

Catchment Solute Balance



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PREFACE

The study of catchments has been part of the core business of CSIRO for many years. In no small part due to this research, Australia is more aware of our natural legacy, the importance of our catchments to our well being, the profound changes in catchment function and health we have brought about, and the opportunities and challenges ahead.

Catchment science embodies diverse fields of research, from detailed physics and chemistry, to biology and ecology, to mathematics and statistics, to sociology and economics. The integration of this knowledge is itself a science. The provision of sound technical underpinning to catchment management is a continuing and rewarding scientific challenge.

CSIRO Land and Water maintains a strong commitment to catchment science in aid of improving the lives of Australians and their environment. Part of that commitment involves reviewing our recent scientific accomplishments, our current research portfolio, and the direction our research needs to take into the future.

This series captures CSIRO Land and Water research in catchment science since 1993, some of the current directions, and where our research should take us. We hope that this serves as basis for continual discussion and active debate on the nature and value of science to issues of high national importance like the health of our catchments.

Technical Reports in this series are:

No. 18: Land Use and Catchment Water Balance: Tom Hatton

No. 19: Catchment solute Balance: Glen Walker

No. 20: Sediment Nutrient Transport and Budgetting: Chris Moran (and contributors)

No. 21: Integrated Catchment Science: Rob Vertessy

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BACKGROUND TO THIS PAPER

On July 4, 2000, CSIRO Land and Water initiated a catchment review to ensure the quality and direction of the catchment science. Results will impact on our strategic direction and resourcing. It was decided that the review would involve firstly the preparation of a set of papers on:

- a) Land use, climate and catchment water balance
- b) Catchment solute balance
- c) Catchment sediment and nutrient balance
- d) Integrated catchment science.

Each paper is to:

- a) capture the whole literature generated by CLW since 1993
- b) describe the original questions and issues driving the research
- c) describe how this research sits with respect to the international literature
- d) describe how the issues and questions have changed
- e) speculate on future directions.

The key issue for this component of the review is dryland salinity. This is also a key issue for the topic 'Land use, climate and catchment water balance', being collated by Tom Hatton. It is inevitable that there will be some overlap between these topics. For the sake of drawing boundaries, it will be assumed that Tom's topic will deal with recharge, groundwater response and risk of land salinisation. This topic will use the framework of the solute balance of a catchment to deal with management of saline land, stream salinisation and groundwater salinisation.

- CSIRO organises its business through sectors, the one most relevant here is the Land and Water Sector. The operational plan from this sector represents what CSIRO believes are the issues and questions driving the research (*cf: objective (d)*). The context to the sector, is summarised as follows:
- a higher level of directed Government intervention will be required to arrest and reverse the current degradation of the Australian landscape. Such programs demand the means to prioritise, plan, monitor, and assess the effectiveness of rehabilitation. Current scientific understanding provides only a limited ability to design and predict the outcomes of rehabilitation, particularly at larger scales. As a consequence, major investments in landscape rehabilitation remain of uncertain worth and effectiveness. The scientific challenge is to underpin rehabilitation efforts with knowledge that enhances the environmental, social and economic outcomes and minimises investment risk.
- the concept of the “triple bottom line” (economic, social and environmental sustainability) and the implementation of ISO 14000 environmental management standards are a growing concern on the part of companies who wish to retain a continuing “licence to operate” from society.
- the focus of NRM is shifting rapidly from piecemeal solutions to integrated regional and catchment approaches. Major integrative projects include Murray-Darling Sustainable Land Use (so-called Heartlands) and Ord-Bonaparte Projects
- the implementation of resource trading (water, carbon, salt) is having a major impact on improving environmental management.
- In the future, regulation will restrict the volume of water available to the irrigation industry and will enforce more stringent standards on the quality of drainage water returned to rivers to reduce the level of contaminants (sediments, nutrients, salt and chemicals).

The relevant expected outcomes from the overall sector include:

- Significant progress on the rehabilitation of landscapes through revegetation and engineering approaches; a reduced rate of increase of dryland salinity; implementation of new landscape and catchment management regimes incorporating resource trading principles for water, carbon and salt; and rural communities using new land use practices and regional approaches to improved NRM.
- Improvements in water quality and restoration of river ecosystems; and improvements in estuarine and river health in urban areas.

Relevant expected outputs include:

- A facility for Governments to weigh options for large scale changes in land use, cropping and grazing practices which will result in more efficient use of water and nutrients to meet the twin goals of increased production and improved ecological sustainability.
- Guidelines to enable Governments and rural producers to assess and enhance the impact of revegetation and engineering on inter-relationships between catchment moisture status, water yield, groundwater recharge, and salt loads in rivers.
- Establishment of the 'Sustainable Development of the Murray Darling Basin' project (Heartlands) in conjunction with MDBC, Commonwealth and State agencies, catchment management authorities and the community by 2001.

More specific outputs include:

- Guidelines to assess and enhance the impact of revegetation and engineering on inter-relationships between catchment moisture status, water yield, groundwater recharge, and salt, nutrient and sediment loads in rivers (by 2003).

- Improved techniques for assessing and restoring groundwater discharge areas (by 2003).
- Guidelines for agroforestry and forestry aimed at controlling land degradation, enhancing biodiversity and increasing profitability (by 2002)
- For the Murray Darling Basin:
 - Quantitative predictions of the impacts of large-scale revegetation on biophysical, ecological and socio-economic processes (by 2002).
 - A framework for assessing options to manage degraded landscapes with a focus on salinity, water quality and yield, and biodiversity whilst improving the overall 'triple bottom line'. (by 2002)
 - A document detailing the institutional and policy changes required at national, state and regional levels to facilitate landscape management of water, salt, carbon and biodiversity.

An external view of the current issues and questions driving the research may be sought from the National Dryland Salinity Program. The program was initiated in 1993 and is managed by the Land and Water Resources Research and Development Corporation on behalf of a consortium of partners, including CSIRO and States. Because of wide consultation process, it provides a means of an external view of the key questions and issues.

- Some of the claimed major achievements of the first phase of the NDSP include:
 - Determination of costs of the problem and the development of guidelines for establishing costs in particular situations.
 - A range of improved tools and techniques for estimating that part of the hydrologic imbalance that is related to deep drainage.

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- A better understanding of the capacity (or lack of) of different farming systems to control recharge and manage salinity.
 - Significant advancement in the conceptual thinking behind development of catchment scale models for salinity management.
 - Improved methods for analysing the extent of dryland salinity.
 - Greatly improved methods of using remotely sensed data to map and monitor the risk of dryland salinity.
 - Identification of critical constraints to progressing better management of dryland salinity.

A second five-year phase of the NDSP is now underway (1998 - 2003). The program has identified four objectives required to meet its goal, which is to research, develop and extend practical approaches to effectively manage dryland salinity across Australia. Of these, the most relevant to this review is objective 3: Management of saline resources. Its aim is to develop an understanding, and demonstrate principles and practices, which enable the beneficial use or rehabilitation of landscape resources impacted by dryland salinity.

- This objective recognises that some parts of the landscape are, or will become, salinised beyond repair and that they are a new resource that we should understand and use for the benefit of the community. Strategies and actions under this objective deal with existing uses such as saltland agronomy, aquaculture and biodiversity conservation, and allow for identification and development of new enterprises which might have biodiversity conservation, export or other economic value. Collaborative R&D with industry groups will be important components of actions under this objective. The strategies under this objective include:
- Review Australian and international knowledge relating to beneficial use and rehabilitation of salinised resources.

- Develop, research, trial and demonstrate best management practices for use or rehabilitation of salinised resources with new and existing industries.
- Develop, trial and demonstrate beneficial use and rehabilitation of salinised resources for biodiversity conservation.
- Develop and trial practices to rehabilitate and manage infrastructure threatened by salinity and its impacts.
- Use trials, demonstrations, and training manuals of best management practice to support beneficial use or rehabilitation of salinised resources in rainfed areas.
- The next most relevant objective is 4: Landscape processes. This aims to develop an understanding of landscape processes and ecosystem functions in areas affected by, or at risk from, watertables and salinity. This objective addresses principles and scientific knowledge which underpins national frameworks for investment in management of dryland salinity. Strategies and activities under this objective deal with both recharge and discharge areas, and specifically look at the linkages between biodiversity conservation, use of land and water resources for primary production, and amenity values from resources threatened by salinisation. Strategies include:
 - Investigate the landscape processes and ecosystem functions, which determine water use and movement in selected landscapes under typical land uses.
 - Use understanding of landscape processes and ecosystem functions to predict the impact of doing nothing and of different resource management options on land, water and biodiversity resources.
 - Trial and further develop tools for assessing watertable salinity risks.
 - Develop watertable salinity management components in quality assurance (QA) pathways for rainfed production systems.

A potential way to view the questions and issues over the last 5 years is to review the proposal of the CSIRO Multidivisional program, Dryland Farming Systems for Catchment Care, which ran from 7/95-7/00. The issues of saline land and stream salinisation are relevant to projects 4 and 5 of this program. The background to project 5, 'Assessing the impacts of dryland salinity on stream salinity', as specified in the proposal was:

Stream salinisation is one of the major costs of dryland salinity and in many instances will drive remediation. A good example of where stream salinity is determining the remedial strategy adopted is in "*The Salinity and Drainage Strategy*" of the Murray-Darling Basin Commission (MDBC). The main objective of "*The Salinity and Drainage Strategy*" is to safeguard Adelaide's water supply. Before this project to assess the impacts of dryland salinity on stream salinity started, little was known about salinity trends within the dryland areas of the Murray-Darling Basin and the contribution of dryland salinity to river salinity. "*The Salinity and Drainage Strategy*" was based almost entirely on management of salinity arising from irrigation within the Murray-Darling Basin, with the assumption that dryland salinity was a relatively small contributor to River Murray salinity levels.

The objectives of project 5 were:

1. To determine trends in salt loads and stream salinity of the various tributaries of the Murray-Darling system in order to assess the impact of dryland salinity on key water resources over next 50 years;
2. To identify "hot spots" with respect to stream salinity and to relate these high stream salinity levels to salinisation risks identified as likely to occur in response to particular land uses;
3. To provide indications of the recharge reduction necessary to change trends in stream salinisation to a rating of "acceptable", by using methodologies developed in Project 3 – Predicting the Impact of Dryland Farming and Land Use on Risk of Salinisation at Regional Scales; and to review the impact of large-scale tree planting on water yield and salt loads to streams.

The background of project 4, 'Living with Saline Land', as specified in the original proposal was:

Current understanding of salinisation processes and the lengths of time taken to reverse rising groundwater levels, leads to the inevitable conclusion that we will need to manage large areas of saline land. It is likely that in many of these areas, we will need to 'live with salt', while in others, engineering solutions will be needed. In all saline areas, it is important to reduce recharge to avoid exacerbating outbreaks of salinity, and to maintain vegetative cover to avoid scalding and erosion and to provide habitat for fauna. Many wetlands occur in low-lying areas and hence are susceptible to salinity and increased periods of waterlogging in root zones.

The relevant objectives of project 4 were:

- Develop a discussion paper on communicating possible landscape changes.
- Complete a model on the water use and sustainability of vegetation over shallow water tables.
- Modify existing components of APSIM so that APSIM can include shallow water tables.
- Prepare a booklet on the water use and sustainability of salt-tolerant vegetation.
- Prepare a booklet on the water use and health of riparian vegetation.

From the above, it is clear that the main issues have not changed a great deal over the last 5 years. There has been a much greater determination to deal with natural resource management issues. This is reflected in development of trading schemes, emphasis on environmental management systems and setting of targets. In most of the State and Federal strategies, the notion of 'living with salt' is strongly reflected and an emphasis on protecting major assets. It is also reflected in the NDSP objective 3, yet receives minor attention in the CSIRO Sector Plan. On the other hand, afforestation and major land use change are heavily

reflected. Whatever the case, it is important to 'underpin rehabilitation efforts with knowledge that enhances the environmental, social and economic outcomes and minimises investment risk'.

OVERVIEW OF CATCHMENT SOLUTE BALANCE

The closure of the salt balance has not been pursued with the same intensity as that of the water balance. Nonetheless, there has still been considerable interest in several aspects of the topic. The salt balance of the whole catchment can be considered as well as the various compartments of the catchment, down to a 1 sq. m. of soil column. Particular compartments of interest are the soil zone in recharge areas, unconfined groundwater systems, deeper groundwater systems, basement rocks, aquitards, soil zones in the discharge areas, salt/saline lakes and streams. Each of these contains a storage of salt and, in most cases, salt is advected with fluxes of water moving from one compartment to another. The mass balance takes the form of:

Change of storage = Inputs - Outputs.

CATCHMENT SALT BALANCE

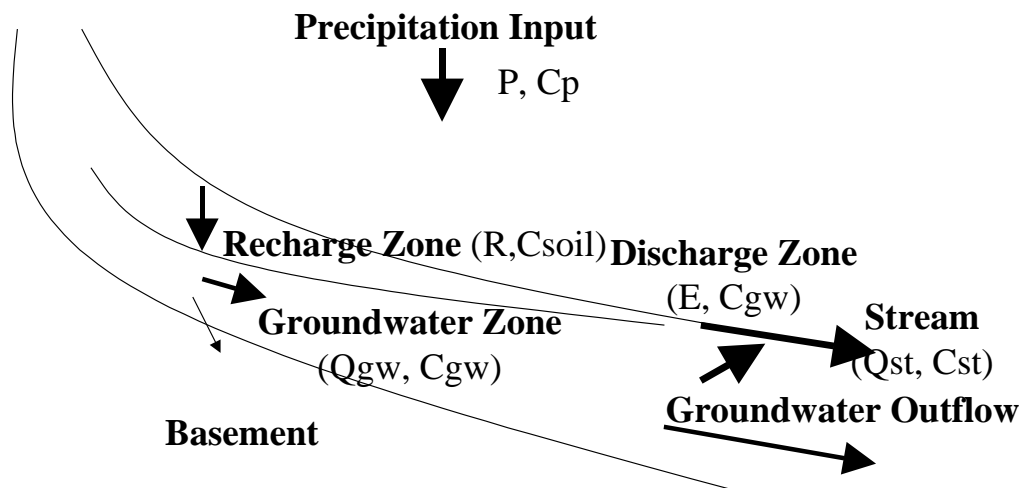


Figure 1 The salt balance of a catchment showing fluxes of water and salt from one compartment to another. Input is through rainfall (P) with mean salt concentration C_p . Other fluxes include recharge

R, lateral groundwater flux Q_{gw} , evaporation through the soil surface E, and stream discharge Q_{st} . Each of these has an associated concentration.

The inputs to the catchment consist of atmospheric salt fall-out either in rain or in dry fall-out (see Walker, 1998). Some salt is recycled from salt lakes (Simpson and Herczeg, 1994) and in some cases fertiliser applications will have some relevant salts. In earlier days, salt was specifically added, but seemingly not enough to affect salt balance. Over drier times in our geological past, there has been salt attached to clay which has blown from salt lakes (parna). The outputs from the catchment usually consist of salt loads to streams or usually less significantly groundwater flow.

Within the catchment, salt moves from the soil zone in recharge areas by deep drainage of soil water into the unconfined system. Leakage can lead to movement of salt between unconfined and confined systems. Some aquitards gradually leach salt resulting from original deposition into the fresher aquifers. Capillary upflow from shallow groundwater leads to salt movement into the soil zone of discharge areas and concentration there from evapotranspiration. Salt can move into streams by direct baseflow, inter-flow and salt wash-off in run-off. Salt can also be derived by weathering of rock.

As salt generally moves with water, the residence time of salt within a catchment is strongly related to that of water and hence to the size of the catchment, permeability of the aquifers and groundwater gradients. Following a change in salt input or salt output, it would be generally expected to take tens, hundreds, thousands or tens of thousands of years to reach a new equilibrium depending on whether the groundwater systems is local or regional in nature. The time to salt equilibrium is much greater than that for hydraulic equilibrium. Under equilibrium, the inputs and outputs for each compartment are equal. This has been used to estimate fluxes of water. For example, the input of salt in rainfall can be used to estimate deep drainage if salt concentration below the root zone is known:

$$R = P C_p / C_s,$$

Where P is mean rainfall, C_p the salt concentration in rainfall and C_s the concentration in the soil. Similarly, equilibrium fluxes can be used for estimating leaching fraction under

irrigation or estimating catchment recharge from groundwater. In areas of accumulation such as salt lakes, the amount of chloride can be used to estimate the flux of water into the area or alternatively the length of time of salt accumulation. The movement of patterns of chloride and chloride isotopes may be used for estimating recharge (Cook *et al.*, 1994; Cook *et al.*, 1995; Tyler and Walker, 1994).

Anthropogenic changes have meant significant changes to these balances. Perhaps, the largest impact has been irrigation. In areas of surface water irrigation, water (and salt) is diverted from streams and returns via drainage flows and groundwater inflows. In groundwater irrigation, salt in the irrigation water is concentrated by plant transpiration and evaporation and leaches back to the groundwater. This recycling of salt can lead to groundwater salinisation. Also, pumping can lead to lateral or vertical movement of saline water from the ocean, deeper aquifers or surrounding groundwater into areas of fresher groundwater.

Another large impact has been the clearance of native vegetation for agriculture. This has led to higher recharge rates and rises in groundwater levels and groundwater discharges. As a result of an increase in groundwater recharge, there is a corresponding increase in groundwater discharge as shown in Fig. 2.

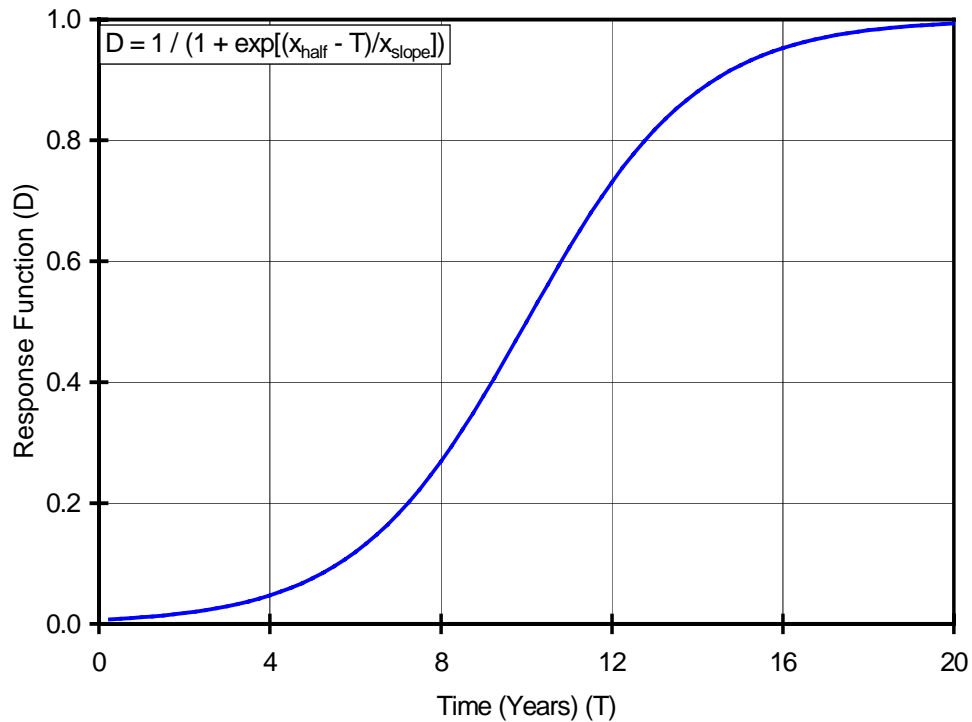


Figure.2 The change in discharge from the groundwater system to either the land surface by evapotranspiration or to streams as a fraction of the change of recharge plotted against the time since the change of recharge. Assuming the system was originally in hydraulic equilibrium, the groundwater system may take several decades to reach a new hydraulic equilibrium.

This discharge can lead to land salinisation, stream salinisation, urban salinity and wetland salinisation. The resulting catchment salt export/input ratio is shown in Fig.3, showing that except for very local groundwater systems, the salt stores are large enough not to be quickly leached. The higher water fluxes can lead to higher salt fluxes and salinisation of groundwater.

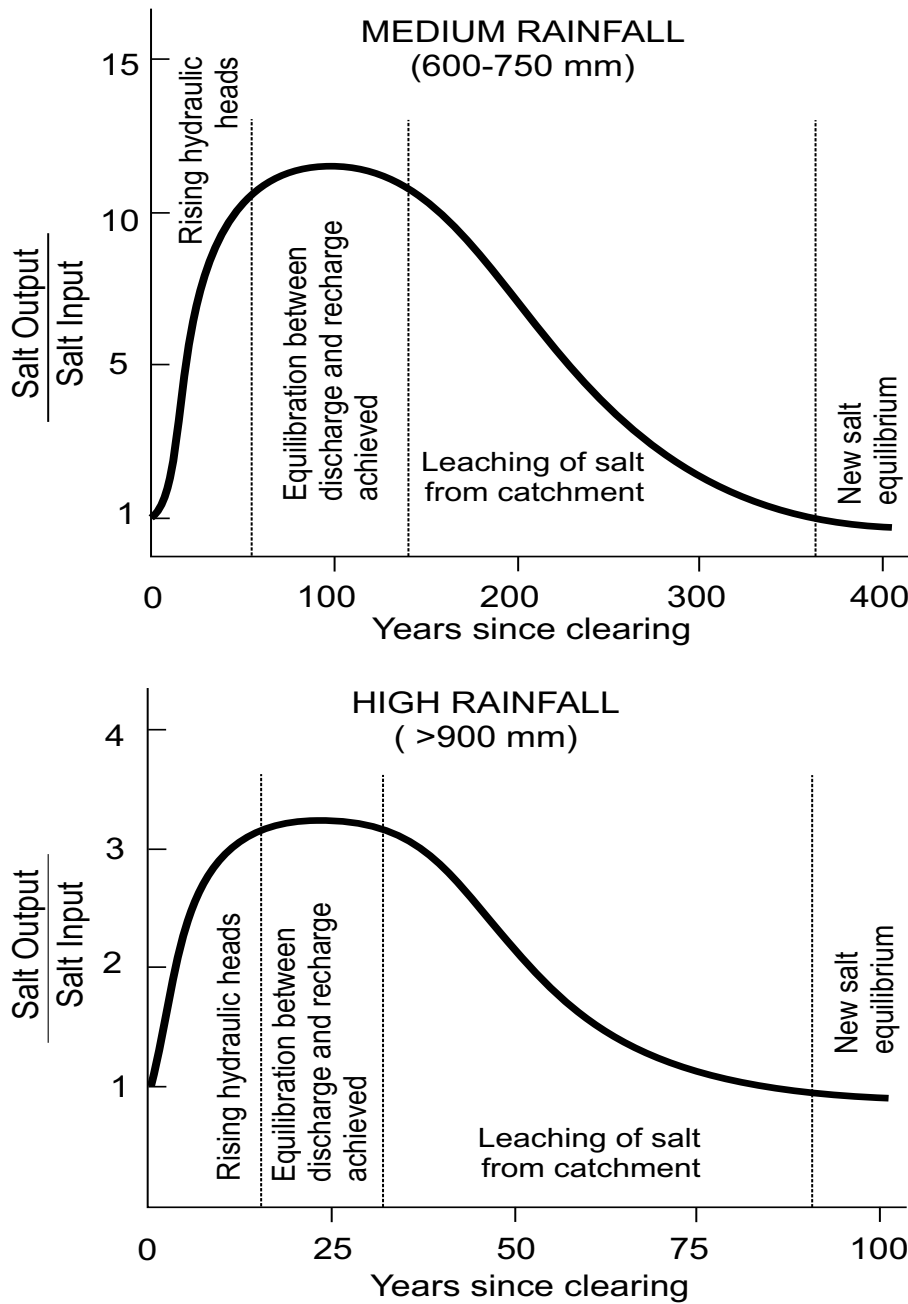


Figure 3 The salt output to input ratio for a catchment in both low and high rainfall zones. As water tables rise, the salt output increases. Salt begins to be gradually leached out of the catchment and catchment returns to a 'salt equilibrium'.

Higher recharge rates have occurred in the past. The occurrences of fresh groundwater in semi-arid areas often reflect palaeorecharge. Similarly, areas of high salinity can reflect lower recharge rates or areas of palaeodischarge. Understanding salt storage in the landscape today requires an understanding of not only the hydrological conditions today but over the recent geological history.

STUDIES OF THE ORIGIN OF SALTS, THEIR DISTRIBUTION AND SALT BALANCES OF CATCHMENTS

Salt balance of the Murray-Darling Basin

Issue: Understanding the salt balance of a system even as large as the Murray-Darling Basin helps us to better put different processes in perspective, understand where the system is out of balance and allows policy to better target salinity remediation schemes. The Murray-Darling Basin (MDB) is very heterogeneous, with a range of geologies, land use and rainfall, contains the vast majority of the irrigation in Australia, regulation of most of the major tributaries and a number of engineering salt remediation schemes. It is also characterised by a sparsity of data outside of the irrigation areas. There have been a number of studies, many by CLW, but also by others. In 1988, an interstate agreement, the MDB Salinity and Drainage Strategy, on managing salinity in the MDB came into force. This largely focussed on the contributions from irrigated areas and involved a scheme of salinity credit offsets. Since then, a number of studies have shown that the dryland contributions may have been underestimated in the original strategy.

Simpson and Herczeg (1994) drew together data from precipitation, river chemistry and groundwaters as a means of calculating chloride fluxes into, and out of the MDB in response to historical changes in land and water management. The results of their analysis of available data suggest that a large fraction of chloride in rainfall in the western Murray Basin is from re-suspended continental dust. Excluding rainfall samples that have high Ca/Na ratios permits a more precise estimate of recent marine deposition of Cl to the MDB. Present calculations suggest that the Darling Basin is storing about 90% of annual input of marine Cl while the River Murray exports 2 to 3 times the annual input to the Murray basin. The large inventories of salt within the two basins, coupled with the present rearrangement of salt due to perturbations in the hydrologic balance, present major limitation for the long-term management of the MDB.

Jolly *et al.* (2000) provided a more detailed water and salt balance along the tributaries. Statistical trends and catchment salt and water balances were used to reconstruct the history

of stream salinisation across the MDB. Establishment of historical stream salinity trends and catchment salt balances was seen as a necessary pre-condition for the development of approaches to predict likely future trends. Analysis of these trends highlights a distinct region of stream salinity and catchment salinisation 'hot-spots' within the Basin. These hot spots are of high priority for detailed investigation and their identification will assist in targeting future remedial work.

For many areas of the MDB, the stream salinity dataset was generally quite limited, with few locations of long record, particularly in the dryland areas. In order to derive historical trends from the intermittent data, a new statistical method was developed. The approach has enabled the determination of historical trends over time at 87 sites distributed across the MDB. The resulting non-linear trends with time will allow stream salinity to be related to processes such as changes in land management, climatic variables, or salt mitigation schemes. Salt and water balances were conducted for 101 stream gauging stations throughout the MDB. This analysis provided a separate method of analysing the stream salinity data with an assessment of the salt O/I ratios. This technique provided a means to identify areas of salt imbalance, high salt load, and high salt load per unit area. However, because of the sparse nature of the data set, the trends and balances should be used as an indication of general behaviour only, and not considered exact for any given location.

Large areas within the MDB showed significant rising trends in stream salinity and salt loads, and generally high catchment O/I ratios, particularly in the eastern and southern dryland regions with annual rainfall of 500 – 800 mm. This finding is consistent with previously mapped dryland salinity areas in NSW and Vic., and consistent with the areas of known rising groundwater trends, and with previous local studies. Streams in the irrigation areas of the basin also showed consistent rising salinity trends, but with salt O/I ratios close to a balance. This may be explained by the large volumes of water and salt that are diverted in these areas, and means that trends in salt loads may actually be decreasing in some cases. Further detailed analysis at a smaller scale is required to account for these diversions. Neither trends nor salt O/I ratios were significant in the northern and western Darling basin

dryland area, perhaps due to the summer dominance of rainfall and slower rates of land clearing. The Lower Murray also failed to show a significant trend suggesting that the salt interception schemes in this region are currently effective.

The analysis indicates that the time lag for response by groundwater may be much shorter in the southern part of the Basin (about 50 years) than in the northern part (greater than 80 years). Although reliable indication of future stream salinity and salt load cannot be obtained from historical trend analysis, there seems little to suggest that current trends will decrease substantially into the future. The project highlighted the difficulty of using Morgan as the only measure of the effects of the Salinity and Drainage Strategy.

Herczeg *et al.* (2000) critically evaluate a number of hypotheses to explain the source of the 100 billions tones of salt in groundwaters of the Murray Basin. These theories include (a) mixing with original seawater, (b) dissolution of salt deposits, (c) weathering of aquifer minerals, and (d) acquisition of solutes via rainfall. Both the total salinity and chemistry of many groundwater samples are similar to seawater composition. However, their stable isotopic compositions ($\delta^{18}\text{O} = -6.5\%$; $\delta^2\text{H} = -35$) are typical of mean winter rainfall indicating all of the original seawater has been flushed out of the aquifer. Br/Cl mass ratios are approximately the same as seawater (3.57×10^{-3}) indicating that NaCl evaporites (which have $\text{Br/Cl} < 10^{-4}$) are not a significant contributor to Cl in the groundwater. Similarly, very low abundances of Cl in aquifer minerals preclude rock weathering as a significant source of Cl. About 1.5 million tons of new salt is deposited in the MDB each year by rainfall. The groundwater chemistry has evolved by a combination of atmospheric fallout of marine and continentally derived solutes and removal of water by evapotranspiration over ten of thousands of years of relative aridity. Carbonate dissolution/precipitation, cation exchange and reconstitution of secondary clay minerals in the aquifers results in a groundwater chemistry that remarkably retains a "seawater-like" character.

Salt balance in SA

The western Murray groundwater Basin underlying the Mallee area represents an almost closed basin with the only outputs being restricted flow to the ocean through the Upper

South East of SA and to the River Murray in SA. Thus, much of the salt discharge to the River Murray in SA was natural. However, additional salt had resulted from the development of irrigation in the Mallee. The high relief of the irrigation areas relative to the river has allowed irrigation groundwater mounds to develop beside the river over highly saline groundwater. To mitigate against these and the natural inflows, various groundwater pumping schemes have been built. Modelling work (Allison *et al.*, 1990) shows that over the next 50-100 years, the increases in salt load from the SA Mallee will dominate all other areas and much of this will result from dryland clearance. The modelling of the effectiveness of salt interception schemes along this part of the river has also been done (Narayan *et al.*, 1994).

Irrigation areas

Outside of the Mallee area, the salt contribution from Kerang Irrigation Areas is the largest single contribution. The salt O/I ratio is approximately 5-6, in this case, the input being from surface water irrigation. Most other irrigation areas have salt O/I ratios less than 1, the one exception being Shepparton which has a ratio slightly greater than one. The irrigation areas in NSW and Queensland have O/I ratios less than one because of groundwater pumping, growing groundwater mounds and non-return of irrigation water to the river. In Kerang, the irrigation area was placed on a paleodischarge area, which has meant that the groundwater system is saline and has quickly become full under irrigation.

Gilfedder *et al.*, (1999, 2000a,b) (non-CLW study; Gilfedder now a CLW researcher) studied in detail the water and salt balance of a border-irrigated bay in the Cohuna area of Kerang. This area is characterised by shallow ground water-tables and salinisation problems. Results showed that the evapotranspiration volume almost wholly explained the soil moisture changes between irrigation events and that deep drainage was negligible. Infiltration was mainly confined to the advanced stages of irrigation, with the soil rapidly becoming saturated across the bay, due to the presence of the cracks. Lateral surface wash off of salt from the soil surface was the main process of salt transport into surface water. Soil salinity measurements showed that, although salt was removed from the near-surface

soil, there was negligible leaching downward through the profile. The results suggest that more efficient irrigation will not lead to the lowering of the shallow ground-water table, but is likely to reduce salt export. This study represents one of the very few detailed studies of salt wash-off processes from saline areas.

For the other irrigation areas on the Riverine Plains of the MDB, salt exports are likely to increase as areas of shallow water tables increase and more drainage is built. In these areas, the focus needs to be on more efficient irrigation, water re-use and use of on-farm and community basins. Recent work in the *disposal basin project* has developed a holistic model of irrigation and on-farm disposal basin in an area of tile drainage. This shows clearly the linkage between irrigation efficiency, climate variability, disposal basins and waterlogging. As costs of disposal start being charged, there will be increased pressure on improving all-round efficiency. However, if reasonable environmental standards are maintained, there is probably not enough appropriate land in the major irrigation areas to prevent export of drainage water outside of the irrigation areas. Moreover, the presence of heavy metals and other contaminants in sediments may mean that we need to treat such basins as possible contaminated sites.

Salt balances in the West Australian Wheatbelt

A study of water and salt balances within a first-order catchment in the WA wheatbelt has shown that the salt load in the main surface drainage comes largely from groundwater discharging upstream from the basement highs and dykes that extend across the surface drainage and conductive channels within the regolith. Although salt fall from rainfall is about 2 g/m²yr (CI), the stream salt load ranges from 180-850 g/m²yr with an O/I ratio of 100-425. Salt storage in the catchment varies from 900 – 4000 g/m² in the top 3 m, to 27 000 – 71 000 g/m² in the 3 – 15 m depth range and 5 000 – 21 000 g/m² below 15 m. Downhole electromagnetic profiles from this and two other catchments has revealed the presence of five types of apparent electrical conductivity profiles which are correlated with the basin geomorphological units. The conductivity profiles are (1) low E_{Ca} (recharge) profile; (2) subsurface peak (discharge) profile; (3) two bulge profiles – a single bulge

(accumulation-weathering) profile and a split (aquifer development) profile; (4) reduced bulge (leaching) profile; (5) high ECa irregular (palaeochannel) profile. Each of these zones have different types of groundwater hydrographs ranging from monotonically rising water levels in the recharge areas to seasonally fluctuating water levels in the discharge areas. The groundwater composition becomes more saline with depth and distance away from the recharge zone. The concentration of salt is explained using geochemical modelling by four main mechanisms: withdrawal of water through uptake by plant roots for transpiration; leakage between aquifers and evaporation upstream of geological structures and near discharge zones. Groundwater discharge calculated using Br and Cl as tracers for the groundwater component fluctuates between 20 and 40 % of streamflow. The downward displacement and leaching of salt stored in the regolith indicates that groundwater discharge will continue to increase causing further rises in stream salinity. The high salt O/I ratio is much higher than from other studies in Australia (see table in back from Ray Evans), but would be similar to that in the Tod River, Eyre Peninsula. This may represent the largest risk in water resource areas i.e. very high salt ratios in lower rainfall country only now starting to rise.

Spatial distribution and origin of soluble salts in central north Queensland

Bui *et al.* (1996) mapped potential discharge zones in the Upper Burdekin River basin and, using 1614 near-randomly spatially distributed soil samples, showed that more salt outbreaks occurred close to discharge areas than expected at random. Bui and Moran (2000) demonstrated a method for regional assessment of the distribution of saline outbreaks for a large area (68,000 km²) in north Queensland. Soil samples were used in conjunction with a digital elevation model and a map of potentially saline discharge zones to examine the landscape distribution of soluble salts in the region. The hypothesis of atmospheric accession of salt was tested for the topographically defined catchment regions feeding into each potentially saline discharge area. Most catchments showed a salt distribution consistent with this hypothesis, i.e. %TSS was large near the discharge areas and decreased rapidly with distance uphill from the discharge areas. In some catchments,

however, local saline outbreaks were apparent at significant distances uphill from discharge areas. The possibility of geological sources of this salt was examined by comparing random point distributions with the location of saline points with distance downhill from geological units (excluding points near discharge zones). The distribution of some saline outbreaks was consistent with the occurrence of Cambro-Ordovician metasediments, Devonian limestone, Upper Devonian-Lower Carboniferous volcanics, and Triassic sediments.

The role of parna as a source of salt

One of the oft-discussed potential sources of salt is the so-called 'parna', a wind-blown clay. It has been suggested that this parna may have contributed to sodic soils and dryland salinity. Parna was deposited over the landscape in a series of events during the Quaternary. Dust entrainment was maximised during glacial periods when the climate was cold, dry, and somewhat windier than at present. Summeral *et al.* (2000) modelled the distribution of such parna in the Young district of NSW using spatial data. The final model showed predictions of parna deposits as follows (1) higher elevations in the Young landscape were the dominant sites of parna deposits (2) thicker deposits of parna occurred on the windward south-west and north-west; (3) thinner deposits occurred on the leeward side of a central ridge feature; (4) because the training set concentrated around the major central ridge feature, poorer predictions were obtained on gently undulating country. The overall role of parna in the salinity story is far from resolved.

Electromagnetic-induction techniques

The issue of salt storage is currently topical with the likelihood of large-scale aerial electromagnetic induction exercises, as announced in the recent Prime Minister's statement on salinity.

Electromagnetic induction (EMI) measures a bulk electrical conductivity. For a given soil, this is a function of the clay content, clay mineralogy, water content and electrical conductivity of the soil solution. For higher salt concentrations, the bulk conductivity can be related to the salt content of the soil. These functional relationships can be determined by comparing

down-hole electromagnetic induction readings to properties of the cored sample taken from the same hole (Cook *et al.*, 1989; Cook *et al.*, 1992). Above ground devices measure a weighted mean of the bulk conductivity with depth. The bulk conductivity of an individual soil layer can be obtained by the inversion of several readings. For fixed frequency devices, this can be optimised for a given depth (Cook and Walker, 1992). The quality of the inversion depends on the response functions, depth of interest, the existence of high-conducting layers not in depth interval of interest, etc. Transient electromagnetic (TEM) devices had originally been too coarse in resolution to be very useful. Recent developments have meant that TEM devices are better resolution. Both fixed frequency and TEM devices can be air-borne (Cook and Kilty, 1992).

Electromagnetic induction devices can be used for a number of purposes (Cook and Williams, 1998). Much of the interest from a salinity perspective has been for mapping recharge and discharge areas. Hatton *et al.*, (1994) showed that the use of many instruments for surveys of discharge areas did not add value to that from using one reading. Cook *et al.*, (1992) pushed this further by using the devices to map high recharge areas in the Mallee. High recharge areas were associated with low clay content and leached zones and hence low EMI readings. On the other hand, higher recharge also means more water and hence higher readings. Hence, even for the Mallee, results could be contradictory without calibration. Salama *et al.*, (1994) have used EMI to estimate salt storages. Outside the Division, they have been used for mapping alluvial aquifers, saltwater intrusion and groundwater contamination.

The wider applicability of air-borne devices has not occurred for a number of reasons:

1. The cost of \$5-10/ha is relatively high compared to historical amounts allocated to NRM investigations and the likely cost of any management plan for the area. For example, it would cost \$5-\$10M to fly over a region of a 1 Mha. Assuming the total investigation is 5% of total plan, and that other investigations need to take place as well as EMI, the cost of the management plan for the region would need to be of the order of \$600 M to justify its use. In some cases, the success or failure of a plan may depend on understanding the underlying

groundwater system and hence expenditure is justified. However, costing would suggest the targeted use of EMI.

2. The current configuration does not enable the EMI to be flown over hillier terrain. Hence the device will need to be targeted towards regional groundwater systems. However, in many areas, there would be little benefit from this data. The likely applicability would tend to be understanding alluvial aquifers in relation to salt storages and discharge into rivers.

Irrespective of the arguments, the use of EMI, along with magnetics, radiometrics and hyperspectral sensing, will become more widespread. The role of the Division will be in the interpretation of such data for hydrological purposes. It is difficult to see any research for straight applications of EMI, other than consideration of EMI as part of an overall integrated hydrological investigation.

It should be noted that a salt storage needs to be linked to groundwater hydrology; as not only does one need to have a source of salt but also a mechanism to move it. High groundwater salinity, as opposed to moderate groundwater salinity, is only important for the issue of stream and groundwater salinisation as moderate groundwater salinities can cause land salinisation. Areas of low groundwater salinity could indicate zones of potential groundwater pumping. For stream salinisation, the zone of interest is shallow groundwater near the stream.

STREAM SALINISATION

Issue: Salinisation of water resources has been one of the key driving forces for salinity management. In the MDB, supply of water for Adelaide and other towns in SA as well as irrigation areas is used to justify major expenditure on salinity mitigation schemes and catchment management. The cheaper prices for desalinating water and better recycling of water means that in future this may be less of an issue for urban supply but would still be an issue for irrigation. Perhaps the strongest argument for protecting streams from salinisation in rural areas is in the restriction of future development. Stream salinity is often used as a symptom of a catchment out of balance and hence is considered more important than the just the salinity issue itself. The MDBC has recently agreed to the setting of end-of-river targets for salinity (loads and exceedance levels for salinity) for each major valley.

Much of the above salt balance work has been conducted for the purposes of stream salinity. However, much less work has been done in relation to predicting the impacts of large-scale land use change on stream salinity and salt load. To predict the impact of management on stream salinity, it is necessary to consider the issues of (1) linkage between land use and water yield, (2) linkage between land use and recharge, (3) groundwater response to recharge, (4) salt storage (5) and salt generation processes. This is in the approximate order of our current knowledge and links all the issues discussed above. The availability of spatial information is such that the ability to predict the appropriate land use management on end of valley targets will never be attainable (*cf* MDBC end-of-valley targets). However, the scope of change required to do so and where to best target is feasible.

Some early studies had been done for regional groundwater systems using groundwater models (Allison *et al.*, 1989; Cook *et al.*, 1997). An early attempt for the more geologically and topographically complex MDB uplands was done with HARSD for the Loddon-Campaspe (Salama *et al.*, 1999). The amount of revegetation required to bring salt loads to required levels was investigated along with other recharge reduction options. This consisted of four

steps. The first was to disaggregate the landscape into so-called 'hydro-geomorphic units' (HGU's), based on geology, slope classes and elevation. Secondly, for each of these HGU's, a linear relationship between groundwater surface and elevation was developed and used to create a groundwater surface. Thirdly, spatial recharge figures were generated using WAVES. Fourthly, a flownet was created using the recharge figures and groundwater surface and this used to estimate aquifer properties. Finally, the relationship between land use on different HGU's and recharge was used to estimate salt discharge to the streams under different land uses. As the flownet is effectively a steady-state approach, time lags associated with the groundwater response was not considered. Nor was the impact of afforestation on water yield. However, it did represent the first effort at the regional scale analysis and dealing with the variety of groundwater systems.

More recent work uses a catchment classification approach. The catchment classification approach differs from the above principally by considering clusters of individual groundwater systems. This was done recently as part of an economic evaluation of salinity management options (Heaney *et al.*, 2000). Pragmatically, the areas of catchment types would not differ greatly from HGU's defined above. The discharge function in response to recharge for each groundwater type is defined, with longer delays for larger systems. This has been built upon the FLOWTUBE model developed for the Liverpool Plains (Dawes *et al.*, 1999). The relationship between afforestation and water yield (Zhang *et al.*, 2000) is used to re-estimate mean water yields. The review of groundwater recharge (Petheram *et al.*, 2000) is used to relate recharge to land use, rather than using a model such as WAVES or APSIM. As with HARSD, the relationship between groundwater discharge and groundwater salinity as estimated from salt balance. The ABARE economic analysis showed that only targeted afforestation can be justified for salinity management.

There are a number of other activities related to salt load and salinity:

- CRC-CH project 2.3 Lu Zhang
- CRC-CH project 2.2 Peter Hairsine
- NDSP 2 project Hamish Cresswell

- NDSP 2 project Lu Zhang
- MDBC Catchment characterisation Glen Walker
- MDBC Lu Zhang.

There still needs to be better understanding of salt load and water flow, salt storage and time delays associated with groundwater responses. There is also a need to work with estimated water flows from operational models such as IQQM and REALMS.

GROUNDWATER SALINISATION

Issue: For many groundwater systems in southern Australia, sustainability is governed by water quality rather than water quantity. Recent changes in COAG has meant that the definition of sustainable yield now encompasses quality. Groundwater salinisation can occur through a number of mechanisms including vertical and lateral movement of saline water into fresher water zone, irrigation recycling and evapo-concentration from shallow water tables. In some areas, a new mechanism has been found: the leaching of salt from the soil zone into a zone of fresh groundwater. For this to occur, one needs a large salt store in the soil zone, underlying fresh groundwater and a mechanism to move the salt, namely increased recharge. While this process is clear, what is not so clear is why saline soil water should overlie fresh groundwater and how one can sensibly predict salinisation risk.

Recent work: The first of these questions has been investigated in the SA Mallee. Soil and groundwater tracer analyses have shown that the Mallee groundwater system is a palaeoresource from periods of higher recharge 20,000 or more years ago. A subsequent drier period since then has led to lower recharge rates and hence higher salt concentrations in soil water i.e. a large salt store in the soil. The size of the store depends on an interaction between the soil texture and past rainfall. In other areas of eastern Australia similar circumstances exist, even though the processes are somewhat different.

Sensible predictions have been obtained for post-clearing leaching by using distributions of measured recharge figures, measured salt stores and measurements and understanding of the relative rates that wetting fronts and leaching fronts move through the soil zone. This avoids using parameters such as soil permeability and root distribution which are not meaningful over any significant scale. While the leaching of the soil salt store can be reasonably predicted, the mixing with shallow groundwater in the underlying karstic aquifer is less reliable. Nonetheless, the predictions are consistent with the few available measurements. The mixing issue is less important for irrigation water, where it has been found in some circumstances, the groundwater can become unusable within 7 years.

Possible future work: Some of the above processes are unavoidable. The only response to such processes are to develop appropriate pumping and irrigation strategies to minimise the problem. The current models are not in a form to do this and require some concerted effort to produce better tools. Also, a better understanding of salt stores in the landscape will allow us to better understand where this may occur elsewhere.

MANAGING SALINE AREAS

Issue: Inevitably, there will be an increase in the amount of saline land into the future. In some situations, it will be important to manage these areas appropriately. There have been optimistic views on the role of vegetation in lowering water tables and little understanding of plant survival strategies in areas of shallow saline groundwater and of the impacts of shallow water tables on soil properties. It is not clear whether there are robust agricultural and ecological systems for saline areas?

Acid sulfate soils

Over 10 years of research in acid sulfate soils has led us to an excellent understanding of the formation of these in areas of dryland salinity. In some Australian catchments, the co-dominant anions in saline groundwaters and soils are sulfate and chloride (Fitzpatrick *et al.*, 1996). These saline soils are associated with geological formations that contain sulfur (i.e. pyrites or sulfate salts) and saline sulfate-rich groundwaters (EC 6-13 dS/m). Preferentially flowing through vertical cracks and old root channels, the sulfate-rich groundwaters seep under pressure to the soil surface where 'potential acid sulfate soils' (pH>6) develop. These soils have distinctive black coloured blotches because of the presence of sulfidic materials. If the water is evaporated, several types of salt efflorescences and iron oxide gels remain on the soil surface. This can result in a large build-up of minerals including gypsum, halite, thenardite, mirabilite and iron oxides (ferrihydrite). These accumulated soluble salt minerals and iron oxyhydroxide minerals are useful indicators of the soil-water processes operating in these catchments and provide possible management strategies for reclaiming such salt-encrusted locations, where only salt-tolerant vegetation will grow (usually sedges and rushes).

If the waterlogged 'potential acid sulfate' soils are disturbed or drained and exposed to the air, sulfuric acid forms and soil pH can drop below 4 (Fitzpatrick *et al.*, 1996). Also, soil pores become clogged with clay and various types of iron oxyhydroxides form (e.g. schwertmannite, natrojarosite or sideronatrite - depending on pH and redox conditions).

Consequently, depending on the soil texture, organic matter content and concentration of ions, different types of 'actual' acid sulfate soil layers form. Because the soil becomes clogged and less permeable, the sulfate-rich ground water, which is under pressure, moves side ways or upslope with consequent redevelopment of the cycle of formation of potential acid sulfate soils (Fitzpatrick *et al.*, 2000). These soils are unstable and erode easily, leaving cemented soil layers, which are relatively resistant to erosion. The processes give rise to saline scalds, erosion gullies and poor water quality in streams and dams.

'Secondary sodic soils' are known to develop from the drainage of saline soils. A case study conducted in the Herrmanns catchment, Mt. Lofty Ranges (South Australia) has illustrated that a sodic soil, with an exchangeable sodium percentage >15%, can develop from a saline soil (EC_{se} >8dS/m) when it is drained following the formation of a nearby erosion gully (Fritsch and Fitzpatrick 1994).

Cook *et al.* (2000) indicated from monitoring studies of the drainage water for sites at East Trinity, Cairns and Pimpama, South East Queensland that considerable acidity is found in the drainage water from these sites. Hydrogen (H⁺), ferrous (Fe²⁺) and aluminium (Al) ions are the dominant acid cations involved. When drainage water is mixed with fresh or marine waters the effect of H⁺ on acidity generation is immediate. Al can release acidity on hydrolyses, while the oxidation of Fe²⁺ to Fe³⁺ both acidifies and removes dissolved oxygen from the water. Strongly acidic waters with low levels of dissolved oxygen concentration are undesirable for most forms aquatic life. Export of acidity from acid sulphate soil is likely to have a major effect on inshore fisheries and breeding grounds especially in periods of flood following drought or periods of low rainfall, where large volumes of acidity can be flushed/leached into sensitive aquatic/marine habitats. Impacts may include low dissolved oxygen, fish kills, epizootic ulceration syndrome, and damage to oysters.

During the processes of oxidation and hydrolysis, iron and aluminium flocs form, that can smother benthic communities. Heavy metals are found in the drainage water at elevated levels and may also be of concern for aquatic organisms. Chronic effects such as habitat

degradation, mortality of marine worms, bivalves, invasion of acid tolerant species (both plant and animal) and avoidance of habitat have been documented elsewhere.

Drainage in sandy duplex soils of WA (not CLW work, Cox now a CLW researcher)

Cox and McFarlane (1995) showed there are several causes for waterlogging in shallow soils in the agricultural areas of Western Australia. It is not surprising therefore that the effectiveness of shallow interceptor drains installed to control the waterlogging was also very variable. Cox *et al.* (1994) used DRAINMOD to predict waterlogging intensity and drain performance in catchments in south-western Australia. Once the soils were saturated, the model accurately predicted drain flows. However, the model could not predict flow early in the season as soils were wetting up – drains commenced flowing well before the model predicted. To accurately predict flows at these times, the highest hydraulic conductivities measured in the field (and sometimes higher) had to be used in the model. The paper was the first to identify the importance of preferential throughflow in these landscapes.

Applicability of plantations for managing shallow water tables

There have been arguments for the widespread use of forestry plantation and commercial agroforestry in the irrigation areas on the Riverine Plain of the MDB as a way of controlling water tables without the adverse impacts of disposal basins or disposal to streams. Silberstein *et al.* (1999) modelled the growth and hydrological impact of a small (2 ha) non-irrigated 21 year old plantation growing over a shallow saline watertable at Kyabram, in the Shepparton irrigation area. TOPOG_Dynamic, an ecohydrological model, was used to simulate the leaf and stem growth, water use and salt accumulation of the plantation, groundwater dynamics, compare these to measurements and assess likely future trends. Groundwater salinity of greater than 2000 mg/L is shown to affect the extent of drawdown of water tables and growth of the trees. Simulations of harvesting a plantation and returning the site to pasture suggested that there may be a severe degradation of future pasture production on that site, as the salt which had accumulated beneath the plantation rises up into the root zone of the pasture when irrigation recommences. When the plantation is irrigated, the wood production is increased, but the increased water requirements, and lesser environmental benefit from a shallower watertable would need to

be considered before irrigation could be recommended. Work is continuing on this but it would appear that the public benefits from water table control and salt storage may not be enough incentive to overcome the economics of trees as an irrigated crop.

Saline agriculture

As the area of saline soils increase, there has been increased interest in the use of salt-tolerant species such as the grasses *Puccinellia* and *Agropyron* and halophytes such as *Atriplex*. Much of the work on these species had focussed on establishment, salt tolerance and productivity. This is reviewed in Jarwal *et al.*, *CSIRO Division of Water Resources Tech Mem 96.7*. More recently, there have been investigations into the transpiration and water use strategies of these species, salt and water table dynamics in the saline areas. *Puccinellia* was found to senesce once conditions began to become saline. *Agropyron* (Bleby *et al.* 1997) was found to continue to use water more and more deeply into the soil profile until groundwater was used in late summer and then senescing. *Atriplex* (Slavich *et al.*, 1998) was found to transpire small volumes of water and extracted water only in the surface soils where rainfall allowed for a small leached zone. The different water use strategies by these plants allow them to survive in slightly different environments and to be tolerant of increasingly saline and waterlogged conditions. The significance of inundation in such environments has probably been underestimated.

Saline floodplains

Salinity can also be found on floodplains of rivers. The international literature on this topic was reviewed by Jolly and Walker (1996). Most of the overseas studies are related to irrigation on the floodplains. A detailed field study was conducted on the semi-arid Chowilla anabranch system of the River Murray. The regional groundwater systems of the western Murray basin discharge into the River Murray in SA. As groundwater moves to the river, it needs to pass under the floodplain. Part of the groundwater discharges to the floodplain, leaving salt in the floodplain soils. Floods leach salt to the groundwater, wash salt off the floodplain soils and add water to the floodplain soils. This discharge to the floodplains has been exacerbated by nearby irrigation and higher river levels caused by

locking. The removal of salt by floods occurs less frequently due to decreased flooding as a result of upstream storages. These two processes combined lead to decline in the health of the riparian vegetation. Most of the remediation options would impact on river salinity. As it is, increased groundwater gradients from floods lead to high stream salinities for up to 18 months following the floods. An understanding of the factors leading to decline of vegetation health, vegetation response to floods, vegetation water use strategies and tree ring isotopes have all been studied. Papers include Akeroyd *et al.*, 1998; Akeroyd *et al.*, submitted; Jolly and Walker, 1993; Jolly *et al.*, 1994; Jolly and Walker, 1996; Jolly *et al.*, 1998; Mensforth *et al.*, 1994; Slavich *et al.*, 1999; Taylor *et al.*, 1996; Thorburn *et al.*, 1994.

Saline wetlands

A similar situation to saline floodplains occurs where wetlands exist in areas of shallow saline water tables. The terrestrial *Melaleuca* vegetation in ephemeral saline wetlands has been studied in the Upper South east of SA. The transpiration rates of the *Melaleuca spp* are higher despite the more saline conditions than at Chowilla (Mensforth and Walker, 1994). This is likely due to the more regular leaching events (every year compared to the 10-30 years for floods at Chowilla). The salt dynamics are different most likely due to the lack of natural drainage for the groundwater system. The vegetation needs to have dynamic root system to avoid waterlogging in the wet winters and the saline conditions in the surface soils.

Groundwater dependent ecosystems

Most of the above studies are in saline areas. Such studies have been possible because of advances in automated plant transpiration measurements, plant-soil-groundwater modelling and isotope techniques for sourcing plant water (Brunel *et al.*, 1995; Walker *et al.*, 2000; Zhang *et al.*, 2000; Walker *et al.*, 1994; Thorburn and Walker, 1994; Thorburn *et al.*, 1993, Thorburn, Walker and Jolly, 1995). It is generally expected that groundwater use of vegetation will increase as the groundwater becomes less saline. However, data suggest that this is not as great as previously believed. Under the COAG reforms, groundwater allocations for ecosystems need to be considered. More work is needed to understand plant water relations for less saline conditions.

Future work

Work on the establishment, salt tolerance, productivity, water use strategies and growth of salt-tolerant vegetation; on the formation of acid sulfate soils; and on the salt and water table dynamics is now fairly mature. It is clear that salinity in many groundwater systems will not be controlled by recharge control. It is also clear that saline agriculture will not be affordable in many circumstances. Future activities could include:

- Searching for more profitable saline agriculture.
- Understanding the impacts of drainage or groundwater pumping in the protection of urban areas and important wetlands. This includes engineering, geotechnical aspects of water table control; physical, chemical and geotechnical properties of saline soils; disposal and the impacts of lower water tables on soils, shallow groundwater and vegetation.
- Understanding how to better manage shallow water table areas, including wetting and drying cycles of wetlands, significance of larger areas of shallow water tables on flooding, the interaction between increased inundation and shallow water tables on salt accumulation and wash-off on soils.
- Better understanding how to estimate of the area of saline land for a given discharge and to cost salinity impacts.
- Better predicting the impacts of increased groundwater discharge on area of saline land, formation of saline patches, gullies and permanent springs.
- Transferring technology from the irrigated areas of the Riverine Plain where engineered water table control has been a fact of life for some

All of the above suggest a much more integrated move to robust agricultural, urban and ecological systems in saline areas (Walker, 2000).

OVERALL SUMMARY, FUTURE DIRECTIONS, SKILLS, GAPS IN KNOWLEDGE

CLW has played a central role in the key issues discussed here.

There are some issues in which CLW has not been involved:

- impacts of salinity on instream biota,
- the role of parna in salinity,
- impacts of catchment scale land use on water quality in irrigated catchments,
- impacts of salinity on infrastructure,
- urban salinity (only a small activity).

The Division has been involved heavily in a number of activities associated with salt balances, origin of salt and salt storages. These activities have been somewhat disparate, having been involved with local issues. However, there has been a failure to capitalise on this by providing a larger picture on salt patterns in the Australian landscape. The availability of more information on this through aerial electromagnetic investigations and radiometrics; and collation of groundwater data for the NLWRA and MDBC Salinity Audit, gives a good platform for further work. The skills in hydrogeology, landscape geomorphology, isotope hydrology and spatial analysis, together with experience in the interpretation of geophysical data are all useful here. The work would be most useful in water resource areas such as the Murray–Darling Basin. Perhaps the appointment of a hydrogeologist/geochemist will help focus this area. Consideration to the investment in rainfall salt inventories should be given. The only widespread dataset (that of Blackburn and MacLeod (1983) came from the wettest period in the MDB since the 1950's. Some further collection, perhaps coupled with water and chloride isotopes may be useful.

There are a number of activities currently underway in stream salinisation. Probably the only missing gap in these activities is the lack of an engineering hydrologist in the MDB to coordinate and focus these activities.

CLW is involved in a number of activities in areas of shallow water tables. My belief is a more systems approach will be required into the future that enables robust agricultural, ecological and urban saline environments. There is a great deal of external activity in niche areas such as selectivity, breeding, genetic engineering, salt production and aquaculture. However to protect wetlands at risk of salinity will require skills in vegetation, soils, geochemistry, engineering, aquatic ecology and hydrology. To protect urban areas at risk of salinity will require not only engineering, but understanding of geomechanics, urban recharge, vegetation, urban hydrology and disposal issues. All of this suggests the ability to integrate across disciplines and a focus on saline areas as a worthwhile activity. Perhaps this can be generated by the formation of a research group on saline systems.

In the area of groundwater salinisation, it is worthwhile to continue a small effort to produce better ways to manage areas at risk of salinity. Better identification of areas at risk may be a side-product of better understanding the spatial patterns of salt storage.

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Catchment	Area	Annual rainfall	Salt output		Salt input		Salt store estimate	O/I ratio	Years of data
	km ²	mm	kg/ha/year	Tonnes/year	kg/ha/year	Tonnes/year	Tonnes		
Angas River, SA ¹	59.6	692	385	2,295	86	513		4.0	13
Dashwood Gully, SA ¹	5.05	804	59	30	100	50		0.6	10
Finnis River, SA ¹	191	770	819	15,640	96	1,830		8.2	16
Williams Creek, NSW * 2	10	640	~ 370	~ 370	~ 20	~ 20	6,000	18.3	1
Begalia Creek, NSW	2.3	740	435	~ 100	35	8.1		12.4	2
Boorowa River, NSW ¹⁰	1,820	550 - 700	440	80,000	26 ⁺⁺	4,700	12 x 10 ⁶	17	1
Murray-Darling * ³	1,060,000	478 ⁺	14.52	1,540,000	13.3	1,400,000	10 ¹²	1.1	18
Murray River* ³	428,000	491 ⁺	35.2	1,506,560	13.54	580,000		2.6	18
Darling River* ³	632,000	469 ⁺	1.43	90,376	12.96	820,000		0.1	18
Goulburn-Broken, Vic 4	19,000	400 - 1500	103	196,000	26 ⁺⁺	49,400		4.0	
Axe Creek, Vic ⁶	250	400 - 600	520	13,000	26 - 40 ⁺⁺	750		17	
Burkes Flat, Vic ⁶	10	480	700	700	40 ⁺⁺			17.5	
MacIntyre Brook, Qld				~ 200,000		~ 200,000		~ 1	
Beacon, WA ⁷		300		400		3,400		0.1	
Welbungin, WA ⁷		300		280		380		0.7	
Davies, WA * ⁵	67	1370	270	1,809	252	1,688		1.1	16
Williams, WA * ⁵	1,400	500	1,300	182,000	62	8,680		21	3
Salmon, WA* ⁹	0.82	1220	208.6	17.1	152	12.5		1.4	10
Wights, WA* ⁹	0.94	1120	1052	98.9	159	14.9		7.5	10
Ernies, WA* ⁹	2.7	820	7.1	1.9	68.8	18.6		0.09	10
Dons, WA* ⁹	3.5	800	8.9	3.1	62.6	21.9		0.12	10
Lemon, WA* ⁹	3.44	820	13.9	4.8	68.6	23.6		0.18	10
Cuballing, WA ⁸	2.3	462	3935	805	17	3.9	87,500	~ 230	6

- 1 Data from Williamson (1)
 - * salt values converted from reported Chloride ion mass using
'salt mass = Cl mass * 2'
- 2 Data from Turner et al (4) and extrapolated to full year
 - † area weighted mean rainfall
- 3 Data from Simpson and Herczeg (5)
- 4 Data from MDBC (6)
- 5 Data from Peck and Hurle (9) - Davies lowest O/I of 8 forested catchments;
 - Williams highest O/I of 7 cleared catchments
- 6 Chris Day, pers comm (Centre for Land Protection Research, Bendigo)
- 7 Data from George (8) - input figures include dryfall
- 8 Data from Salama et al (13)
- 9 Data from Williamson et al (3)
- 10 as represented by data from Prossers Crossing
 - †† Rainfall salt fall figures from Blackburn and McLeod (7) for the period 1974-1977

