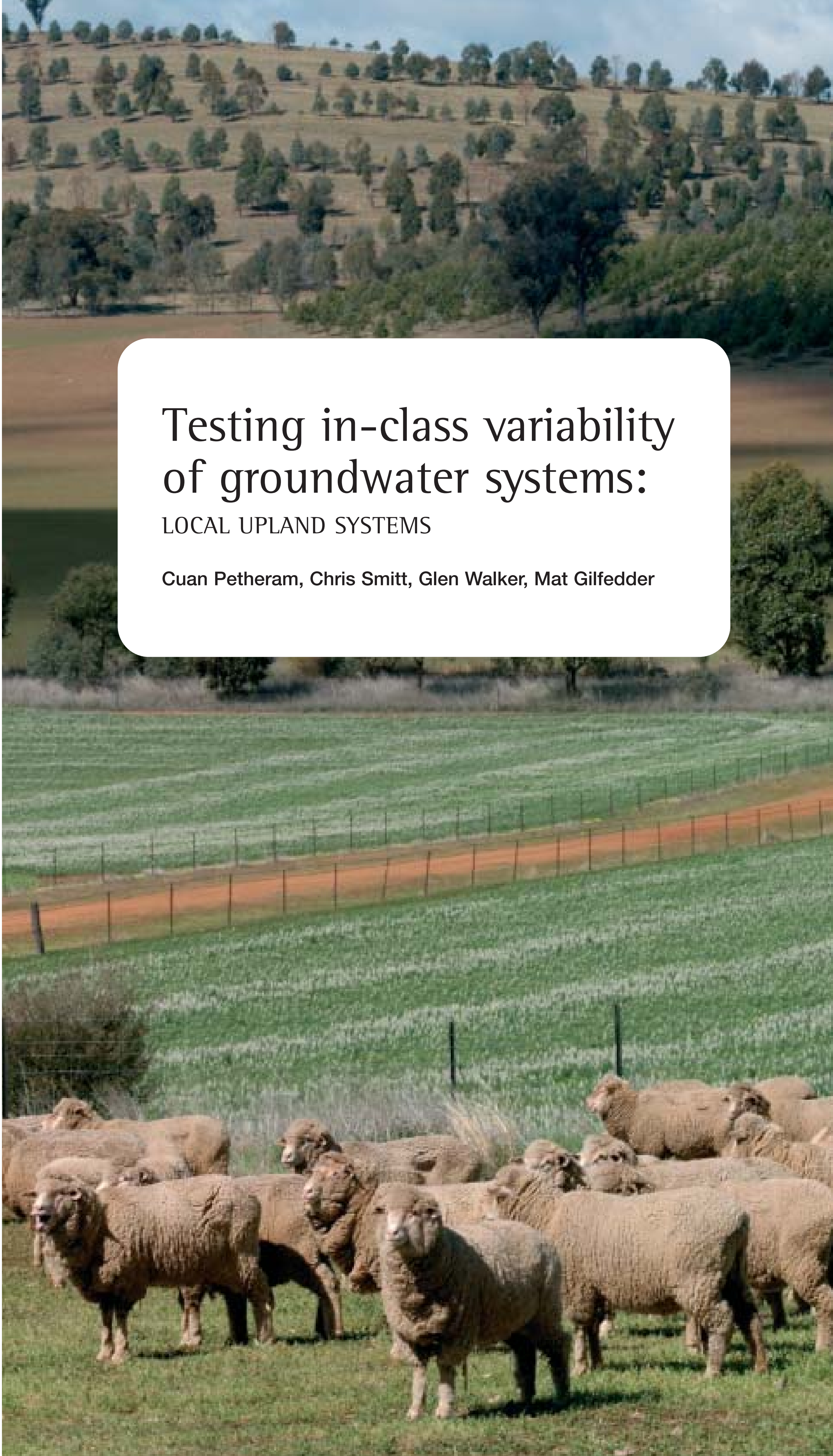

Testing in-class variability of groundwater systems:

LOCAL UPLAND SYSTEMS

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Executive summary

The objective of this report is to partially assess the extent information can be transferred between hydrogeologically similar catchments, by investigating in detail one set of similar catchments.

The utility of the National Catchment Classification (Coram 1998) for transferring information between catchments of the same type is being assessed for Local Type III groundwater systems—deeply weathered, fractured rock aquifer (Coram 1998). This model was chosen because of its prominence in salinised regions in south-eastern Australia. Catchments of this type often occur on shallow slopes on the inland foothills of the Great Dividing Range in New South Wales and Victoria, from crystalline rock that has undergone deep weathering (Coram 1998).

Five catchments were compared—Narroonda, Popes (South Australia), Burkes Flat, Kamarooka (Victoria), and Wattle Retreat (New South Wales). These catchments were chosen because they have been studied in relatively high detail and they exhibit processes leading to salinisation similar to those proposed by the Local Type III model. These catchments encompass a wide variety of scales, gradients, and climatic zones.

The extent to which information can be transferred between Local Type III catchments was tested within a modelling framework. The five catchments were modelled using FLOWTUBE. Catchment parameter values, catchment response to incremental reductions in recharge and the dimensionless similarity of the catchments were compared. The catchment responses to incremental reductions in recharge were reasonably similar. Due to the wide variety of sizes, shapes, gradients, climates and geographic locations of the catchments tested, it is expected that poorly documented catchments of the same type will respond in a similar manner.

The results suggest that there is a considerable range in parameter values but that this is smaller than the range for all aquifer types. However, given the sensitivity of the models to transmissivity and specific yield, the range in values was too high to allow the transfer of 'averaged' values to other hydrogeologically similar catchments with confidence.

Evaluation of a dimensionless similarity parameter (*G*) for each of the five catchments indicates that the parameters, transmissivity, specific yield, length and head may be inter-related. The implications of this are that:

1. the range in catchment responses might not be as great as suggested by standard sensitivity analysis studies
2. surrogate parameters may exist, which would enable aquifer parameters to be transferred to other hydrogeologically similar catchments with greater confidence.

RECOMMENDATIONS

1. Further case studies be captured as part of a groundwater systems framework and analysed objectively for intra-class variation.
2. The applicability and any modifications of the groundwater systems approach be tested for in-class variation of land use impacts on stream salinity and salt loads.
3. If the groundwater systems approach is to be used for assessing the options for engineering and opportunities for saline use, these will need to be analysed in a similar way to biological recharge reduction.
4. Studies relating to impacts of changed land use need to be linked to this work to understand the effectiveness of changed land use in managing salinity.

Table of contents

1. Introduction

Dryland salinisation has been increasingly recognised as one of the main environmental degradation issues in southern Australia (MDBC 1999; PMSEIC 1999; NLWRA 2001). While the magnitude of the problem has been widely accepted, the way to manage the problem has not. Presently, the effects of secondary dryland salinity are estimated to cost more than $270 million annually (PMSEIC 1999) and this is expected to increase over the next 100 years (NLWRA 2001). Salinity adversely affects agricultural production, terrestrial ecosystems and rural infrastructure such as roads and buildings. Rising watertables are also responsible for the salinisation of many streams and rivers where wetlands, other aquatic ecosystems and industrial and irrigation supplies become increasingly saline.

In response to the escalating concerns about the environmental, social and economic impacts of dryland salinity there has been recent significant government intervention (MDBC 1999; PMSEIC 1999). Recently, the Murray-Darling Basin Commission (MDBC) released a strategy that takes a 100 year view of the salinity threats to Basin resources and the potential benefits of salinity control options (MDBC 1999). The key features of the strategy include river salinity targets at the end of each tributary valley, and to protect community values and assets within the tributaries. The strategy aims to prevent the measured river salinity in the Lower River Murray from rising over the next 15 years.

More recently, the Prime Minister announced *A National Action Plan for Salinity and Water Quality in Australia*, which identified some immediate actions to address dryland salinity and deteriorating water quality in key catchments and regions across Australia. The Action Plan builds on the work established under the MDBC, the National Heritage Trust (NHT), and the Council of Australian Governments (CoAG) Water Agreement, while linking together State and Territory strategies. It also plans to implement targets and standards for natural resource management, particularly for water quality and salinity.

While targets lie central to these policies, we are lacking the technical ability to assess what is required to meet them. Unfortunately, at this stage there is only limited hydrogeological information available in a discrete number of intensively studied catchments. Unless we can transfer this information and understanding of these catchments across the broader landscape, there is likely to be wastage of money, time and effort in land management techniques that may not be effective across the broader area.

To address the issue, the *National Classification of Catchments for Land and River Salinity Control* (Coram 1998) was developed. A workshop of salinity professionals from across Australia grouped catchments for which there are similar groundwater processes operating and for which management options are expected to be alike. In developing the classification, 15 different types of catchments were identified, in terms of the key hydrogeological characteristics responsible for salinisation. Fundamental to the classification is the assumption that the processes involved in, and the key factors contributing to the mobilisation and redistribution of salt in a catchment are similar for catchments of similar type (Coram 1998). This classification or framework thus provides a possible mechanism for transferring information between well-documented and poorly documented catchments, provided we can identify the key characteristics of the poorly documented catchments and relate them to the well–documented catchments.

To achieve this, it is necessary to be able to map classes of groundwater systems. Unfortunately the National Classification does not provide a basis for this. Instead, it is the *National Groundwater Flow Systems* (Coram et al. 2000) that provides a method for mapping groundwater flow systems. It does this by dividing the National Classification into different geological provinces and aggregating the non-mappable processes that lead to salinity. These classes have been further

divided at finer scales (1:250 K) for regions of the Murray-Darling Basin. This is at a scale relevant to regional planning on salinity management, yet still fits in a framework consistent at the national and Basin-scale. It provides a tool by which management decisions can be made for a poorly documented catchment, based on previous experiences in 'hydrogeologically' similar catchments. While experienced hydrogeologists have often made these linkages in the past, these have generally been confined to their local area and there has not been a consistent framework across broad regions, nor formal analysis or documentation of the results.

While the concept of catchment classification may have many practical applications in salinity management, the classifications have not been tested. Underlying any classification is the assumption that if two or more catchments are in the same groundwater class, then the response within the catchments to any land management strategies should be similar.

Since increased recharge has lead to salinity, the solution to land salinisation would therefore appear to be the application of large scale agronomic systems or revegetation on high recharge areas to reduce the amount of water entering the aquifer. However, in many cases, the level of recharge reduction required to ameliorate dryland salinity may be economically prohibitive for current agronomic systems. This is partly due to the time lag between implementing any land use strategies and measuring their effect, being in the order of several decades (MDBC 1999). It is also due to the high levels of recharge reduction that may be required. This report investigates the similarity of groundwater responses to a reduction in recharge.

This technical report aims to test the similarity in hydrogeological behaviour and catchment response to a reduction in recharge, for one of the conceptual models (or catchment classes) proposed. The catchment type chosen within the National Classification was 'Local Type III', which is characterised by discharge from weathered, fractured rock aquifers at break of slope. This class was chosen because of its prominence in salinised regions in south-eastern Australia.

Five 'well-documented' catchments of Local Type III have been identified (**see Figure 1**). Physical characteristics of these catchments are summarised in **Table 1**. The similarity of these catchments will be assessed within a modelling framework since (i) there are too few well-documented catchments to enable statistical analysis, (ii) hydrograph records are short and (iii) land management changes have not been implemented in many of the studied catchments.

TABLE 1. Catchment descriptions.

Catchment	Rainfall (mm)	Area (ha)	Average gradient (%)	Salinised area (%)	Groundwater salinity (mg/L)	Land-use	Geology	Dominant soil type
Narroonda (SA)	630	91	2.1	14	3,500	Cleared in 1975. Now planted to annual pastures	Metamorphosed sandstones, siltstones, and mudstones	Loamy sand over clay/ sandy clay
Popes (SA)	550	668	4.2	<5	2,000	Cleared in the 1950s. Now planted to annual crops and pastures	Gneisses, schists and occasional quartzite	Sandy loam over clayey loam/mottled clays
Burkes Flat (VIC)	435	751	1.1	12	12,000	Cleared between 1860 and 1890. Annual pastures, more recently perennial pastures and trees	Ordovician sandstones, siltstones and mudstones	Skeletal and duplex clay soils
Kamarooka (VIC)	427	2108	0.7	8	12,000	Clearing started in the 1860s. Mainly annual crops and pastures and about 12% lucerne.	NNW striking Ordovician shales and sandstones of uniform lithology and structure	Heavy sodic red duplex clays on ridges and calcareous yellow duplex clays on the plains
Wattle Retreat (NSW)	596	575	2.6	5	2,500	Cleared between 1874 and 1900. Currently wheat and other cereal cropping and sheep grazing	Rhyodacitic tuff of ashflow origin	Lithosols, Euchrozems, Red Brown Earths and Solodic soils

Note: Catchments are in winter dominant rainfall zones. Soils are described from top to bottom of catchment and rainfall is catchment mean annual.

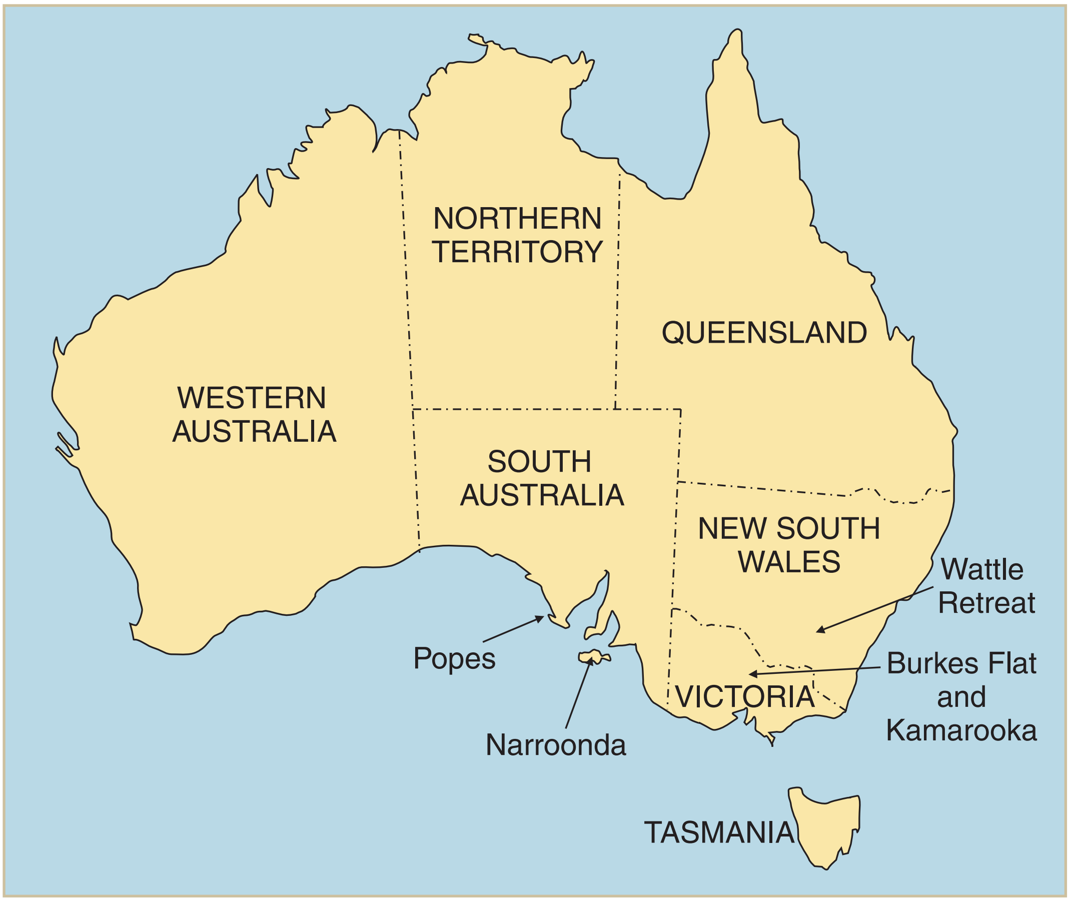

Figure 1. *Location of the catchments chosen for this study.*

The five selected catchments, though considered relatively ‘well-documented’, have few data available. It is proposed that the FLOWTUBE groundwater model (see under Methods below) captures the key processes occurring within the Local Type III conceptual model, while minimising the number of ‘free’ parameters for which assessment through calibration is required.

This technical report will thus investigate:

1. the similarity of catchment response to management practices in the five Local Type III catchments
2. whether aquifer parameters can be transferred between Local Type III catchments

This report is part of a series of reports leading to an analysis of case studies across Australia. Each case study will have a detailed report, explaining the technical basis of salinity management recommendations with relation to catchment characteristics. There will also be two modelling reports detailing the sensitivity of outputs to groundwater parameters and relating these to the case studies. This report will contribute to a comparison of intra-class variations compared to inter-class variations and the importance of these for decisions on salinity management i.e. an assessment of the groundwater systems approach. Finally, the results of these reports will be synthesised into an overview document describing the case studies and their applicability within a groundwater systems framework.

2. Conceptual model and site description

All five local systems are located along topographic divides, and by definition, all water arriving in the discharge area originates from within the catchment boundary. Typically these catchments have two groundwater systems:

1. a shallow ephemeral perched watertable
2. a deeper system occurring in the fractured rocks and weathered bedrock.

This groundwater conceptual model often occurs from crystalline rock that has undergone deep weathering. It is characterised as having groundwater discharge occurring from the deeply weathered fractured rock aquifer where reductions in surface topographic slope coincide with reductions in the hydraulic conductivity as the groundwater moves from unweathered, fractured rock to weathered material. **Figure 2** illustrates a plan view of this catchment type as conceptualised in the catchment classification.

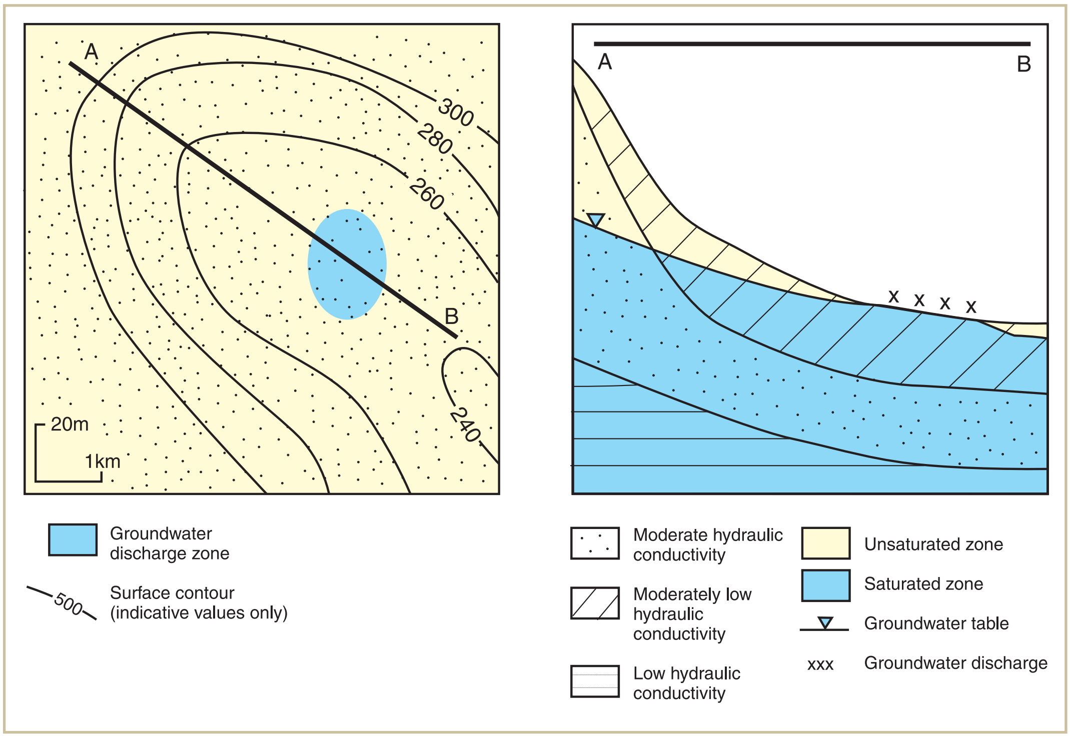

Figure 2. *Local model (iii)—Discharge from weathered fractured rock aquifers at break of slope as conceptualised in the catchment classification (adapted from Coram 1998).*

3. Methodology

3.1 Overview

The modelling work presented in this report uses an existing groundwater flow model, FLOWTUBE (Dawes et al. 1997, 2000) with a new discharge representation (Petheram et al. submitted A). The FLOWTUBE model was developed by CSIRO in order to provide broad-scale recommendations based on limited data (i.e. commensurate with the low level of data available in many groundwater catchments throughout Australia). Earlier versions of the FLOWTUBE code have been applied at Liverpool Plains, New South Wales (Dawes et al. 2001) and the Wanilla catchment in South Australia (Stauffacher et al. 2000).

The method has been broken into three broad sections. The first section provides brief details on the FLOWTUBE code. For a more comprehensive description refer to Dawes et al. (1997, 2001). The second section discusses the conceptualisation and calibration procedures used to model the five Local Type III catchments with FLOWTUBE. The third section outlines the method by which the classification is to be tested.

3.2 The FLOWTUBE model—description

The FLOWTUBE modelling code is based on a finite difference solution to the one-dimensional Darcy's Law for saturated flow in a semi-confined/confined aquifer. All flow is in the direction of interest and only a single conducting layer is considered. FLOWTUBE conceptualises a catchment as a series of elements that form one or more tubes along the aquifer of interest.

Aquifer properties such as ground surface, basement and piezometric surface elevations, aquifer width, saturated hydraulic conductivity, specific yield and recharge can be spatially varied at a series of cross sections along the tube of flow.

Recent modifications to FLOWTUBE (Petheram et al. submitted A) enable it to be used in conjunction with a high-resolution Digital Elevation Model (DEM) data to develop sub-grid parameterisation for groundwater discharge and surface waterlogging. This enables recharge/discharge can be mapped at the sub-element scale.

3.2.1 Model input

The FLOWTUBE model requires four types of input data:

1. structural information that describes the physical dimensions of the aquifer
2. values of the physical parameters of the aquifer
3. data on the temporal distribution of water sources and sinks
4. characteristic curves that relate the piezometric head elevation in each element to an average recharge/discharge value for the element (Petheram et al. submitted A). (Note: DEM of the catchment is required to generate the characteristic recharge/discharge curves, although it is not a direct model input).

The first two input data types are entered into the model using an 'aquifer' text file along with a constant head value at the outlet. The third data type is entered into the model via a 'flux' text file and the fourth data type is entered via a look-up table in the 'discharge' text file. This look-up table enables the model to interact directly with a digital elevation model so that recharge/discharge and areas with shallow watertables can be evaluated at the sub-element scale (Petheram et al. submitted A).

3.2.2 FLOWTUBE output

The model generates three output text files. The first file lists the heads at each node at each output time. The second lists the surface discharge rates for each node at each output time. It details the time, flux out of the aquifer, total discharge to the surface, catchment average recharge and the surface discharge at each node. Finally for each node at each output time, the third file details the flux through the stream, total run-off to the stream and the stream discharge at each node. The head data files may be imported into a spreadsheet to produce groundwater profiles of the catchment or hydrographs at a given cross-section. Because recharge/discharge have been evaluated at the DEM scale, groundwater levels may be draped over a DEM of the catchment to produce a map of areas with shallow water tables.

It should be noted that because FLOWTUBE is not a solute transport groundwater model, areas with shallow water tables will be referred to as waterlogged areas rather than salinised areas. Waterlogged areas have the potential to become salinised over time.

3.2.3 Assumptions in using the FLOWTUBE model

- Groundwater flow in catchments may be represented by a tube or series of tubes.
- Relative to the fractured rock/weathered layer, there is negligible lateral flux through the highly weathered layer.
- The constant head condition is the same under pre-clearing and cleared scenarios.
- All groundwater discharge originates from within the catchments.
- Flow through the fractured rock aquifers can be modelled using Darcy's Law.
- Discharge is a linear function of depth to water table and an extinction depth occurs at 2 m below the ground surface.
- The zero surface used for generating the discharge text file look-up table is a reasonable assumption to the actual piezometric surface (Petheram et al. submitted A).

3.3 Model application

3.3.1 Parameter allowable ranges

The model parameters may be broadly divided into those that can be easily measured and those that cannot be measured with reasonable ease. Those parameters that can be measured and have fixed values are generally related to catchment dimensions (e.g. elevation, catchment width). The remaining 'free' parameters are difficult to quantify through measurement because they are

(i) technically hard to measure,
(ii) exhibit a large degree of spatial variability,
(iii) change with scale, and/or are
(iv) expensive and time consuming to measure.

For this study, the parameters that could not be measured were inferred using the following five methods:

1. correlation of parameter values with more easily measured and documented surrogates, e.g. saturated hydraulic conductivity estimated from measured gravel, sand, silt, clay fractions
2. calibration of the model against some modelled and observed state variables, most often groundwater levels, fluctuations and trends
3. comparison of model predictions of groundwater discharge into streams or through evapotranspiration, with those obtained from stream salt loads, estimates made by other practitioners, or from area of saline land
4. comparison with values obtained at a different spatial (e.g. pump tests) or temporal scale (water balance recharge measurements)
5. transferring values from hydrogeologically similar areas.

These methods are not independent and are often used in combination. For example Methods 1, 4 and 5 above often define the allowable range within which parameters can be fitted using Methods 2 and/or 3.

While the *source* and *allowable ranges* may vary slightly from catchment to catchment, **Table 2** provides a generic description of how the parameters and state variables used in FLOWTUBE were obtained. Refer to Petheram (2002) for catchment specific calibration details.

TABLE 2. Catchment parameters and state variables used in FLOWTUBE.

Parameter	Unit	Method	Source	Allowable Range
Saturated hydraulic conductivity	m/day	Calibrated	Calibrated to hydrograph data and salt load estimates	0.001-2 m/d
Specific yield	–	Calibrated[1]	Time since clearing	0.005-0.1
Current recharge rate	m/day	Calibrated[2]	Calibrated to hydrograph data and salt load estimates	Petheram et al. 2002
Maximum discharge	m/day	Calibrated	Calibrated to hydrograph data and salt load estimates	36.5-365 mm/year
Initial head	m	Measured	Hydrograph records	N/A
Constant head (Outlet)	m	Measured[3]	Topographic map	N/A
Aquifer depth	m	Measured[4]	Lithology log data (pers. comm. local hydrogeologists)	5-50 m
Aquifer basement	m	Measured/ Inferred[4]	Lithology log data (pers. comm. local hydrogeologists)	N/A
Length	m	Measured	Topographic map	N/A
Width	m	Measured	Topographic map	N/A
Elevation	m	Measured	Topographic map	N/A
Pre-clearing recharge rate[5]	m/day	Measured[2]	Petheram et al. 2002b	Petheram et al. 2002b
Pre-clearing groundwater level[6]	m	Modelled[7]		N/A

Note:

1. *This value was fitted by matching the time taken for the heads to rise from pre-clearing levels to the current levels with the time since clearing and the rate of rise observed in the bore hydrographs.*
2. *An estimate of catchment average recharge was obtained from work by Petheram et al. 2002. This quantity of recharge was then spatially distributed across the catchment.*
3. *Constant head values were obtained from an appropriate perennial stream/lake.*
4. *Based on local hydrogeologists interruption of lithology log data and catchment observations.*
5. *This parameter was only used during the second stage of the modelling process in the place of the current recharge rate.*
6. *This parameter was only used during the third stage of the modelling process in the place of the current groundwater levels.*
7. *Pre-clearing groundwater levels were estimated by running the model using a steady-state recharge rate of 1 mm/yr for 1,500 years.*

3.3.2 Generic FLOWTUBE calibration method

There were few bore hydrograph data to test the dynamic behaviour of the model i.e. increased groundwater recharge over time or seasonal dynamics. Therefore the model was calibrated under long-term steady-state conditions by matching the simulated heads to ‘representative’ observed heads. The model calibration procedure was broken into three distinct steps:

1. Matched the piezometric gradient and rate of rise of the modelled heads to the observed heads by altering the saturated hydraulic conductivity, specific yield, post-clearing recharge rate and maximum surface discharge rate within allowable ranges. The maximum surface discharge rate was set to allow as much water to discharge to the surface in order to maintain the piezometric gradient and rate of rise, while being consistent with measured/estimated values of surface discharge. Where there were little spatial data on any parameter, values were kept uniform across the catchment. Generally these catchments were either at or approaching hydraulic equilibrium so the sensitivity to specific yield was low at this stage of the calibration procedure. The gradient of the piezometric head was most sensitive to the saturated hydraulic conductivity values.
2. Once a satisfactory fit was achieved, the model was run for a very long period of time (3,000 years) with an annual recharge of 1 mm to simulate pre-clearing groundwater levels (Petheram et al. 2002b). Where information was available, the simulated pre-clearing groundwater levels were compared to actual pre-clearing groundwater levels. Poor correlation of ‘observed’[#] and simulated groundwater levels resulted in altering the pre-clearing recharge rate within an allowable range. Continued poor correlation resulted in repeating Step 1.
3. The pre-clearing groundwater levels were then used in conjunction with the post-clearing recharge flux file. This step involved altering the specific yield until a representative rate of groundwater rise was achieved i.e. time taken for groundwater levels to rise from the pre-clearing level to: (i) a level that is consistent with the first observations of salinity in the catchment; and (ii) a level consistent with water levels currently observed in the catchment.

This calibration procedure often involved several iterations until all parameters were fitted satisfactory. Discrepancy between the modelled and estimated heads will be some function of the errors due to poor conceptualisation of the catchment (i.e. neglecting relevant processes and/or representing inappropriate processes) and errors caused by the poor estimation of parameters given the sparse data.

Validation of the catchment models were not possible because all available catchment data were used in the calibration process (i.e. hydrographic records were too short to perform a split sample analysis). Confidence in the calibrated parameter values stems from keeping values meaningful and realistic and having an information trail that is easy to follow (this enables the performance of the model under different stresses to be realistically assessed).

Comprehensive descriptions of the calibration of Burkes Flat, Narroonda, Popes and Wattle Retreat catchments are given in Petheram et al. (2002). Kamarooka catchment was modelled as part of NLWRA (2001). A detailed description of the calibration procedure for this catchment is provided in Hekmeijer et al. (2000).

[#] Length of record of groundwater levels precludes any observations of pre-clearing water table elevations. This information is generally derived from nearby catchments that have not been cleared.

3.4 Procedure by which the Classification is to be assessed

As mentioned earlier the similarity of the five catchments is to be tested within a modelling framework. The calibrated numerical models of the five Local Type III catchments will be used to examine and compare the catchments, in terms of their (i) aquifer property values, (ii) groundwater response/behaviour under different management scenarios, and (iii) dimensionless similarity.

Comparison of aquifer properties

This exercise will compare the range of the aquifer properties, transmissivity and specific yield. Because there is little spatial data on aquifer thickness, the models saturated hydraulic conductivity will not necessarily provide a good measure of the lateral groundwater flow. Therefore transmissivity will be used as the basis for comparison, because this term combines the aquifer thickness and saturated hydraulic conductivity in the one parameter.

Comparison of catchment responses

Because there was insufficient data on the spatial distribution of recharge in the five catchments it is not possible to compare groundwater responses under specific management strategies (e.g. trees on upper slopes/ridges, perennial pastures on lower slopes and crops in the valley). The only means of comparing catchment response under alternative management strategies is to incrementally reduce recharge from the current (assumed maximum) rate and compare the groundwater response in each catchment. The response variable of primary interest is the area of waterlogged land. Because there were too few catchments to analyse statistically and there were no ‘control’ catchments, the groundwater responses will be compared qualitatively.

Dimensionless similarity

Another way of assessing similarity is through the use of dimensionless analysis, which combines several variables into a single parameter allowing inter-comparison of different systems (e.g. Reynold’s number for viscous flow and Froude’s number for open channel flow, Street et al. 1996). In this study the dimensionless similarity parameter *G* (Gilfedder et al. 2003), will be used to compare the five Local Type III groundwater systems. This parameter is discussed in further detail in **Section 5.3**.

4. Results

The parameters and state variables used in the FLOWTUBE model are summarised in **Table 3** and the catchment groundwater flow balance and aquifer discharge capacities are summarised in **Table 4**. A comprehensive description of the calibration of these catchments is given in Petheram et al. (2002).

TABLE 3. Summary of parameter values used for each catchment.

Catchment Name	Range of values					
	Ks (m/d)	Aquifer thickness (m)	Transmissivity (m^2/day)	Recharge (mm/yr)	Maximum discharge (mm/yr)	Specific yield
Narroonda (SA)	0.04	10-20	0.4-0.8	35	100	0.025
Popes (SA)	0.005-0.1	16-40	0.2-1	24	200	0.01-0.02
Burkes Flat (VIC)	0.07	50	3.5	14	50	0.04
Kamarooka (VIC)	1	5-50	5-50	18	36.5	0.05-0.1
Wattle Retreat (NSW)	0.3	50	15	35	250	0.06

Table 4. Catchment groundwater flow balance and aquifer discharge capacity.

The aquifer discharge capacity value is the maximum volume the groundwater system discharges without the groundwater head becoming artesian. The assumption here is that for local groundwater systems the 'threshold' rate occurs at the catchment outlet. The aquifer discharge capacity is expressed as the catchment recharge rate equivalent. If the average catchment recharge is greater than this value, the deeper groundwater system will start contributing to salinisation within the catchment.

Catchment Name	Aquifer discharge (ML/yr)	Surface discharge (ML/yr)	Aquifer discharge capacity (mm/yr)
Narroonda (SA)	2	20	1.8
Popes (SA)	24	112	4.1
Burkes Flat (VIC)	13	76	1.4
Kamarooka (VIC)	20	322	1.3
Wattle Retreat (NSW)	53	99	9.5

Figures 3 to 5 illustrate the results of scenario modelling using FLOWTUBE. The figures show the modelled reduction in waterlogged area for incremental reductions in recharge (i.e. expressed as a percentage of the current recharge rate). The waterlogged area is expressed as a proportion of the waterlogged area if the recharge rate remained unchanged (i.e. 100%). It was necessary to present the results in this form because not all of the catchments had attained a hydrologic equilibrium. **Figures 3 to 5** show the predicted reduction in waterlogged area after 20 and 50 years at the reduced recharge rate and at hydrologic equilibrium at the reduced recharge rate.

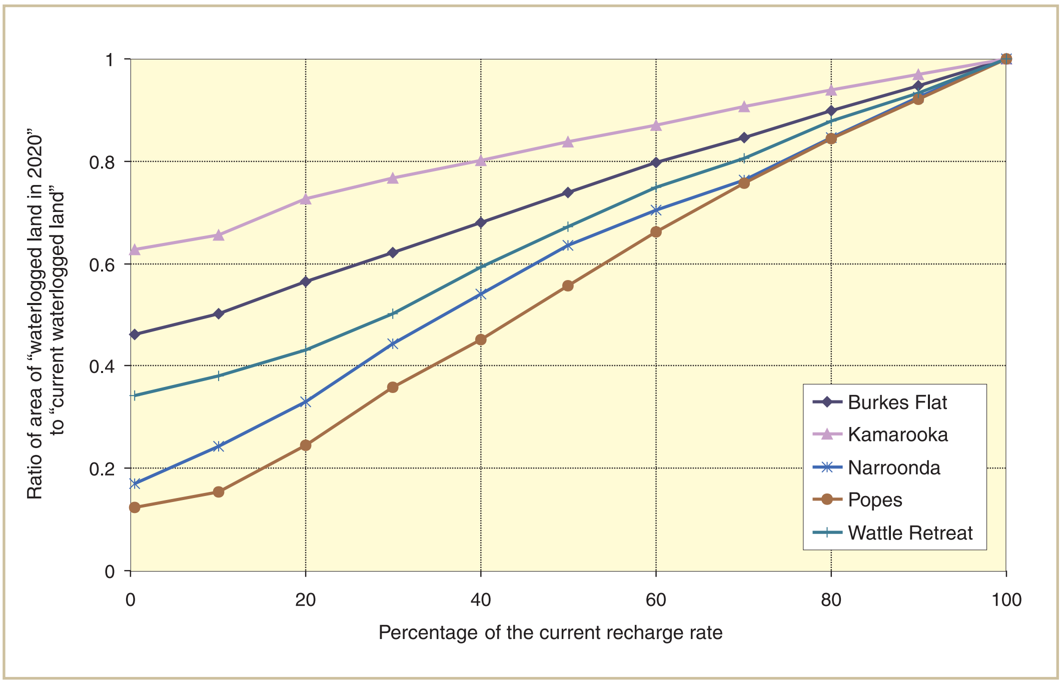

Figure 3. Proportion of the current waterlogged area versus percentage of the current recharge rate after 20 years. The y-axis is the amount of waterlogged land, expressed as a proportion of the amount of waterlogged land if no recharge reduction occurred (i.e. recharge remained at 100% of the current rate for 20 years). The x-axis is the percentage of current recharge rate.

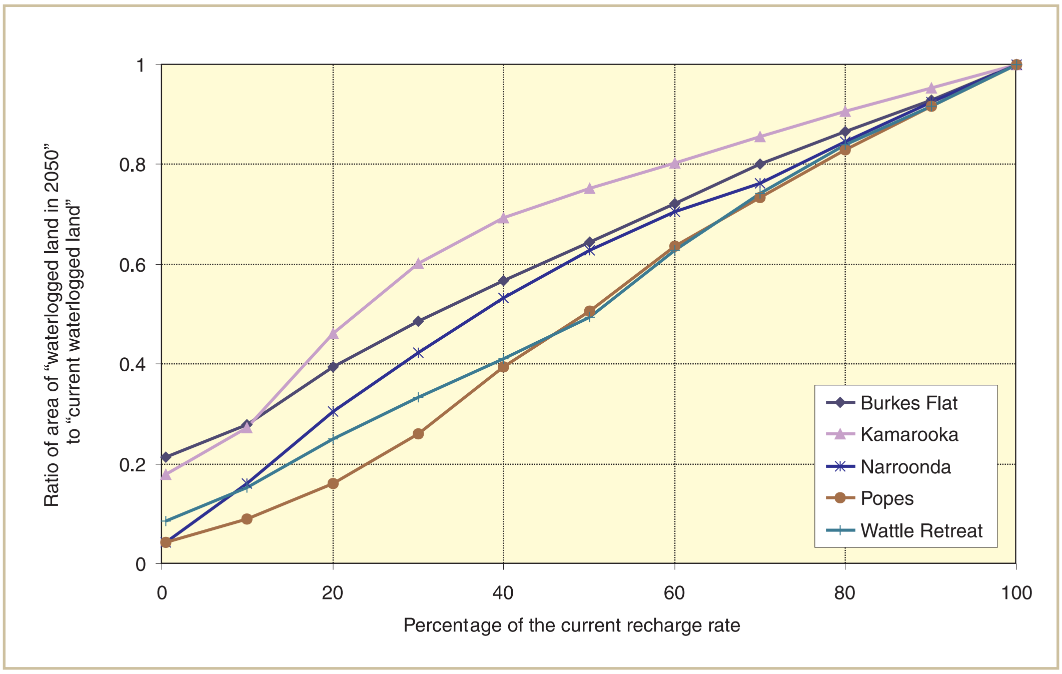

Figure 4. *Proportion of the current waterlogged area versus percentage of the current recharge rate after 50 years. The y-axis is the amount of waterlogged land, expressed as a proportion of the amount of waterlogged land if no recharge reduction occurred (i.e. recharge remained at 100% of the current rate for 20 years). The x-axis is the percentage of current recharge rate.*

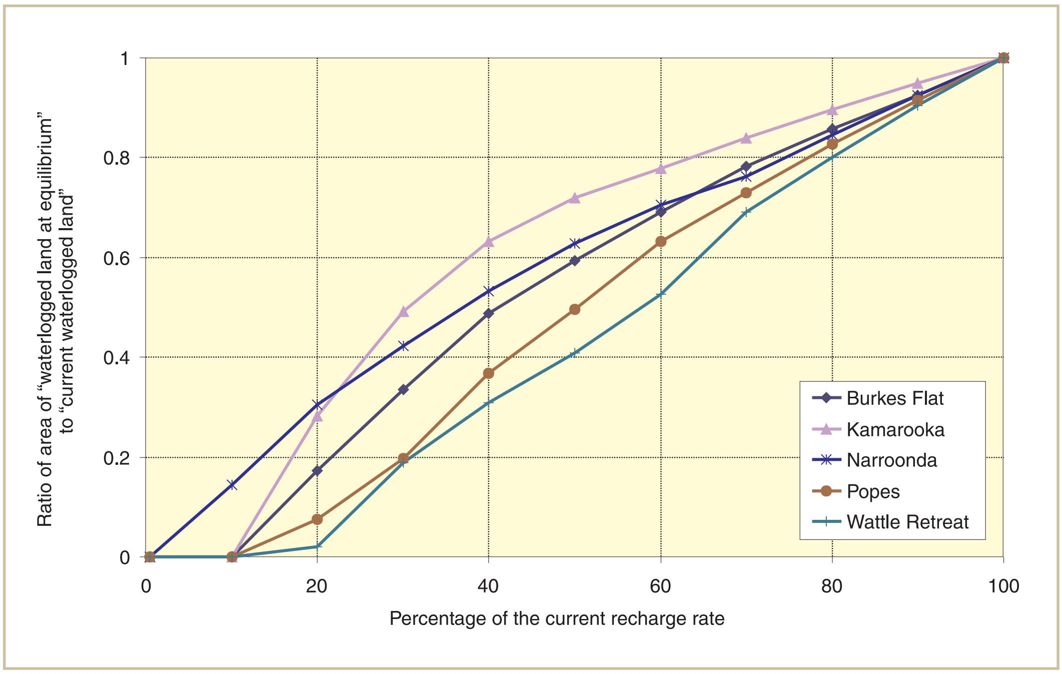

Figure 5. *Proportion of the current waterlogged area versus percentage of the current recharge rate at hydrologic equilibrium. The y-axis is the amount of waterlogged land, expressed as a proportion of the amount of waterlogged land if no recharge reduction occurred (i.e. recharge remained at 100% of the current rate for 20 years). The x-axis is the percentage of current recharge rate.*

5. Discussion

5.1 General observations and trends

The five deeply weathered fractured rock catchments chosen for this comparative study were all either approaching or had attained a state of hydrologic equilibrium. Even though they were comprised of a variety of sizes, shapes, gradients and are from different climatic and geographic zones, all the catchments had to increase their discharge capacity by discharging water to the surface, in order to attain a new hydrologic equilibrium under conditions of increased recharge. The modelling studies indicate that the aquifer discharge capacities in all catchments are low, ranging from 1.5 to 11.3 mm/year (catchment recharge rate equivalent: see **Table 4**).

An example of the transfer of semi-quantitative information for management purposes from these catchments to others of their type would be the use of **Figures 3 to 5** to make generic inferences for local, deeply weathered, fractured rock aquifers, that is:

- Waterlogging will still occur 50 years after recharge reduction, regardless of how extreme the land use change. Even small catchments like Narroonda that initially responded very quickly to clearing of vegetation, take many decades to return to their pre-clearing state after revegetation.
- Reducing recharge by 30% will produce a reduction in the area of waterlogged land of about 10-25% after 20 years, with little improvement thereafter.
- Reducing recharge by 50% will see a reduction in the area of waterlogged land of about 25-50% after 50 years, with only a small improvement thereafter.
- Reducing the recharge by 90% will see a reduction in the area of waterlogged land of between 70-90% at 50 years, and between 85-100% at a new hydrologic equilibrium.
- It is necessary to reduce recharge by between 80 and 95% to remove waterlogging in these catchments.

5.2 Portability of results

To test the similarity in catchment response it would have been preferable to be able to examine a greater number of well-documented Local Type III catchments. Alternatively it would be useful to be able to test the confidence with which these curves can be transferred to other catchments of the same type (i.e. a test area where land use changes have been implemented and changes in land salinisation recorded). Unfortunately the reality of groundwater modelling in Australia means that neither exist. Hence, in the absence of any true quantitative measure, the similarity of the catchment responses has to be assessed within a qualitative framework with judgement imposed by the authors.

Based on the curves in **Figures 3 to 5**, the five catchments behave similarly in terms of simulated response to changed recharge. Although the five catchments vary considerably in size, shape, gradient, climate and topography, their response to reductions in recharge is similar enough to provide a useful range of values for catchment managers.

Generic catchment responses such as the range illustrated in **Figures 3 to 5** would be useful enough to provide first cut estimates of catchment hydrogeological response to reduction in recharge. In conjunction with unsaturated zone waterbalance and economic analysis, these figures would enable the feasibility of implementing land use change to be quickly and easily assessed. In situations where it is not obvious from this analysis whether land use change should go ahead (or not), detailed catchment specific groundwater modelling may be required.

Detailed groundwater modelling requires values of saturated hydraulic conductivity/transmissivity and specific yield. Potentially the classification provides a framework within which values of these parameters may be transferred between hydrogeologically similar catchments.

The range of values for the calibrated catchment parameters, specific yield, transmissivity and maximum surface discharge rate were broad (see **Table 3**). Specific yield varied between one and ten per cent, transmissivity between 0.4 and 50 m^2/day and maximum surface discharge rate between 36.5 and 250 mm/year. The variation in these parameters represents factors of ten, 125 and eight, respectively.

In the absence of a similarly comprehensive study of other catchment types within the classification system, it is difficult to assess the degree of similarity between the parameters in these Local Type III systems. However, the breath of values observed in the deeply weathered fractured rock systems can be put into context by examining the range of values observed in miscellaneous groundwater systems throughout Australia (**Table 5**). In **Table 5** the specific yield varies by a factor of 20 and the transmissivity by a factor of about 500. This range is considerably larger than that exhibited by the five Local Type III catchments.

Freeze and Cherry (1979) state that the saturated hydraulic conductivity in rocks can vary by up to eight orders-of-magnitude (i.e. between $8x10^{-5}$ and 860 m/d). From this it is expected that the transmissivity in rocks is also highly variable.

The range of values of specific yield given by Freeze and Cherry (1979) is between 0.01 and 0.30. When compared with this possible range, the range of specific yield values observed in the deeply weathered fractured rock catchments is quite narrow.

While these comparisons indicate that the range of values for the Local Type III catchments is much narrower than observed in aquifers of different types, they do not allow the assessment of the degree of confidence with which the parameters can be transferred to similar catchments. Sensitivity analysis of the FLOWTUBE model parameters reveals that the range in response of state variables (e.g. watertable) to doubling and halving the specific yield and saturated hydraulic conductivity (i.e. transmissivity) is large. The transmissivity and specific yield in the five Local Type III catchments was found to vary by one and two orders of magnitude respectively. Hence, where more detailed groundwater modelling is required, it is likely that the portability of 'averaged' parameter values (i.e. based on the distribution of values observed in the five Local Type III catchments) to individual catchments will be low. At this stage, use of the distribution of parameters observed in the five catchments is limited to providing a realistic range in similar catchments.

TABLE 5. Parameter values of groundwater systems studied within the Audit and MDBC catchment characterisation program and the integrated catchment scale modelling study.

Multiple parameter values refer to different aquifer formations. Information derived from the 'National groundwater flow systems: underpinning case studies'.

Catchment	Scale	Specific yield	Ks (m/day)	T (m^2/day)
Liverpool Plains (NSW)	Regional	0.2	20-50	3,000-800
Loddon (VIC)	Regional	0.1	49-85	2,600-950
Billabong Creek (NSW)	Regional	0.1	5-20	50-400
Lake Warden (WA)	Regional	0.05	0.1-1	5-50
Axe Creek (VIC)	Intermediate	0.01-1	0.1-2	25-100
Wanilla (SA)	Intermediate	0.01-0.05	0.1-0.5	6-2
Kyeamba (NSW)	Intermediate	0.01-0.1	5-10	100-400

5.3 Dimensionless similarity

The dimensionless similarity parameter *(G)* simplifies the characterisation of a groundwater system by combining transmissivity, specific yield, recharge, length and head (Gilfedder et al. 2003). *G* is effectively a ratio of the time factor related to the lateral draining of an aquifer to the time factor of the groundwater response to recharge, and is expressed in Equation 1:

$$G = \frac{t_H}{t_V} = \frac{\dfrac{T}{S.L^2}}{\dfrac{R}{\Delta h.S}} = \frac{\Delta h.T}{R.L^2} \qquad (1)$$

where t_H and t_V are the time factors related to the lateral draining and vertical filling of an aquifer respectively, *t* is time, *T* is transmissivity, *S* is specific yield, *L* is the characteristic length scale, *R* is the groundwater recharge rate and Δh is the change in groundwater table.

Evaluation of *G* for each of the five Local Type III catchments indicates a strong degree of similarity. Values for *G* varied by less than an order of magnitude (i.e. 0.08 to 0.29). Because the specific yield and transmissivity values for the five catchments vary by one and two orders of magnitude respectively, the parameters used to evaluate *G* must be inter-related. The implications of having inter-related parameters is that variation in catchment behaviour may not be as great as we are led to believe from sensitivity analysis studies.

The notion that the parameters used to evaluate *G* are inter-related suggests that it may be possible to identify easily measured surrogate parameters for transmissivity and specific yield. The existence of surrogate parameters may increase the confidence with which parameters can be transferred between similar catchments. For example, there appears to be a positive correlation between aquifer discharge capacity and recharge, where aquifers with high aquifer discharge capacity tended to also have higher recharge rates. An explanation for this may be that catchments with high aquifer discharge capacities tend to also have high topographical gradients (i.e. potentiometric surfaces are a subdued reflection of the land surface). Systems with higher topographical gradients are generally located in higher parts of the landscape and as a consequence tend to have higher rainfall and hence higher recharge. Thus, the effect of the higher aquifer discharge capacities in these catchments is partly offset by these catchments having to discharge a greater volume of water per unit area. These types of relationships between catchment parameters can provide a possible explanation for the similarity in catchment behaviour given the differences in parameter values.

5.4 Representativeness of catchments and results

While the similarity in these catchments appears sufficient to allow the transfer of semi-quantitative information to other poorly documented catchments of the same type (i.e. **Figures 3 to 5**), it needs to be kept in mind that the five studied catchments were instrumented and relatively ‘well-studied’ because they had salinity problems. However, it is also likely that because of the highly variable nature of fractured rocks (due to varying degrees of fracturing and orientation of fractures), Local Type III catchments will exhibit the highest variation in catchment parameters and behaviour of the different Local classes. Hence, it is feasible that the range of parameters and behaviour of catchments belonging to other Local Types will be smaller.

Catchments of other local systems are not as well-documented as the Local Type III systems. This has made it difficult to compare the catchment responses of different local systems. Without similar information on other catchment types it is difficult to determine whether the catchment responses observed in **Figures 3 to 5** and the range in calibration parameters are specific to just the Local Type III systems or generic to several/all Local system types.

Future research should aim at providing a level of hydrologic understanding similar to that documented for the Local Type III catchments by involving instrumentation and monitoring of catchments of other types. In addition, detailed catchment scale recharge mapping should also be conducted to enable the comparison of the affects of specific land use changes (e.g. planting trees on upper slopes/ridges) between catchments. This would provide a better test of the ability to transfer specific management alternatives to poorly documented catchments of the same type.

6. Conclusions

Given the variety in size, shape, gradient, climate and geographic location of the five study sites, it is held that the response to reductions in recharge is similar enough across the catchments to provide a useful framework for catchment managers working in the Local Type III catchment class.

In the five catchments examined, the range of values for transmissivity and specific yield varied by two and one order-of-magnitude respectively. However, a dimensionless similarity parameter that simplifies the characterisation of a groundwater system by combining transmissivity, specific yield, recharge, length and head, varied by less than an order of magnitude. This result suggests that these parameters are inter-related and that it may be possible to define surrogate variables that increase the confidence with which parameters can be transferred between similar catchments. This requires further work.

While the range of parameter values within the Local Type III systems was small, the variation still led to large differences in simulated response. The differences in response were so large that the predictive use of these parameters is limited to examining relative responses.

If a larger number of Local Type III catchments had been examined, the range of parameter values is likely to have been even greater. While the uncertainty associated with an individual catchment would remain high, the certainty associated with an aggregated result (i.e. stream salt load at the outlet or total amount of land waterlogged) over a large region would increase because of increased confidence that the observed distribution (i.e. sample distribution) is representative of the true (i.e. population) distribution of values. There is also potential to define surrogate variables that may increase the confidence with which parameters can be transferred between similar catchments, but this requires further work.

Because of the highly variable nature of fractured rocks, it is proposed that the catchment type under investigation (i.e. Local Type III) will be the local system that exhibits the highest variation in catchment parameters and behaviour. Hence, it is feasible that the range of parameters and catchment behaviour in other Local Type systems will be smaller, indicating that the catchment classification system may be a useful framework for transferring modelling results and parameter values.

7. Recommendations and future work

In compiling case studies, it has become obvious that there are very few catchment types that an analysis of this type could be applied to. Examples would include the deeply weathered local and intermediate systems. As more case studies occur, an analysis of this type will help test the overall classification system.

Recommendation 1

- Further case studies be captured as part of a groundwater systems framework and analysed objectively for intra-class variation.

This analysis has been largely directed towards the impact of land salinisation. For the Murray-Darling Basin, in particular, and other areas, stream salinity and salt loads are also objectives of any salinity remediation. The current classification has not included some of the factors that would affect these. For example, it does not include conceptual models of how streams are connected to the groundwater systems. Nor does it include the impacts of land use on water yield and flow regime.

Recommendation 2

- The applicability and any modifications of the groundwater systems approach be tested for in-class variation of impacts of land use on stream salinity and salt loads

Other areas of interest from the viewpoint of the classification are the effectiveness of engineering options for protecting assets and opportunities for saline land and water. Some aspects of the catchment classification would be useful to assess these options e.g. transmissivity values, gradients. However, local conditions are also important, including site investigations on pumping yield, suitable sites for disposal water and markets. The catchment models used here are unsuitable in the scale of analysis to really assess these options. There are two relevant *National Dryland Salinity Program (NDSP)* projects: *Options for the Productive Use of Salinity (OPUS)* and assessment of engineering options.

Recommendation 3

- If the groundwater systems approach is to be used for the options for engineering and opportunities for saline use, these will need to be analysed in a similar way to biological recharge reduction.

This analysis considered land use only in its effectiveness to reduce recharge. Other projects are currently being conducted to estimate recharge under different land use (e.g. Landmark, New South Wales salinity strategy). As results become available, these can be used to link actual land uses to effectiveness to control recharge. This water balance framework should be conducted at a level of accuracy commensurate with the degree of hydrogeological detail provided by the catchment classification and ascertained that recharge estimated from these studies is consistent with the hydrogeological framework.

Recommendation 4

- Studies relating to impacts of changed land use need to be linked to this work to understand the effectiveness of changed land use in managing salinity.

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Integrated catchment management in the Murray-Darling Basin

A process through which people can develop a vision, agree on shared values and behaviours, make informed decisions and act together to manage the natural resources of their catchment: their decisions on the use of land, water and other environmental resources are made by considering the effect of that use on all those resources and on all people within the catchment.

Our values

We agree to work together, and ensure that our behaviour reflects that following values.

Courage

- We will take a visionary approach, provide leadership and be prepared to make difficult decisions.

Inclusiveness

- We will build relationships based on trust and sharing, considering the needs of future generations, and working together in a true partnership.
- We will engage all partners, including Indigenous communities, and ensure that partners have the capacity to be fully engaged.

Commitment

- We will act with passion and decisiveness, taking the long-term view and aiming for stability in decision-making.
- We will take a Basin perspective and a non-partisan approach to Basin management.

Respect and honesty

- We will respect different views, respect each other and acknowledge the reality of each other's situation.
- We will act with integrity, openness and honesty, be fair and credible and share knowledge and information.
- We will use resources equitably and respect the environment.

Flexibility

- We will accept reform where it is needed, be willing to change, and continuously improve our actions through a learning approach.

Practicability

- We will choose practicable, long-term outcomes and select viable solutions to achieve these outcomes.

Mutual obligation

- We will share responsibility and accountability, and act responsibly, with fairness and justice.
- We will support each other through the necessary change.

Our principles

We agree, in a spirit of partnership, to use the following principles to guide our actions.

Integration

- We will manage catchments holistically; that is, decisions on the use of land, water and other environmental resources are made by considering the effect of that use on all those resources and on all people within the catchment.

Accountability

- We will assign responsibilities and accountabilities.
- We will manage resources wisely, being accountable and reporting to our partners.

Transparency

- We will clarify the outcomes sought.
- We will be open about how to achieve outcomes and what is expected from each partner.

Effectiveness

- We will act to achieve agreed outcomes.
- We will learn from our successes and failures and continuously improve our actions.

Efficiency

- We will maximise the benefits and minimise the cost of actions.

Full accounting

- We will take account of the full range of costs and benefits, including economic, environmental, social and off-site costs and benefits.

Informed decision-making

- We will make decisions at the most appropriate scale.
- We will make decisions on the best available information, and continuously improve knowledge.
- We will support the involvement of Indigenous people in decision-making, understanding the value of this involvement and respecting the living knowledge of Indigenous people.

Learning approach

- We will learn from our failures and successes.
- We will learn from each other.