1996	879	1102	15	1478	1618
1997	704	883	3	435	445
1998	1225	1536	77	7863	7794

from run-off and subsurface flow from the higher rainfall upland areas. We estimate that the lateral flow may have increased by about 40% following clearing of trees for cropping. It is however more difficult to estimate how much this means as an increase in effective localised recharge as it is not clear what limits it. However, the increase in this component is unlikely to be greater proportionately.

The flooding may be expected to be a major contributor to recharge to the less permeable Narrabri Formation, but over a large fraction of this, there is simply no storage in the aquifer to accept recharge. Rather, it is expected that much of this recharge is lost by evapotranspiration afterwards. The native vegetation on the plains was not trees, but so-called Plains Grass (*Stipa aristiglumis*), adapted to the swampy floodplain areas that characterised the region prior to clearing. The area of shallow watertables is likely to have increased (means less or no buffer to store flood water) and this situation coupled with the deforestation of the upper catchment area has probably led to more flooding in the catchments. For the upper part of the catchment where watertables are deeper, the gradients are also greater and flooding may be expected to dominate the recharge.

We estimate that the localised recharge to the Gunnedah Formation is comparable to the combined net long-term diffuse recharge and flood recharge to the Narrabri. It is likely that the diffuse recharge has increased in the area of shallow watertables and there is some ability through agronomic practices to limit this.

5.4 Biological recharge reduction

The two key issues associated with using biological recharge reduction as a means of controlling salinity are the degree of intervention required and the time response to recharge control. As above, the minimum recharge rate that is likely is about ten per cent of the current recharge. This could only be achieved with a major land use change in the catchment. Perhaps 70% of the catchment would need to be done to achieve ten per cent change in saline areas and a ten per cent decrease in stream salinity. Clearly, this could only be effective if these land uses were nearly profitable in their own right. Replanting of the colluvial fans and changed land use on the lower parts of these may achieve a partial recharge reduction. Again 70% of the catchment may reduce the amount of saline area to ten per cent.

5.5 Groundwater pumping

Given the difficulties of biological recharge control, engineering options may be feasible to control salinity in the shorter-term. The most likely of these is groundwater pumping from the Gunnedah Formation. The groundwater model used here is not suitable for estimating drawdown cones, but it does suggest the recharge volume that can be harvested. While the transmissivity is not as high within the salt affected catchments as in the other subcatchments where groundwater pumping already occurs, it is still reasonable. One of the difficulties that can occur is the drawdown of saline water from the Narrabri Formation. Despite the low permeability of the Narrabri Formation, it is feasible to pump from the 'shoe-string aquifers' but the groundwater will generally be saline and disposal will be an issue.

It is possible that biological recharge options and engineering options may not be economically feasible. In any case, there is likely to be a large area of saline land that is better with some vegetative cover. Because of the saline groundwater, vegetation in the shallow watertable areas is unlikely to use groundwater to any great extent.

5.6 Overall methodology

The methodology consisted of a number of important steps:

1. Disaggregation of the study area into 'unique mapping areas'
2. Development of the conceptual model
3. Conduct of a salt balance study of the catchment
4. Estimation of flows and recharge
5. Use of a simple groundwater model
6. Testing of assumptions using geochemistry
7. Investigation of the role of flooding.

All of the steps were important in testing the options. The development and the testing of the conceptual model for the salinisation processes on the Liverpool Plains catchment was an iterative process. The first step was to identify the areas affected by salinity, then identify the main processes involved and finally build up a framework for the numerical modelling. The resulting conceptual model proved robust and a good platform for the numerical analysis. The groundwater dating gave some insight into the relativity of the timing of the groundwater processes in the different aquifers. It allowed us to eliminate the bedrock as a major player in the observed salinity processes and we could therefore confidently focus the work on the processes in the alluvium.

Since the run-off interflow estimates based on the Holmes and Sinclair (1986) relationship is based on and constrained by observations, we expect the relationship to be both robust and scientifically justified. The model has advantages over more traditional process-based models, requiring data generally available at regional scales and being very easy to apply either to an individual catchment or in a spatial modelling framework. The model developed is consistent with previous theoretical work and showed good agreement with over 250 catchment-scale measurements from around the world (Zhang et al. 2001). It is a practical tool that can be readily used to predict the long-term consequences of reforestation, and has potential uses in many catchment-scale vegetation management studies. For the Liverpool Plains study, it provided us with reliable estimates of run-off interflow. Coupled to the results of the groundwater modelling and the data from the gauging station, it gave some insight in the broad processes controlling waterlogging and salinisation and emphasised the importance of floods.

One of the most critical steps was the estimation of the hydraulic conductivity. This is highly correlated with the fraction of the run-off interflow that recharged. Several constraints needed to placed on the calibration process. If the hydraulic conductivity was towards the highest range of conductivities for gravels, much of the floodwater needed to become recharge and discharge rates needed to be very high in the discharge area. If the conductivity was towards the lowest end of the range for sands, then the only very little run-off interflow recharged the groundwater system and diffuse recharge would have been relatively more important and discharge rates would be too low to cause any problems with salinity.

We have reasonably asserted that a proportion of five per cent enters the groundwater system, and measured about five per cent leaving during flood events, so where does the other 90% go? The only possible sinks are the basement material underlying the Gunnedah Formation, and the storage and evaporation of flood water as it sits on the surface of the plains. While water does appear in the bedrock, ^{14}C results indicate that this is very slow moving and is probably not a significant sink in the system.

This leaves storage on the plains as the only candidate to close the run-off interflow budget. The weather systems in the Liverpool Plains consist of steady frontal rain in the winter months, and more violent convective thunderstorms in the summer months. Zhang et al. (1997) and Ringrose-Voase (pers. comm. 1999) have provided estimates of the amount of available storage in the cracking clays of the Liverpool Plains. In the top 2 m of soil up to 400 mm of storage is available. Anecdotal evidence suggests that the clay plains initially absorb large run-off events, but if followed closely by a second large event, flooding occurs on the saturated plains. If the heavy summer rains cause most flooding events, then it is possible to evaporate a large amount of surface water when the potential evaporation rates are highest to empty this store ready for the next event. The depth to which plants can empty the soil store will therefore contribute to more or less flood events, so the practice of removing deep-rooted perennials for shallow-rooted crops may be a factor contributing to increased flooding.

Thus far the Gunnedah Formation has been modelled as receiving no recharge through the Narrabri Formation due to its high clay content and thickness. Poor management can result in a local impact given that current agricultural systems are leaking water. Under

this regime, no management practice on the plains itself can affect the water levels in the Gunnedah Formation, although these levels are currently rising. The productivity of the plains must be protected by managing crop rotations to minimise water leaving the root-zone and prevent local salinity, while the Gunnedah Formation water levels need a different approach.

The modelling done in this work has not considered engineering options, such as groundwater pumping. If the hydraulic heads in the Gunnedah Formation could be lowered with suitable pumping regimes, then the local watertable would slowly move downwards if surface recharge was controlled. With suitable vegetation management, it may be possible to allow periodic recharge to leach the salt from the new de-watered zone. This would create additional potential root-zone for crops and grasses, along with a storage buffer when large episodic events cause recharge that cannot be controlled by vegetation alone. Careful economic analyses would be required to compare the increased return from cropping enterprises against the cost of pumping and disposal of groundwater. A secondary effect would be the possible contamination of the relatively fresh water in the Gunnedah Formation with saline groundwater currently found nearer to the surface, due to a reversal in head gradient down from the Narrabri to the Gunnedah Formation.

6. Conclusions

- *Importance of flood management:* Flood management is likely to be the single most important issue in recharge and salinity control. The native vegetation on the Plains was not trees, but so-called Plains Grass (*Stipa aristiglumis*), adapted to the swampy floodplain areas that characterised the region prior to clearing. The area of shallow watertables is likely to have increased (means less or no buffer to store flood water) and this situation coupled with the deforestation of the upper catchment area has probably led to more flooding in the catchments. For the upper part of the catchment where watertables are deeper, the gradients are also greater and flooding may be expected to dominate the recharge.

- *Model complexity:* Simple models are good enough to get the processes understanding and the relativities right, some more detailed work is needed for management options implementation (groundwater pumping, localised recharge control, cropping rotations on the flats).

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