



National Classification of Catchments for land and river salinity control

**A report for the RIRDC/LWRRDC/FWPRDC
Joint Venture Agroforestry Program**

Edited by Jane Coram

August 1998

**RIRDC Publication No 98/78
RIRDC Project No AGS-1a**

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ISBN 0 6425 7884 2
ISSN 1440-6845

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Project no. AGS-1A

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FOREWORD

This report was prepared as part of a national project to characterise the range of hydrogeological processes involved in salinisation potential and management. It represents the culmination of two workshops held in Canberra on 21-22 April and 7th October 1997. These aimed to achieve consensus between state and research agency perspectives on the range of conceptual models of salinisation processes used across the country.

The project was funded by the RIRDC/LWRRDC/FWPRDC Joint Venture Agroforestry Program.

This report builds upon the accumulated knowledge of a number of workers in the field of land and water salinisation, and was written collaboratively by a number of authors from State and Commonwealth natural resources agencies.

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Contributors

The conceptual models presented in this paper draw heavily on hydrogeological models proposed by George et al. (1997), and on work undertaken over the last decade by a number of workers in the field. It is not possible to acknowledge all of these contributions individually; however, it is recognised that this paper would not have been possible without the past efforts of many workers.

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The drafting assistance of Pat Pratt, Martyn Moffat, Larry Hollands and Neale Jeffery, Australian Geological Survey Organisation, is gratefully acknowledged.

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Summary

Salinisation of land and water is a growing problem across Australia. There is an urgent need to predict the likely occurrence of catchment salinisation across the continent and to identify the most appropriate and cost-effective land uses for managing rising groundwater and mobilisation of salt into waterways across the country.

This report proposes that a national framework is needed to guide management effort and funding allocations, by synthesising the multitude of local research findings on the causality and remediation of dryland salinisation. It presents a catalogue of fifteen generic hydrogeological models of groundwater systems, that has been developed by experts from across the country. The models describe the broad characteristics of salinisation across Australia, although the relevance of the models to specific sites needs to be interpreted in the context of additional, local data. The models also consider the different scales of processes involved in salinisation, whether these be local, intermediate or regional groundwater flow systems. The specific settings of the models are described for each state where they are known to occur.

The report also proposes that two types of datasets are required to characterise the salinisation processes in each conceptual hydrogeological model. The first, "constants", determine the inherent susceptibility of the catchment to salinisation. The second dataset type, "variables", can be used to determine whether salinisation will actually occur in catchments with the appropriate inherent conditions for salinisation. These datasets form the basis of a hierarchical catchment classification system.

Finally, the report makes a number of recommendations for future research related to classifying catchments for salinisation types and developing appropriate management approaches for each salinisation type.

1. Introduction

1.1. The problem

Rising groundwater levels and salinisation of land and water are growing problems, and there is an immediate need for identifying the most appropriate and cost-effective land uses to manage rising water tables and salt mobilisation across the country. Whilst it is possible to do this at a planning scale for specific, intensively studied catchments, it is not feasible to carry out similar resource-intensive investigations for all other, unstudied catchments, and we currently lack the tools for generalising our knowledge of the processes operating in these catchments to other unstudied catchments at scales that are operationally meaningful. Furthermore, although there is a good understanding amongst specialists of the importance of hydrogeological processes in controlling salinisation, this understanding is not widely appreciated amongst stakeholder groups and funding agencies.

Given that management of dryland salinity problems needs to be based on understanding of the hydrogeological character of catchments (including water balance relationships), there is an urgent need to understand the hydrogeological context of individual occurrences of salinity. This will enable an appreciation of the appropriateness and likely efficacy of proposed salinity management options. In order to ensure that funding of ameliorative strategies is targeted towards the most appropriate techniques for the processes causing salinisation, there is a national need for a holistic approach to predict the likely occurrence of salinisation, and to identify appropriate management priorities on a national basis.

1.2 This report

This report attempts to address the need for a national hydrogeological framework to synthesise the myriad of research findings and knowledge regarding the causality and remediation of dryland salinisation. It presents an overview of salinisation across the country, and management approaches which have often been applied in the past. It then details the requirements of an objective classification system for predicting the hydrogeological processes of salinisation, and the difficulties and limitations in developing such a system. The report proposes fifteen conceptual hydrogeological models which characterise the range of groundwater processes causing salinisation across the continent, describes the occurrence of these models across the continent, and lists the critical datasets required to develop these models. Finally, the report makes a number of recommendations for future work.

1.3 The project

This report is the result of the project "A National Classification of Catchments for Land and River Salinity Control", which was funded by the RIRDC/LWRRDC/FWPRDC Joint Venture Agroforestry Program. Substantial, in kind contributions were also made by the Australian Geological Survey Organisation, State land and water management agencies, and CSIRO Land and Water Division.

The project aimed to provide a consensus between recognised experts on conceptual models of water and solute movement through catchments across Australia, and from this base to identify the minimum data sets required to characterise catchments for salinity management.

The project was in two stages. Initially, a discussion paper was prepared on the use and feasibility of developing a catchment classification system (Hatton, Appendix 1). This was followed up by a two day workshop in Canberra (21st and 22nd of April, 1997) (Appendix 2) to investigate the feasibility of pursuing a classification-based approach to catchment hydrogeology. A subsequent workshop (sponsored by the RIRDC/LWRRDC/FWPRDC Joint Venture Agroforestry Program) was held in Canberra (7th of October, 1997) as a direct recommendation of the initial workshop, to identify a set of conceptual models of salinisation processes across the continent. This report elaborates on the models identified in that workshop.

Experts from each of the state land and water management agencies, CSIRO Land and Water Resources Division, the Australian Geological Survey Organisation, universities and some community

people were involved in this project. Those who made direct contributions to this report are acknowledged in the "Contributors" section.

2. Overview of salinisation problems

2.1 The salinity process

Across the continent, large areas of land and water are experiencing degradation as the result of salinisation processes. Even more extensive areas are considered likely to be degraded in the future. These changes are the result of hydrological disequilibrium caused since European settlement by extensive clearing and the replacement of native vegetation with shallow rooted, water-inefficient crops.

The causes of dryland salinity are now well understood and have been documented comprehensively in other places. It is not intended to restate this information here. However, it is now recognised that a critical combination of hydrologic disequilibrium and a source of salt are necessary for a landscape to suffer from salinisation. When considering the distribution of salinisation throughout Australia, it is not sufficient to understand just the distribution of aquifer types; an understanding of the distribution of salt within a catchment, and how groundwater mobilises this salt store, is also required. Therefore, descriptions of the key factors that influence salinisation must include those factors that control the distribution of salt, as well as those that control the flow of groundwater. Given that dryland salinity is an expression of a dynamic change to the groundwater system, factors such as climate and land use are also critical to understanding the distribution of salinisation.

The physiographic and land attribute combinations that are considered to have the greatest potential for future dryland salinity to occur are:

- hydrogeology - particularly areas where groundwater flow is restricted by changes in subsurface geology;
- land use - particularly where grazing and cropping practices have greatly increased the volume of water infiltrating to the groundwater system;
- climate - particularly areas where annual evaporation greatly exceeds annual rainfall and with winter-dominant rainfall patterns;
- landform - particularly areas where there is a sudden reduction in steepness, such as occurs in foothill areas;

As a first step, this report summarises the range of hydrogeological characteristics that influence the discharge of saline groundwater from aquifers.

2.2 Regional context

The key attributes which together describe the nature of the aquifers which transmit groundwater include geology, physiography and weathering style. These three interrelated characteristics are found in an almost unique variety of combinations in each catchment, but at a broad level some regional similarities can be recognised.

For instance, similar local flow systems can be found in the unweathered to moderately weathered, Paleozoic rocks of the Lachlan Fold belt in the higher relief parts of Victoria and New South Wales. These are significantly different from the lower relief, more deeply weathered areas on the same rock types. Salinisation in these settings is often associated with groundwater movement from unweathered to weathered rock, or with changes in relief.

In Western Australia, deeply weathered low relief Archaean rocks of the Yilgarn Block form another combination. These settings are also similar to the occurrences on Eyre Peninsular in South Australia. Salinisation in these settings is often associated with faults, shear zones and the presence of dykes or other linear features.

The groundwater systems of regional depositional environments provide a third general example of broad hydrogeological similarities. These settings are best exemplified by the Murray Geological Basin of south-eastern Australia, and the Perth Basin in Western Australia. Salinisation in these

settings is often associated with changes in depositional material, both gradual facies changes and abrupt structural changes.

2.3 Extent of dryland salinisation

The following sections summarise the extent of dryland salinisation for each state, and have been compiled from relevant information from the project's relevant state contact.

2.3.1 Western Australia

The extent of current and predicted future likely salinisation in Western Australia is shown in Table 1. Salinisation is considered to be controlled by hydrogeological processes, which affect the distribution of recharge and control the transmission of water and pressure within the saturated zone. Climate also plays a role in the distribution of salinisation, with negligible salinisation occurring in areas with average annual rainfalls of greater than 1100 mm (Ferdowsian et al., 1996).

Hydrological region	1994 area (ha)	Percentage area affected in 1994	Area predicted at equilibrium (ha)	Percentage area affected at equilibrium
South Coast	395,400	9.7	977,180	24.0
South West	273,800	8.3	820,000	24.8
Swan-Avon	759,000	10.0	3,036,200	40.0
Northern	376,250	8.8	1,275,600	30.0
Total	1,804,450	9.4	6,108,980	31.8

Table 1: Areas estimated to be affected by secondary salinity to some extent in 1994 and at hydrological equilibrium in Western Australia (after Ferdowsian et al., 1996). (Areas are considered affected when the yield of the preferred crop or pasture is reduced by at least 50%.)

2.3.2 South Australia

Dryland salinity is recognised as a major land, water and vegetation degradation issue in South Australia (Barnett et al., 1996). In some areas, the process of dryland salinity has degraded land to a point where conventional agriculture is no longer possible. The offsite effects of dryland salinity are also becoming more apparent as water resources are being affected by increasing salinity levels in streams flowing from salinised catchments. The extent of salinisation in South Australia in 1993 is summarised below in Table 2. In general, salinisation is not observed in areas with an average annual rainfall of greater than 700 mm.

Region	Extent of salinisation (ha)	Approximate percentage of total area in region
Upper South East	260,000	26.0
Coastal Plain (Southern Mallee)	57,000	9.0
Lower Eyre Peninsula	28,000	5.0
Upper Eyre Peninsula	21,500	3.0
Kangaroo Island	9,600	4.0
Mid North	8,000	<1.0
Yorke Peninsula	5,000	<1.0
Mt Lofty Ranges	2,800	1.0
Total	391,900	

Table 2: Areas in South Australia estimated to be affected by secondary salinity in 1993 (Henschke, pers. comm.)

2.3.3 Victoria

The total area of secondary dryland salinity in Victoria is estimated to be at least 120,000 hectares, or approximately one percent of the total cleared or naturally treeless, non-irrigation, non-urban land in the state (Allan, 1994). Table 3 shows the extent of dryland salinisation in each identified salinity region. A total of five thousand groundwater discharge sites have been mapped, and range in size from less than one hectare to two thousand hectares (Allan, 1993). An additional 250,000 hectares of land have been estimated as being subject to natural (also known as primary) salting (Allan, 1994).

The annual percentage increase in dryland salinity across the state has been estimated as being at least 2%, although this can vary between zero and 15% at individual sites (Allan, 1994). These estimates are based on general groundwater level rises of between 20 and 40 cm/yr.

Salinity Region	Area of secondary dryland salinity ¹ (ha)	Approximate percentage of total area in region (ha)
Avoca	5,600	0.9
Avon-Richardson	10,500	3.6
Campaspe	3,200	0.9
Corangamite	10,900	0.7
Glenelg (mapping incomplete)	20,000	1.0
Goulburn	3,500	0.3
Lake Wellington	10,000	4.5
Loddon	7,400	1.0
Mallee (mapping out of date)	15,000	0.6
North East	300	<0.1
South East (excluding Lake Wellington catchment)	10,000	0.6
Wimmera (excluding Avon-Richardson catchment)	13,000	1.0
Total (including estimates of areas known to occur but which have not yet been mapped)	~120,000	1.0

Table 3: Areas in Victoria estimated to be affected by secondary salinity in 1994 (from Allan, 1994)

¹ Secondary dryland salinity estimates do not include areas considered to have had pre-European (primary) salinity except where these areas have expanded or been reactivated as the result of land use changes

2.3.4 Tasmania

Approximately 20,000 hectares, or about one percent of the agricultural land in the State, are estimated to be affected by soil salinisation (L. Matthews, pers. comm.). Areas affected by salinisation include extensive areas on King and Flinders Islands, in the Midland area, in South East and North East Tasmania and in the Derwent Valley.

2.3.5 New South Wales

Approximately 120,000 hectares of land are estimated to be currently affected by dryland salinity (Bradd & Gates, 1996), while a further 5,000,000 hectares are considered to be at risk of future salinisation on the basis of their physical characteristics. A more rigorous estimate of the area currently affected and a likely time frame for salinisation increases is not available for NSW.

The river basins most susceptible to dryland salinity are the Lachlan, Murrumbidgee and the Macquarie river basins. Areas of major concern that have a high to very high dryland salinity hazard index are found in a north-south belt just north of Canberra (Yass River Valley), and in the southwestern part of the Lachlan River catchment, east of Wagga Wagga in the Murrumbidgee River catchment, and east of Dubbo in the Macquarie River catchment. Dryland salinity potential is less severe in the north of the State.

2.3.6 Queensland

A total 10,000 hectares of land were identified as being severely affected by salinisation in 1991, with another 75,000 hectares of land considered at risk of being affected by rising groundwater in the future (Gordon, 1991). Table 4 shows the extent of dryland salinisation in each region. There has been no published update of the current extent of salinity, but a revision by staff from the Department of Natural Resources in 1995 has modified the estimate of land severely affected by dryland salinity to 15,000 hectares (Gordon, pers. comm.).

Region	Area affected (ha)	Potential area (ha)
North	250	1,600
West	40	unknown
Central	3,900	13,400
South	2,600	4,380
South-East	3,400*	56,900
TOTAL	10,190	74,680

Table 4: Areas identified by survey questionnaire as severely affected by induced salinity in Queensland in 1990/91 (from Gordon, 1991).

**Area was estimated from extent of major occurrences of salinity, and differed from the total area estimated in the region (9655 ha).*

Salinisation occurs on a wide range of geological units in Queensland, but is predominantly associated with basalts or lateritised basalts. Within these units salinisation is commonly associated with the less permeable clay alluvia. Most affected areas are located in coastal and sub-coastal regions receiving more than 500mm and less than 1500 mm annual rainfall. The risk of salinisation in Queensland is generally lower than in other states due to summer dominant rainfall patterns where evaporation almost always exceeds rainfall. Under these conditions the soil profile is rarely fully saturated and recharge occurs only when a succession of wet periods does not allow the profile to dry out.

2.3.7 Northern Territory

To date there has been only minor clearing of native vegetation for agriculture and no occurrences of dryland salinity have been recognised. In a territory wide assessment of dryland salinity hazard, Tickell (1994) concluded that, if broad scale clearing were to take place, dryland salinity would be unlikely to become a major problem. The main reasons for this are that in the higher rainfall areas where deep rooted vegetation is abundant, salt storages are low. Contrastingly, in the more arid areas where salt storages can be high, deep rooted vegetation is either sparse or absent. Both situations generally preclude the development of dryland salinity.

2.4 Past approaches to managing land and river salinisation

The surface manifestations of rising groundwaters have been widely recognised for several decades now, and a range of management approaches have been attempted. These approaches generally consist of trying to prevent rainwater from infiltrating to the groundwater system (for example, modifying vegetative cover to more water-efficient pastures and crops, or enhancing native vegetation cover), or removing water from the groundwater system before it discharges at the ground surface (for example, agroforestry plantations and drainage systems) either as the groundwater is in transit to the discharge zone or in the discharge zone itself. The most commonly applied approaches are discussed below.

2.4.1 Interception of water in the unsaturated zone

Revegetation of recharge areas

Planting of trees in groundwater recharge areas has been attempted as a means of reducing the amount of water infiltrating to the groundwater system. This approach has additional 'on-site' benefits through providing shelter for livestock and increasing habitat for native species. Agroforestry can also be a means of supplementing landholders' primary incomes.

This approach has also generally had limited known success, for a number of reasons. The first is that extensive planting of recharge areas would be required to significantly reduce the amount of water reaching the groundwater system. The second is that recharge areas are often quite distant from areas of land and water salinisation, and so the areas which need to be planted are often managed by landholders who do not suffer the effects of salinisation. The third is that agroforestry in recharge areas may not produce any significant financial benefits where recharge areas have skeletal soils and low soil fertility, and plantation growth rates are accordingly low. Finally, slow tree growth rates also mean that it generally takes trees some years to develop to a stage where they have significant benefits in controlling groundwater rise.

Perennial pastures

Widespread planting of perennial pastures has been promoted as a financially and logistically viable option for managing salinisation by graziers. The rationale behind this approach has been that perennial pastures make more use of available soil water throughout the year than annual pastures; that deep rooted perennial pastures have a greater ability to extract water directly from shallow water tables; and that this approach has some chance of widespread implementation by landholders as it permits continuation of existing agricultural practices.

This approach has been successfully applied in some cases, for example Burke's Flat (Avoca catchment, Victoria). This approach has generally had limited known success, however, partly because it has not been well monitored, partly because it has generally not been widely adopted, and partly because, even where it has been widely adopted, perennial pastures alone do not use sufficient water to impact on the water balance and are still generally a localised solution to what is often a much more widespread problem.

Modified cropping practices

Altering cropping practices from regular fallowing to a rotational cropping system has been suggested as a viable means of reducing groundwater recharge. This approach has a reasonable chance of widespread adoption, and may be a useful adjunct to other approaches particularly when used in conjunction with perennial pastures; however, on its own it is unlikely to have a sufficient effect on rising groundwater levels.

2.4.2 Interception of water from the saturated zone

Agroforestry at break of slopes

Agroforestry plantations at the 'break of slope' have been widely touted as an appropriate means of managing salinisation, by intercepting groundwater before it discharges at the surface. The benefits of this approach are, in theory, that it not only reduces the amount of groundwater discharging downgradient of the plantation, but that the plantation can act as a viable supplement to landholders incomes whilst providing shelter for livestock and habitat for native species.

This approach has been successfully adopted by individual landholders in some areas; for example, the Warrenbayne catchment, Victoria. However, in a number of other cases, break of slope plantations have either failed to grow at economically viable rates as the result of climatic or nutrient limitations, or have failed completely, either because the plantation has not intercepted the main lateral flow of groundwater or because the groundwater being intercepted has been too saline for tree survival. As a general rule, the efficacy of this technique varies with the hydrogeological and climatic characteristics of the site.

Groundwater pumping

At first glance, pumping of groundwater is an appealingly straightforward means of removing the problem of salinisation, by directly reducing groundwater pressure and thereby lowering groundwater levels. The main issue with this approach is the means by which the pumped groundwater is disposed, as groundwater is often too saline to be used directly for irrigation purposes. However, in cases where groundwater salinities permit utilisation for agricultural or other purposes, groundwater pumping can be a viable means of managing groundwater rise.

2.5 Shortfalls of the approaches to managing salinisation

There is little doubt that, in some cases, the management approaches discussed above have ameliorated dryland and river salinisation. However, in many cases, the processes of dryland and river salinisation have shown little change in response to these management strategies. This partly reflects the fact that management strategies are not based on an understanding of how much recharge needs to be intercepted to achieve measurable results. This may also be partly because the monitoring history is too short to detect any changes.

The variable success rate of management approaches is also a reflection of the variation in geology, geomorphology and climate that occurs across the continent. This variation means that management approaches that have been successful at specific locations may not be appropriate at other sites. Nonetheless, catchment communities are now applying management options for their region based on demonstration sites that may bear no physical resemblance to their local conditions. For instance, "break of slope" tree plantings are now widely accepted as a viable management option over much of southern Australia, although they are only likely to be effective where the local geology, groundwater salinity and climate are appropriate.

The scale of the hydrogeological processes controlling salinisation is another important determinant of the efficacy of management approaches. Not only do larger scale systems usually involve more complex hydrogeological processes, the number of stakeholders and landholders needed to implement management changes also increases with the distance between recharge and discharge zones. Frequently, the processes controlling groundwater rise are much broader than can be addressed by merely local approaches, although management effort often tends to be focussed on local groundwater discharge zones.

To achieve the most effective use of time, money and effort, management actions need to be chosen so that they are appropriate for the characteristics of individual sites and salinisation processes. However, in the vast majority of catchments, there is a very limited understanding of the interaction between hydrogeological characteristics and the manifestation of salinity. Whilst detailed studies have been made of the characteristics of land and water salinisation in some specific catchments, these cannot currently be readily generalised to other catchments, nor is it feasible to conduct such resource-intensive studies in the majority of catchments. Such detailed studies also tend to be used solely within the state which conducted them, so models of groundwater behaviour are not necessarily applied to catchments in other states, despite similarities in the processes which operate. Thus, despite a high level of understanding of the broad processes of catchment salinisation and some detailed studies of the processes of specific catchments, we currently lack the ability to predict salinisation risks and appropriate management options in unstudied catchments.

3. A systematic approach for managing salinisation

3.1 Need for a systematic framework

As is apparent from the discussion above, we do have a reasonable understanding of the broad processes of salinisation and of approaches which can be successfully applied to reduce the problem in specific settings. However, these approaches are not all successful at all settings, and despite the large amounts of funding already directed towards managing salinisation we are faced with a growing problem across the continent. There tends to be an ad hoc approach to managing salinisation in a national context: funding, time and effort are all too often applied to the problem according to other priorities than would be determined from a thorough understanding of the processes underlying salinisation. Given that funding for ameliorating salinisation is not infinite, there is an obvious imperative for being very focussed in managing the problem, to achieve the best results for the time, money and effort invested.

In order to address the problem of land and water salinisation in a focussed and efficient way, we need:

- to determine where the different management approaches discussed in the preceding section are appropriate and cost-effective;
- to be able to identify hydrogeological types where specific management options are likely to be effective in controlling groundwater rise and salinisation;
- to be able to extend the findings of detailed studies of individual catchments to other, similar catchments where the same management approaches are likely to be effective;
- to be able to identify where and what proportion of these catchments would need to be treated to manage groundwater rise;
- a national overview of the extent and processes of salinisation, so that funding for ameliorative measures can be targeted towards the most appropriate management options at sites where there is a realistic chance of ameliorating salinisation.

Despite these compelling needs for a systematic approach to managing salinisation, no national framework for determining catchment behaviour currently exists. Models of landscape types or structures which could lead to salinisation have been proposed for local areas, but these have neither been systematically mapped nor formally related to responses to various land use options. Experienced field scientists often make this linkage, but it is confined to local circumstances and is not formally documented.

A national catchment classification system has to provide a systematic approach and a scientific basis (as far as is possible) for management decisions and funding allocations. (For example, determining where management activities should be focussed in catchments, and what sort of management activity is appropriate and cost-effective.) It should provide conceptual models of our various hydrological systems that permit identification of catchments and landscape units which will respond hydrologically, ecologically and productively in a similar way to land use. This will enable understanding gained from intensively studied catchments to be used to manage catchments for which we have only a minimum of data and understanding. Such a system should also provide a framework within which research and development funding decisions can be optimised.

3.2 Difficulties in developing a national catchment classification system

Several issues complicate the development of any national classification system and the conceptual models which would underpin it.

The first is the difficulty in identifying the critical biophysical characteristics that determine salinisation potential; for example, geology, climate, physiography, soil type and depth, drainage. Whilst the process of salinisation can be conceptualised as a disequilibrium between current and past rates of groundwater recharge and discharge, a number of characteristics influence the degree of this disequilibrium. It is no simple task to identify those which are critical to assessing salinisation risk.

The second issue is the complexity and spatial heterogeneity of factors controlling groundwater rise and salt mobilisation. Structures resulting from events in the geological past (the intrusion of a dyke, uplift along a fault plane, sea level change) and variations in stored salt can from place to place exert a strong and to some extent a seemingly unpredictable influence on salinisation processes. Whilst our understanding of regional systems (at a scale of 1:100,000) is quite good, developing a classification system at a sub-catchment scale is more complicated. There are a set of principles that underlie each hydrogeological unit at a strategic planning scale, but there are variants that need to be appreciated at the operational scale. For instance, the broad processes of salinisation in a deeply weathered (lateritised) granitic landscape in Western Australia are very similar to those occurring in the Eyre Peninsula in South Australia, and in the Dundas Plateau in Victoria. However, in Western Australia, the presence of a igneous dyke will interfere with the groundwater flow to produce a local variant of the broad salinisation process. Similarly, in the fractured Palaeozoic rocks of southeastern Australia, local combinations of relief and structural features (faults) produce a set of variants. Thus, whilst we can produce a defensible hydrogeological model for an idealised hillslope made up of "typical" rock properties, in practice it may be rendered inaccurate by the presence of an unknown dyke or bedrock high.

Thirdly, the range of spatial and temporal scales involved in characterising catchment processes also complicates the development of a national classification of catchments. In some areas, local hydrogeological systems can be underlain by, and interact with, larger regional aquifer systems (length scales of hundreds of kilometers) with their own unique hydrogeological and hydrochemical properties. Whilst the broad hydrogeological features control *whether* salinisation occurs, the smaller, local-scale features, which can be more difficult to predict, control *where* regional discharge occurs. In order to implement appropriate management strategies it is important to understand the influence of both regional and more localised groundwater systems on salinisation processes.

These factors mean that no generic catchment classification system will ever be right at all scales, all of the time, nor will it be any more accurate than the datasets upon which it is based. The challenge is to develop a system that is right and accurate enough of the time to be a useful tool at a strategic and operational management level, so that it meets the level of certainty required by those wishing to invest in land management change.

3.3 Previous work in developing a national catchment classification system

The rate and quantity of groundwater movement reflects a balance between the volume of groundwater, and the ability of the aquifer to transmit it. Groundwater discharge and associated salinisation occurs when the ability of the aquifer medium to transmit or carry the groundwater, its "transmissivity", is diminished. This can occur through reductions in the cross-sectional area of the aquifer due to structural or topographic changes; in the hydraulic conductivity of the aquifer due to compositional changes, or through increases in the upgradient pressure on the groundwater in the aquifer. These changes can often be interrelated.

Over the past two decades, the number of conceptual hydrogeological models of salinisation has expanded from the simplified 2-D slice models typical of hydrogeology text-books, to other more complex 2-D slices which accommodate the geological variability within the landscape. Initial valley floor and hillside models (Wood, 1924; Nulsen and Henschke, 1981) based on vertical transport from a shallow watertable and variability in transmissivity caused by bedrock highs, have recently been

further refined to incorporate other structural features which influence groundwater flow (George et al., 1997).

Conceptual models of salinity processes have also been developed by workers in Victoria (for example, Dyson (1983, 1990), Tickell and Humphreys (1987), Macumber (1991), Ryan (1993)). These include models applicable to upland fractured rock systems, granitic rocks, deep lead and shallow alluvial, aeolian and marine sedimentary groundwater systems.

A number of conceptual models of salinity processes in New South Wales have been summarised in Salt Action (NSW Government, 1993). Salinity process models for specific catchments have also been described in numerous unpublished university theses, particularly for the Begalia (Evans, 1995), Dick's Creek (Corpuz (1990); Herwantanko (1991); Scott (1990)), Wattle Retreat (Bradd (1988)), and Williams Creek (Bradd (1993), Corpuz (1990) catchments, and for the Liverpool Plains (Broughton (1992, 1994)).

In Queensland, Shaw et al. (1987) identified a set of common landform types with characteristic recharge and discharge zones, and associated restrictions to flow. These included a basalt form (capping), a catena form (hillslope), valleys with restrictions (basement highs or constrictions), alluvial valleys with very low hydraulic gradients, ancient colluvial systems, multi-layered aquifers with varying transmissivities, systems where groundwater and throughflow is impeded by dykes, systems affected by the confluence of streams, and systems influenced by restrictions to water flow due to faulting. These landform types can be used to highlight locations where salting is likely to occur in conjunction with other factors such as water quality and salt sources.

Most of these models have wider application than simply to the state or region for which they were initially developed. For example, the Victorian models have broad application to a wide area ranging from the inland slopes of the Great Dividing Range of northern Victoria, to the western footslopes of the Great Dividing Range throughout New South Wales and into Queensland. Furthermore, land management activities have not always been linked to the models within the states or regions they were developed, and have not always been at an appropriate management scale.

4. Developing a national catchment classification system

It is proposed that the broad features of common occurrences of salinisation across Australia can be described by the fifteen hydrogeological models described below. The specific settings of the models are detailed for each state where they are known to occur. It is important to emphasise that these models cannot, in isolation from other data, predict the occurrence of soil and land salinisation. The relevance of the models to specific sites needs to be interpreted in the context of additional, local data. Additionally, in many cases, several of these models may operate within a single catchment.

The models are listed according to whether they represent local, intermediate or regional flow systems primarily because these scales reflect the ease with which salinisation can be managed. However, in a number of instances, groundwater behaviour may be the result of several superimposed systems; for example, the specific area of discharge may be controlled by local hydrogeological features although the general region is controlled by regional processes.

The local hydrogeological systems described below have shallow circulation depths and have recharge and discharge areas close together. They tend to occur in areas of higher relief, and are usually unconfined. The typical scale of a local flow system is in the order of one to three kilometers.

The intermediate hydrogeological flow systems described below are intermediate in scale between the local systems and regional systems. They tend to occur in foothills and valleys, over a horizontal scale in the order of five to ten kilometers. Intermediate flow systems may be overlain by local flow systems.

The regional hydrogeological systems described below have deep circulation depths, and recharge and discharge areas separated by considerable distances. The aquifers are usually confined, and groundwater residence times are long. The typical scale of a regional flow system is in the order of fifty or more kilometers, and regional flow systems are likely to be overlain by local and intermediate flow systems.

The broad features of local, intermediate and regional systems are summarised below in Table 5.

	Local flow system	Intermediate flow system	Regional flow system
<i>horizontal scale</i>	• 1-3 kilometers	• 5-10 kilometers	• >50 kilometers
<i>Geomorphology</i>	• subcatchments in higher relief areas on edges of plateaus and ranges	• alluvial and, occasionally, glacial valley fill in foothills and valleys	• broad riverine plains on depositional basins
<i>Geology</i>	• fractured metamorphic and igneous rocks • colluvial sediments • aeolian sediments	• fractured metamorphic and igneous rocks shallow (<50 metres deep) alluvial and colluvial sediments	• deep, interbedded marine, alluvial and aeolian sedimentary sequences (several hundreds of metres deep)
<i>structural features influencing groundwater flow</i>	• subsurface low hydraulic conductivity features such as bedrock highs and dykes • termination of aquifer at erosional surfaces	• Reductions in hydraulic conductivity with distance from sedimentary source or aquifer weathering • reductions in hydraulic gradient or aquifer thickness with shallowing of the ground surface • subsurface low hydraulic conductivity features such as bedrock highs and dykes	• reductions in hydraulic conductivity with distance from sedimentary source or associated with structural deformation (faulting, folding) • reductions in hydraulic gradient or aquifer thickness with shallowing of the ground surface

Table 5: Summary of the broad features of local, intermediate and regional systems

4.1 Local model (i) - Discharge over lower hydraulic conductivity structures

In this catchment model, seeps develop by direct outflow and evaporation where groundwater flow is restricted by subsurface structures with lower hydraulic conductivity (Figure 1). This model is characteristic of local flow systems above relatively impermeable bedrock, but could also occur where aquifers overlie less hydraulically conductive sediments. The occurrence of this model of groundwater discharge across the continent is summarised in Table 6.

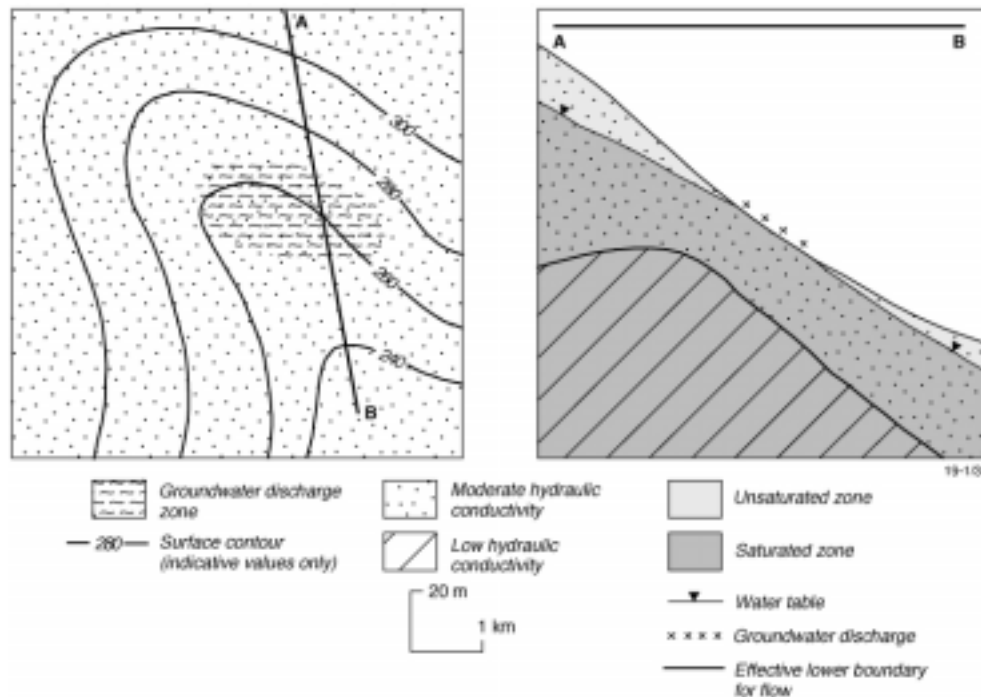


Figure 1: Diagrammatic representation of Local model (i), in (a) plan view and (b) cross section

State	Distribution
WA	Widespread throughout southwest WA, this form of groundwater discharge occurs as hillside seeps on the Archaean Yilgarn Craton and the Proterozoic Northampton and Albany Fraser orogen on the South coast, commonly west of the Meckering line. Seeps develop by evaporation and direct outflow of groundwaters, and tend to be smaller (~1 hectare) and fresher (<5,000 mg/L) than other salinisation types. Type example: Upper "52 Creek" catchment, Konjonup
SA	Widespread throughout SA, this type of groundwater discharge usually occurs from fractured rock aquifers in valleys, but can also occur on hillslopes above bedrock highs. Type examples: Seddon Plateau, Kangaroo Island Eastern Mt Lofty Ranges Waitpinga on Fleurieu Peninsula Cleve Uplands on Eastern Eyre Peninsula Lincoln Uplands and Tumby Bay, Lower Eyre Peninsula
NSW	In NSW this form of groundwater discharge occurs from fractured Devonian granites and Ordovician/Silurian fractured metasediments overlain by Tertiary basalts. Discharge areas occur as surface scalds where bedrock highs occur (for example, as the result of differential depths of weathering). Type examples: Box Hill, Inverell Dick's Creek, Yass Mumbil, Wellington

Table 6: Occurrence of Local model (i) in each state

4.2 Local model (ii) - Discharge from unweathered rock aquifers at the break of slope

In this model, groundwater discharge occurs with a reduction in topographic gradient at "breaks of slopes", where the aquifer conductivity or the hydraulic gradient is too low to transmit the same

volume of groundwater as occurs further uphill (Figure 2). Hydrogeological characteristics are less important than topographic location in this model, which is characteristic of areas with relatively sudden decreases in ground slope. The model has superficial similarity with Local model (iv) "Discharge from colluvial/alluvial slopes", but in this model groundwater discharge is controlled primarily by sudden reduction in aquifer cross-sectional area at the break of the slope. The occurrence of this model of groundwater discharge across the continent is summarised in Table 7.

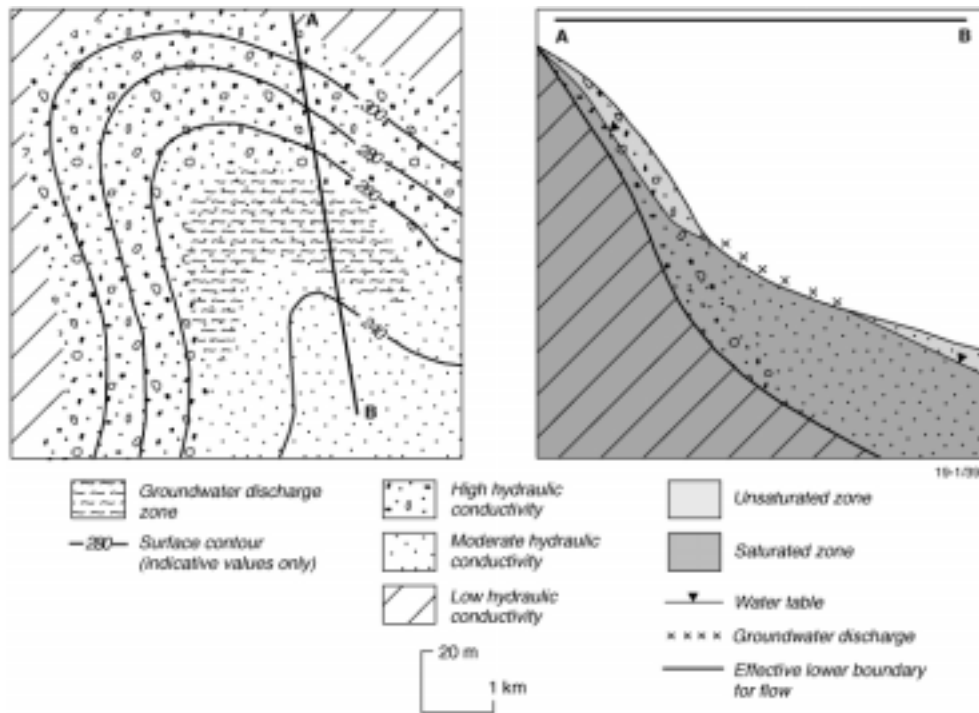


Figure 2: Diagrammatic representation of Local model (ii), in (a) plan view and (b) cross section

State	Distribution
WA	Groundwater discharge according to this model is widespread throughout south west WA, and usually occurs where groundwater flow occurs through deep regolith. Seeps tend to be larger (>10 hectares) and more saline (>15,000 mg/L) than those from the preceding models. Type example: Toolibin catchment, Central wheatbelt Wallatin Creek catchment, Central wheatbelt
SA	In SA, groundwater discharge according to this model occurs from both sedimentary and fractured rocks in areas where steep ranges sharply change gradient to broad alluvial flats. Type examples: Eastern and western boundaries of Cummins-Wanilla Basin North-south valley systems in Mid-North
Vic	This form of groundwater discharge is widespread in weathered, fractured sedimentary, metamorphic and igneous upland terrains. Type examples: Everton, Greta (Ovens Valley) MolyullahTatang (Goulburn-Broken catchment) Black Range (Loddon/Avoca catchment)
NSW	This form of groundwater discharge is widespread throughout the tablelands regions in NSW. The most important feature of this model is the change in topographic gradient. Salinised areas occur around the gradient change and are usually relatively small (100-1000 m ²). Type examples: Upper Mooki Valley, Liverpool Plains catchments within the Yass River Valley

Table 7: Occurrence of Local model (ii) in each state

4.3 Local model (iii) - Discharge from weathered fractured rock aquifers at break of slope

In this groundwater model, groundwater discharge occurs from deeply weathered fractured rock aquifers where reductions in surface topography coincide with reductions in the hydraulic conductivity as groundwater moves from unweathered, fractured rock to weathered material (Figure 3). Groundwater discharge according to this model often occurs on shallow slopes on the inland foothills of the Great Dividing Range in New South Wales and Victoria, from crystalline rock which has undergone deep weathering. The model has considerable superficial similarity with Local model (ii) "Discharge from unweathered rock aquifers at break of slope"; however, groundwater discharge according to this model reflects the termination of relatively high hydraulic conductivity, unweathered material at the eroded break of slope. The occurrence of this model of groundwater discharge across the continent is summarised in Table 8.

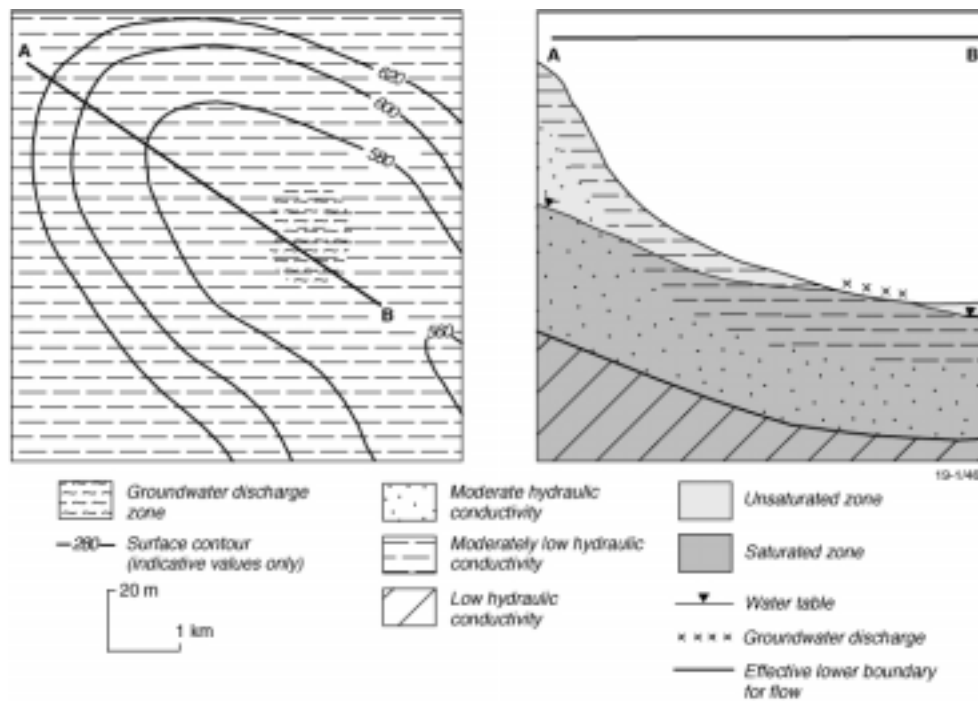


Figure 3: Diagrammatic representation of Local model (iii), in (a) plan view and (b) cross section

State	Distribution
SA	Mt Lofty Ranges, Mid-North, Lower Eyre Peninsula, Kangaroo Island
Vic	In Victoria, this model occurs in fractured Ordovician and Siluro-Devonian sediments and metasediments on the northern foothills of the Great Dividing Range. The concentrations of groundwater salts are high (TDS~15,000-25,000 mg/L) and discharge zones result in areas of bare earth and/or spiny rush. Type Example: Kamarooka-Cumberg Flats Burkes Flat Moonambel
NSW	Type example: Western slopes of the Great Dividing Range

Table 8: Occurrence of Local model (iii) in each state

4.4 Local model (iv) - Discharge from colluvial/alluvial slopes

In this model, groundwater flow occurs in colluvial sediments with high hydraulic conductivities, and is discharged either as the result of changes in aquifer thickness, or in aquifer material (Figure 4). Groundwater flow according to this model is characteristic of alluvial/colluvial fans extending from ranges. The model has superficial similarity with Local model (ii) "Discharge from unweathered aquifers at break of slopes", but is primarily controlled by the reduction in hydraulic conductivity with increasing distance from the source material.

In Victoria, much salinisation defined by this model has been known as Break of Slope salinity. However, it is actually an example of where groundwater discharge is primarily controlled by the gradual reduction in hydraulic conductivity in colluvial material rather than a change in topographic gradient. This colluvial material overlies bedrock that effectively has no hydraulic conductivity.

The occurrence of this model of groundwater discharge across the continent is summarised in Table 9.

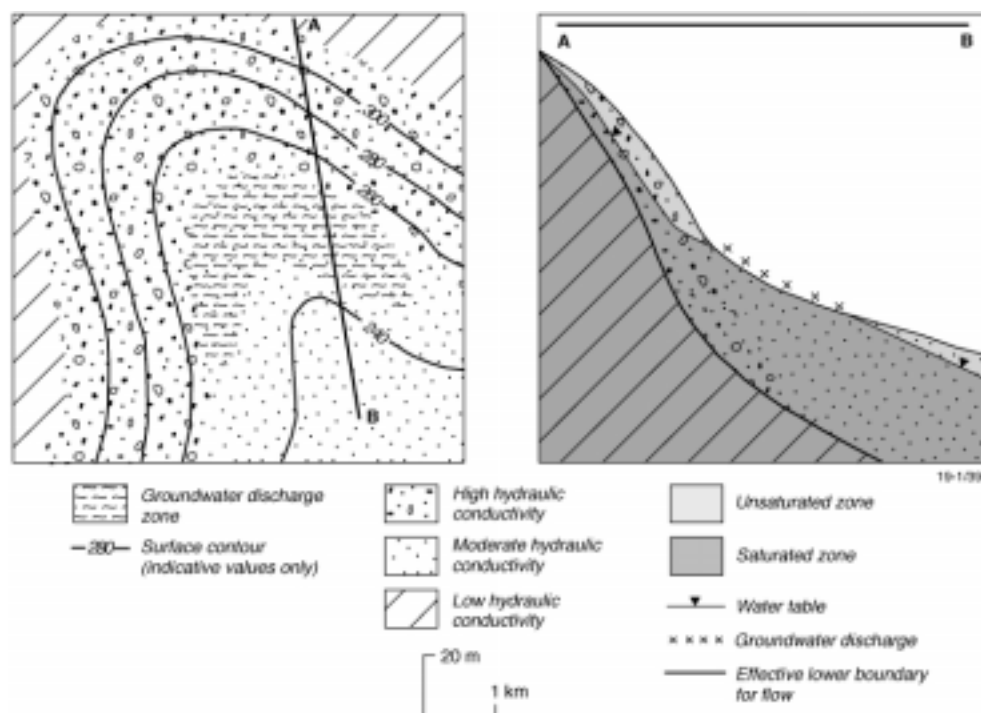


Figure 4: Diagrammatic representation of Local model (iv), in (a) plan view and (b) cross section

State	Distribution
Vic	This model is characteristic of granitic areas. Groundwater salinity is typically 1,000-5,000mg/L, and strongly artesian discharge can occur at discharge zones. Type example: the Warrenbayne-Boho area
NSW	Type example: Goran Basin
QLD	This form is not particularly common in QLD but does occur in Central QLD on Tertiary sediments and on the Eastern Darling Downs on basalt. This form occurs where coarser sediments have been deposited as an old alluvial fan which is subsequently buried or partially buried with clays. Water moving through the soil enters the colluvia or alluvia of former land surfaces which act as aquifers for water transmission. Discharge areas occur where a restriction is present, such as deep clays, more recent alluvia, or finer sediments deposited over coarser materials. Type examples: Boonah area, south east QLD Burdekin Valley right bank

Table 9: Occurrence of Local model (iv) in each state

4.5 Local model (v) - Discharge controlled by stratigraphy (sediments/basalts)

In this model, groundwater discharge occurs from local or perched systems where high hydraulic conductivity layers terminate at erosional surfaces or at faulted/unconformable contacts (Figure 5). The important characteristic of this model is the contrast in hydraulic conductivities between layered aquifers. It usually occurs in sedimentary sequences or basaltic rocks. This model is very similar to Local model (vi) "Discharge from perched aquifers", except that in this case discharge occurs from a permanent, usually larger, saturated zone rather than a seasonal, relatively small saturated zone. The occurrence of this model of groundwater discharge across the continent is summarised in Table 10.

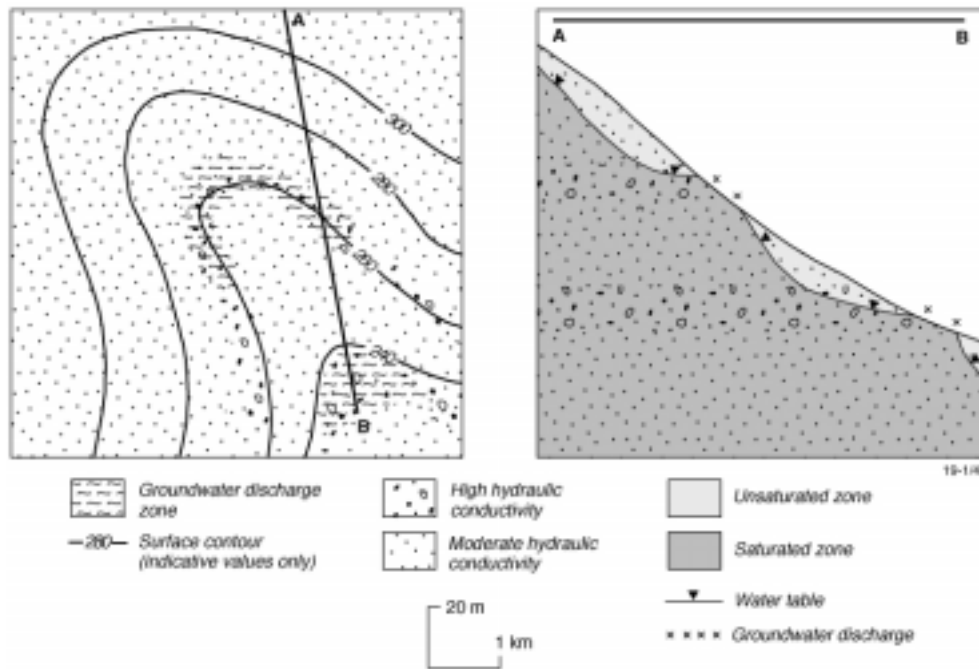


Figure 5: Diagrammatic representation of Local model (v), in (a) plan view and (b) cross section

State	Distribution
WA	This model occurs where local groundwater systems (sometimes in conjunction with perched systems) discharge from sedimentary beds. It is common in systems which contain the Tertiary Pallinup, Werrilup and related formations which sit unconformably on weathered Archaean or Proterozoic basement of the south west and south coast. Type example: East Boyup Brook catchment, south west region In the North Perth Basin, discharge also occurs according to this model from local and perched systems as the result of changes in stratigraphy near faults. Discharge occurs as hillside seeps or downgradient of the fault where the surficial aquifer fills and discharges by evaporation or seepage. Type example: Dandaragan, Caren-Caren Brook catchment
Vic	Groundwater discharge occurs according to this model in areas of Tertiary and Quaternary basalt flows, and at the interface of scoria cones and basalt flows.
NSW	There are numerous local examples of this model across all areas where dryland salinisation occurs. In particular, this model occurs in Cretaceous sediments around Dubbo, and in Triassic sediments west of Gunnedah.
QLD	This model of groundwater discharge is the most common form of salinisation in QLD, and potentially occurs over the whole range of climatic zones in the state where Tertiary and Quaternary basalts overlying fine sediments. Lateritic and ironstone cappings are variations of this form. Discharge occurs from both recent and well-weathered basalts, and basalt gravels in old valley infill areas. Underlying, lower hydraulic conductivity sandstones and mudstones inhibit continued downward water movement. Layering within the basalt and bole (post weathered) layers also provide regions of variable permeabilities which can restrict groundwater flow. Type examples: Eastern Darling Downs; Central Queensland; Kingaroy area; Rockhampton area

Table 10: Occurrence of Local model (v) in each state

4.6 Local model (vi) - Discharge from perched aquifers

In this catchment model, groundwater discharge occurs from perched aquifers with thinning or termination of hydraulically conductive layers that overly less hydraulically conductive layers (Figure 6). This model is characteristic of unconfined groundwater systems in unconsolidated sediments, although may also occur from other perched aquifer systems. The model is often associated with boundaries within the weathered zone, such as clay layers in lateritic profiles. The model differs from Local model (v) "Discharge controlled by stratigraphy" because of its perched nature above an unsaturated zone. The occurrence of this model of groundwater discharge across the continent is summarised in Table 11.

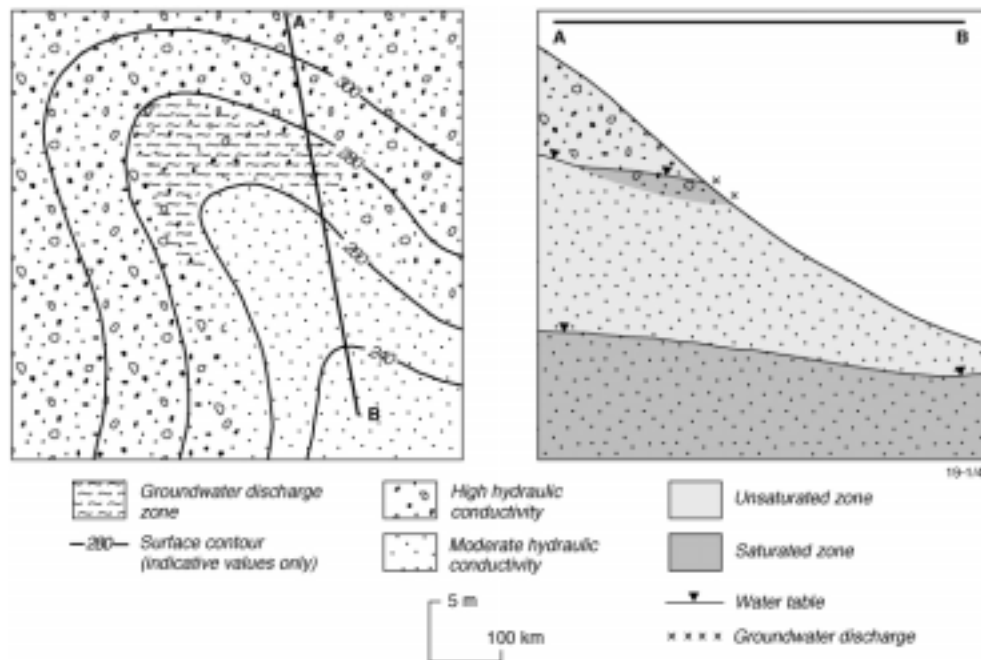


Figure 6: Diagrammatic representation of Local model (vi), in (a) plan view and (b) cross section

State	Distribution
WA	In WA, this model is widely applicable to unconfined Tertiary or younger sands in the eastern and northern agricultural regions. Groundwater discharge according to this model is characteristic of the eastern wheatbelt sandplains, although it also occurs in other areas where sands or lateritic gravels overlie saprolite and/or clay-rich regolith as the aquifer thins. Seeps are typically small (<5 hectares) and relatively fresh (~5,000 mg/L). Type example: East Belka catchment, Bruce Rock, eastern wheatbelt
SA	This type of salinisation potentially occurs statewide where perched or unconfined Tertiary aquifers discharge at the base of sandhills. Type example: Agery-Weetulta and Minlaton catchments, Yorke Peninsula
Vic	Salinisation according to this model is widely applicable to the dune fields of the Mallee, where young aeolian sands overlie the less hydraulically conductive Parilla Sands. It also occurs in Permian age fluvioglacial sediments where relatively permeable, weathered sediments overlie low hydraulic conductivity, unweathered sediments at shallow depths. The scale of these processes range from local to intermediate. Type example: Mallee dunes

Table 11: Occurrence of Local model (vi) in each state

4.7 Local model (vii) - Discharge controlled by linear features of contrasting hydraulic conductivity

In this model, groundwater discharge occurs where lateral groundwater flow is impeded by reduced hydraulic conductivities perpendicular to the main direction of flow (Figure 7). The hydraulic conductivity reduction may be due to the presence of lineaments, dykes, or materials of contrasting

hydraulic conductivity which are juxtaposed as the result of faulting or intrusion. Groundwater discharge may also be associated with increased recharge to the aquifer system as the result of a zone of enhanced hydraulic conductivity along the contact between the linear feature and the aquifer. In all of these cases, however, the controlling factor in this form of groundwater discharge is the contrast in hydraulic conductivities across the linear feature. The occurrence of this model of groundwater discharge across the continent is summarised in Table 12.

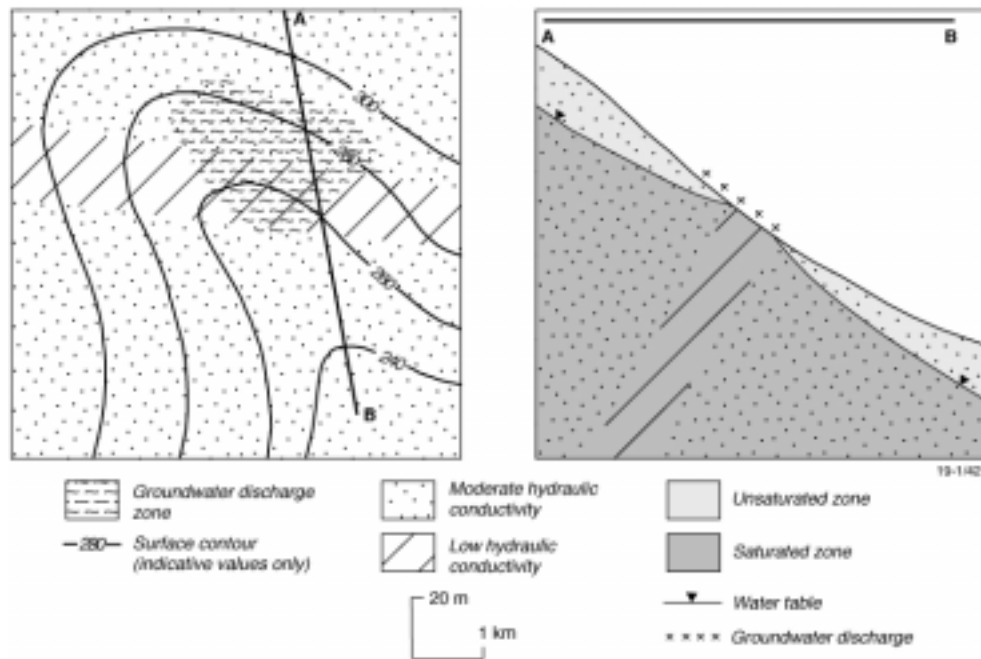


Figure 7: Diagrammatic representation of Local model (vii), in (a) plan view and (b) cross section

State	Distribution
WA	In WA, linear structures such as mafic dykes can act as both carriers and barriers to groundwater flow, depending on their mode of emplacement and their weathering history. Groundwater discharge occurs according to this model from basement Archaean igneous rock and lower saprolite as the result of linear structures such as quartz and mafic dykes and shear zones which act as carriers parallel to the main direction of flow. This form of salinisation is widespread throughout south-west WA, and is common in the south-west of the Yilgarn Craton. Type example: Denmark catchment, south coast; Westdale catchment, central wheatbelt Groundwater discharge also occurs from both saprolite and basement systems within the Yilgarn and Northampton blocks where there are igneous dykes that act as vertical barriers to groundwater flow. Other intrusive bodies such as quartz dykes and shear zones may also act as barriers to groundwater flow. Groundwater systems may be cellular or interconnected, and seeps are generally >10 hectares and have a salinity of >10,000 mg/L. Type example: West Narrogin catchment, Williams River
SA	Possibly in compartmentalised flow systems of the eastern Mt Lofty Ranges (not well documented)
NSW	At the Big Flat catchment, discharge from the Wittingham Coal Measures occurs at a fault where the groundwater system flows into the lower hydraulic conductivity Wollombi Coal Measures. However, in this salinisation type, the specific aquifer is less important in this catchment model than the contrast between the aquifers on either side of the fault. Type example: Big Flat Creek catchment, Hunter Valley
QLD	This form of groundwater discharge is widespread throughout the climatic range where less fractured or weathered dykes occur across the direction of slope. Where groundwater movement downslope is interrupted by these structures, incipient or permanent salting areas develop. Type examples: Burdekin area, north QLD Central QLD

Table 12: Occurrence of Local model (vii) in each state

4.8 Local model (viii) - Discharge from low hydraulic conductivity aquifers

In this model, groundwater discharge occurs from low hydraulic conductivity sediments or saprolite at local topographic lows where the surface topography falls below the unconfined water table (Figure 8). The controlling factor in this form of groundwater discharge is the difference in the rate of recharge compared with the hydraulic conductivity of the transporting medium, and the shape of the landscape. This form of salinisation tends to occur where an undulating ground surface intersects a relatively shallow water table. The occurrence of this model of groundwater discharge across the continent is summarised in Table 13.

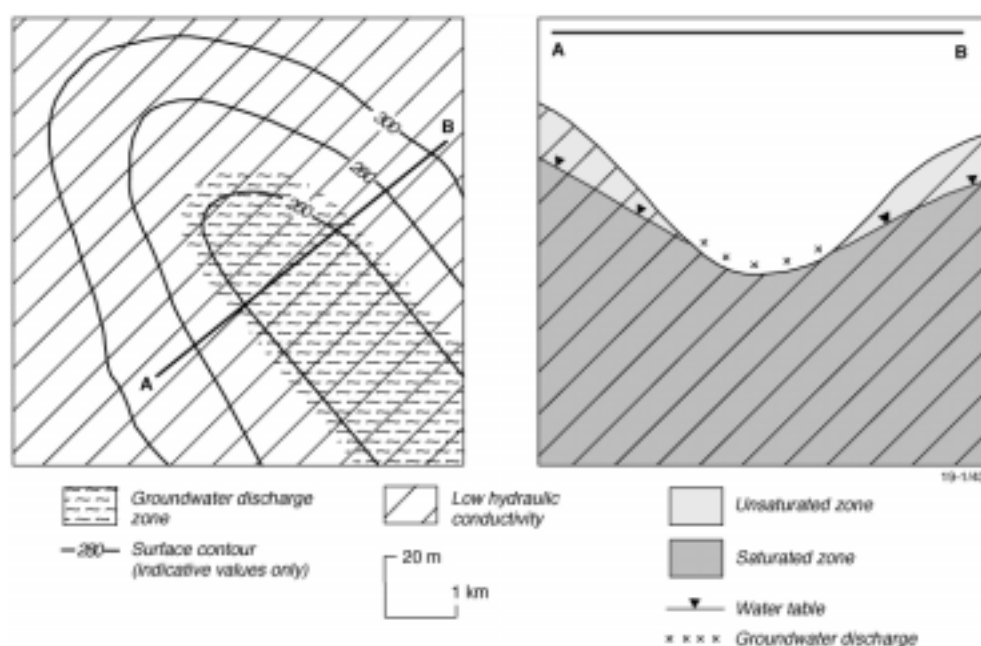


Figure 8: Diagrammatic representation of Local model (viii), in (a) plan view and (b) cross section

State	Distribution
WA	Throughout the SW of Western Australia, small playas and other lakes, swamps and depressions typically overly materials of low hydraulic conductivity (saprolite and sediments) containing saline groundwaters (5,000 - 250,000 mg/L). Upwards heads may be strong in underlying, high hydraulic conductivity aquifers. Many topographic lows are already active discharge areas (salt lakes or circular saltland systems), while others currently lie above rising watertables but are prone to become groundwater discharge areas as groundwaters approach equilibrium. Type examples: Mills Lake Catchment, South Coast, Morilla Swamp, Northern Wheatbelt
Vic	In Victoria, groundwater discharge according to this model is associated with low hydraulic conductivity marine sediments (mainly silty clay) in high rainfall areas. Groundwater salinities range between 2,000 to 10,000 mg/l. Groundwater discharge generally occurs through capillary discharge, and can be very seasonal. Type examples: Heytesbury, Barwon Downs

Table 13: Occurrence of Local model (viii) in each state

4.9 Intermediate model (i) - Capillary discharge from unconfined aquifers in valley floors

In this model, groundwater discharge occurs from intermediate flow systems in low-lying areas as the result of gradual reductions in aquifer transmissivity (Figure 9). This model is characteristic of groundwater flow in broad open valleys, and is primarily driven by a reduction in aquifer cross-sectional area as flow from flanking, higher relief areas converges in, and turns parallel to, the valley floors. This flow can be further influenced by reductions in hydraulic conductivity within the valley floor environment. Generally the zone of groundwater discharge coincides with the zone of flow convergence. Subsurface features (such as lenses of lower hydraulic conductivity sediments, or layers of lower hydraulic conductivity resulting from a subsurface unconformity) may also influence the actual site of the discharge zone. The occurrence of this model of groundwater discharge across the continent is summarised in Table 14.

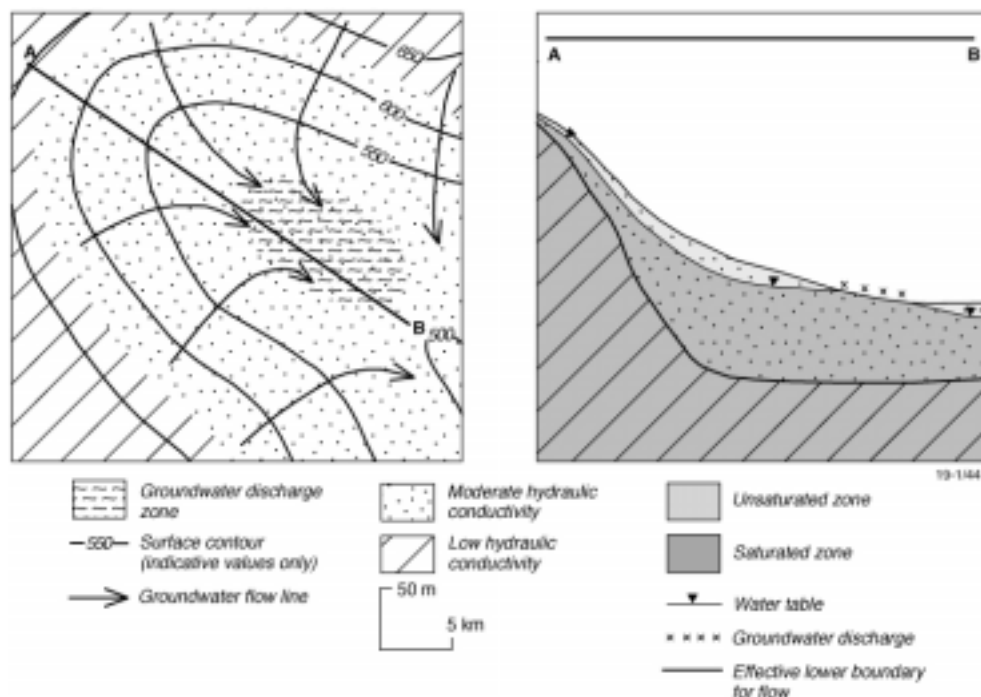


Figure 9: Diagrammatic representation of Intermediate model (i), in (a) plan view and (b) cross section

State	Distribution
WA	Widespread throughout WA on all geological systems, discharge according to this model occurs by evaporation (rather than direct discharge) at valley sites where gradients are low, evaporation rates high and drainage is poor. This type of groundwater discharge causes large areas of salinisation (100s to 1000s of hectares in extent), with very saline to brackish waters (typically >35,000 mg/L). Type examples: Belka valley Yilgarn Salt River catchment Swan Avon system
SA	This form of groundwater discharge occurs at broad flats are underlain by sedimentary aquifers with lenses of low hydraulic conductivity sediments. Type examples: Upper South East MacGilvray Plains on Kangaroo Island Jamestown flats in Mid North Agery-Weetulta catchment on Yorke Peninsula Driver River catchment, Upper Eyre Peninsula
Vic	Type examples: Ovens Valley

NSW	Geologically/geographically restricted to Permian - Recent sediments, groundwater discharge in this category occurs where groundwater in a high hydraulically conductive sandstone aquifer is discharged at an angular unconformity where it flows into less hydraulically conductive alluvium. Local groundwater processes are overprinted on this larger scale process, with discharge occurring where locally recharged water cannot percolate into a system undergoing groundwater discharge from intermediate flow systems. Type examples: Yarraman Creek, Lake Goran catchment (north eastern NSW)
QLD	Two types of this form commonly occur in Queensland. In the first type rock bars or resistant sediments restrict water flow in flat valley floors or where existing aquifers thin out. The catchment throat is often narrowed in width and/or depth. Discharge areas develop in the region upslope of the restriction. The second type is a similar form where there is no geological restriction to groundwater flow but where the hydraulic gradient reduces to a very low level. This is less of a problem in wide valleys where water can spread out over a wide area, thus minimizing water level rises. This form is evident in Queensland where large salt loads have accumulated in the unsaturated zone at the interface between shallow water tables and tree roots. Remobilisation of this salt causes the observed salinisation. In these valleys salinity gradients increase with distance from the head of the valley. Type examples: Lockyer Valley, south east QLD In several locations the construction of roadways has led to a reduction in aquifer transmissivity in valley floors and resulting development of salinity. Type examples: Eastern Darling Downs, south QLD Cattle Creek catchment, north QLD

Table 14: Occurrence of Intermediate model (i) in each state

4.10 Intermediate model (ii) - Discharge from semi-confined aquifers controlled by facies changes and changes in aquifer geometry

In this model, groundwater discharge occurs from intermediate confined or semi-confined aquifer systems as the result of gradual reductions in hydraulic gradient down the flow line, as the hydraulic conductivity of the intermediate aquifer is reduced (Figure 10). Discharge usually coincides with low points in the topography. Groundwater flow according to this model is characteristic of confined palaeodrainage line aquifers which either thin with distance from source material or which are diminished/terminated as the result of bedrock structures. The occurrence of this model of groundwater discharge across the continent is summarised in Table 15.

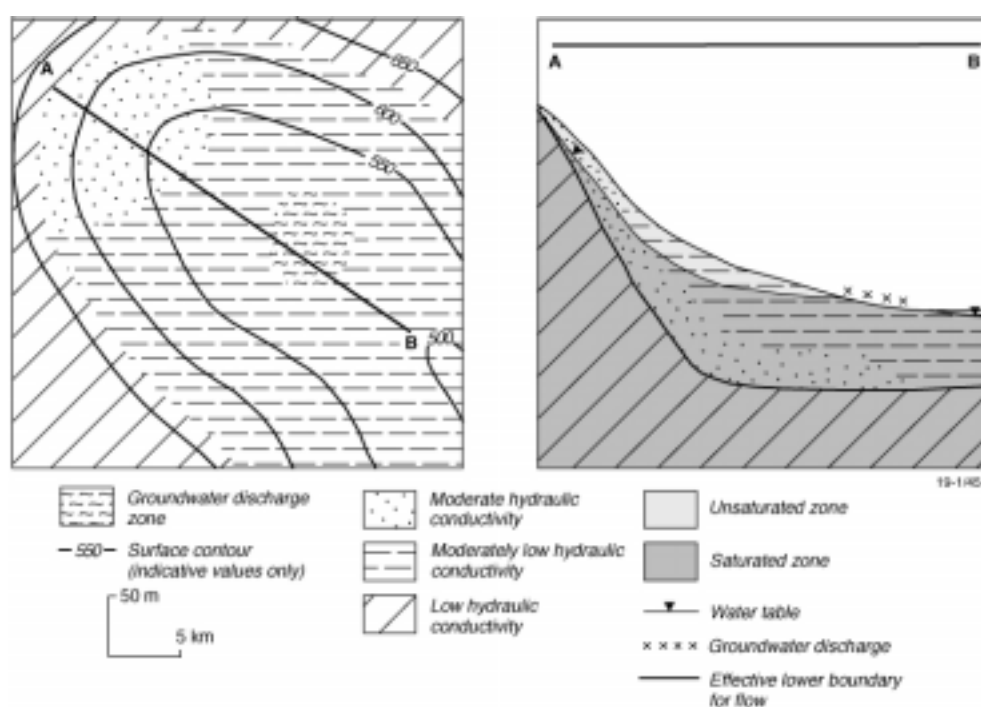


Figure 10: Diagrammatic representation of Intermediate model (ii), in (a) plan view and (b) cross section

	Distribution
WA	This model has widespread occurrence along the zone between the poorly defined and well defined drainage systems (Meckering line), and is associated with strong vertical flows in some areas. Groundwater discharges from sedimentary aquifers with changes in the shape of palaeo-drainage channels, and may be localised or extensive depending on the local seepage mechanism. Type example: Towerrinning-Darlingup subcatchments, Blackwood catchment
NSW	In the Lake Goran and Pine Ridge catchments, there is little surface outflow from the catchment and water transport largely occurs through high hydraulic conductivity gravel and sand aquifers of the Narrabri aquifer. Physical geological constrictions from bedrock outcropping at the mouths of these catchments impede the flow of groundwater and areas of salinisation occur upgradient of these constrictions. Type examples: Pine Ridge catchment, north eastern NSW

Table 15: Occurrence of Intermediate model (ii) in each state

4.11 Intermediate model (iii) - Discharge from unweathered fractured rock aquifers at break of slope

In this groundwater model, groundwater discharge occurs from unweathered fractured rock aquifers where hydraulic gradient is reduced in association with reductions in surface gradient (Figure 11). This model is very similar to Local model (ii) Discharge from unweathered aquifers at break of slope, except that in this case the process occurs over a scale of 10-20 kilometers and down a relief of 20-30 metres. The occurrence of this model of groundwater discharge across the continent is summarised in Table 16.

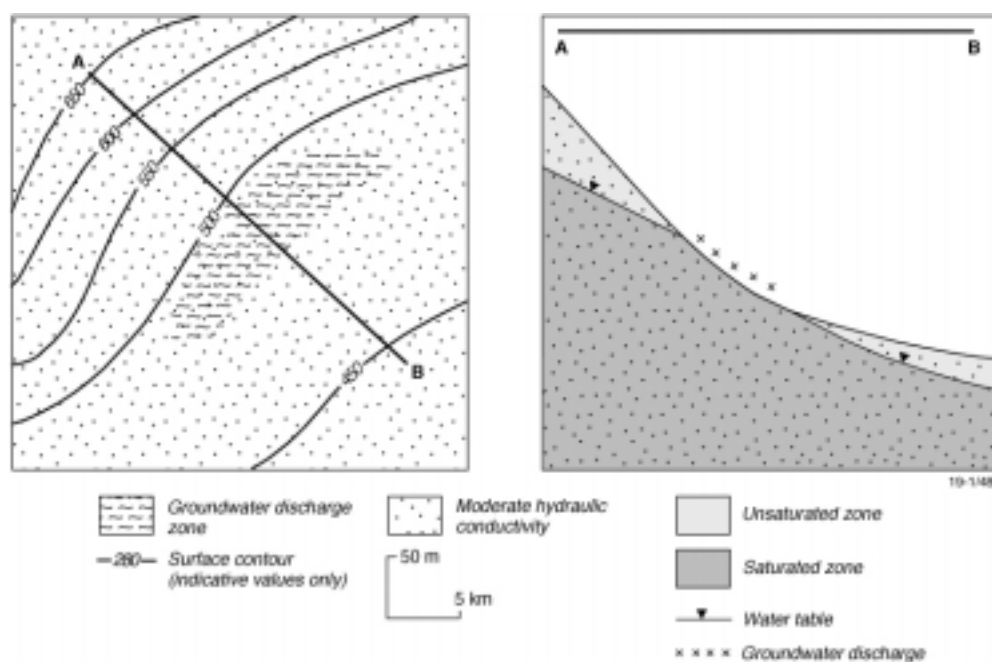


Figure 11: Diagrammatic representation of Intermediate model (iii), in (a) plan view and (b) cross section

State	Distribution
Vic	In Victoria, this model occurs in fractured Ordovician sediments and metasediments. Although it causes considerable land salinisation, the most significant issue associated with this form of dryland salinity is the export of saline water in streams (TDS~3,000-10,000 mg/L) to downstream irrigators. Type Example: Axe Creek catchment

Table 16: Occurrence of Intermediate model (iii) in each state

4.12 Intermediate model (iv) - Discharge across topographic divides controlled by large, transmissive, linear structures

In this model, groundwater discharge occurs from fractured rock aquifers where a linear zone of higher hydraulic conductivity cuts across a number of topographic catchments and where the base of this zone is deep enough to permit groundwater flow between topographic catchments (Figure 12). The key difference between this intermediate system and a local flow system in a similar setting is the greater elevation difference between the local topographic lows within catchments, and the base of the high hydraulic conductivity structure between the catchments. In this system, the difference is great enough for groundwater flow to occur between topographic catchments. This model is characteristic of intermediate groundwater flow systems in faulted aquifers, in low relief terrain. The occurrence of this model of groundwater discharge across the continent is summarised in Table 17.

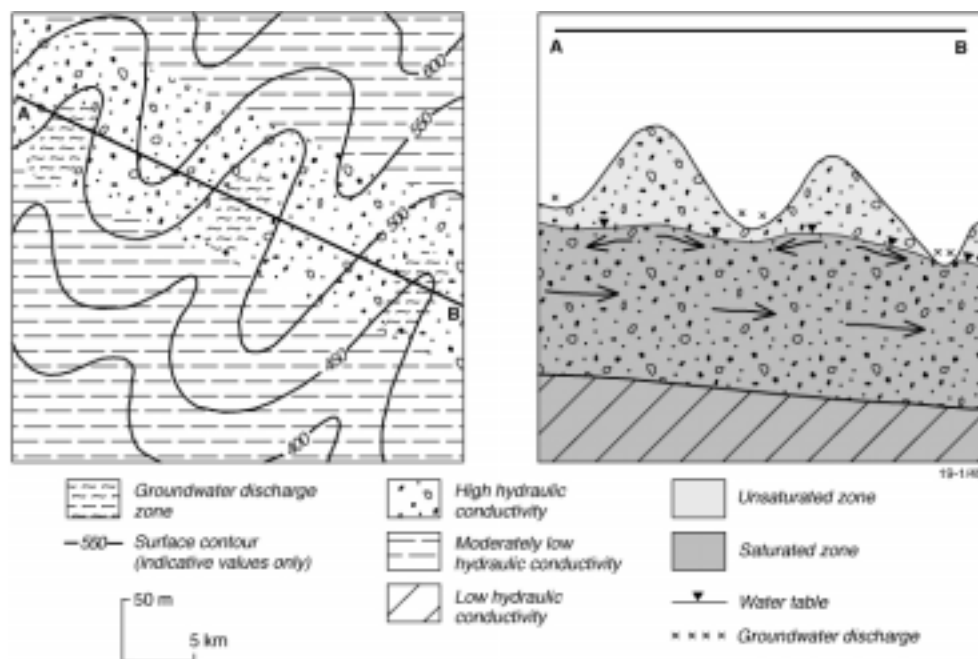


Figure 12: Diagrammatic representation of Intermediate model (iv), in (a) plan view and (b) cross section

State	Distribution
WA	In Western Australia, this model applies where groundwater flow occurs between topographic catchments in fractured rock and regolith systems. Highly saline (20,000 mg/L) groundwater discharge occurs at large faults via springs in hilly terrain and via seepage/evaporation in lower energy systems. Type example: Date Creek subcatchment, Blackwood catchment system
Vic	This form of salinisation occurs in unweathered, high hydraulic conductivity Palaeozoic catchments in association with major fault zones. Type example: Axe Creek catchment (associated with the Whitelaw Fault)

Table 17: Occurrence of Intermediate model (iv) in each state

4.13 Regional model (i) - Regional confined and semi-confined aquifer discharge controlled by structure

In this model, groundwater discharge occurs from regional confined and semi-confined aquifer systems as the result of relatively abrupt changes in hydraulic gradient, usually at low points in the topography where the hydraulic conductivity of the regional aquifer has been reduced through structural changes in the stratigraphy such as faulting and folding (Figure 13). This form of groundwater discharge is characteristic of deep sedimentary basins, where aquifer transmissivities are reduced as the result of faulting, folding or the presence of angular unconformities. The occurrence of this model of groundwater discharge across the continent is summarised in Table 18.

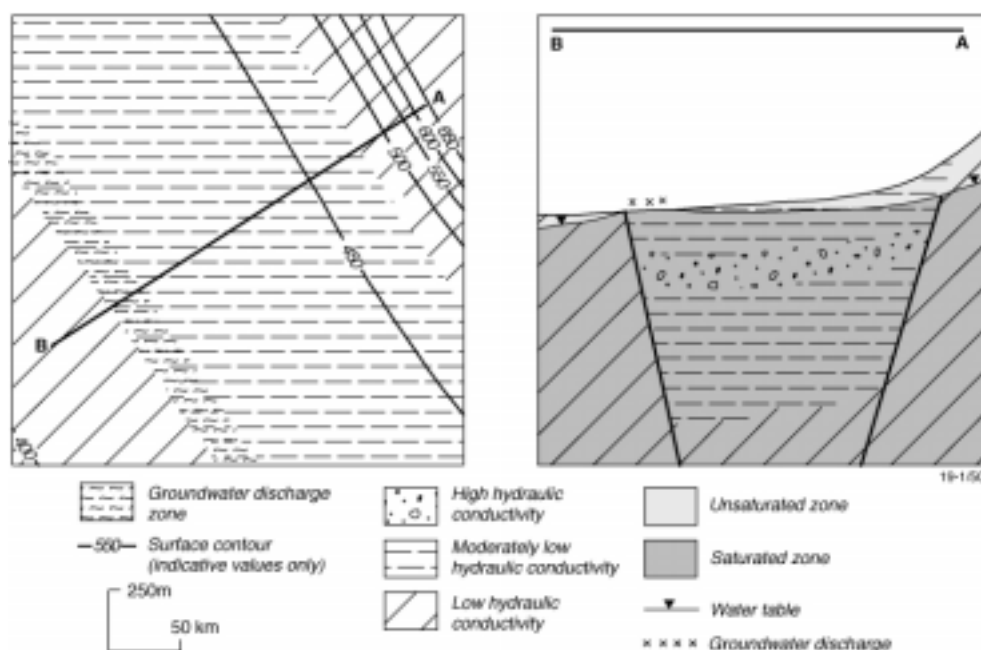


Figure 13: Diagrammatic representation of Regional model (i), in (a) plan view and (b) cross section

State	Distribution
WA	Widespread throughout western areas (Perth Basin) and some southern areas (North Stirling Basin), this model is applicable to large aquifer systems in deep sedimentary basins, where discharge occurs either by direct seepage (springs) or evaporation from shallow water tables. Faults may also influence the area of discharge. The area and extent of salinisation is dependent on the region. Type example: Waterloo to Vasse, southern Perth Basin, where discharge occurs from the deeper aquifer into surficial aquifers and on to the soil surface

Table 18: Occurrence of Regional model (i) in each state

4.14 Regional model (ii) - Regional confined and semi-confined aquifer discharge controlled by facies change

In this model, groundwater discharge occurs from regional confined or semi-confined aquifer systems as the result of gradual reductions in hydraulic gradient down the flow line, as the hydraulic conductivity of the regional aquifer is reduced (Figure 14). Discharge usually coincides with low points in the topography. This form of groundwater discharge is characteristic of extensive, unconsolidated sedimentary basins. In these settings, gradual changes in transmissivity eventually result in regional discharge systems that include shallow lake systems. The occurrence of this model of groundwater discharge across the continent is summarised in Table 19.

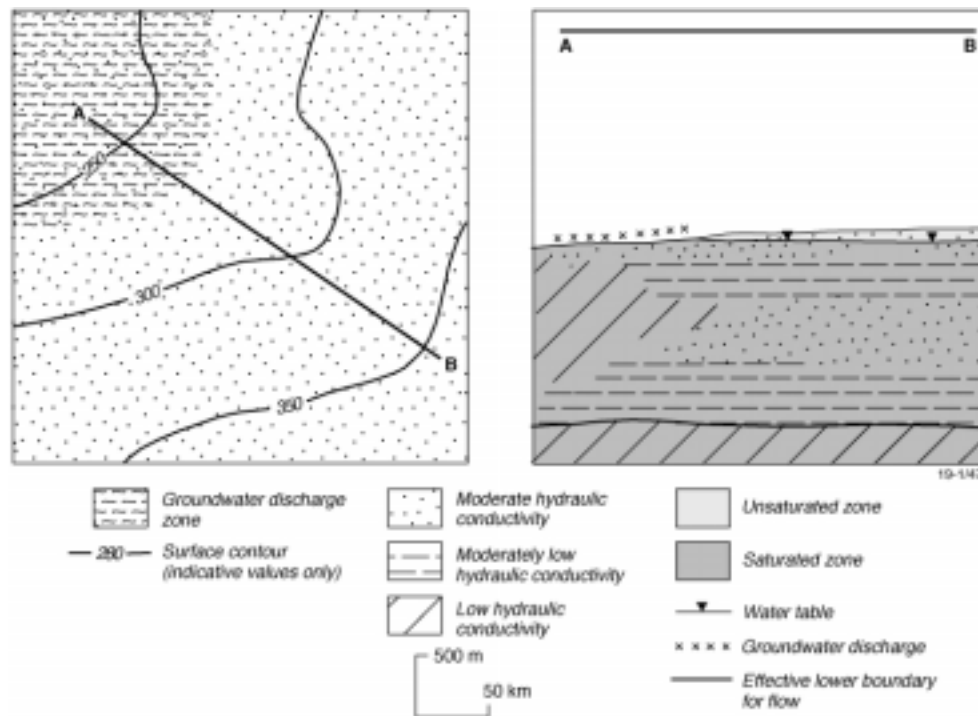


Figure 14: Diagrammatic representation of Regional model (ii), in (a) plan view and (b) cross section

State	Distribution
Vic	Groundwater discharge occurs according to this model in the eastern Riverine Plains and the eastern margins of the Murray Darling Basin where the hydraulic conductivity of the regional confined alluvial ("deep lead") aquifer system is gradually reduced as it becomes distal from its sediment source. Discharge can also occur with changes in aquifer thickness due to bedrock highs. Type example: Loddon catchment Campaspe catchment
NSW	Groundwater discharge occurs according to this model in the western margins of the Riverine Plains and the Murray Darling Basin, from regional confined alluvial ("deep lead") systems similar to those in Victoria. Type example: Western Riverine Plain, Murray Basin

Table 19: Occurrence of Regional model (ii) in each state

4.15 Regional model (iii) - Regional unconfined to semi-confined aquifer discharge controlled by topography

In this model, groundwater discharge occurs from regional unconfined and semi-confined aquifer systems at low points in the topography where the surface topography falls below the unconfined water table (Figure 15). This form of groundwater discharge is characteristic of regional groundwater systems where an undulating ground surface intersects a relatively shallow water table. The occurrence of this model of groundwater discharge across the continent is summarised in Table 20.

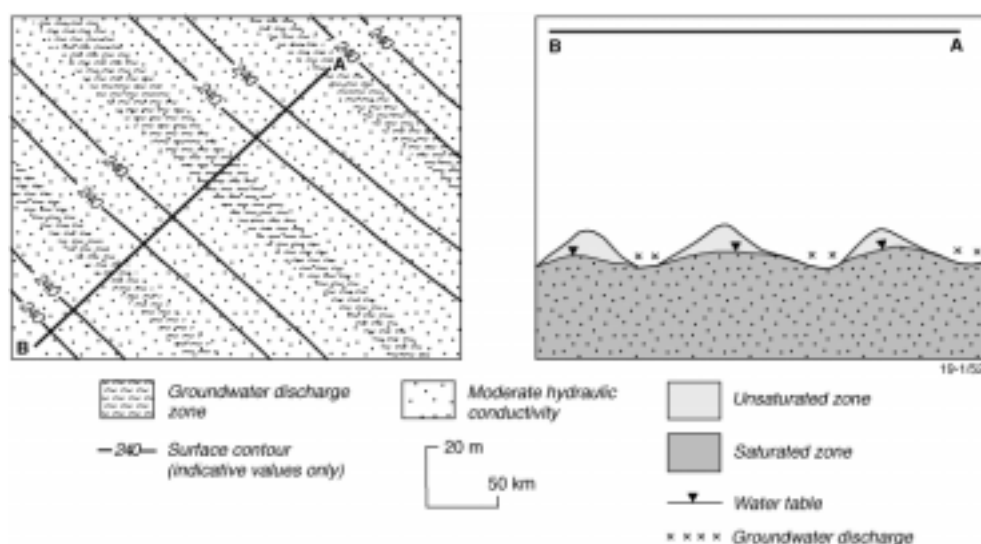


Figure 15: Diagrammatic representation of Regional model (iii), in (a) plan view and (b) cross section

State	Distribution
SA	Groundwater discharge occurs according to this model from Quaternary and Murray Group limestones in the South-western Murray Basin. Type example: Cooke Plains
Vic	This model is characteristic of groundwater discharge in the Mallee area, where semi-confined, high TDS content (~30,000-50,000 mg/l) groundwater in the fine-grained Parilla Sand is discharged in troughs between surficial sand dunes. Type example: Lake Tyrrell east Manangatang Groundwater discharge also occurs according to this model in Western Basalt Plains in conjunction with the change from the regional unconfined basalt aquifer to much lower hydraulic conductivity lacustrine sediments. Type example: Lough Calvert area

Table 20: Occurrence of Regional model (iii) in each state

5 Application of the catchment models

5.1 Spatial analysis approach

Identifying the models presented above is the first step in developing a national framework for determining catchment hydrogeological characteristics and identifying the most appropriate management options. The next step would involve assessing the hydrogeological characteristics of all catchments across the continent. This would require a process of applying analysis decision rules to a set of spatial datasets considered to be critical for defining the catchment models (a "minimum dataset").

In many cases, the assignment of hydrogeological models to individual catchments would be a complex process and would involve iterative assessment of the regional, intermediate and local flow processes operating. For example, in a regional flow system, the general region of groundwater discharge may need to be identified by applying the appropriate regional hydrogeological model; however, the specific location of groundwater discharge is likely to be defined by the superposition of the appropriate intermediate model upon this region, followed by the appropriate local hydrogeological model upon this area. Other factors such as the local topography may also need to be taken into account when determining discharge areas. For example, discharge may occur downgradient of a topographic high in response to subsurface structural features which coincide with the topographic high, depending on the degree of transmissivity contrast about the structural features.

5.2 Minimum data sets needed to characterise groundwater systems

This report has presented an overview of salinisation in terms of the hydrogeological processes that control groundwater flow through catchments. As discussed in section 2.1, however, other factors such as land use, climate, and landform influence whether, and where, salinisation occurs. It is proposed that two types of critical datasets are required to characterise the processes responsible for salinisation.

The first, "constants", determine the inherent susceptibility of the catchment to salinisation should particular conditions occur. These are:

- topography (position in the catchment),
- catchment physiography/shape,
- aquifer properties,
- structural geology,
- geomorphology,
- drainage or surface flow characteristics
- regolith (thickness, type),
- soil attributes.

The second dataset type, "variables", can be used in conjunction with the datasets above to determine whether salinisation is actually likely to occur in catchments with the appropriate inherent conditions for salinisation. These include:

- climate (precipitation, evaporation),
- land use,
- rates of groundwater rise,
- depth to water table,
- recharge rate,
- stream salt loads,
- condition of vegetation.

Groundwater salinity, soil salt store and native vegetation reflect factors that determine whether salinisation is likely to occur, and should also be included in this group.

These datasets form the basis of a hierarchical catchment classification system. The "constants" are the primary tools to determine whether a catchment has the potential to develop salinisation at some point given the appropriate conditions. The "variables" are secondary tools which quantify these conditions to determine whether, and when, groundwater rise and salt mobilisation are likely to result in significant land or water salinisation. Some of these "variables" are the factors we may be able to manipulate to manage land and water salinisation.

6. Recommendations for future work

The conceptual models of catchments proposed in this report are the first stage in what should be an iterative process to classify and understand the behaviour of catchments across Australia. A number of recommendations must therefore accompany this work:

- (i) Recognised local authorities and groups with experience in catchment characterisation and salinity remediation should review the salinisation models identified in this report. This will ensure both accuracy and ownership of the classification system.
- (ii) The salinisation models identified in this project should be used to classify catchments across Australia. This system should be based upon readily available or collectable minimum datasets identified in this project. This will enable a systematic overview to be made of the extent, type and severity of salinisation problems across the country, and should enable local results from intensively studied catchments to be extended to similar, unstudied catchments.
- (iii) The hydrogeological characteristics and groundwater trends of 'type' catchments of each salinisation type should be quantified, using existing data and the results of previous studies wherever possible.
- (iv) Water balance models (both conceptual and numerical) should be developed for each salinisation type using existing, data rich catchments as case studies wherever possible. These models should permit quantification of the salinisation risks, rates of hydrologic change and optimum management options for each salinisation type.
- (v) The models developed for each salinisation type should be used to assess the impacts (extent and timing) of land use changes on salt and water balances in each salinisation type (for example, the effectiveness of Break-of-Slope tree planting; the relative desirability of plantations in upslope, midslope and lower slope positions, or in proximity to significant geological structures which control the hydrology of the catchment).
- (vi) Funding for research and management works should be targeted towards salinisation processes with the highest risk of occurrence and the greatest chance of successful remediation according to the numerical models and past experiences across the continent.
- (vii) The results from the modelling should be translated into a user-friendly rule-based analysis for on-ground managers to identify their particular groundwater system and the optimum management solutions for related salinisation types.

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Glossary

alluvial	deposited by a river
angular unconformity	lower, older beds dip at a different angle to younger, overlying beds
aquifer	water bearing rock unit
Archaean	older than 2,500 million years
artesian	groundwater held under pressure in an aquifer
basalt	a fine-grained, volcanic rock
basement	unweathered igneous or metamorphic rock covered with unconsolidated sedimentary material
bedrock	unweathered, consolidated rock beneath the regolith zone
biophysical	relating to biological and physical processes
break of slope	the point on a slope at which topographic gradient is reduced
capillary discharge	discharge occurring as the result of the suction between water and solids in the unsaturated zone
colluvial	transported by gravity
confined flow	groundwater flow that is restricted by overlying rocks and is consequently under pressure
crystalline rock	igneous or metamorphic rock
deep lead	buried sediments from an ancient river system
discharge	flow of groundwater from the saturated zone to the earth surface
downgradient	further down along a gradient
dryland	cleared or naturally treeless, non-irrigation, non-urban land
dyke	a linear body of igneous rock that cuts across other rock structures
faulting	a rock fracture along which observable displacement has occurred
geomorphology	the study of land forms
granitic rocks	coarse-grained, igneous rocks
hydraulic conductivity	the rate at which water is transmitted
hydraulic gradient	the change in ground water level elevation over the distance at which the change occurs
hydrochemical	relating to the chemistry of water
hydrogeological	relating to groundwater
hydrological	relating to surface water
igneous	rocks that formed through crystallisation of magma
impermeable	relatively impervious to the passage of water
infiltration	the unsaturated movement of water through the soil and regolith
lacustrine	derived from a lake
laterite	hard material made of iron oxides
mafic	consisting predominantly of iron and magnesium rich minerals
metasediments	metamorphosed sediments
numerical model	computer model based on mathematics
orogen	a period of geological deformation
palaeodrainage	drainage lines that existed in the geological past
Palaeozoic	545 - 230 million years ago
perched aquifer	a hydraulically conductive rock with saturated groundwater flow that is underlain by an unsaturated zone
perennial pastures	pastures that grow all the year round
permeable	able to transport water
primary salinity	saline groundwater discharge that existed prior to European land use changes
Proterozoic	2,500 - 545 million years ago
recharge	infiltration of water from the earth surface to the saturated zone
regolith	weathered rock
salt mobilisation	transport of salt stored in the unsaturated zone by rising groundwaters
salinisation	the process by which saline groundwater is discharged into streams and at the earth's surface
saprolite	weathered material with the same volume as the original rock material

secondary salinity	discharge of saline groundwater that has occurred as the result of European land use changes
sediments	derived from erosion of pre-existing rocks
seeps	areas where there is continuous discharge of groundwater
semi-confined	transient between confined (under pressure) and unconfined (under atmospheric pressure only)
skeletal soil	thin, poorly developed soil
stratigraphy	stratified rocks, particularly sedimentary and volcanic rocks
surface scalds	areas where continuous discharge of saline groundwater has resulting in denudation of the soil
Tertiary	65 million years ago to the present
topographic gradient	steepness of the ground surface
transmissivity	ability to transmit water, reflecting both the hydraulic conductivity and the area of the rock
unconfined flow	groundwater flow that is not restricted by overlying rocks and which is consequently at atmospheric pressure
unconformity	a plane that separates older rocks below from younger rocks above, and represents a break in deposition
unconsolidated	loosely compacted; uncemented
unsaturated zone	the zone above the water table that is not saturated in water
water table	the upper surface of the saturated zone
weathering	the process by which rocks are decomposed

APPENDIX 1