AN OVERVIEW OF MODELLING TECHNIQUES AND DECISION SUPPORT SYSTEMS AND THEIR APPLICATION FOR MANAGING SALINITY IN AUSTRALIA

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INTRODUCTION

In Australia, computer models are being used to support the development and implementation of salinity management strategies. These models facilitate the assessment of the impacts of salinity management options, and enable the outcomes of implementation to be quantified. Models can be used to estimate both potential benefits and any unwanted impacts of management actions.

There is a myriad of salinity models developed or under development across Australia. A recent stock take of models conducted by URS for the National Action Plan for Salinity and Water Quality (URS Australia 2002) contained details of over 100 models that can be used to assess salinity management options. While it could be argued that such a vast number of models is overkill, many of these models focus on different processes and aspects of salinity.

This paper reviews the range of modelling techniques and approaches used in Australia to improve the management and understanding of dryland salinity. The numerous modelling approaches being used in Australia have evolved to answer a variety of questions across different scales. While the main focus of this paper is on biophysical models, some case studies highlighting social and economic models and decision support tools currently being used in Australia are also be presented.

GENERAL MODELLING CONCEPTS

Computer models are mathematical representations of natural or economic systems. These can be very complex and highly variable in time and space. Often it is not possible or practical to represent these systems in great detail, and simplifying assumptions are commonly made. This is done for a number of reasons, including lack of basic data and that all the factors and processes affecting system behaviour are either not fully understood or are considered of less importance.

Although usually applied to spatial data, scale can also be relevant in a temporal sense. The spatial scales we are most interested in from a salinity management perspective are:
- property scale;
- subcatchment or catchment scale;
- river basin scale;
- regional scale;
- state scale; and
- national scale.

The scale of application of a model, both spatially and temporally has a major influence on its structure and detail. Aspects of natural processes that are important at one scale may not be relevant at another. Model complexity is often correlated with the scale of input data. As a general rule, more complex models require more detailed data, measured at finer scales; the simpler models require less detailed data, measured at broader scales. Equally, there is little or no benefit in modelling at a level of complexity beyond that supported by available data. There is little to be gained by using complex models with questionable estimates of input data (commonly referred to GIGO, Garbage-In Garbage-Out). Conversely, simpler models that require simple inputs often do not adequately capture all the necessary processes to represent the system under consideration. Therefore, there is a fine balance between available data, model complexity and desired outputs from the model.

From a temporal point of view, scale is reflected in the time step of the model. Models simulate the behaviour of systems over a period of time, which may range from hours to decades or more. Most models do this by calculating how the status of the system changes over a series of time steps in response to input data. That is, they calculate system status one step at a time over whatever the time period of interest is. Models may operate at different time steps such as hourly, daily, monthly, seasonal, or annual. Alternatively, they may operate without use of a time step, for example, average annual.

The time period over which a model is run also influences its complexity. It is rarely viable to apply highly complex modelling over long time periods, often due to a lack of climate data measured at short time steps (e.g. hourly). One solution is to run a carefully selected and smaller number of detailed model simulations and use these results to parameterise a simpler model that can then be more widely applied. This approach has the potential to distil the essence from more complex modelling into a simpler modelling framework.

REGIONAL FOCUS OF SALINITY MODELS

A number of factors must be considered to better understand why there is such a wide range of salinity models developed or under development across Australia. A major factor is the differences in the way that salinity is expressed and recognised in the environment across Australia. During the National Land and Water Resources Audit, Coram *et al*. (2000) developed a National Groundwater Flow Systems Map that identified 11 groundwater flow systems related to the scale and nature of hydrogeological processes causing dryland salinity (Figure 1). This map illustrates the diversity of hydrogeological processes across Australia.

For example, agricultural areas in Western Australia and South Australia tend to be dominated by local and intermediate systems in Precambrian geologies. Discharge often occurs in local topographic lows, where the surface topography falls below the unconfined water table or at break-of-slope in unweathered rock aquifers. In contrast, the upland areas of eastern Australia tend to be dominated by local and intermediate systems in Palaeozoic geologies. Discharge from fractured rock aquifers is often observed at the break-of-slope due to a reduction in hydraulic conductivity as groundwater moves from unweathered, fractured rock to weathered material. The spatial variability of groundwater flow systems means that the manifestation of salinity across Australia can take many forms. The development of salinity models across Australia has been strongly influenced by this variability.

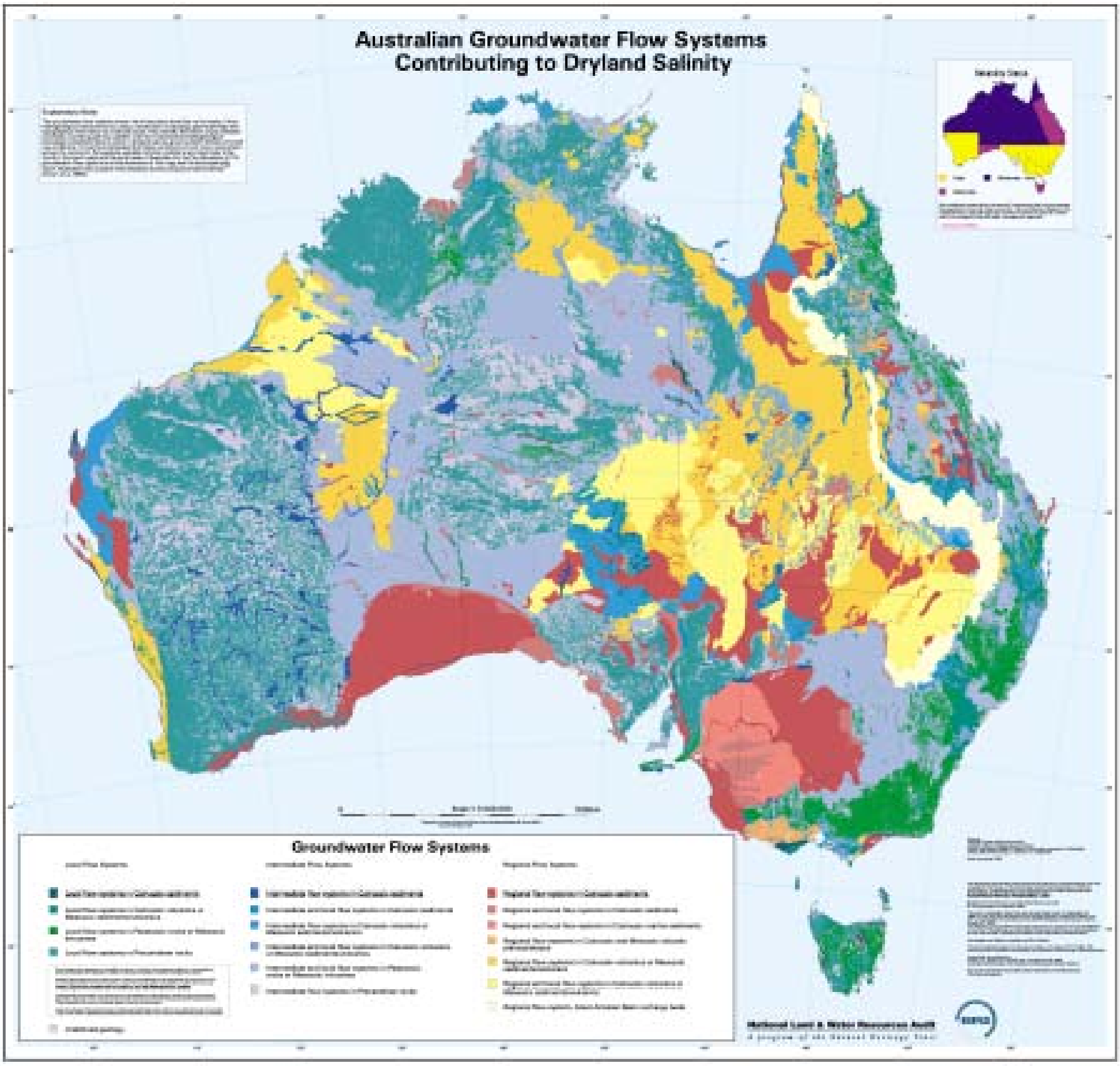

Figure 1: Groundwater flow systems of Australia (Coram *et al.* 2001).

In Western Australia, salinity is often observed as a landscape expression across large spatial areas due to rising water tables. Dryland salinity is basically caused by increased recharge resulting from vegetation change that raises the watertable, bringing naturally stored salts to the surface. In Western Australia, the main focus is on problems that develop from surface salinity such as loss of agricultural productivity and biodiversity, damage to infrastructure, and degradation of water supplies. The models being used in Western Australia reflect these processes by estimating water balance (particularly recharge) at paddock and catchment scales and linking to groundwater modelling to assess the changes in recharge required to effect a significant change in the final spatial extent of landscape salinity.

In South Australia, there are two main goals for salinity management. The first is to protect Adelaide's drinking water by keeping salinity in the Murray River below 800EC, at least 95% of the time on a daily basis. The second is to prevent future impacts of landscape salinity on agricultural land, biodiversity and infrastructure. A major focus for modelling in South Australia has been recharge reduction in areas near the Murray River to prevent direct discharge of saline groundwater into the river. Models that emphasise the prediction of stream salinity rather than groundwater salinity are of limited use in South Australia because there are no significant tributaries of the Murray River in South Australia.

In eastern Australia, salinity is recognised as a stream salinity issue rather than a landscape salinity issue. This does not mean that landscape salinity is not important in eastern Australia. Rather, it means that the first, most recognisable and measurable expressions of salinity have been increases in stream EC caused by surface expressions of dryland salinity in upland areas. There is little doubt that this focus is due to asset protection, in particular, stream salinity in the Murray River and consequent impacts on drinking water quality in Adelaide.

The major focus of salinity management in eastern Australia has been the concept of achieving a stream salinity target. Salinity targets can be defined in terms of a stream salt load (tonnes) or a concentration (Electrical Conductivity, EC). They express desirable salinity conditions in each catchment at some future date (for example, 2010). There are generally two types of salinity targets considered. The first is an end-of-valley target is a water quality target defined at the outlet of a catchment and expresses the overall salinity condition to aim for. The second is a within-valley target that can be water or land-based, and are defined at key points within a catchment to reflect desirable salinity levels at these locations. Consequently, salinity modelling in Eastern Australia has a stream EC focus to assess stream targets. Models have been developed that predict future increases in stream EC as well as the impacts of intervention strategies on stream EC. Complex groundwater modelling in Eastern Australia has typically focussed on groundwater allocation or groundwater contamination rather than salinity.

SALINITY MODELLING IN AUSTRALIA

Salinity models can be used to quantify many questions related to salinity management, for example, audit analyses (forecasting of future stream salinity trends and areas of land salinisation), identification of “hotspots” with respect to stream salinity and landscape salinity, prioritisation of areas for investment into managing dryland salinity, quantifying the impacts of management interventions on salinity, and implementation and monitoring of on-ground works. A variety of modelling tools are being used across national, state, regional, catchment, subcatchment and property scales. Similarly, many decision support systems are scale (spatial and temporal) dependent. In Australia, the larger number of salinity models being used are generally complementary rather than competing in that they address different aspects of salinity processes across different scales. Models can be used to quantify where salinity is an issue, when it is likely to become an issue, how bad it is likely to get and what are the likely impacts of intervention strategies.

Generally, biophysical salinity modelling in Australia can be classified into four broad categories: salinity hazard models, trend models, scenario models and river basin models. Some examples of salinity models and decision support tools that are currently being applied in Australia are summarised in Table 1. While this list only contains a subset of the models available, it includes many of the major modelling tools being applied in Australia

Table 1: Some examples of salinity models and decision support tools in Australia

	Area	Focus	Summary
Hazard			
BRS	Australia	Landscape	Composite index of climate and soil properties
Queensland	Qld Murray-Darling Basin	Landscape	Composite index of recharge potential, discharge sensitivity and salt stores
Trend			
MDBC Audit	Murray-Darling Basin	Stream	Linked rising groundwater model with current stream salinity trend to predict future stream EC and salt loads
NLWRA	Australia	Landscape	Identified of current and future areas of shallow water tables. Linked to impact assessment on agriculture, urban and infrastructure
Scenario			
BC2C	Murray-Darling Basin	Stream	Predicts regional scale impacts of afforestation and other land use changes on mean annual water yield, recharge, and stream salinity
CATSALT	Subcatchment	Stream	Evaluates impacts of land use changes in a catchment on daily time series of water yields, salt loads and salinities exported from the catchment.
MODFLOW	Catchment to Regional	Groundwater	Evaluates the effects of management options on aquifer behaviour including effects of water usage patterns and changes in recharge regime due to land use changes
FLOWTUBE	Catchment	Groundwater	A simple groundwater model for examining the effects of a range of recharge and discharge options on catchment groundwater.
River Basin			
IQQM	River valleys (NSW)	Stream	Salt transport model linked to NSW water allocation model (IQQM) to route salt through river networks
REALM	River valleys (Vic)	Stream	Salt transport model linked to Victorian water allocation model (REALM) to route salt through river networks
Decision support			
LUOS	Property to catchment	Property Planning	Evaluates impacts of land use changes at a site on water yields and salt loads exported from the catchment. Evaluates benefits indices for six additional environmental services via a set of analytical toolkits.
SALSA	Regional	Regional Planning	Compares the costs of alternative land use scenarios in the Murray-Darling Basin

Salinity Hazard Modelling - Where *might* salinity be an issue?

In this paper, the following definitions of hazard and risk are assumed.

> Salinity Hazard: The inherent landscape or catchment characteristics that predispose a particular area to the development of salinity.

Salinity Risk is a measure of the likelihood of salinity occurring as a result of the interactions between land use, water balance, climate and other activities.

Salinity hazard maps identify areas where landscape salinity might be an issue. Salinity hazard is derived from an understanding of areas of recharge, discharge, salt stores and groundwater flow systems. When compiled and verified by local knowledge, the salinity hazard map can be used in an initial catchment planning framework to raise awareness of the potential for salinity given these physical factors. However, the major limitation of the hazard approach is that it is a static representation of a dynamic process, and only considers the factors that predispose a landscape to salinity. It does not consider the likelihood or risk of salinity actually occurring. For example, it is possible that some areas identified as high salinity hazard may have a negligible risk of salinity. While this may initially appear confusing, these definitions of hazard and risk are entirely compatible with the definitions of hazard and risk adopted under Occupational Health and Safety guidelines (e.g. Australian Standard for Risk Management - AS/NZS 4360).

A range of organisations since the late 1980s has produced salinity hazard maps. Such modelling is usually undertaken using a composite index method in a GIS environment based on spatial data; for example, soils, topography, salt stores, climate, and groundwater flow systems data. Some better known examples were released by Bureau of Rural Sciences, BRS (Dent and Veitch, 2000), New South Wales (Bradd *et al*. 1997) and the Queensland Department of Natural Resources and Mines, QDNRM (Moss *et al*. 2002). The BRS map (Figure 2) was derived for the whole of Australia based on rainfall surplus (rainfall in excess of evaporation) overlaid with soils with inherent salinity. It has since been refined using topographic constraints. The areas of salinity identified are strongly influenced by the climatic data. The map illustrates some areas, especially across northern Australia, where salinity is not considered an issue.

In Queensland, salinity hazard maps have been produced for all the NAP priority catchments. These maps and data sets evolved from earlier composite index modelling. The current approach is to define three interim data layers that determine salinity hazard, namely: recharge potential, discharge sensitivity and salt stores. A range of base data layers including climate, topography, soils, geology and groundwater flow systems are required to derive each interim layer. Importantly, local knowledge is used to verify the extent and severity of the salinity hazard prior to release to the community. The advantage of this approach is that the cause of salinity hazard (e.g. high discharge potential) is identified. Consequently, management actions can be developed that specifically address the cause for salinity rather than a generalist approach to salinity, which may not provide effective outcomes.

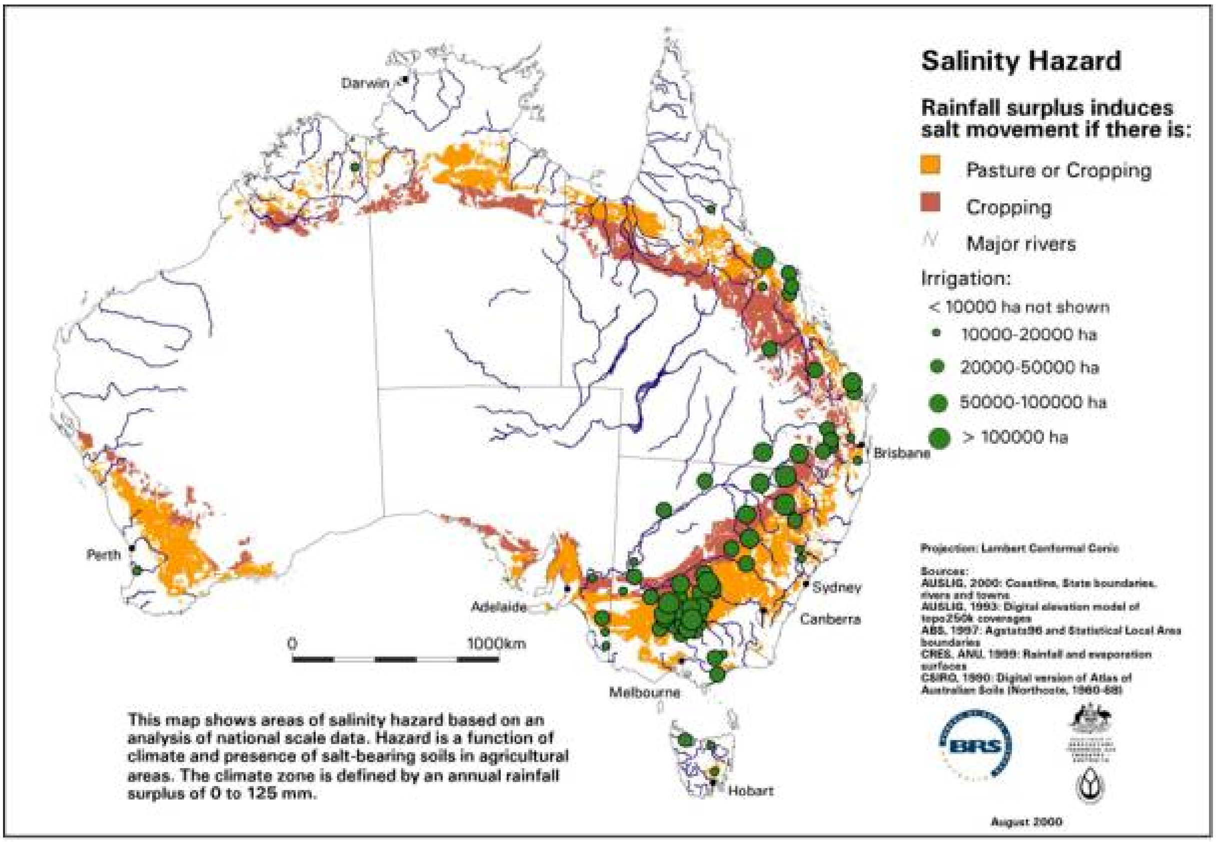

Figure 2. Salinity hazard map of Australia (Dent and Veitch 2000).

Trend Modelling - How bad will salinity get in the future?

Trends can be predicted for stream salinity, for example, the Murray-Darling Basin Salinity Audit (Murray-Darling Basin Ministerial Council, 1999) or landscape salinity, for example, the National Land and Water Resources Audit (Natural Heritage Trust, 2001). With this type of model, trends through time are statistically derived from historical data and extrapolated into the future. Trend models are typically applied at broader scales, for example, catchment to national scales.

The use of trend modelling to determine future salinity impacts is a relatively new science. Jolly et al. (1997) reported on salt mass balances and trends for catchments in the Murray-Darling Basin. This was followed by the Murray-Darling Basin Salinity Audit (Murray-Darling Basin Ministerial Council, 1999) that dramatically increased the awareness of salinity as a major environmental issue in Australia. The Audit forecast substantial increases in stream salinity throughout the Murray-Darling Basin over the next 100 years and potential impacts on urban water supplies and aquatic environments. This audit was based on the "rising groundwater" model where groundwater rise trends are statistically derived from historical bore data and extrapolated into the future. Increases in groundwater discharge and stream baseflow can be calculated from the estimates of the amount of land affected by shallow groundwater into the future.

The National Land and Water Resources Audit (Natural Heritage Trust, 2001) provided information on the areas affected by shallow water tables, now and into the future. This audit had a landscape focus rather than a stream focus; however, it did not actually consider salinity. Rather it considered current and future extents of shallow water tables regardless of whether they were saline or non-saline. Each State undertook separate analyses that were merged into a final product. Differences in project resources, quality of data, and conceptual frameworks across Australia resulted in differences in methodology across States. Therefore, it is difficult to compare results between States. However, despite its weaknesses, this audit was a major step forwards in the creation of spatial data sets that identify of areas potentially affected by salinity. This modelling was also used to evaluate the biophysical and economic impacts on agricultural land, urban development, and infrastructure (roads, railways, and other engineering structures).

Scenario Modelling – What are the impacts of salinity management actions?

The majority of salinity models in Australia have been developed to assess scenarios. This type of model estimates the impacts of different management scenarios on hydrology and salinity. A scenario can represent a land use, a land management change or an engineering solution. Each scenario is simulated over a fixed period of climatic data, for example the 1975-2000 Murray-Darling Basin benchmark period. By standardising the climate input, differences between simulations can be calculated and used to quantify the impacts of the scenario on the water balance, catchment hydrology and salinity. These types of models are not being used for future trend modelling. That is, they do not consider rising water tables, increasing stream salinity, or climate change. There is a clear need to link scenario modelling with trend modelling to assess transitional change and impacts on future trends.

Scenario models are usually applied at a subcatchment to catchment scale, but more detailed models can be applied down to individual paddock scale. Some of the key models that are being used to quantify unsaturated zone hydrology, groundwater, and catchment scale hydrology and salt export are described below.

Unsaturated zone models. A number of relatively simple water balance models have been applied to predict how climate, vegetation, soils and land management influence the water balance as part of a wider salinity modelling activity. Some applications include AgET in Western Australia (Argent 1999), GRASP pasture production model in Queensland (Owens *et al*. 2003), PERFECT cropping systems model in Queensland (Owens *et al*. 2003), New South Wales (Littleboy *et al*. 2003) and Victoria (Baker *et al*. 2001; Beverly *et al*. 2003), APSIM cropping systems model (e.g. Asseng et al. 2001; Baker *et al*. 2001), and the GRASSGRO pasture production model in Victoria (Baker *et al*. 2001; Beverly *et al*. 2003). Although these are five different models, they share many conceptual similarities. All are bucket-type models that simulate the 1-dimensional or paddock scale water balance. They do not simulate lateral flow or hydrological connectivity within a catchment. More complex models that account for sub-daily infiltration processes based on soil physics (e.g. Richards Equation) have been applied to predict recharge in smaller, focus areas and subcatchments. Some examples include HYDRUS as part of the CATSALT model in New South Wales (Tuteja *et al*. 2003), SoilFlux in Victoria (Daamen *et al*. 2002) and the TOPOG model to investigate the accumulation of salt in the root zone of a tree plantation over a shallow water table (Silberstein *et al*. 1999). These more complex models have more demanding data requirements that often prevent widespread application.

Groundwater models. The major groundwater models used for salinity modelling in Australia are FLOWTUBE (Dawes *et al*. 2000) and MODFLOW (McDonald and Harbaugh 1988). FLOWTUBE can assess long-term trends in groundwater levels, and estimate rates of rise of groundwater, length of the flowtube with water at or near the catchment surface, and the periods of time over which groundwater movements will take place. It provides preliminary estimates of impacts of land use changes on average water levels in groundwater flow systems and times to transition from one equilibrium state to another. In Western Australia, groundwater modelling using the FLOWTUBE model has been undertaken to assess the magnitude of changes in recharge required to produce a significant change in the final extent of salinity (e.g. George *et al*. 2001). It has also been applied in other areas of Australia including the Liverpool Plains in New South Wales (Dawes *et al*. 2000), Eyre Peninsula in South Australia (Stauffacher *et al*. 2000), and northern Victoria (Baker *et al*. 2001).

The MODFLOW model is a complex 2-dimensional model of groundwater flow. In Australia, it has been widely applied but primarily for groundwater allocation and contamination modelling rather than for salinity modelling. It evaluates the effects of management options on aquifer behaviour including effects of water usage patterns and changes in recharge regime due to land use changes. The Murray-Darling Basin Commission undertook a major study using MODFLOW to improve the understanding of the groundwater flow systems and assess the associated water resources. Five major modelling studies covered the regions of the Lachlan Block, the Southern Riverine Plain, the Lower Murrumbidgee, the Lower Darling, and the South Australian and Victorian Mallee. These studies assessed land and water management options and estimated impacts on groundwater resources, river and aquifer interaction and salinity. Other examples of the use of MODFLOW for salinity modelling include the comparison of different land management options in terms of their effects on crop productivity, stream flow, stream salt load, and stream salinity (Daamen *et al*. 2002) and as one component of the Victorian Catchment Assessment Tool model.

A range of groundwater models across three scales: regional, floodplain and wetland are also being applied in South Australia (e.g. Pavelic *et al*. 1997). The floodplain model determines the current salt accumulation and seepage within the floodplain and its effects on riparian vegetation health. It also predicts future salt attenuation, accumulation and seepage, and their impacts on riparian vegetation and river salinity due to future irrigation developments and irrigation management scenarios. The more detailed wetland model is designed to estimate changes in salt load and water use from wetlands from different management regimes.

Catchment hydrology and salt balance models. A large number of models have been used throughout Australia to estimate catchment hydrology. This section focuses on examples that have been used directly for salinity modelling. In Western Australia, the CATCHER model (Argent 2000) links to their 1-dimensional AgET model and estimates how planting of crops in different areas within a catchment affects catchment scale water balance. This can then be linked to FLOWTUBE to assess groundwater response.

Within the Murray-Darling Basin a number of models have evolved to estimate catchment hydrology and salt balances. This is not surprising given the publicity and emphasis of stream salinity in the Basin. The BC2C model predicts the regional scale impacts of afforestation and other land use changes on mean annual catchment stream flow, groundwater recharge, and stream salinity. BC2C is a simple model based on the Zhang *et al*. (2001) hydrological model coupled to a groundwater response function. The model disaggregates spatially into groundwater flow systems, predicts land use impacts on water yield, partitions hydrology into recharge and runoff and estimates salt exports. Outputs from BC2C are “first-cut” estimates of impacts of land use changes on groundwater response times for transition from one equilibrium state to another and estimates of impacts of land use changes on water yields and stream salt loads. The BC2C type modelling has been applied to assess reafforestation scenarios in the Macquarie catchment (Herron *et al*. 2003), linked to farm-scale economics in the Little River catchment in central New South Wales (Nordblom *et al*. 2003), and the assessment of regional salinity management scenarios (Heaney *et al*., 2000; Hajkowicz *et al*. 2003).

The CATSALT suite of models in New South Wales (Tuteja *et al*. 2003) assesses the contribution of salinity management actions to meeting salinity targets and supports the planning and prioritisation of salinity management investment at state, regional and subcatchment scales. CATSALT evaluates impacts of land use changes in a catchment on a daily basis on water yields, salt loads and salinities exported from the catchment. Current work is improving CATSALT to evaluate interactions with adjoining areas within a catchment. The model has been applied and tested across nine focus subcatchments in New South Wales (e.g. Tuteja *et al*. 2003, Vaze *et al*. 2003) and is supporting a roll-out of salinity models across approximately 150 subcatchments in New South Wales.

In Victoria, the Catchment Assessment Tool or CAT, integrates a range of models operating across scales. It contains detailed unsaturated zone models to simulate land use impacts, a catchment scale hydrology model and a detailed groundwater model. CAT was developed to estimate changes to water partitioning from land use change, engineering works, and management change at the catchment and farm scale. The current version of CAT only considers hydrology and does not include salt balance modelling.

River Basin Modelling - How much salt moves through the river system?

Models such as IQQM, REALM and MSM/BIGMOD have been developed to support Water Sharing Plan development in regulated and unregulated streams, and water resource management in general. These models evaluate the effects of management options on regimes of water, salinity and other water quality parameters through rivers systems and the impacts on the various categories of water users. This type of model has the potential to provide the linkage between catchment-scale salinity modelling and water allocation modelling. These three models estimate water flow only and are currently being upgraded to model salt movement through river basins. When connected to a catchment model, the impacts of a land use change on hydrology and salt loads can be tracked down the river network to a mid-valley or end-of-valley target site. A salt transport model also forms part of a stream EC trend model as it provides the analytical framework to predict the impacts of future increases in groundwater discharge and stream baseflow on salinities and salt loads in the river network.

Decision Support Models – What if?

Decision support systems can be defined as the integration of expert knowledge, management models and timely information to assist in making day to day operational and long range strategic decisions (Thompson *et al*. 1992). Key concepts are the ability to evaluate "what if" questions and to predict the effects of decisions. At its broadest definition, a decision support system (DSS) is any methodology that is helpful to a decision-maker to resolve issues of trade-offs or prioritisation through the synthesis of information. In this sense, it is not necessary that the DSS be computer-based, although the use of computers allows for “what-if” scenarios to be rapidly calculated and discussed. A multiple-objective decision support (MODSS) approach is preferred when there are many and possibly conflicting objectives to be addressed simultaneously, which is an important consideration in developing sustainable management actions to reverse salinity impacts. Additional characteristics of decision support systems conducive for catchment and regional scale planning include:

- A comprehensive and systematic framework for ensuring that a wide range of alternative plans are formulated and appropriately researched to meet the needs of natural resource management across economic, environmental and social/cultural and institutional considerations.
- Provide decision-makers with a structured process to gather and display the required data in a clear and transparent framework. Integrating community values with best available knowledge.
- A MODSS is not a substitute for the considered opinion of the decision-maker; these systems do not make decisions. Decision-support systems are not decision-making systems.
- Many decision-support systems are not designed to find an optimal solution. MODSS aim to achieve a solution though an evaluation of a range of options against stated decision criteria.

A number of DSS tools have been developed and applied by a range of State and Commonwealth Agencies. In New South Wales, the Land Use Options Simulator or LUOS (Herron and Peterson, 2003) is a property planning tool for salinity management and for delivery of environmental services, comprising salinity, carbon sequestration, terrestrial biodiversity, soil retention, water quality and acid sulphate soils. This tool can be used in the field in interactive sessions with landholders to explore property planning options that give desired outcomes for salinity and other environmental services. Currently, LUOS evaluates impacts of land use changes at a site on water yields and salt loads exported from the catchment, with other environmental services under development.

The SALSA model (Salinity and Landuse Simulation Analysis has been designed to compare the costs of alternative land use scenarios in the Murray-Darling Basin (Bell and Heaney 2001). The biophysical component of SALSA is underpinned by an earlier version of the CSIRO BC2C model. SALSA first establishes the costs of a baseline scenario, then considers and compares the costs of alternative scenarios. For example, the model has been used to estimate the benefits and costs of reafforestation options for salinity management in the Macquarie-Bogan catchment (Heaney et al. 2000). The net benefits of reafforestation scenarios for a range of land discharge systems, groundwater response times, groundwater salinity and soil types were determined. In another study, SALSA has been applied to quantify the economic benefits of improving water use efficiency in the South Australian Riverland. The results indicate an overall reduction in salt load of around 20 per cent in 2050, generating agricultural benefits of up to $11 million (Heaney and Beare, 2000).

The Murray-Darling Basin Commission and CSIRO, along with consultants URS and AWE, have developed a Mallee-specific Interim Rapid Assessment Tool (SIMRAT) to evaluate the salinity impacts of interstate water trade. It contains a log-normal formulation of time response of drainage flux to recharge (Cook), a CSIRO groundwater unit response approach, surface water system, tile drainage, dilution effects of water transfers and the MDBC suite of model runs. It is both a spreadsheet based (Microsoft Excel) and GIS based tool that outputs salinity impacts and costs for a 100 year timeframe.

In Queensland, Facilitator (Lawrence and Shaw, 2002) is a generic multi-criteria analysis tool developed to provide a simple, transparent decision framework to integrate multiple objectives, multiple stakeholders and varied data sources and bodies of knowledge. It was developed using algorithms and aggregation techniques from a prototype decision support system developed by the USDA Agricultural Research Service (Lane *et al*. 1991, Yakowitz *et al*. 1992). Options are scored against decision criteria as a measure of impacts, and the criteria are weighted according to an order of importance. The outcomes provide a prioritisation of the options.

JavaAHP (Zhu and Dale 2001) is a relatively simple tool, web-based DSS. The tool builds hierarchy trees of stated preference as described by Saaty (1980), which differs to the matrix or effects table approach that underlies Facilitator. The weighting techniques available in JavaAHP are the AHP (Saaty 1980) and SMARTER (Edwards and Barron 1994), and the aggregation technique is the weighted summation method. It can only be run when the user is connected to the JavaAHP web site. The analyses are password protected and therefore can be made available to chosen stakeholders or other decision-makers, thus allowing easy access to current analyses.

FUTURE DIRECTIONS FOR SALINITY MODELLING

This paper has provided an overview of current salinity modelling in Australia and has recognised the diversity of the current suite of modelling tools available. We do have an excessive number of models being used across Australia, but it is not as shameful as one may conclude by simply looking at a single list of models. It must be recognised that models have been developed for a range of specific applications; hazard mapping, trend forecasting, assessing scenarios and river basin modelling. The diversity of models also reflects the major biophysical processes causing salinity that varies across Australia.

To overcome some of the current duplication within salinity modelling in Australia, there are some strategic directions that should be followed. There is little doubt that biophysical models are valuable tools to investigate interactions between processes and management options. In his review of crop yield models, Ritchie (1991) reported six criteria against which specification of the ideal model could be matched. According to Ritchie, the ideal model should have:

- balance between all component processes;
- general applicability in space and time;
- realistic data requirements;
- ability to be linked with other models,;
- structured programming; and
- and user-friendliness.

In addition to Ritchie’s criteria, there are some other important considerations.

- Access to the necessary and competent skills and training to apply the model;
- transparency of the model; its structure, algorithms, underlying assumptions, and honest statements of model strengths and deficiencies;
- confidence in how well the model represents reality or the validity of the model; and
- quantification of uncertainty in model predictions.

Model Integration

One of Ritchie’s criteria especially relevant to salinity modelling is the ability to be linked with other models There are no integrated modelling frameworks currently available in

Australia that capture all aspects of salinity management. However, many components of such a system exist and substantial progress is being made towards integrated frameworks.

Some specific needs are:

- better integration of scenario and trend models so that the impacts of land use scenarios on future salinity trends can be assessed; and
- better integration with models and decision support systems used for other Natural Resource Management issues so that the impacts of intervention strategies on a range of environmental benefits can be assessed.

In eastern Australia, there is a variety of salt balance models currently being used (BC2C, CAT, and CATSALT). These different approaches have evolved from previous research activities and reflect data availability, skills within organisations and organisational priorities. They generally lack integration. The lack of a consistent salt balance modelling approach within the Murray-Darling Basin has led to anomalies in model output along State borders and results that cannot be readily compared across States. A new CRC for Catchment Hydrology Project commenced in 2003 to develop a salt balance model that will provide consistent output across eastern Australia as part of State, Murray-Darling Basin and National investment and catchment planning reporting mechanisms. This project has been designed to supplement and build on, rather than replace, existing salt balance modelling. It brings together components and strengths of existing modelling activities rather than building a new model from scratch.

Model Accreditation

To gain confidence and acceptance of model predictions, better peer review, client review and accreditation of models are required. This rarely occurs but is currently being addressed, in part, under the National Action Plan and Murray-Darling Basin Operational Protocols. According to the Murray-Darling Basin Operational Protocols (Murray-Darling Basin Commission 2003):

> "A model developed by a State Contracting Government must be capable of predicting the effect of all accountable actions undertaken in the State, and of any delayed salinity impacts, on the salinity, salt load and flow regime at each site at which compliance with an end-of-valley target is to be measured in each of 2015, 2050, 2100, and in such other years as the Commission may determine."

The protocols list a total of 33 specific criteria that will be used to evaluate models in the Murray-Darling Basin. Models used to evaluate contributions of salinity management actions to end-of-valley targets and impacts at Morgan are required to go through this process by 2007, and seven year cycles thereafter.

Improved communication between model developers, model users and end-users of modelled information is required throughout the modelling process from model conceptualisation, development, evaluation and application. This is required to ensure that a model is used appropriately in relation to the processes simulated and more importantly, the scale at which the model is valid. It will also improve community understanding and acceptance of the model and the modelled results.

Model Uncertainty

Model uncertainty is a quantitative measure of the confidence in a model prediction, for example, 650EC ±80EC. Modellers rarely present any assessment of model uncertainty, despite numerous requests for this information from end-users of models, particularly when model output is being used to support policy decisions. This is a major limitation of current salinity modelling activities in Australia. For a simple model (e.g. a regression equation), model uncertainty is a trivial calculation. However, for models more complex in time and space, it is far from a trivial calculation to express model uncertainty.

The question of how to quantify uncertainty, or even whether we can quantify model uncertainty for more complex models is currently a debatable issue in the scientific community. The quantification of model uncertainty across the suite of salinity models currently being used in Australia represents a major challenge for the future.

Model Validation

Model validation tests that a model is accurately mimicking reality. Many salinity models used in Australia are unvalidated. Validation improves confidence in the model itself (structure and algorithms) and the parameterisation of the model. It is traditionally undertaken by comparing model output against a measured and independent data set that was not used for model development, calibration or parameterisation. Unfortunately, such data sets are rare. Rarer still are those data sets that include the range of different data types (e.g. streamflow, stream EC, groundwater levels, and soil water balance) needed to validate a more complex model that simulates system behaviour rather than a single process.

It must be remembered that no model can ever be completely validated because there is insufficient data available to completely validate a model for all climates, landuses, soils, geologies and groundwater flow systems. If we had sufficient data to completely validate a model, then the model itself would be superfluous. By nature, models extrapolate the limited data we have in time and space

Given these limitations in data available for model validation, some other alternatives are possible.

- Cross-validation of models is possible when a range of conceptually different models are applied to predict the same output. Enhanced confidence is achieved if model outputs are similar for all models. For example, confidence in an integrated model is increased if similar estimates of catchment recharge are obtained from unsaturated zone, groundwater and catchment hydrology models. Model cross-validation is being increasingly used in salinity modelling in Australia to overcome data limitations.
- Qualitative validation is the subjective assessment of model performance by independent experts. Greater confidence can be obtained through the qualitative validation of a model as it develops through a series of prototypes. Salinity modellers in Australia despite more frequent use in other disciplines (e.g. economic modelling) have generally overlooked qualitative model validation.

Software Development and Support

The software limitations identified by Ritchie in 1991 are still relevant despite the enormous growth in computing power and software. Integrated modelling platforms such as the CRC for

Catchment Hydrology Modelling Toolkit have great potential to provide a software environment to facilitate the development and application of salinity models in the future.

Decision Support Systems

Decision support software development needs to consider negotiation principles as a component of their functionality. This involves software functionality, flexibility to view inputs and outputs in a variety of ways. The application of decision support systems must also be carefully facilitated by trained staff to ensure the aspirations of all stakeholders are addressed throughout the process. Currently, there is a deficiency in spatial decision support systems that allow for spatial and temporal trade-offs of environmental, economic, social and institutional requirements at the catchment and regional scales. This will be an essential requirement as regional bodies develop and implement their regional resource plans that address salinity, water quality and biodiversity actions.

CONCLUSIONS

Computer models are valuable tools to support the development and implementation of natural resource management strategies to combat salinity. Models enable the impacts of salinity management options to be assessed, and the outcomes of implementation to be quantified. Models can be used to:

- identify priority areas for salinity intervention;
- quantify the hydrological impacts of salinity management scenarios; and
- forecast future trends in both stream and landscape salinity.

A wide range of modelling and decision support tools that address numerous aspects related to salinity management have been developed and applied across Australia. Spatial variability in hydrogeological and salinity processes across the continent has defined the focus and content of these models. The complete integration of scenario models, trend models and decision support systems has yet to occur, but significant progress has been made towards this goal.

Some other major areas that require improvement to enhance the acceptance and confidence in salinity modelling in Australia include:

- improved communication, review and accreditation of models,
- increased effort in independently validating models; and
- provision of uncertainty estimates in model output.

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