Dryland Salinity Risk Assessment in Queensland

Report prepared for the Consortium for Integrated Resource Management

by Adrian Webb

February 2002

CIRM

Queensland Government
Natural Resources and Mines
Department of Primary Industries
Environmental Protection Agency

The University of Queensland

Griffith University

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BACKGROUND – WHO AND WHAT IS CIRM?

The Consortium for Integrated Resource Management (CIRM) operates as a formal linkage mechanism through a network of key officers from its six partner organisations – three Queensland government departments (Natural Resources and Mines, Primary Industries, and the Environmental Protection Agency), two universities (University of Queensland and Griffith University) and CSIRO. It was formed in 1993 and has evolved as a mechanism for facilitating the planning and coordination of collaborative research initiatives. It has links to the community through its partners and through an association with the Landcare and Catchment Management Council. The CIRM Board acts as a reference group for CIRM's activities, and is composed of the CEOs of each of the partner organisations.

The benefits of implementing such a process include:

- facilitating the coordination and integration of natural resource management research among partner organisations and providing an efficient means of assisting project innovators to move new collaborative proposals forward
- minimising the start-up or 'transaction' costs of joint projects
- minimising the duplication of effort and resources
- access to established communication linkages
- developing and strengthening research partnerships, both with CIRM partners and beyond, including the community.

It is now universally acknowledged that resource management issues extend far beyond the scope of any single agency or organisation – that they are the responsibility of us all and they need to be dealt with in an integrated, holistic way. This means that CIRM's charter is even more relevant today than it was in its beginnings.

Because it is a *process* rather than an entity in its own right, CIRM does not undertake the activities of a centre or other formalised institutional structure. Nor should it be seen as in any way competing with, or usurping the role of, individual partners or their key staff. Rather, its aims are collaboration, brokerage, communication and a shared approach to common issues.

Examples of CIRM-facilitated activities include ARC-SPIRT (now ARC-Linkage) projects worth many millions of dollars, successful establishment of the Cooperative Research Centre for Coastal Zone, Estuary and Waterway Management, several major wastewater renewal and use programs, an international watershed project, and earlier workshopping of social issues associated with sustainable natural resource management.

More recently, CIRM has concentrated on the following four major priority areas for which it is preparing scoping papers:

- social and community dimensions of natural resource management
- management of aquatic ecosystems
- dryland salinity risk assessment
- water renewal.

This report on Dryland Salinity Risk Assessment in Queensland is the fourth position paper developed around those focus areas for the CIRM partners.

Preface

This paper has been prepared in response to a request by the Consortium for Integrated Resource Management (CIRM) for a paper on the current national status of dryland salinity risk assessment, with an emphasis on current approaches and their applicability to the Queensland situation. Specific questions posed included:

- What salinity risk assessment techniques are available?
- What techniques are most appropriate for the current available data and the types of landscape, land use and groundwater flow systems in Queensland?
- Could other more useful techniques be used with improved data, and what data would be needed?
- What emerging technology might be available in the next five years?
- Where are the capabilities to address the R&D/knowledge gaps?
- What are the key elements of an ongoing monitoring system for dryland salinity?

Experience gained from the recent dryland salinity program in the National Land and Water Resources Audit (NLWRA) and the National Dryland Salinity Program was used as the main input to this paper, which is not a review; rather it is an overview presenting an appreciation of the current status of dryland salinity risk assessment nationally, and some of its constraints and opportunities.

CIRM partners wish to use this paper to assist in making decisions on opportunities for R&D, and in planning for dryland salinity management responses in Queensland, particularly with reference to the Queensland component of the National Action Plan for Salinity and Water Quality (Commonwealth of Australia 2000).

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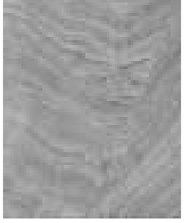

Executive Summary

Introduction

The recent national audit of dryland salinity (*Australian Dryland Salinity Assessment 2000*, NLWRA 2001), and other State plans have highlighted the need for an ongoing assessment of the risk of dryland salinity, and evaluation of the most appropriate management responses. In addition, they have brought into focus the inadequacy of the available biophysical and economic data for achieving this. Using broadscale data, several regions in Queensland have been assessed as being at high risk of developing dryland salinity; subsequently, planning efforts in the State have identified the need for a well-defined risk assessment approach and framework for evaluating land-use management options at the catchment to subcatchment scale.

While there is considerable knowledge about the processes involved in dryland salinity and the management options available, there is a need for knowledge at the subcatchment scale (property level). Also, because there have been a relatively small number of catchment scale land-use/hydrology studies throughout Australia, there have been limited opportunities to develop extrapolation skills. Consequently, confidence in assessment of land-use impacts is decreased as the intensity of examination is increased.

This paper provides a brief background on the causes of dryland salinity; a current assessment of salinity risk assessment methods; and a description of the characteristics of the Australian groundwater flow systems contributing to dryland salinity in Australia. In addition, it identifies an approach to salinity risk assessment and priority thrusts that are appropriate to the Queensland situation.

It is generally accepted that dryland salinity in Australia is the result of changes in the water balance brought about by replacement of the natural vegetation with agricultural systems that use much less water. The extra recharge to groundwater systems has resulted in increased discharge and salt movement to the land surface and to streams.

There is sound scientific evidence that all the factors contributing to salinity hazard exist over large areas of the semiarid zones of northern Australia. In landscapes prone to dryland salinity risk, the timeframes and the extent of degradation depend upon the interaction of four key factors:

- *Climate*—the amount of water input to the catchment surface through rainfall—timing and amount of rain in particular are critical.
- *Land use*—this determines the soil–water balance, particularly how much water is lost through evapotranspiration and hence the amount of water available in the root zone, which can infiltrate to the groundwater system.
- *Salt stores*—the amount of salt stored in the catchment and available for mobilisation.

- *Hydrogeology*—the structural and geomorphic features of the catchment that determine how much groundwater can be stored, how far it will flow, and what will cause it to discharge.

Of the four key factors, land use is the only one that can be managed feasibly.

It is well recognised now that dryland salinity is a groundwater management problem requiring understanding of scale and process issues. The management options selected need to account for the time taken for groundwater response.

In order to make decisions on how to manage dryland salinity appropriately, it is necessary to assess the effects of land use on the water balance and on groundwater. These are referred to as 'risk assessments' and are a crucial component of planning in any salinity management strategy.

Salinity risk assessment

While the presence of large salt stores in a landscape (inherent possibility of the area salinising) may be a component of salinity hazard assessment, this becomes a risk only when the water balance is altered (for example by clearing). This increases the probability that the salt store will be mobilised and reach the soil surface or enter streams or groundwater. Risk assessment methods aim at predicting the future spatial extent of dryland salinity.

A number of risk assessment approaches have involved calibration using 'training sets' of data, and most are aimed at predicting the spatial extent of salinity. The methods assign 'risk factors' to characteristics or attributes of processes, and attempt to combine these to assess overall risk. Some studies explicitly use a separate set of data to 'validate' the approach. (This data is usually from areas geographically close to the main area of interest.) The three broad groups of methods are:

- composite index methods—rely on user experience
- strongly inverse methods—based on statistical relationships
- trend-based methods—incorporate temporal change.

Composite index methods combine a number of salinity risk factors that are weighted depending on operators' experience and understanding of the process. Each data layer such as soil type, land cover, geology, and topography is ranked, weighted and summed using a linear additive model to produce a map of salinity risk. These methods rely on the expertise and knowledge of the user, and they generally apply in a region where the factors interact consistently. They are very useful as a first phase of compiling current knowledge and focusing priority activities. In Queensland this method was used to combine a number of landcsape attributes to represent the inherent characteristics of the landscape associated with dryland salinity hazard mapping.

Strongly inverse methods include current salinised areas as a spatial dataset. These methods statistically determine the relative weights of the risk factors based on the actual datasets available. Examples are the 'weights of evidence' approach used by Bradd et al. (1997), and the decision-tree approach of Tassell (1995). No consistent set of factors has been defined, and the choice is largely determined by the available data. The main difficulty with statistical approaches is their inability to predict salinity for processes not included in the risk factors. For example, salinity risk from rising groundwater in regional groundwater systems will not be predicted if all the risk factors used in the training set relate to topographic position, climate, and geology. Such approaches cannot predict the rate of change of salinity.

Trend-based methods, based on trends in land, streams and groundwater can be used to predict temporal changes in salinity. They are far more powerful for evaluating the impact of salinity on land management.

As available data prevent the use of trend-based methods in most of Queensland, it will be necessary to rely on composite index and catchment water balance modelling approaches using the best available data.

In case study catchments, analysis of the hydrogeological conditions and the modelled response of groundwater flow systems to land-use change have confirmed that the concepts of the Australian Groundwater Flow Systems can be applied more widely across Australia. The modelling approach has also indicated that different types of groundwater flow system respond differently to land-use changes, in terms of both the time taken for the change to take effect, and the degree of change necessary.

The salinity risk assessment framework proposed for Queensland is based on the approach used for the National Land and Water Resources Audit case studies, and is similar to that being implemented in New South Wales by the Department of Land and Water Conservation.

Gaps

Salinity management at catchment and regional scales requires:

- knowledge of, and data on, groundwater systems (types and attributes) including the alluvial zones of the major irrigation areas
- groundwater level and trend data including non-alluvial areas
- elevation, regolith and soils data across the State to support terrain analysis and assessment of salinity risk at the catchment scale—this is particularly important in the lower relief landscapes west of the Great Dividing Range
- a monitoring and evaluation framework to ensure that all data gathering has an objective basis and will allow land management responses to be evaluated over time.

Proposed thrusts

Given the current state of knowledge about dryland salinity and the risks posed by current and future land use in Queensland, the following thrusts are proposed to improve capacity to assess the risk of dryland salinity and to evaluate management responses.

1. **Collation and capture of biophysical data to underpin analyses of risk assessment**

   Groundwater: The greatest priority should be given to obtaining more information about the groundwater systems and their behaviour in the cropping and grazing regions of the State, particularly those that have been extensively cleared in the last 40 years.

   Salinity surveys: All data from previous salinity surveys and studies carried out by the Department of Primary Industries (DPI) and the Department of Natural Resources and Mines (NR&M) should be captured digitally, together with any associated data on shallow groundwater.

   Geological structures: There is very good appreciation nationally about the role played by geological structures in controlling groundwater movement, particularly discharge. There would seem to be considerable merit in carrying out some analyses of the airborne magnetics data and the airphoto/Landsat data in the key catchments nominated for the National Action Plan for Salinity and Water Quality, to capture information on landscape structures.

   Soils and regolith characteristics: The current data available for much of the State is at less than 1:500 000 scale, but it is acknowledged that for catchment scale management and assessment, data at 1:250 000 scale or greater is required, particularly in areas where there is more intensive agriculture and horticulture. Improving methods of assessing resources so that data can be obtained at appropriate scales should be a priority.

2. **Model development**

   Experience in the national audit case studies and in the evaluation of the whole approach to risk assessment has emphasised the deficiencies in the model framework currently available to predict changes in hydrogeology—particularly recharge changes due to changed land use. There is very poor ‘meshing’ of the point models predicting water balance changes and the prediction of recharge from groundwater models. The prediction of salt loads is also highly uncertain. There is a clear need for further development of models and frameworks to ensure that predictions of changes in water balance and salt transport resulting from various land management options can be more confidently supported.

3. **Development of a groundwater flow system map for Queensland at a scale of 1:250 000**

   The current hazard map for Queensland was based on a groundwater flow system map derived from 1:2 500 000 scale data. This was useful as an initial attempt at hazard assessment at the national scale, but is not suitable for management support at the catchment scale or for definition of priority activities State-wide. The improved groundwater flow system map should be underpinned by a well-resourced information management system to capture iterative improvements in datasets.

4. **A salinity risk assessment to focus activities**

   An upgraded salinity risk assessment should be carried out using a 1:250 000-based groundwater flow system framework, to identify priority areas and to focus more detailed studies.

5. **More detailed salinity risk assessments on representative catchments using the best information available on groundwater and regolith characteristics**

Building on the approach applied in the NLWRA case studies, more detailed understanding of the catchment water balance and salt transport processes operating in representative catchments would improve confidence in predictions of land-use effects on catchment water balance and the behaviour of groundwater flow systems in the northern environments of Australia. They could be used to monitor and evaluate land-use impacts in more detail than could be implemented feasibly across all catchments. A subset of key indicators might be applied in the wider catchments of interest.

More detailed studies in these catchments might include:

- detailed hydrological investigations (including drilling where required) to develop conceptual groundwater systems models
- detailed measurement of recharge to groundwater under natural vegetation and current land use, using a designed piezometer/bore network, lysimeters and other soil physics-based methods
- targeted airborne and/or ground based geophysics
- regolith/soils characterisation
- measurement of stream salt load out of the catchment or subcatchment
- water balance modelling (initially using the best available data) to provide an overview of deep drainage (potential recharge) across a range of important soils and agro-ecological regions similar to those reported by Keating et al. (in press, see figure 7). Opportunities for linking with the national program, Redesigning Australian Agricultural Landscapes, should be pursued.

Studies of recharge under natural and agricultural land-use systems in Australia where direct measurements have been made are relatively few, particularly in natural systems and in northern Australia. Since estimation of recharge is a very important aspect of water balance-testing of scenarios (particularly in relation to assessment of salinity risk), the establishment of some key research sites on which to measure (and estimate) recharge under natural and agricultural systems in northern Australia should be given a high priority.

6. **Monitoring and evaluation system**

The Australian Dryland Salinity Assessment 2000 (NLWRA 2001) identified that throughout the States and Territories there were very serious deficiencies in capabilities for monitoring dryland salinity. Clearly, an objective management strategy requires a purpose-designed monitoring system that enables the impacts of land-use management on the land and water attributes responsible for dryland salinity to be evaluated.

The objectives of dryland salinity monitoring programs are:

- evaluation of the effectiveness of previous management activities in terms of their impacts on extent and effects of dryland salinity

- development of knowledge about the processes causing dryland salinity
- provision of data to enable the likely future extent/severity/impact of dryland salinity and the likely timeframes of management responses to be predicted.

Monitoring efforts need to be relevant at a catchment scale, and within a clearly defined evaluation framework. That is, how the data is to be used needs to be clearly understood to ensure that the specifications of monitoring programs are relevant.

Following a review of the monitoring systems for dryland salinity throughout Australia, Coram et al. (2001c) have identified a number of recommended and alternative monitoring attributes that should form the basis of future systems. The recommended attributes directly measure the landscape response to management activities. Alternative attributes (sometimes referred to as 'surrogates' or 'interim' performance indicators) measure activities that are likely to impact upon landscapes and cause a landscape response related to dryland salinity.

Recommended attributes (Coram et al. 2001c)*:*

- Percentage retention of native deep-rooted vegetation in high risk areas
- Long-term groundwater level and salinity trends
- Long-term stream salinity and salt load trends
- Extent of land salinised
- Agricultural system productivity

Alternative attributes (Coram et al. 2001c)*:*

- Land-cover change and vegetative health mapping
- Land-use change mapping
- Catchment planning based on resource assessment and daily water balance modelling
- Proportion of landscape where water-efficient land use is adopted
- Volume of water or salt pumped from the groundwater
- Volume of water/mass of salt intercepted and disposed of
- Increase in long-term productivity from salinised areas
- Increased farm returns from salinised areas
- Proportion of potential discharge zone applying alternative salt-tolerant land use
- Rate of adoption of new salt-related industries

The characteristics of groundwater flow systems determine the rates of response to how such attributes as groundwater levels are managed. Therefore, the choice of monitoring attributes is likely to be influenced by the groundwater flow system and the objectives of the management activities. For example, groundwater levels in areas dominated by regional groundwater flow systems are unlikely to respond in a short timeframe, and therefore the monitoring attribute chosen for regular evaluation of progress from a management activity might be the change in perennial vegetative cover over the main recharge zones of a catchment.

Other core data required for evaluation of management responses are information on:

- climate
- digital elevation
- hydrogeological characteristics of the catchment
- soil–water characteristics and parameters for modelling purposes
- crop, pasture and forestry production data.

A monitoring system might be tiered (nested) so that core data such as changes in groundwater levels, stream water volume and salt concentration, vegetative cover and land-use systems are monitored at the catchment level in all catchments of interest, while more detailed spatial monitoring of these attributes and others is limited to representative catchments. The objectives of the monitoring in representative catchments are more detailed. A major goal is to develop knowledge so that responses in the wider set of catchments can be understood and explained, and confidence in predictions of risks under a range of scenarios can be increased. Protocols and standards should be consistent with any agreed nationally.

1

Dryland salinity risk assessment

Introduction

Salinisation of land and water resources is a major land degradation issue in Australia and presents challenges to land managers and governments in terms of how to manage it, and who should pay.

The recent assessment carried out by the National Land and Water Resources Audit and State and Territory governments (NLWRA 2001) provided a national overview of the distribution and impacts of dryland salinity. Although there are constraints in the methods and data used across the States, the key conclusions were sobering:

- About 5.7 million hectares lie within regions mapped to be at risk or affected by dryland salinity. It has been estimated that in 50 years' time the area of regions with a high risk may increase to 17 million hectares (three times as much as now).
- Some 20 000 km of major roads and 1600 km of railways occur in regions mapped to have areas of high risk. Estimates suggest these could be 52 000 km and 3600 km respectively by the year 2050.
- Salt is transported by water. Up to 20 000 km of streams could be significantly salt-affected by 2050.
- Areas of remnant native vegetation (630 000 ha) and associated ecosystems are within regions with areas mapped to be at risk. These areas are projected to increase by up to 2 million hectares over the next 50 years.
- Australian rural towns are not immune—over 200 towns could suffer damage to infrastructure and other community assets from dryland salinity by 2050.

Efforts to arrest the spread of salinity have achieved only modest success and evidence suggests that the problem will continue to grow. It poses a great national challenge to the sustainability of water supplies, productive land-use systems and ecosystem functions.

Dryland salinity has more pervasive impacts than some of the other degradation issues such as soil erosion, eutrophication of streams and loss of riparian zone vegetation, but is also very closely linked with them. Dryland salinity is difficult to manage because of the lasting nature of the impacts on soil and water resources, and on the stability of ecosystems. In common with other land degradation issues, it is most widespread in the developed agricultural zones of the southern half of Australia. Many of the remedial or preventative options for managing dryland salinity often result in improvements in the other suite of issues. These positive outcomes are sometimes not taken into account when the benefits–costs of dryland salinity management options are evaluated.

Two broad forms of salinity are recognised in Australia:

- **Primary** or naturally occurring salinity is part of the Australian landscape, and reflects the development of this landscape over time. Examples are the marine plains found around the coastline of Australia, and the salt lakes in central and western Australia. Salts are distributed widely across the Australian landscape. They originate mainly from depositions of oceanic salt by rain and wind. Salt stored in the soil or groundwater is concentrated through evaporation and transpiration by plants. In a healthy catchment, salt is slowly leached downwards and stored below the root zone, or out of the system.
- **Secondary** salinity is the salinisation of land and water resources caused by the way people use the land. It includes salinity that results from rises in the watertable due to irrigation management systems (irrigation salinity) and from dryland management systems (dryland salinity). Both forms of salinity occur when salt in the soil is mobilized by rising watertables. There is no fundamental difference in the hydrologic process.

This paper focusses on dryland salinity.

Opportunities for prevention in northern Australia

The recent national dryland salinity audit (NLWRA 2001) and other plans have highlighted the need for an ongoing assessment of dryland salinity risks, and evaluation of the most appropriate management responses. In addition, they have brought into focus the inadequate biophysical and economic data available on which to assess the risks and impacts, and have emphasised the need for properly designed and supported monitoring systems.

The recent audit identified northern Australia as a particular case for more detailed assessment of dryland salinity risks, on the basis that it is far better to invest in prevention than to attempt control or management after the event. Treating the cause of salinity through recharge reduction may be effective in reversing salinisation in only a few responsive groundwater systems. Once the salinisation process is under way, it is extremely difficult to slow, halt or reverse in order to protect water and land resources.

Two factors that must be present for a salinity risk to occur after clearing or change in vegetation cover are:

- presence of stored salt in the soil, regolith or groundwater systems
- increased draining of water beneath the root zone following tree clearing or vegetation change.

Although salinity analysis has focused on southern Australia, sound scientific evidence (Gunn 1967, Shaw et al. 1994, Bui et al. 1996, Williams et al. 1997, Bui 2000, Gordon et al. 2000) shows that *all the factors that contribute to salinity hazard also exist over large areas of the semiarid zones of northern Australia.*

Hazard assessments have been carried out in Queensland as part of the audit program and are being used as an initial basis for planning Queensland dryland salinity management. Northern Australia has seasonal patterns of high evaporation and summer rainfall. A common misconception is that these patterns mean that land clearing and other vegetation management cannot increase the amount of water draining below the root zone to intercept the salt and move it to lower positions in the landscape and to rivers, streams and wetlands. *Hydrogeological evidence does not support this perception.*

The summer wet season rainfall pattern in northern Australia is concentrated between December and April. These rainfall patterns respond to vegetation change (particularly the removal of deep-rooted perennial species) in a similar way and extent to the winter-dominant rainfall patterns of southern Australia where salinity is widespread (Williams et al. 1997, Gordon et al. 2000, Stirzaker et al. 2000). In northern and central Queensland, a change in vegetation can significantly increase the water that drains beneath the root zone (figure 1). It is important to conduct water balance analysis on a daily basis, to see evidence of increased deep drainage following clearing. Coarse, monthly analysis of water balance can be misleading and forms part of the basis for current misconceptions.

Hazard assessment has confirmed that large areas of the tropics and subtropics have a potential salinity problem if clearing occurs. Broadscale land clearing with little or no regard for the salinity hazard is a recipe for repeating the problems of temperate Australia.

Detailed assessment of areas identified as having a hazard, particularly areas of extensive clearing in central and southern Queensland, is essential for underpinning vegetation and land management guidelines, and for current efforts in planning at the catchment scales as part of the response to the National Action Plan for Salinity and Water Quality (Commonwealth of Australia 2000).

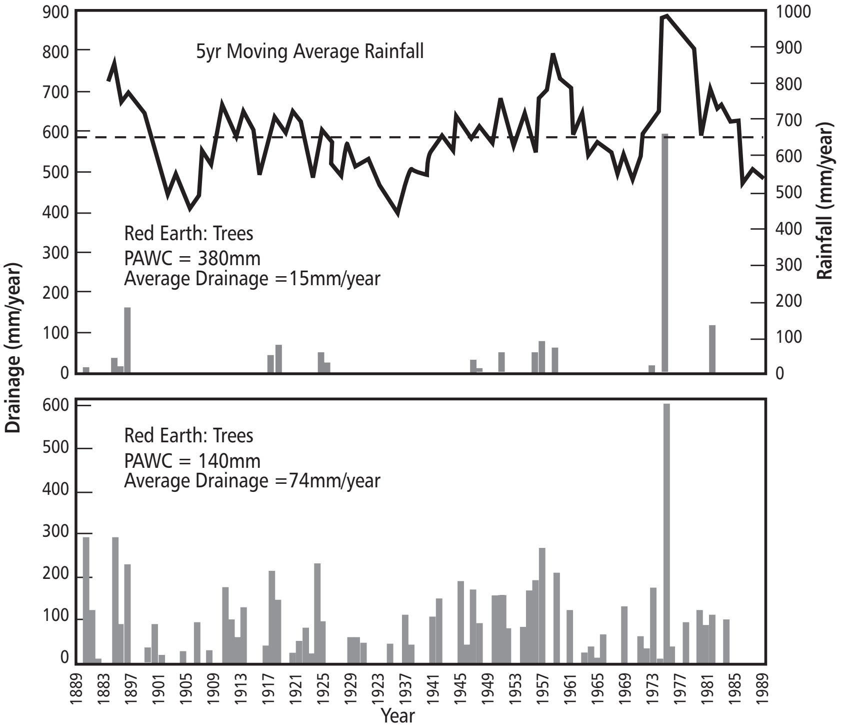

Figure 1. One hundred years of simulated deep drainage beneath trees and perennial native grass compared with drainage beneath perennial native grass pastures for a deep permeable soil near Charters Towers, Queensland
Note the greatly increased drainage beneath grass (Williams et al. 1997).

Since several regions in Queensland have been assessed as having a high hazard from dryland salinity, the need for a detailed assessment of the risks has led to a review of the current methods and approaches to risk assessment, and an identification of an improved approach for the future.

Context

The context of this paper is that, while there is considerable knowledge about the processes involved in dryland salinity and the management options available, there are major difficulties in applying much of that knowledge at the subcatchment scale (property level). This occurs because of the need for appropriate datasets, and the need to rely on the less certain results of extrapolating from finer-scale or broader-scale studies. Consequently, in practice, our confidence in assessment of land-use impacts of management options decreases as we increase our intensity of examination (figure 2—stylized).

At the broad scale, we can say with confidence that certain land-use options will decrease the amount of recharge in a catchment, and this will lead to a reduction in discharge and salt transport to streams. However, as we try (without very detailed studies) to apply this experience/knowledge at a subcatchment (property) scale, our confidence in the size, location of options and rate and location of responses decreases. This is partly a reflection of the variability and uniqueness of landscapes, and partly a reflection on the need for further data and tools to readily apply this 'knowledge'.

This paper provides a brief background on the causes of dryland salinity, a current assessment of salinity risk assessment methods and an examination of the characteristics of the Australian Groundwater Flow Systems contributing to dryland salinity in Australia. It then suggests a salinity risk assessment approach and priority thrusts appropriate to the Queensland situation.

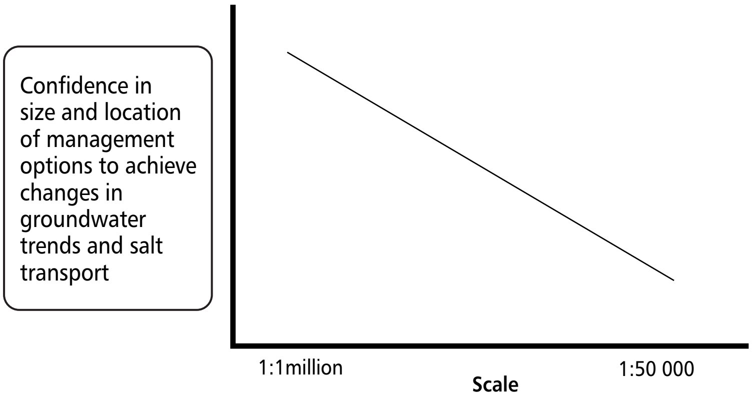

Figure 2. Level of confidence in predictions

2

What causes dryland salinity?

Salts can be found in most Australian landscapes. They originate from weathering of rocks or from oceanic salt brought in from the ocean by rain or wind. Salt in the soil or groundwater is concentrated through evaporation and transpiration by plants. Native vegetation evolved to use available rainfall, and in many ecosystems developed a tolerance to salts. Replacement of native vegetation with crops and pastures that have shallower roots and different growth patterns changed the rate and amount of water use. Consequently the water balance in landscapes changed, leading to excess water moving to depths beyond root zones to the groundwater. Australia's present dryland salinity problems are due to rising groundwater levels bringing salt to the soil surface and into the waterways.

There are few if any landscapes in southern Australia that are completely immune to the salinity problem. Most landscapes have some potential for dryland salinity to develop, given particular hydrological conditions. Not all landscapes however have the same risk of developing salinity within a given timeframe, and not all will develop the problem to the same extent. The timeframes and the extent of degradation depend upon the interaction of four key factors:

- *Climate*—the amount of water input to the catchment surface through rainfall—timing and amount of rain in particular are critical
- *Land use*—this determines soil–water balance (particularly the amount of water lost through evapotranspiration) and hence the amount available in the root zone, which can infiltrate to the groundwater system
- *Salt stores*—the amount of salt stored in the catchment and available for mobilisation by groundwater
- *Hydrogeology*—the structural and geomorphic features of the catchment that determine how much groundwater can be stored, how far it will flow, and what will cause it to discharge.

Climate and land use are the most temporally variable, while salt stores and hydrogeology are the least. Clearly these factors interact. For example, salt stores are influenced by long-term rainfall patterns, proximity to the sea, and geomorphic features.

We already have a reasonable understanding of climate and how it varies in major agricultural and pastoral areas of Australia. Climate information is readily available for use in assessments of water balance and runoff. Rainfall in excess of evapotranspiration and soil storage at any time of the year can result in accessions to groundwater. Episodic rainfall events are known to be a major cause of groundwater rises, in both the northern and southern parts of Australia.

Land use is a major determinant of catchment water balance; on average, under forested areas, there is less water draining to groundwater systems than under grazed or cropped areas. Even under episodic events, the extra storage capacity under forests results in less drainage to the groundwater.

Salt stores are not well understood and remain a major challenge. Airborne geophysics and ground based geophysics methods are being used and further developed for application at various scales. Where salt stores are known to exist, an important requirement is knowledge of the most appropriate land-use systems for particular landscape positions, to ensure that the salt is kept ‘immobilised’.

The hydrogeology of much of Australia is not well understood, particularly as it influences management opportunities for salinity control. However, there have been sufficient studies and experience gained by a relatively small number of scientists nationally, to collate knowledge into a broad framework to assist salinity risk assessment and to guide selection of management options (Coram ed.1998, Coram et al. 2000). This framework is considered later in this paper.

Salinisation processes

Water movement in the landscape transports salt and drives land salinisation. The processes of water movement responsible for salt movement in the landscape, conceptualised in figure 3, are:

- recharge—water enters the system to become part of the groundwater
- discharge—groundwater leaves the system by evaporation or evapotranspiration
- transmission—water and dissolved salt move from recharge areas through the soils and aquifers.

These conceptual processes are really a combination of many biophysical processes that operate at a great range of scales from local (e.g. 20–100 m in a small catchment, from the upper slope and crest to the valley floor), to regional scales (e.g. 100 km from uplands through aquifers to alluvial plains sometimes outside the originating catchment). This complexity of

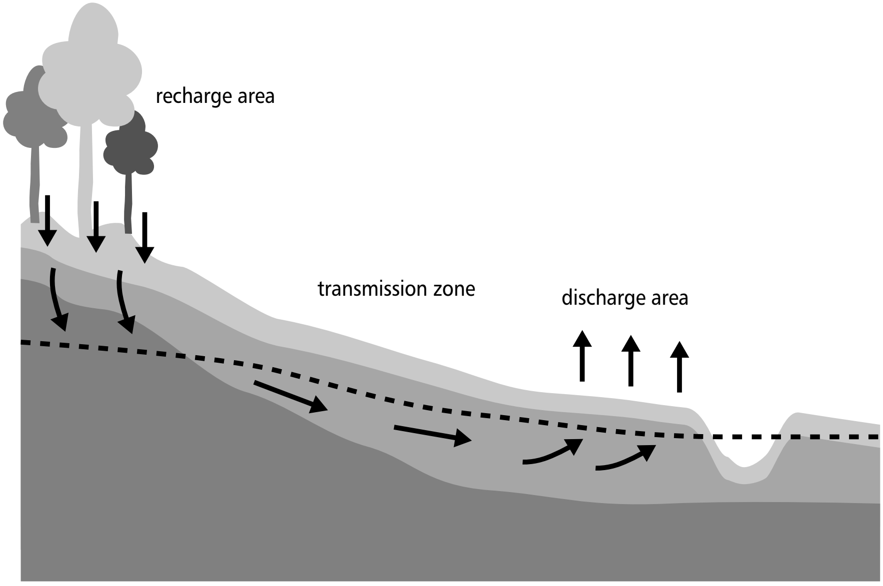

Figure 3. Conceptual model of landscape hydrologic processes (DNR 1997)

processes and scales poses considerable challenges in the assessment of risks associated with changes in land use.

Under stable climatic conditions and natural vegetation, catchments tend to establish a dynamic hydrological equilibrium, where water entering the landscape systems is balanced by water flowing out (i.e. recharge is balanced by discharge); hence the landscapes also tend to be in salt balance. When the hydrological equilibrium is disturbed through factors such as clearing of perennial vegetation, the recharge/discharge processes adjust towards a new equilibrium. Extra water entering the system (recharge) generally causes increased pressure in aquifers, and watertable rise. This often results in an increase in discharge and resultant salinisation of land and/or water. These processes are graphically presented in figure 4.

Recharge

Recharge is the process of water entering the groundwater; it occurs through infiltration and drainage of water through the regolith and into the groundwater systems. It can occur in all parts of the landscape, including through stream banks and beds. The factors controlling recharge are:

- climate
- landscape geology and geomorphology
- type of groundwater system
- land use (particularly the type and extent of vegetative cover as it impacts on evapotranspiration)
- soil properties.

The interaction of these factors determines the water balance and the various pathways by which water moves in the landscape. It is the change in water balance that ultimately results in changes in recharge and discharge.

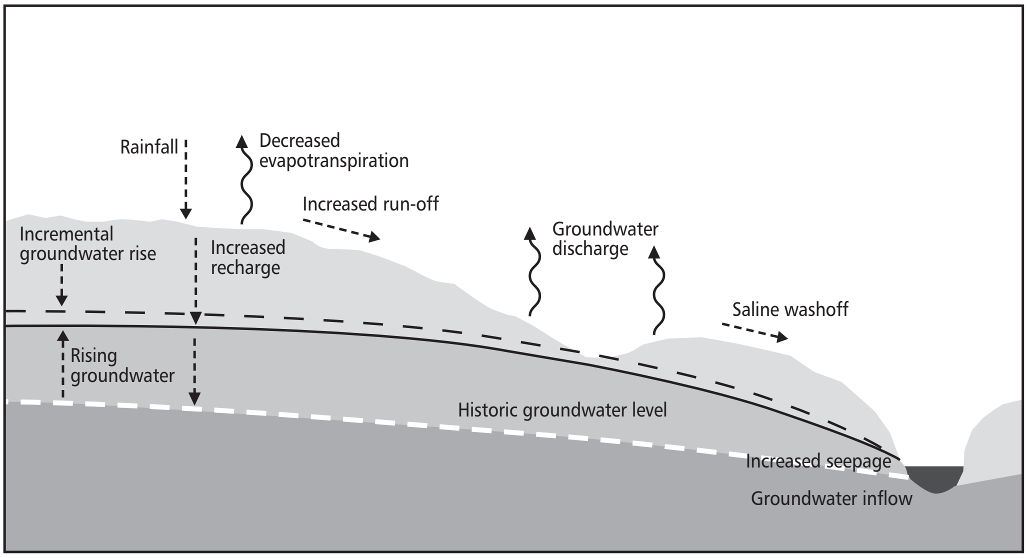

Figure 4. Hydrologic processes modelled in the Murray–Darling Basin Commission Salt Loads Study (reproduced from MDBC 2000)

A comprehensive range of methods for estimating recharge has been presented in Zhang and Walker (eds. 1998). These cover groundwater chemical methods, soil physical methods, catchment-scale modelling, groundwater level response methods, groundwater modelling, soil–water tracers and electromagnetic induction techniques.

Discharge

Discharge areas generally occur where there is some hydrologic restriction to the down-slope transmission of water, which causes it to flow towards the soil surface. These areas often occur where the land is flat or poorly incised. The watertable in a discharge area is usually at or close to the surface, and seasonal fluctuations in depth tend to be less than those in recharge or transmission zones. Waterlogging is often associated with a discharge area. The rate of upward movement of the groundwater will determine the degree of salinisation that occurs at the surface.

Salama (1998) recognises three forms of discharge:

- **Point discharge** is clearly defined and limited in extent.
    - It occurs through springs and seeps where down-gradient sections of confined aquifers are exposed to the surface; or through hydraulic barriers such as dykes or changes in soil from one which is more transmissive to one which is slowly transmissive (e.g. deep sandy soil to clay soil).
    - It enters streams and lakes through increased hydraulic gradient and seepage velocity.

  Discharge of salt to streams generally occurs through runoff, interflow and baseflow. Although baseflow may be a small proportion of streamflow, the amount of salt discharged can be a large proportion of the total salt load.

- **Diffuse discharge**—continuous, spatially-distributed discharge to the atmosphere resulting from upward flow of groundwater. Most water is lost by diffuse discharge at low rates over large areas at low topographic elevation. Three examples of diffuse discharge quoted by Salama (1998) are:
    - loss rates by evaporation from a watertable at 10 m in the Sahara—about 2 mm per year (Fontes et al. 1986)
    - loss rates from a ‘dry’ salt lake bed in South Australia—90 mm and 230 mm per year (Allison & Barnes 1985)
    - loss rates from watertables at about 1 m in bare irrigated soils—1 mm to 10 mm per day (Thorburn et al. 1991).

- **Biological discharge**—water is discharged from the soil and groundwater into the atmosphere through evapotranspiration by vegetation. Rates of discharge are determined by root depth and depth and salt concentration of the groundwater. ‘For the roots to absorb water, the osmotic suction of the root solution must exceed the suction of the groundwater and the capillary fringe’ (Salama 1998).

Methods for estimating discharge using physical and chemical techniques, groundwater processes and modelling and electromagnetic techniques have been described in detail in Zhang and Walker (Series editors 1998).

Transmission

Transmission is the process whereby water moves from recharge areas towards lower elevation areas in a zone approximately parallel to the land surface or deeper, rather than upwards towards the surface. Soils of transmission zones tend to be deeper and less permeable than those in recharge areas, and depth to the watertable is usually less than in recharge areas (DNR 1997). The rate of transmission in the landscape depends on the hydraulic conductivity of the 'aquifer', the gradient driving the flow, the area through which the flow can move, and the time period of the flow.

The type of material in the aquifer determines hydraulic conductivity. In well-sorted sand and gravel hydraulic conductivity is generally high, whereas in clay-rich aquifers it is very small. The gradient of the flow, or the hydraulic pressure, is increased as water is added to the system. This pressure transmits through the aquifer and causes a watertable response in discharge areas. The area available for the groundwater to flow out of the catchment is often much smaller than that where recharge occurs, and is a major constraint on the rate at which increased water can move out. Hence discharge often occurs near these points in the landscape.

Salt mass balance

Salt mass balance occurs when there is equilibrium between the salt entering the catchment by rain or wind, and that leaving via the groundwater or in surface streams. Salts tend to be stored in the unsaturated zone of the landscape below the root zones of natural vegetation. In some landscapes derived from marine sediments, and in deeply weathered laterised landscapes, salt stores can be huge. The other large store of salt can be in groundwater.

Constraints

Conceptual landscape models (figures 3 and 4) assist greatly in describing the hydrologic processes responsible for salt movement in a landscape, and provide a basis for modelling/estimating the land-use and land management impacts on water and salt. It is important to remember that conceptual models are just that – *conceptual*, and are not promoted as accurate representations of the actual landscape–hydrologic relationships. They provide a useful framework for addressing the various components in more detail. This has led to the development of risk assessment approaches based on the conceptual understanding of the processes operating in a catchment using a range of modelling and analytical methods.

3

Salinity risk assessment

While large salt stores in a landscape (inherent possibility of the area salinising) may be a salinity hazard, it becomes a risk only when the water balance is altered (for example by clearing) and probability increases that the salt store will be mobilised and reach the soil surface or enter streams or groundwater. Risk assessment is thus the analysis of landscape, land use, and hydrologic factors to evaluate this probability of salt mobilisation.

The recent national audit of dryland salinity—*Australia's Dryland Salinity Assessment 2000* (NLWRA 2001) highlighted a number of constraints faced by landholders and government in determining the spatial extent of dryland salinity and the future risks associated with current or alternative land-use systems. It is well known and accepted that groundwater drives salinity. Changes in the water balance related to land-use changes have changed the hydrologic equilibrium, leading to increases in groundwater recharge, rising groundwater trends and associated increases in saline discharge. In general, the risk factors relating to dryland salinity are well understood, but it is difficult to convert them into a spatial distribution of risk across large areas. For much of Australia, there is insufficient data to enable the conceptual models to be applied. In some cases, where data does exist, it is not at a scale that enables the appropriate questions to be asked.

In their recent review of risk assessment methods, Gilfedder and Walker (2001) highlighted the difficulties in assessing risk because of the complexity in spatial scales of the various drivers of groundwater changes. These complexities are related to variations in the type of groundwater system (local/regional/intermediate); aquifer thickness; hydraulic conductivities; widths; gradients; and features such as dykes, faults and basement highs. Add to these the spatial variations in soils and land-use patterns, and the complexity of predicting hydraulic behaviour across areas should not be a surprise. Therefore, conceptual models are employed in an attempt to deal with the spatial and temporal complexity of these biophysical processes. *These models then prescribe the types of data that are required for monitoring and evaluating salinity risks.*

Risk assessment methods aim at predicting the spatial extent of dryland salinity. Gilfedder and Walker (2001) provide the basis for many of the following descriptions and comments. Other information is derived from working papers prepared by CSIRO Land and Water as part of the development of the Dryland Salinity Work Program for the National Land and Water Resources Audit (Webb, Creighton & Scott 1998).

A number of risk assessment approaches have involved calibration using 'training sets' of data, and most are aimed at predicting the spatial extent of salinity. The methods assign 'risk factors' to process characteristics or attributes and attempt to combine these to give an overall risk. Some studies use a separate set of explicit data to 'validate' the approach, but this is usually data from areas geographically close to the main area of interest. The three broad groups of methods are:

- composite index methods—relying on user experience
- strongly inverse methods—using statistical relationships
- trend-based methods—incorporating temporal change.

Composite index methods combine a number of salinity risk factors that are weighted depending on the operator's experience and understanding of the process. Each data layer such as soil type, land cover, geology, and topography is ranked, weighted and summed using a linear additive model to produce a salinity risk map. Tickell (1994) used this method to derive the salinity risk to the lands of the Northern Territory. Searle and Baillie (1998) ranked each risk factor using a rule-based weighting in an index-based linear additive model to predict salinity hazard in south-east Queensland. In recent times, NR&M has used a modified composite index method to develop hazard assessment maps. The hazard assessment process removed the land use change (or risk) component of the methodology and focused on the spatial distribution of the inherent attributes related to dryland salinity. The approach was based on key landscape attributes associated with the groundwater flow systems described by Coram et al. (2000).

The FLAG fuzzy logic approach (Roberts et al. 1997) involves use of a normalisation technique to evenly weight the risk factors, before combining them in a set of rules based on experience. The approach acknowledges that only digital elevation data are widely available at the small catchment and regional scales in Australia.

Composite index methods rely on the expertise and knowledge of the user, and they generally apply in regions where the risk factors interact consistently. They are very useful in the first phase of compiling current knowledge and focusing priority activities. As data requirements and time and costs associated with analyses tend to be much less, these methods are usually inexpensive compared with those used for process-based catchment models.

Strongly inverse methods include information on current salinised areas as a spatial dataset. These methods statistically determine the relative weights of the risk factors based on the actual datasets available. Examples are the 'weights of evidence' approach used by Bradd et al. (1997), and the decision-tree approach of Tassell (1995). No consistent set of factors has been defined, and the choice is largely determined by the available data. The main difficulty with statistical approaches is their inability to predict salinity for processes not included in the risk factors. For example, salinity risk from rising groundwater in regional groundwater systems will not be predicted if the risk factors used in the 'training set' all relate to topographic position, climate, and geology. Such approaches cannot predict the rate of change of salinity.

Trend-based methods provide opportunities to predict temporal changes in salinity and are far more powerful for evaluating management impacts. There are three general approaches for measuring trends in salinisation of land, streams and groundwater.

Trends in land salinisation are obtained by mapping changes in extent over time. A simple example is the regular ground mapping of the change in extent of salinisaton at key sites in the range of hydrogeological units in Victoria. Another is the use of geophysical or other remotely-sensed data that reflects dryland salinity. Furby et al. (1995) used sequential Landsat TM data to determine changes in areas affected by salinity in the Western Australian wheat-belt. Trend mapping programs for dryland salinity based on this approach (Evans et al. 2000) have been promoted widely following this success. In already salinised areas, this approach is very useful when predicting increases under the same climate and land-use conditions.

Stream salinity trends give an integrated result of changes in hydrology and salt movement for a catchment. In Victoria, regression methods have been used to elicit the relationship between these trends and risk factors such as climate, proportion of forest cover and rock types (Greig & Devonshire 1981). The regressions cannot be readily transferred to other catchments and regions, but the approach itself can be, if sufficient data are available. Variability in flows due to climate extremes and episodic events make this approach difficult. In addition, lack of suitable flow and salinity records has been a major problem for those who have attempted this approach (Jolly et al. 1997, 2001).

Another method based on stream data is the salt balance approach (Jolly et al. 1997, 2001) that has been used to evaluate salinity status and likely future trends. This approach measures the imbalance of salts leaving a catchment compared with those entering in rainfall. If the ratio is greater than 1, it is assumed that the catchment is not in hydraulic equilibrium, and land use is causing an increase in salinity discharge. Measurement of salt input is not always easy because of the lack of available data on the salt content of rainfall, and the fact that catchments may not have been in equilibrium prior to land-use changes. This is an issue particularly where catchments have very long response times. These stream-based methods provide an integrated picture over time. Without a process understanding, however, they cannot be used to predict future changes due to impacts of management. Often, the scale of measurement is catchment-wide, whereas management occurs only over a part.

Monitoring of groundwater pressure is regarded as the best method for measuring salinity trends (I. Jolly, pers. comm.), and has been used in a number of studies (Kirkby, 1994, NLWRA 2001). Although groundwater trends will vary according to climate, they are good indicators of risk where there are records for a long-enough period of time. For a consistent picture, it is necessary to stratify bores on the basis of groundwater type, landscape element and the aquifer being monitored. In some areas, there is an absence of bores with long-term records. If, however, a systematic network is established, then it may be expected that a groundwater trend in a particular groundwater type, land use and climate will have a similar trend to one monitored with those same characteristics (Salama et al. 1996). The development of such a network needs to be made a high priority.

Trends in groundwater can be correlated with trends in stream salinity. As stream salinity can be the most costly form of the problem, it is important to understand how the groundwater systems and the surface water are linked. Because of stream gauging networks, there are some long-term records of stream salinity available, and these should provide a broader perspective of trends, as has occurred recently in the Murray–Darling basin (Williamson et al.1997, Jolly et al.1997). As streams coming out of a catchment integrate many of the processes happening within that catchment, catchment water quality and trends are a good indication of its health. However, as with salinity hazard mapping, historical trends give a picture of what is happening now, but may not indicate regional groundwater systems that may have a major impact later.

Data issues

While the risk factors relating to dryland salinity are generally well understood, the spatial distribution of these risk factors across large areas is not well-developed. This has been attempted in a number of previous studies, but the choice of relevant datasets has been very inconsistent. This is due, in part, to the fact that there has been no unified, national approach to risk assessment. This was highlighted in the Australian Dryland Salinity Assessment 2000 (NLWRA 2001). It may also be due to differences in geology, climate, extent of the study area or differences in available datasets. Before a comparison can be made of the risk factors used in previous studies, it is important to understand the scale of the processes operating, the available input data, and the scale of interest to the client.

On the latter point, clients may be interested at the national, regional, catchment or farm scale. Their interests may be related to policy, assessment of the extent of the problem, targeting funds, or regional, catchment or farm planning. As discussed previously, the groundwater processes associated with both land and river salinisation occur at local (small catchment) and/or regional scales. Often the data is not available at the scale of the processes (e.g. the only national soils coverage is at 1:2 000 000, and this is too coarse for understanding processes in a subcatchment).

A summary of the data used in a number of salinity risk assessments is presented in table 1. Differences in the data give some insight into the way investigators have implicitly built process into the methods at various scales. In these studies, the scale has been largely determined by the extent of the study area and the availability of relevant datasets at that scale, rather than the scale of processes. The risk factors chosen in the studies are geology, vegetation/land use, soils, climate and terrain attributes. Many of the chosen spatial datasets have an implicit, rather than explicit, connection to the salinity risk factors.

Mapped attributes are often used as surrogates for the actual risk factor. For example, while soils, vegetation and climate combine in a specific way for recharge, each is generally kept as a separate risk factor. Similarly, though the specifics of the groundwater systems are not included, geology and a mix of terrain attributes have become surrogates.

Another reason for choosing datasets with implicit relationships has been the high degree of correlation between possible factors causing difficulty with some of the statistical methods used. For example, elevation is highly correlated with rainfall, soils and land use. Dowling et al. (1997) have chosen to use only two terrain attributes derived from elevation to avoid any confusion in determining which risk factor is dominant. A special case of the use of surrogates is the application of terrain attributes. Since digital elevation data is one of the few datasets available across Australia, it has been increasingly used to infer parameters for which datasets are not available. For example, a combination of geology and slope classes can lead to use of land units or aspect as a surrogate for solar radiation.

Since groundwater parameters are particularly difficult to determine spatially, a number of terrain attributes have been used to infer groundwater processes. For example, for local groundwater systems that may mirror the surface water catchments:

- a flow accumulation parameter may be used to determine the contributing area above any given point (Searle & Bailie 1998)
- vertical curvature may infer break of slope (Furby 1995), or relative lowness (Dowling et al. 1997).
- groundwater flow out of the catchment can be inferred by determination of gradient at the outlet of the catchment.

For non-local systems, there are variations in some of these parameters (HARSD 'Upness index' in FLAG). In some cases, landform classifications such as hills, slopes, and valley floors have been used.

There are constraints on the degree to which these factors can be rationalised, given the differences in available datasets and the diversity of processes leading to salinity. The National Catchment Classification for Land and Stream Salinisation (Coram et al. 1988) has attempted to address this problem. One of the underlying principles of this classification is that the groundwater-related risk factors are the same for all catchments of the one type, and a standard suite of groundwater system and terrain attributes can be applied.

Catchment modelling

Recharge-related risk factors can also be tackled uniformly. It is now possible to develop recharge relationships that can easily be incorporated in a GIS framework using a number of modelling packages such as WAVES, PERFECT and APSIM. These can simulate the recharge processes using national sets of climatic data, together with the many water balance studies that have been carried out on a variety of land uses, climatic zones and soil types.

In heterogeneous catchments, recharge estimation by modelling requires the disaggregation of the catchment into land units that are considered to have homogenous recharge–discharge behaviour. Although one-dimensional modelling may be appropriate in some simple landscapes, in most catchments three-dimensional recharge modelling is required to take account of 'important lateral processes affecting inputs to the groundwater system' (Hatton 1998). Distributed parameter models are complex and data-intensive, but in many cases offer the only cost-effective alternative to assessing the impacts of land use on catchment hydrologic behaviour.

Much of our current understanding of dryland salinity processes comes from a number of well-studied catchments. The aim of such studies is to attempt to understand the processes, and then to apply this knowledge to other catchments. Since the cost of acquiring further data is high (especially data related to subsurface processes), extrapolation techniques generally necessitate the use of existing data and/or the judgment of experienced professionals. The ability to predict and extrapolate the impacts of changed land use has been the aim of many process-based modelling exercises. Modelling of such changes depends on understanding how the groundwater system works and how this relates to the drivers of the system—land use and climate. In most places, it may not be too difficult to predict where salinity will occur as this is often in low-lying areas, in breaks of slope, or behind constrictions or structural features; however, to predict the impact of changing land use on part of a catchment requires a much better understanding of its groundwater system.

In catchments for which there is enough suitable data, it is possible to model the groundwater processes, recharge, discharge and cost of salinity. Except in some fractured rock systems, the processes can be modelled through conventional groundwater techniques (Gilfedder & Walker 2001) using models such as MODFLOW and AQUIFEM-N. In some cases, both surface water balances and groundwater can be simulated within the same model—examples of these are TOPOG-IRM and MIKE-SHE. Some simplified groundwater models that have been developed for specialised applications are the groundwater component of HARSD, FLOWTUBE ,and some analytical solutions. Other models specialise in the simulation of deep drainage that leads to recharge, for example WAVES, APSIM, PERFECT and AgET. Most of the models quoted have been described by Rosemary Hook (1997) in her directory of Australian modelling groups and models.

Groundwater models such as MODFLOW and AQUIFEM-N usually require estimation of the parameters—recharge, specific yield, conductivity, and aquifer thickness at each cell, which is usually of the order of a few hundred metres to a few kilometres. The amount of work required depends on the complexity of the conceptualisation and the steepness of the terrain. *The confidence of the predictions depends on the quality of the conceptualisation and the quality of available information.* However, even in an intensively studied catchment such as the Liverpool Plains in New South Wales, there is a paucity of data for non-irrigated areas.

The key advantage of such models is that any type of groundwater system can be modelled, provided appropriate data are available. Both the TOPOG and MIKE-SHE models require parameters associated with soils, vegetation, climate and terrain for each cell, as well as the groundwater parameters. If surface water processes are to be modelled accurately, cells need to be less than about 50 m square and an accurate digital elevation model is required. In practical terms, this means the maximum area would be in the order of 10 km2.

The FLOWTUBE model in the Liverpool Plains (Dawes et al. 2000) is an example of a simplified groundwater model that captures the key processes of the groundwater system. The groundwater component of the HARSD approach uses a steady-state flownet to simulate groundwater processes. The advantages of these simpler models are the speed at which they can be calibrated and the ease with which they can be interpreted. Their main drawback is their lack of applicability to all groundwater systems.

The chief output of most groundwater models is the prediction of trends. Where groundwater pressures are near or above the ground surface, the area is considered to be at risk of salinity. With some interpretation, these may be translated into areas of salinity, effect on production yield, or damage to infrastructure. The aim of such models is to assess the impacts of various management practices on these trends. The recent case studies carried out as part of the Dryland Salinity Theme program for the National Land and Water Resources Audit are good examples of the application of these models (NLWRA 2001).

Airborne geophysics has been developed to the stage where it is being used to improve understanding of the hydrogeology of catchments, and confidence in assessing risks of dryland salinity and mobilisation of salt to streams. In particular, at a catchment scale, it provides a framework for developing an understanding of the landscape and its primary attributes (soils, regolith, salt-store and geology). This enables land managers to focus and prioritise the more detailed but expensive ground- based investigations. The National Airborne Geophysics Project concluded that airborne geophysics can significantly contribute to a better assessment of the risk of dryland salinity occurring in any given area, and that its continued use is expected to lead to better decision making at both catchment and paddock scales (George et al. 1998). It was emphasised that, in order to gain the most use for detailed management plans at catchment and paddock level, airborne geophysics needed to be supplemented with a number of other datasets including:

- topography and drainage
- air photos
- watertable depth and quality
- multi-spectral data (satellite and airborne)
- geology
- climate data
- soils–land management units
- land use
- vegetation cover
- cadastre
- road networks.

As a result of recent developments, airborne geophysics technology (Lawrie et al. 2000) is likely to be implemented in key catchments selected by the States as part of the National Action Plan for Salinity and Water Quality (Commonwealth of Australia 2000).

Additional groundwater and regolith datasets are needed to improve the rate at which the data can be translated into risk assessment activities that will contribute to improved catchment planning. In the short term, skills to interpret the geophysical data are also required.

Table 1: Data used in risk assessments in Australia

Author	Study area	Extent	Geology	Soils	Vegetation/cover	Climate	Landform	Other
Bradd et al. (1997)	New South Wales	All	1:1 500 000 or 1:2 500 000 NSWLIC classes	1:1 500 000 or 1:2 500 000 NSWLIC classes	1:1 500 000 or 1:2 500 000 NSWLIC classes present vegetation	1:1 500 000 or 1:2 500 000 NSWLIC classes	1:1 500 000 or 1:2 500 000 NSWLIC classes	1:1 500 000 or 1:2 500 000 NSWLIC classes *Land use no info.* Groundwater resources (yield and quality) salinity training set
Bradd et al. (1997)	Yass Valley	All	1:250 000 unconsolidated sediments; acid volcanics; sed, granite	1:25 000 survey (alluvial, lithosol, podsolic, solodic, terrace)	Land use (crops, grassland, timber, water body)		slope class–source and resolution not cited	Hydrogeology (depth to watertable) ? not cited salinity (training set)
Tassell (1995)	Tout Park New South Wales	2.5 x 4.5 km	1:250 000; survey (lithology, dykes, lineaments)		Normalised Difference Vegetation Moisture index		DEM 10m grid from survey (slope, aspect, elevation)	Discharge and salinity training set EM31 survey
Tickell (1994)	Northern Territory	All		Lateritic soils 1:2 000 000	1:5 000 000 Atlas of Aust. Res. (forest-woodland-shrubland-grassland)	Rainfall (mm) Evaporation (mm)		Groundwater salinity (mg/L) 1:250 000 aquifer yield (L/s) 1:250 000
Bui et al. (1996)	Dalrymple Shire, Queensland	68 000 km2		1:2 000 000 (Northcote,1968) 1:1 000 000 (Isbell1970) (soil—landform, parent material, thickness, depth, sub/dominant types) Survey 1721 sites (EC1:5)	30 m Landsat TM plus survey with hand held radiometer		DEM 18 sec or 500 m (stream network, slope, catchment boundaries)	Groundwater (G/W resources of Qld 1:2 500 000; bore data for depth, EC, ions) Permeability (high medium low) Drainage (good, moderate, poor)
Kirkby (1999)	Jamestown, South Australia	10 x 12 km	1:250 000 classes (quartzite, shale, quaternary deposits and local formations)	1:50 000 classes (skeletal, 10 loams, alluvial)		rainfall referenced—not cited	DEM from 1:25 000 points contours (2 m) to 30 m quintic (slope)	

Table 1 continued : Data used in risk assessments in Australia

Author	Study area	Extent	Geology	Soils	Vegetation/cover	Climate	Landform	Other
Kirkby (1999)	Jamestown, South Australia	1 x 3 km	As above: drilling	As above: profiles	As above	As above	As above	Hydrogeology (piezometers—rainfall response, recharge potential, groundwater, contours, hydraulic conductivity) EM survey (salt, moisture and clay content)
Dowling et al. (1997)	Tout Park, New South Wales	2.5 x 3.5 km					DEM (a local and a regional position in the landscape)	Discharge and salinity training set
Campbell Furby (1995)	Moora Esperance, Narrogin, Western Australia	125 x 115 km 180 x 78 km 150 x 140 km		Soil landscape AgWA	Landsat TM 30m res. MSS		DEM from 10 and 20m contours (Flow Accumulation in 4 classes)	Salinity - surveys
Evans et al. (2000)	Kent River, Western Australia	Not cited		Soil maps for 6 sub-areas	As above		DEM from 10 and 20m contours (Slope, aspect, profile/tan/mean curvature, Flow Accum., s)	EM 360 site surveys
Greig & Devonshire (1981)	Victoria Brisbane	All	Prop. igneous, sedimentary and metamorphic. Source uncited		Height and density Revised Atlas of Aust. Resources	Rainfall (av. annual near gauging stations)		Stream salinity (gauging stations)
Searle & Baillie (1998)		33,000 sq km	1:250,000 (volcanic fringe, dykes, faults, salt source)	1:1,000,000 Isbell et al. 1:2,000,000 Northcote (alluvium, laterite zone or fringe)	1:5,000,000 (Natural Veg. AUSLIG, 1989)	Rainfall (av.annual .05degree hor.res.)	DEM from 1:100,000 20m ctrsto 100m grid (Plan/Prof curvature, Wetness index)	Salinity - surveys (1046 validations)

4

The groundwater flow systems framework

What is it?

Successfully applying results and information gained from one catchment to other catchments remains a challenge to those providing technical support to landholders and catchment managers. It has led to the development of the National Classification of Catchments for Land and River Salinity Control (Coram ed. 1998). Further development to include definition of the groundwater systems controlling dryland salinity (Coram et al. 2000) has provided a framework for identifying management options, and a basis for targeting investment. Though (as in any classification system) there are limitations to the application of this system, the concepts underpinning it can be applied at larger scales such as individual catchments.

The groundwater flow systems framework (GFS) has been used to focus the collation of information on management options for dryland salinity (NLWRA 2001), and is a key component of proposed improvements to the way it is assessed and monitored nationally (Coram et al. 2001c).

The framework is a classification system based on the inferred hydrogeological characteristics of catchments across the continent. Eleven groundwater flow system types that control dryland salinity have been identified within five distinct hydrogeological provinces (table 2, see figure 5). These flow systems reflect more specific geological and topographical characteristics and define two levels of information critical to management:

- the extent of the flow system
- the type of hydrogeological and topographical features influencing dryland salinity.

Differences in the groundwater flow systems have significant implications for dryland salinity management and monitoring. Groundwater flow systems characterise similar landscapes in which similar groundwater processes contribute to similar salinity issues, and where similar salinity management options apply. There are three broad types of flow systems: *local, intermediate and regional*. Each of these determines how appropriate any land-use system is with respect to dryland salinity management, and the system used for monitoring the effects of salinity control activities. For example, there will be little effect from carrying out reforestation of tens or hundreds of hectares of land if the processes controlling salinity occur across tens of thousands of hectares.

Flow system characteristics

Local flow systems respond rapidly to increased groundwater recharge. Watertables rise rapidly and saline discharge typically occurs within 20–30 years of water imbalance. These systems can also respond relatively rapidly to salinity management practices. They provide the

Table 2: Summary of the relationship between hydrogeological provinces, groundwater flow systems and hydrogeological models

Hydrogeological province	Groundwater flow system (Coram et al. 2000)	Hydrogeological models [as described in Coram, ed. (1998)]
Deeply weathered Precambrian rocks	Local flow systems in Precambrian rocks	Local discharge controlled by linear features of contrasting hydraulic conductivity Local discharge over lower hydraulic conductivity structures Local discharge from weathered rock aquifers at break of slope
	Intermediate flow systems in Precambrian rocks	Intermediate discharge in valley floors Intermediate discharge controlled by large, transmissive linear structures
	Intermediate flow systems in Cainozoic sediments	Intermediate discharge controlled by facies change and changes in aquifer geometry
Palaeozoic rocks	Local flow systems in deeply weathered terrain	Local discharge over lower hydraulic conductivity structures Local discharge from weathered rock aquifers at break of slope
	Local flow systems in fractured rock aquifers	Local discharge over lower hydraulic conductivity structures Local discharge from unweathered rock aquifers at break of slope
	Local flow systems in colluvial aprons	Local discharge from colluvial/alluvial slopes
	Intermediate flow systems in Palaeozoic rocks	Intermediate discharge from unweathered fractured rock aquifers at break of slope Intermediate discharge in valley floors
Mesozoic sediments	Local flow systems in Cainozoic volcanics or Mesozoic sediments/volcanics	Local discharge from low hydraulic conductivity aquifers
Cainozoic/mesozoic volcanics	Regional flow systems in Cainozoic volcanics or Mesozoic sediments/volcanics	Regional discharge controlled by structure Regional discharge controlled by topography Local discharge controlled by stratigraphy
Cainozoic sediments	Regional flow systems in Cainozoic sediments	Regional discharge controlled by facies chang
	Regional and local flow systems in Cainozoic marine sediments	Regional discharge controlled by topography Local discharge from perched aquifers

greatest opportunity for farm-based catchment management programs for mitigation of dryland salinity. Local systems are fully contained within small catchments; the area contributing to groundwater discharge is readily identifiable; and the required modified management practices are more easily implemented. Management responses typically include:

- modifying cropping practices to use more water in situ (eliminating or reducing fallow periods and maximising crop or pasture growth)
- revegetating key recharge areas with perennial species (trees, perennial pastures, agro-forestry)
- introducing local interception schemes or shallow groundwater pumping for use of water elsewhere

- employing local, across-property management planning, particularly for vegetation management
- managing pasture to encourage a higher percentage of vigorous, high water-using perennials.

Intermediate flow systems have a greater storage capacity and permeability than local systems and take longer to 'fill' in response to increased recharge. Saline discharge typically occurs within 50 to 100 years after water imbalance/agricultural development. The scale and responsiveness of these groundwater systems present greater challenges for effective salinity control.

Intermediate flow systems operate on the scale of subcatchments to the major river basins, and often involve groundwater transmission over distances in excess of 20 to 30 kilometres; hence these systems are affected by the management systems of many landholders and often by a number of land uses. The size of the systems and the complexity of land uses make management of the groundwater systems difficult.

Intermediate systems are unlikely to respond to farm-based management systems alone due to the scale of action required and the need to address existing elevated groundwater flow regimes. Engineering options such as pumping and drainage, and 'living with salt' options are important in salinity management. Revegetation of large parts of catchments, as farm or plantation forestry or for nature conservation objectives, may be required as part of major changes in land-use patterns. Pumping of good quality groundwater for irrigation is a possible option to relieve pressure in intermediate flow systems.

Regional groundwater flow systems have a high storage capacity and high permeability, and take much longer than local or intermediate flow systems to develop groundwater discharge. Saline groundwater discharge may not occur for more than a hundred years after agricultural development/water imbalance. Likewise, any remedial measures will take a very long time to become effective.

Regional groundwater flow systems are the most difficult to manage by changing farm management. The scale on which they occur is so large that farm-based catchment management is ineffective in bringing about the scale of groundwater reduction required in the time expected by business enterprises. Salinity mitigation involves widespread community action on issues of common concern such as vegetation management controls. Engineering measures to protect high value assets and infrastructure also need to be adopted. Development of strategies for 'living with salt' may be essential in these systems because of the long lag time before control measures will have an impact, and because of the social and economic costs of any changes to land-use patterns.

These systems operate over hundreds of kilometres—at the scale of major river basins. Hundreds of landholders in regional communities farm the groundwater catchments and need to be involved in any control measures. As with intermediate systems, salinity control programs are particularly hampered by elevated groundwater that has resulted from excessive recharge since agricultural development. These conditions buffer against any potential benefits that might otherwise be generated by changed land management practices.

The groundwater flow systems in Queensland are shown in figure 5.

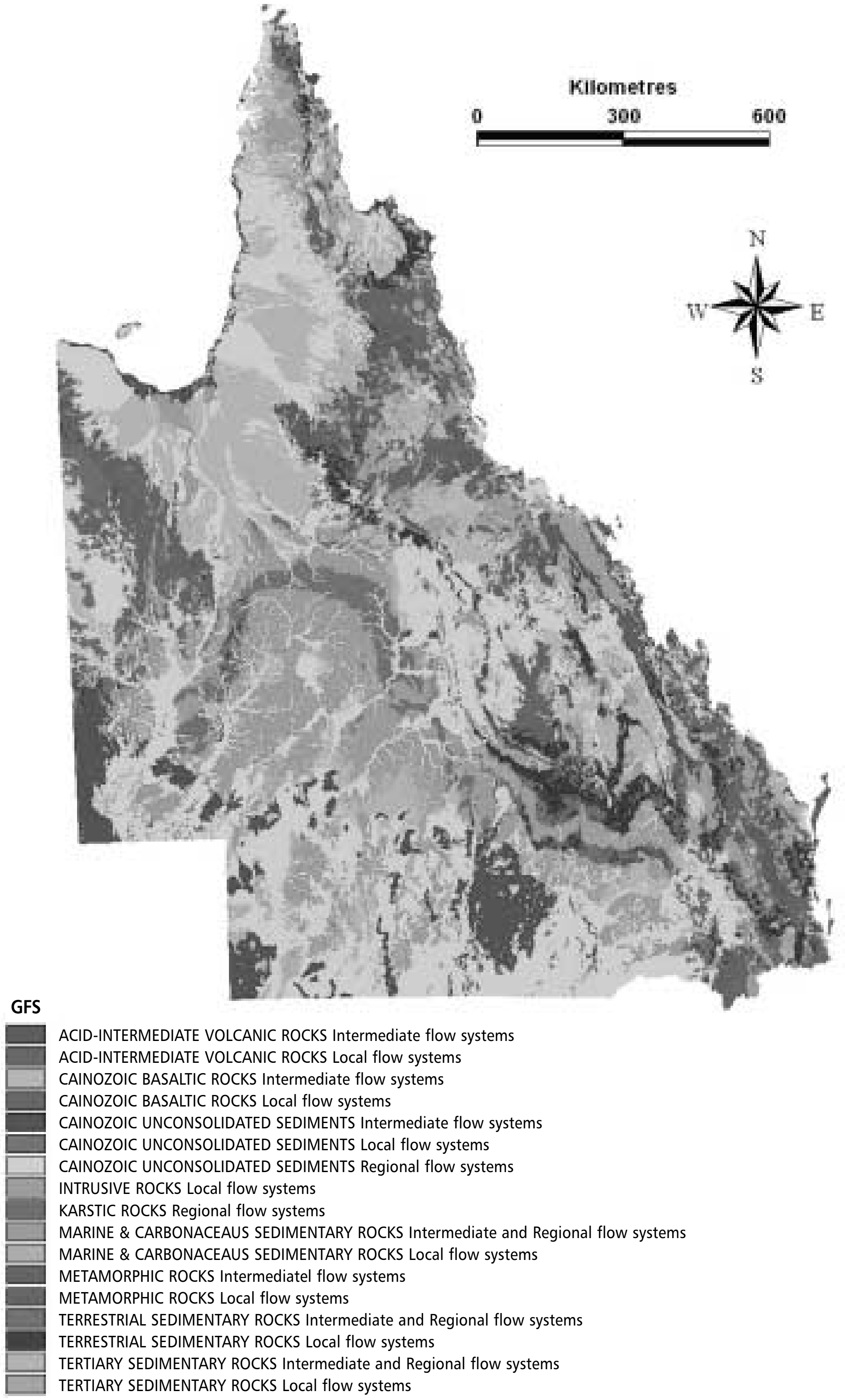

Figure 5. Groundwater flow systems in Queensland (provided by J Moss NR&M)

Implications for Queensland

The current national representation (Coram et al. 2000) is too coarse for catchment-based planning, but the underlying principles are applicable at the catchment scale. Classification or initial disaggregation of the landscapes in catchments on the basis of the characteristics of the groundwater flow systems recognised by Coram et al. (1998) is proposed as the most appropriate strategy for future salinity risk assessment activities in Queensland, since it builds on the accumulated experience from hydrologists and scientists involved in dryland salinity management across the States.

The groundwater flow systems map presented in figure 5 shows that much of the land in Queensland designated as having a high salinity hazard during the recent assessment for the NLWRA, is classified as having regional and intermediate flow systems. In southern Australia, these flow systems are causing considerable concern because of the challenges posed in managing groundwater levels. In Queensland, salinity discharge sites have been identified in intermediate flow systems in the central coastal area abutting metamorphic and granitic landscapes, and in the central west plains on marine and carbonaceous sedimentary rocks with intermediate and local flow systems. No formal monitoring of these groundwater systems has occurred to date. Most experience has been in dealing with dryland salinity from local groundwater flow systems; better definition of those areas with intermediate and regional flow systems has become a clear priority.

Case studies

Under The National Land and Water Resources Audit dryland salinity work plan, case studies were carried out in catchments in southern Australia as part of an evaluation of the groundwater flow systems–catchment water balance approach for assessing the risk of dryland salinity. The case studies employed a number of models covering a range of scales and purposes, from estimation of yields and water balance under crops and pastures, to estimation of groundwater trends across the landscape.

The objective was to identify:

- the areas of the catchment where changes in recharge would most affect salinity
- how much recharge reduction would be required to reduce salinity by a given percentage in an area of salt-affected land
- what land-use and farming system options would reduce recharge enough to manage salinity
- what information was necessary for an economic analysis of the costs, benefits and viability of the options for change
- what constraints there were to achieving the required change.

A final overview report (Coram et al. 2001a) provides an analysis of the lessons learned from the case studies and the overall approach adopted. This and other detailed reports of the individual case studies are available on the Audit website at www.nlwra.gov.au/atlas. Four catchments were selected on the basis of their salinity status and availability of information, and because they represented some of the most salt-affected groundwater flow system types in

Australia. They were the Lake Warden catchment in Western Australia, the Wanilla catchment in South Australia, the Kamarooka catchment in Victoria, and the Upper Billabong catchment in New South Wales. Because of the nature of the modelling tools available, the water balance modelling was undertaken in two components and at two different scales as described below (Coram et al. 2001a).

Groundwater flow

A broad catchment scale groundwater modelling approach was used to predict likely dryland salinity scenarios under different recharge regimes. The model used was *FLOWTUBE* (W. Dawes, pers. comm.)—a simple groundwater model based on conservation of mass with groundwater flows calculated using Darcy's Law. All flow occurs along a tube of one or more arms that represent the groundwater flow system of interest, and recharge and discharge are distributed both spatially and temporally.

Deep drainage

A detailed point scale analysis was undertaken to model the magnitude of water infiltrating below a number of different farming systems. *APSIM v1.6* (Agricultural Production Systems Simulator) was used for the simulations involving crops. *APSIM* is an agricultural systems simulation tool with a modular structure with modules corresponding to major processes such as water balance, soil organic matter dynamics, crop growth, etc. (McCown et al. 1996).

GrassGro (v2.1.2b) was used for the pasture systems. It allows analysis of grazing systems in southern Australia in terms of pasture and animal production, gross margins and year-to-year variability (Moore et al. 1997). In the Wanilla catchment, a soil-vegetation model, *WAVES*, was used to estimate shallow subsurface lateral flow (Dawes et al. 1998). *WAVES* is similar to *APSIM-SWIM* since it simulates soils using Richards' Equation to describe water movement, and uses models of plant growth and water use.

A combination of *APSIM*, Grassgro and *WAVES* enabled deep drainage (water infiltrating beneath the plant root zone) to be predicted under different farming systems, using the estimated excess water volumes (from *APSIM* and Grassgro simulations).

Outcomes

Coram et al. (2001a) concluded the following:

> Whilst there are a number of limitations to the combined modelling approach used, it has provided a useful technique for comparing the timeframes and realistic management options for catchments at risk of dryland salinity in a range of groundwater flow system types across Australia. The groundwater modelling used in these studies served as a useful 'first cut' to determine whether there is a likelihood of managing dryland salinity within a planning horizon, identification of the amount of recharge reduction necessary to slow, halt, or reverse dryland salinity, and the likely timeframes of doing so. The farming systems modelling approaches used in these studies then provided information about the excess water likely to infiltrate beneath different farming systems. This was used qualitatively to identify farming systems likely to achieve recharge reductions that the of the order of magnitude indicated by the groundwater modelling to be necessary for dryland salinity management.

> As with any modelling approach, the concurrence between the modelling results and the real catchment behaviour is limited by how well the model characterises the important characteristics and processes of the catchment. In this project, modelling was undertaken using existing data from catchments believed to be data rich. As the project proceeded, however, it became very evident that even 'data rich' catchments have only minimal data for specifying model inputs and for verifying model outputs. This does not lessen the value of the models as tools for investigating a range of hypothetical scenarios in even data poor catchments, but it does mean that further data collection will generally be necessary to apply a similar modelling approach to data poor catchments (the majority).

Analysis of the hydrogeological conditions and the modelled behaviour of groundwater flow systems to land-use change in each of the case study catchments elsewhere in Australia has confirmed that the concepts developed in the 'Australian Groundwater Flow Systems Contributing to Dryland Salinity' project could be applied more widely across Australia. The modelling approach has indicated that there are clear differences in how groundwater flow system types respond to land-use changes, in terms of how long it takes for the change to take effect, and what degree of land-use change is necessary (Coram et al. 2001a).

A major limitation of the case studies is that there was no integrated modelling approach to provide credible prediction of crop growth, pasture growth and water balance, or to simulate catchment-scale groundwater and salt transport. However, such an approach is not currently available, and other groups attempting similar tasks have encountered this same problem (Coram et al. 2001a). This is partly a result of the different scales at which the modelling was undertaken. The farming systems models predict deep drainage past the bottom of the root zone, while the groundwater models require actual recharge to the groundwater system as input. In many cases, processes that occur beneath the bottom of the root zone, yet above the groundwater system, and which influence the amount of vertical flow are being modelled. Such processes may cause diversion of the deep drainage by low permeability strata, resulting in lateral movement. The significance of these processes depends on the depth of the groundwater as well as the local stratigraphy.

While there are clearly a number of limitations to the modelling approach used, it has provided a useful technique for scoping the size of the problem and comparing the timeframes and realistic management options for catchments at risk of dryland salinity in a range of groundwater flow system types across Australia. This approach is already being applied in the Murray–Darling basin in Queensland; the Macquarie, Bogan, Castlereagh, Lachlan and Murrumbidgee catchments in New South Wales; the North-east, North Central, Wimmera, and Mallee regions in Victoria; and the Murray–Darling basin in South Australia.

Data requirements

The minimum dataset required to effectively implement a salinity risk assessment (Coram et al. 2001a) is identified below:

Hydrogeological conceptual model

In order to develop a credible conceptual model of the catchment hydrogeology to underpin the groundwater modelling, the following data are required:

- sufficient groundwater level information to construct a groundwater flow net for the catchment

- stratigraphical descriptions and bore details parallel and perpendicular to the main groundwater flow paths in the catchment
- hydrogeological characteristics of the hydrostratigraphic units, ideally from pumping tests within the catchment, but from relevant hydrostratigraphic units outside the catchment if necessary
- groundwater hydrographs from bores representing the range of hydrostratigraphic and geomorphic variation in the catchment
- map(s) of the current extent of salinity.

Groundwater modelling

In general, if there is enough information to define a conceptual hydrogeological model of the groundwater system, a model can be constructed and run to simulate the behaviour of that system. For the simplest implementation of a FLOWTUBE model, the following data are required:

- a (uniform) spread of water levels to allow estimation of groundwater surface
- a (uniform) spread of bore lithology data to estimate the physical size of the conducting aquifer (i.e. thickness, extent, width, base of material, any confining layers)
- a (uniform) spread of measurements of, or surrogates for, the state properties of the aquifer material (hydraulic conductivity, porosity or storage coefficient or specific yield)
- estimates of the location and amount of water sources to the conducting aquifer, that is, point and diffuse recharge rates and their spatial distribution.

Other data required include stream flows and salt loads, local climatic trends, and land-use changes.

Management implications

A number of management implications can be drawn from the current research:

- Dryland salinity is a groundwater problem.
- Managing salinity means managing groundwater systems where dryland salinity is a risk.
- Managing groundwater systems requires understanding of scale and process issues.
- Management options need to consider groundwater response timeframes.
- To deliver responses within acceptable timeframes.
- A combination of traditional and innovative options is needed to deliver responses within acceptable timeframes.

5

Future direction in Queensland

Data constraints

As stated earlier, the recent salinity audit (NLWRA 2001) identified northern Australia as a particular case for more detailed assessment of dryland salinity risk on the basis that prevention is likely to be a far better investment than any attempt at control or management after the event.

It is clear from the most recent assessments and planning activities in Queensland that there are considerable constraints to the sophistication (certainty) that can be applied to salinity risk assessments at the regional and catchment scale. The analytical framework is still being developed, and data on risk factors driving dryland salinity is very limited both spatially and temporally. In carrying out risk assessments the two basic aspects to consider are:

- the questions being asked
- the availability of data.

Asking ‘What are the questions being asked and by whom?’ should indicate the scale at which the assessment is required; how soon it is required; the confidence associated with the estimates; and the resources/inputs necessary. Identifying where salinisation is likely to occur at a subcatchment level is likely to require a different set of data, at a different scale, and with a higher level of confidence than that at a regional scale. Most cases will require a wider range of tools/models, and depending on the types and costs of possible threats, it may be necessary to develop a more detailed model.

The groundwater flow system (GFS) is a logical framework on which knowledge gained in other studies can be integrated and applied to salinity risk assessment in Queensland. However, spatial identification of the GFS is still constrained by the need for improved data on the attributes underlying the classification. Even at 1:250 000 scale, surrogates will be required to apply the GFS in a GIS analysis. The ‘validation’ study on the GFS concluded that the Australian groundwater flow systems map was reasonably accurate at a regional scale, but the scale of available data would limit its application at this stage.

One of the major concerns with the current map (1:2 500 000 scale) is that it is based on the underlying geology in areas where Cainozoic sediments (surficial deposits) may have an important control on hydrogeology. Under cleared conditions, some of these areas may develop significant saline discharge areas in local flow systems. How these connect to the underlying regional flow systems of the Great Artesian Basin is unknown. Future improvements in defining the groundwater flow systems will require studies to elucidate the hydrogeology of these eastern areas flanking the Great Artesian Basin (for example the Desert Uplands where significant clearing of natural vegetation has occurred recently).

Additional data will be needed to use trend-based methods of risk assessment in Queensland, and initially reliance will be placed on composite index and catchment water balance modelling approaches using the best available data.

The principal requirement of the various assessments will be the input of biophysical data, mainly through modelling. Of the list of inputs required in the risk assessment approach (figure 6), some (e.g. soil properties, geology, land-use cover) are not readily available at better than 1:1 m scale. Digital elevation data are available at larger scales, but are costly, and as yet not widely available. Additional data on groundwater levels, unrestricted in terms of time series, is required. Also required is further data on hydrogeology, aquifer characteristics and salt loads in the regolith. Data and parameters for water balance models are still very restricted in terms of spatial coverage, so representative values are usually used. This seriously limits not only the risk assessment approach that can be applied, but also the confidence that can be placed on the outputs.

The salinity risk assessment framework (figure 6) proposed for Queensland is based on the approach used by for the National Land and Water Resources Audit case studies (Coram et al. 2001a), and is similar to that being implemented in New South Wales by the Department of Land and Water Conservation (M. Littleboy, pers. comm.).

It is clear from this framework that evaluation of water and salt balance relies on a number of analytical components or models with varying utility for the specific questions being asked. For example, different types of models are appropriate for evaluating water balance at the point and small paddock scales), while others are more appropriate for use at the catchment scale, and for groundwater hydrology. Evaluation of land-use impacts on water and salt at the catchment scale generally requires the use of all of these types of models. Each has a specific suite of data requirements, assumptions and constraints. Those identified above are examples of models being used nationally for estimating components of salinity risks. *The input variables/attributes required are quite demanding, and the level of confidence in the output is largely dependent on these data being available at the appropriate scale.*

The major data requirements to undertake dryland salinity risk assessment in Queensland are:

- knowledge of, and data on, the types and attributes of groundwater systems in Queensland away from the alluvial zones of the major irrigation areas
- groundwater level and trend data in non-alluvial areas
- elevation, regolith and soils data across the State to support terrain analysis and salinity risk assessment at the catchment scale—particularly important in the lower relief landscapes west of the Great Dividing Range
- a monitoring and evaluation framework to ensure that all data gathering has an objective basis and will allow land management responses through time to be evaluated.

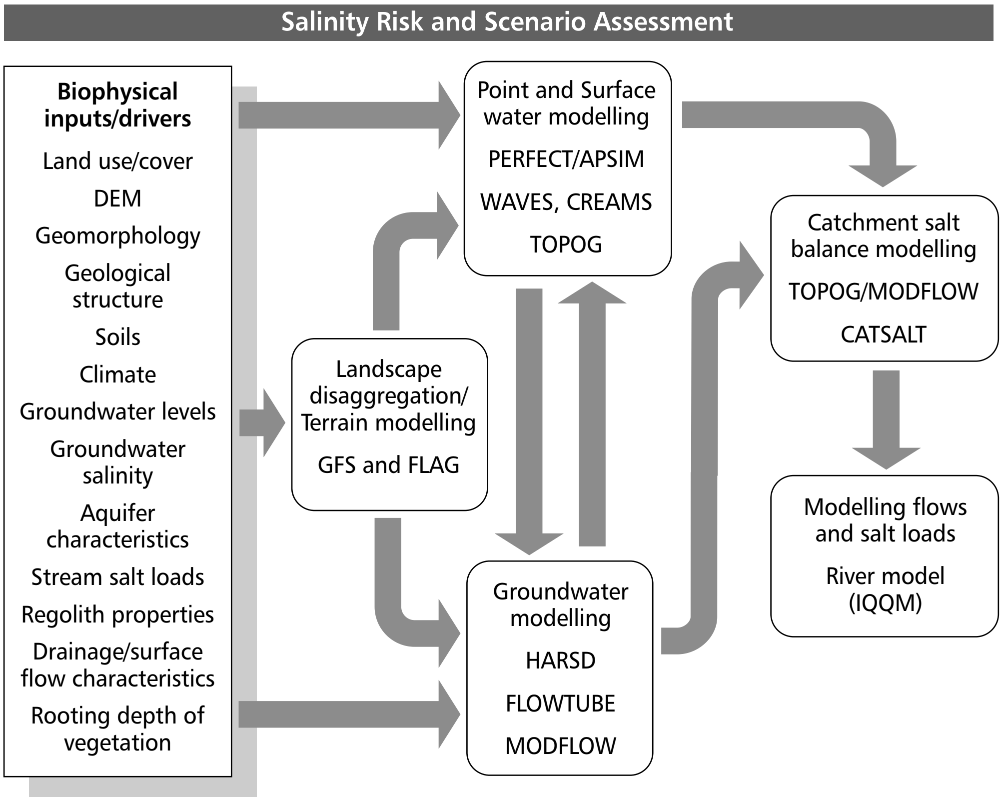

Figure 6. Salinity risk assessment framework

Priority thrusts

Given the current state of knowledge about the dryland salinity risks posed by current and future land use in Queensland, the following thrusts are proposed to improve capacity to assess the risk and to evaluate management responses.

1. **Collation and capture of improved biophysical data to underpin risk assessment analyses**

   Groundwater: The greatest priority should be given to obtaining additional information about the groundwater systems and their behaviour in the cropping and grazing regions of the State, particularly those that have been extensively cleared in the last 40 years. An emphasis should be placed on rigorously reviewing old files and reports associated with groundwater drilling and other groundwater investigations, with the objective of capturing any useful information on groundwater depths and trends, groundwater quality, and aquifer and regolith characteristics. The source material should include publications, files or reports from Commonwealth agencies such as the Australian Geological Survey Organisation, University theses and mineral exploration companies where possible. The eastern flanks of the Great Artesian Basin should be given particular attention, as this is an important area of uncertainty with the Australian groundwater flow systems map in Queensland. Some judicious groundwater chemistry studies might provide some evidence of connectivity between any significant groundwater systems developed in the Cainozoic deposits. These might be the areas where use of airborne geophysics is targeted.

Salinity surveys: All data from previous salinity surveys and studies carried out by DPI and NR&M should be captured digitally, along with any associated data on shallow groundwater. In the salinity hazard assessments carried out for the National Land and Water Resources Audit, it was stated that much of this data is not available digitally and did not form part of the groundwater assessments.

Geological structures: The role that geological structures play in controlling groundwater movement, particularly discharge, is well understood nationally. A range of landscape/ structural models contributing to dryland salinity have been identified within Queensland (DNR 1997), and have been incorporated into the National Classification of Catchments for Land and River Salinity Control (Coram ed. 1998). Much of this type of information is not readily available for assessment of the salinity risk of catchments; however, there are three major sources at the scale required—aerial photographs, Landsat data, and in some areas, aerial magnetic surveys. Aerial photography is already widely available in most parts of the State identified as having a high salinity hazard, though little detailed terrain/structure analysis (aerial photo interpretation) by professionals has occurred to date. Also, little or no analysis of Landsat data has, as yet, taken place. Neither has there been much review of existing magnetics data across the main regions of the State as part of salinity risk assessment. There would seem to be considerable merit in carrying out some analysis of the airborne magnetics data and the airphoto/Landsat data in the key catchments nominated for the National Action Plan for Salinity and Water Quality to capture information on landscape structures.

Soils and regolith characteristics: The current data available for much of the State is at less than 1:500 000 scale, but it is acknowledged that for catchment scale management and assessment, data at 1:250 000 or greater is required, particularly in areas of more intensive agriculture and horticulture. Therefore, options for capturing appropriately scaled data through enhanced resource assessment methods should be progressed.

2. Model development

Experience in the audit case studies and in the evaluation of the whole approach to risk assessment has emphasised the deficiencies in the model framework currently available to predict changes in hydrogeology, particularly recharge changes due to changed land use. There is very poor 'meshing' of the point models predicting water balance changes and recharge from groundwater models. The prediction of salt loads is also highly uncertain. There is a clear need for further development of models and frameworks to ensure that predictions of changes in water balance and salt transport resulting from various land management options can be more confidently supported.

3. Development of a groundwater flow systems map for Queensland at a scale of 1:250 000

The current hazard map for Queensland was based on a groundwater flow systems map derived from 1: 2 500 000 scale data. This was useful as an initial attempt at the national scale, but additional information will be needed for management support at the catchment scale, or for definition of priority activities Statewide. It is suggested that an improved version of the groundwater flow systems map be developed using data at 1:250 000 scale, and a digital elevation model (DEM) more accurate than the 9 sec DEM used previously. The improved groundwater flow system map should be underpinned by a well-resourced information management system to capture iterative improvements in datasets.

4. **A salinity risk assessment to focus activities**

   An upgraded salinity risk assessment should be carried out using 1:250 000 based groundwater flow systems framework to identify priority areas and to focus more detailed studies. This assessment will probably be the main technical basis for initial support of catchment groups tasked with developing salinity management plans. It is unlikely that there will be sufficient resources to carry out more detailed analyses of all catchments considered 'at risk', and this first level analysis may be the main assessment for the immediate future. This may have implications for the level and type of technical support required to respond to catchment group demands. Some form of interactive workshop planning using the approach of Phil Dyson and others in the MDBC and Victorian Government programs may provide the most suitable level and type of support. This involves using the best available data to develop a conceptual model of the groundwater systems operating in the catchment, identifying the constraints to or opportunities for management, and the most feasible methods for monitoring the success of the management options selected.

5. **More detailed salinity risk assessments of representative catchments**

   Building on the approach applied in the NLWRA case studies (NLWRA 2001), more detailed understanding of the catchment water balance and salt transport processes operating in representative catchments would improve confidence in prediction of land-use effects on the catchment water balance and behaviour of the groundwater flow systems operating in the northern environments of Australia. They could be used to monitor and evaluate the land-use impacts in more detail than could feasibly be implemented across all catchments. A subset of key indicators might be applied in the wider catchments of interest. An important part of risk assessment is estimation of the impact of climate change.

   Catchments might be selected on the basis that they are:

   - representative of the main groundwater flow systems as per the upgraded analysis using 1:250 000 scale data
   - of socioeconomic importance

   and on the basis of:

   - their terrain slope and function characteristics (accumulation and dispersion indices)
   - the current availability of data—particularly for recharge to groundwater—and aquifer characteristics.

More detailed studies in these catchments might include:

- hydrological investigations (including drilling where required) to develop conceptual models of groundwater systems
- measurement of recharge to groundwater under natural vegetation and current land use using a designed piezometer/bore network, lysimeters and other soil physics based methods

- targeted airborne and/or ground-based geophysics
- regolith/soils characterisation
- measurement of salt load out of the catchment or subcatchment
- water balance modelling (using the best available data initially) to provide an overview of deep drainage (potential recharge) across a range of important soils and agroecolo cal regions similar to those reported by Keating et al. (in press, figure 7).

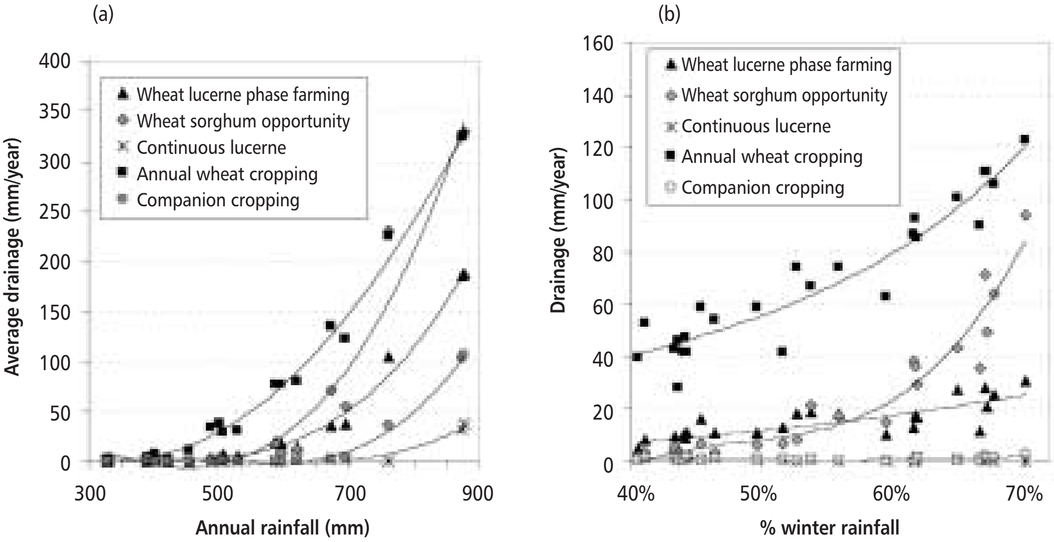

Figure 7. Simulated annual drainage for alternative farming systems (a) E–W transect and (b) N–S transect. Points show climate stations, lines regressions on climate variable. Red earth soil; no fallow weeds. (Keating et al, in press)

Opportunities for linking with the national program, 'Redesigning Australian Agricultural Landscapes' and the Landmark program within the Murray–Darling Basin, should be pursued.

Studies of recharge under natural and agricultural land-use systems in Australia where direct measurements have been made are relatively few, particularly in natural systems and particularly in northern Australia (Petheram et al. 2000). Since estimation of recharge is a very important aspect of water balance-related scenario testing, especially in relation to assessment of salinity risk, the establishment of some key research sites to measure (and estimate) recharge under natural and agricultural systems in northern Australia should be given a high priority. The various methods for measuring recharge have been described by Bond (1998), and Petheram et al. (2000), and summaries of the various studies carried out in Australia are presented.

6. Monitoring and evaluation system

Australian Dryland Salinity Assessment 2000 (NLWRA 2001) identified very serious deficiencies in capability to monitor dryland salinity across the States and Territories. Clearly, an objective management strategy requires a purpose-designed monitoring system to enable land-use management impacts on the land and water attributes responsible for dryland salinity to be evaluated.

The objectives of such monitoring programs are:

- to evaluate the effectiveness of previous management activities in terms of their impacts on the extent and effects of dryland salinity
- to increase knowledge of the processes causing dryland salinity
- to provide the data required to predict the likely future extent/severity/impact of dry land salinity, and the likely timeframes of management responses.

Monitoring efforts need to be relevant at a catchment scale, and within a clearly defined evaluation framework; that is, the use of the data needs to be clearly understood so the specifications are relevant to the purpose.

Following a review of monitoring systems for dryland salinity across Australia, Coram et al. (2001c) have identified a number of recommended monitoring attributes that directly measure the landscape response to management activities. They have also identified alternative attributes (sometimes referred to as 'surrogate' or 'interim' performance indicators), which measure activities that are likely to impact upon landscapes and cause a response related to dryland salinity. Use of these attributes should form the basis of future systems.

Recommended attributes (Coram et al. 2001c)

- Percentage retention of native, deep-rooted vegetation in high risk areas
- Long-term groundwater level and salinity trends
- Long-term stream salinity and salt load trends
- Extent of land salinised
- Agricultural system productivity

Alternative attributes (Coram et al. 2001c)

- Land-cover change and vegetative health mapping
- Mapping of land-use change
- Catchment planning based on resource assessment and daily water balance modelling
- Proportion of landscape where water efficient land use is adopted
- Volume of water or salt pumped from the groundwater
- Volume of water/mass of salt intercepted and disposed of
- Increase in long-term productivity of salinised areas
- Increased farm returns from salinised areas
- Proportion of potential discharge zone applying alternative salt-tolerant land use
- Rate of adoption of new salt-based industries

As the characteristics of groundwater flow systems determine the rates at which attributes such as groundwater levels respond to management options, they also influence the choice of monitoring attributes. For example, groundwater levels in areas dominated by regional flow systems are unlikely to respond quickly to changes in management; therefore the change in perennial vegetative cover over the main recharge zones of a catchment might be the monitoring attribute chosen for regular evaluation of progress.

Other core data required for evaluation of management responses are:

- climate
- digital elevation
- hydrogeological characteristics of the catchment
- soil–water characteristics and parameters for modelling purposes
- crop, pasture and forestry production data.

In all catchments of interest, a monitoring system might be tiered (nested) so that core data such as changes in groundwater levels, stream water volume and salt concentration, vegetative cover, and land-use systems are monitored at the catchment level, while more detailed spatial monitoring of these attributes and others is limited to representative catchments. The objectives of monitoring in representative catchments are more detailed. A major goal is to develop knowledge so that responses in the wider set of catchments can be understood and explained, and confidence in predictions of risks under a range of future scenarios can thus be increased. Protocols and standards should be consistent with any that have been nationally agreed.

Skills base required

In figure 6, the requirement for a range of biophysical data, hydrogeological skills, a number of surface and groundwater models, and considerable modelling capacity is emphasised.

Hydrogeological skills

Of the CIRM partners, staff of NR&M have hydrogeological skills, and limited experience with salt transport studies. Staff from the University of Queensland and Griffith University have similar skills and also some experience in salt transport studies. Staff of CSIRO Land and Water—based principally in Adelaide in Perth—have substantial skills and experience in both areas. Their Canberra, Adelaide and Perth groups are well-connected with the Centre for Groundwater Studies.

Outside CIRM, a number of State Government agencies, the Centre for Groundwater Studies, the ICAM group in the Australian National University (ANU), the CRC for Catchment Hydrology, and a number of consulting firms also have expertise in the field. The Victorian Department of Natural Resources and Environment, New South Wales Department of Land and Water Conservation (NSW DLWC), Primary Industries South Australia and the Western Australian Department of Agriculture all have skills in hydrogeology that are focussed on the management of dryland and irrigation salinity. They are also well linked to the CSIRO skills.

The Centre for Groundwater Studies has the following partners:

- CSIRO Land and Water
- University of Western Australia
- Flinders University of South Australia
- Water and Rivers Commission Western Australia
- Ministry of Planning Western Australia
- Water Corporation Western Australia
- United Water International Pty. Ltd.
- Department of Water Resources South Australia
- Milieutech Environmental Management Pty Ltd.

Few private industry groups have skills and experience in hydrogeology and salinity management. The principal groups are Sinclair Knight Mertz (SKM), in Melbourne and Perth, URS Australia, Salient Solutions (Ray Evans), Phil Dyson and Associates, and PPK Environment and Infrastructure.

Crop and pasture water balance modelling

The CIRM partners have considerable skills and experience in crop and pasture water balance modelling through the NR&M group at Indooroopilly and the Agricultural Production Systems Research Unit (APSRU) group at Toowoomba and Indooroopilly. So that greater confidence may be placed in estimates of drainage across the natural communities in regions with high salinity hazard, it may be necessary to further strengthen skills in and knowledge of water balance in the natural vegetation/forestry area within CSIRO Sustainable Ecosystems and APSRU (Huth et al. 2001).

NSW DLWC is developing a specialist group with modelling skills in this area.

Catchment hydrology modelling

Staff of the Indooroopilly and Toowoomba groups of NR&M, CSIRO Land and Water, Griffith University and the University of Queensland provide CIRM’s expertise in catchment hydrology modelling.

Other groups with specific expertise are the CRC for Catchment Hydrology, the CRES group at ANU and consulting groups such as SKM and URS.

Terrain analysis

As terrain analysis is one of the most important components in developing a conceptual model and the basis for assessment, it is a special requirement in all risk analysis. Among the CIRM partners, Mike Grundy and his team in NR&M, and CSIRO Land and Water in Canberra, Adelaide and Perth have particular skills. Outside CIRM, the CRES ANU group is probably the leader nationally. Of the State agencies, WA Agriculture is probably the best in this activity.

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