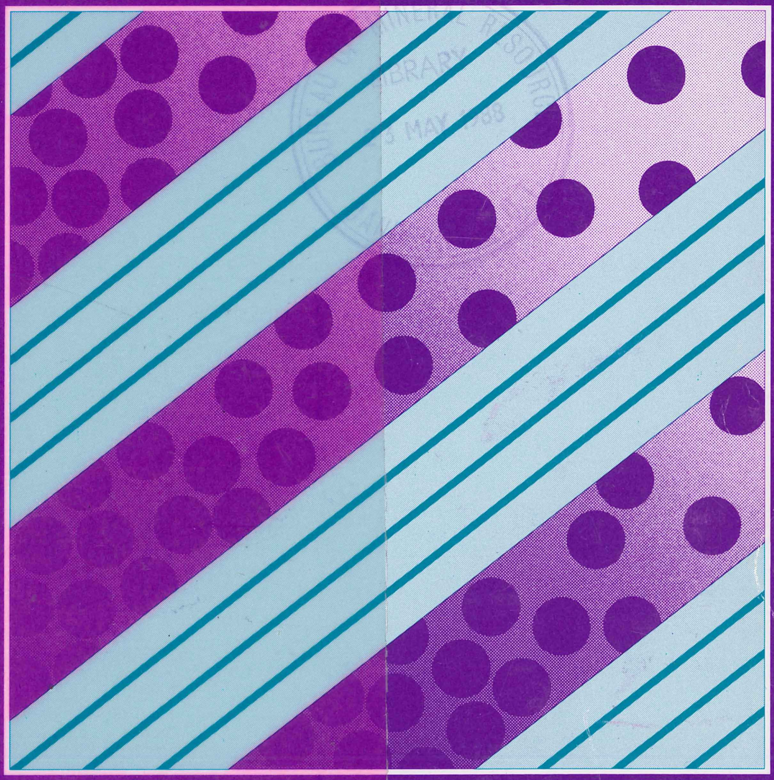
GROUNDWATER 12

Studies in Hydrogeology

MURRAY BASIN 88: ABSTRACTS

Geology, Groundwater and Salinity Management Conference

CANBERRA, 23-26 MAY 1988



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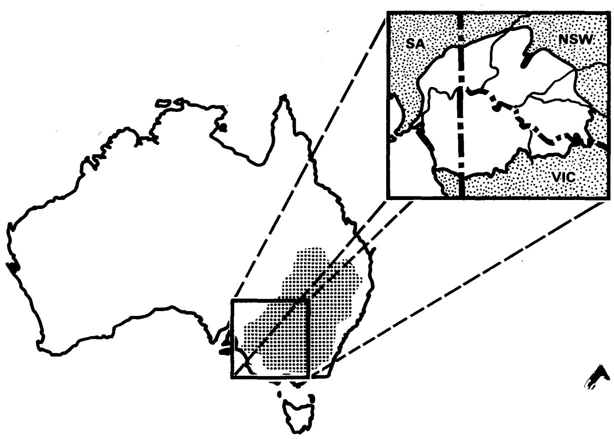

ABSTRACTS
MURRAY BASIN 88 CONFERENCE

(CANBERRA, 23-26 MAY 1988)

compiled by

C.M. Brown & W.R. Evans

(BMR Division of Continental Geology)

Published as a contribution to the joint Commonwealth and States Murray
Basin Hydrogeological Project

MURRAY BASIN 88 CONFERENCE
GEOLOGY, GROUNDWATER AND SALINITY MANAGEMENT
CANBERRA 23-26 MAY, 1988

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MURRAY BASIN 88

GEOLOGY,GROUNDWATER AND SALINITY MANAGEMENT
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FOREWORD

MURRAY BASIN

The Murray Basin contains some of the most important agricultural land in Australia and currently generates several billion dollars in agricultural income. It is also an area of great natural beauty – a special place for many Australians. Unfortunately clearance of natural vegetation and irrigation have been accompanied by both rising groundwater-levels and discharge of saline waters. In order to develop salinity management strategies an understanding of the systems in which these salinity problems have developed is essential. In particular, it is fundamental that the relationships between aquifer geometry, recharge, groundwater flow and distribution of surface discharge features be fully understood.

GEOLOGY

The Murray Basin forms a closed groundwater basin which consists of a thin veneer (200-600m) of sedimentary rocks containing a number of aquifer systems with limited storage capacity. A knowledge of the basin-wide subsurface stratigraphic framework is an essential prerequisite to understanding the factors controlling groundwater flow. Saline surface discharges can be related to aquifer thinning, either over basement structures or due to lateral changes in sediment type. The surface geology of the Basin provides a record of environmental change in the Basin, reflecting past fluctuations in climate and sea-level as well as interactions between surface geomorphic processes and fluctuating groundwater tables. Fossil (currently inactive) saline discharge sites can be recognised and are commonly areas where there is a particular risk of future salinity problems. The surface geology therefore helps us to define not only those changes which are 'natural' and those which are man-induced but also gives us insights into what the future may hold for the Basin as groundwater levels continue to rise. The surface geologic record shows us that at times the Basin has been even more saline than it is at the present day.

GROUNDWATER

Groundwater is extensively used by irrigators and graziers and the future viability of many of the agricultural communities in the Murray Basin region is increasingly dependent on the controlled development and management of the water resources of the Basin. Rising saline groundwater has resulted in extensive areas of formerly productive agricultural land being turned into saline wastelands and trees have been killed by waterlogging of their roots. In some areas orchards have been damaged by the use of saline river water for irrigation. In addition, the quality of drinking water has deteriorated for many towns and cities (including Adelaide) which depend on water from the River Murray for their supplies. Against this background the Commonwealth and the States of New South Wales, Victoria and South Australia have been placing greater emphasis on the need to develop a better understanding of the groundwater regime of the Murray Basin.

SALINITY MANAGEMENT

Salinity in the Murray Basin is Australia's most critical environmental problem. Salinisation is responsible for the loss of agricultural production in the Basin in the order of $215 million per annum through adverse effects on plant growth and land degradation. Some of these effects are cumulative and essentially irreversible. Consequently it is a matter of urgency to identify and understand the causes of salinity and develop a strategy for salinity management. As most salinity problems in the Murray Basin are related to groundwater it follows that salinity management and groundwater management must be pursued jointly. Salinity management must be pursued in a way that ensures the continuation of productive agricultural land and maintains river salinity at an acceptable level. It must also be done in a way which allows for the sustained and efficient use of groundwater and does not jeopardize the basin's groundwater resources in the shallow or deep aquifer systems. A full understanding of the groundwater mechanisms involved in salinisation will enable us to identify those areas under greatest threat from future increases in salinity, establish priorities and develop salinity management options. Inevitably there will be not one but several strategies brought to bear on the range of salinity problems within the Basin, but there can be little doubt that groundwater management will be pivotal to most if not all of them.

Peter J. Cook
Chief, BMR Division of Continental Geology
(Chairman of Organising Committee)

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RECHARGE, SALINITY AND LAND-USE CHANGE IN THE MALLEE REGION

G.B. Allison, G.R. Walker, M.W. Hughes, P.G. Cook, and I.D.Jolly

CSIRO Division of Water Resources

PMB 2, Glen Osmond, SA, 5064.

The Mallee Region is the extensive inland plain covering much of the Murray Basin in South Australia and extending to New South Wales and Victoria. The predominantly Eucalyptus vegetation is an excellent scavenger of water and because of this, a large salt storage is created in the soil (Nulsen & others, 1986). When the Mallee vegetation is replaced by shallow-rooted crops and/or pastures, there is a large increase (by about two orders of magnitude) in the recharge to the unconfined aquifers. This higher recharge will lead eventually to higher water tables as well as mobilisation of the salt stored in the soil. Because of the size of the Murray Basin and the extent of clearing, this will have a significant impact on the salinity and quantity of groundwater inflows to the Murray River. It is therefore important to understand the mechanisms operating in this environment and to be able to estimate changes in recharge.

A number of papers (Allison & Hughes, 1983; Allison & others, 1985; Leaney & Allison, 1986) have addressed this problem in the South Australian Mallee Region by the use of various techniques, including those involving chloride, carbon-14 and tritium. This problem has also been the subject of an AWRAC-funded project at CSIRO, Adelaide as well as a chlorine-36 project involving that laboratory, ANSTO and the ANU (Davie & others, this volume).

The various techniques consistently show that the diffuse fluxes of water under Mallee vegetation are less than 0.3 mm yr^{-1} (approximately 0.1% of rainfall). Recent work (Jolly & others, this volume) has shown the possibility of a small diffuse discharge from the water table even though the water table may be at a depth of 30-50m.

Because of the small diffuse fluxes involved, the effect of point sources may be emphasised. Certain landscape features show signs of run-on and ponding and very preliminary estimates show that these could be significant (Cook & others, this volume).

After the Mallee is cleared, the predominant land use is crop-pasture rotation with wheat being grown one year in about three. The paddocks are often left bare for 1-2 years immediately following clearing, during which there may be enhanced recharge.

The principal features used in estimating the new recharge rates following clearing are the 'wetting' or 'suction' front and the solute front (Figure 1). The 'wetting' front is the location in the soil profile of the change of the matric suction following clearing, and represents the range of influence of the increased fluxes. The solute front indicates the actual water associated with the increased recharge behind the wetting front. The rate of movement of these fronts depends on the soil type and is slower in clay soils.

The estimates of recharge following clearing are 5-30 mm yr^{-1} depending on soil type. Because of the depth to water table, the suction front in many areas is still well above the water table, and much of the effect of clearing is yet to be observed.

This information is being used in a groundwater model of South Australian portion of the Basin (see Barnett & others, this volume) to estimate future trends of the piezometric heads and salinities of the groundwater.

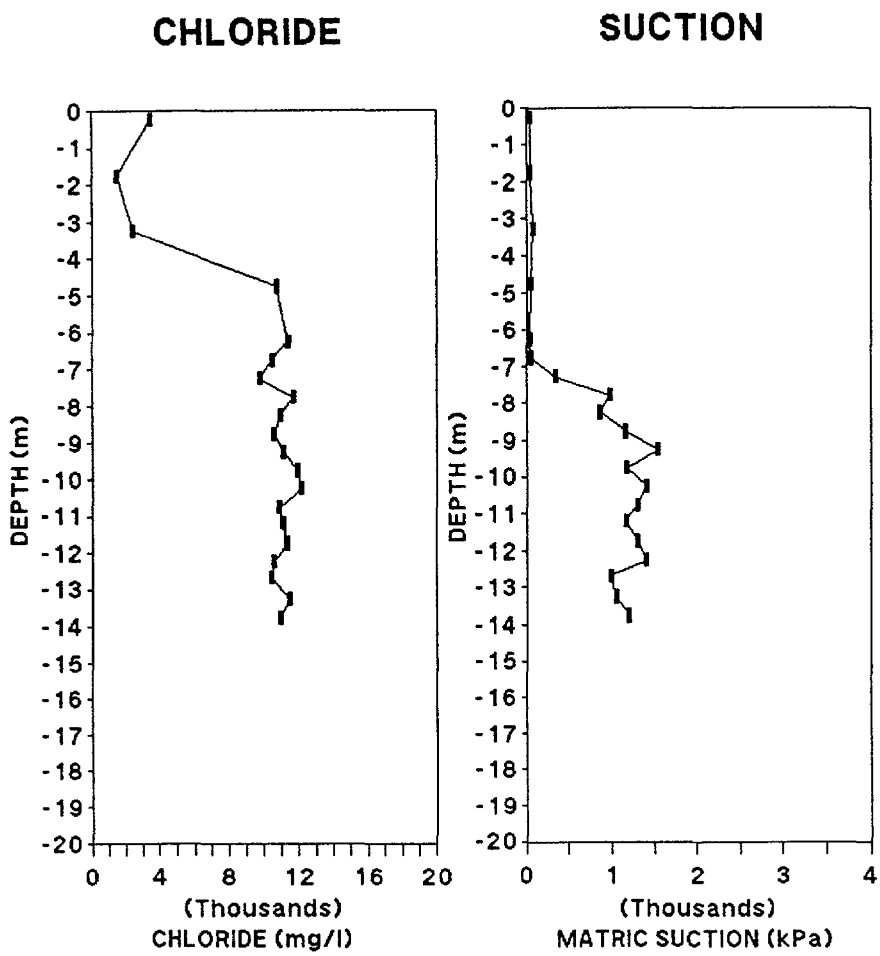

FIGURE 1 : A comparison of the chloride and suction profiles in a paddock cleared approximately 9 years ago near Kulkami, South Australia.

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PRIMARY AND SECONDARY ENVIRONMENTAL PROBLEMS CAUSED BY SALINE GROUNDWATER INTRUSIONS INTO THE WIMMERA RIVER, VICTORIA

Dr. John Anderson and A.K. Morison
Kaiela Fisheries Research Station
P.O. Box 1226, Shepparton, Vic., 3630

A recently completed study of the environmental flow requirements for the Wimmera River established that saline groundwater intrusions are occurring in an extensive area of the Wimmera River, producing stable and long-lived vertical density gradients and stratification. Saline water approaching seawater concentrations accumulates as stable saline pools in the bottom of the river bed. Saline pools were found in the Roseneath area upstream of Horsham, at Lower Norton downstream of Horsham and also in extensive areas from Polkemmet to Horseshoe Bend and between Antwerp and Jeparit. Significantly, the saline pools were absent from the Horsham and Dimboola Weir Pools and most of the deeper waters in the Little Desert National Park upstream of Dimboola. Some sites coincided with areas where the river bed intersected the uppermost portions of the regional Parilla Sands aquifer as evident by laterised silty sands, active precipitation of iron, water tables almost uniformly 1-2 metres above river level, sodium chloride precipitation and in some cases extremely saline seepages from the bank to the river. It is most likely that the saline pools are produced as a result of saline groundwater entering the river from above surface seeps or directly through the subsurface bed and banks.

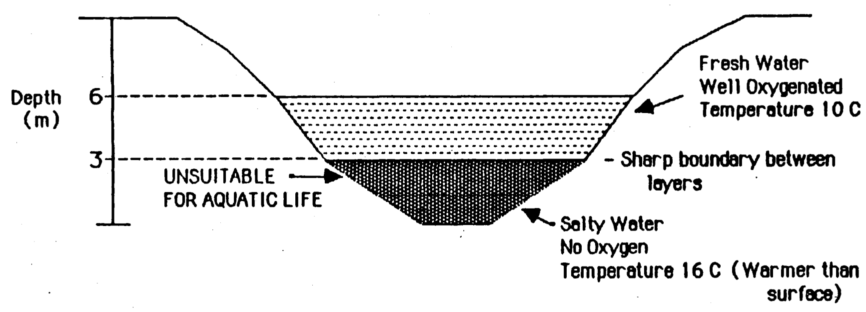
The major environmental problem associated with the groundwater intrusions arise not through the increased salinity itself, as most fish and other aquatic organisms can tolerate moderate salinities, but through the stable density stratifications produced by the conductivity gradients and subsequent deoxygenation of the saline pools. The deoxygenation either arises because the low dissolved oxygen levels of the groundwater intruding in the pools is retained and there is little or no replenishment of oxygen to the bottom of the pools, or it arises secondarily through the decomposition of organic matter in the saline pools once they form due to the low mixing and low rate of replenishment from the overlying surface layers. Because of the low oxygen levels the saline pools are uninhabitable for fish or other aerobic organisms. As a result there is a substantial reduction in the volume of water, and area of bed substrate which is available as habitat for fish and macroinvertebrates and a consequent lowering of the production of the river section affected.

The saline pools are extremely stable. Low to moderate discharges have little or no affect and the flow passes as a surface layer over the top of the saline pools. Major flow events (bankfull discharges) remove the saline water but the saline pools quickly reform once the flow declines again (less than two months).

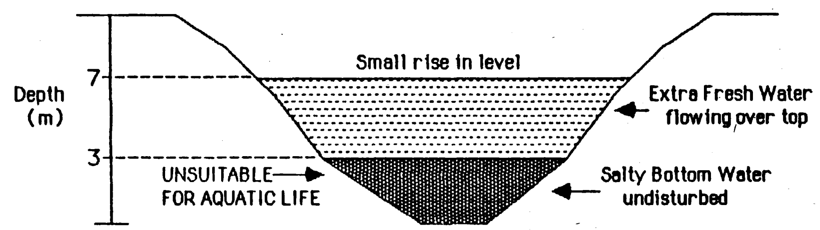
There are two secondary effects of the saline groundwater intrusions which cause further environmental problems:

1. Severe short-term changes in environmental conditions can occur when saline water (anoxic or hypoxic) which has accumulated in the channel bed during low flow periods or flow stoppages, passes as a 'slug' of water ahead of a flow front. Such first-flow events have caused fish-kills in the Wimmera River. The combination of major simultaneous changes in salinity, temperature and dissolved oxygen levels can be lethal to aquatic organisms. Once again this may considerably extend the area affected by groundwater intrusions beyond the vicinity of the primary source.

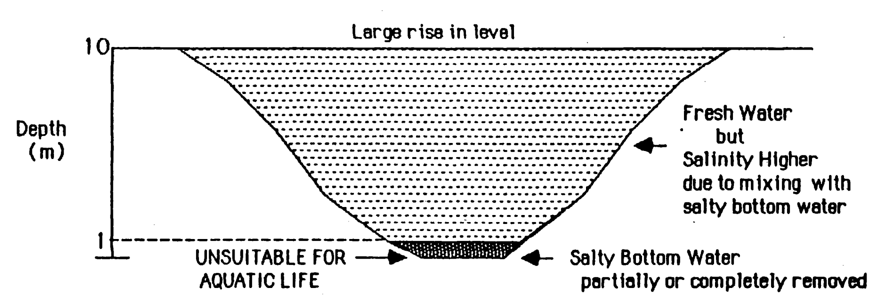
NORMAL WINTER CONDITION - 2 Separate Layers



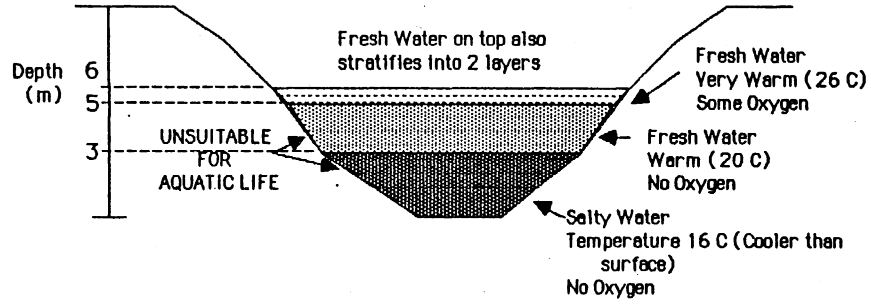
AFTER SMALL WINTER FLOOD - 2 Separate Layers



AFTER LARGE WINTER FLOOD - 1 or 2 Layers



SUMMER CONDITION - 3 Separate Layers



2. The total area degraded by the saline groundwater intrusions was shown to be considerably increased because of secondary salinity stratification which arose downstream of the site of the intrusion. Saline water which was moved downstream ahead of successive flow fronts produced three or more layers of water of different salinity which remained for long periods during low flow periods. Conductivity gradients of as little as 500 μS/cm were sufficient to produce a stable stratification which led to severe deoxygenation below the halocline. This led to severe deoxygenation problems and reduced the vertical mixing produced by subsequent flow events. This appeared to be the cause of the stratification and severe deoxygenation which occurred in the Little Desert National Park and Dimboola Weir pool areas during the summer of 1987. Consequently the area affected by the saline water intrusions can be secondarily increased by saline water being carried downstream into relatively deep and poorly mixed pools to form multiple layers.

Despite the association found between the saline water in the pools and the regional Parilla Sand aquifer, the intrusions appeared to be localised rather than regional, both on a broader and finer scale. Saline pools were not found in all deep pools within a major river section. Similarly saline pools were often found in a particular scour pool when a deeper scour pool on the next meander bend downstream had no saline water present. This offered some hope that there may be a localized solution to the problem. However, if groundwater levels continue to rise the problems in the Wimmera River would be expected to worsen before the regional groundwater issue can be tackled.

It would be expected that similar saline groundwater intrusions are occurring elsewhere in other rivers in Northern Victoria, especially with the rise in regional groundwater levels in the irrigation areas. It would also be expected that similar severe environmental problems associated with salinity stratification and hypoxia would also occur in the downstream sections of other rivers below major off-stream diversion points. Many of these downstream river sections are highly regulated and have very little flow during the summer months.

Severe environmental problems may be produced in areas which do not currently receive saline groundwater from natural drainage through the disposal of groundwater pumped to lower water tables.

Further work is required to determine the extent of the problem throughout Northern Victoria and to predict the future implications of a continuing trend for a rise in water table, and consequent natural and artificial drainage of saline groundwater into the rivers and streams.

RIFTING AND BASEMENT RIDGES IN THE MURRAY BASIN REGION

V. Anfiloff
BMR Division of Geophysics
G.P.O. Box 378, Canberra, A.C.T. 2601

Summary

This paper presents a speculative interpretation of the geophysics of the Murray Basin region, and the similarities between its mobile belts and the African Rift system. The Murray Basin region has numerous structures which may be analogues of the African Rift system. One of the fundamental aspects of African rifts is their partitioning into separate compartments by cross-cutting basement ridges. The possible analogues are the Renmark, Tarrara, and Menindee Troughs along a common axis, and at least two other belts where granites occupy compartments. The Scopes Range structure is a partition between the Menindee and Bancannia Troughs, but in this case basement ridges also fan out from it across the Darling Basin. These basement ridges are interpreted in terms of a balanced compression network. It is envisaged that adjustments in the network would cause strike-slip movements, which would trigger rifting, which in turn would trigger igneous activity.

In the Murray Basin, linear troughs and mobile belts produce a coherent rectilinear pattern of gravity highs and lows apparently disposed along an ancient crustal fracture system. The gravity lows represent troughs and possibly coaxial granites underneath. The highs represent belts of volcanics. Magnetic data help recognise some of these components. A Tertiary belt which could be a young rift appears to be forming between the Balranald and Wentworth Troughs. It could show how young rifts step out from older ones to form a series of parallel belts.

Introduction

The Murray Basin is part of a chain of broad basins in eastern Australia which includes the Eromanga and Surat basins. Basement ridges separate them from each other, and cut through them forming sub-basins. In the Murray Basin a thin blanket of Tertiary sediments form a blanket cover 200-300m thick overlying Palaeozoic basement containing numerous troughs, and remnants of some older cover such as the Devonian sediments of the Darling Basin. A major question is whether the basement ridges and basins formed together in response to a widespread process, or whether basins form separately at different times, and basement ridges are incidental. The age of most of the basin cover is Tertiary, but remnants of Devonian cover equivalent to the Eromanga Basin are present.

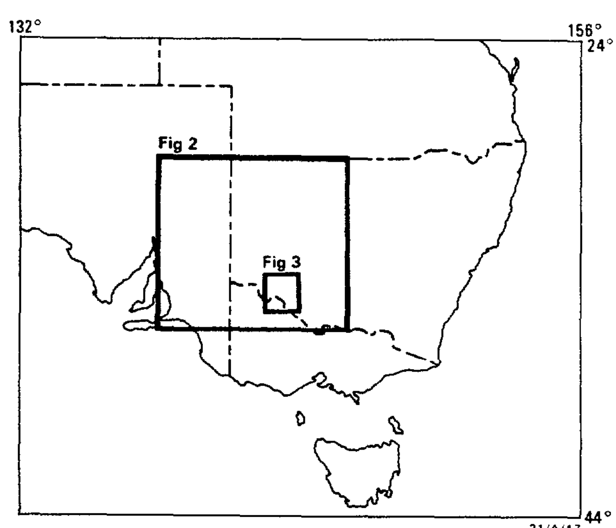


Fig. 1 Location of study area

In Africa, the main rifts are separated from each other by narrow strips of basement. New seismic studies show that each rift develops as

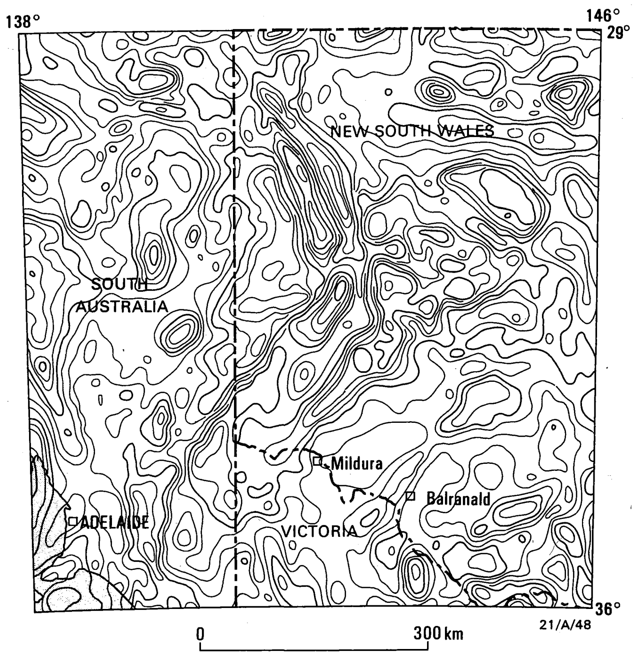


Fig. 2 Gravity contours in the Murray Basin area.

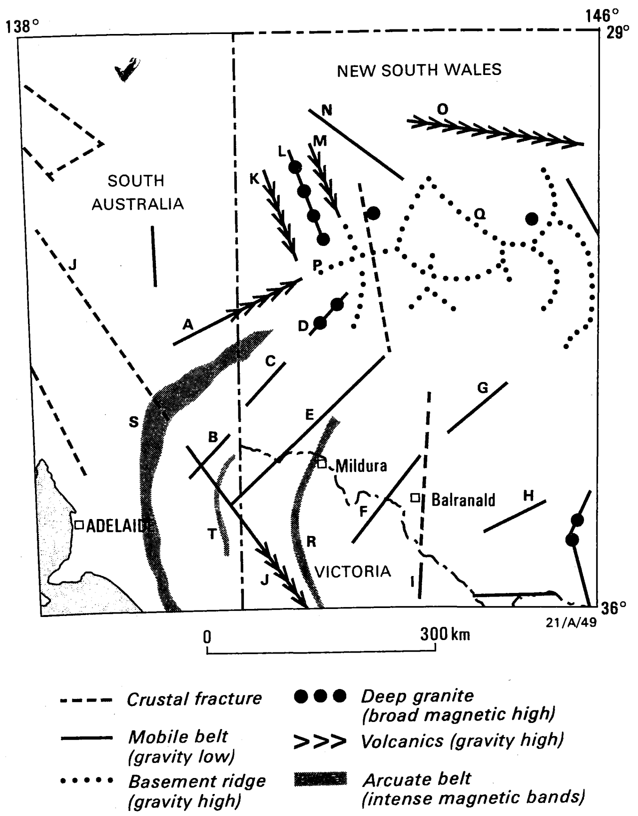


Fig. 3 Tectonic framework in the Murray Basin area.

a series of compartments in a line, each compartment being separated by a cross-cutting basement ridge (Rosendahl, 1987). The framework around the African rifts has not been mapped using gravity data. In the Murray Basin, gravity data shows how compartments and basement ridges are related to each other. Basement ridges have a major effect on ground water flow in Tertiary aquifers, and the rifting process is therefore important.

Gravity and magnetics in the Murray Basin region

The Murray Basin is the only broad basin in Australia where an extensive detailed coverage of airborne magnetic data is available (Tucker & others, 1985). The largely undeformed sediments are virtually transparent to gravity and magnetic data and this makes it possible to produce an accurate map of the tectonic framework under the basin.

The preparation of compatible gravity and magnetic pixel maps on a 1.0 minute mesh makes it possible to produce two types of displays. The first involves inserting parts of one into the other. Magnetic inserts in the gravity display for the Murray Basin region (Anfiloff, 1985) shows that several major broad magnetic highs are coaxial with gravity lows in the Bancannia and Menindie Troughs. Another type of combined display involves merging both images in an image display system. This reinforces some trends and enhances the definition of the framework.

Linear belts

Fig. 2 shows the gravity anomalies in the Murray Basin region (Fig. 1), and Fig. 3 shows the tectonic framework interpreted from this and magnetic data. The region is dominated by a coherent rectilinear framework of mobile belts and rifts. Some belts intersect orthogonally. Anfiloff (1983) proposed that such linear belts represent the original crustal fracture system in Australia. The Renmark (B), Tarrara (C), and Menindee (D) Troughs represent three compartments along a common rift axis. The Anabama Granite at A represents a compartment of a rift and is in line with a linear belt of magnetic highs extending westwards out of the Broken Hill area. A granite at I appears to be in line with a compartment between F and G. The long lineament J is attributed to a major crustal fracture which extends into the Adelaide Geosyncline. At its southern end, it includes the Stavely Belt of volcanics (Brown & others, in press), which produces a gravity high and a disturbed magnetic pattern.

A mobile belt is defined here as a series of compartments in a rift which accumulate sediments and volcanics, and some are later invaded by granites. Each compartment in a rift can be dominated by a different type of intrusive. Gravity lows represent sediments in a trough or a granite. Some granites are deep in the crust, others are part of the basement. Broad, smooth magnetic highs appear to signify granites at depth, because they are often present when the gravity low over a trough is too large to be explained by sediments. Disturbed magnetic zones are likely to represent shallow mafic bodies. The situation where a granite is shallow or a mafic body is deep can be discriminated by gravity if seismic information on sediment thickness is available. A deep mafic body under a trough of sediments would cause a gravity high cancelling the low due to sediments, while a shallow granite would be recognizeable by the presence of a gravity low without a sediment trough. The magnetic properties of granites are quite variable and are not fully understood. Sometimes shallow granite bodies can be identified from the shapes in the magnetic pattern.

The Scopes Range structure (P) is a narrow section of basement bounded by steep faults separating the Bancannia Trough (L) from the Menindee Trough (D). Both troughs have associated magnetic highs which are attributed here to deep granites. They also contain roughly the same Palaeozoic sections (Brown & others, 1982), and may therefore be conjugate belts. The Bancannia Trough appears to be flanked by volcanic belts at K and M and a similar belt may occur at O. The feature at N is a linear gravity low about which little is known. The Wentworth Trough (E) has a prominent gravity low but very little magnetic expression except for linear trends where it intersects the Stavely trend along J.

The magnetics along the Stavely Belt has high frequency components superimposed on a broad high. They may represent a deep granite underneath the shallower volcanics. The moderate and somewhat ill-defined gravity high along the belt could represent the cancellation of one by the other. If so, this would be the only case so far recognised of the predictable vertical juxtoposition of volcanics in a rift over a granite in basement. The more normal situation involves a deep granite under a rift filled with sediments, which produces a large gravity low, such as in the Bancannia Trough. If the granite is part of the basement under the trough rather than a pluton deep in the crust, two cycles of coaxial rifting are implied, one on top of the other. In either case, the Stavely volcanics would be thicker than suggested by the gravity high.

Arcuate features

Arcuate structures occur under the Murray Basin at R, and in a major belt skirting the Murray Basin at S. The belt at S consists of many discontinuous contorted and faulted segments. They are very shallow and form a broad arc which wraps around the outside of the orthogonal mobile belt system defined by the J and B-C-D axes. Where they outcrop, they are associated with the Kanmantoo Palaeozoic metasediments, and the Proterozoic Adelaide fold belt system (Brown & others, in press). Under the Murray Basin cover, a second arc at R has a symmetrical disposition on the inside of the orthogonal system defined by the J and E axes. It is smoother and more continuous than the outer arc, but very little is known about it.

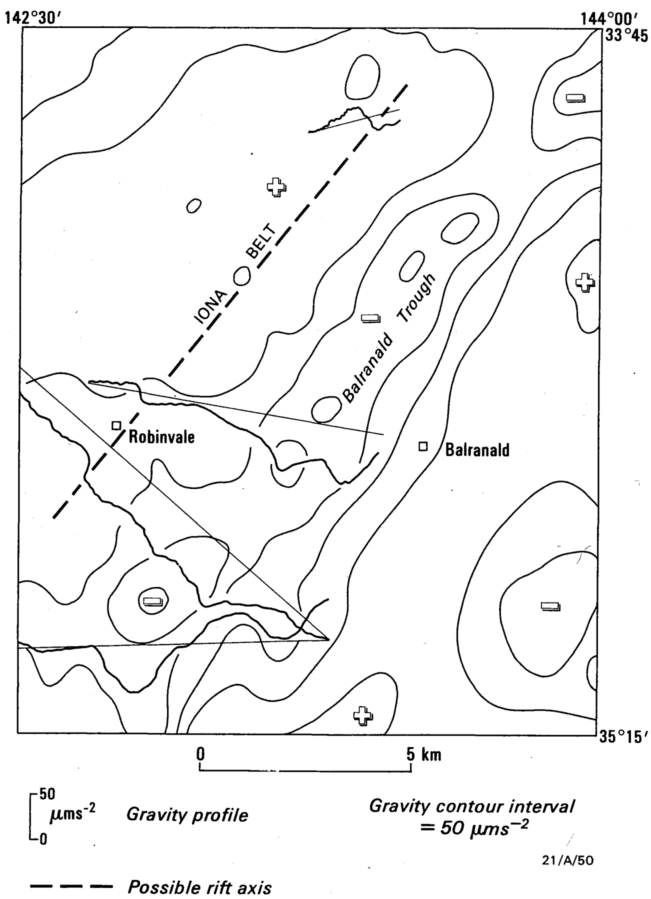


Fig. 4 Gravity profiles across the Iona Belt near the Balranald Trough.

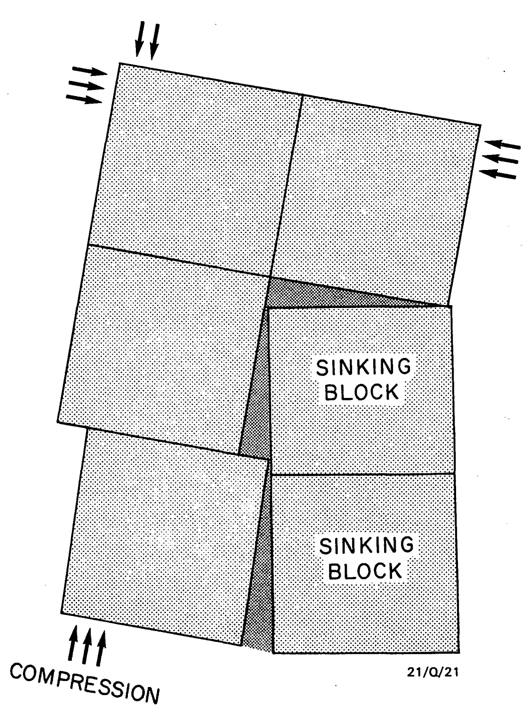


Fig. 5 Development of compartmentalised rifts and conjugate rifts by strike-slip movements along crustal fractures.

Development of a new rift

Recent geophysical work in the Murray Basin (Odins & others, 1985; Anfiloff, 1987) has revealed what appears to be a young rift structure. Fig. 4 shows a long, narrow, structure detected by three detailed gravity profiles, situated between and parallel to the Balranald (F) and Wentworth (E) Troughs. The profiles show a 10 km wide ridge-trough combination of almost identical size in all three cases. The northern structure was investigated using refraction data (Odins & others, 1985) and shows a 50 m ridge flanking a 50 m trough. Ground magnetic data failed to detect this structure, and it is also absent from airborne data. Gravity modelling of the refraction structure indicates a large density contrast of 0.7 t/m^3 (Anfiloff, 1987), which is consistent with unconsolidated Tertiary overlying Palaeozoic basement. This situation makes gravity very effective for mapping basement topography in conjunction with groundwater studies. The structure has a consistent form over a distance of 110 kilometres and is named the Iona Belt here. It has produced a topographic ridge and has therefore been active in the Tertiary. It is too narrow to be caused by thermal or isostatic mechanisms. A more probable mechanism would be a compressive strike-slip movement. It could be a young rift, a precursor of a mobile belt, and it could explain the predominance of parallel belts in some parts of Australia. It could imply that although linear belts develop independently of each other, their direction is governed by anisotropy resulting from the extra strength produced by intrusives in older mobile belts.

Basement ridges

Basement ridges are long, narrow protrusions of basement into overlying cover. They can be an erosional feature, or the product of active tectonics. Only the latter are discussed here. They are bounded by steep faults, and therefore produce sharp gravity anomalies. When recently active such as in the Iona Belt, they can form topographic ridges. A significant factor tectonically is that such ridges never protrude above the level of basement outside the basin (the pre-subsidence level), or project through the cover being deposited in the basin, and are probably not therefore caused by uplifting forces. This led Anfiloff (1982) to suggest they are caused by differential subsidence; that they subside less rapidly than adjacent basement because horizontal forces chanelled along them impede subsidence. The mapping of basement ridges in the Murray Basin for groundwater purposes is providing a valuable insight into processes related to the formation of broad depressions, particularly as the basin cover is undisturbed. At P, east of Broken Hill, a network of large interconnected basement ridges is revealed in reconnaissance gravity data, but this data is too coarse to reveal narrower ridges which are also important to ground water research. The Scopes Range structure is part of the basement ridge at P, and bifurcates eastwards along a network of lesser ridges which penetrate into the Darling Basin.

Conclusions

Under the Murray Basin, tectonism appears to be controlled by a rectilinear system of crustal fractures. The framework is coherent and includes conjugate orthogonal belts. It is proposed that mobile belts have developed along fractures by strike-slip movement producing compartmentalised rifts which have been individually converted to mobile belts by intrusion of granites and mafic volcanics. Rifting is often polycyclic. Basement ridges are another major component of the framework. They form partitions in rifts and fan out across the basin. Narrow basement ridges protruding upwards into the sediment cover have been successfully mapped using gravity data, but are transparent to airborne magnetics.

It is proposed that basement ridges represent the chanelling of pervasive horizontal compression through the crust. When these forces are being balanced, strike-slip movements would occur initiating rifting and igneous activity. At the same time, compression may interfere with subsidence producing flanking ridges. Ridges which partition mobile belts may represent the pivotal points of crustal blocks which have rotated slightly during strike-slip movements (Fig.5), and the term 'node' has been applied to these structures. The Scopes Range ridge, which separates two apparently conjugate belts, the Bancannia and Menindee Troughs, is the best example of a node with important tectonic connotations because basement ridges emanate from it across the basin.

A young belt of probably Tertiary age is apparently developing parallel to older mobile belts, and may be a rift. It suggests that mobile belts can develop individually, but the strength in older belts resulting from igneous activity including massive granites, may force them to exploit parallel fracture directions, resulting in a series of parallel belts. These may overlap with the older belts producing complex wider belts.

Major arcuate structures which flank and underly the Murray Basin have a symmetrical and coherent relationship to orthogonal and possibly conjugate mobile belt systems. They are interpreted as the by-products of mobile belt development, possibly the gravity sliding of sediment cover in response to uplift along the mobile belts.

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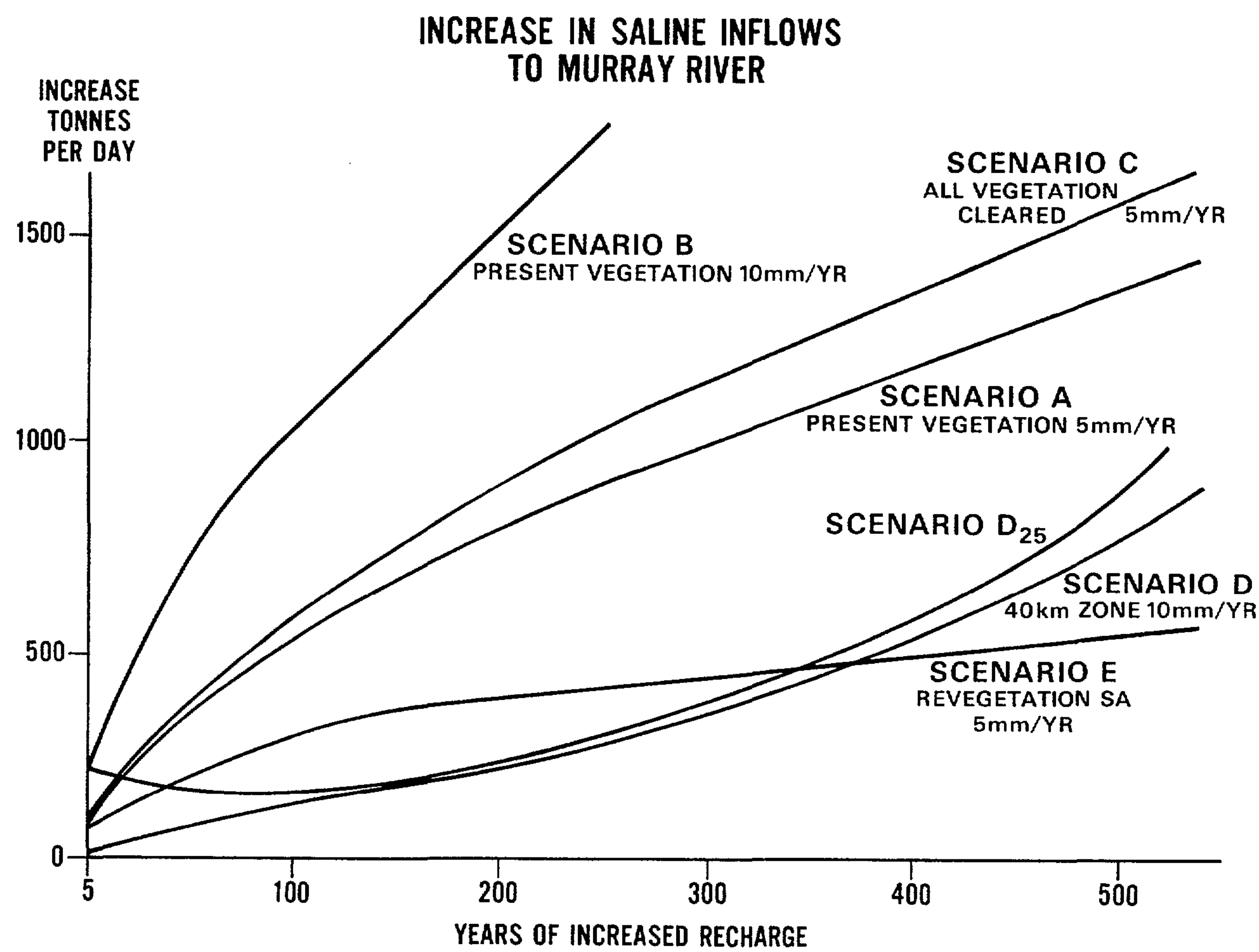
SCENARIO MODELLING OF AQUIFERS IN THE MALLEE REGION

S.R. Barnett
SA Department of Mines and Energy
PO Box 151, Eastwood, S.A. 5063

Recharge rates derived by the CSIRO Division of Water Resources Research beneath cleared and uncleared native Mallee vegetation were applied to a three layered finite element computer model of the Mallee region of South Australia and Victoria. A rate of 0.1 mm/yr was applied to vegetated areas, with values of 5 and 10 mm/yr being used for cleared areas in a variety of scenarios which included complete clearing and revegetation of certain zones.

The resultant rise in the water table from the increased recharge lead to higher inflows of saline groundwater to the River Murray. The model calculated the increase in these inflows at various times after the effects of the higher recharge had reached the water table (which lies at a depth of 30-40 m below ground level).

The calculated inflows were then used in MURKEY, a river flow and salinity model for the Murray River, to calculate the resultant increase in river salinity at Morgan. With the present vegetation distribution in the Mallee and a conservative value of 5 mm/yr for the increased recharge over cleared areas, an increase in salinity of 70EC at Morgan is predicted 50 years after the increased recharge reaches the water table. This would cost the state of SA $4.7 million annually.



MURRAY BASIN - SALINITY AND DRAINAGE STRATEGY

D.J. BLACKMORE

Murray-Darling Basin Commission

7 Moore Street, Canberra 2600

Land salinisation and River Murray salinity are recognized as one of the highest priority issues for resolution in the Murray Basin. One of the problems affecting the resolution of this issue was how to solve the River Murray salinity problem in a co-ordinated and equitable way, taking into account the various interests and priorities of the three States involved. The advent, in November 1985, of the Murray-Darling Basin Ministerial Council with its objective, to 'promote effective planning and management for the equitable, efficient and sustainable use of water, land and environmental resources of the Basin', now provides the opportunity for co-ordinated and co-operative management policies to be developed and implemented.

The paper examines the factors taken into account when developing the Draft Salinity and Drainage Strategy. Also discussed are the future challenges facing natural resource managers in understanding the hydrogeological changes now occurring and how this will impact on the future management of the land and water resources of the Basin.

Development of the Salinity and Drainage Strategy

In the past much of our research and development effort has been concentrated on understanding processes occurring in the top two metres of the land surface. There is no doubt that many of the processes which effect the long-term sustainability of land originate from physical changes occurring in the top two metres. However, in the Murray Basin one of the dominant factors that will effect long-term natural resource management strategies, is an understanding of the hydrogeology of the Basin and its interaction with the surface and near surface soils on which we rely for the productivity and the environmental amenity of the Basin.

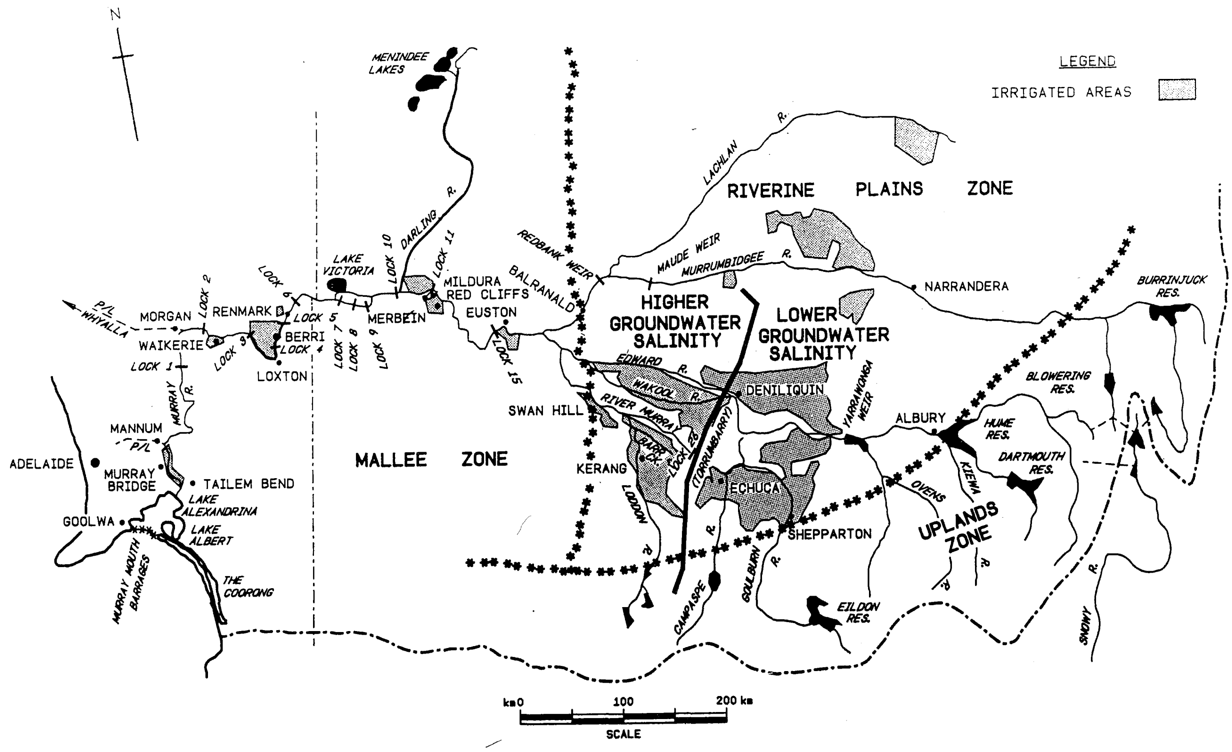
The methodology adopted by the Working Group in developing the Strategy was to:

- assess the physical situation and underlying hydrogeology
- determine what actions are economic from a Basin perspective, taking into account the hydrogeological changes that are expected over the next 30 years.

Hydrogeological Differences

There are significant differences in the hydrogeology of the various regions that comprise the Murray Basin. By far the dominant single feature is a change in groundwater salinities that occurs about midway down the Riverine Plains Zone of the Basin. The location of the change can be approximately delineated, by a north-south line passing through Torrumbarry Weir (refer Figure of River Murray zones and development).

Groundwater salinities on the eastern side of this hinge line are in the order of 1000 to 5000 EC units while groundwater salinities on the western side of the hinge line are 20000 to 50000 EC units and can exceed 80 000 EC units in some locations. This change in groundwater salinity dominates what options are practical and economic to implement, to protect land from salinization.



RIVER MURRAY - ZONES AND DEVELOPMENT

Economic Assessment

The economic assessment of land salinisation and river salinity depends on our understanding of the changes that are likely to occur in the future. In particular, our understanding of the increase in the effects of land salinisation in the irrigation and dryland areas. Also the cost and consequences of works and measures proposed to treat the problem need to be quantified. It is estimated that over the next 30 years an additional 310,000 hectares of irrigated agriculture will be affected by high watertables. The consequent effect on productivity and environmental amenity depends on a range of factors related to each environment. The challenge in the future is to carry out the detailed hydrogeological assessments required so that these impacts can be better quantified as can the effects of the various remedial action proposed. This will require increased emphasis on regional hydrogeological investigations in the future.

Key Elements of the Salinity and Drainage Strategy

Taking into account the economic assessment and the underlying hydrogeological processes occurring in the Murray Basin, the key elements of the Draft Salinity and Drainage Strategy which provides for a reduction in River Murray salinity and for the upper States to drain some of their high value irrigation land on the Riverine Plain are:

Base Line Conditions

- current river salinity levels are to be adopted as the base line for evaluating responsibility for all future actions which affect river salinity.

- each State will be responsible for its future actions which affect River salinity.

Initial Program

- The three States and the Commonwealth will jointly fund cost effective salt interception schemes to reduce River salinity by 80 EC (median salinity at Morgan).
- Upper States may increase river salinity by up to 15 EC (median salinity at Morgan) as a consequence of joint funding of the salt interception program.

Future Program

- Beyond the joint program of works, States have the option of contributing to the costs of any further schemes that are identified, and will receive a salinity credit in proportion to their contribution to the cost.
- River salinity improvements obtained by any action in one of the States are to be credited to that State.

Administration

- The Strategy is to be embodied in a Salinity and Drainage Agreement and administered by the Murray-Darling Basin Commission.

Implementation of the Strategy

The Strategy provides for each State to be accountable for future actions. However, to assess accountability will require detailed monitoring and interpretation of the hydrogeological changes that are occurring in the Basin, together with ongoing monitoring of changes that are occurring to the land and water resources of the Basin. The future challenge that faces all resource managers is to obtain the necessary understanding of the longer term changes that are likely to occur to ensure that appropriate land and water management policies are implemented in the short to medium term.

The Strategy is the starting point for action rather than an end point. It opens the way for States to tackle their high priority land salinisation problems and to initiate the necessary detailed regional planning. This is now occurring in Victoria and to a lesser extent in New South Wales and South Australia.

REFERENCE

Murray-Darling Basin Ministerial Council 1988 - Discussion Paper No 1 - Draft Salinity and Drainage Strategy January 1988.

ENVIRONMENTAL AND SALINITY HISTORY OF THE MURRAY BASIN IN THE LAST 500,000 YEARS

J.M. Bowler

Museum of Victoria

To European eyes of the 1880's, the landscape of the inland plains was a hostile reminder of a strange continent where plants, animals and people were so different from the homelands of England, Scotland or Wales. The reaction of the early settlers was predictable and understandable – remove the bush, divert rivers to irrigate the dry and, in terms of European agriculture, largely intractable plains.

It was not only the plants, animals and original occupants that were so foreign, it was the very landscape itself. For lying within that landscape was a record of past episodes of natural salinity changes that for so long remained obscure and unknown to early developers and subsequent generations. Only now are we beginning to understand how the natural landscape of the Murray Basin has, in past times, been subjected to major episodes of salinisation, so severe as to make the present crisis appear more like a minor perturbation.

The Australian landscape preseves effects of increasing aridity, perhaps extending through more than the past 4 million years. Progressive increases in evaporation associated with reduced rainfall, assisted in the effective build-up of salts. Low rainfall, combined with reduced run-off, facilitated salt storage accumulation. About 500,000 years ago, the situation reached crisis point under those special cyclic changes that have accompanied the major global glacial-interglacial oscillations of Pleistocene time. Events of the last 100,000 years and especially the last 50,000 years demonstrate the extent and magnitude of those landscape changes (Fig. 1).

The general features of the natural change involved an early long wet period in which floods were frequent and prolonged. Lakes previously dry, filled with fresh water; watertables rose throughout the region. As long as there was abundant surface flushing, the effects of saline groundwaters were probably restricted to the loss of deep-rooted vegetation. The major change came with the approach of the most intense phase of the last Ice Age, about 25-16,000 years ago. Accelerated winds, hot summers and low rainfall, combined to produce episodes of droughts, the intensity and duration of which had not been experienced in the Australian landscape for some 50,000 years earlier. Lakes, previously carrying fish and other freshwater biota, became saline. The Aboriginal occupants, already occupying the Murray Basin for more than 10,000 years, saw their food resources turn into saline wastelands.

Strong summer winds blew clouds of salt-laden dust to the southeast depositing salts, many to be later recycled through soils and streams back to the inland plains. Dunes, many of which were initiated by saline conditions, spread across the face of the land.

About 15,000 years ago, the harsh glacial climates improved; winter temperatures rose, frost incidence decreased and the strong summer winds of glacial summers moderated. These conditions encouraged the return of trees to the landscape resulting in the gradual drawdown of previously high watertables.

For the next 10,000 years, despite changes in water-balance, a general vegetation-groundwater equilibrium was sustained. No evidence is observed of major saline-erosional events.

Today, just 200 years after European arrival, the situation has drastically changed. In just a brief 100 years of intensive agriculture on the Victorian plains, the landscape has responded by reverting to conditions more typcial of Pleistocene times. But now the watertable rise is a direct function of human rather than natural climatic changes.

The continuing rise in watertables is no longer asssociated with a regional rise in lake levels. Some lakes, as in Western Victoria, have fallen rather than risen over the past 100 years. In the northern plains however, many groundwater discharge playas have been reactivated.

Under modern drought conditions, the strong effects of evaporative pumping now result in salt crystallization at, or near the surface, a phenomenom most conducive to soil destruction and erosion as occurred in dust storms of 1983.

In a brief 100 years we have reproduced expressions of saline Pleistocene environments. To reverse those trends requires even closer examination of just how the natural system operates. In this context, the lessons from the past must guide us into the future.

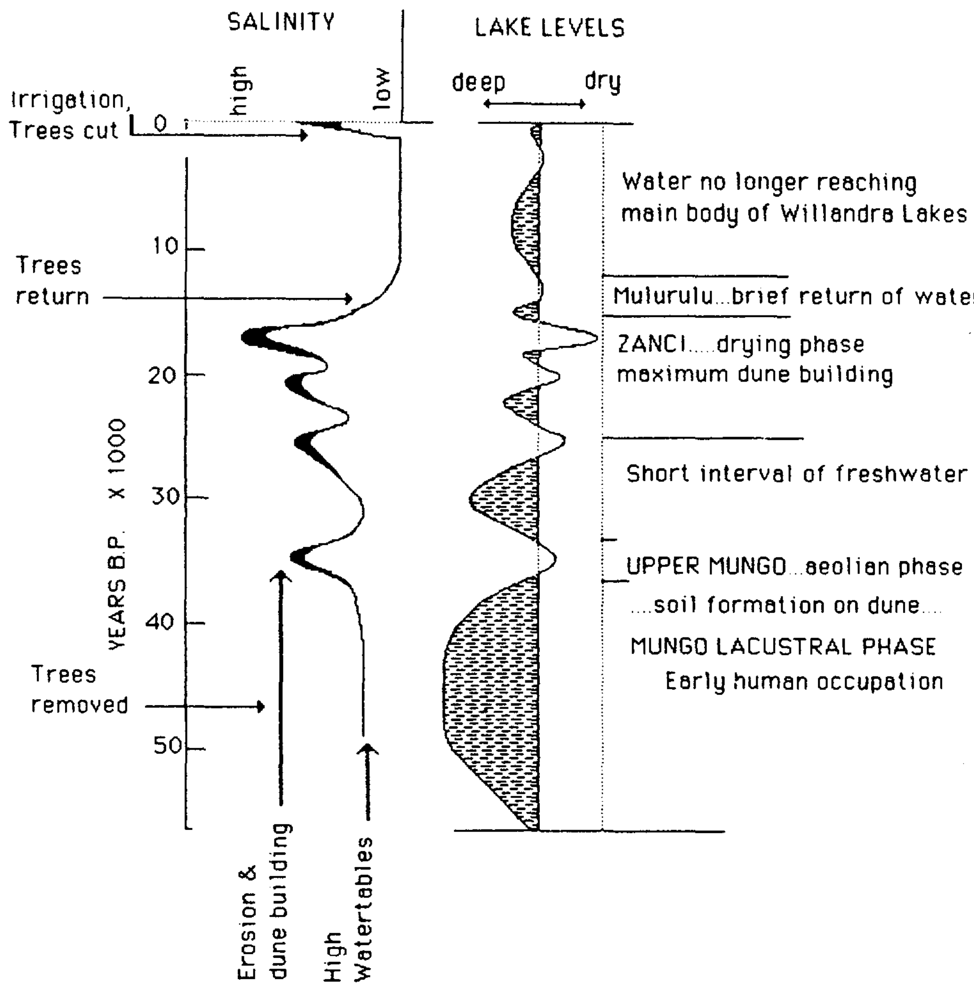


Fig. 1: Generalised record of lake level oscillations in SE Australia over the past 50,000 years. Data drawn mainly from Willandra Lakes in western NSW supplemented for last 10,000 years from western Victoria
Changes in groundwater levels are inferred from lake hydrologic data. Peak salinity and dune-building events at 36,000 to 18,000 correspond to episodes of high evaporative concentration following periods of high watertables.
Change in salinity and groundwater levels of the past 100 years is mimicking conditions that occurred naturally in Pleistocene time.

GROUNDWATER MANAGEMENT IN THE WAKOOL DISTRICT N.S.W.

G.J. Brereton & D. Hoey
New South Wales Department of Water Resources
Deniliquin, N.S.W.

The Wakool Irrigation District is located approximately 850 km SW of Sydney and 350 km N of Melbourne. The District covers over 200,000 hectares and uses an average 250,000 ML on 40,000 hectares of irrigated land each year.

Water tables in the Wakool/Tullakool area have historically been shallow. The first watertable survey in 1944 (8 years after irrigation commenced) indicated an average depth of groundwater of 9 m. Intensification of irrigation in 1949 when dairying and rice was introduced on a large scale, led to increased groundwater accessions. Heavy rain and flooding in 1956 accelerated watertable rises. Salinization and waterlogging have become apparent from this time on.

In the 1960's experimental tubewell drainage was found to successfully control groundwater levels in the shallow 'shoe string' aquifers, (prior streams). Effluent was discharged to the Niemur river (and hence eventually to the Murray) though this caused problems downstream at low river flows, and pumping restrictions had to be enforced under low flow conditions.

The first plan for a drainage scheme, in 1973, was reinforced by wet conditions in 1974-75, when 45,000 ha were found to have watertables within 2 m of the ground surface. After numerous studies, the present scheme was initiated in 1978 as a joint Commonwealth/State project. Construction began in 1979; Stage I was completed in 1982 and Stage II completed in early 1988.

The Wakool/Tullakool Sub Surface Drainage Scheme consists of 48 pump sites (predominately tubewells with a few spearpoints) pumping via a series of spur lines into two main collector lines. Each main line is approximately 25 kilometres long, discharging to separate evaporation basins where salt production can take place.

The scheme has pumped over 50,000 ML of groundwater with over 800,000 tonnes of salt being removed, over the period 1981-87. This has resulted in the lowering of watertables over 21,000 ha by more than half a metre. By comparison regional shallow watertables have risen by an average of 0.2 metres/year outside the protected area. Limited EM-38 soil salinity surveys have indicated that areas classed as salt affected have decreased from 72% of the sampled area in 1982 to 46% in 1984. This translates to a benefit in crop production of $750,000 over this period (Grieve & others, 1986).

The principal aim of the sub surface drainage scheme was to lower watertables to below 2 metres, to prevent further salinisation and allow leaching of salts to below the root zone. From a hydrologic viewpoint the scheme has been successful. However the scheme has operation and maintenance costs of $300,000/year. Therefore a number of management strategies are being examined to minimise the cost, while at the same time maximising the area of land protected. Examples include intermittent operation of tubewells, discharge of pumped effluent to surface water supplies for re-use, and encouragement, with the N.S.W. Department of Agriculture, of better on-farm irrigation management to reduce groundwater accessions.

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OVERVIEW OF THE GEOLOGY OF THE MURRAY BASIN

C.M. Brown

Division of Continental Geology, Bureau of Mineral Resources

G.P.O Box 378, Canberra City, A.C.T. 2601

During the past one hundred years the Murray Basin has become one of the most important agricultural regions in Australia, and currently generates several billion dollars in annual income. Clearance of natural vegetation and development of irrigation schemes have, however, resulted in rising groundwater levels and discharge of saline groundwaters into the landscapes and river systems of the basin, creating salinity problems that threaten to have an increasingly adverse impact on the regional economy. Salts have basically been concentrated at the surface of the Murray Basin by evaporation and have then been re-cycled into underlying shallow aquifers – a process which is greatly enhanced during periods of high groundwater levels and surface discharge. Groundwaters in many near-surface aquifers have become increasingly saline as a consequence of several such periods of high groundwater levels during the past several hundred thousand years. Part of the reason for the build-up of salinity is therefore climatic, but, part is also due to the underlying stratigraphic and structural architecture of the basin. At many sites the driving mechanisms for groundwater discharge can be related to flow disruption, high pressures and upward leakage created at permeability barriers formed where aquifers are significantly thinned by concealed basement barriers or are stratigraphicaly thinned by lateral changes in lithology. A knowledge of the subsurface structural and stratigraphic framework of the basin is therefore an essential prerequisite to understanding the relationships between aquifer geometry, recharge, groundwater flow and distribution of surface discharge features. This paper describes the evolution of the basin-wide structural and stratigraphic framework of groundwater occurrence in the Murray Basin and discusses the regional relationships between the architecture of the concealed Tertiary geology and the discharge of saline groundwaters as recorded in the Quaternary geology of the surface of the basin.

Surface Geological Record

The surface of the Murray Basin (Fig.1) is almost entirely mantled by Quaternary morphostratigraphic units which provide a record of fluctuation in climate and groundwater levels (e.g. Macumber, 1980, 1983; Bowler, 1983; Bowler & Wasson, 1984; Bowler & Teller, 1986). It is apparent from the extent of fossil groundwater discharge complexes that salinization of the landscape has been considerably more widespread, under 'natural' conditions at times in the recent geologic past. Current land-use practices have resulted in rising groundwater levels thereby replicating the conditions conducive to increased salinization in the past, and resulting in re-activation of 'natural' groundwater discharge systems. Surface geological mapping of Quaternary units (e.g., Brown & Stephenson, 1985) can thus be used to identify those areas where there is a particular risk of future salinity problems as groundwater levels continue to rise.

Basin Architecture

Structural Framework: The low-lying, saucer-shaped Cainozoic Murray Basin extends over 300,000 sq.km. of inland southeast Australia, and is flanked by subdued mountain ranges of Proterozoic and Palaeozoic fold belt rocks. Concealed basement rocks of the coastal Padthaway Ridge (Fig.2) form a southwestern rim to the basin, separating it from the Southern Ocean. The Cainozoic succession of the Murray Basin form an extensive but relatively thin cover of sediment, consisting of a maximum thickness of 600m in the main depocentre beneath west-central areas, 300-400m beneath the west-

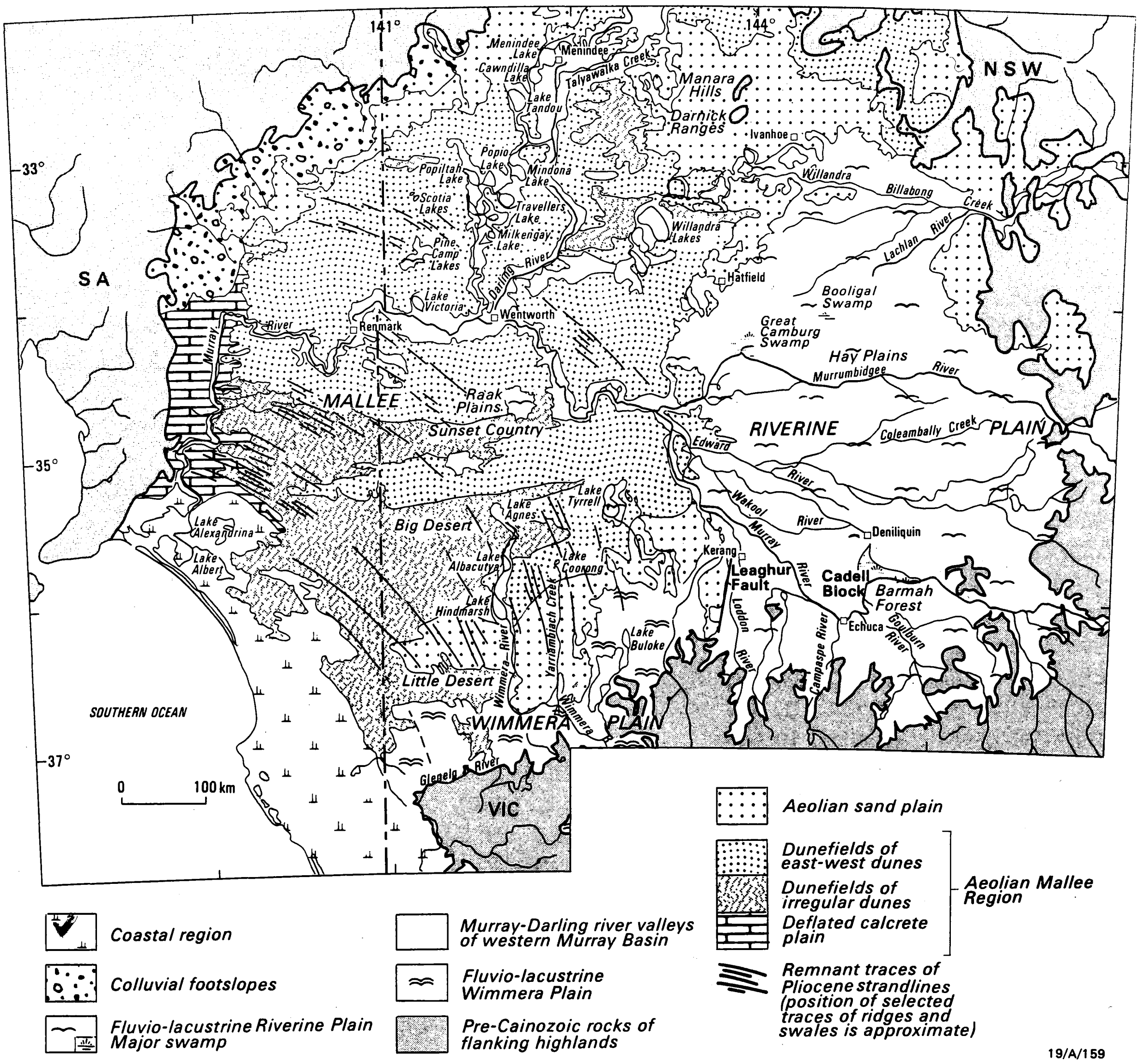

Fig. 1. Geomorphic regions of the Murray Basin

central Riverine Plain, and generally less than 200m beneath northern, eastern and southern areas. The Murray Basin is thus a largely closed groundwater basin, with limited groundwater storage capacity. Internal surface and groundwater drainage is towards the topographically depressed central-western depocentre, which effectively forms a groundwater sump. In the west, the River Murray acts as an effluent drain providing the only natural conduit for removal of excess salt water from the basin, and only manages to escape to the sea via a gorge incised into up-faulted Tertiary sediments of the Pinnaroo Block. Significant quantities of saline groundwater seep into the River Murray where it erodes into Tertiary sediments.

Regional geophysical data indicate the presence of arcuate northerly trending structural belts beneath the Murray Basin. These are concave to the east, and trend to the north-northwest beneath the southern part of the basin and to the northeast beneath northern areas (Brown & others, in press). The basement is also strongly deformed by northerly fold and fault trends, cross-cut by NE-SW and NW-SE fracture sets. The geometry of the overlying Murray Basin has largely been determined by this basement configuration, and subtle re-activation of basement structures has strongly influenced Cainozoic sedimentation patterns and modern surface drainage patterns, as well as groundwater flow and surface discharge patterns. The shape of the Riverine Plain and the convergence of surface drainage towards its central-western apex, for example, are strongly influenced by the configuration of concealed basement ridges.

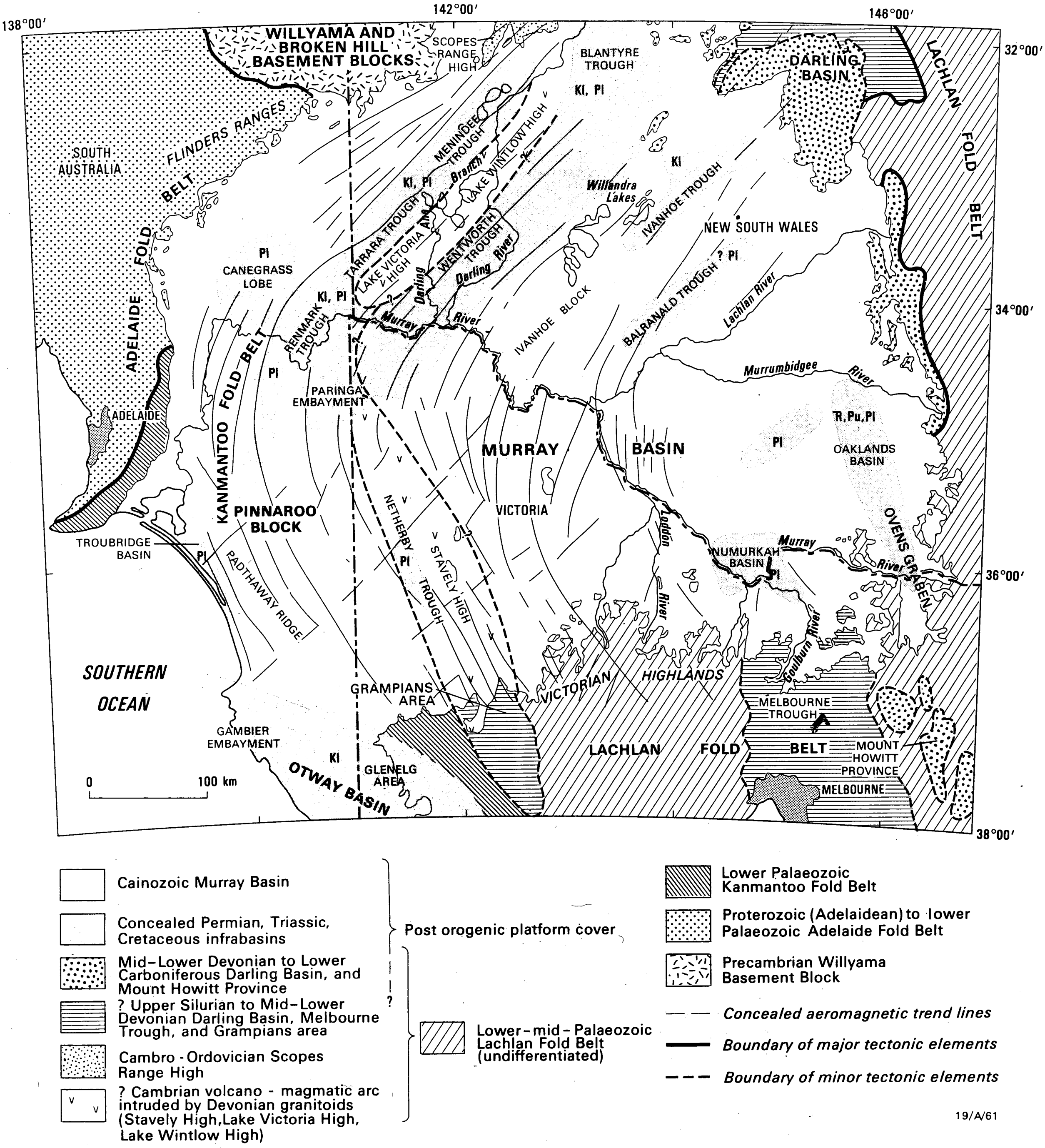

Fig. 2. Framework tectonic elements and underlying infrabasins

Cainozoic Stratigraphic Framework: Within the Tertiary succession (Lawrence, 1975; Ludbrook, 1961; Woolley & Williams, 1978) at least three major depositional sequences have been identified – Paleocene-Eocene to Lower Oligocene, Oligocene-Middle Miocene, and Upper Miocene-Pliocene (Fig.3; Brown, 1983, 1985; Brown & Stephenson, 1986). Non-marine sand, silt, clay, and carbonaceous sediments predominate in the east and north, but each of the depositional sequences includes marine sediments in central to southwestern areas (Table 1). A representation of the geology is shown on Fig.4. Framework tectonics have provided the primary control on development of the Murray Basin, but Cainozoic sedimentation patterns have also been strongly influenced by the interactions between superimposed secondary tectonic, eustatic, and palaeoclimatic controls.

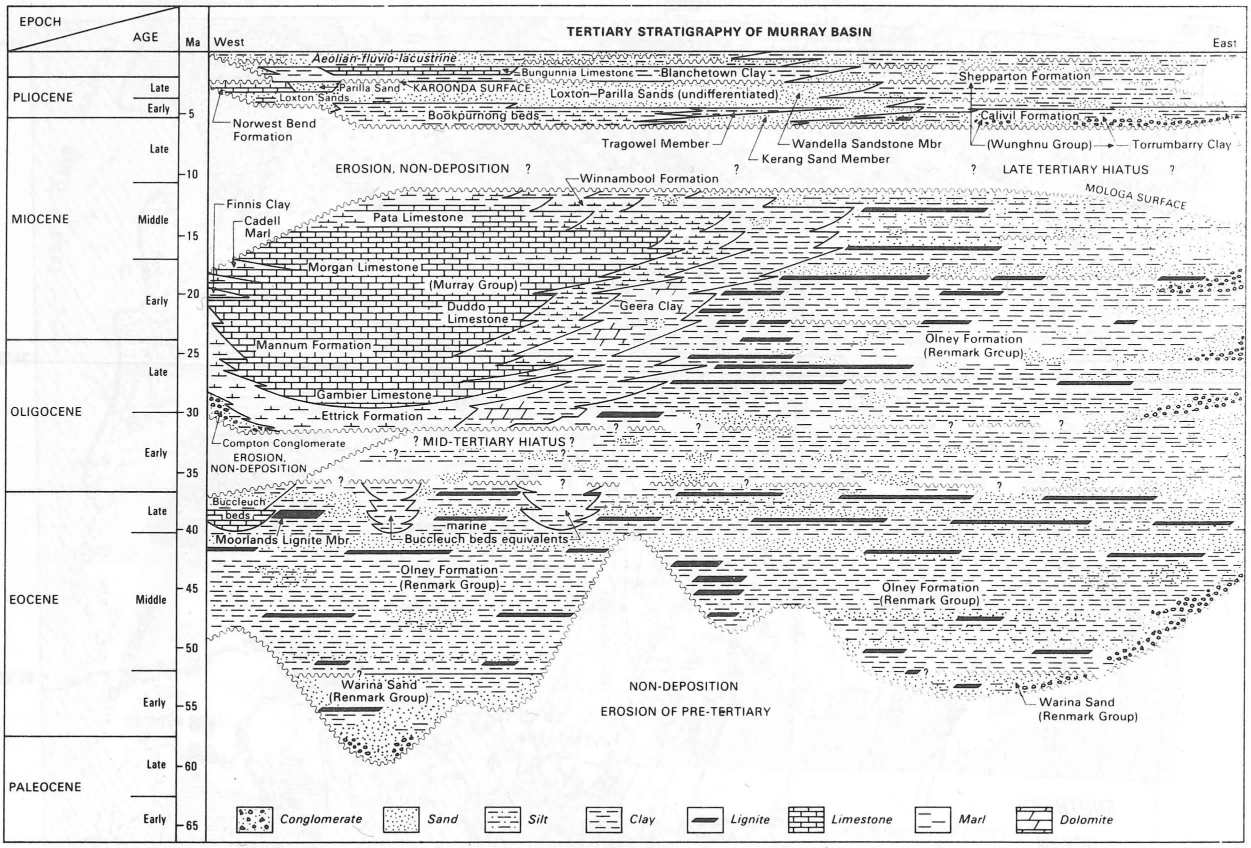

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Fig. 3. Tertiary stratigraphy of the Murray Basin

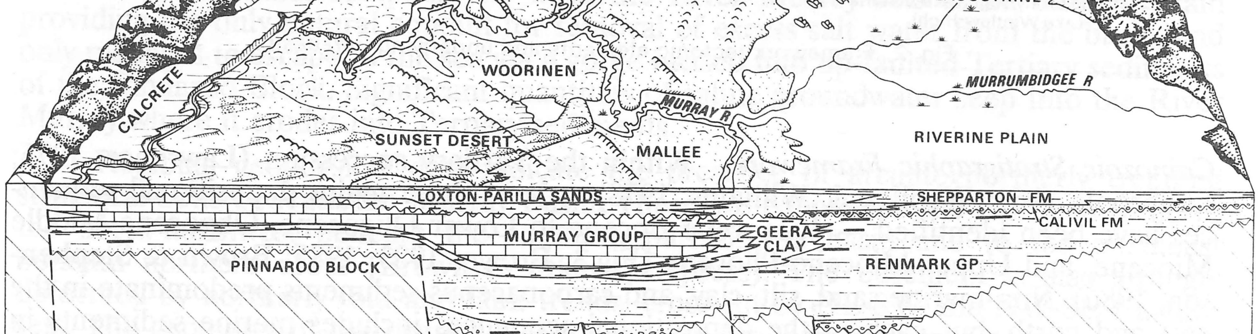

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Fig. 4. Representation of the geology of the Murray Basin

TABLE 1 – DEPOSITIONAL SEQUENCES OF THE MURRAY BASIN

Paleocene-Eocene-Lower Oligocene sequence: At the base of the Tertiary succession, deep bores have encountered a fluvial unit of weakly consolidated medium to coarse quartz sands with minor intercalated carbonaceous fine sand, silt and clay (?Paleocene-Eocene Warina Sand of Renmark Group). The unit is locally up to 200m thick, but is mainly restricted in distribution to central-western parts of the basin. Thinner basal sands of uncertain age which underlie west-central areas of the Riverine Plain are also tentatively assigned to the Warina Sand. The unit is overlain by unconsolidated, thinly bedded carbonaceous silt, sand, and clay of the Olney Formation (Renmark Group), characterised by the abundant presence of carbonised and pyritic plant remains, and with common intercalations of lignitic coal and peat. The formation is thought to have been deposited predominantly in fluvio-lacustrine environments but palaeontological evidence indicates that minor marine and marginal marine components are increasingly prevalent towards the top of the Olney Formation in western areas. In the southwest these components are intercalated with Late Eocene (to ?Early Oligocene) shallow-marine glauconitic calcareous clay, thin bryozoan limestone, and minor carbonaceous sand (Buccleuch beds). Deposition of the Olney Formation was restricted to the Eocene-Early Oligocene in the west, but continued into the Middle Miocene in the north and east. Sedimentation during this extended period was probably intermittent, and the succession contains a number of stratal breaks. Oligocene-Miocene sediments of the Olney Formation are, lithologically indistinguishable from Eocene-Lower Oligocene sediments, and therefore the variously dated components are regarded as parts of a single lithologic unit.

Oligocene-Middle Miocene sequence: A marine transgression in the late Early-Oligocene (Fig.5a) resulted in deposition of the marine and marginal-marine formations of the Oligocene to Middle Miocene Murray Group sequence. The Oligocene Compton Conglomerate occurs at the base of the Murray Group, but is patchy in distribution and lithologically variable, consisting of residual quartz-pebble conglomerate with a ferruginised matrix as well as shallow-marine glauconitic clay and calcareous sandstone. In most areas, however, Oligocene glauconitic calcareous clay (marl) of the Ettrick Formation forms the basal unit. This is succeeded up-sequence by Late Oligocene to Middle Miocene (Fig.5b) shallow-marine platform limestones, consisting of coarse-grained skeletal debris admixed with varying proportions of calcareous clay, micrite and quartz sand (collectively known as 'Murray Group limestones'). These are calcarenitic in the west, but are increasingly fine-grained to the southeast. To the north and east, the platform limestones grade into a narrow zone of glauconitic calcareous clay and thin limestone of the Winnambool Formation, deposited in restricted-marine platform and lagoonal environments. The Winnambool Formation is essentially a younger diachronous equivalent of the lithologically similar Ettrick Formation. These units in turn grade laterally into the Geera Clay, consisting of black, locally carbonaceous silty quartz-rich mud and clay with minor dolomite and sand intercalations, deposited in shallow to marginal-marine environments - including extensive interdistributary-bay and tidal-flat environments. To the north and east the Geera Clay in turn interfingers with deltaic and fluvio-lacustrine silt, sand, clay, and peaty coal (further Olney Formation of Renmark Group). During the subsequent retreat of the sea from the basin in the Mid-Miocene, the Olney Formation, the Geera Clay and the Winnambool Formation appear to have partly prograded back over the top of the platform limestones so that the Geera Clay partly envelops the marls, which in turn partly envelop the limestones. Deposition of the platform carbonates and associated terrigenous clastics of the Murray Group sequence ceased by the late Middle Miocene to early late Miocene.

Upper Miocene-Pliocene sequence: A further short-lived marine transgression-regression can be correlated with deposition of the last major Tertiary depositional sequence. At the base of the sequence the Late Miocene Bookpurnong beds consist of clay and marl deposited over the disconformity surface in shallow-marine environments (Fig.5c). These are flanked to the north and east by marginal-marine sand of the basal undifferentiated Loxton-Parilla Sands (Parilla Sand, as defined in S.A. is restricted to younger cross-cutting fluvial deposits of Pliocene age, but the name has been applied in Vic. & N.S.W. to sands which are predominantly equivalent to Loxton Sands of S.A.). The basal Loxton-Parilla Sands are in turn flanked to the east and north by coarse-grained quartzose sand and gravel of the fluvial and fluvio-lacustrine Calivil Formation which form an extensive sand sheet underlying much of the eastern and northern Murray Basin. The Calivil Formation also infills concealed entrenchments within older sediments and basement rocks of adjacent highland valleys. An extensive sand sheet was deposited over much of the western Murray Basin during the final retreat of the sea from the basin in the Early Pliocene (further undifferentiated Loxton-Parilla Sands: Fig.5d). It consists of various shallow-marine, lower shore-face and beach quartz sand deposits, as well as younger inter-ridge and cross-cutting, fluvial and estuarine deposits, which together form a composite strand-plain deposit. Beach-ridge and swale complexes form prominent surface features over much of the composite strandplain, although several generations of cross-cutting and disconformable estuarine and fluvial deposits dominate the succession exposed in the River Murray Gorge, where estuarine oyster beds of the Norwest Bend Formation were deposited during a minor subsequent rise in sea-level in the Late Pliocene. In the east, the Pliocene regression can be correlated with deposition of fine-grained clastics and polymictic sand and gravel of the Pliocene to Quaternary Shepparton Formation by aggradation in a fluvio-lacustrine floodplain environment.

Quaternary Sedimentation: In the east and north of the Murray Basin, fluvio-lacustrine sedimentation continued intermittently throughout the Quaternary (further Shepparton Formation), resulting in development of the modern Riverine Plain. Farther west the Tertiary is partly overlain by a thin veneer of Pleistocene fluvio-lacustrine clay (Blanchetown Clay) and minor dolomitic limestone deposited in a Pleistocene megalake – Lake Bungunnia. These are further overlain by the arid and semi-arid Mallee landscapes of late Pleistocene-Holocene aeolian sediments (Woorinen Formation; Molineaux-Lowan Sands). Surface drainage is almost entirely absent in the west, apart from the entrenched courses of the Murray and Darling Rivers. Fluvial sedimentation continues within the confined flood plains of the modern rivers (Coonambidgal Formation & other undivided alluvial deposits), entrenched within older fluvial and aeolian landscapes. Small but numerous and widely distributed lacustrine deposits (including Yamba Formation & other undivided saline lake deposits) are also present throughout the basin.

TABLE 2 – AQUIFERS OF THE MURRAY BASIN

At the base of the succession the Renmark Group aquifer consists of the Warina Sand, Olney Formation and Buccleuch beds, and is separated from the overlying Murray Group aquifer in the west by a Mid-Tertiary confining layer consisting of the Oligo-Miocene Ettrick Formation, Winnambool Formation and Geera Clay. Towards the southwest, the Murray Group aquifer is overlain by the near-surface 'Pliocene Sands aquifer', but farther to the east and north is separated from it by an Upper Tertiary confining layer consisting mainly of the Bookpurnong beds, but which also locally includes regressive components of the Winnambool Formation and Geera Clay. The Pliocene Sands aquifer is a composite body consisting of Loxton-Parilla Sands (& Norwest Bend Formation) in the west and Calivil Formation in the east. Beneath the Riverine Plain and adjacent highland valleys the Pliocene Sands aquifer directly overlies the Renmark Group aquifer system and is overlain by the Shepparton Formation aquifer system.

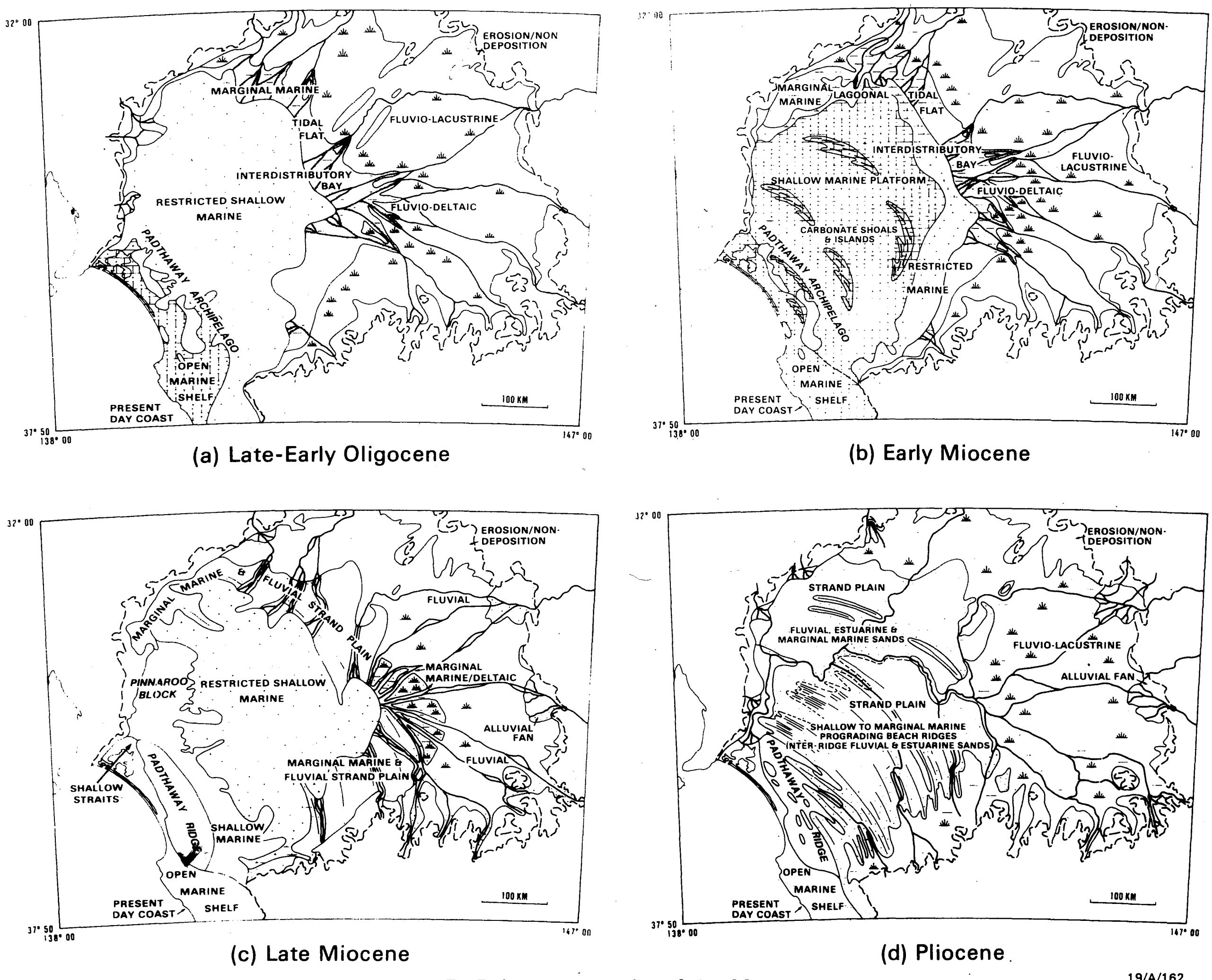

Fig. 5. Palaeogeography of the Murray Basin

Aquifers

Early Cretaceous weathering surfaces over Pre-Cainozoic basement form an impermeable seal at the base of the Murray Basin and the known groundwater resources are almost entirely confined to the Cainozoic succession, which can be translated into a number of regional aquifers and confining layers (Fig.6; Table 2).

Relationship between basin architecture and surface discharge of saline groundwaters:

Numerous active and fossil groundwater discharge complexes have been mapped at the surface of the basin – major complexes occur in the Manara, Darling/Darling Anabranch, Scotia, Pinecamp, Willandra, Hatfield (western Riverine Plain), Kerang, Tyrrell, Buloke, Manangatang, Walpeup, Raak, and Noora areas). Groundwater tends to flow towards low-lying areas of subsidence and thicker sediments in the central-west of the basin, and as noted above, development of most groundwater discharge sites can be related to the influence of basement structure and/or basin stratigraphy on aquifer geometry. For example, an extensive area of fossil saline lake and gypsum clay pellet lunette deposits at the northwestern margins of the Riverine Plain (Hatfield region) has developed over a zone where the Renmark Group aquifer thins from several hundred metres to less than 50m over an up-faulted but concealed basement ridge (Iona Ridge)

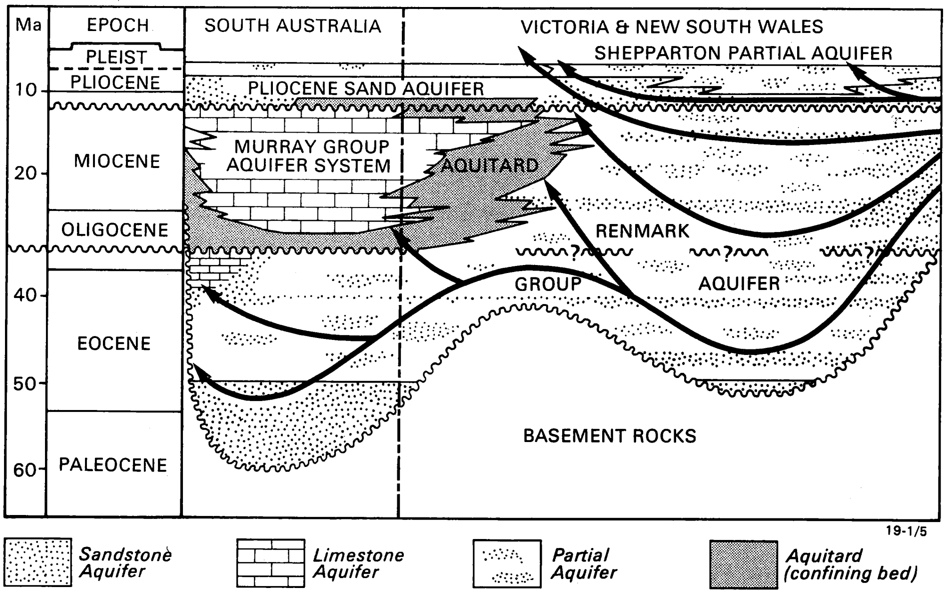

Fig. 6. Aquifer systems of the Murray Basin

of the adjacent Ivanhoe Block. The currently inactive Hatfield discharge complex can be identified as an area at risk from future salinity problems as groundwater levels continue to rise. Farther west, in the Mallee regions of the western Murray Basin, highly saline groundwaters of the Loxton-Parilla Sands (part of Pliocene Sands aquifer) locally intersect the surface to form groundwater discharge lake complexes. At Raak Plains, for example, groundwater outcrops in topographic lows, underlain by thick sediments – groundwater flow towards the River Murray is disrupted by the presence of a concealed basement block, overlain by thinner sediments and up-faulted to the northwest of the Danyo Fault (Macumber, 1980).

An example of aquifer thinning due to lateral changes in sediment type occurs where the Renmark Group aquifer is separated from the Murray Group aquifer by marginal-marine fine-clastics of the Geera Clay and calcareous clays of the Winnambool and Ettrick Formations (Mid-Tertiary confining bed). These formations are thickest in an arcuate belt extending from southern Victoria, through northwest Victoria, into southwestern New South Wales and into northern South Australia. The Geera clay in particular, is one of the key aquitards of the basin and the permeability barrier created where it stratigraphically replaces the Renmark Group has resulted in disruption of groundwater flowlines towards central-western areas of the basin, and upward leakage into overlying aquifers – which finds surface expression in a broad band of active and fossil groundwater discharge complexes. Beneath the southwest extremity of the Willandra Lakes, for example, the Renmark Group is laterally replaced by thick Geera Clay – this is likely to have resulted in disruption to groundwater flow, and at times, surface discharge into the lake system. A further example of stratigraphic control occurs in the south and east, where sands and gravels of the fluvial Calivil Formation become increasingly fine-grained into the basin, and laterally interfinger with finer-grained sediments of the basal Shepparton Formation and Loxton-Parilla Sands – the resulting permeability barrier finds surface expression in the discharge of saline groundwaters in the lower Loddon Valley (Macumber, 1978).

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ORIGINS OF CHLORIDE VARIATION IN THE MURRAY BASIN USING ENVIRONMENTAL CHLORINE-36

G.E. Calf[1], J.R. Bird[1], J.R. Kellett[2], and W.R. Evans[2]

[1]Australian Nuclear Science and Technology Organisation, Lock Mailbag 1, Menai NSW 2234

[2]Bureau of Mineral Resources, Geology and Geophysics, GPO Box 378, Canberra ACT 2601

INTRODUCTION

The potential contribution of Chlorine-36 to the study of the dynamics of the chloride cycle throughout the late Quaternary has recently been reviewed by Bentley & others (1986). All applications depend on the interpretation of systematic deviations of the specific activity of the isotope from that found at input. These are evident from a plot of ^{36}Cl/Cl versus ^{36}Cl/L (Figure 1). The addition of dead chloride results in a vertical displacement downward while isotope decay results in movement towards the origin. Evaporation (or ion filtration) result in a displacement to the right and the addition of low salinity water causes a displacement to the left. Underground production of ^{36}Cl due to the reaction of neutrons with ^{35}Cl increases both the ^{36}Cl/Cl ratio and the ^{36}Cl/L values. The mixing of two bodies of water or the addition of chloride with a different ^{36}Cl/Cl ratio causes a movement between points representing the two initial sets of values. The relation between points on such a plot can therefore be used to diagnose which factors are responsible for changes taking place along an aquifer.

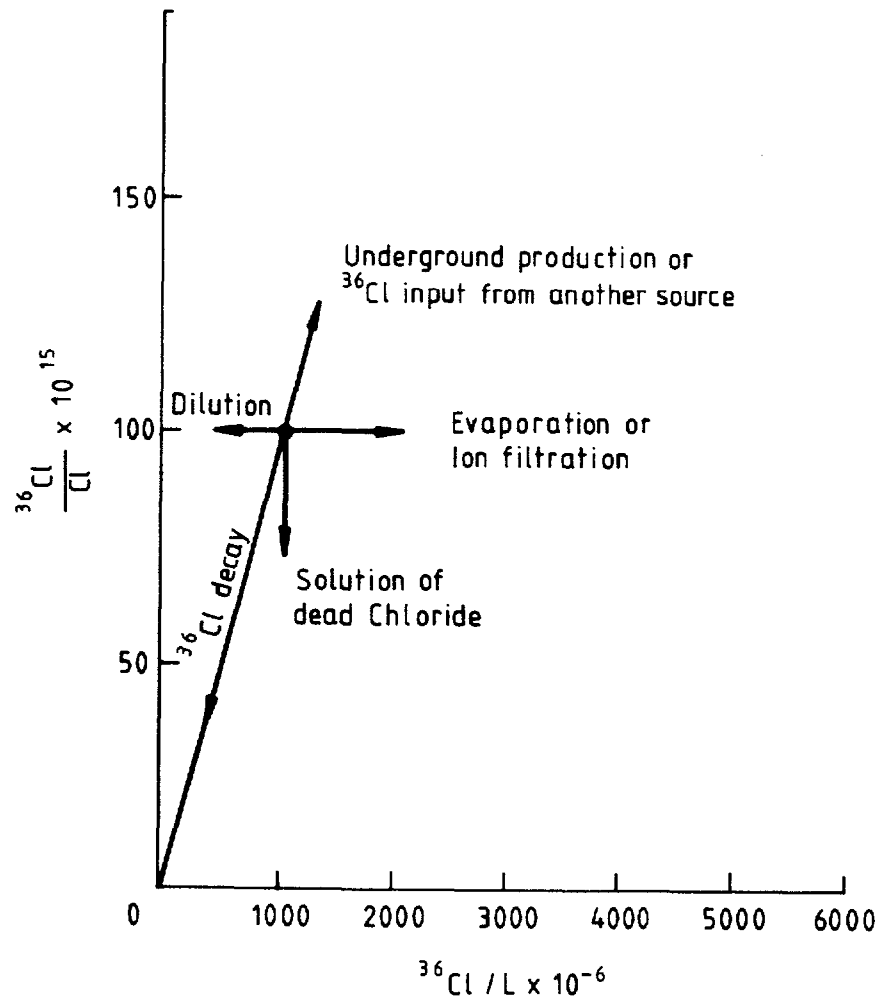

Figure 1. THE ^{36}Cl/Cl RATIO VERSUS THE ^{36}Cl CONCENTRATION (in atoms ^{36}Cl/L)

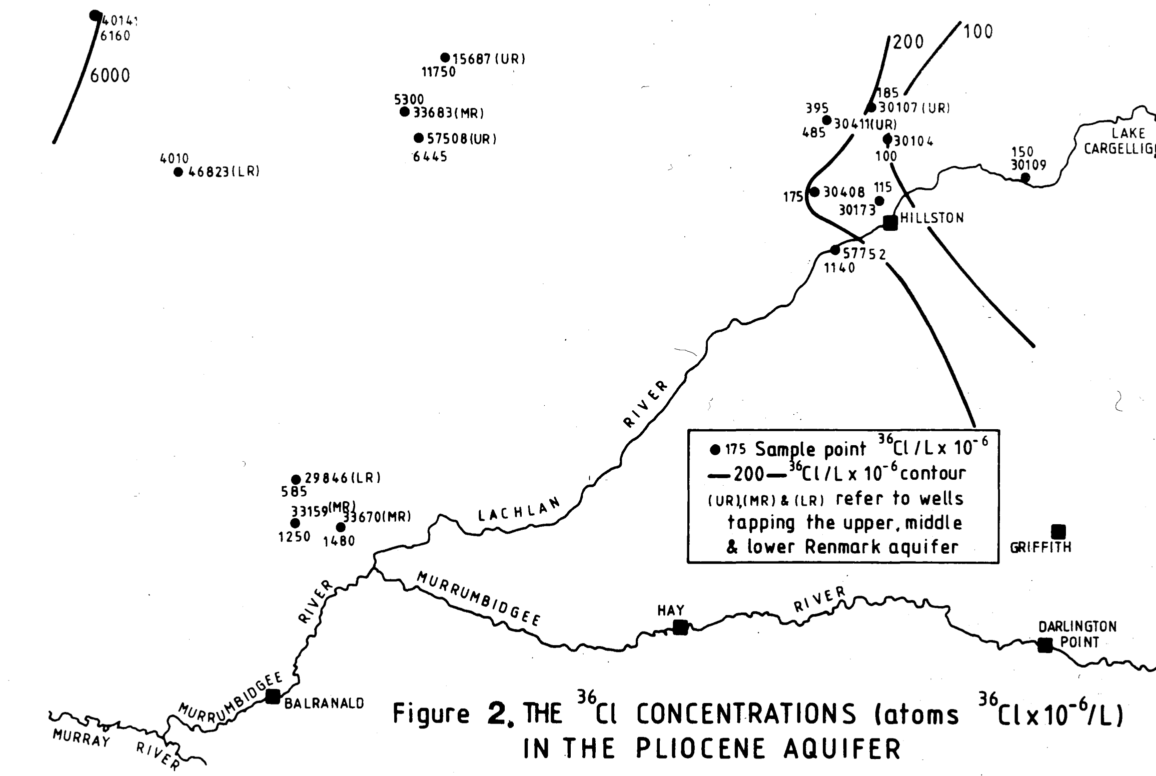

Figure 2. THE ^{36}Cl CONCENTRATIONS (atoms $^{36}Cl \times 10^{-6}/L$) IN THE PLIOCENE AQUIFER

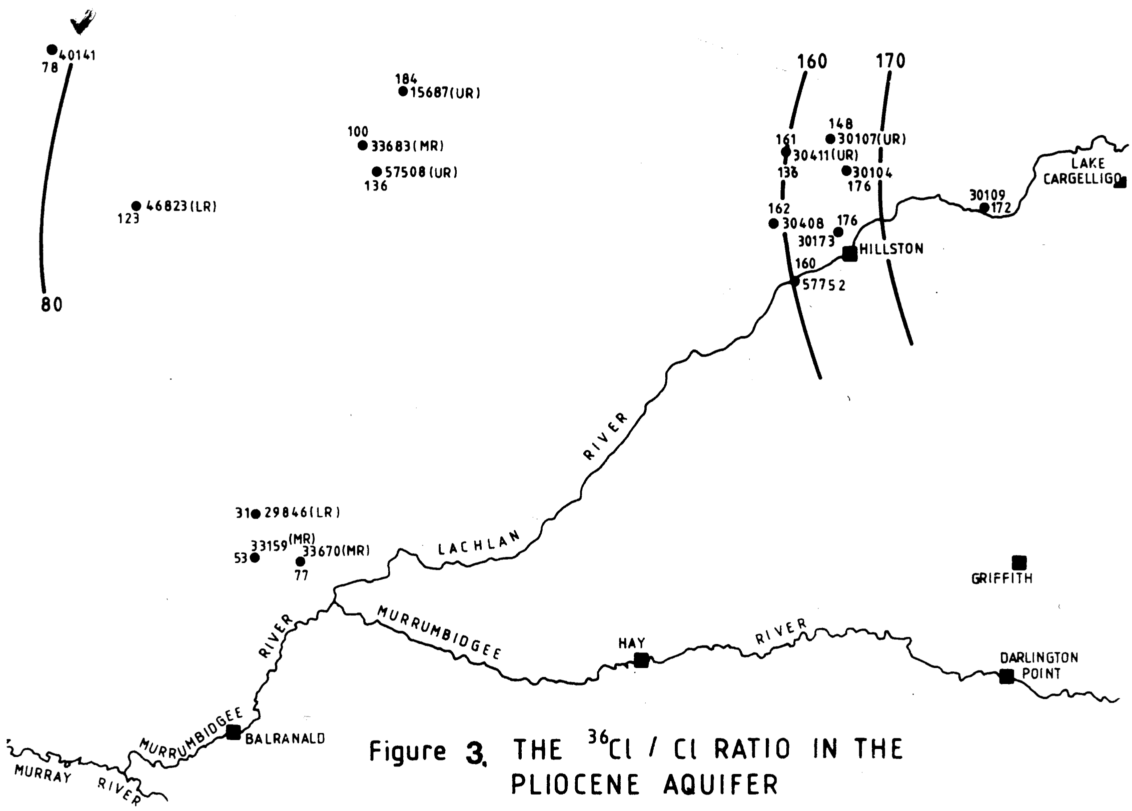

Figure 3. THE ^{36}Cl / Cl RATIO IN THE PLIOCENE AQUIFER

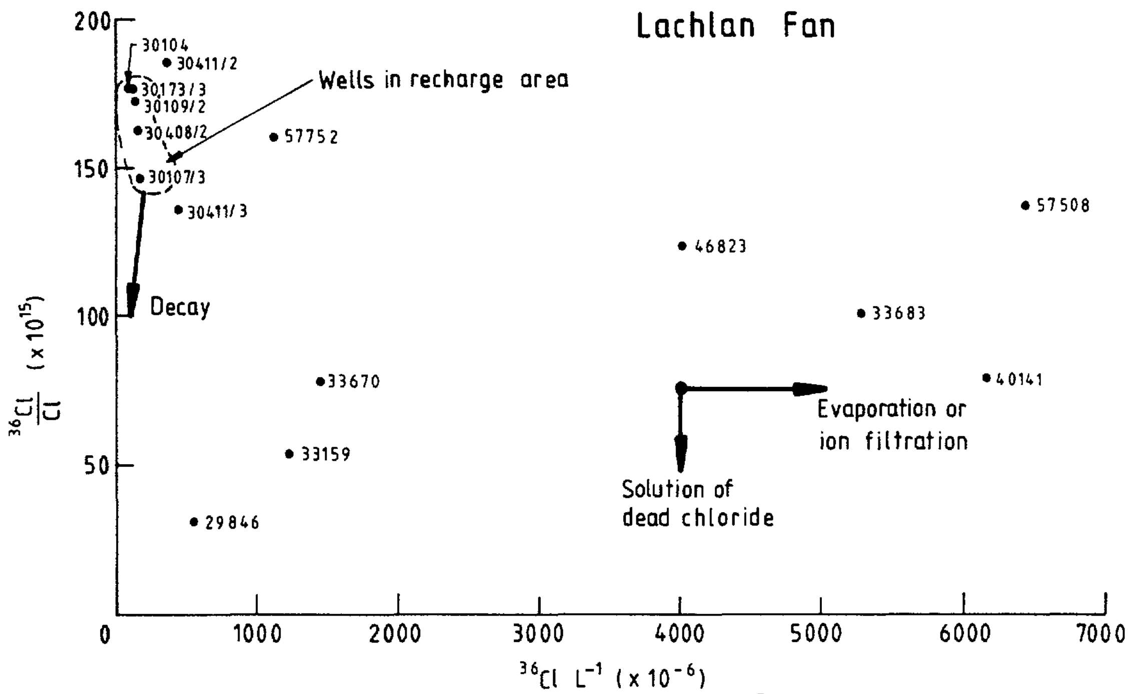

Figure 4. THE ^{36}Cl / Cl RATIO VERSUS THE ^{36}Cl CONCENTRATION (in atoms ^{36}Cl / L)

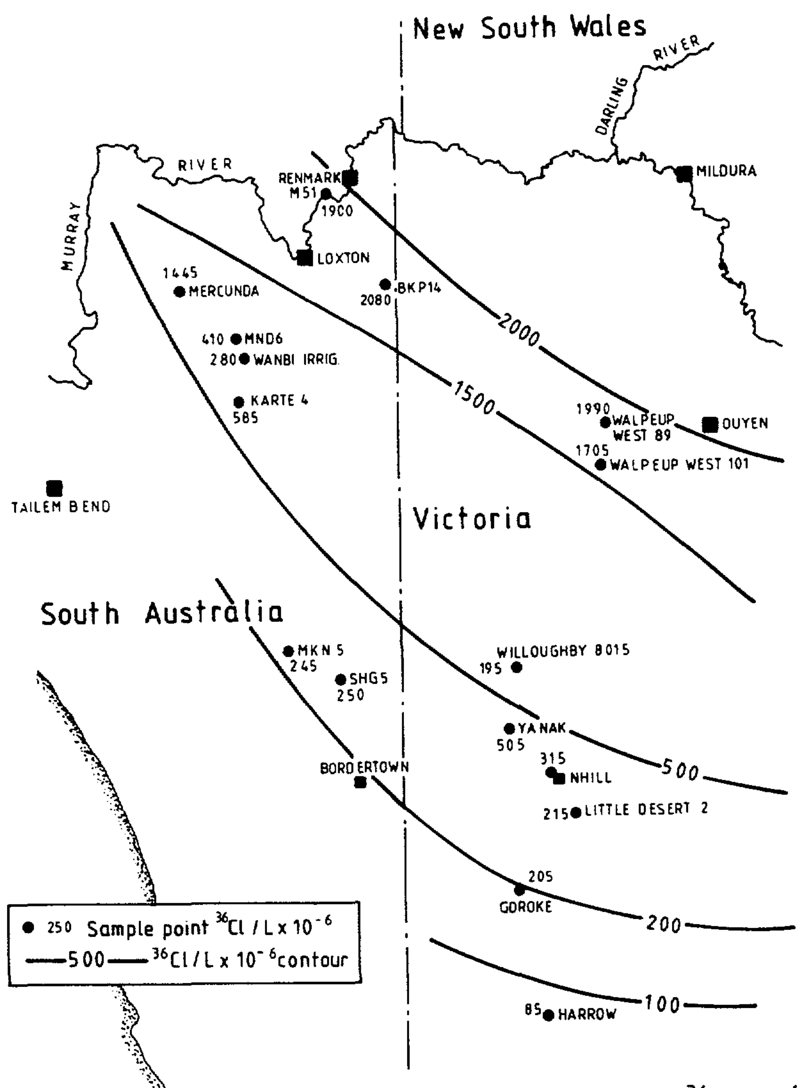

Figure 5. THE ^{36}Cl CONCENTRATION (atoms ^{36}Cl x 10^{-6}/L) IN THE MURRAY GROUP LIMESTONE AQUIFER

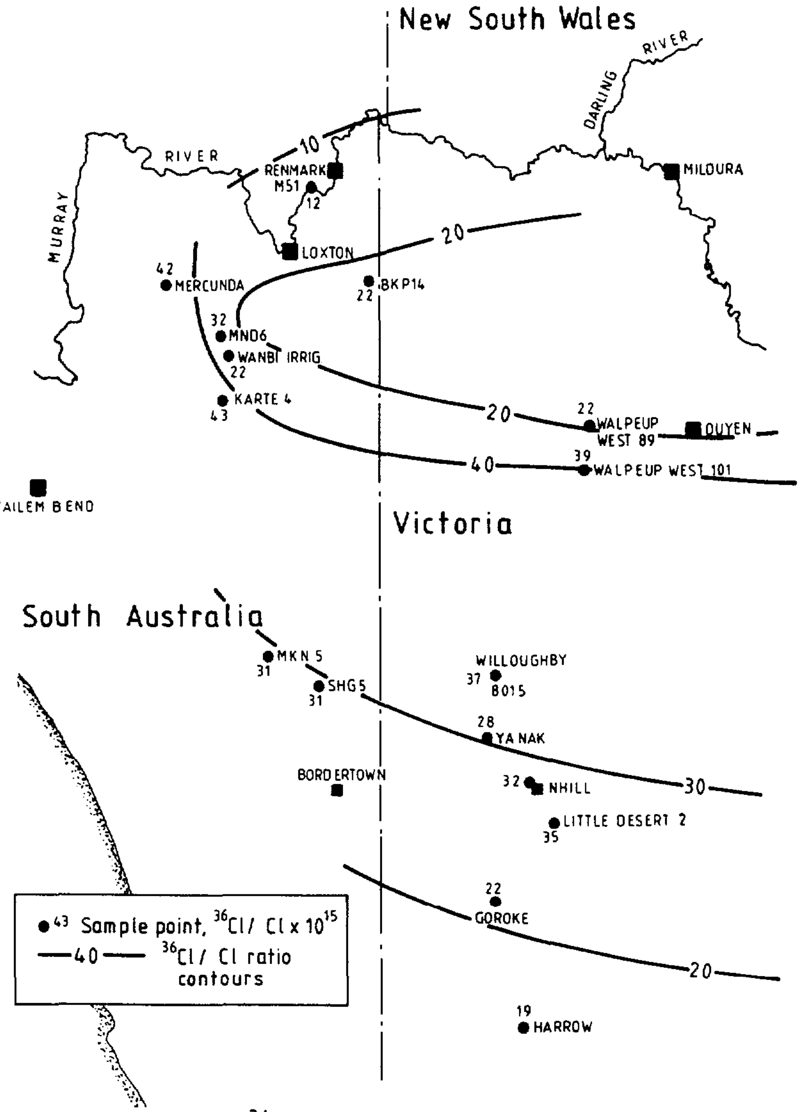

Figure 6. THE ^{36}Cl/ Cl RATIO IN THE MURRAY GROUP LIMESTONE AQUIFER

THE LACHLAN FAN

Sixteen ^{36}Cl/Cl ratios have been measured for wells in the Pliocene and Renmark aquifers and the results, as well as the distribution of ^{36}Cl concentrations (atoms ^{36}Cl/L), are shown in Figures 2 and 3. In the recharge area, the ^{36}Cl/Cl ratio is about 170×10^{-15} compared with 100×10^{-15} for the Great Artesian Basin (Bentley & others, 1986) and 20×10^{-15} in the Murray-Mallee recharge area (Figure 6). These values reflect the influence of different amounts of 'dead' marine salt spray being mixed with naturally occurring ^{36}Cl in these areas (Hutton & Leslie, 1958; Blackburn & McLeod, 1983).

A plot of ^{36}Cl/Cl versus ^{36}Cl/L is shown in Figure 4. Displacement of points downward and to the right is observed between the recharge area and the furtherest part of the flow-line studied. This indicates that solution of dead chloride and evaporation are important. If the change occurs uniformly down the flow-line, it can be calculated that evaporation increases the chloride concentration by about 8 mg/L per km while solution of dead chloride also increases the chloride concentration by about 9 mg/L per km. This model implies that from recharge to 250 km along the potentiometric flow path, about 98% of the water is lost by evaporation. At the opposite limit of no evaporation, the dead chloride input must be doubled. Further

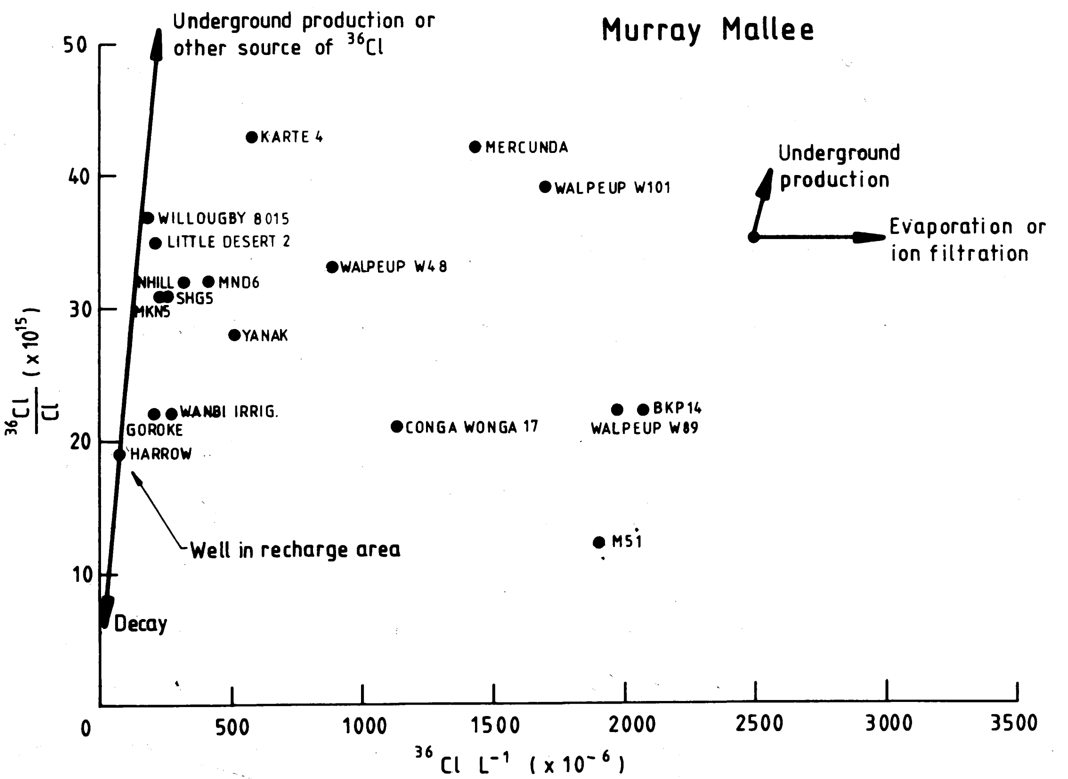

Figure 7. THE ^{36}Cl/Cl RATIO VERSUS THE ^{36}Cl CONCENTRATION (in atoms/L)

measurements are needed to obtain more information on the progress of these processes through the aquifer.

THE MURRAY-MALLEE

Analyses of ^{36}Cl from 20 wells have been carried out and the distributions of ^{36}Cl/L and ^{36}Cl/Cl ratio for the aquifer are shown in Figures 5 and 6. A plot of the ^{36}Cl/Cl ratio versus ^{36}Cl/L is shown in Figure 7. The figure presents an interesting contrast with results for the Lachlan Fan (Figure 4) where the ^{36}Cl/Cl ratio at recharge near Harrow is the smallest value observed. This is consistent with the proximity of the sea as a source of 'dead' chloride but the ratios tend to be lower than expected from reported chloride precipitation rates (Hutton & Leslie, 1958; Blackburn & McLeod, 1983) except nearest to the sea.

Values of ^{36}Cl/Cl increase systemically as the water moves along the flow line in a north-northwesterly direction (Figure 6). This increase may be interpreted as being caused by underground production of ^{36}Cl and mobilisation of secular equilibrium chloride. However, the values of ^{36}Cl/L increase in a north-northeasterly direction which is consistent with an exponential decrease in sea spray Cl^- concentration with distance from the coast. It is therefore possible that recharge of the aquifer is occurring from rainwater infiltration over the whole area. If this is the case, the lower values of ^{36}Cl/Cl occurring near Mildura requires that there be some contribution from salt in the unsaturated zone or mixing with groundwaters from the east having lower ratios.

Further measurements are needed to quantify contributions from each of these processes. Assuming the change in chloride is uniform along the 230 km flow line between Harrow and Mercunda, it can be calculated that evaporation increases the chloride concentration by about 5 mg/L per km and causes about 87% of the water to be lost.

CONCLUSION

Repeat measurements on material from one location show that the variation from sample preparation and measurement is of the order of +/-7%. This is sufficient accuracy for use together with total chloride assay to study systematic trends arising from such processes as:

- the influence of marine chloride on recharge water in different parts of Australia;
- the importance of evaporation in aquifers in the Murray-Darling basin; and
- the significance of remobilisation of 'dead' chloride in some areas.

It should be emphasised that these results are only preliminary and further measurements are needed to characterise the various sources of chloride. There are also many gaps in the data. Sampling programs in wells separately tapping the Pliocene and Renmark aquifers in the Lachlan Fan need to be carried out so that detailed analysis of the chloride variations can be made. Further work in the Murray-Mallee area also seems warranted to clarify the origin and movement of chloride.

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POONCARIE GEOLOGICAL MAPPING – PALAEOHYDROGEOLOGICAL INDICATORS

Roger G. Cameron
Geological Survey of New South Wales

Geological mapping for the Pooncarie 1:250,000 sheet is over 50% complete. The stratigraphic scheme and associated nomenclature closely follows that used by the BMR on the provisional 1:1,000,000 Murray Basin geological map (Brown & Stephenson, 1985). Minor additions include four aeolian units instead of three and two alluvial units instead of one. This paper describes both late Devonian and Pliocene to Early Pleistocene sequences (with their capping duricrusts) and draws some preliminary palaeoenvironmental conclusions.

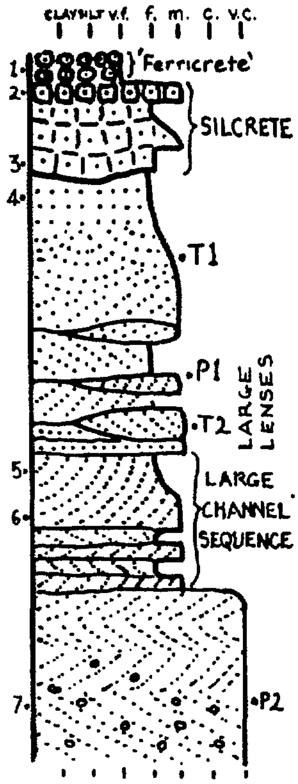
Previously unmapped outcrops of basement rocks of Late Devonian to Early Carboniferous Mulga Downs Gp. sedimentary rocks have been plotted in both the Mulurulu and the Manfred 1:100,000 sheet areas – in the latter case extending the known limits of Manfred Range outcrop. These rocks are tentatively correlated with the (uppermost) Crowl Creek Fm. of the Mulga Downs Gp. further to the east in the Wrightville to Mt. Allen region. This correlation is based on the similarity of the patterns of variation in lithology, palaeocurrent directions and stratigraphic units; and the similarity of small scale sedimentological features. The main hydrogeological point of this work is that it changes the interpretation of the basement morphology in the Manfred - Mulurulu area. Along the northwestern edge of the Ivanhoe Trough, the 50m asl contour and outcrop pattern are much more extensive and linear in a NE-SW direction than is shown at present on preliminary maps of base of Tertiary contours (J. Kellett, pers. comm). Similarly, structure contours northwest from Lake Mulurulu are altered (Figure 1).

There are three types of rocky Tertiary outcrops within the Pooncarie sheet area that have implications for Late Pliocene and Early Pleistocene palaeoenvironment and, by extension, palaeo-hydrogeology. First, there are outcrops of clay-cemented quartz arenites, the ?Parilla Sand, along the Neckarboo Ridge. Second, there are oolitic ironstones of the ?Karoonda surface (C. Brown, pers. comm.). Third, there are two different types of silcrete deposits: one forms as a sheet-like capping on top of the Tertiary sandstones and the other forms a pseudo-breccia with an underlying columnar structure and occurs within ?pre-Woorinen dunes. Localities demonstrating these features and their relationships are The Cliffs, The Ampitheatre, Tarcoola and Melton Grove, described below.

At *The Cliffs* (Fig. 2) on the northwestern shoreline of Lake Mulurulu, up to 9.0m of fluvially deposited (or reworked) Tertiary sands have been uplifted and variably cemented forming a cliffline that is further exposed by gullying. The lithology is primarily a clay-cemented medium-grained quartz arenite that is capped with a 1.5m duricrust profile which is a sheet-like to platey medium to fine-grained anatase-rich silcrete with a sharp lower boundary. The embayed quartz grains fine upwards and the micro-crystalline matrix becomes more turbid and opaque upwards. This silcrete grades upwards into a cobble ferricrete. The underlying fluvially reworked ?Parilla Sand is a clay-cemented quartz arenite characterised by both large and small scale fluvial cross beds and trough cross beds indicating a southerly paleoflow. The degree of clay cementation – the matrix is kaolinite, smectite and calcite – decreases downsequence where interstitial clay argillans demonstrate the pedogenic origin of the clays. Nearby council quarries expose the top of the ?Parilla Sand in which there is virtually no silcrete formed under the aeolian cover.

The silcrete capped ?Parilla Sand at *The Amphitheatre* (on Garnpang property) is poorly exposed around the rim of a crater-like depressin (1.5km E-W, 0.7km N-S,

FIGURE 2: PROFILE, MINERALOGY & FIELD OBSERVATIONS, THE CLIFFS, LAKE MULURULU.



	QTZ	KAO	SME	FEL	CAL	ANA	BEDDING
							P = Primary S_0 T = Trough X-beds
The: Cliffs 1	D	?T	-	-	-	S	
Cliffs 2	D	?T	-	-	?T	T	
Cliffs 3	D	-	-	-	-	S	T1: Strike 075° Dip 28°S
Cliffs 4	D	T	-	-	S	-	P1: Strike 075° Dip 15°S
Cliffs 5	D	M	S	?T	M	-	T2: Strike 070° Dip 35°S
Cliffs 6	D	M	S	T	S	-	
Cliffs 7	D	M	S	T	S	-	
SCALE: 1cm=1m							P2: Strike 075° Dip 10°S

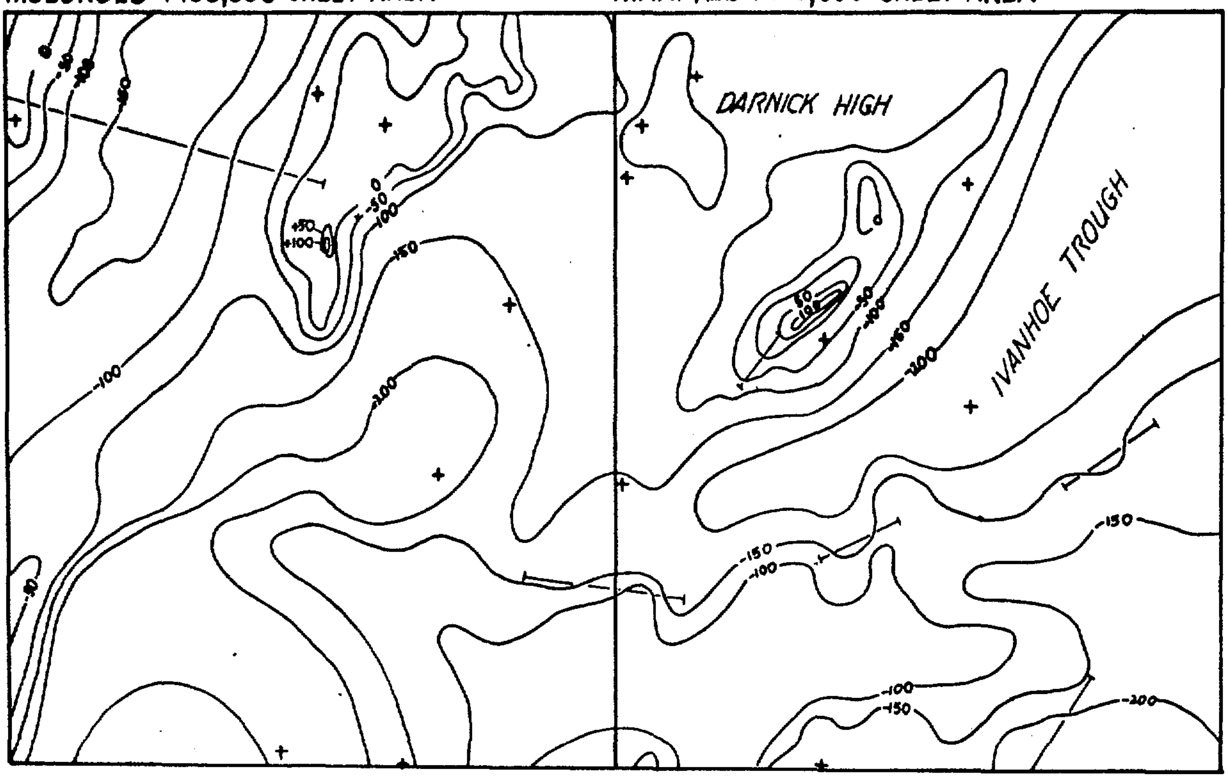
ABBREVIATIONS USED:
QTZ = Quartz, KAO = Kaolinite, CAL = Calcite, FEL = Feldspar, SME = Smectite, ANA = Anatase.

D=Dominant (>60%), A=Abundant (60%-40%), M=Moderate (40%-20%)
S=Small (20%-5%), T=Trace (<5%).

FIELD DESCRIPTIONS:
The Cliffs 1 (T47689): Very fine-grained light brown silcrete.
The Cliffs 2 (T47690): Medium-grained clay-cemented quartz arenite with thick white silcrete rind.
The Cliffs 3 (T47691): Fine-grained, buff, clay-cemented quartz arenite with buff, fine-grained silcrete rind.
The Cliffs 4 (T47692): Fine-grained, light buff, clay-cemented quartz arenite.
The Cliffs 5 (T47693): Fine- to medium-grained, partially clay-cemented quartz arenite.
The Cliffs 6 (T47694): Fine- to medium-grained, red-buff, clay-cemented quartz arenite.
The Cliffs 7 (T47695): Medium- to coarse-grained, light buff, clay-cemented quartz arenite.

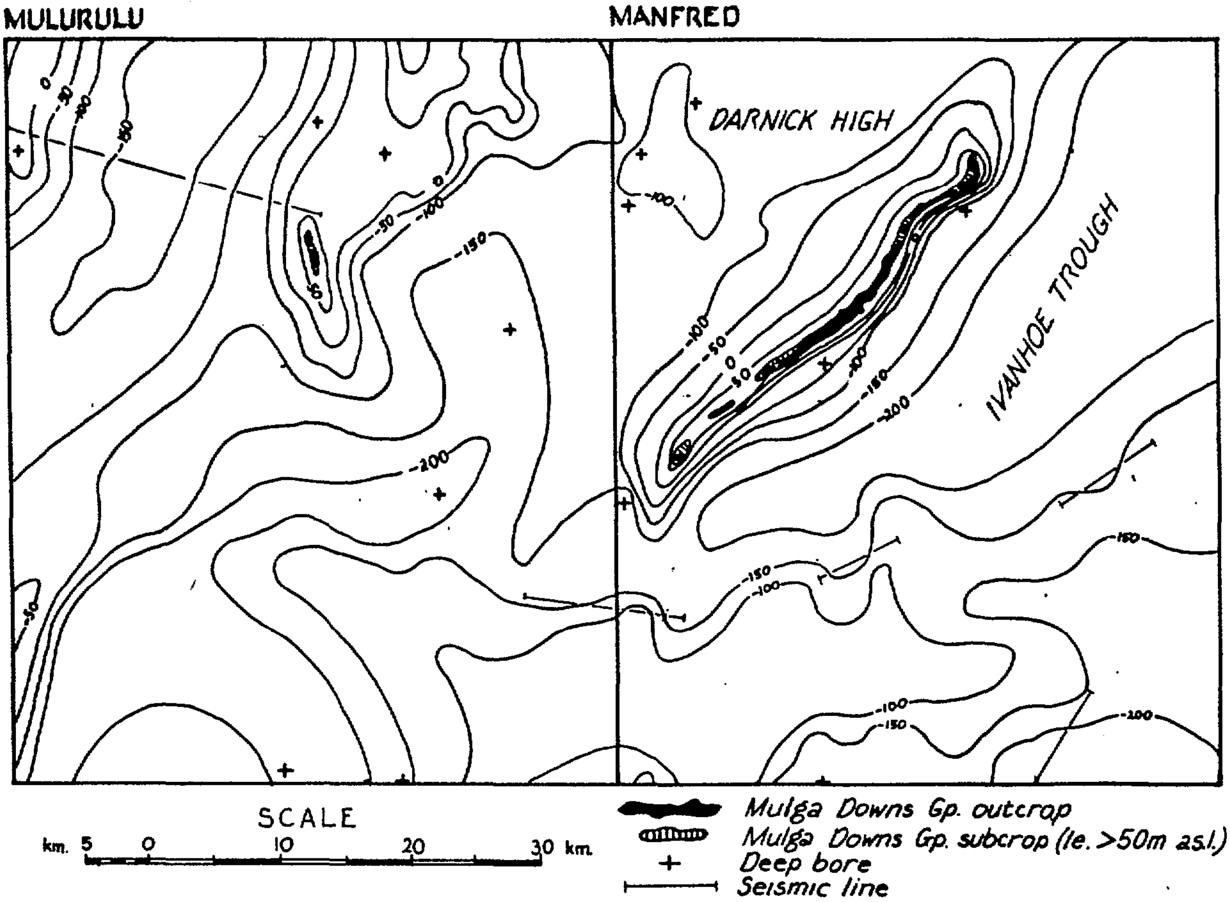
FIGURE 1: CONTOURS TO BASE OF TERTIARY - PRELIMINARY BMR EDITION

MULURULU 1:100,000 SHEET AREA MANFRED 1:100,000 SHEET AREA



MODIFIED CONTOURS TO BASE OF TERTIARY - SHOWING BASEMENT OUTCROP

MULURULU MANFRED



25m-30m deep). Sedimentary structures in the underlying Tertiary sandstone are largely obscured by scree. The significant feature of this locality is that discrete amorphous silcrete cobbles (cobble 'Knollenstein': cf. Wopfner, 1978) are sporadically being exposed by erosion from the base of the silcrete cap.

There are four E-W oriented oolitic ironstone ridges located in a small Late Pleistocene lake at *Tarcoola* property SE from Pooncarie village. The longest ridge is 350 m with the oolitic ironstone forming a capping to clay-cemented quartz arenite. The ironstone averages 0.4m thick and ranges up to 1.0m. These ridges define a ?Karoonda-equivalent surface that may have been a lake floor which is 3m to 5m above the present lake floor. Additionally, a few weathered boulders of ironstone show laminar bedding which is also consistent with lacustrine deposition. A modern analogue for oolitic ironstone formation in shallow lakes is Lake Chad in Central Africa where oolites form at delta fronts (Byrnes & others, 1985).

Silcrete occurs within pre-Woorinen dunes at *Melton Grove* property. Here, a pseudo-breccia of rounded silcrete boulders to cobbles overlies polygonal silcrete columns. The matrix is opaline to crypto-crystalline and varies in opacity (in thin section). The quartz grains are angular and embayed. This profile has been 'draped' with a subsequent carbonate matrix. Thin sections of the silcrete/carbonate boundary show silcrete exfoliating into the carbonate.

Some preliminary palaeoenvironmental conclusions are:

1: That fluvial re-working of the Parilla Sand had a S to SSE palaeoflow direction during the Late Pliocene.

2: That clay cementation within the Parilla Sand along the Neckarboo Ridge is pedogenic and probably occurred before the earliest aeolian deposition around the Pliocene/Pleistocene boundary.

3: That the earliest aeolian sand sheet deposits inhibited the formation of sheet-like (?Early Pleistocene) silcrete that sporadically caps the Parilla Sand.

4: The oolitic ironstone may be an Early Pleistocene delta front lacustrine deposit.

5: The pseudo-breccia and underlying columnar silcrete within the pre-Woorinen dunes is probably 'Middle' to Late Pleistocene.

6: The two forms of silcrete show differences with respect to the Central Australian silcretes in the nature of the substrata, their morphology and their relationships.

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COMMUNITY AWARENESS FOR SALINITY CONTROL

P.H. Cock, M. Holt & T. Blake
Graduate School of Environmental Science
Monash University
Clayton, Vic. 3168

The Victorian State government has selected the Goulburn Broken Region as a pilot area for the development of effective strategies for the control of salinity. Part of this is the development of a community education program.

A team was drawn together from the Graduate School of Environmental Science at Monash University and the Faculty of Applied Science at Victoria College (Rusden), to investigate levels of community awareness and response to salinisation, and to evaluate present community education strategies and mobilization. This paper will present the results of this study.

A questionnaire was used to survey the extent to which different sections of the community were aware of salinity, and how importantly they viewed it in comparison with other community issues. Further questions probed the extent of the respondents' knowledge of salinity, and their willingness to take part in salinity control activities.

A total of 4,977 returns were obtained representing 3.6% of the regional population. Results revealed a high level of awareness of salinity (72.5%), although salinity was rated below social and economic issues facing the community. Tree clearing and planting were seen as the key cause and solution respectively, while responsibiltity for salinity control was believed by 73.0% to be that of government, farmers and the local community together.

The results of interviews with key personnel from a range of strategic target groups are then discussed. These varied from Bankers, Real Estate Agents and Service Clubs to Church Ministers and School Principals. Responses revealed a varied level of awareness and concern.

The State Government's regional strategy for community mobilization is then examined in the context of the community response to date. The pilot management program has played a major role in catalysing community response, in particular, facilitating the development of a co-operative group approach to salinity control. That is, where farmers join together with the aid of extension officers and the support of groups such as Conservation volunteers and the local Apex clubs to act to control salinity. The actions of such 'land care groups' has then been used to mobilize the media to facilitate public awareness and support for the government's action. This examination concludes with recommendations of ways by which the community education strategy can be developed further for sustained support for public and private actions.

LOCALISED RECHARGE IN THE WESTERN MURRAY BASIN

Cook, P.G., Jolly, I.D., Walker, G.R. and Walker, C.D.
CSIRO Division of Water Resources
Private Bag 2, Glen Osmond, S.A., 5064.

Introduction

Recent studies in the Western Murray Basin using unsaturated zone chloride profiles have estimated recharge rates under native mallee (*Eucalyptus* spp.) vegetation at between 0.05 and 0.08 mm yr^{-1} (Allison & Hughes, 1983). Carbon-14 studies of groundwater suggested a mean recharge rate of between 0.1 and 0.2 mm yr^{-1} for the region (Leaney & Allison, 1986).

Because of this discrepancy, together with the fact that the recharge fluxes are very low, a study was undertaken to assess the importance of localised (point source) recharge through low points of the landscape.

Studies using aerial photography have identified a number of small clearings in areas of undisturbed mallee vegetation. The clearings occupy natural depressions in the landscape and may have formed as solutional depressions in calcrete. They are apparently not the result of mans' activities. Because of the absence of the water-efficient mallee from these areas, and evidence of runoff into them, the possibility exists for them to be sites of localised (enhanced) recharge.

Site Description

The clearing selected for detailed study is located near Boolgun in the Western Murray Basin (34^0 23' S., 140^0 3' E.). The cleared area occupies a topographic depression and is approximately 250 m long and 40 m wide. Tree-form mallee (*Eucalyptus oleosa*) occur at the edge of the clearing, with the salt-tolerant *Atriplex stipitata*, *Rhagodia spinescens*, *Zygophyllum eromaeum*, *Maireana trichoptera* and *Maireana pentatripis* also common around the margins. The floor of the depression is very flat, and vegetated mainly by ephemeral grasses of *Helipterum* and *Stipa* spp. Two topographic lows (with a relief of only 20 cm) occur in the clearing, and these are identified by lower densities of *Stipa* sp. The floor of the depression is free of the calcrete rubble which characterises the surface of the surrounding areas.

Recharge Estimation

A detailed survey of the apparent ground conductivity was made with the Geonics EM31 conductivity meter (McNeill, 1986). Apparent conductivities in the clearing range between 22 and 39 mS m^{-1}, and are lowest at the lowest topographic positions. Apparent conductivities under the mallee range between 55 and 110 mS m^{-1}. Calibration surveys with the EM31 conductivity meter in the Murray Basin have determined that variations in apparent conductivity largely reflect differences in salt and water content of the soil to 6 m depth (Hughes & others, in prep.). While at this stage the EM technique is largely qualitative, the low conductivities measured in the depression indicate low soil salinity and hence higher recharge.

Three cores have been drilled at the Boolgun site. BOL02 was located under mallee, 20 m west of the clearing. BOL01 and BOL03 were located in the clearing. BOL01 was drilled at the lowest topographic position, where the lowest apparent conductivities were measured. BOL03 was drilled on the ridge between the two topographic lows. Chloride concentrations of the soil water were measured for each of the three cores (Fig. 1).

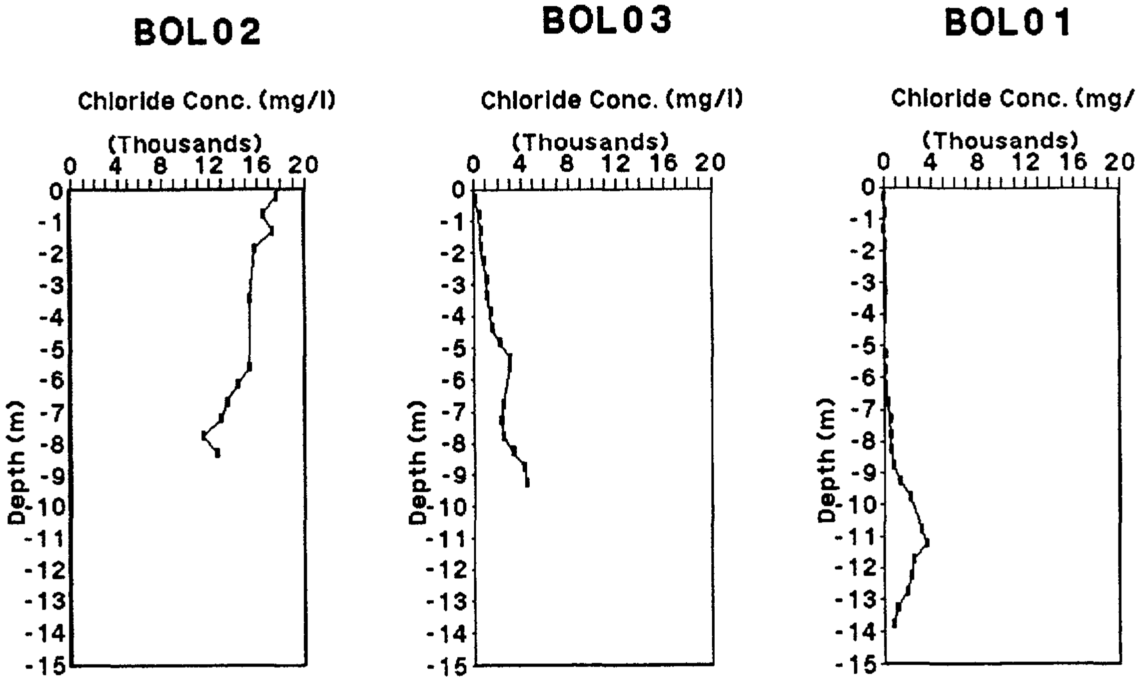

Figure 1. Unsaturated zone chloride profiles from the Boolgun clearing: BOL02 under mallee, BOL03 and BOL01 in clearing.

Estimates of the recharge rates through the base of the clearing can be made from the unsaturated zone chloride profiles using methods described by Allison & Hughes (1978, 1983). When water containing chloride percolates into a soil subject to major water loss by transpiration, chloride profiles would be expected to show an increasing concentration from the surface to the bottom of the root zone. Beneath the root zone, chloride concentrations should be constant with depth. If we assume a one-dimensional, vertical piston flow, as well as little surface runoff or lateral flow, then recharge rates can be calculated from the chloride mass balance:

$$C_p P = C_r R$$

where C_p and C_r are the chloride concentrations of rainfall and recharge respectively, P is precipitation, and R is recharge rate (Allison & Hughes, 1978). In this area of the Murray Basin C_pP is taken to be 750 mg $m^{-2}yr^{-1}$ (Blackburn & McLeod, 1983).

The chloride concentration to 9 m depth in BOL02 (under mallee) ranges between 13,000 and 18,000 mg/L. Taking C_r =17,000 mg/L, the estimated mean recharge rate is 0.04 mm yr^{-1}, which is in good agreement with estimates of recharge under mallee obtained from previous studies (Allison & Hughes, 1978, 1983).

Chloride concentrations in BOL01 and BOL03 are much lower, reflecting the increased recharge at these sites. The chloride concentration in BOL03 increases from the surface to a value of 4,000 mg/L at 9 m depth. As the chloride concentration below the root zone should be constant, and the ephemeral grasses would have a rooting depth of less than 1 m, this suggests that the tree-form mallee surrounding the clearing have roots extending underneath it, and are taking advantage of this water source. Taking C_r = 4,000 mg/L, the recharge rate for BOL03 becomes 0.2 mm yr^{-1}.

The mean chloride concentration of recharging waters in BOL01 is approximately 100 mg/L (between 0 and 6 m) giving a recharge rate for this hole at 7.5 mm yr^{-1}. A bulge in the chloride profile occurs between 10 and 12 m, corresponding to a zone of very low water content. It is possible that this bulge marks the position of a lone mallee root. The chloride concentration begins to drop below the bulge to be 800 mg/L at 14 m.

Discussion

Chloride profiles from the Boolgun site show enhanced rates of groundwater recharge through the base of the depression. Recharge rates obtained from the chloride mass balance are between 0.2 and 7.5 mm yr^{-1}. This technique, however, assumes one-dimensional, vertical flow. If runoff occurs from the calcreted areas around the depression, then the method may underestimate the actual recharge rate. It is likely that runoff contributes more water to the depression than direct rainfall, and so these calculated rates may be several times too small. Work is continuing in an effort to refine the estimates.

With this in mind, it is difficult at this stage to assess the hydrological importance of these natural clearings. Preliminary calculations have been carried out by assuming a mean recharge rate of 5 mm yr^{-1} over the whole of the depression. In the remaining mallee, natural clearings appear to have a density of one per 5 km^2, suggesting that 20% of all water recharging to the unconfined Murray Group aquifer may be occurring through these clearings. However the likelihood of runoff into the depression, and the possibility of diffuse discharge occuring under mallee (see Jolly & others, this volume), mean that this figure may actually be as high as 50% .

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THE APPLICATION OF ^{36}Cl MEASUREMENTS TO GROUNDWATER MODELLING

R.F. Davie[1], L.K. Fifield[2], J.R. Bird[1], T.R. Ophel[2], G.E. Calf[1]

[1] ANSTO, Private Mail Bag 1, Menai, NSW 2232, Australia

[2] Department of Nuclear Physics, ANU, GPO Box 4, Canberra, ACT 2601, Australia

1. Introduction

Chlorine-36 is a naturally occurring radioactive isotope with a half life of 301 +/-4 thousand years. The high solubility of the chloride ion in water makes this an ideal isotope for the study of hydrological systems. The ratio of ^{36}Cl to stable chloride in typical environmental samples is of the order of a few parts in 10^{14}. It has only been due to the development of Accelerator Mass Spectrometry (AMS), over the last decade, that it has become possible to detect ^{36}Cl at typical environmental levels. Measurements of ^{36}Cl in environmental samples are presently being made using the 14UD accelerator at the Australian National University (Fifield & others, 1987).

2. Natural ^{36}Cl in Atmospheric Precipitation

Chlorine-36 in the atmosphere is produced primarily by cosmic ray spallation reactions on atmospheric ^{40}Ar. This cosmic ray induced production has a latitude dependence which has been discussed by Bentley & others (1986). The ^{36}Cl produced in this manner is mixed with atmospheric chlorine salts of a terrestrial origin which contain essentially no ^{36}Cl. This produces a variation in the ^{36}Cl/Cl ratio in atmospheric precipitation, from a few parts in 10^{15} on the coast to several hundred parts in 10^{15} in continental interiors. This variation reflects the dominant influence of marine salts in near coastal regions.

Calculated ^{36}Cl/Cl ratios of atmospheric precipitation in and around the Murray Basin are shown in Figure 1. These ratios vary by approximately one order of magnitude over the Basin.

3. Modification of the ^{36}Cl Signal in subsurface aquifers

It is the modification of the ^{36}Cl signal that allows information on the movement of salt and water within an aquifer to be deduced. Factors that may affect the ^{36}Cl signal include: radioactive decay; subsurface production; dissolution of ancient salt evaporites; evapotranspiration and ion filtration; the mixing of two water bodies; and the addition of modern salt originating from atmospheric precipitation. The effects of these processes are summarized in Figure 2, and are discussed below.

3.1 Radioactive decay and subsurface production of ^{36}Cl

The half life of ^{36}Cl is 301,000 years. Therefore, decay of ^{36}Cl is only important in systems which operate on time scales which are of the order of or greater than this period. In extreme cases, where aquifers flow over periods which are long compared with the half life, and where radioactive decay is the dominant process, the decay of the ^{36}Cl signal can be used as a dating tool. The study of the Great Artesian Basin is a good example of the use of ^{36}Cl in the dating of old groundwaters by this method (Bentley & others, 1986).

Conversely, ^{36}Cl can be produced in subsurface chlorine as a result of neutron capture reactions on ^{35}Cl. The neutron flux for this reaction is produced as a result of natural radioactivity in the aquifer matrix. If radioactive decay and subsurface production are the dominant processes affecting the ^{36}Cl signal, then the ^{36}Cl/Cl ratio will asymptotically approach the secular equilibrium value characteristic of the aquifer

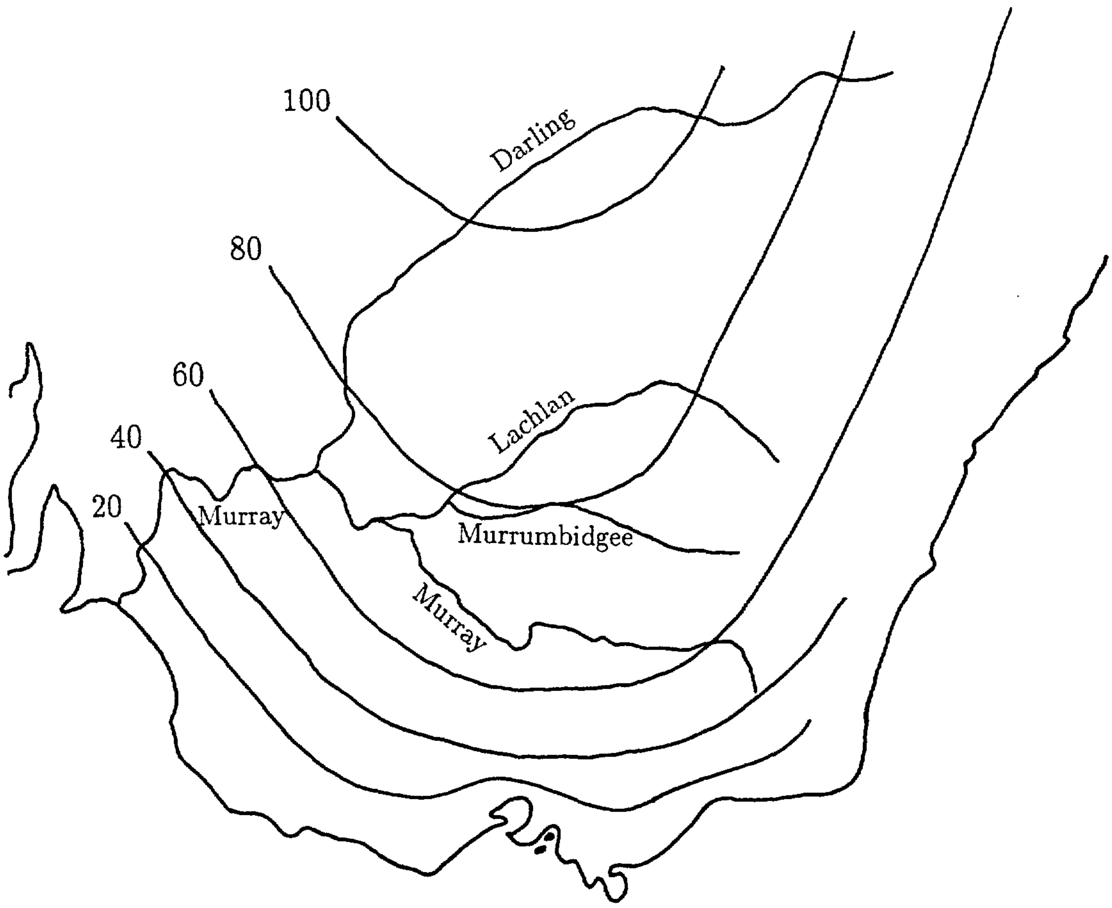

Figure 1 Calculated $^{36}Cl/Cl$ ratios of atmospheric precipitation in and around the Murray Basin. Contour lines of the $^{36}Cl/Cl$ ratio are shown in units of 10^{-15}. These estimates of the $^{36}Cl/Cl$ ratio were based on measurements of the salinity of atmospheric precipitation carried out by Hutton and Leslie (1958) and Blackburn and McLeod (1983).

environment. This secular equilibrium ratio depends upon the local U and Th concentrations, and the chemical composition of the aquifer matrix. Typical secular equilibrium $^{36}Cl/Cl$ ratios range from ~ 4 x 10^{-15} in sandstones to ~ 30 x 10^{-15} in granites (Bentley & others, 1986), while ratios in materials with unusually high U to Th content can be very much higher. As with radioactive decay, the time constant affecting the approach to secular equilibrium is the ^{36}Cl half life. Therefore, subsurface production will only be important in systems which operate on time scales which are of the order of or greater than this period, unless the secular equilibrium value is very high as a result of large U and Th concentrations. In situations where the $^{36}Cl/Cl$ ratio of the recharge water is very low relative to the secular equilibrium value, the residence time of salt in the system is long, and production of ^{36}Cl is the dominant process, then it would be possible to use subsurface production of ^{36}Cl as a dating tool. Such a situation may exist in confined aquifers which recharge near to the coast. However, we are not aware of any studies that have used subsurface production as a dating tool.

3.2 Evaporation and ion filtration

Evaporation or ion filtration will affect the ^{36}Cl concentration in the water, but leave the $^{36}Cl/Cl$ ratio in the water unaltered. Therefore, these processes have a distinct ^{36}Cl signature.

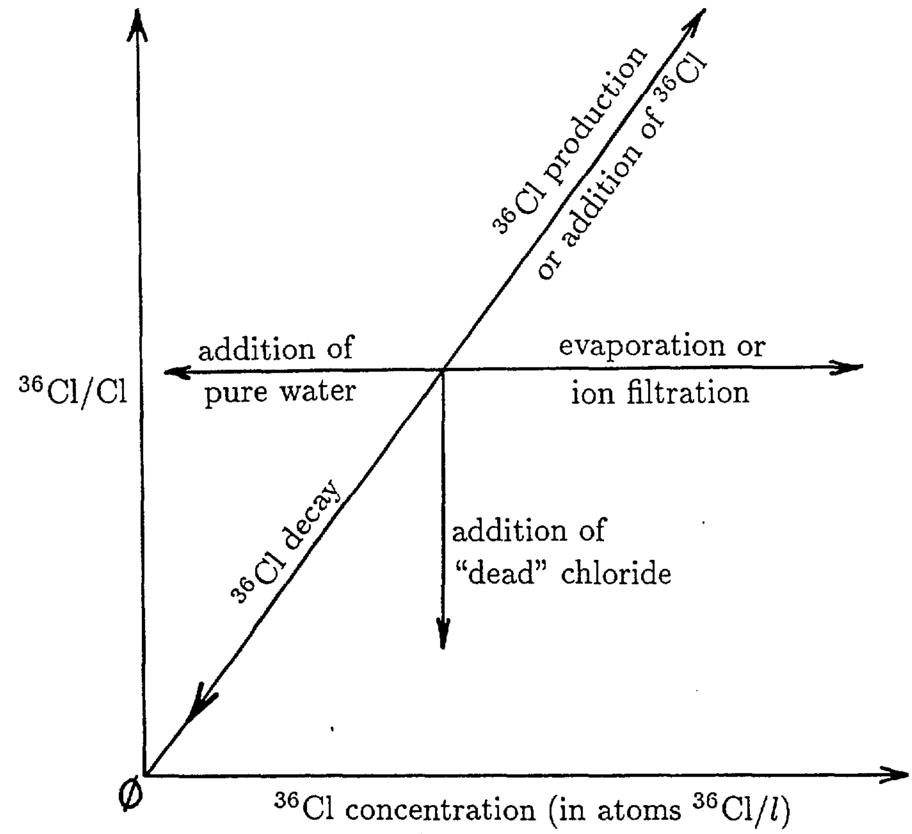

Figure 2 The effect of various environmental processes on the ^{36}Cl signal.

3.3 Incorporation of salt into the aquifer

The incorporation of salt into the aquifer will affect the ^{36}Cl signal in the manner that reflects the ^{36}Cl/Cl ratio of the added salt. For example, the effect of the dissolution of ancient salt evaporites, which will contain very little ^{36}Cl, would be quite different to the addition of relatively modern salt which has accumulated as a result of atmospheric precipitation.

Hence, in favourable circumstances, ^{36}Cl measurements can be used to distinguish between different possible sources of additional salt, and between the addition of salt versus evaporation or ion infiltration as a mechanism for increasing salinity.

3.4 The mixing of two water bodies

The mixing of two water bodies alters both the ^{36}Cl concentration and the ^{36}Cl/Cl ratio in the water to values intermediate between those of the two original water bodies. The extent of the effect depends in a linear fashion upon the degree of the mixing. On a diagram such as figure 2, mixing would move the ^{36}Cl concentration and ^{36}Cl/Cl ratio on a straight line joining the positions of the two initial water bodies. Therefore, the mixing of two water bodies has a well defined ^{36}Cl signature.

4. The use of anthropogenic ^{36}Cl to monitor modern recharge rates

Chlorine-36 was produced in atmospheric nuclear explosions on or near seawater, primarily during the late 1950's. This pulse of ^{36}Cl has been observed in water samples and in Greenland ice (Bentley & others, 1986). These studies show that the pulse of

^{36}Cl which resulted from these explosions was more than an order of magnitude above natural background levels.

The position of this ^{36}Cl bomb pulse within a soil profile has been used to monitor modern recharge rates in an arid region of New Mexico (Bentley & others, 1986). More recently, Allison & others (1988) have measured the bomb pulse in a soil profile from the Murray Basin to assess the modern recharge rate.

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THE NATURE OF SOME ILL-POSED PROBLEMS ARISING IN AQUIFER MODELLING

C.R. Dietrich*+, G.N. Newsam*, R.S. Anderssen*++, F. Ghassemi+ and A.J. Jakeman+

* Centre of Mathematical Analysis, Australian National University.
+ Centre for Resource and Environmental Studies, Australian National University
++ Division of Mathematics and Statistics, CSIRO

Introduction:

Management of groundwater in the Murray basin requires simulation of the effects of various strategies (e.g. interception schemes) on flow in aquifers. Such simulations usually examine the evolution of the piezometric head subject to changes in the distribution q of recharge/discharge under the following governing equations for the time-dependent and steady-state problems respectively:

$$div(T\, grad\, \varphi) = q + S\, \partial\varphi/\partial t \qquad (1)$$

$$div(T\, grad\, \varphi) = q \qquad (2)$$

However, use of these equations to track changes in φ (and so in the flow $u = T\nabla\varphi$) under changing recharge require knowledge of the general aquifer structure, and in particular of the transmissivity coefficient T, the storage coefficient S. But S and T cannot be measured directly, except at great cost; databases on aquifers usually consist principally of head measurements. Therefore the equations must first be used to deduce S and T from presently available head data before they can be used to predict future behaviour. Furthermore in many cases the background recharge away from pumps is not known, particularly after changes in land cover and use, so the equation must also be used to deduce it. Thus there are actually three, not one, problems that are to be solved through use of the models (1) or (2). The purpose of this paper is to elucidate the structures of these three problems, to highlight the differences between them, and to show how their special form affects the construction of algorithms for their solution.

Well-Posed and Ill-Posed Problems:

For clarity we shall only consider the steady state problem (2). In this case we shall term the three problems identified above as:

The Direct (or Forward) Problem: Given T and q, find φ

The First Inverse Problem: Given φ and q, find T

The Second Inverse Problem: Given T and φ find q

In practice the situation is less clear-cut, available data and prior knowledge usually gives partial information about all three variables, so the problem becomes one of estimation of the missing information by the calibration of the aquifer through use of the equations. Nevertheless the uneven distribution of data means that this general calibration problem usually has the overall form of one of the above three problems. The names given to the problems reflect their form: the first problem is the standard problem in which the flow is to be predicted as a function of the parameter T and control q, while either of the remaining problems is in some sense a reverse of the standard problem as the parameter or control is now to be estimated from measurements of the flow. Note that paired direct and inverse problems linked in this manner are quite common in groundwater studies, so that the points made in the paper about the problems above have a wider application.

The distinction drawn between the first problem and the second and third problems on the other hand reflects a fundamental difference between them. A reasonably accurate solution to the first problem can be constructed purely from reasonably accurate data together with the model equations. However solutions for the second and third problems cannot be fully estimated from available data and the equations alone; additional prior information must also be invoked. The reason for this is that solutions to the first problem are stable with respect to noise in the data (slight errors in the data give rise to only slight errors in the estimate of the solution). However solutions to the second and third problems are unstable with respect to noise (slight data errors may give rise to unboundedly large errors in the estimate of the solution).

In recent years a new branch of mathematics, the theory of *ill-posed problems*, has been developed to describe the salient features of problems such as the inverse problems listed above. In the language of this theory the forward problem is well-posed, while the inverse problems are ill-posed. Well-posed problems have a unique solution that is stable with respect to perturbations in the data or model; ill-posed problems have solutions that may be nonunique and are unstable with respect to noise. The aim of the paper is to use the theory to describe the main features of the inverse problems and to show how these features determine algorithms for their solution.

After introducing the theory of ill-posed problems, the paper considers application of the theory to aquifer modelling. First the question of uniqueness is examined and shown to be related to the question of boundary conditions. The forward problem requires specification of conditions around the entire boundary of the aquifer for uniqueness. In contrast the second inverse problem requires no boundary conditions. The first inverse problem lies between these extremes; in certain subregions of the aquifer transmissivity may be uniquely defined by the equation alone, while in other regions values of transmissivity on at least some part of the boundary or interior may be needed to ensure uniqueness. The important point is that in either case the extra information necessary for uniqueness in the inverse problem is *not* the same as that needed for uniqueness in the forward problem.

Next the stability question is addressed. The paper briefly reviews the use of the *singular value decomposition* (or SVD) in stability analysis of linear ill-posed problems (the SVD is a simple generalization of the eigendecomposition of an operator) using recharge estimation as a case study. Error magnification is controlled by the size of the reciprocals of the singular values, so the rate at which the singular values decrease towards zero in turn defines the *ill-conditioning* of an ill-posed problem. In many practical problems, such as recharge estimation, the ill-conditioning can be simply related to the number of differentiations of the data that are needed to reconstruct the solutions. Once the singular values fall below a certain threshold, error amplification in associated components becomes so large that they are no longer trustworthy. Thus only the first few *low frequency* components in the singular function expansion of the solution can be accurately estimated from the model and the data; the remaining terms must be estimated from prior knowledge. Low frequency components are almost always smooth and slowly oscillatory, thus only the smooth slowly-varying part of the solution can be recovered with any certainty from model and data alone.

These results suggest that numerical methods for the solution of ill-posed problems be based on an expansion of the solution as a series of smooth functions, coupled with use of the SVD to gauge the number of components reliably determined by the model and data. The remaining components may be set to zero, or be chosen on the basis of prior knowledge. The paper briefly relates these methods to the standard methods of stabilizing inverse problems in aquifer modelling, such as regularization.

These ideas may now be applied to a stability analysis of the present. Equation (2) may be formally written as:

$$L(\varphi,T) = q \tag{3}$$

where L is linear in both φ and T. Now the direct problem may be formally written as:

$$\varphi = [L_1(T)]^{-1}q \tag{4}$$

where the operator $L_1(T)$ depends linearly on T, is stable with respect to (w.r.t.) small perturbations in T, and has a bounded inverse. These last two conditions imply that φ is stable w.r.t. small perturbations in either T or q. Likewise the first inverse problem may be written as

$$T = [L_2(\varphi)]^{-1}q \tag{5}$$

where the operator $L_2(\varphi)$ depends linearly on φ and has a bounded inverse. However it is no longer stable w.r.t. to small perturbations in φ. Thus T is stable w.r.t. small perturbations in q but is unstable w.r.t. to perturbations in φ. Finally (3) may be used to directly solve the second inverse problem; in this case $L(\varphi,T)$ (and therefore q) depends linearly on both φ and T but is unstable w.r.t. to perturbations in either.

Construction of Numerical Solutions:

The ideas developed in the previous section are next used to construct methods for numerical solution of the three problems. Such methods may be classified into two general classes: *direct* methods in which the solution is gauged by its ability to fit the model, and *indirect* methods in which the solution is gauged by its ability to fit the data. The advantages and disadvantages of each are briefly reviewed, with the paper settling on a direct method based on a Galerkin approximation of the equations coupled with a spectral representation of the functions. The actual construction may be summarized as follows:

i. A regular shaped subregion ω of the aquifer Ω is chosen.

ii. Sets of smooth basis functions $\{\Phi_p\}_{p=1,P}$, $\{\Theta_i\}_{i=1,I}$ and $\{\vartheta_k\}_{k=1,K}$ defined on ω are chosen and used to expand out φ, T and q respectively. The coefficients in these expansions are represented by the vectors ξ,η and q, respectively. Thus, for example:

$$T(x,y) = \Sigma_{i=1.I}\, \eta_i\Theta_i(x,y) \tag{6}$$

iii. A set of smooth test functions $\{\Psi_m\}_{m=1,M}$ is chosen and used to approximate the continuous equation:

$$div(T\, grad\, \varphi) = q \qquad \text{on } \omega$$

by the following set of M discrete equations:

$$\int_\omega div\,(T\, grad\, \varphi)\, \Psi_m = \int_\omega q\Psi_m \qquad m = 1,....M \tag{7}$$

iv. Finally the expansions of ii. are substituted into (7) to give M equations relating ξ,η and q which may be symbolically represented as:

$$L(\xi,\eta) = q \tag{8}$$

The major advantages of this method are that it may be applied to any of the previous three problems, and that its relatively simple structure permits the type of stability analysis outlined in the previous section. Some examples of the performance of the algorithm on the problem of transmissivity estimation are presented along with a summary of observed behaviour in numerical solutions.

Finally the authors are at present developing a computer package for display of data on aquifers coupled with the solution of the direct and inverse problems based on the above algorithm. The package is being developed on an Apple Mac II PC; this machine was chosen as it combines good graphics and a user-friendly interface with considerable numerical processing power. When finished the software will generate imterpolations of available scattered head values, plot contour maps and flow lines for these interpolations, and use the interpolations to generate solutions to the various problems, along with diagnostics on the accuracy and reliability of the solutions. All these tasks may be performed interactively, freeing the hydrogeologist from tedious tasks such as interpolating scattered data on maps, and providing a frame work for rational modelling.

IS BROADSCALE REVEGETATION ECONOMIC AND PRACTIAL AS A GROUNDWATER AND SALINITY MANAGEMENT TOOL?

R.G. Dumsday
La Trobe University
R. Pegler
Department of the Arts, Sport, the Environment, Tourism and Territories
D.A. Oram
La Trobe University

Some Land Degradation Issues

In considering the seriousness of Australia's land degradation problem, it has been suggested that Australian land users have failed to either develop or adhere to land management systems that are consistent with the long term sustainable utilisation of the soil resource. While the full economic cost of land degradation in the Murray-Darling Basin (MDB) has not been determined, agricultural production foregone from just cropland and irrigated agriculture is estimated at $214.6 million per annum.

Excessive vegetation clearance has caused direct costs to rural producers. Productivity has been affected by decreasing soil fertility, exposure of croplands, loss of fodder reserves and lost opportunities in production such as farm forestry. Individual landusers may fail to appreciate the decline in productivity due to its gradual, long-term course. Productivity losses are likely to be masked by seasonal fluctuations, improved techniques and use of fertilizers and herbicides. In addition, the reduction to land value caused by degradation is not always readily recognised.

Clearing and the replacement of deep-rooted native vegetation by shallow-rooted annuals, particularly in higher rainfall areas, has been identified as a major cause of increased groundwater recharge and land salinisation in the Basin. In addition, the vegetation clearance has had some effect on river salinity.

So far, the approach to salinisation and water logging problems has been largely to treat the symptoms by substantial investment in engineering works. Treatment of the causes of salinity by implementing improved vegetation management programs is necessary.

Improved vegetation management and revegetation of degraded and degrading lands will lead to significant improvements in surface water quality. By reducing accessions to groundwater, improved vegetation management can reduce salt movement to rivers. Revegetation will also often reverse or control many of the forms of land degradation referred to earlier. Although the planting of pine trees on previously cleared land may not meet the objectives of native flora and fauna conservation, it will assist in controlling dryland salinity and erosion and reducing aquifer recharge.

Conservation of the natural environment can be achieved through the creation of nature reserves on public land, encouraging the preservation of remnant native vegetation on private land and re-establishment of native vegetation on previously cleared land.

Clearing controls can be useful in protecting remaining native vegetation of significance and can ensure that clearing is limited in aquifer recharge areas, on land having a particular degradation hazard and in areas of high conservation value or other special significance. While clearing controls are most easily implemented on Crown lands and Crown lands under private lease, they can be extended to freehold land.

The possibility of targetting existing fiscal and industry assistance measures to the needs of priority areas of the Basin requires examination. In addition, the introduction of appropriate new assistance and incentive measures could provide impetus to the implementation and effectiveness of vegetation management strategies.

The efficient and effective utilisation of extension and education programs is also of major significance. As Governments are currently devoting considerable resources to these programs, the established infrastructure forms an excellent base for providing additional information on vegetation management to landusers.

The Murray-Darling Basin Ministerial Council and the Vegetation Management Strategy

The general objective of the MDB Ministerial Council is to 'promote and co-ordinate effective planning of the land, water and environmental resources of the Murray-Darling Basin'. Its goals are:

- improvement and maintenance of water quality for all beneficial uses – agricultural, environment, urban, industrial and recreation;
- the control of existing land degradation, the prevention of further land degradation, and where possible the rehabilitation of land resources, to ensure the sustainable utilisation of these resources; and
- conservation of the natural environment of the Basin and the preservation of sensitive ecosystems.

To assist in the attainment of these goals, the Council is developing a Natural Resource Management Strategy, of which a key component will be a Vegetation Management Strategy.

The draft Vegetation Management Strategy proposes the following objectives:

(i) retain existing native vegetation to maintain genetic diversity, viable wildlife populations and provide wildlife refuges;

(ii) encourage tree planting and other revegetation where it is the most appropriate form of land degradation control, e.g. dryland salinity and soil erosion control;

(iii) encourage improved vegetation management to protect surface water quality and reduce aquifer recharge;

(iv) encourage tree planting where it is the most economic and sustainable form of land use, e.g. agroforestry; and

(v) develop community awareness of the value of vegetation and encourage consideration of vegetation management issues as part of the planning process in the Basin.

Proposed actions under the draft Vegetation Management Strategy fall under four headings – clearing and development controls, management of degraded and degrading lands, assistance and incentive measures, and community awareness. In addition, the draft Strategy will interact with other programs in land, water, aquatic and riverine resources, flora and fauna and parks and reserves. The authors describe experience in these areas and the proposals for review and change.

The Economic and Practicalities of Controlling Groundwater and Salinity

A major obstacle to controlling groundwater and dryland salinity is the lack of control over rainfall. This obstacle negates many of the management practices effective in the control of irrigation salting. However, in dryland farming the amount of water reaching the groundwater and causing salinity problems is far less than under irrigation, suggesting that management would only need to produce minor changes in the existing hydrological balance to be effective in dryland areas.

The authors distinguish between regional recharge strategies and local discharge strategies. Recharge strategies can basically be considered as preventative measures aimed at reducing deep percolation to the groundwater, over large areas of land, by the increased and more efficient use of soil water supplied by rainfall.

The available recharge control mechanisms can be considered under three categories – reforestation and agroforestry strategies, agronomic strategies, and engineering strategies.

The benefits of using trees in reforestation and agroforestry programs are reviewed. It is suggested that the economic benefits of these programs are frequently over-estimated due to neglect of factors such as the opportunity costs of the area occupied by shelter belts and the time taken for their establishment. It is also suggested that the current arrangements for marketing commercial timber and setting prices are an important cause of the lack of private tree plantings.

Other factors which discourage private land holders from participating in forestry-based programs are the availability of labour and management skills needed to produce high quality timber products, the relative profitability of alternative enterprises, the availability of capital to establish the agroforestry enterprise, the investor's assessment of risk and attitude to long-term investment, and the potential benefits derived from agroforestry in mitigating soil erosion problems and buffering against periodic slumps in markets for agricultural products.

For these reasons it is probable that, even though there appears to be benefits from forestry-based activities, while simultaneously controlling groundwater levels and dryland salinity, added incentives would be required to persuade farmers to move from current practices to forestry-based systems. On the other hand, in some areas, modifications to existing farming systems are capable of significantly reducing deep percolation while increasing income, without requiring major managerial changes.

Water Yield and the Benefits of Controlling Groundwater and Salinity

In concentrating on the issues of groundwater levels, salinity and water quality, the importance of water yield has been somewhat neglected in recent economic literature. Work done in the Campaspe Catchment of the MDB indicates that if water yield was valued in excess of about $35 per ML the cost of stream flow foregone by reducing deep percolation would, in fact, outweigh the benefits from reduced salinity.

These results appear to be in conflict with other research in Australia which generally predict a net social gain from reduction in salinity problems, particularly stream salinity. However, in most other studies the value of water yield was ignored. In one study the water yield would need to be valued at $18 per ML to offset the gains from salinity control. In another study it would only need to be valued at $4.50 per ML.

Segregated versus Aggregated Models and the Economic Implications for Groundwater Management

A West Australian economic study did not distinguish between runoff and groundwater, with water yield coefficients calculated for each land use based on runoff measurements alone. Similarly, a Victorian study did not make this distinction and used average potential evapotranspiration rates as an inverse measure of water yield coefficients. While there must be some aggregation of variables in regional studies such as these, masking the hydrological interaction between deep percolation and runoff would appear to have important implications in terms of the effect of land use on stream salinity.

The ability to distinguish between factors within the hydrological system is one advantage of the farm-level simulation and linear programming approach. In addition, the farm-level approach enables components within land use systems to be segregated. Rather than determining the aggregate effect of crop rotation on salinity, for instance, the component parts such as crop, fallow and pasture, can be distinguished, enabling their relative contribution to the problem to be evaluated. This knowledge assists in the development of the most cost-effective means of controlling salinity.

A segregated approach also reduces the risk of mistakenly concluding that a particular land use contributed to salinity. For example, a Victorian study suggests that wheat growing can aggravate salinity problems and should be curtailed in areas prone to salting. However, the 'cropping' land use is an aggregate of the crop and fallow phases within the rotation. As indicated earlier, the substitution of short fallow for long fallow, and lucerne for annual pasture, dramatically reduces deep percolation suggesting that the wheat phase contributes little to groundwater recharge. In terms of suitable land use, recommendations on the restriction of long fallow rather than on wheat cultivation would appear more appropriate.

Conclusions

It is concluded that broadscale revegetation is not universally economic or practical as a groundwater and salinity management tool but that its use should be evaluated in terms of local conditions. On the other hand, it is also suggested that vegetation management should be more widely interpreted to include all vegetation which may be utilised to effectively and efficiently control groundwater and salinity.

The numerous impediments to the widespread adoption of forestry-based systems may not be easily overcome by various forms of government assistance, particularly given the current mood of governments facing large fiscal deficits. It should also be noted that for some areas there may be little that can be done at reasonable cost by governments or private individuals, given current technology and prices, to reverse or halt the development of groundwater and salinity problems. Solutions may depend on the development of new technology, new institutions or changes in the demand for the products from land.

GEOLOGICAL AND HYDROGEOLOGICAL ASSESSMENT OF THE VICTORIAN PORTION OF THE MALLEE, WITH PARTICULAR REFERENCE TO THE BASAL TERTIARY RENMARK GROUP.

J.M. Duran* and R.B. Nott**

*** Royal Melbourne Institute of Technology, Melbourne Vic. Aust.**

**** Department of Water Resources, Vic. Aust.**

While there is a considerable amount of information already available for the Pliocene sand aquifer and the Murray Group limestone aquifer, until recently there was virtually no hydrogeological information for the Basal Tertiary Renmark Group Aquifer.

Recent drilling in the far north west of Victoria has largely overcome this deficiency by providing basic hydrogeological data on water quality and hydraulic head for the Renmark Group aquifer.

The drilling sites were generally located from geophysical interpretation of pre-Tertiary basement structures, particularly where these structures were thought to influence the hydrodynamics of the Renmark Group Aquifer, which in turn may significantly effect the hydrodynamics of the overlying aquifers, particularly with respect to groundwater discharge to the River Murray, eg. Lambert Island.

The major aim of the drilling program was to establish a monitoring network to enable trends within the Renmark Group to be observed and allow the significance of these trends to be evaluated with respect to the salinity problem. At present a follow up drilling program is being co-ordinated to establish a monitoring network for the Murray Group limestone and Pliocene Sand aquifers at all the recently drilled Renmark aquifer sites.

Besides the recent drilling program an assessment of all the available information for the Renmark Group, both stratigraphic and hydrogeological was undertaken for the entire Mallee and Wimmera Regions of Victoria. The primary objective of this assessment is to delineate the spatial distribution and thickness of the aquifers and identify geological controls affecting the occurrence and movement of groundwater.

SALINE WATER DISPOSAL OPTIONS

Richard Evans
Rural Water Commission of Victoria
590 Orrong Road, Armadale, Victoria 3143

Perhaps the most perplexing aspect of all salinity control strategies in the Murray Basin is what to do with the saline water. Saline water is the inevitable consequence of both naturally occurring and man induced changes in the groundwater system. Considerable emotion and misinformation surrounds the range of disposal options. It is important to appreciate that the water acts as the mobiliser of the salt. Some scope exists to minimise the volumes of saline water produced by the adoption of strategies which aim to immobilise salt by reducing inputs to the groundwater. These practices must be encouraged. Nonetheless, the production of large volumes of saline water from the Murray Basin is a long term inevitability. It occurs in numerous forms:

- naturally occurring and land use change induced saline groundwater discharge to rivers and lakes
- surface drains from irrigation areas.
- tile drainage and groundwater pumping effluent in irrigation areas.
- drain base flow
- discharge from groundwater interception schemes.
- surface runoff from saline areas.

The bottom line of almost all salinity and land management strategies and plans is disposal.

A detailed assessment of the current and possible future options in the Murray Basin is presented in the paper.

Traditionally most thinking has been polarized into either River Murray or Non River Murray options. Generally, the intelligent use of both options in a conjunctive manner is technically and economically preferable. The optimum balance between the two broad options is dominated by groundwater salinity. In recent times much greater attention is being paid to reuse options and, in irrigation regions, reuse of saline water is probably the major disposal technique. Total reuse however, can only occur over a finite time span (typically measured in only tens of years) before degradation of soil and groundwater salinity occurs and often does not represent a long term sustainable option. However, reuse in some circumstances can be practically indefinite. Maintaining the appropriate salt balance in the root zone is essential for long term viability.

River Murray options can be grouped into uncontrolled outflow (in the case of most non point naturally occurring or man induced saline inflows) or controlled outflow (e.g. from groundwater pumping, flushing of an evaporation basin etc.) The controlled outflow can be regulated to take advantage of flood flows and downstream salinity adverse effects. The option of dilution flows specifically to reduce river salinity at various key times is currently practiced to a small extent, but is generally not economic. A far greater volume of saline water is disposed to the Murray River than to the Non River Murray options. It is clear that the River Murray disposal options should be considered much more, but only under carefully controlled conditions.

The Non-River Murray Options cover evaporation basins (with or without salt harvesting), aquifer disposal, desalinisation and pipelines to the sea. In addition, there is extensive use of River Murray lagoons and backwaters in some areas to dispose of irrigation drainage waters. Much misconception surrounds evaporation basins. There is no such thing as a non leaky basin. They all leak. The question is not do they leak, nor even how much, but rather, what is the adverse effect of the leakage and over what time period will it occur? Bad past practices have, understandably, given evaporation basins a poor name. It is hoped that well sited current and future basins will reverse the current poor image. Many evaporation basins have a relatively short finite life and hence do not represent a sustainable solution. A review of all major current and near future evaporation basins is presented and the technical, environmental and social aspects of evaporation basins are evaluated.

Aquifer disposal occurs in three main forms. Firstly, shallow disposal bores are common in South Australian irrigation regions and practised to a small extent in Victoria and New South Wales. The out-of-sight out-of-mind mentality pervades in many areas. In most areas where it is practised it causes significant adverse effects by displacing highly saline groundwater to the Murray River. This practice should be actively discouraged in or near the Murray trench. Secondly, deep aquifer injection is not currently undertaken anywhere in the Murray Basin. However, it is under active study for two specific projects in New South Wales. Finally, evaporation basin leakage can be a desirable or undesirable occurrence. A range of different situations are discussed. In general, the critical factor in aquifer disposal is a good understanding of the rate of transmission of the pressure and salt in the aquifer.

Desalination is very expensive and not an economic or practical option.

A variety of pipelines to the sea have been costed over the years and generally shown to be highly uneconomic. However, disposal of South Australian Riverland saline water via a pipeline to St. Vincent's Gulf may be economic in several decades.

Disposal to River Murray lagoons and backwaters has been shown to provide a very cheap but generally unsatisfactory solution. The environmental disbenefits are often severe and the displacement of more saline groundwater to the Murray River may be significant. In some cases they act virtually as holding basins prior to the next major flood.

All disposal options are economically evaluated and contrasted. A key factor influencing the economics of disposal is the salinity of the water. Different options became more attractive with higher salinity waters, while some options are essentially independent of the salinity. For low salinity water, reuse and controlled outfall (often with holding basins) via the River Murray are clearly most economic. As the salinity increases, evaporation basins become more economic. Most other options (except for well located shallow aquifer injection bores) are much more expensive.

Social perceptions of feasible disposal options are often poor. The environmental disbenefits of salinity in general are enormous. Some disposal options tend to concentrate the environmental disbenefits where by a smaller proportion of the environment is affected, albeit more severely. Environmental effects can be grouped into firstly those factors which generally have short term disbenefits on the ecosystems and secondly, those which have long term hydrogeological consequences. Considerable investigation and evaluation of environmental effects of the major salt disposal options (principally evaporation basins) is currently underway. Environmental effects are becoming a key factor in the choice of the preferred option.

An effective saline water disposal strategy for the entire Murray Basin is one of, if not the, highest priority for dealing with salinity. Economic and environmentally acceptable options exit now, albeit politically difficult at the local scale. A strong conviction to discourage the less desirable options (e.g. most disposal bores) and encourage the good options (e.g. well sited evaporation basins, and controlled outfall) is called for.

Looking to the future, much greater attention will need to be paid to discharge management. Huge areas of the Mallee contain unmanaged discharge regions which act to provide a degree of protection to dryland areas. More consideration of how to manage these predominantly naturally occurring discharge areas may have significant long term benefits. Also in the future, we will need to consider how best to maximise the use of all technically and environmentally feasible disposal sites. Hydrogeological processes at all scales will dominate these considerations.

OVERVIEW OF THE HYDROGEOLOGY OF THE MURRAY BASIN

W.R. Evans and J.R. Kellett

Hydrogeology Research Group, Division of Continental Geology,

Bureau of Mineral Resources, Geology and Geophysics

GPO Box 378, Canberra City ACT 2601

The majority of the salinity problems of the Murray-Darling Basin are groundwater related, (Macumber, 1984). To be able to adequately manage these problems, in both the long and short term, it is necessary – if not mandatory – that the groundwater processes in the Murray-Darling Basin are understood.

The Murray-Darling Basin can be subdivided into five groundwater regions (Fig. 1); the Murray geological (or groundwater) basin – referred to as the Murray Basin; that part of the Murray-Darling Basin underlain by the Great Artesian Basin (GAB) which contains two regions, the deeper GAB sequence and the overlying unconsolidated Cainozoic materials (referred to as the Darling River Basin); and the

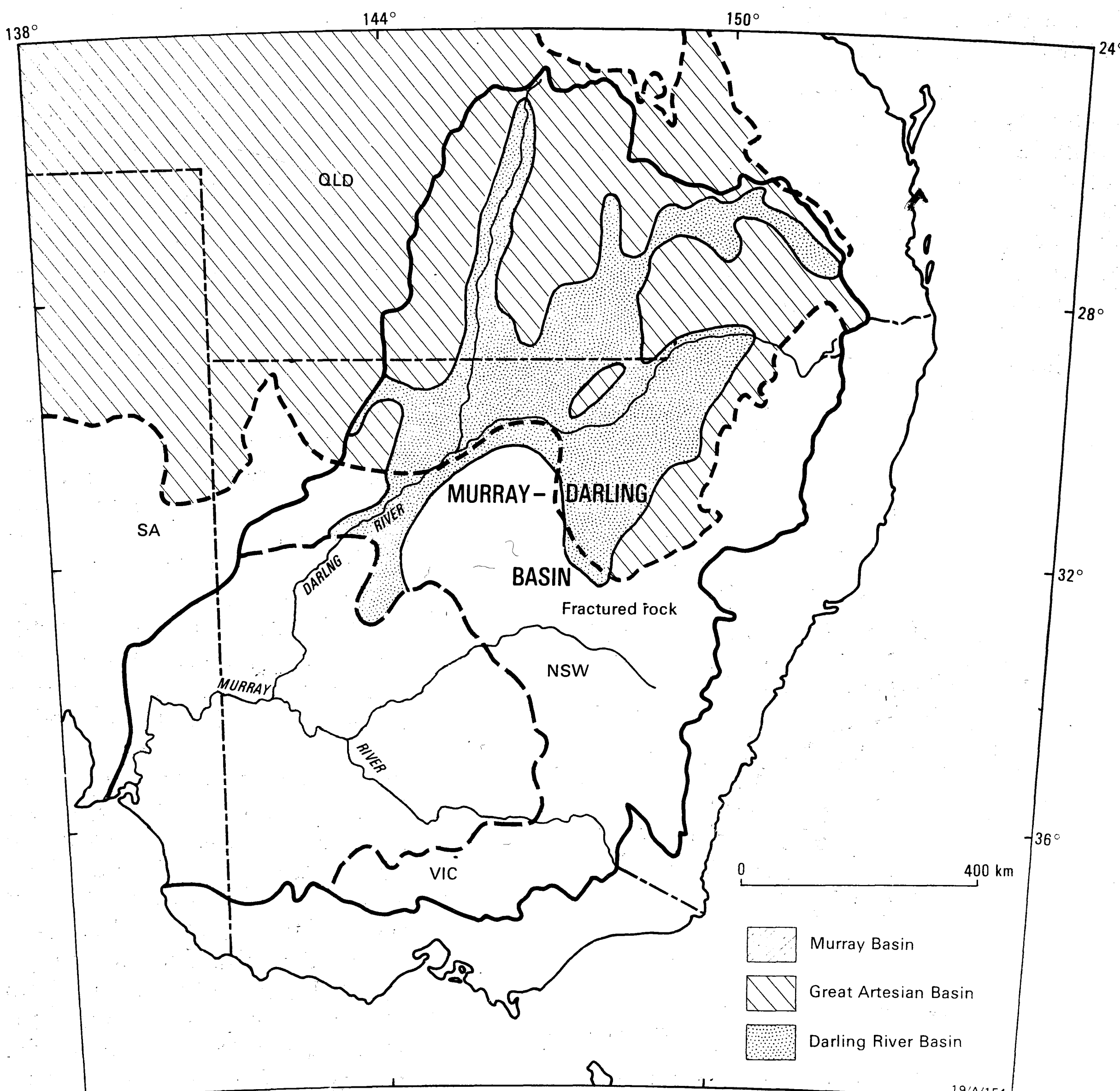

Fig. 1. Murray-Darling Basin groundwater regions

remaining area of the Murray-Darling Basin underlain by fractured rock aquifers which is divided into northern and southern regions. The Murray Basin can be further subdivided into two sub-regions, the Riverine Plain to the east, and the Mallee landform association to the west. The transfer of groundwater between the aquifers of the various regions is regarded as minimal and each system can be thought of as being largely self-contained although few data are available. Water from aquifer systems is, however, transferred across regional boundaries as surface water base flow.

These regions can be ranked in order of priority in terms of the overall effect of groundwater process on problems of river salinity and land degradation. Evans (in press) detailed three levels of regional priority. These levels were dominated by the Murray Basin and the southern fractured rock region – the Uplands of northern Victoria and southern New South Wales – as the highest priorities.

Murray Basin

The Murray Basin Hydrogeological Project was established as a long-term study to improve the understanding of the groundwater regime of the Basin by examining it as a single entity, unencumbered by State boundaries. The project is being undertaken jointly by South Australian, Victorian and New South Wales geological surveys and water authorities and by the Division of Continental Geology of the Bureau of Mineral Resources, Geology and Geophysics. The southern fractured rock province is being studied, to varying degrees, by state agencies.

The Murray Basin is a low-lying, saucer-shaped, intracratonic basin which underlies an area of 300,000 sq. km. of southeastern Australia. The Basin is a closed groundwater basin consisting of a thin veneer (200 - 600 m. thick) of Cainozoic unconsolidated sediments and sedimentary rocks containing a number of regional aquifer systems (Brown, 1985; Brown & Stephenson, in prep.). The Basin can be divided into two subregions on the basis of surface geomorphology and relatively thick, structurally controlled sediment accumulation, an eastern zone underlying the Riverine Plain and a western zone underlying the Mallee region.

Aquifers

The widespread basal, confined *Renmark Group aquifer* is made up of lower Tertiary fluvial clay, silt, sand and minor gravel; carbonaceous sediments are ubiquitous throughout the Renmark Group. In some areas it is possible to further subdivide the Renmark Group into three aquifers - the upper, middle and lower aquifers according to lithologic, water quality, water pressure and palynologic criteria. The lower Renmark Group aquifer, which includes the restricted distribution of Warina Sand (found only in the very deepest parts of the western subregion), is found in the deeper troughs of the Basin and is absent from on top of the numerous upthrown ridges between the troughs. This aquifer would include both the lower and upper sub-systems of the

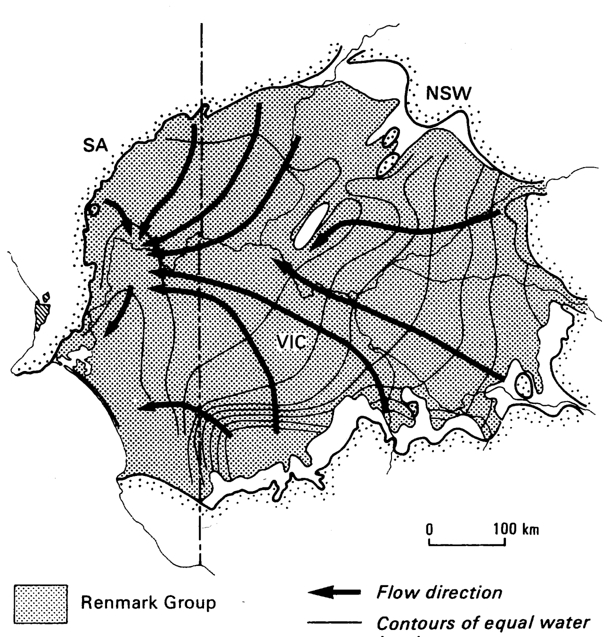

Fig. 2. Renmark Group flow regime

Renmark Beds as defined in South Australia. As more information becomes available, it may be neccessary to further subdivide this lower aquifer. The middle and upper Renmark Group aquifers are more widespread. These latter aquifers thin, however, across the boundary between the two subregions. Flow in the three aquifers occurs from recharge areas around the Basin margins, towards the centre of the western subregion (Fig. 2) – the area of thickest sediment accumulation – where the pressure regime is such that groundwater leaks upward into the overlying sediments (the Murray Group aquifer). In general the salinity of the groundwater in these aquifers increases proportionally with distance along flow lines from fresh, within the recharge areas, to saline (30,000 mg/L total dissolved solids – TDS) in the zone of upward leakage. There is also a pronounced vertical layering of salinity between the three aquifers, with the saltier water occurring in the upper and middle aquifers in the central parts of the Basin and similar salinities throughout the three in the east, where the water is relatively fresh, and the far west, where the water is relatively saline. The aquifers are utilised for major irrigation purposes in the east, in conjunction with the overlying Pliocene Sands aquifer, and for stock supply purposes, particularly from the lower Renmark Group aquifer, in the central part of the basin.

The *Murray Group aquifer* comprises middle Tertiary marine limestone, and occurs in the western subregion underlying the Mallee regions of South Australia and western Victoria. The aquifer underlies the Pliocene Sands aquifer and overlies the Renmark Group aquifer – being the time equivalent of the middle and upper Renmark Group aquifers. The Murray River forms a hydrogeologic divide for the aquifer, separating a northern confined to semi-confined saline flow system and a southern confined-unconfined fresher flow system. The majority of the aquifer system lies to the south of the river and flow is from the recharge areas of the southern Wimmera north-northwesterly towards the discharge zones along the Murray River (Fig. 3). This southern flow system contains reasonably fresh groundwater, is extensively utilised for irrigation and town water supply, and is coming under increasing pressure for further development. The northern flow system is a poorly developed aquifer system draining waters from the Broken Hill Block southward towards discharge zones along the Murray River. This flow system is saline, with salinities ranging up to 30,000 mg/L TDS.

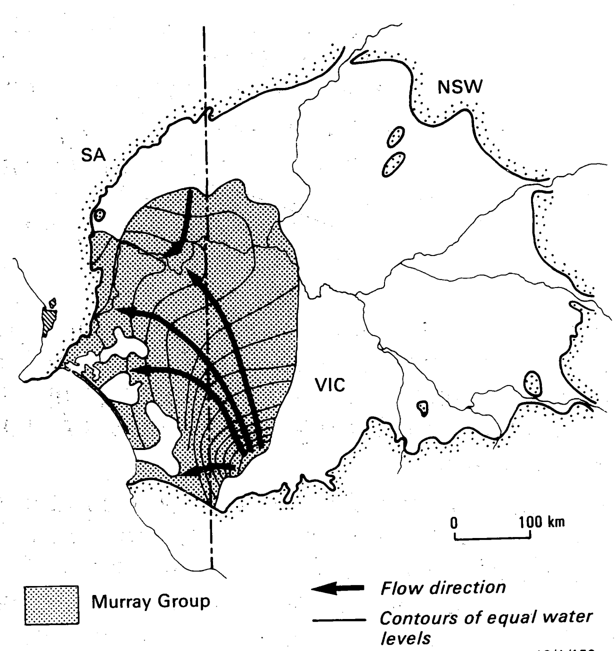

Fig. 3. Murray Group flow regime

The *Pliocene Sands aquifer* – a composite of marine sand and silt of the Loxton-Parilla Sand generally in the western subregion, and fluvial gravel, sand, silt and clay of the Calivil Formation generally confined to the eastern subregion – forms a blanket over most of the basin. Recharge to this aquifer system is very complex. The Calivil Formation is confined and receives recharge from downward leakage, through the overlying Shepparton Formation around the Basin margin; a significant proportion of this recharge is from stream bed leakage. The Loxton-Parilla aquifer is generally unconfined and receives recharge by – (a) diffuse downward leakage from rainfall over most of it's extent, and – (b) by lateral transmission from the adjacent Calivil Formation. Regional and local flow systems can be identified within the Pliocene Sands

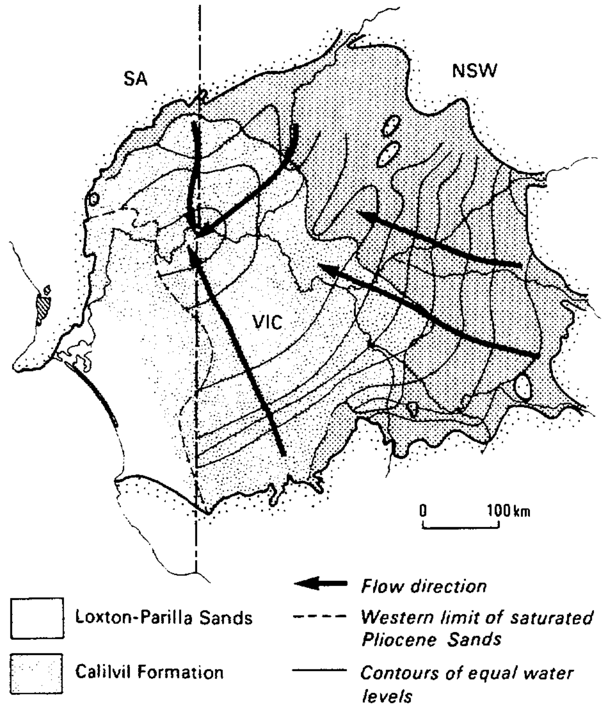

Fig. 4. Pliocene sands flow regime

aquifer (Macumber & Fitzpatrick, 1986). Regional flow patterns (Fig. 4) are from the recharge areas at the Basin margins towards the discharge zones along the Murray River. There is a disturbance to the flow system near the boundary between the Calivil Formation and the Loxton-Parilla Sands due to the change in permeability as a consequence of changing aquifer lithologies. This aquifer is heavily drawn upon where the water is fresh – within the Basin's irrigation areas of New South Wales and Victoria - but becomes far too salty (20,000 - 50,000 mg/L TDS) for use further west. The aquifer is unsaturated in the southwest of the basin where the Loxton-Parilla Sand is discontinuous or where it directly overlies the Murray Group aquifer.

In the east, underlying the Riverine Plain, the *Shepparton Formation aquifer* overlies the Pliocene Sands (in the Mallee region the Pliocene Sands are blanketed by aeolian material). Comprising Pliocene to Quaternary clay, silt and sand, the Shepparton Formation aquifer is of only local importance as a source of water because of its heterogeneity and, hence, low permeability, but is important because it lies immediately below most of the eastern irrigation areas. Some useful irrigation supplies are obtained from shallow spear-point systems tapping 'shoe-string' sands in 'prior' stream channels. Water quality is highly variable being a complex function of hydraulic conductivity, depth to watertable and development history – a range of natural salinities up to 20,000 mg/L TDS has been observed.

The Murray Group aquifer is separated from the Renmark Group aquifer by a confining bed composed of Ettrick Formation and Winnambool Formation/Geera Clay, and, in places, from the Pliocene Sands aquifer by the Bookpurnong beds. In the eastern and northern parts of the basin, the Pliocene Sands aquifer directly overlies the Renmark Group aquifer, thus allowing direct hydraulic connection between the two aquifers. It is in these areas that the Renmark Group aquifer receives large volumes of recharge by downward leakage through the Pliocene Sands.

Recharge and Discharge

Recharge to the regional aquifer systems is twofold. The deeper confined aquifers have recharge zones generally around the basin margins, related to specific point source areas that sometimes correlate with the sites where the major rivers that drain into the basin cross the boundary between the Basin and the uplands zone. The shallower unconfined aquifers receive water from both point source zones at the Basin margins and diffuse zones over the majority of the aquifer's surface. Discharge from the deeper aquifers is by upward leakage through confining layers to the watertable aquifer. The majority of discharge from the watertable aquifer is, either to the lower reaches of the Murray River and its tributaries, or by direct evaporation from the capillary zone. The volumes of water that enter the system via diffuse downward leakage to the watertable are, by virtue of the fine hydrologic balance of the aquifers and the large surface area of these diffuse zones, of significant importance to the regional hydrologic regime. The hydrologic system attains an equilibrium with all its inputs and outputs over time, so a large change in the rate of diffuse zone recharge, as is the case where natural vegetation has been cleared, is enough to drastically change this balance. During times of very high rainfall, diffuse zone recharge dominates accessions to the watertable aquifers (Macumber, 1983), resulting in large irreversible increases in groundwater levels. Leakage between aquifers is a dominant process, and can contribute significantly to aquifer recharge and discharge.

Geological mapping of the basin has highlighted the distribution of both active and old inactive - fossil - groundwater discharge complexes. The recognition of a number of extensive fossil discharge complexes reveals that groundwater levels have been high in the past and that although current farming practices have accentuated salinity problems, the Murray Basin has in fact seen much more widespread land salinisation under natural conditions in the recent geologic past – during the last 500,000 years. The driving mechanism for groundwater discharge at several active and fossil sites can be related to high pressures and upward leakage created at permeability barriers formed where the aquifers are truncated stratigraphically by facies changes or are significantly thinned by concealed basement barriers.

Evapotranspiration is the main mechanism for concentrating the salts in the groundwater. As a consequence, the aquifer systems of the basin show a layering of salinity, the most saline waters occurring toward the top of the sequence, the fresher water occurring at the bottom of the sequence. Natural salinity of groundwaters is variable, ranging up to 300,000 mg/L TDS. In general, the better-quality water is found around the basin margins. Very little connate salt -old seawater- is present in the aquifer systems. The primary source of salts is from atmospheric accessions over the recent geological past – the last 500,000 years.

The groundwater system is undergoing a profound change. Aquifer water levels are increasing over most of the southern parts of the basin. This change has been brought about by an increase in regional recharge rates due to a reduction in evapotranspiration rates in recharge zones – a direct consequence of the changing land management practices since the late 19th century. Land clearing and irrigation have both contributed to the increase.

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SALINE GROUNDWATER INTERCEPTION AND DISPOSAL AT MALLEE CLIFFS/LAMBERT ISLAND.

J. Forth, Dr S. Perrens*, and Dr P. Rowley*
Groundwater Resource Consultants, Brisbane
***Dames & Moore, Sydney**

INTRODUCTION

Recent studies by the Department of Water Resources (New South Wales), and the Rural Water Commission of Victoria identified a 3.75km river reach at Mallee Cliffs/Lambert Island where there was a significant gain in river salinity as a result of groundwater inflows. In 1986/87 Dames & Moore were engaged by the Department of Water Resources, acting for the River Murray Commission, to make field investigations and prepare a study as to the feasibility of intercepting, and safely disposing of, saline groundwater reaching the River Murray in the Mallee Cliffs/Lambert Island area. This paper summarises the project results.

GEOLOGY

At the Mallee Cliffs/Lambert Island site (Figure 1) the following geological succession occurs:

PERIOD	GROUP	FORMATION
Quaternary		Coonambidgal/Woorinen
Tertiary		Parilla Sand, Bookpurnong beds
	Murray	Geera Clay
	Renmark	Olney Formation

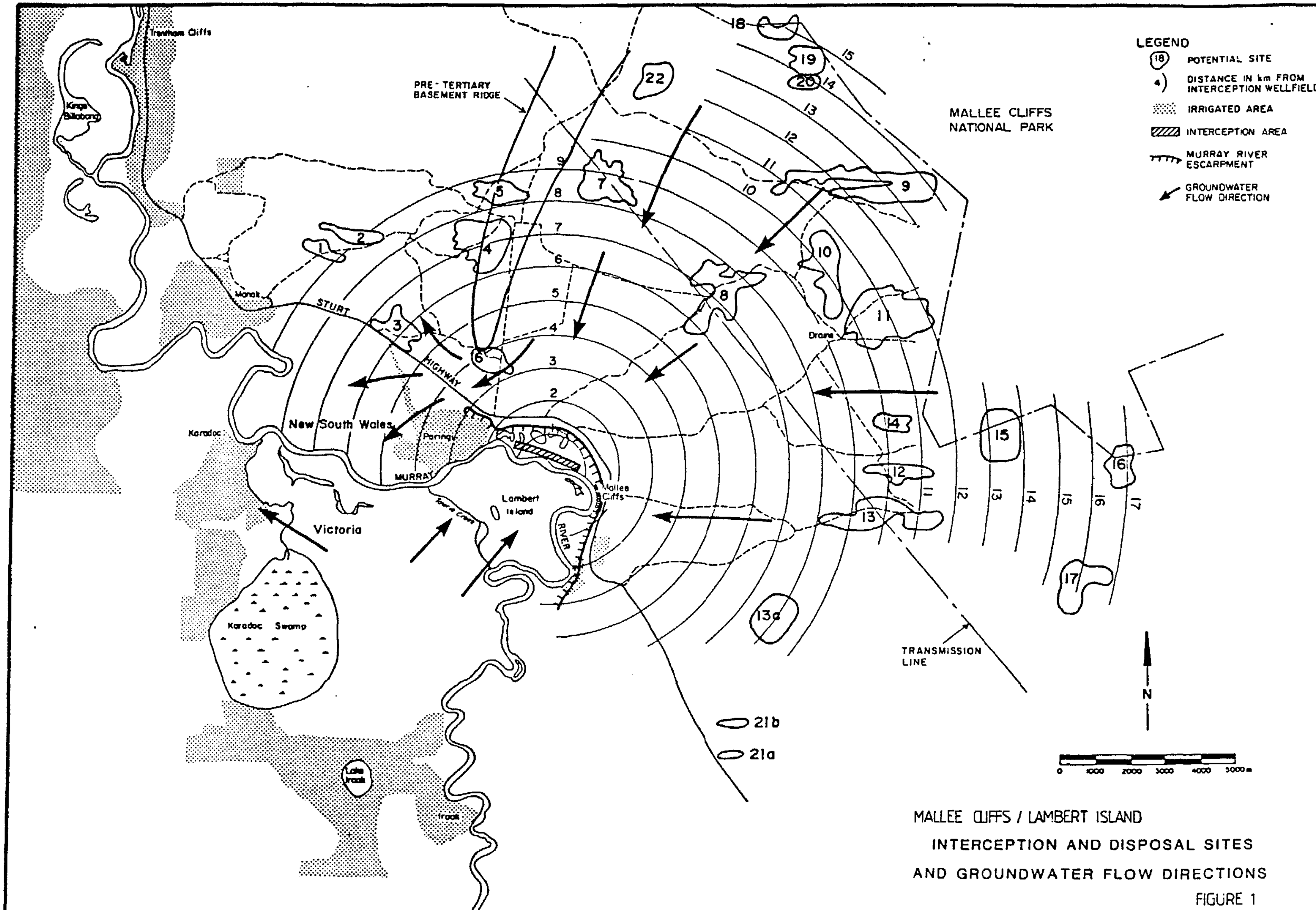
The Murray Trench Escarpment (Figure 1) marks the northern limit to the erosional flood plain of the present river. South of the Escarpment, alluvium rests directly upon the Parilla Sand and north of the Escarpment the Parilla Sand is overlain by Blanchetown Clay.

In the northwest, the basin sediments are truncated by, and draped over a NNE trending pre-Tertiary basement ridge.

HYDROGEOLOGY

The Parilla Sand Aquifer is the main regional aquifer and extends throughout the study area. It contains in places an upper lower permeability layer and south of the escarpment includes overlying Quaternary alluvial sands which are in direct contact. Its groundwater has an average TDS concentration of almost 40,000mg/L. Groundwater flow in the Parilla is from the west, but in the study area is deflected by the pre-Tertiary basement ridge to flow south, and discharges to the Murray River (see Figure 1).

Investigations near the River have shown that the Parilla Aquifer there has a thickness of 40m and a transmissivity of 1500 to 2000m^2/d. Lithological data from north of the Escarpment indicates that permeabilities are lower there and are probably about 15m/d.



MALLEE CLIFFS / LAMBERT ISLAND

INTERCEPTION AND DISPOSAL SITES

AND GROUNDWATER FLOW DIRECTIONS

FIGURE 1

RIVER ACCESSION

River water quality surveys have established that in a 3.75km reach at Mallee Cliffs/Lambert Island, there is a saline accession of 105t/d which is equivalent to a groundwater inflow of about 2500m^3/d.

The zone of saline accession can be further identified by the observed differences in water levels between the shallow alluvial aquifers and the Parilla Aquifer. Changes in groundwater level observed during a lowering of Mildura Weir identify the same zone.

SALINE GROUNDWATER INTERCEPTION

Pump testing and subsequent computer modelling has indicated that the saline groundwater can be intercepted by a single line of wells on the NSW side of the river (see Figure 1).

Various combinations of pumping wells were evaluated (using pump test data) and the results can be summarised as follows:

NO. OF WELLS	TOTAL PUMPAGE (m^3/d)	INTERCEPTION EFFICIENCY
4	3000	72%
4	3300	77%
3	3300	76%

SALINE WATER DISPOSAL

Twenty two potential disposal sites, north of the Escarpment, were identified and evaluated (see Figure 1 for locations).

Blanchetown Clay occurs throughout this area and it was thought this would provide an effective floor seal so initial investigations were directed to locating a site with suitable form. However, it was found that at some sites the Blanchetown clay in this area can be permeable and that it contains widespread sands which potentially could transmit any pond leakage to the escarpment or the Paringi Irrigation Area.

Only one site, Site 19 14km north of the River, was located which satisfied all the selection criteria. The site comprises two basins, separated by a dune ridge, totalling 100ha in area within a 2m contour. The site is underlain by top soil and 4m of silty and sandy clay directly overlying the Parilla Sand. The Blanchetown Clay here has an average permeability of 2.4×10^{-1} m/d which could lead to pond leakage rates up to 0.44mm/d.

DISPOSAL EVALUATION

Disposal options considered included:

- Storage, concentration, pumpage to river in high flows.
- Storage, concentration, leakage/bleed to Parilla Aquifer.

It was assumed that interception pumping would occur when river flows were less than 20GL/d (about 75% of the time) at pump rates of 3300m^3/d, and that pumpage back to the river would only occur when river flows exceed 80GL/d.

Under these conditions a 100ha pond would provide sufficient storage for the first option with pond salinities reaching 300 000mg/l. If leakage/bleed totalled 400m/d, a 74ha pond would suffice.

Natural leakage from a 74ha pond at Site 19 would be $300m^3$m/d so provision need only be made for a bleed of $100m^3$/d to satisfy the second option. This could be done with a caisson type structure as the Blanchetown Clay is only 4m thick.

The effects of a combined leakage/bleed of $400m^3$/d were simulated and it was found that after 50 years continuous leakage with interception pumping, saline accesssions to the river would have re-stabilised with an increase in river accession of $16m^3$/d. The balance would be intercepted.

CHANGES IN GROUNDWATER LEVELS AND WATER CHEMISTRY SOUTHEAST NEW SOUTH WALES

G.W.B. Gates and R.M. Williams
New South Wales Department of Water Resources
P.O. Box 156, Leeton. N.S.W. 2705

A census of private bores was carried out in Southeast N.S.W. in October, 1987 (see Figure 1 for locality). The census covered an area of 17,900 square kilometres and was centred on two trial catchments of 'Wattle Retreat' at Cootamundra and 'Begalia' at Yass. The area is known to have significant dryland salinity problems.

Dryland salting (seepage salinity or salt scald as it is sometimes known) is reported to be expanding in southeast New South Wales (Wagner, 1986). There are in excess of 1000 sites in the study area averaging from 2 to 5 hectares in size.

It is becoming generally accepted that a reduction in evapotranspiration and interception storage occurs when shallow rooted annual agricultural crops and pastures replace deep rooted perennial native forests (eucalyptus). This in turn results in an increase in groundwater recharge and rising water levels.

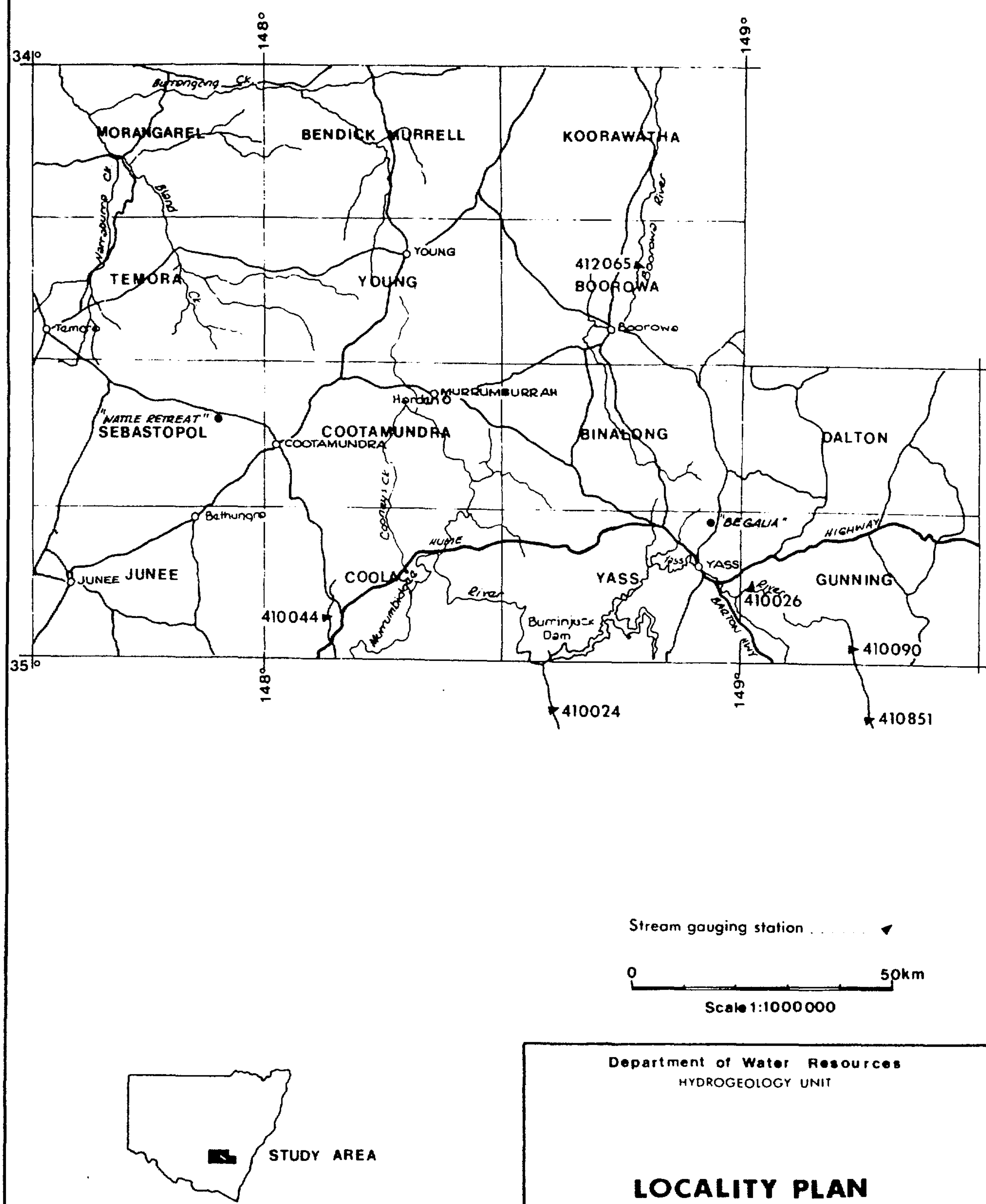
The study area is located within the Lachlan Fold Belt, a geological zone of folded metamorphic and volcanic rocks ranging from Ordovician to Devonian in age. Tertiary and Quatenary sediments occur along the major tributaries to a maximum depth of 100 metres.

With a few minor exceptions there has been a significant increase in groundwater levels right across the study area. Figure 2.1 shows the magnitude of the changes. Potentiometric levels have increased on average 4m over the 72 year period of record (1915-1972). Other details are:

Maximum increase	= +24.4m
Maximum fall	= -7.5m
Median change	= +2.9m
Standard Deviation	= 5.5m

The following observations have been made:

- The oldest bores generally exhibit a large water level rise (Figure 2.2).
- Bores which recorded the largest groundwater level rises (greater than 10 metres) all had significant areas of their catchment under cropping.
- The relationship between water level rise and geology is a local one rather than regional. Groundwater flow paths suggest recharge occurs in the immediate catchment and discharge is to water courses lower in the catchment.
- Fracture intensity of the catchment rocks is the dominant geological control that governs the location of recharge and recharge rates.
- No relationship has been established between average rainfall and water level changes i.e. there are as many rises in the lower rainfall area in the west as in the higher rainfall areas in the southeast.



Department of Water Resources
HYDROGEOLOGY UNIT

LOCALITY PLAN

FIG. 1·1

DEPARTMENT OF WATER RESOURCES - HYDROGEOLOGY UNIT

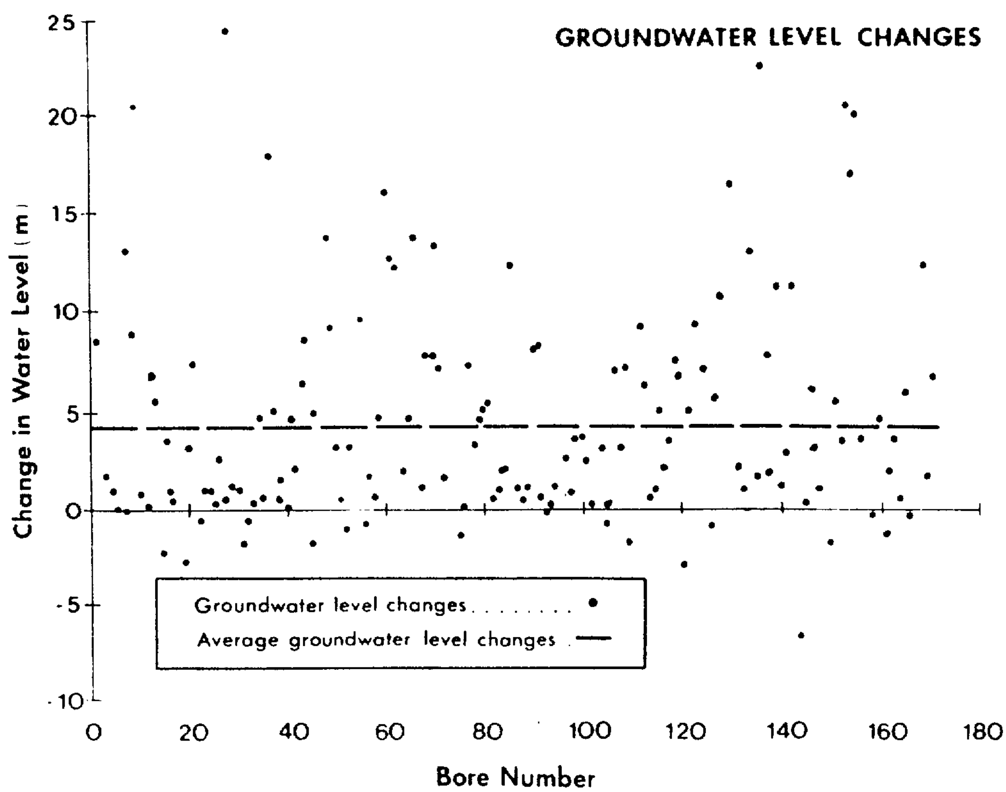


FIG. 2·1

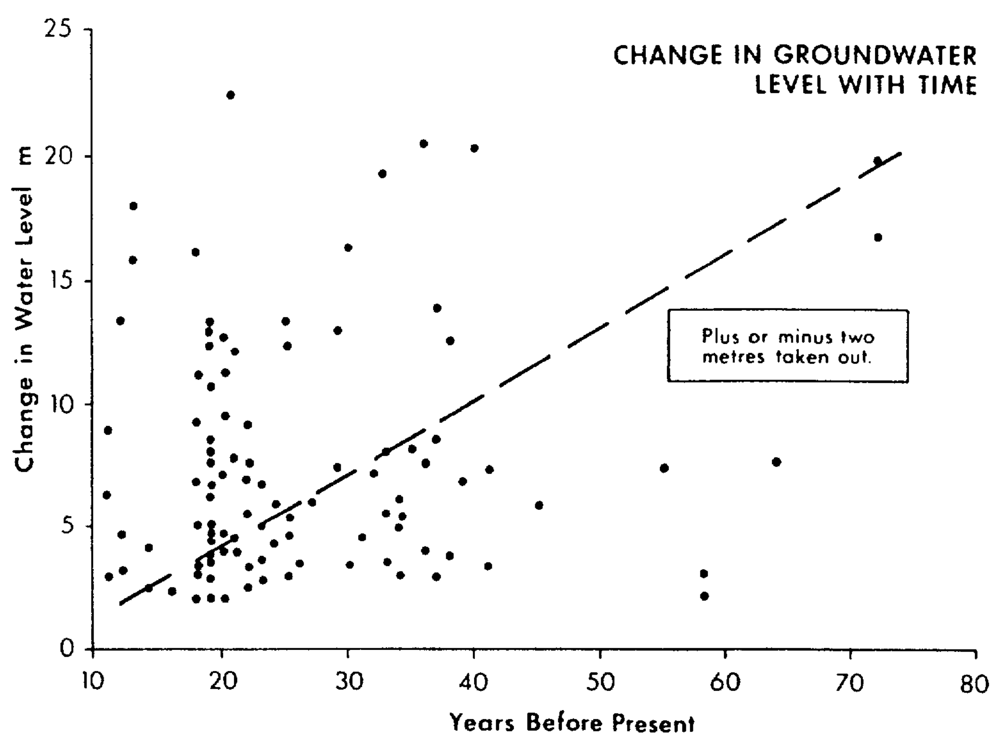


FIG. 2·2

Groundwater Chemistry

Groundwater chemistry was examined to determine groundwater/rock interactions and their effect on the evolution of groundwater quality. Full chemical analyses are available for 28 sites and electrical conductivity values at 141 sites.

Groundwater salinities increase in a general sense from east to west across the study area.

From principal component analysis and statistical analysis of the data, it was found that the waters trend from HCO_3 dominance through a mixed HCO_3/Cl dominance to Cl dominance with increasing salinity. A number of other trends were also observed i.e.:

- increasing Cl, Ca, Mg with decreasing Na and HCO_3
- increasing Na, Cl with declining HCO_3.

There is a significant correlation between Na, Cl and conductivity indicating the groundwater trends towards NaCl dominance.

Impact on Surface Water

The salinity of water in all streams examined is increasing with time. The salinity signal is diluted as water moves downstream because of the volume of inflow and the intergration of different salting signatures.

The rise in groundwater levels causes an initial increase in stream baseflow and later as the seepage/evaporation processes become established on salinised areas, overland flow transports salts to streams after rainfall events.

The data indicates that while the catchments are flushed by flood flows, the salt store available for mobilisation is quickly restored because the high water levels driving the salinity system are in place.

It is unclear if the increase in stream salinity which commenced many decades after clearing will be linear or if the rise to equilibrium will be exponential.

Identifying the principal areas of recharge and reducing deep percolation is the key to success in reversing the observed rising stream salinity trends. This can be done by altering land management practices to hold existing salt in the catchment by lowering groundwater levels.

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ACCESSIONS STUDY ON THE RIVERINE PLAIN

David Ife
Rural Water Commission of Victoria

1. INTRODUCTION

The Riverine Plain in northern Victoria has been subjected to major land modifications in the last 100 years. A vegetation map produced in 1847 gives an indication of the virgin situation in northern Victoria:

- Between the Mallee and the Loddon River – 'Scrub'
- Between the Loddon River and the Campaspe River – 'Extensive grassy plains'
- Between the Campaspe River and the Goulburn River – 'Open forest country, good grass with belts of scrub'
- Between the Goulburn River and the Murray River – 'Box and Gum forests'.

The depth to watertable in the Shepparton Region prior to agricultural development is not known in any detail, but some of the records from water supply bores which were sunk to supply new townships give an indication. It appears that the regional watertable was at a depth of 30 - 50 m below surface over most of the plain prior to extensive land modification. Areas close to the rivers, such as Echuca, had a higher watertable, possibly reflecting hydraulic connection between the surface watercourses and the shallow aquifers.

Low watertables persisted until agricultural development commenced in the mid nineteenth century. Two factors have contributed most to the high watertable problems.

(a) The Clearing of Native Vegetation

Deep rooted vegetation played an important role in maintaining the original hydrologic balance, and the relationship between clearing of trees and the onset of salting has been established for a long time, although the mechanisms are only now being fully understood.

Clearing of native trees to make way for agricultural development has resulted in the reduction of canopy cover and removal of deep roots. The combined effect has been increased recharge and mobilisation of salts. The increased recharge has caused the water table to rise, bringing the salts, formerly held in the unsaturated zone and groundwater, with it. Salinisation of soils can occur when the water table is high enough to permit evapotranspiration from it. The water table may rise still further until ultimately groundwater discharge occurs through direct evaporation and extensive salinisation results.

(b) Irrigation

The salinity and waterlogging problems which are now evident in parts of the irrigated areas are largely the result of 100 years of irrigation. Replacement of native deep rooted vegetation with shallow rooted crops and pasture has increased the opportunity for infiltration below the root zone. Once the land is irrigated accession to the watertable is greatly increased and it rises. The natural hydrologic balance is upset and a new equilibrium is struck in which input to groundwater is balanced by discharge from the watertable to the plant root zones and soil surface by capillary action, and by seepage to artificial and natural drainage channels.

When the watertable rises close to the surface, plant growth can be inhibited by intermittent or permanent waterlogging of the root zone and then by the concentration of salt around the roots which reduces the plant's ability to take up water.

2. WATERTABLE ACCESSION

The Upper Shepparton Formation is composed of aquitards interspersed with alluvial channel sands. The piezometric levels in each aquifer determine the movement and magnitude of groundwater flow in a horizontal and vertical direction. The Calivil Formation which underlies the Shepparton Formation has a lower piezometric level over most of the Shepparton Region and under this condition acts as a drain for 'deep seepage'.

There are two mechanisms by which vertical recharge can occur – piston flow or flow along preferential paths. Piston flow can be envisaged as a saturated front moving down through the sediments at a uniform rate, whereas flowing along preferential paths is selective and non-uniform, being controlled by the permeability of the medium and the degree of interconnection of permeable zones. It is likely that both mechanisms are valid, their applicability depending on scale and local conditions.

Accession, or vertical recharge, is controlled by the vertical hydraulic conductivity of the conducting medium, which is usually unknown. Work is now proceeding in the Shepparton Region to gain a better understanding of this factor.

3. DETERMINATION OF ACCESSION RATES

Vertical hydraulic conductivity can be determined by direct or indirect means. Direct methods include special pumping tests (e.g. the ratio method and piezometer tests). Indirect methods, which produce an answer through inference, include techniques such as computer flow modelling and soil salinity monitoring. These techniques have been used, and are still being used, in the Shepparton Region. Some examples will be discussed.

4. CURRENT INVESTIGATIONS

(i) Computer Modelling

Groundwater flow models have been set up for three subregions within the Shepparton Region – the Girgarre area, the Ardmona-Toolamba area and the Tongala area. The head distribution is well known in these areas, which have had monthly piezometric readings over a number of years. Aquifer characteristics are also reasonably well understood from pumping test data. Therefore, using two dimensional groundwater flow models (single layer and multi layer) it has been possible to estimate recharge (and discharge) using calibration techniques.

Results of these modelling studies vary according to intensity of irrigation, degree of groundwater pumping, soil type and aquifer conditions.

(ii) Pumping Tests and Piezometer Tests

Specialised testing has been undertaken to determine vertical hydraulic conductivity of clays in the Upper Shepparton Formation.

(iii) Soil Salinity

Soil salinity profiles can be interpreted in terms of rates of recharge/discharge. Work has been done in different irrigation and dryland environments using chloride levels and total salts. An electromagnetic induction probe (EM39) is being used to define electrical conductivity profiles in bores. It is intended to log the same bores on a regular basis to determine rates of change in salinity profiles and changes in aquifer salinity under pumping conditions.

(iv) Local Scale Modelling

In conjunction with the Department of Agriculture and Rural Affairs, a small area is being examined in detail using various techniques for estimating recharge. Vertical slice modelling will also be used.

These studies are at various stages and our understanding of recharge and discharge processes is far from complete. The hydrogeological system is complex and problems of heterogeneity and scale make results extremely variable. A clear understanding of the physical conditions is a vital prerequisite for estimation of rates of accession.

APPLICATION OF LANDSAT THEMATIC MAPPING TO STUDIES OF GEOLOGY AND SALINITY IN THE MURRAY BASIN

R.M. Johnston and J. Kamprad

Bureau of Mineral Resources, Geology and Geophysics

GPO Box 378, Canberra ACT 2601

Increasing salinity of soils, groundwater and streams in the Murray Basin is considered to be one of the most serious environmental problems facing Australia at the present time. Groundwater levels throughout the region are rising steadily, causing widespread land degradation and the decline of surface water quality, with the potential for further expansion of the problem if current trends continue unabated. Rising groundwater levels are linked to land management practices, such as irrigation and replacement of natural vegetation with crop and pasture species, which causes increased accessions to groundwater. Salinity appears to be a perennial problem in much of the Murray Basin. Geological studies of the area have shown that the western Murray Basin has been subject to arid to semi-arid climatic conditions for much of the Late Pleistocene and Holocene; relict Late Quaternary groundwater discharge zones and terminal lake complexes, indicating high levels of salt in the landscape, are common. Rapid increases in salinity levels in recent times indicate that present agricultural practices are reproducing some salinisation processes that have occurred under natural conditions. An understanding of past and present hydrological regimes is central to any study of salinisation induced by land management practices, and to formulation of strategies to control and ameliorate the problem. Rising groundwaters will initially reactivate discharge zones active in the past; these zones represent areas most at risk. Recognition and monitoring of these zones will provide valuable information relating hydrological regime to increasing salinity.

The Bureau of Mineral Resources' Murray Basin Program is involved in collection and analysis of geological and hydrological data on the basin. A sub-project was initiated to assess the applicability of basic uncorrected LANDSAT TM data to studies in the Murray Basin and in particular to the identification of active and relict salt lakes and groundwater discharge zones. In addition, an attempt was made to delineate the distribution of mineral salts within these areas.

LANDSAT 4 and 5 provide spectral data in 7 bands in the visible and near infrared regions from an advanced multispectral scanner called the Thematic Mapper. Distinctive spectral reflectance properties can be used to identify various types of vegetation, soils and other components of the land surface; however, spectral reflectance curves of the terrains studied can be used only as a general guide because of atmospheric attenuation and instrumental characteristics inherent in the uncorrected digital data.

As a first step in assessing the usefulness of the TM data, uncorrected digital data were processed for three lake complexes with active groundwater discharge zones in the Mallee Region, north of Lake Victoria in western NSW. TM data for the area were recorded on 25 September, 1986. The dominant landuse in the area is grazing of sheep. Vegetation consists mainly of stands of mallee and casuarina with widespread saltbush of various species. Vegetation has been affected to varying degrees by clearing and grazing. The geomorphology of the area is dominated by Late Pleistocene to Holocene saline lakes surrounded by aeolian dune fields and sand plains. The saline lake complexes, with intermittently active salinas, represent groundwater discharge zones. Active salinas are currently very small compared to the maximum extent of lakes in the past. The maximum extent of lakes is delineated by a dry playa floor consisting of gypsum-rich clay deposits forming extensive gypsite flats, vegetated by saltbush species. Active salinas occur in topographic lows, entrenched within the former lake floors.

Deposits within the salinas typically consist of black anoxic muds underlying ephemeral salt crusts, usually composed of a mixture of complex sulphates and halite. Distinct zones are observed in the lakes, both laterally and vertically, but are ephemeral.

Contrast enhanced composite images from the uncorrected LANDSAT TM data give a quite detailed display of vegetation, geomorphology and landuse patterns. While images of data from each band showed slightly different features, a composite image of bands 1 (blue), 4 (red) and 5 (green) was found to give best definition of most features. Variation in vegetation is distinct, with changes across fence lines emphasizing the important control which grazing exercises over vegetation. Stands of mallee and casuarina can be distinguished from saltbush, and some distinction can be made between types of saltbush. Although changes in vegetation on the ground can be related to colour changes on the images, the reverse is not always true; very complex vegetation patterns displayed on the LANDSAT images are frequently not obvious on the ground. While it is not possible at this stage to unequivocally identify vegetation types on the images, depth of colour can be used as a rough guide to the density of cover.

Comparison of LANDSAT data with mapped geology, showed that TM data delineate both active salinas and ancient playas very well. Zonations within the active salinas are also well defined. Dunes within the lakes are easily distinguished by their vegetative cover, but those bordering the lakes are poorly defined since their vegetation merges with that of the surrounding plains. Vegetation differences between dune and swale emphasise the east-west trending dune sets of the Woorinen Formation, giving good definition of these areas compared to the aeolian sand plains.

Most TM bands indicate zonation in several of the active salinas, but patterns are not always coincident and assigning each zone to real phenomena is complicated by the seasonal variability of the salinas and the time difference between collection of field and TM data. Ground checking indicated that it is possible to use colours generated in false-colour composite TM images as a rough guide to the surface characteristics, rather than the exact mineralogy, of salt lakes. If corrected data are availabe, it may be possible to correlate TM data with laboratory spectral data for mineral species and identify mineralogical zonation within the lakes.

The techniques developed for the Lake Victoria region were tested in a second area at Magenta Hill, north of Balranald, to assess the general applicability in other areas of the Murray Basin. LANDSAT TM data for this area were recorded on 26 August, 1986. The area has well developed ancient lake and lunette complexes, but no currently active seepage zones. Soil salinities are very high, and salt efflorescences in the soil are common after rain. The area is one where rising groundwater levels may lead to reactivation of previous seepage zones, and as such is considered to be a high risk area for the development of dryland salinity. Landuse is mainly grazing of sheep. Vegetation is dominated by various types of saltbush in the playa floors, with mallee dominant in other areas.

Using the same composite image as in the original study (1+4+5) gives excellent delineation of geomorphic features, vegetation and landuse patterns. There was not, however, direct correspondence between the image generated for Magenta Hill and those for the Lake Victoria region, using the same bands. Since the two LANDSAT scenes were collected on different days, there is a difference in overall brightness of the scenes, despite similarities in terrain. This may be due to generally wetter conditions at the time the Magenta Hill scene was recorded, causing a decrease in the overall reflectivity. Thus care must be exercised in interpreation of images taken at different times and over different areas.

This exercise has demonstrated that the basic uncorrected LANDSAT TM data are a valuable tool for mapping of presently active salinas and ancient salt lakes. Used in conjunction with field checking, LANDSAT images may be useful in detecting areas at risk from rising saline groundwaters. Zonations within active salinas can be distinguished using composite images, but the ephemeral nature of features on the surface of salinas must be taken into account when attempting to assess the significance of these zones. Detailed delineation of salina mineral zonation was not possible using uncorrected TM data, but may be possible using data corrected for atmospheric and instrumental effects.

ACKNOWLEDGEMENTS

The assistance of W.R. Evans and C.J. Simpson, BMR, is gratefully acknowledged.

DIFFUSE DISCHARGE/RECHARGE UNDER NATIVE VEGETATION IN THE WESTERN MURRAY BASIN

I.D. Jolly, G.R. Walker and P.G. Cook
CSIRO Division of Water Resources
Private Bag 2, Glen Osmond, S.A., 5064.

INTRODUCTION

Previous studies of groundwater recharge in the western Murray Basin have provided estimates of diffuse recharge under native vegetation of the order 0.05-0.20 mm/yr (Allison & Hughes, 1983; Allison & others, 1985; Leaney & Allison, 1986). These rates were derived from point estimates using unsaturated zone profiles of environmental chloride, and from measurements of carbon-14 activity in the unconfined Murray Group aquifer. Following clearing of native vegetation, recharge is enhanced several orders of magnitude with new rates in the range 3-40 mm/yr (Allison & Hughes, 1983; Allison & others, 1985; Jolly & Cook, unpublished data).

Recent work in this part of the Basin has indicated that in some situations there can be a net discharge under native vegetation rather than recharge. This is thought to arise from the ability of the deep rooted (>20 m) mallee (*Eucalyptus* spp.) vegetation to extract water from deep (30-50 m) water tables. This hypothesis is supported in part by the work in Western Australia of Nulsen & others (1986), who recorded the existence of mallee roots at 28 m depth and concluded 'that the mallees are adapted to the semi-arid environment by virtue of their ability to store water deep in the soil profile for use during dry summer months'. Although the fluxes involved are probably no greater than 0.05 mm/yr, this phenomena serves to highlight the importance of localized recharge under native vegetation in this part of the Basin (refer Cook & others, this volume).

DISCHARGE ESTIMATION

Estimates of diffuse discharge were calculated from the chloride profiles of a number of deep (25-35 m) cores drilled to (or close to) the water table near Borrika (Latitude 35° 2' S, Longitude 140° 3' E) and Kulkami (Latitude 35° 9' S, Longitude 140° 17' E) in the central Western Murray Basin. The chloride profiles are of the type described by Johnston & others (1980) as 'bulge' form profiles. Typically the chloride concentrations are less than 500 mg/L in the top 2 m of the soil surface, and increase monotonically to approximately 15,000 mg/L at about 5 m. From 5 m to approximately 20 m they remain constant at around 15,000 mg/L, and then decrease slowly to about 2,000-4,000 mg/L at the bottom of the profile. Figure 1 shows one such chloride profile along with its associated matric suction profile. Although the matric suction data are not used for the discharge estimation, they provide supporting evidence of this phenomena.

Groundwater discharge in the form of evaporation from bare soil surfaces has been estimated using chloride profiles (Allison & Barnes, 1985). Although we are estimating groundwater discharge by plant transpiration, the principles remain the same, and are based on the one dimensional convection-diffusion equation for solute transport:

$$q_s = -D_s \, \partial c/\partial z + c q_w \qquad (1)$$

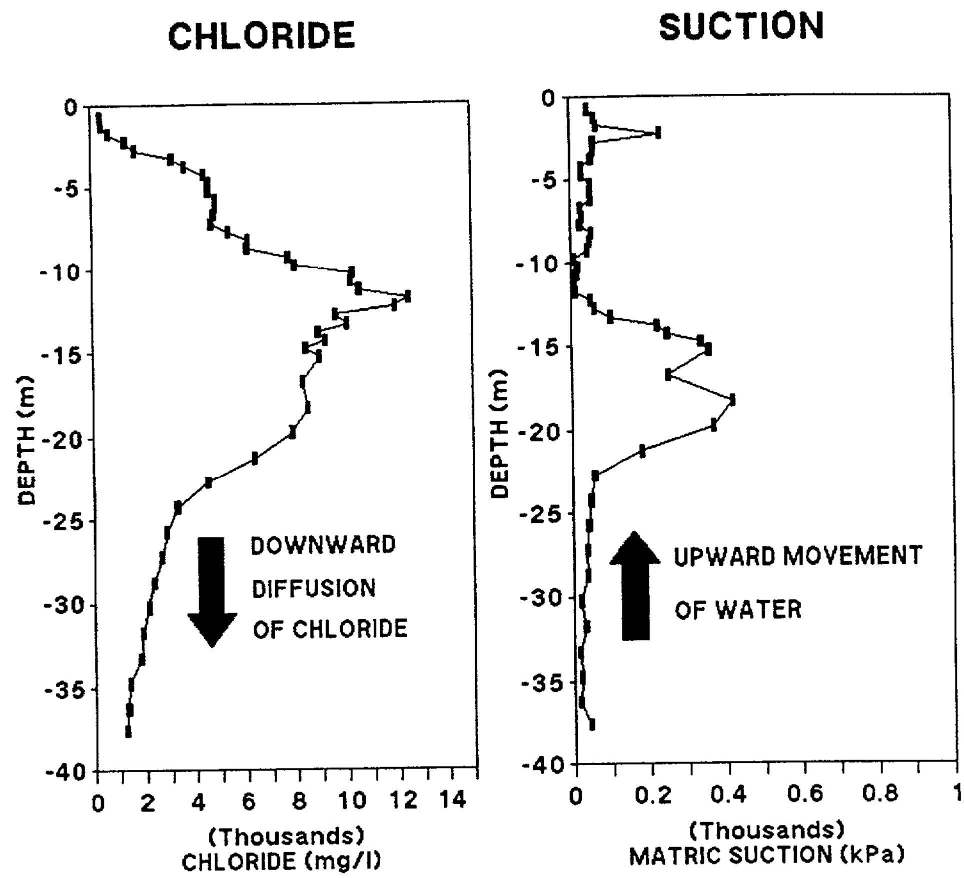

FIGURE 1 : Chloride and matric suction profiles for a hole near Kulkami (KUL07). Note that although it is located in a paddock cleared 6 years, the bottom 20 metres is thought to represent pre-clearing conditions.

where q_s is the solute flux; D_s is the effective solute diffusion coefficient in the soil water; q_w is the soil water flux; c is the solute concentration in the soil water; and z is depth (positive downwards). If steady state conditions are assumed (a reasonable assumption given the age of the mallee vegetation and the absence of significant climatic change in the last few thousand years) then $\partial q_s/\partial z = 0$ (i.e. the solute flux is constant with depth) and equation (1) can be solved for c subject to constant boundary conditions. As we are only interested in the section of the chloride profile below the root zone (where the chloride concentrations begin to decrease from their maximum of approximately 15,000 mg/L), the upper boundary is taken to be the bottom of the 'bulge' section, and the bottom of the profile (usually the water table) is taken as the lower boundary.

The solution of equation (1) has the following form :

$$c = (c_0 - c_1)\exp(-q_w/D_s\, z) + c_1 \qquad (2)$$

where c_0 is the chloride concentration in the soil water at the upper boundary, and c_1 is the chloride concentration at the lower boundary. A plot of ln $|c - c_1|$ vs z has $-q_w/D_s$ as its slope thus enabling calculation of the soil water flux q.

Equation (2) was used to estimate the discharge flux as described above. The appropriate impedence factors used to determine the effective diffusion coefficient (D_s) were derived from an empirical relationship (Clarke & Barley, 1968), and the diffusion coefficient (D_0) used was that of NaCl at 16°C. The analyses which were carried out indicate that the water flux q_w is of the order 0.02-0.05 mm/yr and directed upwards.

CONCLUSIONS

The results reported here are of a preliminary nature and subject to a number of assumptions. The most important of these are: 1) that the profiles are in steady state; 2) that the soil water flux is one dimensional and vertical; and 3) that the chloride diffusion coefficient is constant with depth. It should also be noted that not all of the profiles examined exhibited the behaviour described here. Future work will involve carrying out the above analyses with the chloride diffusion coefficient varying down the profile, and considering the case of non-steady state conditions.

Nevertheless, the results obtained to date are of considerable interest as they highlight the importance of localized recharge under native vegetation in this portion of the Basin. Although these findings raise questions as to the mechanisms of recharge under native vegetation, the aquifer scale estimates of recharge reported by Leaney & Allison (1986) are still considered to be valid. In any case the most important aspect of groundwater recharge in this portion of the Basin is that it has increased several orders of magnitude since European settlement, resulting in a potential salinity problem of considerable magnitude.

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IMPACT OF SALINE WATER DISCHARGE ON SOIL DEGRADATION AND EROSION

R.S. Junor

Soil Conservation Service of N.S.W.

22 Pitt Street, Sydney

The nature, extent, cause and effects of dryland salinisation are described as they result from the discharge of saline seepage in non-irrigated areas in the Murray-Darling Basin. Whilst such salinisation is seen primarily as a precursor to erosion, its role as a separate form of soil degradation and its relationship to land use problems in irrigation areas and to water quality issues are viewed as current concerns with much wider environmental ramifications.

In New South Wales dryland salinity of this type has to date not been considered serious, compared with the situation in some other states. However, concern is spreading, and modern methods of detection and mapping are indicating that the potential exists for this form of land degradation to become very much more extensive, particularly in southern parts of the state. The implications of this for the Murray-Darling Basin, especially with respect to land use, watertables, runoff and water supplies generally are discussed.

Whilst control methods are reasonably well understood, prevention of future degradation of the soil resource is an area requiring long term research and development of predictive technology combined with land use policies that may require some radical changes in concepts, attitudes and current land use practices.

Both the community and Governments need to 'grasp these nettles' in an atmosphere of co-operation, recognising the impacts that these changes will have on individuals and their needs and looking forward to the cumulative benefits that will be achieved for the whole community.

Today, an integrated approach to soil, water and vegetation management strongly supported by land use planning at all levels requires priority actions if salinity of the Basin and its land and water resources are not to become the environmental disaster of the third century of settlement in Australia.

MODELLING IN THE MURRAY BASIN: AN OVERVIEW

F. Kalf
Australian Groundwater Consultants Pty Ltd
273 Alfred St., North Sydney, N.S.W. 2060

Modelling of aquifer systems has now become commonplace in groundwater hydrology. Modelling is both a science and an art. Analytical solutions remain a useful technique but finite difference or finite element methods are generally used because of their greater flexibility. In the Murray Basin, models have been constructed of the entire basin and also on a regional and site specific scale. Most models so far reported are deterministic; isothermal; non-density dependent; two-dimensional; quasi or fully three dimensional. All deal with simulating groundwater flow with only 2 reportedly using, in addition, a solute transport simulator and 1 a surface water process model. No simulations have so far been reported that use a stochastic approach. In view of the data uncertainties that still exist in the basin such an approach may be desirable in some circumstances to quantify resulting uncertainties in the generated results. These results could form important input to decision-making associated with the salinity management of the Basin.

TOWARDS A BETTER UNDERSTANDING OF THE GROUNDWATER FLOW AND CHEMISTRY ON THE MALLEE/RIVERINE PLAIN BOUNDARY IN THE CENTRAL MURRAY BASIN

J.R. Kellett

Hydrogeology Research Group, Division of Continental Geology

Bureau of Mineral Resources, Geology and Geophysics

GPO Box 378, Canberra City ACT 2601

The Pooncarie and Balranald 1:250,000 sheets straddle the NSW section of the western Riverine Plain and mallee country in the central area of the Murray Basin. Prior to 1986 little was known of the hydrogeology of the sheets; data consisted of 6 boreholes fully penetrating the Tertiary sequence, 22 seismic traverses with only two drillhole calibration points and approximately 130 shallow stock bores, about half with driller's logs. In 1986, eight sites were drilled on the Pooncarie sheet under a joint venture between BMR and DWR; nine sites were drilled on the Balranald sheet during 1987.

All holes were drilled to basement and a short core was cut in the pre-Tertiary rock. Two or three piezometers were installed at various depths at each site. The drilling program provided control for the seismic data and enabled construction of structure contours for the pre-Tertiary surface, Tertiary aquifers, flownets and yield - salinity maps for each of the major aquifers on the Pooncarie and Balranald sheets.

(a) The Pooncarie Sheet

The dominant control on the hydrogeology of the Tertiary aquifers is the Ivanhoe Block, a composite structure consisting of two northeasterly trending basement ridges separated by a saddle. The western limb of the Ivanhoe Block, the Neckarboo Ridge, extends southwesterly towards the Murray River and partitions the coarse-grained Tertiary sediments of the Darling River provenance in the west from the much finer-grained sediments of the Lachlan-Willandra provenance in the east. The easterly limb of the Ivanhoe Block, the Iona Ridge, sharply delineates the boundary between the western Riverine Plain and mallee country. There is a one-to-one correspondence between both limbs of the Ivanhoe Block and the elevated topography of the mallee country and both ridges appear to be fault-bounded with throws of up to 150 m.

The Willandra Trough occupies the intermediate ridge-basement depression and its aquifers are hydraulically connected to those of the Ivanhoe Trough in the northeast. Devonian sandstone outcrops of the Manfred Range and the prominent ridges to the northwest of Lake Mulurulu define the Darnick High, an uplifted and tilted block on the northern edge of the Pooncarie sheet. Uplift on the Darnick High postdates tectonism associated with the Neckarboo and Iona Ridges.

The top of the Renmark Group occurs at elevations up to 40m asl on the basement ridges and a mean elevation at sea level in the infrabasin troughs. Channels filled with Calivil Formation sediments (and possibly younger sands) in the north and Geera Clay in the south are incised into the Renmark Group in the Willandra and Balranald Troughs at depths to -60m asl. Similarly, the Pliocene aquifers are draped over the basement highs and have undergone Quaternary channelling in the troughs. Relict beach ridges of Parilla Sands outcrop at elevations up to 100m asl on the southern section of the Neckarboo Ridge.

Geophysical logging and sampling of the drillholes revealed significant downhole variation in groundwater salinities in the Renmark Group aquifers, and for this reason the Renmark Group has been subdivided into three units; there is a strong correlation between the subdivision based on groundwater chemistry/lithology and palynological zonations (Truswell,1987). To the east of the Neckarboo Ridge the lower Renmark Group aquifers always contain the best quality waters and the upper Renmark the worst.

The lower Renmark Group is restricted to the infrabasin troughs, and the bounding basement escarpments constrain flow in these aquifers to a direction sub-parallel to the trough axes. In the Willandra Trough, flow in the lower Renmark Group aquifers is impeded by aquifer thinning below Lake Garnpung, and this induces upwards discharge into the overlying middle and upper Renmark Group sediments. There is also a pronounced lower Renmark discharge zone around Hatfield in the Balranald Trough and this may well be related to buried granitic basement pinnacles.

Discharge zones in the middle and upper Renmark Group aquifers occur near the boundary of the Geera Clay and these areas coincide with pronounced salinity gradients in these aquifers. The upper Renmark Group comprise the oldest Tertiary sediments on the Darnick High.

The Pliocene and Quaternary aquifers are generally unconfined on the basement ridges and are confined beneath the gypsum playas of the infrabasin troughs; in these environments groundwater salinities of the order of 35,000 to 50,000 mg/L TDS have been produced from evaporative concentration and refluxing.

(b) The Balranald Sheet

Drilling on the Balranald sheet has shown that the southerly Neckarboo Ridge splays into two major basement ridges; one ridge trends to the southwest and intersects the Murray River at Lambert Island, and the other ridge strikes southeast and appears to represent the northerly extension of the Tyrrell Fault Block. The Willandra Trough follows a similar arcuate trend and is probably hydraulically connected to the aquifers of the Tyrrell Sub-Basin. The Iona Ridge becomes subdued to the south of Wintong and links with a granitic basement high occupying the Murray-Murrumbidgee River interfluve southwest of Balranald.

The western two thirds of the Balranald sheet is underlain by the Geera Clay – a marine equivalent unit of the middle Renmark Group sediments. The Geera Clay aquitard forms a significant permeability barrier to groundwater throughflow in the entire Renmark Group system and induces artesian conditions in peripheral lower and middle Renmark Group aquifers – flowing artesian bores were constructed at Perekerton and Kyalite during the joint BMR - DWR drilling program.

The drillhole in the Great Cumbung Swamp (at the terminus of the Lachlan River) struck basement at -361 m, showing that this area is the depocentre of the Balranald Trough.

(c) Numerical Simulation

The hydrogeological investigations on the Pooncarie and Balranald sheets have permitted boundary conditions to be specified for a deterministic model (MODFLOW) of the hydrodynamics of the Tertiary aquifers in the central Murray Basin. The model dimensions are 25 x 35 x 5 cells, each (10 x 10) km, and the area covered includes the Ivanhoe Block, western Riverine Plain and Hillston Fan. The active cells are bounded by the Neckarboo Ridge in the west, by Devonian outcrop in the north and by the Lachlan - Murrumbidgee - Murray Rivers in the south. All of these boundaries are true dividing streamlines for groundwater flow. In addition, the model employs 73 interactive river cells.

Discretization problems and preliminary results are discussed.

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GEOLOGICALLY INDUCED DRYLAND SALINITY AT YELARBON, BORDER RIVERS AREA, NEW SOUTH WALES QUEENSLAND.

Michael J. Knight
Centre for Groundwater Management and Hydrogeology,
University of N.S.W., Kensington, 2033, NSW.

Belinda J. Saunders
Groundwater Technology Inc. Bankstown, N.S.W.

Michael Williams
Water Resources Department, Sydney, N.S.W.

John Hillier
Queensland Water Resources Commission, Brisbane, QLD.

This paper discusses the origin of a large salinized land scald ("*Yelarbon salinity scald*") located in the Murray-Darling River Basin head waters near Yelarbon beside the Dumaresq River that defines the border between Queensland and New South Wales. Fig.1.

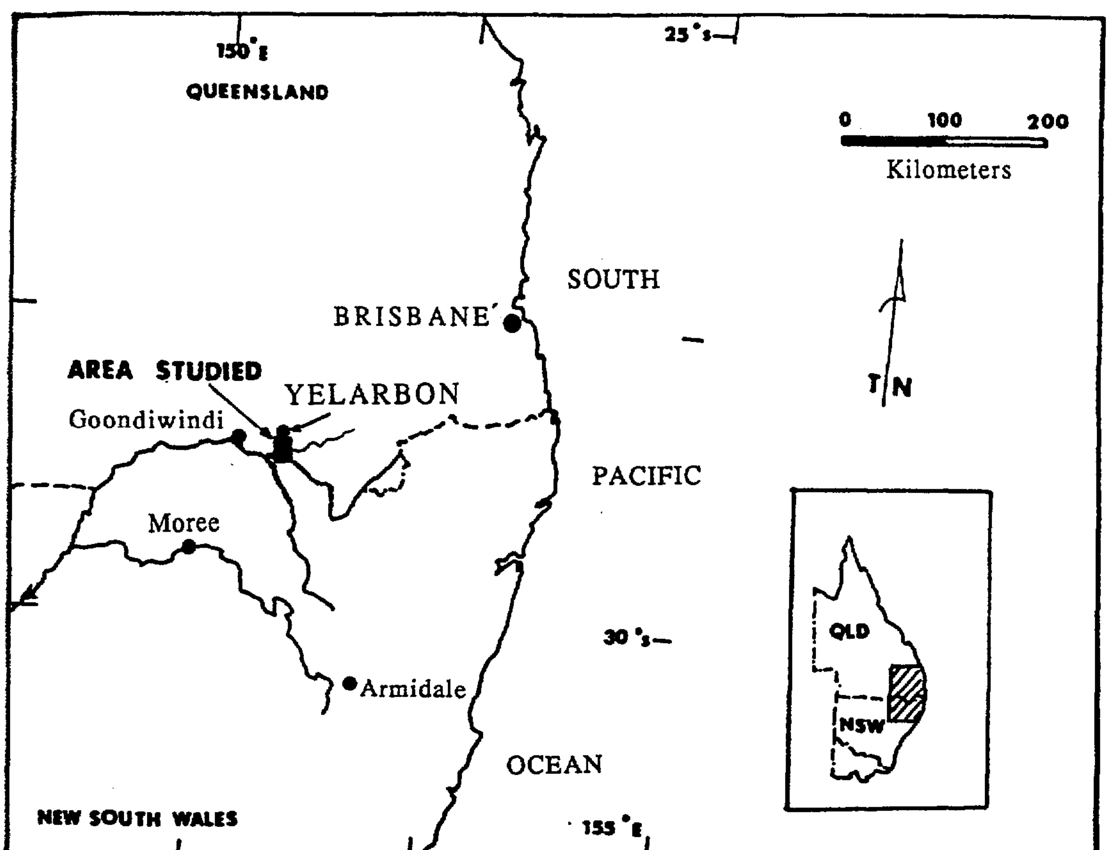

Fig. 1 Location of the Yelarbon Salinity Scald on the border of Queensland and New South Wales.

The scald is a severely eroded land surface that is 47.75 km^2 in area and contains saline and alkaline hard setting duplex soils (DY 2•43), Northcote (1966), developed on a Pleistocene - Recent fluvial parent material. The soils are also called solodized solonetz (Great Soil Group name) because they have columnar structure and high exchangeable sodium in their clay B horizons, Fig. 2.

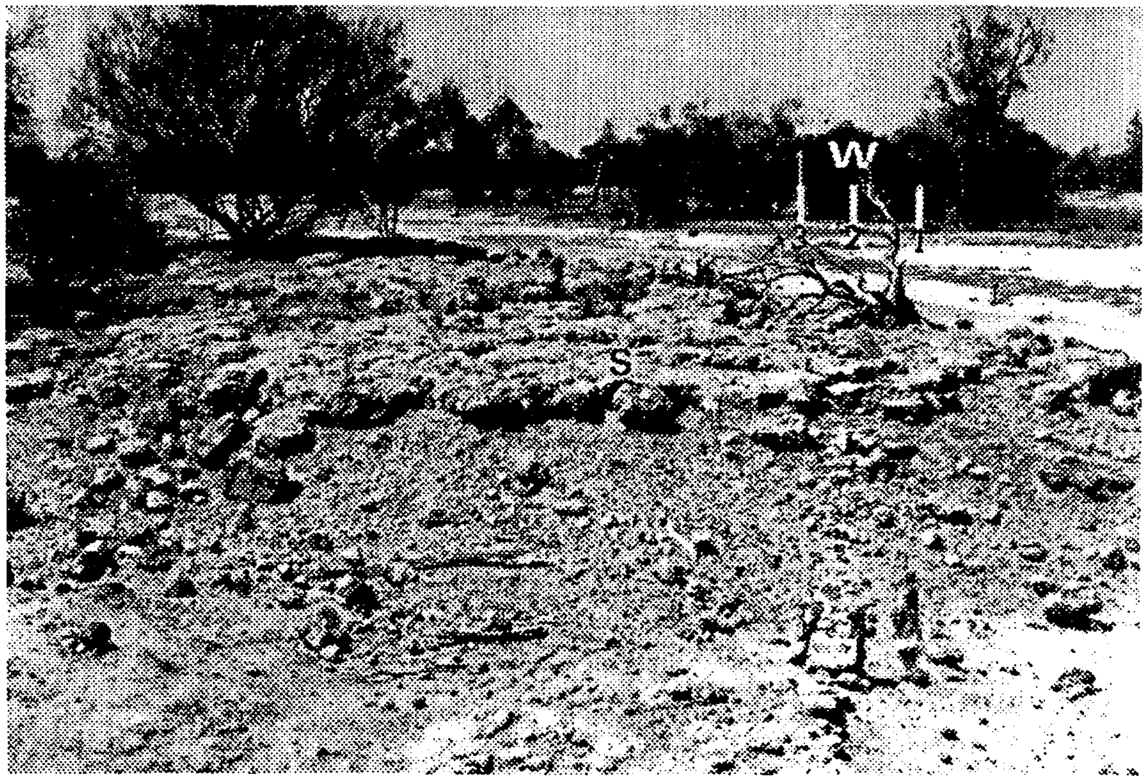

Figure 2 Eroded Yelarbon salinity scald, 100m south of Keetah Bridge, NSW showing: (S) exhumed columnar structure of the solodized solonetz B horizon and (W): Department of Water Resources Bore 36697; (1): 8-14m (S.W.L.- 7m); (2): 52-58M (S.W.L. - 5m); and (3): (74-80m, flowing).

The time period for the saline soil pedogenesis is estimated to be greater than would be available for land clearing. Soil erosion has exposed the bleached A_2 horizon and salt encrustation occurs on the land surface. These effects combine to produce a very light tone that is easily seen on Landsat MSS scene 096-80 taken on 29/9/81 and on panchromatic air photos. In plan the scald is subrectangular with an east-west width of 5.5km, Fig. 3.

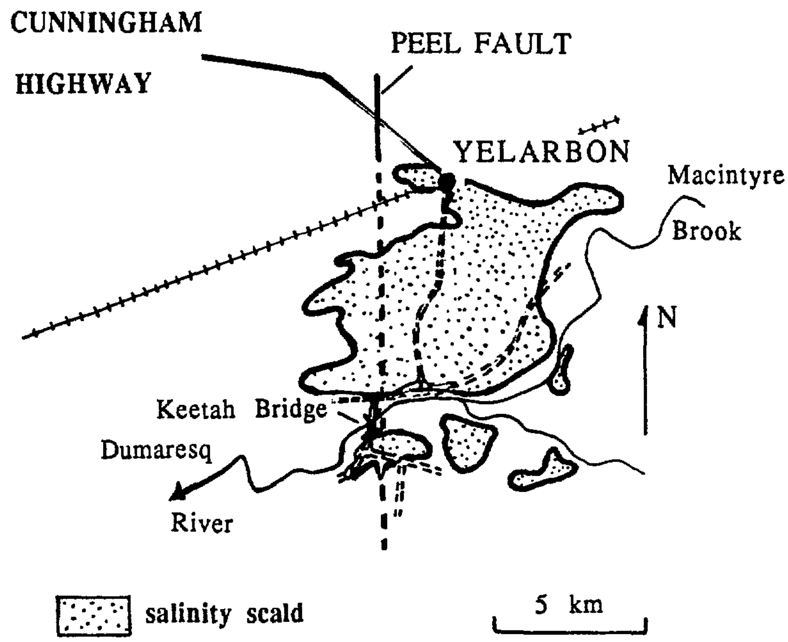

Figure 3. Map of Yelarbon salinity scald.

The scald is located on an extension of the Peel Fault. Evidence for the fault includes; displacement of alluvium, (Williams & others, 1987); a 1.5m fault line scarp on the Cunningham Highway 4.5km north-west of Yelarbon; a linear magnetic intensity anomaly below the scald that indicates the fault is 3230m deep (Saunders, 1987) and involves the basement rocks (Surat Basin and New England Orogen), drainage pattern defeat and reversal that shows recent fault activity. The fault is also in the position predicted by Korsch and Harrington (1987) from the regional tectonic considerations.

The hydraulic gradient of the water table steepens (downwards by 200%) across the fault which is probably caused by aquifer displacement. There are flowing artesian pressure groundwaters at depth below the fault (slotted section at 74-80m in Bore 36697/3 has a standing water level +0.2m). It is proposed that these deeper high pressure zones are linked to the upper aquifers causing high salinity (NaCl type) waters of the uppermost alluvial aquifer to diffuse to the groundsurface giving rise to the scald.

A regional assessment of groundwater chemistries from bores separated into alluvial and basement aquifers has been made using trend surface computer techniques.

There are residual third order trend (higher than regional trend) anomalies for chloride and Sodium Adsorption Ratio (SAR)* in the alluvial aquifers (Saunders, 1974) that support the concept of vertical fractionation of Cl^-, Na^+ Ca^{2+}, Mg^{2+} during the diffusion of groundwaters up the fault to result in sodium clay soils at the ground surface and chloride rich groundwaters.

$$*SAR = \sqrt{\frac{Na^+}{(Mg^{2+} + Ca^{2+})/2}}$$ with concentrations in meq/l

There are no such anomilies in the deeper basement rock aquifers. The groundwater - Peel Fault model proposed for causing the Yelarbon salinity scald is illustrated schematically in Fig. 4. There is no geological support for a saline lake alternative model.

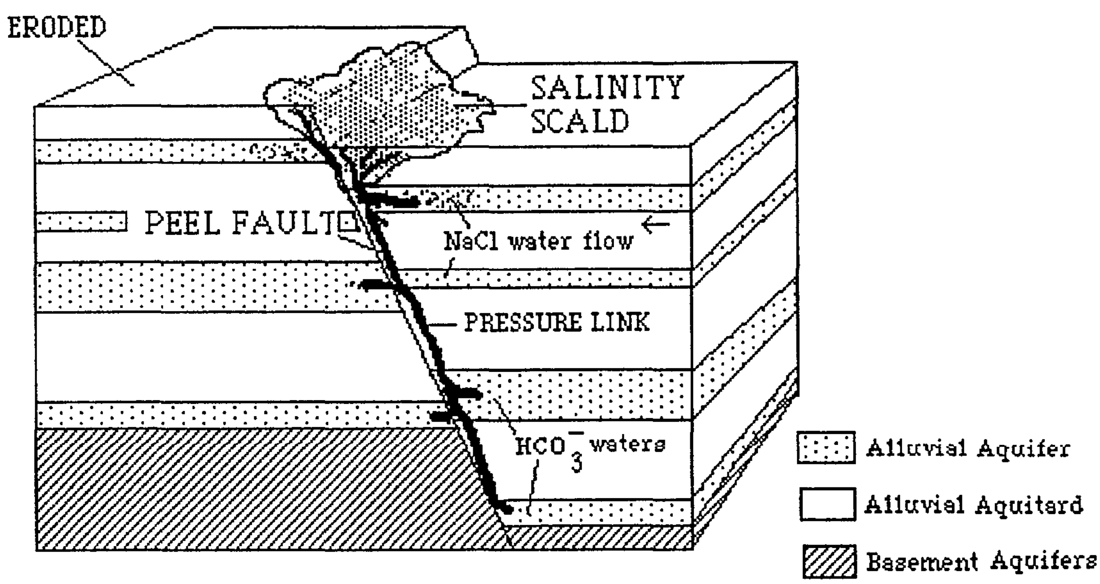

Figure 4. Schematic model showing the relations between groundwater, the Peel Fault and the salinity scald near Yelarbon.

ACKNOWLEDGEMENTS

Mrs. B. Collin typed the text and Mr. Glen Atkinson of the Soil Conservation Service is thanked for assistance with Landsat image and soil studies. Dr. Paul Lennox commented on the regional tectronic patterns of the area.

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CONJUNCTIVE USE OF SURFACE WATER AND GROUNDWATER IN THE MURRAY BASIN: SCOPE AND PROBLEMS

R.C. Lakey
Victorian Department of Water Resources
35 Spring Street, Melbourne, 3000.
R.M. Williams
N.S.W. Department of Water Resources

Introduction

The Murray Basin is a geological structure which occupies an area of 300,000 square kilometres in south-western new South Wales, north-western Victoria and the eastern part of South Australia. The Basin contains a sequence of sedimentary deposits of Tertiary and Quaternary age with a maximum thickness of some 600m. Many of the formations within the sequence are aquifers and they contain groundwaters of widely varying salinity. The margins of the Basin are abutted by fractured Palaeozoic rocks.

There has been increasing interest in the groundwater resources of the Basin during recent years, partly because of their potential for development and use, but also because of their complex inter-relationships with surface waters and the consequent implications for surface water salinity. This paper addresses the potential for conjunctive usage of surface water and groundwater to optimise the long-term management of land and water resources within the basin.

Watertables have risen over recent years especially in the Riverine Plain regions of New South Wales and Victoria and are now causing problems of waterlogging and salinisation particularly in irrigation areas and topographic depressions. In addition, saline groundwater discharge is causing increases in stream salinity and land salinisation throughout much of the basin.

In conjunction with other land management strategies to lower recharge rates, pumping of both low and high salinity groundwater for distribution to existing users, dilution or disposal, is a potential method for the partial control of rising water tables and associated land management problems.

Groundwater

There are huge reserves of groundwater in the Basin, but it is not uniformly distributed. While topography and climate influence how and where groundwater occurs, geology is the major controlling factor affecting groundwater storage, yield, quality and replenishment. Land management practices in particular, irrigation, clearing, cropping and grazing practices, are also important and have significantly altered the natural (pre European settlement) hydrologic equilibrium giving rise to a widespread increase in recharge.

Reserves of low salinity groundwater in terrestrial deposits located in the east and south eastern areas of the basin are being developed for large scale irrigation to an increasing degree. Significant groundwater development has also occurred in the south western part of the basin where extensive marine aquifers are being developed for irrigation.

Surface Water

The Murray Darling River System is the largest in Australia. The Basin comprises three rivers systems:

* the Murray System, draining parts of southern New South Wales and the northern half of Victoria;
* the Murrumbidgee System, draining central and southern New South Wales; and
* the Darling System, draining the northern part of the basin and extending north outside the geological basin.

The Basin's rivers are mainly fed by run-off from the inland slopes of the Great Dividing Range which forms the eastern and southern boundaries of the Basin. The river flows not only vary greatly across the Basin but also vary significantly from year to year.

The annual average run-off per unit area over the Basin is only about 3% of average annual rainfall. In many areas much of the run-off occurs as occasional floods and as such it is not economic or practical to construct storages to utilise these water resources.

The average annual discharge and variability of the Murray increases as it flows westward to the sea. The total water reaching the Murray in an average year is about 12,000 GL although this may vary from 2,500 GL to 40,000 GL.

Seasonal distribution of rainfall and run-off across the basin is also quite marked, with a pronounced summer concentration in the north and a winter/spring peak in the south.

A consequence of the naturally high variability of flows is that a large number of storages have been built to regulate river flows and increase the security of supply for off-stream users. Large dams have been constructed in the headwaters of the major river systems and numerous locks and weirs control river levels in the middle and lower reaches of most rivers.

Present Usage

Irrigation is the dominant water use. The extensive alluvial flood plains of the Murray River and its tributaries have enabled the development of the most important irrigation districts in Australia.

Water use in the Basin for 1983/84, a period of generally below average consumption was 9340 GL. Of the water used 89% went to irrigation, 4.4% for urban use (of which almost 20% was used in Adelaide) and 6.5% for stock and domestic needs. Only about 6% of the water used was from groundwater sources.

OVERVIEW OF GROUNDWATER PROBLEMS OF THE MURRAY BASIN

C.R. Lawrence
Victorian Department of Water Resources

This paper identifies a number of technical problems within the area of groundwater management of the Murray Basin, as well as surface water and land use management where groundwater is a major component. Further the organisational constraints to efficiently solving the existing problems and planning to minimize future problems are also aired.

Based on earlier investigations the Murray groundwater basin may be defined by the Tertiary sedimentary basin covering approximately 300,000 km^2. It acts as a semi-closed groundwater basin from which there is limited underflow to the sea in the far south east and outflow to the lower reaches of the Murray River. The Murray groundwater basin lies within the southern part of the far more extensive Murray-Darling surface drainage basin.

The basin is characterized by hydrogeologic conditions of:

* saline groundwater throughout much of the central part of the basin with better quality water limited to the periphery and the limestone aquifer in the south-west.
* flat topography, a semi-arid climate, combined with the closed nature of the basin result in broad saline discharge zones on the central part of the basin, and potential for the creation of other similar discharge zones.

Prior to the clearing and development of the Murray Basin in the late 19th century, one can surmize that the groundwater system was in steady-state with respect to the water budget and almost steady state with respect to the salt budget. The net effect of man's intervention by clearing, surface water irrigation and substantial groundwater development has been for the water table to rise, adversely affecting the land and streams, through salt accessions.

For groundwater itself two problem areas are emerging, one is degradation of quality through salt-build up, and the other is localized depletion of the resource.

There are signs that several mechanisms are contributing to the degradation of groundwater quality. The main mechanism is that caused by concentrated return water from irrigation, sometimes with the addition of NO_3 and PO_4, reaching the water table. The shallow alluvial aquifer at Shepparton (Vic) is showing signs of salt-build up from irrigation with a channel water - groundwater blend. This is also the case in the limestone aquifer in Padthaway and Stirling (S.A.) where groundwater is used for irrigation. In both areas increases of up to 100 mg/L/yr have been recorded.

Areas prone to this type of degradation are where the applied water is of poor quality combined with recycling, the aquifer is unconfined to semi-confined, there is low natural recharge and low lateral groundwater movement.

Unabated this can cause the groundwater to become unusable. Under the South Australia-Victoria Groundwater Border Agreement for the limestone aquifer near the southern part of the basin controls on the extraction rate with respect to amount of lateral groundwater movement have been introduced.

Other management options applicable to this situation are to use the best quality groundwater at a given location, regardless of depth, and irrigate downgradient of the pumped bore instead of near the site of the bore.

Another mechanism is migration of saline groundwater towards highly stressed aquifers in a basin where there is considerable variation in groundwater quality both laterally and vertically through the basin. Examples of this type of degradation are mainly limited at this stage to individual bores tapping the deep alluvial aquifer to the east of Rochester and the limestone aquifer to the north of Murrayville. Areas under threat in the long-term are the eastern margin of the limestone aquifer and the down-gradient part of the deep alluvial aquifers on the eastern part of the basin.

Other situations which can lead to degradation of groundwater quality are from leakage of evapotransporation ponds (e.g. Wakool), injection bores (e.g. Waikerie), waste disposal sites, and concentration of salts through evaporation over areas of shallow water tables (e.g. irrigation districts and the valleys of the Darling & Murray Rivers).

Despite the overall effect of the groundwater store of Murray Basin continuing to increase there are situations where there has been or is localized and temporary depletion of the resource caused by intense extraction of groundwater.

Areas where this has occurred are within clusters of irrigation and urban bores, causing a regional drawdown in the potentiometric surface. In the Nhill district (Vic) there is a repetitive seasonal decline of up to 10 m in the potentiometric surface of the Limestone aquifer. Also in the Rochester district (Vic) there was a regional drawdown in the potentiometric surface of up to 20m during the 1982/83 drought caused by doubling the number of irrigation bores to more than 60. In both cases controls have been introduced on the spatial distribution of irrigation bores.

Also at the margin of the basin there is the less serious problem of the risk of reduced recharge from forest plantations affecting supplies (e.g.. Merino, Vic).

In addition to the above-mentioned problems more directly associated with groundwater development there are those which arise from the more general problem of ineffective integration of surface water and groundwater in decision making. For example there are what appear to be non-optimal choices of surface water in preference to groundwater at Tullakool (NSW) and Yarrawonga - Cobram (Vic). Also for design and operation of the components of surface water schemes embracing weirs, lochs, channels, holding basins, and drainage schemes could well have varied given the knowledge on the implications for the groundwater system and in turn the surface water and land.

For future decision making this type of problem could be minimized by comprehensive and sytematic analysis combined with organisational adjustment. The recent establishment of the Murray-Darling Basin Ministerial Council is a crucial step towards that end.

OPTIONS FOR SALINITY MANAGEMENT IN IRRIGATION AREAS

D.G.Leslie
Dwyer Leslie Pty Ltd
85 Lowanna St., Braddon, A.C.T.

1. Introduction

I have taken the opportunity of making a minor change in the title of this paper from 'Options for Land Management in Irrigation' to 'Options for Salinity Management in Irrigation Areas' as the former appears to refer to such a narrow – and not very promising – part of the spectrum of possible management options.

The question of management of the land and water resources of the Murray Basin has exercised the minds of people connected with it for more than 50 years. The pace of studies, investigations and analyses has intensified in the last 20 years and there is now available a vast library of published and unpublished work. The following is merely a glimpse of part of it.

2. The Cause of the Problem

As most of those attending the conference or reading the papers prior to this one will now know, to use the words of the Conferences brochure, 'Salinity is ......Australia's most critical environmental problem'. The aspect of it being dealt with here is high and saline watertables in irrigation areas caused by a change in the hydrologic cycle following the advent of European farming some 150 years ago. Unfortunately the corollary does not apply. That is, removal of European farming and restoration of prior conditions, whatever that means, will not, repeat not, reverse the process – at least in a time scale of interest to us, our children, or their children's children. The increases in pressures in the major aquifer systems occasioned by the change in the hydrologic cycle, to all intents and purposes, are irreversible except by pumping. The situation now is that the majority of areas have saturated sub-soils. Thus, the immediate cause of problems, the culprit so to speak, the major contributor to those damaging high watertables, is now rainfall rather than direct irrigation applications.

It has become very fashionable to call for treatment of the cause, rather than the symptoms, of the salinity problem. This leaves me somewhat mystified as I do not know of any physical or legislative means of controlling rainfall, attractive though that notion is. If such means, scientific or judicial, do exist I would be grateful to know about them.

3. Management Options Available

It follows from the above that the only means available in the short to medium term to completely deal with the salinity problem in irrigation areas is to treat the symptoms rather than the cause. That is, the objective is to control high watertables particularly where these are saline. The benefits of so doing can be postulated in economic, social and environmental terms. As such discussion will become far too complicated for presentation here, the simple surrogate of "productivity" or 'agricultural production' will be used for economic and social benefits. It also follows that there are only two basic sets of options available, namely:

– to prevent water getting into the watertable; or
– to remove water from the watertable.

In relation to these two basic sets of options it should immediately be made clear that the only part of the soil profile of interest is the top couple of metres (a little more or a little less depending upon whether we are interested in pasture areas, horticulture/viticulture areas, or forests). Therefore, is an understanding of the geology and hydrogeology more important than an understanding of the soil physics or agricultural practices? Perhaps some one else has provided the answer.

The benefits of reducing the rate of increase in pressure in the deep or shallow aquifer systems are:

- delay in the onset of surface waterlogging and salinisation;
- reduction in the volume of sub-surface water which may have to be removed; and
- reduction in productivity losses related to waterlogging.

The benefits of removing water from the watertables arise from both waterlogging and salinisation effects upon productivity.

The following sections of the paper describe the techniques available under each of the above main headings. The descriptions given arise from work done in the Riverine Plains region of Northern Victoria. They are also generally applicable to the Riverine Plains of NSW whilst the problem in the horticulture and viticulture areas of South Australia is a little different. Horticulture and viticulture occupy a very small proportion (less than 10%) of the Riverine Plains and hence most comment and discussion relates to pasture areas.

4. Watertable Accession Control at the Public Scale

Surface Drainage:

This is perhaps the most obvious method of removing both rainfall and any excess irrigation run-off. Standard forms of constructed surface drainage are expensive (usually more than $1000 per hectare served), have quite low productivity benefits, do not result in major reductions in accessions to the watertable and tend to mobilise salts to the detriment of downstream water users. None the less some form of surface drainage would appear to be essential to any management program not the least for its 'salt conduit' potential and its effect upon regional perceptions. The most economically attractive forms of surface drainage are likely to be the shallow forms such as improved natural drainage lines together with improved on farm drainage and re-use systems.

Reduction or Redistribution of Water Entitlements:

Given that only about one fourth to one third of total accessions are directly due to irrigation applications, even complete cessation of irrigation is unlikely to achieve a great deal.

Trees:

It may be possible for public scale tree planting schemes to control watertables in recharge areas but they are unlikely to do so in discharge areas. However, they are not the most efficient or cost effective means of achieving such control and in any event the discharge areas are the major problem.

5. Watertable Accession Control On-Farm.

There are a number of things which a farmer can do to reduce accessions to watertables and prevent waterlogging. These include:

- Land-forming and re-layout including within farm re-structuring.

- Improved on-farm drainage (usually included in re-structuring designs).
- Installation of re-use systems (again usually undertaken as part of re-structuring).
- Improved water use management. The largest improvement usually results from Government based administrative changes such as 'water on order' systems. Adoption of appropriate pricing policies are likely to have an even more marked effect.
- Groundwater pumping and re-use on-farm.
- Tree planting along laneways and in shelterbelts etc.

Extension services and incentives by way of cash grants or concessional loans are now available for these activities. The farmers' reasons for taking them up are usually short to medium term farm management/productivity/profitability reasons and unfortunately, even if universally adopted, they would still not have a great impact on watertables.

6. Sub-surface Drainage at the Public Scale

The most cost-efficient method of controlling high watertables and salinity in the Riverine Plains zones of NSW and Victoria is undoubtedly sub-surface drainage. There is an argument that it is the only effective means of control. However, it is not without its problems which include:

Methods other than groundwater pumping are probably excessively expensive (tile drainage for example) and hence, for both physical and economic reasons, sub surface drainage is likely to be restricted to areas with suitable aquifers.

The principle problem is the disposal of the resulting saline effluent – the subject of another conference paper.

Disposal of highly saline effluents is particularly difficult whence sub-surface drainage is usually further restricted to areas with aquifers of reasonable quality (perhaps not greater than about 5000 EC).

The experience of the Shepparton irrigation region in Northern Victoria (covering some 500,000 ha about half of which is irrigated) is that perhaps two thirds of the area likely to be at risk in the future can be reasonably readily protected by sub-surface drainage methods. The balance of the area at risk has high salinity aquifers or no aquifers and is thus much more difficult to protect.

7. Conclusion

A substantial proportion of land salinisation in irrigation areas of the Riverine Plains can be controlled by sub-surface drainage, the constraint being that salt disposal problems are kept within manageable limits. The principal technique is likely to be groundwater pumping from the shallow aquifer systems. Control is likely to be more efficient if combined with an appropriate (modest) level of surface drainage and basic on-farm layout and operational improvements.

The economic, social and environmental benefits of such protection programs are likely to exceed the costs.

Given that the total resources required to achieve this effective level of protection is likely to be equivalent to the cost of a new office for a few Federal politicians, then 'Australia's most critical environmental problem' is a small problem indeed.

HYDROGEOLOGICAL INVESTIGATIONS IN THE UPPER SOUTHEAST OF SOUTH AUSTRALIA

A.J. Love

S.A. Department of Mines and Energy, PO Box 151, Eastwood, S.A., 5063

F. Stadter

S.A. Department of Mines and Energy, PO Box 93, Naracoorte, S.A. 5271

INTRODUCTION

In 1984 a significant area of the Upper South East of South Australia (see locality plan) was proclaimed under the S.A. Water Resources Act to manage groundwater withdrawals in the region. This was considered necessary because

- there was a relatively high density of irrigation in parts of the area
- preliminary assessments of groundwater availability indicated that extraction had approached or possibly even exceeded replenishment in parts of the area
- there was evidence of groundwater quality deterioration in the western part of the region
- a rapid expansion in irrigation was evident (3840 ha in 1978 and 12 260 ha in 1984).

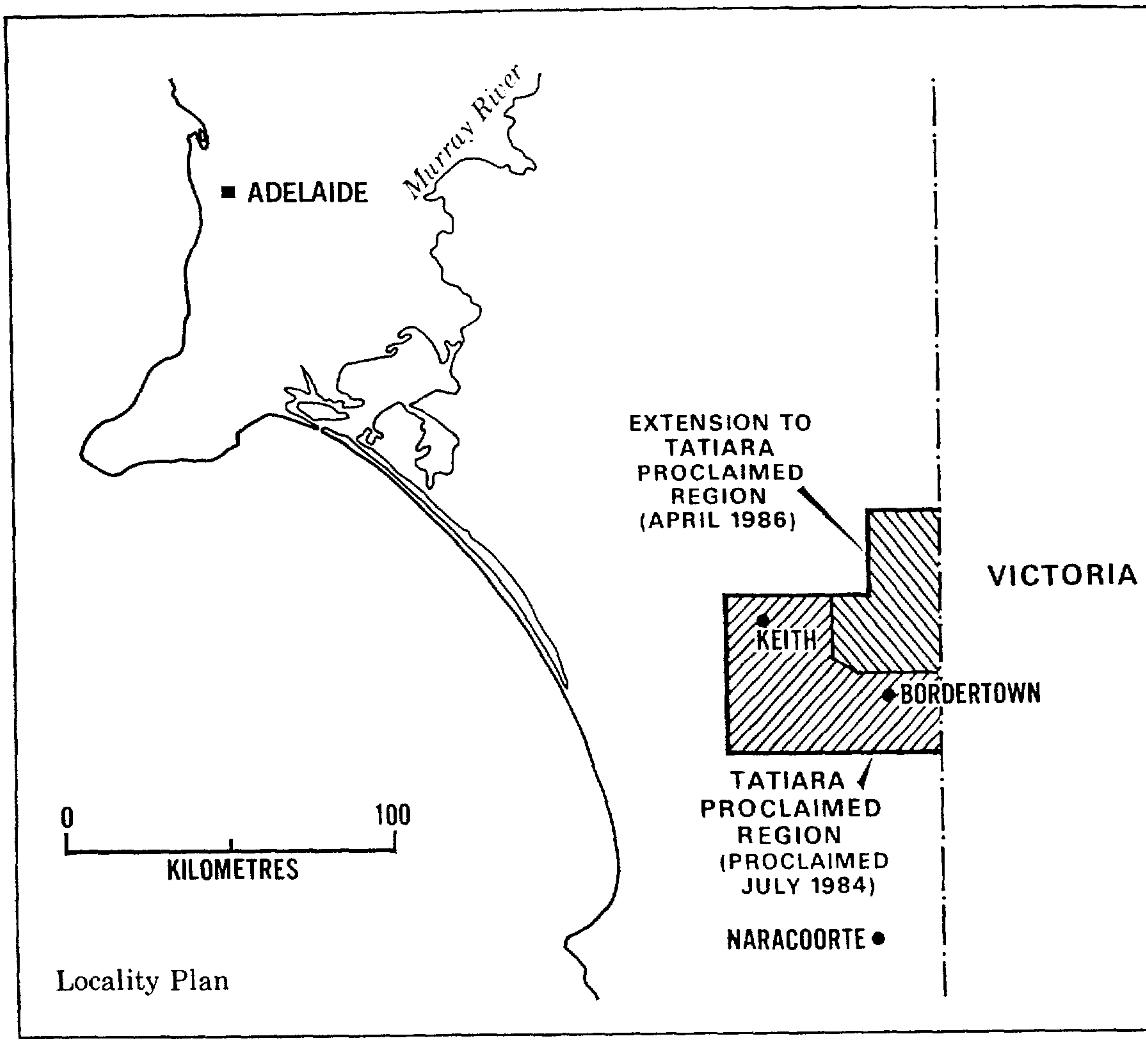
The gross value of the irrigated agricultural production from the region has been assessed to be approximately $25 million per year. Lucerne seed and pasture are the predominant irrigated crops, particularly in the western part of the region where the marginal quality of the groundwater precludes the irrigation of more salt sensitive crops. Elsewhere, the irrigated crops include small seeds, vegetables, oil seeds and cereals.

The initial groundwater management policy for the entire region was to limit additional irrigation development until a detailed assessment of sustainable groundwater use was undertaken. Hydrogeological investigations have included the establishment of groundwater monitoring networks for both potentiometric and salinity information, extensive drilling programmes, aquifer testing and quantification of groundwater recharge.

GEOLOGY

The study area is located on the southwest margin of the Murray Basin and contains sediments of both the Murray Basin and the Padthaway Ridge. The sedimentary pile generally increases in thickness away from the Padthaway Ridge towards the northeast and east. The lithologies in the central and eastern portion of the region are typical of the Murray Basin sequence with the deposition of the Renmark Beds, Buccleuch Beds, Ettrick Formation, Murray Group Limestones and Pliocene sands. In the west the Murray Group Limestones were truncated in the late Pleistocene and the sedimentary sequence is more typical of the Padthaway Ridge with the deposition of the Coomandook, Bridgewater and Padthaway Formations.

GROUNDWATER SYSTEMS



Locality Plan

Two major groundwater systems occur in the region, a confined aquifer an unconfined aquifer.

Confined aquifer

The confined aquifer system is a series of thin interbedded limestone and san aquifers separated by thin clay confining beds within the Renmark Beds and Buccleuc Beds. Groundwater inflow is from the southeast across the Victorian border. There is general increase in salinity from around 1 300 mg/L in the east up to about 3 000 mg/ in the west. Little use has been made of these groundwater resources because of th general availability of adequate supplies from the unconfined aquifer.

Unconfined aquifer

The unconfined aquifer is a multilithological system within units of the Tertia Murray Group Limestones and the Quaternary Padthaway, Bridgewater ar Coomandook Formations. Tertiary and Quaternary aquifers merge in the central we of the area where they are hydraulically interconnected. The depth to the water tab varies considerably throughout the region. To the east the water table occurs at depti of about 45 metres, while the western part of the area is characterized by a shallc water table generally less than 5 metres below ground level.

Groundwater movement is in a general west to northwest direction through tl region. There is considerable variation in hydraulic gradient across the region caused l changes in aquifer permeability, variation in aquifer thickness and the effects of local recharge.

Aquifer sediments have both a high primary permeability and an even higher secondary permeability in areas of solution activity. This dual permeability is reflected in the variation of transmissivity throughout the region from 500 to over 14 000 m^3/day/m.

The main inflow into the system is through recharge from local rainfall and lateral throughflow. Lateral throughflow across the Victorian Border has been estimated to be 14 000 ML/yr (Stadter & Love, 1987). Recharge occurs via two mechanisms; diffuse and point recharge. Diffuse recharge has been estimated from chloride profiling and changes in groundwater storage to be of the order of 10-20 mm per year in the eastern portion of the region and up to 50 mm per year in the western sector. Point recharge occurs via surface discharge into numerous runaway holes in the Bordertown and Mundulla area. About 2 300 ML/yr is estimated to be recharged to the unconfined aquifer via this point recharge.

Groundwater quality increases from about 1 500 mg/L in the eastern portion of the area to in excess of 9 000 mg/L in the west. There is some groundwater quality stratification, particularly in the southwest, where a marl horizon separates marginal irrigation quality water (about 2 000 mg/L) from overlying saline water of about 10 000 mg/L.

The monitoring of groundwater salinity has been undertaken since 1978 to observe any changes in groundwater quality resulting from irrigation practices. The results indicate that annual increases in groundwater salinity of up to 330 mg/L are evident in a number of irrigation wells. It is considered that the salinity increases observed to date are caused mainly by the downward leaching of salts which remain in the soil profile following irrigation. This leaching is enhanced in areas of higher recharge and where the water table occurs at relatively shallow depth i.e. the western portion of the region.

GROUNDWATER RESOURCE ASSESSMENT

An attempt was made to model the groundwater system by the use of a groundwater computer modelling package. However, an accurate determination of the water balance via this method proved to be difficult because of the regional nature of the assessment, the variability in aquifer properties, lack of accurate data in some areas, and a time constraint for management decision-making.

The approach subsequently taken for the groundwater assessment was to divide the region into 7 sub-areas, and to determine a separate water balance for each. Consideration was given to the hydraulic continuity of the unconfined aquifer across the region i.e. the groundwater outflow from one sub-area must balance the inflow into the sub-area which is immediately down-gradient. The results of this assessment indicate that to minimise the effects of any long term groundwater quality deterioration, particularly for irrigators located downgradient of areas with a high level of irrigation development, the maximum possible groundwater throughflow should be maintained. The management philosophy that has therefore been adopted for the next five years is to maintain groundwater allocations at the level of local recharge within each sub-area.

Further investigations are to be undertaken to examine in detail the cause of the groundwater quality deterioration in the western part of the area, together with a further attempt to establish a usable groundwater computer model for the region for determination of longer term management policies.

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PALYNOSTRATIGRAPHY OF THE CENTRAL WEST MURRAY BASIN

M.K. Macphail
Consultant
29 Abbey St, Gladesville
E.M. Truswell
Division of Continental Geology, Bureau of Mineral Resources
GPO Box 378, Canberra ACT 2601

Palynological investigations have been undertaken in the central part of the Murray Basin, New South Wales, to provide a biostratigraphic framework within which to interpret the regional stratigraphy. Such a chronological framework is necessary to understand the geometry of economically important aquifers. For example, in the central western part of the basin, groundwater flow within the Renmark Group is impeded by the impermeable barrier of the Oligocene-Miocene Geera Clay. Further east, lateral equivalents of the Geera Clay are represented by sediments of the Olney Formation (Renmark Group); aquifers in this interval are lithogically similar, and Oligo-Miocene units difficult to distinguish from those of the Eocene, although they show markedly differing salinities. Palynology, by establishing time differences between the units, serves as a tool to distinguish the upper, middle and lower aquifers of the Renmark Group.

The study is based on quantitative analyses of a number of fully cored boreholes which penetrated sequences of Murray and Renmark Group sediments. These included Manilla-1 in the Wentworth Trough, Woodlands-1 in the adjacent Lake Victoria/Lake Wintlow High and Piangil West-1, drilled in northwest Victoria through the thickest known section of the Geera Clay. Additional data comes from cuttings recovered from six boreholes in the Pooncarie and Balranald 1:250,000 map sheets. Localities are shown in Fig. 1.

PREVIOUS PALYNOLOGICAL INVESTIGATIONS: PROBLEMS AND METHODS

Earlier palynological investigations, mainly into the Cainozoic sequences, have largely been concentrated in the eastern sector of the Murray Basin (Martin, 1984a, b, c). An exception is the detailed analysis of the fully cored borehole Oakvale-1 in the far west (Truswell & others, 1985).

Throughout the basin, Middle Eocene to Middle Miocene sequences are frequently rich in well preserved spores and pollen. The assemblages, while not lacking in diversity, tend to be dominated by a few major types, and it is often difficult to find in them species which have a short time range and which elsewhere provide good stratigraphic markers. Also, time ranges in Murray Basin sequences are in some cases quite different from those in coastal basins which have provided stratigraphic standards and reference sections. For these reasons, earlier investigators applied a range of biostratigraphic techniques to subdivide Murray Basin Cainozoic sequences. Three distinct methodologies can be distinguished: subdivisions based on them, and the relation of these to a standard Tertiary timescale, are shown in Fig. 2.

1. 'Standard' zonal biostratigraphy attempts to identify, within the Murray basin, zones which have been defined in other basins. Most commonly it has been the concurrent range/assemblage zones defined in the Gippsland Basin (Stover & Evans, 1973; Stover & Partridge, 1973; Partridge, 1976) which have been applied. Difficulties in applying this zonation within the Murray relate to the identification of the Late Eocene Upper

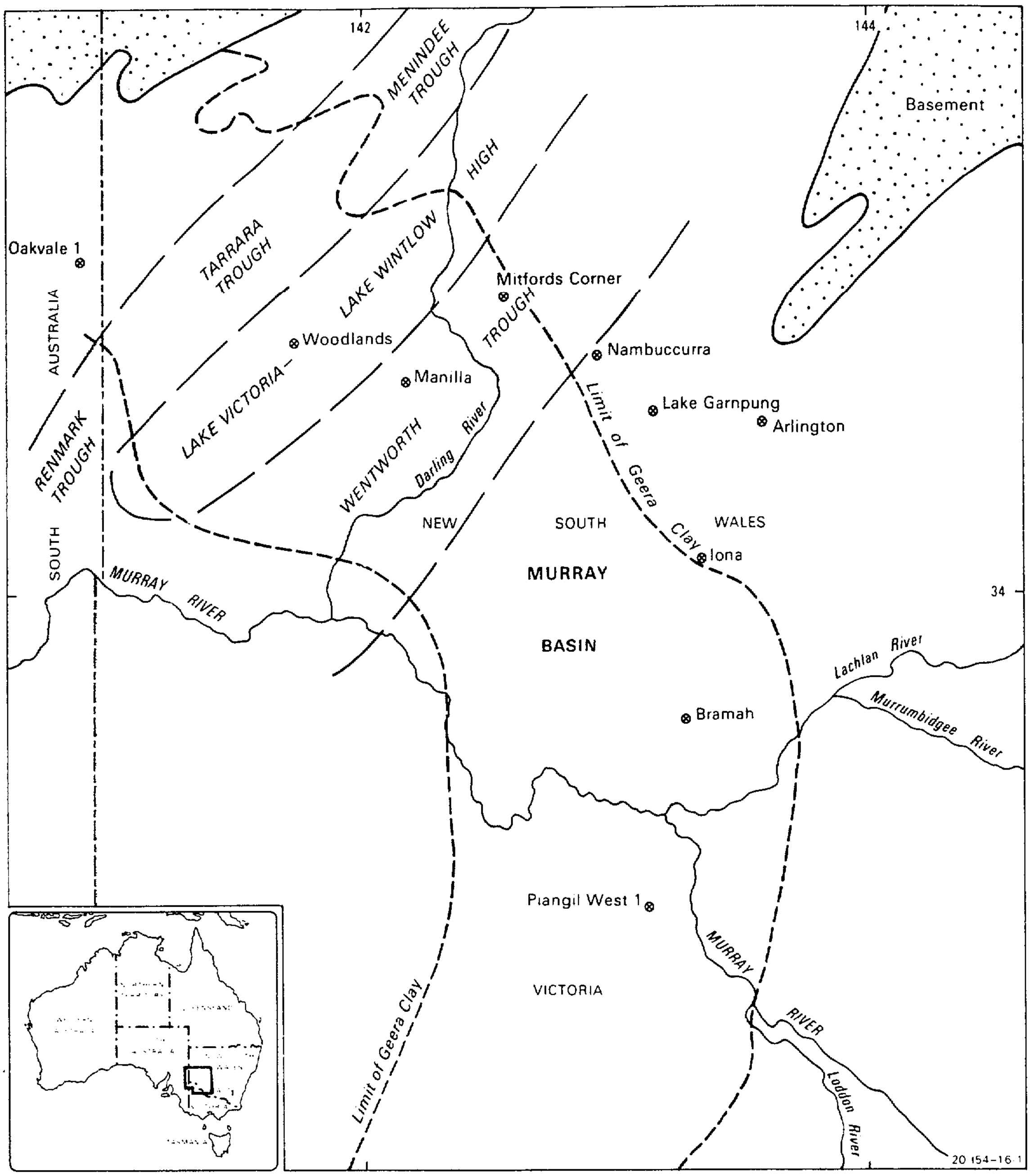

Fig. 1. Location of sites used in palynological study

Nothofagidites asperus Zone, and to the subdivision of the overlying, Oligocene *Proteacidites tuberculatus* zone.

2. Quantitative techniques, which include Martin's (1984a) 'ratio method', involve the use of high frequencies of selected pollen types, expressed in terms of a ratio of those to major botanical groups. These have obvious ecological implications, which limit their biostratigraphic application, but they are useful within limited geographic areas.
3. Another quantitative technique uses relative frequencies of all major taxa within the palynological assemblages. At Oakvale-1, changes in relative frequencies were used to identify 2 major zones and four subzones within the Late Oligocene/Early Miocene, with zone boundaries statistically calculated using degrees of similarity between adjacent pollen spectra. Again, pollen frequencies are subject to some ecological control.

In the present study, most reliance has been placed on standard zonal stratigraphy, supported in some instances by analyses of frequency changes in major taxa.

MAJOR RESULTS OF THE PRESENT STUDY

Identification of Cretaceous Sequences

Palynological analyses have shown the presence of Early Cretaceous sediments in cores from Manilla-1 (Macphail, 1987) in the central Wentworth Trough, and in cuttings from Mitfords Corner-1 in the northern end of the trough (Truswell, 1987). Sediments at both sites are non-marine; coarse sands in the 120 m thick section in Manilla-1 suggest correlation with the Pyap Member of the Monash Formation of the Renmark Trough. Sequences at both sites contain pollen and spores of the *Dictyotosporites speciosus* Zone, of late Neocomian through Early Albian age (Dettmann, 1986); further work is necessary to refine this age assignment. At Manilla-1 the section includes charcoal conglomerates, presumably resulting from catastrophic burning of Cretaceous conifer forests.

Biostratigraphic subdivision of Cainozoic sequences

The palynological analyses have provided a provisional time-stratigraphic framework within the Renmark and Murray Group sequences. This is expressed primarily in terms of Gippsland Basin zones as follows:

1. The Middle *Nothofagidites asperus* zone includes the oldest sediments sampled. The *Nothofagidites asperus* zone, of Middle to Late Eocene age, was originally defined in the Gippsland Basin but has since been extended and redefined. Stover & Partridge (1973) originally recognized separate Lower and Upper *N. asperus* zones in the Gippsland Basin. Subsequently, two subzones were recognized within the Lower *N. asperus zone* (Partridge, 1976); the upper of these became the Middle *N. asperus* Zone, the lower took the name of the original unit, and became the Lower *N. asperus* zone proper.

Middle *N. asperus* Zone microfloras were identified in Woodlands-1, between 351-363 m, in Renmark Group sediments (Macphail, 1988a); comparisons with the Gippsland Basin suggest that the upper part of the zone is present. Similar assemblages were recovered from Renmark Group sediments in Piangil West-1 (Macphail 1988b) but with less confidence as only cuttings were available. Lignites in the Arlington and Iona bores were assigned by Truswell (1987) to the Lower *N. Asperus* zone, but re-evaluation of species ranges suggests they may belong to the Middle *N. asperus* interval.

2. The Upper *N. asperus* Zone has proved difficult to identify in the Murray Basin, largely because it is transitional in character between the Middle *N. asperus* and overlying *Proteacidites tuberculatus* Zones (Martin, 1977). The excellence of the section in Woodlands-1 provided fresh criteria which allow recognition of an Upper *N. asperus* Zone equivalent, and the unit was identified in Woodlands-1 between 328-340 m.

In Piangil West-1, cuttings in the Renmark Group between 240-320 m have been assigned to a transitional Upper *N. asperus*/Lower *P. tuberculatus* interval.

3. For the *Proteacidites tuberculatus* Zone, the difficulty in finding the accessory species used to subdivide the zone in the Gippsland Basin led Martin (1984 and papers cited therein) to use the ratio method to effect subdivisions in the Murray Basin. These have been used minimally in the current study. The Gippsland Basin criterion for defining the zone base, viz,

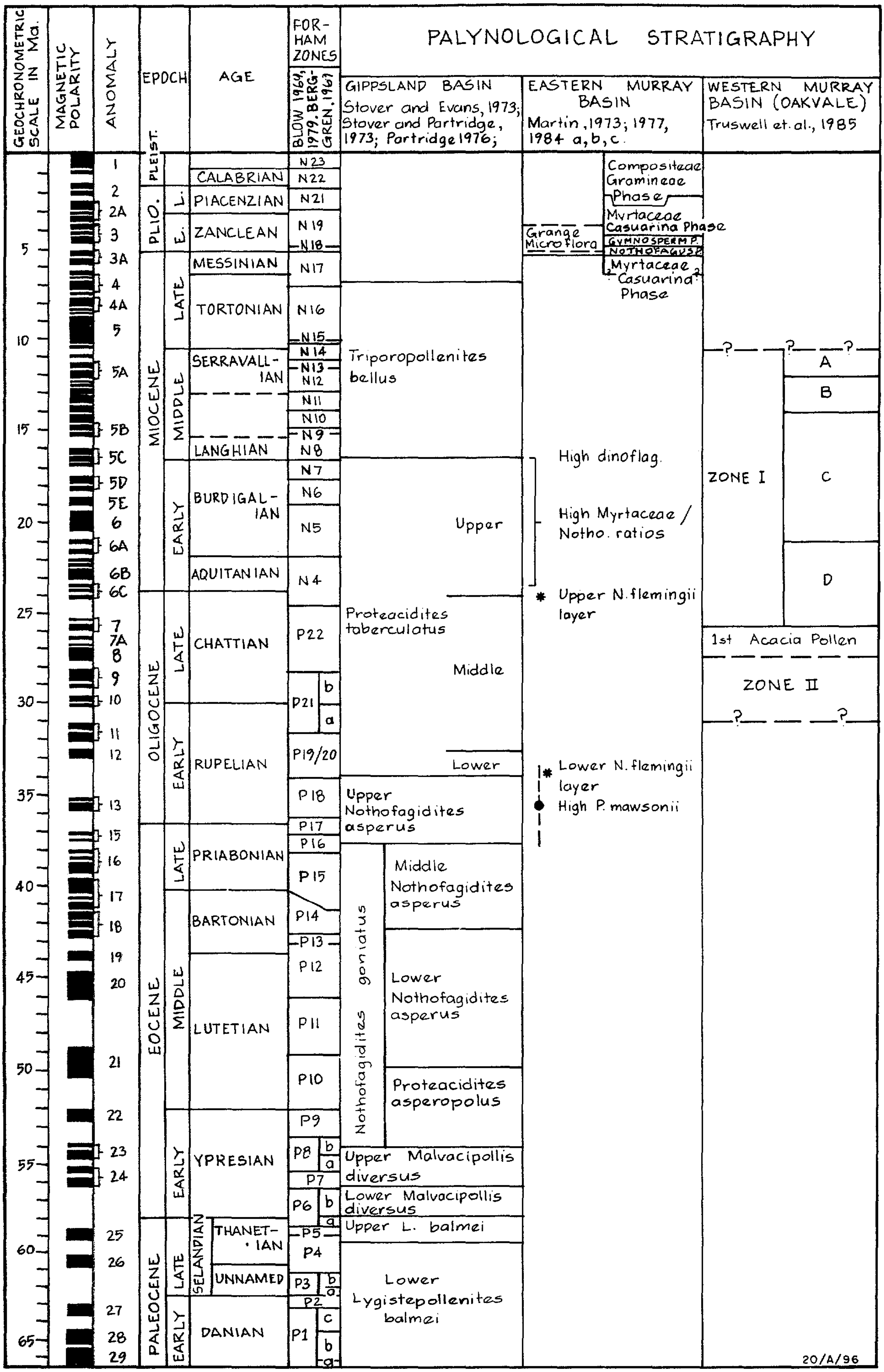

Fig. 2. Palynological zones used in the Murray Basin: calibrated against timescale of Berggren and others (1985)

the first appearance of *Cyatheacidites annulatus*, has been augmented by using the first appearance of *Chenopodipollis chenopodiaceoides*.

Thus defined, the unit encompasses the upper part of the Renmark Group; where this is overlain by the marine formations of the Murray Group it extends upwards to the middle of the Geera Clay. In sequences east of the limit of marine transgression, its upper boundary lies within the middle aquifer of the Renmark Group (= Olney Formation).

4. The nominate species of the *Triporopollenites bellus* Zone of the Gippsland Basin has been identified widely, and has been used as a datum on which to align the sections examined. In the Murray Basin the zonal interval includes a number of taxa which, in the Gippsland Basin, terminate their ranges in older parts of the sequences. In the western Murray Basin the *T. bellus* Zone spans the upper part of the Geera Clay; in the east it encompasses part of the middle and all of the upper aquifers of the Renmark Group.

Identification of marine influence in the Eocene

A marginal marine influence is reflected by dinoflagellates in Middle and Upper *N. asperus* Zone sediments of the Renmark Group in Woodlands-1. This is far to the north of previously established limits of marine transgression in the late Eocene to Early Oligocene, suggesting that the influence of the sea was felt beyond the recognized limits of the Buccleuch Embayment (Brown & Stephenson, 1986). Further, the thickness of Renmark Group sediments at this site, plus their marginal marine character, suggests that the area of the Lake Victoria - Lake Wintlow Gravity High may have been a depression since at least Early Tertiary time. While the events in Woodlands may be broadly correlated with Late Eocene high stands of sea level identified by Haq & others (1986), resolution of the palynological zones is too coarse to identify individual high peaks on the global curve.

Middle *N. asperus* Zone sediments in Piangil West-1, recognized only in cuttings samples, contain similar dinoflagellates, and suggest that the marine incursion was an extensive one.

VEGETATION HISTORY FROM QUANTITATIVE ZONATION

All fully cored sites examined record a shift in dominance of major pollen taxa in the Late Oligocene to Early Miocene interval. This change formed the basis of the zonation erected in Oakvale-1, where pollen assemblages of the older, Zone II unit are dominated by *Nothofagus brassi* type pollen and high values of Myrtaceae, and younger, Zone I assemblages are characterised by reduced *Nothofagus* and by increases in Araucariaceae and podocarpaceous conifers. This is interpreted as reflecting a change in regional vegetation from evergreen rainforest, growing probably under year-round precipitation, to a drier type of rainforest growing under mildly seasonal conditions of rainfall.

The same shift in pollen frequencies was observed at all sites examined in the study, and there is some evidence to suggest that the ecological shift was diachronous across this part of the Murray Basin. The resolution afforded by sampling intervals and uncertain biostratigraphic boundaries is inadequate to determine the precise range in time of the vegetation change from site to site. At Oakvale-1, the change occurs in the *P. tuberculatus* Zone in the Late Oligocene; at Manilla-1 it occurs higher in the same zone, and in the late Early Miocene. It is similarly placed in Piangil West-1. In Woodlands-1, the highest frequencies of Araucariaceae, indicating Zone I assemblages, occur well up into the *Triporopollenites bellus* Zone. The apparent diachroneity of these changes in pollen frequency cautions against their being used as chronological markers.

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THE SALINITY PROBLEM IN SOUTHERN AUSTRALIA – AN OVERVIEW

P.G. Macumber* and P.R. Dyson+

*Victorian Department of Water Resources

+Victorian Department of Conservation, Forests and Land

Throughout southern Australia we are today experiencing a wide ranging and fundamental readjustment in environmental equilibrium caused by the filling up of the regional aquifers in response to land use changes brought about by European settlement (Macumber, 1978a, 1978b, 1980, 1983, 1984). One major manifestation of these changes is the widespread appearance of salinity throughout the landscape. The changes now under way stem from the extensive clearing of trees from both the highlands and the plains (Macumber, 1978, 1983, 1984; Jenkin, 1979, 1983; Dyson, 1985; Dyson & Jenkin, 1981). In addition there has been the introduction of new agricultural practices including large scale irrigation and the control and modification of river systems.

As a consequence, rising water tables are bringing salt previously stored in the aquifers to the surface where it effects soils, streams and vegetation, causing widespread salinization. This process is occurring in almost every regional geographic and climatic setting, including the highlands, the Mallee and the inland and coastal plains. It effects virtually all major irrigation areas. For instance in northern Victoria, the Loddon Valley has 250,000 ha underlain by shallow saline water tables. In the Goulburn irrigation area there is now about 120,000 ha with shallow water tables; this area is expected to double in the next 40 years if nothing is done. In the dryland areas, the effects are twofold, leading to both land and stream salinization. For instance, virtually all streams in southwestern Victoria are brackish or saline due to groundwater outseepage, and this same process is now gradually affecting tributary systems feeding the major rivers of northern Victoria.

Rises in regional groundwater pressures are best documented from the Riverine Plain. For instance, in the Goulburn/Murray Plains rises varying from 0.1m/yr to 0.2 m/yr are recorded from a number of piezometers from both dryland and irrigated regions alike (Macumber 1980, 1983, 1984). The deep regional aquifers are important sub-surface drains, however as groundwater pressures rise the effectiveness of these deep drains decreases with the consequent spread of local groundwater discharge and hence an expansion in the salinized areas. If the observed pressure rises were to continue at present rates, it can be predicted that the entire Riverine Plain in Victoria – dryland and irrigation areas alike – will become a zone of regional groundwater discharge within 100 years. At present this situation occurs in the Kerang Irrigation District in Victoria and the Wakool ID of NSW, where water tables are within capillary reach of the surface, and salinity is a major problem.

Similarly, groundwater pressure rises are occurring in the dryland highland areas, the plains and in the Mallee (Macumber, 1980, 1983; Jenkin & Dyson 1983). Some indication of the impact of dryland salinity on streams can be had from the Axe Creek study (Williamson, 1983). Williamson demonstrated that the volume of salt passing down the Axe Creek over the period 1966-1981 averaged 15000 tonne/annum. This is 9% of the annual salt load of the Barr Creek. Yet Axe Creek is only one of a number of similar streams discharging high salt loads into the major rivers of northern Victoria. The salt source in these catchments is derived from salt stored in bedrock aquifers underlying the catchments. Indeed salt stores within the highland catchments are relatively high with salinity levels of the bedrock aquifers ranging from 3000 mg/L up to 30000 mg/L TDS. (Dyson, 1986). Analysis of recharge and groundwater flow trends in the Mallee region of South Australia has led to predictions of a significant long-term increases in salt inflow into the River Murray; (however, there is still much conjecture about the timing and extent of this occurrence.)

The rises in groundwater pressures are continuing unabated throughout much of the landscape with little evidence that equilibrium is near being reached. In those instances where equilibrium is close, it is an essentially brackish to saline equilibrium which has, in the case of the irrigation districts on the plains (e.g. the Kerang Region), a high increasingly saline water table which oscillates seasonally but lies always within capillary reach of the groundsurface. In undulating settings, as are the cases in the Mallee and the highlands, the inevitable result of continuing water table rises is saline depressions or brackish to saline land and stream systems respectively. That is, under the present land-use techniques the trends in rising water tables will continue with the gradual expansion in land and stream salinization being inevitable and essentially irreversible. To this extent the salinity problem is seen as being fundamentally a groundwater problem.

The threats to agriculture in the eastern States are mirrored in West Australia, where salinity induced through rising groundwater pressures is a major threat to surface water supplies and to agricultural land. The annual cost of salinity to Australia is estimated to be about $95 million, while that to Victoria alone is about $50 million which could rise to close to $100 million in 50 years if nothing is done.

The present trends are not unique but represent the most recent of a number of similar saline cycles which have occurred naturally in the past in response to fluctuations in climate. These ancient saline cycles have left their imprint in the soils, sediments, landforms and groundwaters.

While the general trends in land and stream salinization are very clear, the eventual extent and degree of salinization is still being assessed. The ultimate effects will obviously depend on the extent to which remedial action can be taken. It is clear, however, that while much can be done in some areas, in others it will take a considerable time and effort to stop, let alone reverse, the present trends. In some areas it is unlikely that any solution will be found, and land will go out of production.

SALINITY CONTROL

Salinity Provinces

The salinity problem is therefore fundamentally a groundwater problem, and its solution lies essentially in water table control. This can be achieved by either techniques which reduce accessions to the water table, or by sub-surface drainage which lowers water tables. Where groundwater control cannot be achieved, and water tables rise to within capillary reach of the surface, the only options available are those onfarm measures which optimize the otherwise saline conditions. This is the 'living-with-salt' situation or saline agriculture, with its implied loss in productivity.

There are a large number of options available for salinity control, however particular options are only technically feasible in areas with specific physical characteristics. It must be clearly understood that control techniques successful in one region will not necessarily work in a different region. In recognition of these physical differences and their importance to salinity control, the concept of salinity provinces has been adopted. The salinity provinces are based on hydrogeological and geomorphological criteria, each province having its own small range of technically feasible control options. Distinct provinces exist for the highlands, the Mallee, the plains, and the irrigation districts etc. Victoria has been divided into 15 salinity provinces. Although defined in Victoria, the similar geographic settings across southern Australia enable the province concept to be adopted for other States. A full account of the Victorian salinity provinces is given in Macumber & Fitzpatrick (1987).

Dryland and Irrigation Areas

There are fundamental differences to the approach to salinity control in the irrigation and dryland areas and a there is a basic division between dryland provinces and irrigation provinces. The dryland areas are further subdivided on the basis of the nature of the groundwater flow system – local systems or type 'A' where recharge and discharge areas are close by, and regional flow systems or type 'B' where recharge is some significant distance from the discharge areas and may cover a number of catchments or even a whole drainage basin. Over 70% of the dryland area has regional groundwater flow systems in Victoria.

In irrigation regions, salinity provinces are determined by a combination of hydrogeological characteristics which influence control options. These are based on aquifer depth – deep (regional) and shallow (local) aquifer systems – and on aquifer salinity. For instance, the saline shallow and deep groundwaters of the Loddon Province (IL) precludes groundwater pumping with re-use. By contrast, the fresh deep and shallow aquifers of the Murray Province (IM) enable conjunctive groundwater and surface water usage and does not pose the same immediate off-farm disposal problems as in IL or even the Goulburn Province (IG). In general these divisions closely follow catchment lines.

INTEGRATED SALINITY CONTROL - The Salinity Management Option Tree (SMOT).

In order to make informed decisions on the goals and objectives for salinity management, it is necessary to know what the consequences of pursuing alternative goals are for individuals, regions, the State as a whole and other States. Decisions must be based on well defined technically feasible control options. In this way the consequences of alternative strategy options or scenarios can be clearly spelt out. The salinity management option tree (SMOT), provides a conceptual and operational framework on which an overall salinity control strategy can be developed (Macumber & Fitzpatrick, 1987). It is based on the range of presently available technically feasible control options and provides a framework for assessing the implications and outcomes of various combinations of choices of options. Having identified the implications and outcomes of particular paths, the final selection of a preferred path(s) can be made by assessing the degree to which the outcomes satisfy the overall objective. Decisions about the path (or combinations of paths) to be followed will require inputs from the economic, social, environmental sources as well as the community.

SALINITY CONTROL OPTIONS - Irrigation Regions

In irrigation districts the increased groundwater accessions are greatly exacerbated by imported water, and lead to even more rapid water table rises than would otherwise be the case. In addition, salt is imported in irrigation water and gradually accumulates in the soils and shallow groundwaters. Salinity control using on-farm management techniques, while important, cannot prevent salt accumulation; furthermore, they can at best limit the rate of water table rise, not stop it short of capillary reach of the surface. The inevitable result is high water tables, salinization and varying loss of productivity.

Where sub-surface drainage is not practical, the 'living with salt' option aims at optimizing farm productivity under high water table conditions.

To avoid the establishment of permanent high saline water tables in irrigation areas, sub-surface drainage is essential. The aim of sub-surface drainage is to lower water tables to below 1-2m from the surface (depending on soil and crop type) either by groundwater pumping or tile drains. Successful groundwater pumping requires suitable aquifers and, in the case where the pumped groundwater is used for irrigation, salinities of less than about 3000 mg/L.

The largest constraint to salinity control by sub-surface drainage is the need for disposal of groundwater effluent. High priority must therefore be given to the evaluation of different disposal options. Clearly the disposal of salt is the key issue with sub-surface drainage. This in turn relies heavily upon the eventual outcome of the River Murray agreement on salt disposal. The sub-surface drainage option is further limited by the availability of suitable aquifers from which to pump. As a consequence, it is likely that less than 40% of the Victorian irrigation areas can be protected by this means. It is likely that less than 35% of all irrigated land in the Riverine Plain will have suitable aquifers for groundwater pumping. Sub-surface drainage provides the best and probably only means of preventing saline agriculture in irrigation districts.

Dryland Areas

In dryland regions the reduction of accessions to the groundwater is likely to be the most appropriate salinity control technique for most areas. The most economically viable options are agronomic and on-farm measures aimed at reducing accessions. Groundwater pumping is not a viable option for most of the dryland provinces where in general brackish to saline groundwaters and low permeability aquifers predominate. Exceptions to this occur in the cases of the highland valleys (Province HC) and certain regions of the Riverine Plain (Province PR), where suitable aquifers permit localized irrigation.

In the case of the local flow systems (less than 30% of the highland area and 10% of the Mallee) where cause and effect lie in close juxtaposition, treatment of the recharge areas may have a fairly rapid response in the adjacent salt affected discharge areas. This is the case at Bourkes Flat in the Avoca catchment where the successful use of lucerne has reversed the previously upwards directed water table trends (Dyson, 1986). In regional flow systems, which make up the bulk of the dryland areas, treatment must be on a regional or multi-catchment scale. Here, salinity control may take many generations to achieve and in some instances it may be virtually unattainable. This is the case for the regional saline aquifers of the Mallee where water tables are seemingly related to major recharge events during the very wet years. No control methods short of extensive replanting are available and even with a total cover there can be no reversal of the present salinity pattern. However, even on a local flow system, the control of salinity is restricted by the limited number of deep rooted species capable of controlling water tables. These include trees, lucerne, tree lucerne and phalaris. Even these few have only limited application in some areas. As a consequence, intensive research is now under way to improve plant-water use by existing species, and increase the number of additional deep rooted species capable of limiting or even preventing groundwater accessions.

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TREES FOR COMBATING SALINITY

(Poster Presentation)

N.E. Marcar[1], T.K. Vercoe[1], M. McDonald[1], L.A.J. Thomson[1], N. Aswathappa[1], V.J. Hartney[1] and J. Cummins[2]

[1] CSIRO, Division of Forestry and Forest Products

P.O. Box 4008 Canberra ACT 2600

[2] NSW Soil Conservation Service

Orange NSW 2800

Background

Salinity and waterlogging represent major categories of land degradation in the Murray-Darling Basin. To date most of the economic costs have been incurred in irrigation areas, however, seepage and scalding also threaten considerable losses of productive land in dryland agricultural areas. The key to successful control of dryland salting is improved water management which will usually include tree planting in combination with agricultural and engineering measures (Morris & Thomson, 1983). Successful interception of water passing beyond the root-zone in recharge areas is important for long-term reductions in groundwater accessions. Establishment of trees in groundwater discharge areas for the purposes of lowering raised water-tables is an important element in the reclamation of salt-affected soils. This practice may markedly reduce the upward movement of salts to the soil surface and allow easier re-establishment of pastures and crops. In irrigation areas, tree planting for groundwater control will probably be confined to non-productive areas such as road verges, laneways, in channel and drain reserves, and around farm buildings (Acil, 1983), unless economically important, fast-growing, salt and waterlogging-tolerant species can be found.

Current Research

The Division of Forestry and Forest Products (DFFP) has recently undertaken a major collection of salt-tolerant tree and shrub germplasm and instigated glassshouse and field evaluation for salt tolerance.

Sampling the germplasm of potentially salt-tolerant species is an important first step in developing trees for combating salinity. Seed sampled by the Australian Tree Seed Centre (DFFP) from populations growing naturally in saline areas has provided valuable base material for screening and selection.

Important factors in sampling seed include:

(1) broad area sampling of a population to encompass genetic variation.

(2) sampling from individuals at a spacing designed to decrease the possibility of collections from siblings.

(3) recording data on the habitat and microenvironment of each individual (including associated species, size and position of the individual in the landscape and soil characteristics).

(4) recording a detailed location for the collection site including latitude, longitude and elevation.

In glasshouse screening experiments for salt tolerance, 3 to 4 month old seedlings were salinised with step-wise increases of a mixed salt solution or NaCl in sand culture using automated drip-irrigation. Measurements were made of survival, symptom development and height growth. Large interspecific differences were found in salt tolerance of tropical and subtropical *Acacia*, *Melaleuca*, *Eucalyptus* and *Casuarina* species (Aswathappa & Marcar 1988). For example 50% of *Acacia stenophylla* seedlings were still alive at 1850 mol m^{-3} salinity and continued height growth up to 1000 mol m^{-3}, whereas in *A. torulosa* 50% of seedlings were dead at 350 mol m^{-3}. Some of these species have temperate provenances which can be utilised in southern Australia.

In the colder Tableland zones of NSW, salt-tolerant trees must also be able to withstand the often severe winter frosts. Several frost-tolerant *Eucalyptus* species have been recently screened for salt tolerance (Marcar 1988). Ten species in the subgenus *Monocalyptus* were all found to be very salt-sensitive (no survival at 300 mol m^{-3} NaCl) whereas those in the subgenus *Symphyomyrtus* were moderately salt-tolerant (100% survival at 300 mol m^{-3}). Species in the informal series *Ovatae* viz. *E. ovata*, *E. aggregata* and *E. camphora* proved most tolerant, however, these were still significantly less salt tolerant than other more-tolerant species such as *E. camaldulensis*. Surface and/or subsurface waterlogging is frequently associated with soil salinity in southern Australia, particularly during the wetter winter/spring months. In glasshouse experiments, waterlogging significantly decreased growth and transpiration of plants subject to salinity. These responses were related to stomatal closure, reduced development of aerenchyma and an increasing inability of roots to exclude salt ions.

The Division of Forestry and Forest Products is also involved in the microporpagation of individual seedlings selected for salt tolerance. Micropropagation has the advantage over cuttings of a much higher multiplication rate, a greater degree of control and small space requirements (Hartney 1984). The range of clonal material is continually being increased as more salt and salt/waterlogging tolerant selections from different genera become available, but earlier work has placed emphasis on *Eucalyptus*.

It is essential that salt-tolerant material identified from glasshouse screening experiments or field sampling be rigorously evaluated under field conditions. This Division is involved with the NSW Soil Conservation Service in small-scale tree species evaluation trials on saline sites near Yass, Ryalston and Wellington. Sites have been characterised for soil salinity and are also monitored for changes in watertable heights. For the most part only frost or cold-tolerant species have been included. Species performing well after 6 months include *Acacia saligna*, *A. stenophylla*, *Casuarina glauca*, *Melaleuca halmatuorum*, *Atriplex undulata* and *E. camaldulensis* (CML 52 clone). The severe adverse effects of surface waterlogging coupled with soil salnity has once again been demonstrated on these sites.

Conclusions

Considerable progress has been made in the sampling and glasshouse evaluation of Australia's salt-tolerant woody flora but we urgently require informatiron on:

(1) the most suitable tree and shrub species/provenances to plant on and near to saline seeps and scalds, e.g. on the Tablelands and Slopes regions of southern and central NSW

(2) the most effective means of establishing these species

(3) the impact of these species on groundwater tables, salt concentrations in the root-zone and soil amerlioration

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PALYNOLOGY OF THE LATE CAINOZOIC IN THE MURRAY BASIN AND ITS BEARING ON THE SALINITY PROBLEM

Helene A. Martin
School of Biological Science, University of New South Wales.
Michael Knight
Centre for Groundwater Management and Hydrogeology, University of New South Wales.

Palynology is widely used as a tool for correlations but interpretations of vegetation, climate and other features of the environment are possible. Inferences of relative rainfall and vegetation type (e.g. tree cover versus grassland) may be interpreted in terms of relative recharge, and groundwater storage (e.g. high watertables) over time. Some possible conclusions regarding potential for salinity development (rock weathering to release element) may also be made in particular circumstances for specific times. Conclusions about subsequent salinity status of a particular lithological unit may be difficult due to later changes in groundwater regime. Subsequent hydraulic pressures, different from those of deposition, may cause changes or complete replacement of pore fluid chemistries giving rise to new salinities.

The components which may be present in an assemblage are as follows:

1. Spores and pollen of land plants indicate the general type of vegetation which is used to deduce climate. Fig. 1 shows a diagramatic representation of the palynological evidence, vegetation and precipitation for the Lachlan Valley (Martin 1987). The vegetation was forests up to the late Pliocene/Pleistocene when it became more open, i.e. woodlands, grasslands. There was a climatic gradient parallel to that of today, i.e. drier inland and wetter to the south east and the major changes shown in Fig. 1 are found in the Murray Basin also (Martin 1986). Thus Fig. 1 is applicable to the Murray Basin.
2. Swamp and aquatic angiospersm (flowering plants) generally indicate fresh to perhaps sometimes brackish water.
3. *Azolla*, the water fern indicates fresh water although it is usually found associated with a high nutrient status.
4. Algae are probably the best indicators of salinity at deposition. The ones most commonly found as fossil are *Pediastrum* and Zygnemataceae: fresh water. *Botryococcus*: fresh-brackish water and dinoflagellates: mainly marine but some, e.g. *Saeptodinium* are fresh water.

Interpretations are not always straightforward. Pollen from more than one type of vegetation may be deposited in the same sediments. More than one mutually exclusive indicators of salinity may be present. For example, *Pediastrum* may be carried out in fresh water discharge and be mixed with marine dinoflagellates. Conversely, some marine dinoflagellates may occur in otherwise non-marine environment, thought to be carried in by tsunami.

The mid Miocene-early Pleistocene palynology in the Murray Basin is reviewed. This period is critical because of developing aridity. There are relatively few pollen occurrences from this period because as the climate became drier, the swamps, lakes etc., required for pollen preservation, became fewer and restricted in number.

Figure 2 shows the extent of the latest early Miocene to mid-late Miocene *T. bellus* zone which was deposited at the height of the Miocene transgression.

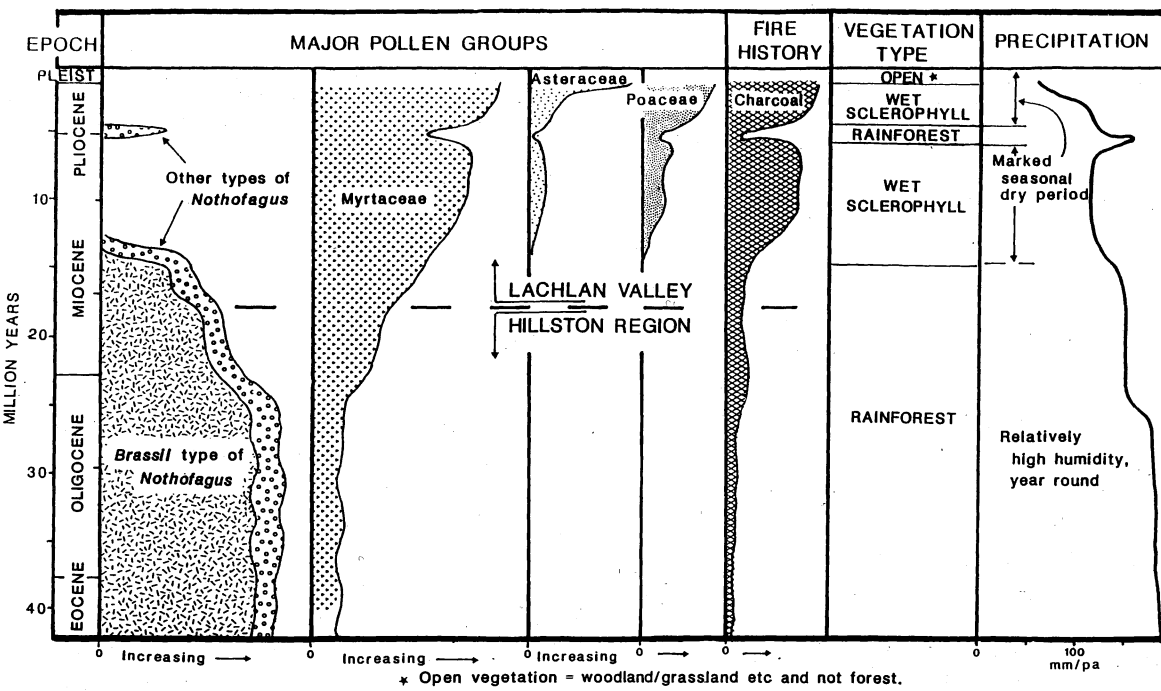

FIG 1. Summary diagram of palynological events and their interpretation for the Lachlan River Valley. This summary is applicable to the Murray Basin also.

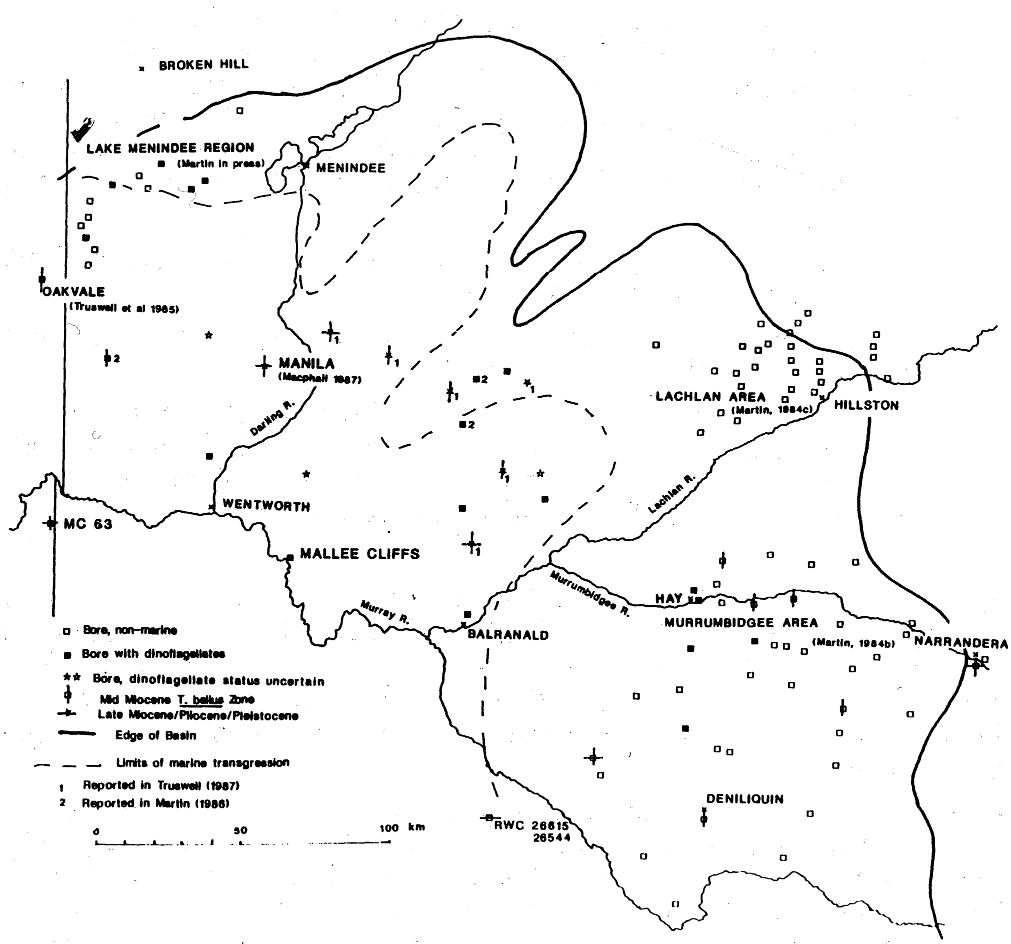

FIG 2. The Murray Basin locality map.

Predictably, dinoflagellates are found in the marine and marginal marine regions. They are also found at Hay, some 70 km from what is regarded as the limits of the marine transgression. The river channel probably became flooded by the rising sea. Other bores east of Hay may contain a few dinoflagellates. The land vegetation was predominantly forest, with some open swamps in the west (Truswell & others. 1985).

Of the few late Miocene-Pliocene occurrences (see Fig 2), MC63 has the best sequence which is remarkably like that in the Lachlan River Valley. Mitford's Corner and Bramah fit the general vegetation type for this period. There would have been a good tree cover with a shrubby understorey. The early Pliocene sequence of MC63 contains only a few dinoflagellates, and some fresh water algae, reflecting a predominantly fresh water environment which may have become brackish from time to time. The Plio-Pleistocene is found in Manilla and Mallee Cliffs (see Fig 2).

Rural Water Commission Bore 26615 at Tresco (Fig 2) in Victoria, intersects the Pleistocene Blanchetown clay at 31-32 m depth. The vegetation was probably woodland, i.e. appreciable numbers of trees but with an open canopy and a ground cover of small plants. The assemblage contains only fresh water algae and no dinoflagellates: clearly fresh water deposition, as would be expected from the geological history. A black sand aquifer at 28-29 m with similar fresh water algae indicating fresh water conditions of deposition produced water that precipitated in the outlet pipe. The precipitate contained $Al(OH)_3$: 48-81%, HCO_3: 2.22%, SO_4: 14.89% and Cl^-: 7.41%. The groundwater in the aquifer of the adjacent bore 26544 had an electrical conductivity of 40,600 μS/cm at 25 C, pH: 4.5, Cl^-: 21,780 mg/l. These salinities are higher than that of sea water and are inconsistent with a fresh water depositional environment. They indicate a partial invasion of saline water from another source as well as some in situ chemical evolution, subsequent to deposition.

ACKNOWLEDGEMENTS

We are indebted to the Department of Water Resources, New South Wales and Rural Waters Commission of Victoria (D. Ife) for assistance in this project. Mrs A. Eade analysed the White precipitate. An ARGA grant provided financial assistance for work on dinoflagellates.

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SHEPPARTON REGION SALINITY MANAGEMENT PLAN: APPLICATION OF GROUNDWATER FLOW MODELS

J. Nolan and A. Brinkley
Victorian Department of Water Resources

The uncertainty in the projections of long term degradation of agricultural land within the Riverine Plain Shepparton Region has resulted in an intensified research and investigations programme which will culminate in the development of The Shepparton Region Management Plan.

Although the root of the problem, rising groundwater levels in response to clearing of native vegetation and irrigation, is clear, long term projections of groundwater levels for what are considered technically viable watertable options have been limited by the lack of a flexible analytical tool, namely numerical modelling. By incorporating temporal and spatial variability numerical modelling avoids the necessity of using steady state and spatially lumped analytical techniques.

Technical issues with respect to watertable control which are best addressed by numerical modelling are:

- Limitations on Salt disposal out of the Region
- Groundwater disposal requirements to maintain existing salt balance
- Groundwater pumping requirements for watertable control,
- Potential for on-farm re-use of groundwater,
- Effect of Whole Farm Plans on accessions and surface drainage.

The salt disposal out of the region will be an external constraint set by the Murray Darling Ministerial Council. A Draft Salt Disposal Strategy is already in circulation. It is envisaged that the Salt Disposal Entitlement for the Shepparton Region will be approximately 15 EC units. This will provide an upper limit on the extent of groundwater pumping with disposal and surface drainage.

Maintenance of the existing salt balance requires the disposal of imported salt through the channel supply system and natural drainage lines which is in excess of the aquifer drainage capacity through the Deep Lead and the Shepparton Formation aquifers. Modelling to date has established the relative insignificance of the lateral drainage through the Shepparton Formation compared to Deep Lead Drainage.

Slice modelling along the major Deep Lead drainage lines has quantified the current deep drainage across the region. Further modelling will establish the optimum salt export through the Deep Lead. With this knowledge the long term salt export requirements of sub-surface drainage waters will be readily identified.

- Groundwater pumping from the shallow aquifers where the available aquifer yield is adequate, and from the Deep Lead where the vertical drainage is not insignificant,
- Tile Drainage where the aquifer yield is inadequate,
- Reduction in accession due to changing agricultural and irrigation practices in addition to surface drainage.

A regional waterbalance model has been developed to determine the optimal watertable control package within the constraints of an assumed regional salt disposal allocation. The model is a two-dimensional finite difference numerical model of the watertable aquifer which accounts for deep drainage, estimated from slice modelling, as a loss from model cells. The region is spatially discretized into 2.5 km. by 2.5 km cells. Stress periods are constant monthly intervals.

Preliminary calibration and verification between 1974 and 1980 has indicated the sensitivity of the waterbalance to groundwater pumping. In areas of high groundwater usage, such as the Tongala area and the eastern Murray Valley, the assumed groundwater extractions exceeded the estimated recharge by a factor of approximately two. The poor calibration in pumped areas may be due to two factors. Firstly, an over estimate of groundwater usage and secondly, neglecting the potential for increased recharge as a result of an increase in the salinity of applied water in areas with groundwater pumping and also bad estimates of average pressure.

The inaccuracy of the groundwater usage estimates have highlighted the need to increase the current metering of licenced bores from approximately 10% to 100%. Long term management of the groundwater system is dependent upon a knowledge of the groundwater usage and its effect on water quality. In the absence of comprehensive metered data DITR have conducted a groundwater usage survey across the Victorian Riverine Plains. All landowners with licenced groundwater bores have been interviewed to determine their historical usage. This enhanced data will be incorporated in the recalibrated model.

Several workers have evaluated the relative importance of the salinity of applied water on the leaching fraction. Significant increases in leaching fractions with higher salinity waters have been found for the Lemnos Loam and the Nanella Fine Sandy Loam soils. The results of these investigations will also be incorporated in the recalibrated model.

The importance of surface drainage as a mechanism for disposal of subsurface drainage waters cannot be underestimated. Because of its high cost surface drainage will be the limiting factor in any economical evaluation of the management options and the scheduling for surface drainage across the region. Apart from changing agricultural and irrigation practices, surface drainage with associated tile drainage is the only option for water table control in areas with low yielding aquifers. Upon calibration of the water balance model, management options will be evaluated on the basis of land management areas which are classified on the basis of hydrogeological and hydrological characteristics in addition to crop culture and environmental worth.

SOLUTE TRANSPORT MODELLING IN THE SHEPPARTON REGION

A.M. Oakes
Rural Water Commission of Victoria
590 Orrong Road, Armadale, 3143

The change in land use practices since European settlement has resulted in large rises in watertable levels on the Riverine Plain and the mobilisation of natural and imported salts within the aquifer systems. In the Shepparton Irrigation region in northern Victoria (an area of approximately 500,000 ha) there are large areas with watertables within 2 m of the surface. In response to this rise, a number of private and government groundwater pumps have been installed. These pumps have been successful in locally maintaining watertable levels at a 'safe level', generally 2-3 m below surface. Much of the moderately saline (typically 1000 - 5000 EC) pumped groundwater is reused either directly on farms, typically diluted with good quality irrigation water, or reused within the region (via Commission channels). As a consequence, little salt is being removed from the region with the existing salt within the system being recycled and further salt added with imported irrigation and rain water.

The Method of Characteristics (MOC, Konikow & Bredehoft, 1978) computer program for solute transport in groundwater has been applied to approximately 32 000 ha of the Ardmona-Toolamba area, an area containing 30 RWC and several private groundwater pumps. The model is being used to:

- quantify time scales for aquifer salinisation in the absence of salt export;
- determine necessary salt export requirements to protect groundwater quality;
- quantify intrusion rates for the migration of poor quality water from adjacent areas to pumping zones;
- examine the local behaviour of pumps with high concentrations, particularly for the situation where a regional salt balance is beig maintained;

The model draws on earlier work by Kleindienst (personal communication) using a 2 layer finite element flow model (AQUIFEM-N, Townley, 1987), that treats the Shepparton Formation, to a depth of 30 m below surface, as 2 active layers with leakage to the underlying Calivil/Renmark aquifer system provided by the DITR regional model. This model has been calibrated for surface recharges/discharges for a five year period at a monthly time step given known pump rates. The leakage algorithms in the MOC model were modified to allow the upper Shepparton Formation Aquifer to be treated as an active layer with leakage to the passive lower Shepparton Formation. Additional coding was added to allow the calibrated AQUIFEM-N model parameter values to be transferred to the modified MOC model via an interpolation routine. A routine was added to calculate the salinity of the groundwater recharge as a function of the salt mass removed by pumps, the spatial distribution of pumps, the salinity of irrigation supply water and the relationship between irrigation application rates and groundwater accession rates.

The paper presents the results of the simulations to date. It discusses some of the difficulties in applying the method of characteristics technique for the Ardmona-Toolamba area, particularly for large time scale simulations. The relative importance of the dispersion, advection and mixing processes in solute transport are also discussed. It is shown that within the study area that transport is dominated by the vertical flow component. The simulations confirm that mass transport in groundwater is an extremely slow process.

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MODERN FLOODPLAIN SEDIMENTATION IN THE MURRAY BASIN – BARMAH LAKES AND THE GREAT CUMBUNG SWAMP

(Poster Display)

P.E. O'Brien, R.V. Burne and G. Bickford

Division of Continental Geology, Bureau of Mineral Resources

G.P.O. Box 378, Canberra, A.C.T., 2601

The sediments of the Riverine Plain are products of fluvial deposition. Studies requiring a knowledge of facies distribution in fluvial sediments have had to rely on models developed from a few modern river systems, mostly from Europe and North America. To improve these models, BMR has started a study of modern floodplain sedimentation in a number of Australian river systems. So far pilot studies in Western Australia and the Murray Basin are underway. This poster displays some of the results from the Murray Basin work. It covers two contrasting areas of floodplain sedimentation, the crevasse splay - floodbasin lake system along the Murray River at Barmah Lakes and the 'inland delta' of the Lachlan River, the Great Cumbung Swamp.

BARMAH LAKES

The Barmah Lakes formed when the Cadell Fault diverted the Murray River and reduced its gradient. Initially the Murray flowed north around the fault scarp via the Gulpa Creek and Edwards River courses. While it followed these courses, elevated ground water tables produced a lake and lunette system in the area north of Barmah. The Murray then abandoned the Edwards River course and flowed south into this lake basin.

The Murray channel divides the lake basin in two with Moira Lake on the western side and Barmah Lake on the east. Low natural levees flank the Murray channel. They are breached towards the upstream end of the lakes by inflowing channels and by outflow breaches at the downstream end. The upstream breaches are constructing crevasse splays. The lake shores away from the Murray channel are also prograding into the lake because sediment is brought in by overbank sheet flow from upstream during high floods and by creeks fed by upstream flooding and ground water.

The lake basins away from active inflow breaches are floored with grey silty clay both in open water areas and in the extensive beds of rushes (*Juncus ingens*). A crevasse splay starts as a simple breach about 20 m wide in the Murray levee that feeds water into the lake through a funnel-shaped gap in the reeds around the lake edge. Poorly-sorted fine sand is deposited in a sheet at the downstream end of the crevasse. With time, the splays develop levees, first colonized by rushes and reeds, then by eucalypts and grasses, flanking a main channel. The channels have sandy beds whereas the levees consists of silts and clays overlying sand. Where active crevasse channels enter the lakes, they build a mouth bar of rippled fine sand that takes the form of a broad lens up to 30 cm thick, and tens of meters in lateral extent. As the splay channels lengthen, they receive less and less flow so they are filled by grey to black clay and colonized by rushes and grasses.

The Barmah Lakes depositional system resembles the classic Mississippi delta depositional model (Coleman, 1966) in that it consists of levees and crevasse splays building out into floodbasin lakes. It differs from the Mississippi model because the floodbasin is very shallow so that the Barmah Lakes system can only deposit a sequence of floodbasin clays passing up into mouth bar sand overlain by levee clays and silts that will be less than 2m thick.

GREAT CUMBUNG SWAMP

The Lachlan River ends in about 40 sq. km. of marshlands known as the Great Cumbung Swamp. Though most maps show the Lachlan joining the Murrumbidgee River south-west of the Great Cumbung Swamp, water seldom flows between the two rivers. Even during high floods, the area between the swamp and the Murrumbidgee is flooded mostly by water from the Murrumbidgee. Three processes possibly contribute to the swamps existence. Floods on the Murrumbidgee have constructed a low alluvial ridge which prevent the Lachlan flowing south, a line of Pleistocene lunettes forms a topographic barrier to the west and the Lachlan water is lost from the swamp so that it does not develop into a lake which might then overflow and cut a channel through the topographic barriers. The water may be lost by evaporation and transpiration or into underlying aquifers. Recharge of the aquifers seems likely because salinities do not exceed 2 ppth in the swamp, even though the climate is semi-arid.

Upstream from the swamp, the Lachlan River is sinuous and 20 m wide and up to 2 m deep. Its banks are lined with stands of cumbungi (*Typha orientalis*). It has levees about 30 cm high. The channel consists of fluid dark grey clay containing abundant gas bubbles overlying progressively stiffer clay. Below 50 cm from the surface, beds of sandy clay up to 8 cm thick probably represent deposition by large floods. As it flows into the swamp, the river channel becomes wider, up to 70 m, and less sinuous with less pronounced levees. Cumbungi is replaced by reeds (*Pragmites australis*). It then becomes narrower and more sinuous again and is partly overgrow with cumbungi in places. Eventually, the channel becomes a shallow, sinuous, ephemeral channel that peters out before reaching the Murrumbidgee.

The bulk of the swamp area is *Phragmites* marsh with standing water less than about 20 cm deep. Different areas are subject to varying degrees of desiccation depending on slight differences in elevation. Open water areas within the marsh are probably semi-permanent lakes whereas the edges of the *Phragmites* marsh and the channel levees are more frequently exposed.

All environments in the Great Cumbung Swamp, including the channel, deposit black clay. In *Phragmites* and cumbungi beds, the clays are covered by a layer of rotting vegetable matter and are full of roots. In the river channel, the clay is very soft on the surface but becomes stiffer with depth. When dried out, deep cracks form in the clays. Thus, the final depositional product of the Great Cumbung Swamp would be a blanket of black clay showing varying degrees of bioturbation by roots and subtle textural variations caused by pedogenesis.

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SHEPPARTON FORMATION WATERTABLE MAPS AND DEEP LEAD POTENTIOMETRIC SURFACE MAPS OF THE RIVERINE PLAINS, SHEPPARTON REGION

(Poster Presentation)

A. Olshina
Department of Water Resources

Predictions of the future agricultural potential of the Shepparton Region is in part dependent on the ability to predict the depth to groundwater for the range of watertable control/exploitation options envisaged. This series of posters presents an attempt to map the watertable and Deep Lead pressures for 1980 and 1986, and to show the changes that have taken place over this period.

Whilst the mapping of the Deep Lead Pressures was a relatively simple exercise, the mapping of the watertable proved to be a more complex task, requiring a more rigorous hydrogeological assessment.

The most significant finding was the presence of anomalous vertical and horizontal hydraulic gradients within some areas, which supports the hypothesis that perching is a significant factor. The prediction of future groundwater levels in areas where perching is significant is expected to prove unreliable if estimated using saturated groundwater flow techniques. Management of groundwater levels in such areas would require the development of control techniques different to those employed for watertable control.

A review of the bore data currently available showed major deficiencies, including lack of bore construction data and questionable reliability of monitoring data in a large number of cases. Examples of the anomalies which may result through the use of unvetted data are presented.

MURRAY DARLING BASIN LAND AND WATER MANAGEMENT POLICY AND PLANNING FRAMEWORK

Dr John Paterson and Mr Peter Sutherland
Department of Water Resources
35 Spring Street, Melbourne Vic 3000

Effective management of the Murray Darling Basin depends as much on institutional and political mechanisms as on sound technical knowledge of physical processes. This paper examines the institutional and political imperatives which have lead to major initiatives in resources policy for the Basin. Important factors likely to shape future decision making are highlighted and lessons are drawn from the strategic thinking behind the Draft Salinity and Drainage Strategy.

MILESTONES IN INTERSTATE CO-ORDINATION

Major developments in the evolution of resource management policy for the Basin have been:

1914 River Murray Waters Agreement (RMWA) and Subsequent Amendments

The RMWA has served the contracting States reasonably well over seventy years of water resource development for consumptive uses. The success of the Agreement has stemmed in large part from the autonomy it gave States to pursue their own development goals within well defined constraints on entitlements to the shared resource (Paterson, 1987). By the 1970's, however, it became apparent that the Agreement was not equipped to resolve the emerging conflicts on water quality and resource degradation problems generally.

In 1982 the agreement was broadened in an attempt to address these issues, but failed to adequately prescribe the rights and responsibilities of States in relation to these new areas. Consequently despite prolonged bureaucratic machinations there was little real progress. If anything territorial rivalries were entrenched. Attempts by States to internalise solutions to salinity problems resulted in some programs of dubious cost-effectiveness from a basin perspective.

Political input was needed to attempt a negotiated settlement at a higher level of accountability.

1985 Formation of the Murray Darling Basin Ministerial Council

In November 1985 a Ministerial Council comprising twelve Ministers from the Commonwealth, Victoria, New South Wales and South Australia was established 'to promote effective planning and management for the equitable, efficient and sustainable use of the water, land and environmental resources of the Basin'. In a short space of time the council has refocussed efforts on tackling shared resource management problems across the Basin. This approach recognises that no State will be left unscathed by the growing problems which beset the Basin.

Involvement of land and environment portfolios has broadened the perspective from which problems are looked at. Hitherto, administration of the RMWA had been dominated by the relatively narrow agenda of operational water authorities.

1987 Council Adoption in Principle of a Draft Salinity and Drainage Strategy

The Draft Strategy provides a long term framework for the co-ordinated management of River Murray salinity and land salinisation and waterlogging in the Murray-Darling Basin. Key features of the Strategy are:

(i) A program of works and measures to maximise net Basin benefits. The program strikes an optimum balance between measures to reduce River salinity and to control land salinisation and waterlogging;

(ii) A baseline for apportionment of rights and responsibilities of the respective States in relation to actions which influence the shared resource of the River; and

(iii) Cost-sharing arrangements for joint funding of a program of salt interception schemes to reduce River salinity.

1988 Formation of the Murray Darling Basin Commission

The new Commission exercises statutory responsibilities under the RMWA as well as advising Council on broader land, water and environmental matters.

LESSONS FROM THE PAST

Historically, interstate initiatives for managing the resources of the Basin have been about resolving conflicts after problems have emerged rather than forward planning to maintain the amenity of the shared resources. Several factors have contributed to this 'reactive' approach to interstate co-ordination, including:

(i) Lack of understanding of the longterm costs and consequences of development decisions;

(ii) The imbalance of power between States with competing interests. SA had everything to lose and little to gain by unfettered development of the shared resource, whilst the Upper States, to varying degrees, perceived they had little to lose and much to gain; and

(iii) Short term penalties for inaction were tenable for some if not all the parties even if the long term consequences were unthinkable.

This apparent lack of any community of interest lead Clarke (1982) to conclude that States were of their own accord incapable of resolving their conflicting interests. Recent developments give cause for greater optimism. Since formation of the Ministerial Council in 1985 substantial progress has been made in laying foundations for action on major problems in the Basin. By focussing on actions to maximise basin benefits from a national perspective the Draft Salinity and Drainage Strategy was able to find a way out of the endless squabbling over pre-existing rights and apportionment of 'blame'. Agreement on cost-sharing arrangements was relatively straightforward once it became clear that each of the States stood to gain substantial benefits from pursuit of national economic goals.

The uncharacteristic pace of progress on such complex problems is due in part to a growing concordance of self interest between the parties coupled with alignment of political wills to act.

It would be naive to ignore the competing needs and priorities of States. Also the difficulty of initiating and sustaining management programs with payback periods far greater than the three or four year political term of governments should not be underestimated. However the heightened awareness of problems amongst influential groups within the rural sector and the strength of the environmental movement as an electoral force are likely to maintain basin issues high on the political agenda.

Enduring interstate agreement on management Strategies for the Basin will only occur where:

(i) The perceived benefits to each State outweigh the costs;

(ii) The entitlements and obligations of each State for actions which affect the shared resource are precisely defined;

(iii) The instruments of co-ordination do not unduly interfere with institutional powers for internal resource management.

Before tackling issues like groundwater management, vegetation management, erosion control, wetland management and stream management we must ask what aspects, if any, are appropriate matters for interstate action. The answer is those aspects which can significantly compromise the uses of shared resources. Clearly stream stability, drainage and wetland management in the Murray River floodplain and River water quality fall into this category.

FUTURE CHALLENGE

We are entering a critical era of resource management where failure to act in time may mean losing the option of arresting and reversing the trend of degradation. This point has already been passed for some parts of the Basin. The initial program of measures forming part of the Draft Salinity and Drainage Strategy has bought time to allow more radical, high risk programs for land and water management to be evaluated. We are left with the sobering thought that decisions by this generation may determine the fate of the Basin irreversibly.

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RECENT HYDROGEOLOGICAL INVESTIGATIONS IN THE NORTHERN LODDON AND AVOCA CATCHMENTS, NORTHERN VICTORIA

M. Pratt, R.C. Lakey & P.G. Macumber
Department of Water Resources, Victoria

During the period 1985/86, the Victorian Department of Minerals and Energy has undertaken an extensive hydrogeological investigation in the northern Loddon and Avoca River catchments. The objectives of this investigation are to:

(i) establish a regional network of groundwater monitoring bores;
(ii) provide hydrogeological input to salinity investigations and management plans; and,
(iii) provide a more quantitative understanding of the hydrogeology of the region and establish an adequate data base for regional numerical modelling of the groundwater flow system.

Forty additional observation bore sites have been established. A review of all existing government and private exploration bore data has also been undertaken, together with a survey of the Rural Water Commission's extensive shallow observation bore network. This survey was undertaken to check construction detail, measure water levels and collect groundwater samples for analysis. This paper presents an overview of the results of this work.

GROUNDWATER PUMPING / RE-USE IN NORTHERN VICTORIA: RECHARGE PROCESSES, AQUIFER SALINISATION AND FARM PRODUCTIVITY

B. Prendergast and A.F. Heuperman

Institute for Irrigation and Salinity Research, Tatura 3616

INTRODUCTION

Shallow watertables and soil salinisation are causing agricultural productivity losses in the Shepparton Region of northern Victoria. Watertables must be controlled if irrigation is to remain viable because of inevitable economic losses and the high potential risk of environmental damage in areas where there is no drainage; salt disposal to the River Murray must also be minimised. Tile drainage is considered a less economical drainage option than groundwater pumping because pumpable aquifers exist under most of the region and pumped groundwater can be integrated into on-farm irrigation management with minimal disposal to the River Murray. This paper looks at the relationships between recharge, rootzone salinity and groundwater degradation which will ultimately determine the economic viability of the pumping/reuse strategy. Six years of data, collected on a 610 ha area, are used to look at problems encountered in the field application of this management system.

PUMPING / RE-USE: ITS EFFECT ON SOILS AND PRODUCTIVITY

In order to assess the implications of the regional hydrology on agricultural management, aquifer salinity and groundwater recharge must be seen in the context of plant yields. A simple model to describe this system can be envisaged by initially considering flows into and out of the system to be zero. This situation is not far from reality in the long term as flows into and out of the deeper aquifers will be minimal and lateral flows in local groundwater systems are small.

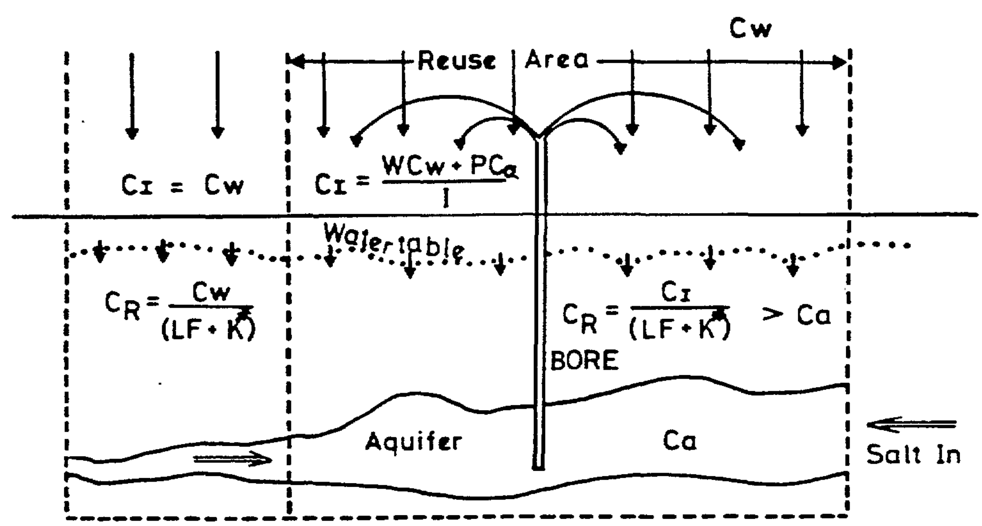


FIG 1: Groundwater Flow under Reuse of Groundwater.

The equations to describe this system are:

$$P = I.LF + K \quad (1)$$

$$IC_i = PC_a + WC_w \quad (2)$$

$$I = W + P \quad (3)$$

where P is the depth of pumped groundwater, I is the depth of applied water, W is the depth of channel water plus rainfall, LF is the leaching fraction, K is the depth of preferential recharge, C_i is the average applied water concentration, C_w is the concentration of channel water plus rainfall and C_a is the aquifer concentration. The preferential recharge and the leaching fraction are considered separately as the leaching fraction leaches salts from the plant rootzone and has a different affect on yields. Bernstein & Francois, (1973), derived the following relationship between rootzone salinity and irrigation water salinity

$$C_{\bar{s}} = [C_i \ln(1/LF)]\,(1-LF)^{-1} \quad (4)$$

where $C_{\bar{s}}$ is the average weighted root zone salinity.

They showed that this equation accurately described rootzone salinity in leaching experiments with alfalfa.

Solving equations (1), (2), (3), and (4) and setting $K^* = K.I$ yields

$$C_{\bar{s}} = \{C_w + [K^*(C_a-C_w) + LF\,(C_a-C_w)]\,(1-LF)^{-1}\}\ln(1/LF) \quad (5)$$

The relationship between rootzone salinity and leaching fraction can then be plotted for different aquifer salinities assuming values for C_w and K^*.

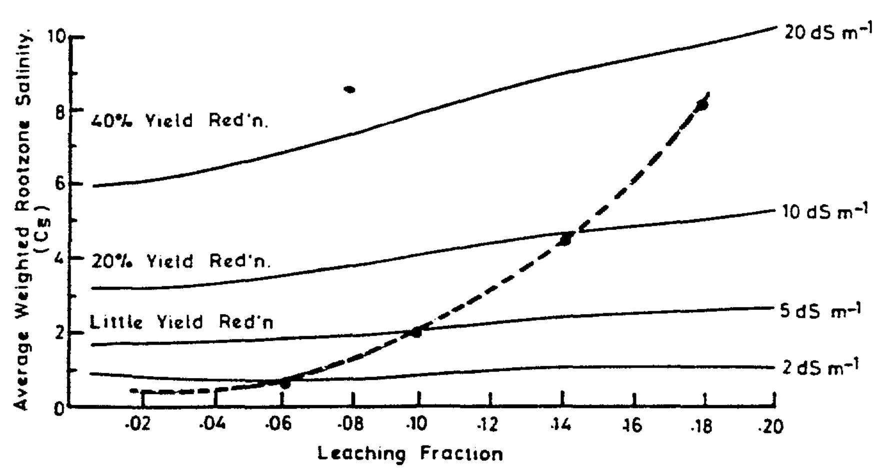


FIG 2: Rootzone Salinity in Perennial Pasture for Groundwater Reuse. (K^* = .05, C_w = 0.1)

The relationship between yield of perennial pasture, rootzone salinity and leaching fraction can be calculated from work done by Mehanni & Repsys (1986), and Lyle & others (1986) on Lemnos Loam, the most common soil type in the district. This is plotted with equation (5) to show how aquifer salinity affects yields of perennial pasture in different areas in the Region, by association with hydrogeological maps.

Recharge into and out of the system can be accounted for in the calculations by alteration of equation (1). Different agricultural practices can be described by these relationships and economic optimisation performed on these options to find the most appropriate management system for a particular area.

It can be seen in the long term that, as groundwater degrades, the operating point on Fig. 2 will move along the broken line to progressively higher rootzone salinities and thus decreased productivity levels. Therefore the maintenance of groundwater quality is a major priority of the re-use strategy.

GROUNDWATER DEGRADATION: THE TONGALA GROUNDWATER PUMPING/RE-USE PROJECT

Background

The project is located in the Shepparton Region, east of the township of Tongala in an area with traditionally shallow watertables. During the late seventies farmers became aware of the effects of this situation on their productivity and agreed to install groundwater pumps on their properties where feasible. Pump installation was encouraged by the 1982/83 drought and at the end of the 1982/83 season, 15 groundwater pumps were operational in the 610 ha project area. Pump location, soil types and observation piezometer sites are shown in figure 3.

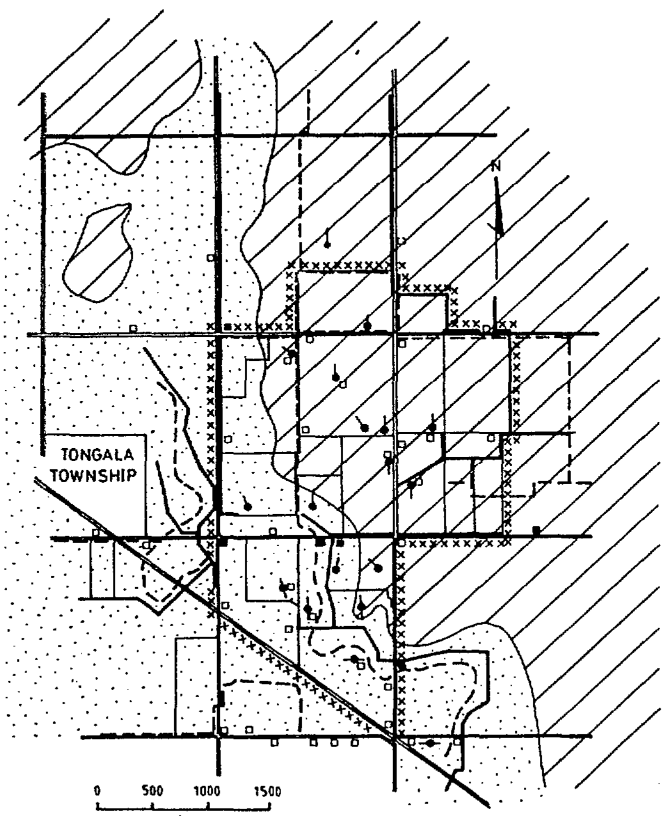


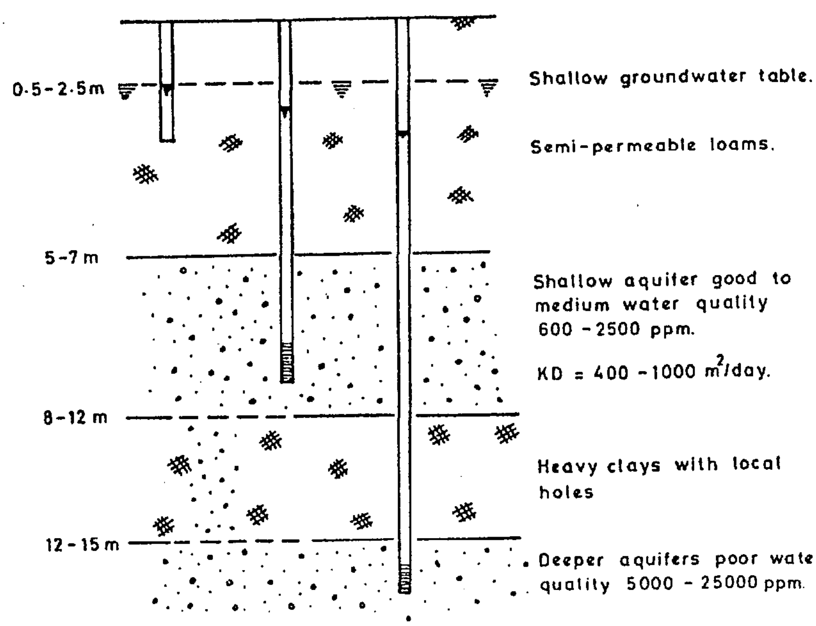
FIG 3: TONGALA PROJECT AREA

LEGEND:
- piezometer > 13m below N.S.
- piezometer < 13m. " "
- pump
- prior stream levee soils.
- flood plain soils.
- road
- railway
- channel
- drain
- farm boundary
- xxx project area boundary

Aquifer situation in the project area.

The pumps are extracting water from shallow aquifers in the Shepparton formation which are relatively narrow 'shoe-string sands', deposited in the channels of prior streams (Butler 1950, Macumber 1978).

FIG 4: General aquifer situation in Tongala area.



The aquifers are semi-unconfined and are in most cases underlain by heavy clays. At about 13m below surface another aquifer system is found at several locations in the project area. The two systems are locally inter-connected. Figure 4 presents a diagram of the aquifer situation in the project area.

Watertable levels, pumped volumes and degradation under re-use.

The three main processes that will alter the salinity of pumped groundwater under re-use management will be:

(a) irrigation salt inputs
(b) regional discharge from or recharge to deeper aquifers
(c) mixing of groundwaters through pumping

Irrigation salt inputs in the Tongala project area are about 300 tonnes per year. For salt balance to be obtained this would mean that about 220 ML per year would have to be disposed of. Failing to do this will result in an average increase in groundwater salinity of about 7 ppm TDS per year. Phreatic and piezometric levels in the project area are measured in a network of 69 shallow observation wells, 6 deep (13 m) and 24 shallow (13 m) piezometers. The average shallow watertable closely follows the piezometric pressure levels in the shallow aquifer system, showing its unconfined nature. Pressure levels in the deeper aquifer system are generally lower, indicating vertical recharge and salt leaching from the shallow aquifers.

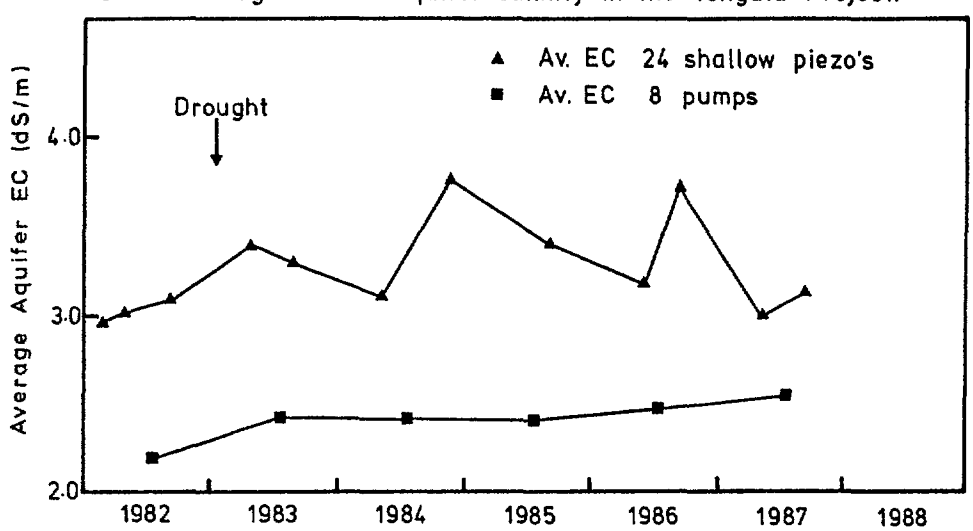
Heavy pumping of the shallow aquifer system during the 1982/83 drought brought the average piezometric levels in both groups close together creating a situation with potential saline water intrusion into the shallow aquifer. This situation will have been even more pronounced at the pumpsites where drawdowns in the shallow aquifer system reversed the downward pressure gradient in the profile.

Since the 1982/83 drought, average watertable levels in the area fluctuated between one and two meters below the surface which is generally considered safe for perennial pasture.

Extraction rates in the area over the last 6 years ranged between 1.6 and 3.2 ML/ha/year. Analysis of chloride profiles in the area gives LF's from nearly zero on the heavier soils to 20% on the lighter soils under re-use. The high pumping rates indicate that some of the extracted water originated from outside the reuse area, resulting in higher rootzone salinities than is necessary to maintain watertables in the reuse area.

Aquifer salinities as measured in the network of piezometers are presented in figure 5. The period of observation is not long enough to draw conclusions on long term trends. Degradation can be expected to increase when present vertical downward gradients approach zero.

FIG 5: Average shallow aquifer salinity in the Tongala Project.



CONSEQUENCES FOR THE FUTURE MANAGEMENT OF THE REGION

Once groundwater re-use becomes more widely adopted, yield reductions are likely to increase over areas of higher groundwater salinities if current management practices for perennial pasture continue. Greater use of more salt tolerant species such as lucerne will have to be considered.

Groundwater degradation is the principal environmental and economic problem associated with re-use. Disposal to maintain salt balance is unlikely to have a measurable short term effect on aquifer salinities.

In areas where good quality groundwater is surrounded or underlain by poorer quality water, low pumping rates and careful management will be essential to avoid accelerated groundwater degradation.

If watertable control is aimed for, the irrigation shandy quality is determined by both the recharge and the aquifer salinity. Therefore in areas where watertable control results in poor quality shandies, the pumped groundwater should be distributed evenly over the farm to minimise overall rootzone salinity. Where high pump intensities exist, sub-regional salt redistribution should be considered.

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EROSION AND DEPOSITION ALONG THE MIDDLE MURRAY: IS SALT INVOLVED?

Ian Rutherfurd
(Department of Geography, Monash University)
Mark Ellaway
(Department of Geography, Melbourne University)

The role of salt in soil stability is well documented. Salt can cause soils to either disperse, or flocculate. For a given soil the boundary between the flocculated and the dispersed states is dependant upon the sodium adsorption ratio (SAR), concentration of salts, pH and mineralogy (Heinzen & others 1977). This paper examines the possible influence of rising salinities in the Middle Murray (Torrumbarry to Lock 9) upon patterns of erosion and deposition since 1869.

Comparison of long profile surveys (published 1876, 1927, and 1981) shows that the bed of the Murray has generally aggraded since the 1920s (Rutherfurd, in prep.), with a significant zone of deposition below the Wakool Junction, across the Mallee (Figure 1). This zone corresponds with a dramatic drop in turbidity below the Wakool Junction (Figure 2). Despite the difficulties of relating turbidity to suspended sediment the assumption is made that suspended material is settling out in this reach of the river and contributing, to some degree, to the deposition across the Mallee. Cunningham & Morton (1983) conclude that salinity at Morgan is increasing at 2.53% per year (although other results suggest 1 - 3% per year at most locations (ACIL, 1983)). The mean gradient of the river bed increases to 14.5 x 10^{-5} between Nyah and the Wakool Junction, after which it drops suddenly to about 5 x 10^{-5}. Over the same reach salinity levels rise dramatically with the input from Barr Creek and the Loddon and Wakool Rivers. Could a threshold have been passed where increasing salinity causes flocculation of suspended clays, and the drop in gradient across the Wakool Junction combined with the effect of the Euston Weir pool, are enough to produce deposition?

There is also evidence of bank erosion between Albury and Wentworth with actively eroding banks and undermined River Red Gums, although there is no evidence that the rate of erosion has increased over the last century. Is it possible that salty Murray water flowing past the banks, or hypersaline groundwater seeps, could be encouraging erosion? Is this material then flocculated and deposited on the bed? In other words, does increasing salinity produce a redistribution of material from the banks to the bed of the Murray? If this scenario has any substance, rising water-tables across S.E. Australia may influence channel morphology in many streams. Further, the salinities involved may be lower than previously considered important.

Laboratory Tests

Bank material and water samples from seven sites between Torumbarry and Lock 9 were collected by the Murray Darling Basin Commission in March 1988. Salinities were low, turbidities varied relative to the mean for these sites. Particle size, measured with a Malvern laser particle analyser, was not a good indicator of particle size (r = 0.24; Table 1). However when placed in an ultrasonic bath, particles in saltier water generally decreased in size more than particles in less salty water, suggesting that flocculation may be influencing particle size — even at the low salinities measured in the Murray.

FIG 1: DIFFERENCE IN MEAN BED ELEVATION: RIVER MURRAY, 1876 TO 1981.

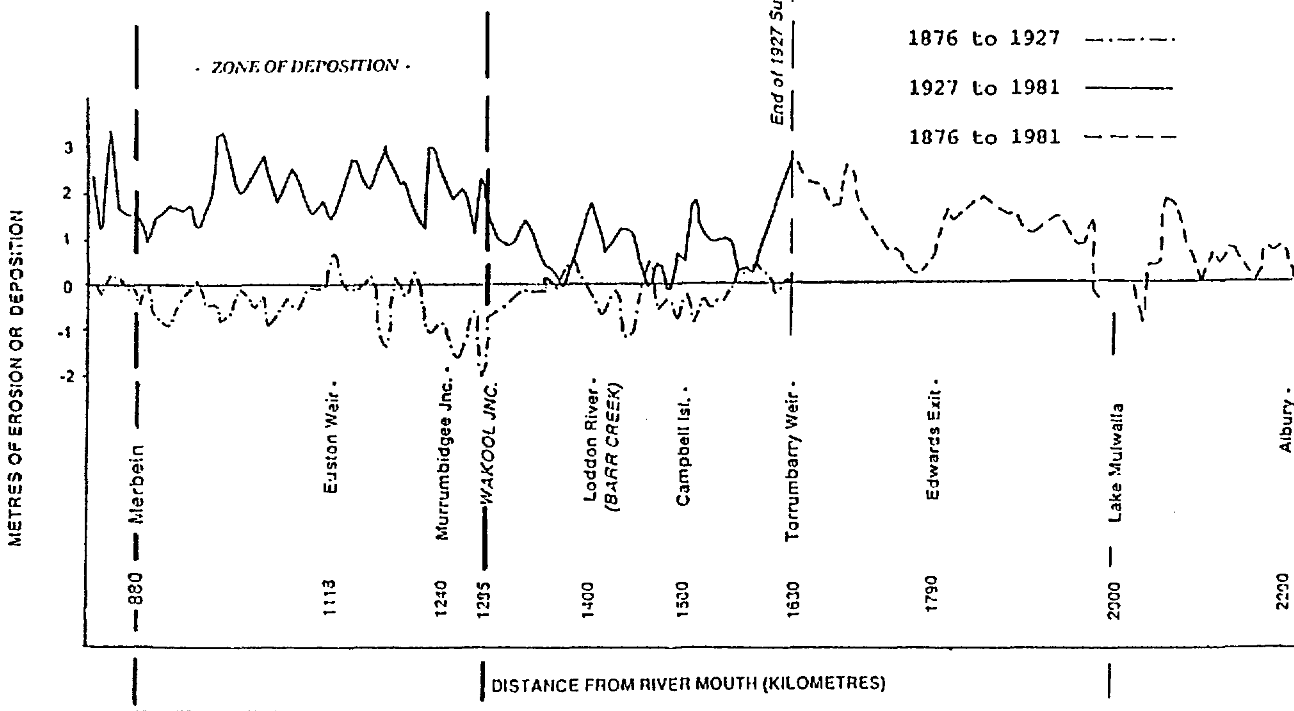
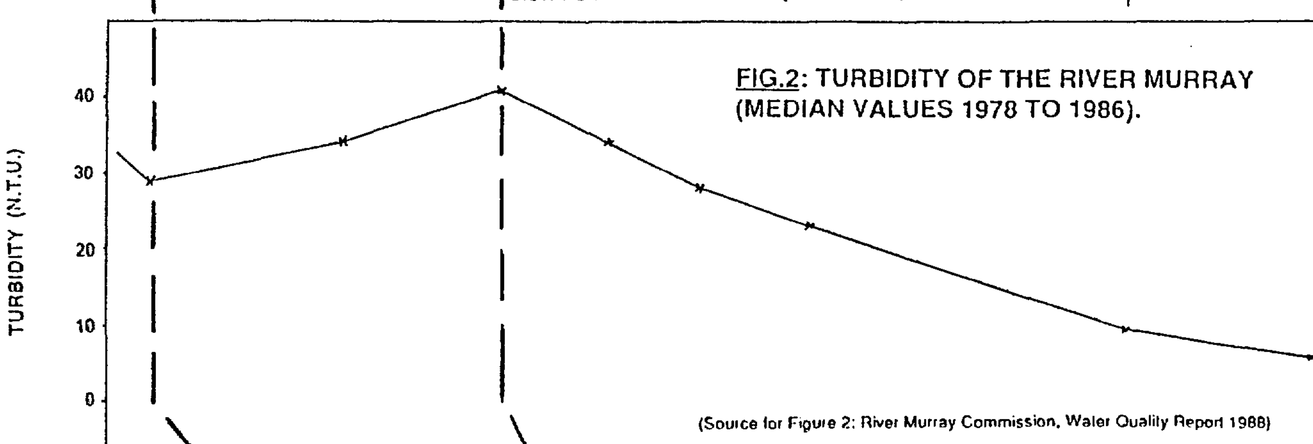
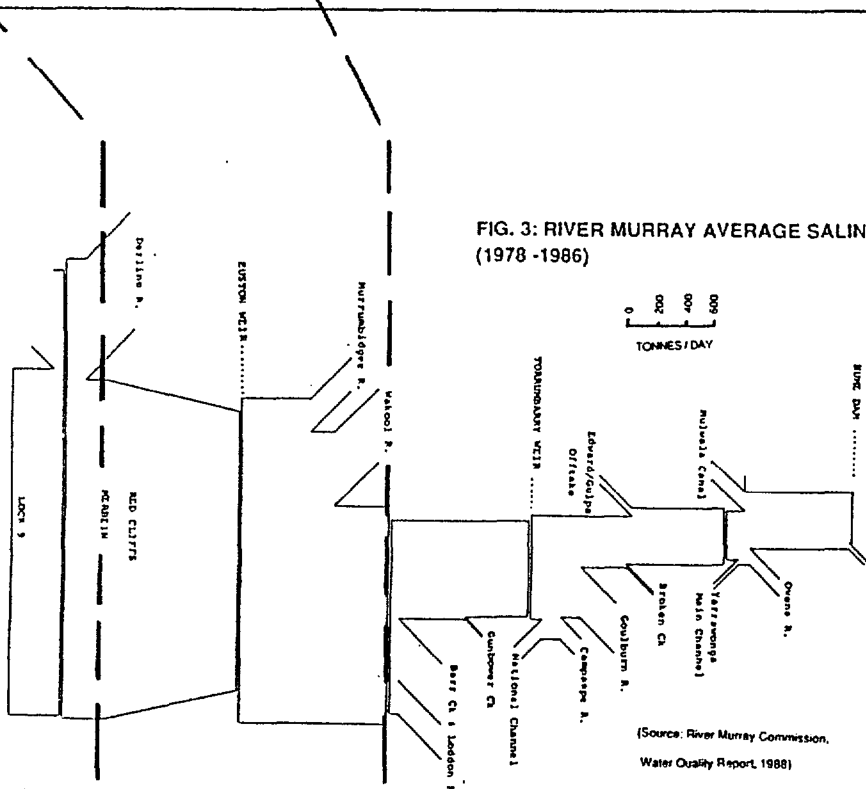


FIG.2: TURBIDITY OF THE RIVER MURRAY (MEDIAN VALUES 1978 TO 1986).



(Source for Figure 2: River Murray Commission, Water Quality Report 1988)

FIG. 3: RIVER MURRAY AVERAGE SALINITY LOADINGS (1978 -1986)



(Source: River Murray Commission, Water Quality Report 1988)

TABLE 1: RIVER MURRAY WATER SAMPLES: MEASURED PARAMETERS.

	TORRUM-BARRY	BARR CK.	SWAN HILL	WAKOOL RIVER	D/S WAKOOL	EUSTON	MERBEIN	DARLING RIVER	LOCK NINE
SALINITY (E.U.25 C)	78	3391	244	171	224	197	355	838	444
MEAN PARTICLE SIZE (um)(Run 1)	8.7	18	9.7	8.7	11.3	8	11.4	8.3	14.4
MEAN PARTICLE SIZE (UM)(RUN 2)	7.8	10.6	7	(?)	7	5.6	6.9	(?)	5.7
DIFFERENCE IN PARTICLE SIZE	0.9	7.4	2.7	(?)	4.3	2.4	4.5	(?)	8.7

Bank Samples

If material is eroded from the banks, will increased salinities in the river reduce the distance that bank material will be transported, because of flocculation? This was tested with silt and clay from the Murray's banks in a still settling tube, using turbidity as a measure of settling rate. Calles (1983) found that salinities over 500 mg/L increased settling rates, and this is confirmed here, although we found a significant effect at salinities down to 100 mg/L. The problem is whether the flocculated particles could survive any turbulence. Calles (1983) suggests that flocculation becomes easier with each resuspension. This is being tested by repeatedly resuspending samples and measuring the settling rates.

Dispersion of Bank Sediments

The influence of salt upon bank resistance is being tested on bank samples using Eckman's Dispersion Test, and the Pin-Hole Test (Sherard & others 1976). The latter gives a qualitative measure of resistance to erosion. Other work in progress; is the sampling of bed material above and below the Wakool Junction, identification of any salt wedging below the Loddon or Wakool Junctions, and the possible role of salt crystals in physically breaking-up bank material.

Provisional Conclusions

Some flocculation seems to be occuring even at the low salinities presently experienced in the Murray. Low salinities also increase settling rates in a still column of water. More evidence is needed before the pattern of erosion and deposition in the Middle Murray can be attributed to rising salinities.

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IDENTIFICATION OF LOCAL GROUNDWATER SYSTEMS INFLUENCING WATER QUALITY IN THE OVENS AND KIEWA HIGHLAND TRIBUTARY VALLEYS

A. Shugg

Victorian Department of Water Resources

Groundwater investigations in the Upper Ovens and Kiewa Valleys started in a systematic manner in the 1960's. An appraisal of the valley floor sequences was initiated and attempts to trace the Calivil Formation equivalent, or 'deep leads' are made. In the middle of the last century gold miners in Morses Creek a tributary of the Ovens at Bright had mined the deep leads for gold.

Detailed groundwater investigations have been carried out in the Kiewa Valley at Kergunyah, and in the Ovens Valley at Myrtleford, Barwidgee and Bright.

The tributary valleys of the Murray River; the Ovens, Kiewa and Mitta Mitta upon entering the highland and alpine portions of their catchments become confined to steep, long narrow valleys with limited flood plain floors. In this portion of their tract they change from meandering to braided streams. The long strip like valleys extend 60 - 200 kilometres into the mountains and have flood plain widths ranging from 1 - 8 kilometres. They become valleys of considerable topographic and hydraulic relief.

The valley catenaries; the stream and thalweg and valley wall elevation show a development of considerable relative displacement, with relief exceeding 500 m in the upper catchment. Outcrops of the water table as elevated valley wall springs and in bedrock mine addits occur at elevations several hundred metres above the perennial stream thalweg and within a horizontal distance of four kilometres. Within this framework large groundwater fluxes may be anticipated.

In the alluvial valley floor sequences of the Ovens River and Kiewa River local groundwater flow cells have been identified with a discharge locus being coincident with the perennial gaining stream. A positive vertical upward hydraulic gradient of 0.05 or more may be attained in the vicinity of the gaining stream. Long term monitoring of observation bores has revealed that the magnitude of the gradient fluctuates and has a seasonality.

Groundwater quality in the highland portion of the river valleys systems does not usually exceed 400 mg/L for total dissolved salts. Although the local accumulation of soil salts has been noted in the Ovens Valley near Myrtleford.

The groundwater chemistry in the highland valleys shows some specification within the flow systems with differentiation possible within the alluvial and the bedrock sequences. Differentiation is on the basis of major ion chemistry, total iron, sulphate and bicarbonate concentrations. The chemical facies enable the following tentative breakdown of the groundwater flow systems; apron and colluvial fan deposits, shallow alluvial, deep alluvial, shallow bedrock and deep bedrock.

Permeability estimated for Ordovician bedrock systems and its saprolitic derivative have been based upon specific capacity data. These indicate that in the highland reaches of these valleys that permeability overlap with the alluvial sequence may occur in the range 0.5 - 10 m/d. That permeability resolution is in the upper reaches may be insignificant and facilitate the communication between the groundwater chemical facies.

WOOLPUNDA GROUNDWATER INTERCEPTION SCHEME: CAUSE AND EFFECT

Andrew Telfer

Engineering and Water Supply Department, GPO Box 1751, Adelaide, SA., 5001

The Woolpunda Groundwater Interception Scheme (WGIS) is to be built along the River Murray in South Australia between Waikerie and Overland Corner (Figure 1) to intercept saline groundwater discharge into the River Murray. The interception scheme is being constructed on behalf of the Murray-Darling Basin Ministerial Council and is an important element in the strategy aimed at combating river salinity increases, rising water levels and land salinisation throughout the Murray Basin.

Two aquifers dominate the hydrogeology in the WGIS Project Area; the unconfined Murray Group limestone aquifer and the confined Renmark Group aquifer. They are separated by the Ettrick Formation aquitard.

The Renmark Group aquifer is recharged at the Basin margins and regional groundwater flow is toward the northern River Murray in South Australia (Figure 2). This region must therefore be a major discharge zone for the Renmark Group confined aquifer. In the discharge zone the head difference between the two aquifers induces upward leakage of groundwater from the Renmark Group aquifer to the Murray Group aquifer. The upward leakage contributes to the maintenance of the natural groundwater mound approximately 15 km south of the River and to the similar though less well defined mound north of the River (Figure 1). These mounds control groundwater discharge into the River Murray in the Project Area. Therefore, basin-wide hydrodynamics are causing Renmark Group groundwater to discharge into the River

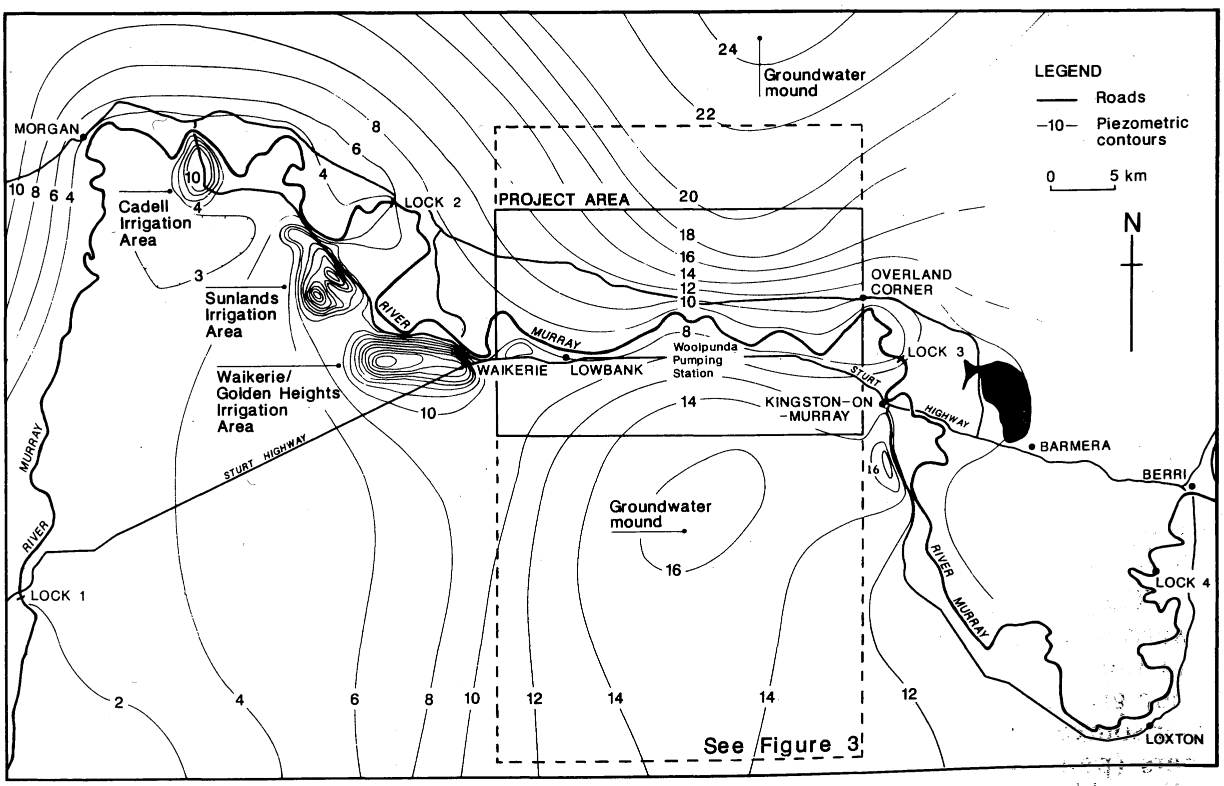

FIGURE 1 WATER TABLE CONTOURS - MURRAY GROUP AQUIFER

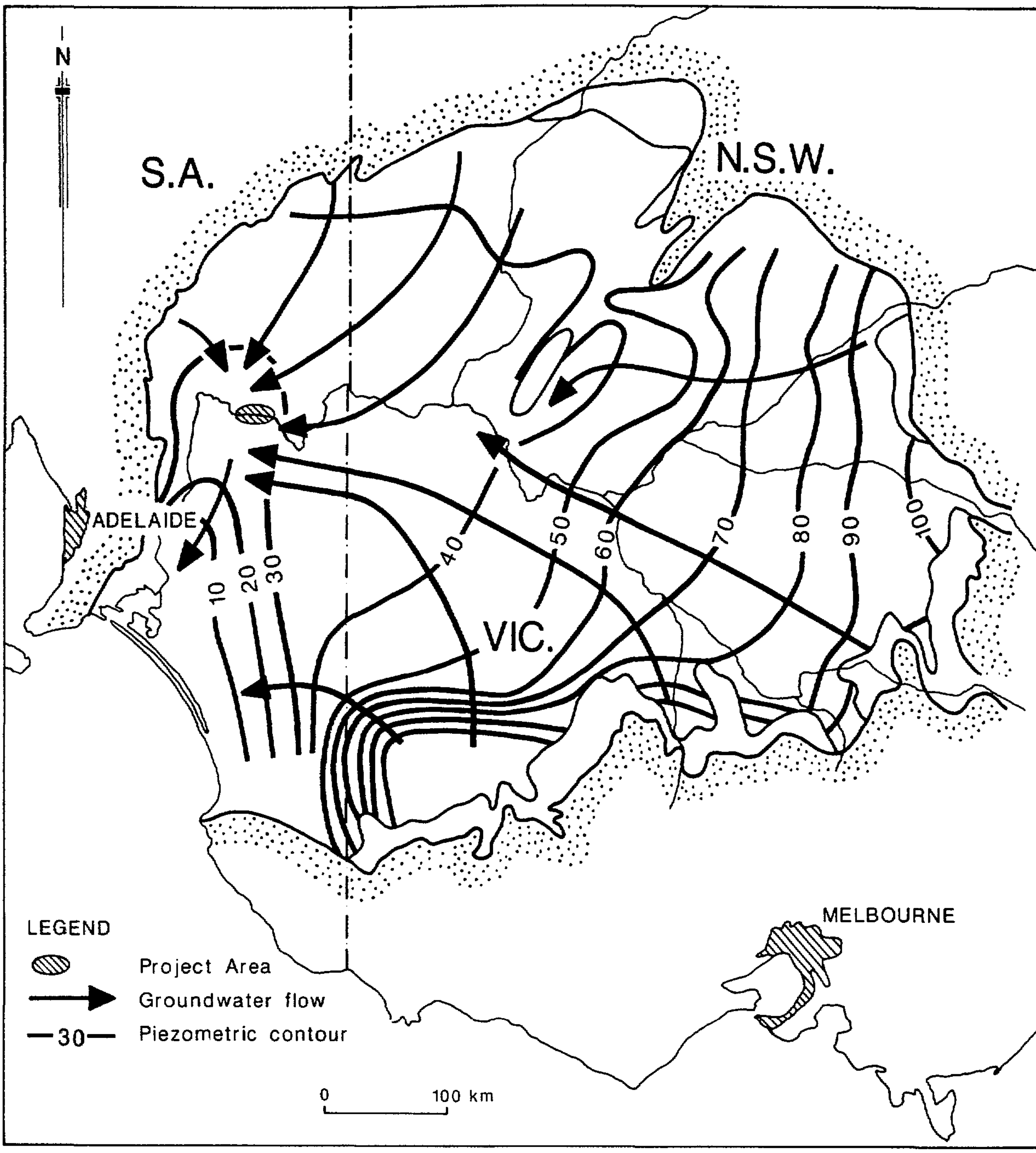

FIGURE 2 PIEZOMETRIC SURFACE AND FLOW LINES OF THE RENMARK GROUP AQUIFER

Murray via the Murray Group aquifer. The following hydrochemical data supports this concept.

The River Murray separates two distinct hydrochemical populations (Figure 3). Within each population the Murray Group groundwater is hydrochemically similar to or a dilute equivalent of Renmark Group groundwater (Figure 3).

The hydrochemical similarity of the aquifers and the observed potential for upward leakage indicate that the Murray Group groundwater has been largely derived from the Renmark Group aquifer in this area. However at some sites the Murray Group groundwater appears to have been diluted by low salinity water from another or other sources (Figure 3). This dilution is consistent with the identification by Allison & others (pers. comm.) of flushed zones in areas of internal drainage in the Murray Mallee which indicate anomalously high rainfall recharge rates.

The existence of two distinct hydrochemical populations separated by the River Murray indicates that flow in all aquifers is toward the River. This flow pattern occurs

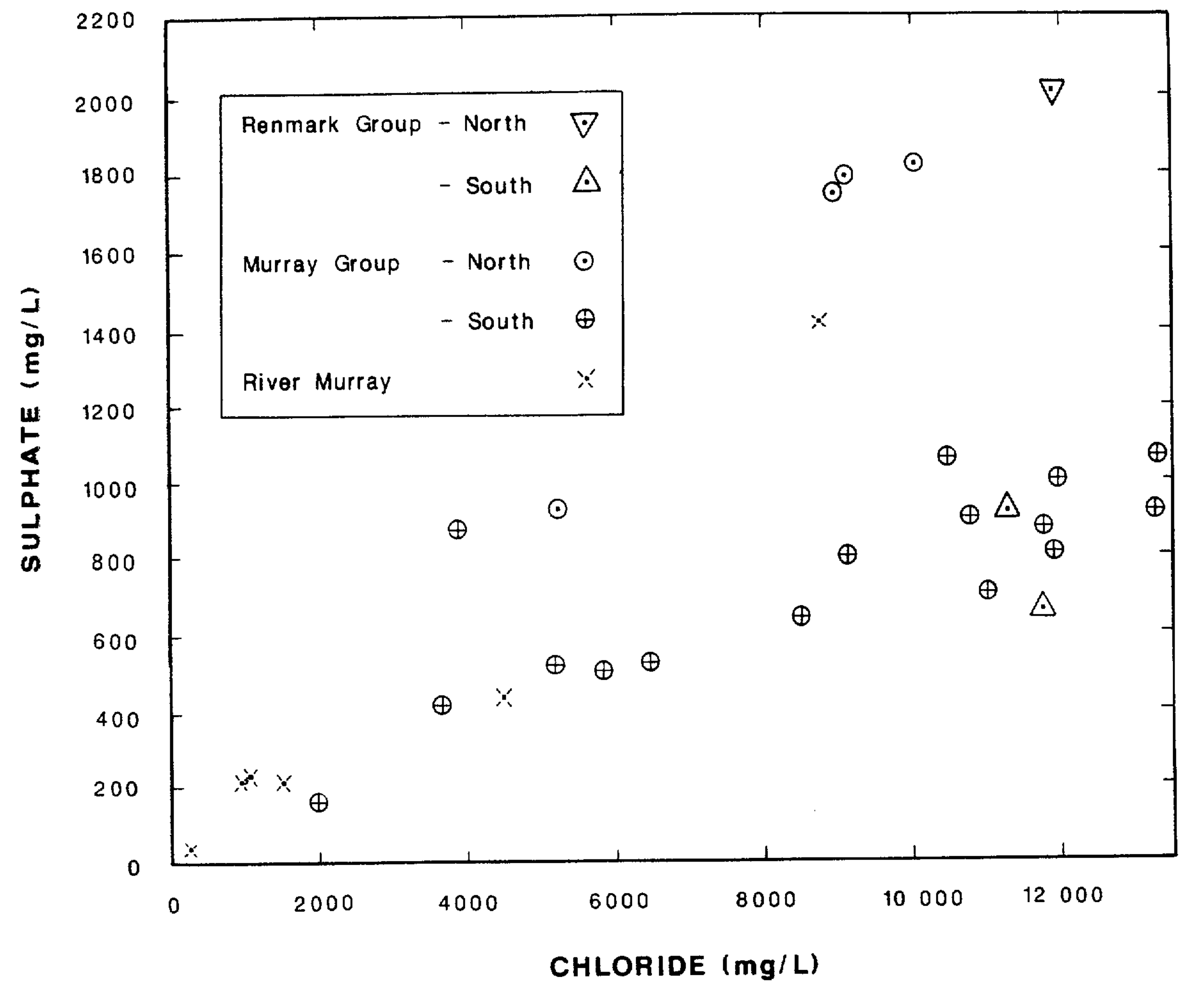

FIGURE 3 HYDROCHEMISTRY OF THE AQUIFERS IN THE PROJECT AREA

because the River is the hydraulic boundary for the Murray Group aquifer and controls the shape of the water table (Figure 1), which in turn controls the potential for upward leakage from the Renmark Group aquifer (Telfer, 1987a).

The distribution of groundwater discharge into the River Murray is influenced by the bathymetry of the River and the density contrast between 450 mg/L river water salinity and 20 000 mg/L groundwater salinity. These two variables combine to generate a hydrostatic head which varies with river depth. The hydrostatic head differential at any datum beneath the River can vary by up to 0.26 m, assuming a River depth differential of 13 metres. River depth can vary from 2 metres to 15 metres in any River reach. Conceptual computer modelling has shown that this hydrostatic head difference is capable of redistributing regional groundwater flow over a radius of several hundred metres from the deepest sections of the River (trenches). Since the trenches are elongate parallel to River flow and are therefore well flushed, they are the focus for a large proportion of the groundwater discharge to the River.

The density driven discharge mechanism has been observed and measured on the River (Telfer, 1987b)). Water samples collected from the bottom of two trenches can be identified as deriving from either the north or south hydrochemical population (Figure 3).

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HYDROGEOLOGY OF THE VICTORIAN MALLEE TRACT OF THE MURRAY RIVER

Rob Thorne and Greg Hoxley
Rural Water Commission of Victoria
590 Orrong Road, Armadale, Victoria 3143

INTRODUCTION

The hydrogeology of the Victorian Mallee Tract of the Murray River has been studied intensively during the Nyah to South Australian Border Hydrogeological Investigation, preliminary results of which have been reported by Thorne, (1987).

The aim of the study was to investigate the hydrogeology of the region between Nyah and South Australian border adjacent to the Murray River, to make assessments of the impact of irrigation on the aquifers in the area, and thus, the effect on the Murray River. The understanding gained is to be used in management of irrigation developments.

An overview of the findings are presented and the results of groundwater models that have been developed for the stuy area are summarised.

GEOLOGY

The investigation has concentrated on the shallower deposits in the region that contain aquifers which may react to irrigation. The main unit of relevance is the Parilla Sand, a marine deposit 30 to 60 metres thick, consisting of fine to medium sands which are frequently silty or clayey, but tending to be cleaner in the western part of the study area. There is an associated upper finer grained unit that may have a lateritic weathering profile developed, although in some cases this has been fully or partially eroded.

Overlying the Parilla Sand, in most areas, is the fluviolacustrine Blanchetown Clay, which consists of predominantly clays to silts, with thin sand deposits being not uncommon. This is overlain by the aeolian Woorinen Formatiron of calcareous clays and linear sand dunes.

Into this landscape the ancesteral Murray River Systems have incised a trench that varies in both width and depth over the study area. Within this trench four alluvial terrace systems have been recognised. In general, the river systems have deposited a continuous sand unit that forms the Channel Sands. These sands are medium to coarse grained with minor clayey lenses, overlain by alluvial floodplain material that consists of clays and sandy clays.

The Tertiary sediments have been shown to be considerably affected by tectonic action and a number of fault movements have truncated or warped the Parilla Sand aquifer, disturbing the hydraulic flow in the region. This activity does not appear to have affected the Channel Sands unit directly but has controlled the extent of its deposition and the morphology of the Murray Trench. The situation in the Mallee tract is thus complex with, in general, a two aquifer system that has been affected by tectonics.

HYDROGEOLOGY

The two aquifers in the Study area are the Parilla Sand and Channel Sands aquifers. These may be separated by an aquitard, the Blanchetown Clay, although this is not always the case. In general the Parilla Sand aquifer contains highly saline water

(30,000-50,000 EC) while the Channel Sands aquifer is fresher with a wide range of values (1,000-30,000 EC).

The Channel Sands aquifer is in direct connection with the Murray River and the water levels nearer to the river respond to flood events in the river. This aquifer may become confined at the high flow stages due to the overlying floodplain material. No steady state level has been observed in the Channel Sands, it is perpetually rising and falling nearer the river. This effect has diminished to be imperceptible, in most cases, by 2 km from the river. Where the Parilla Sand is separated from the Channel Sands, there is no response to river floods in the Parilla Sand. There are cases where the Parilla Sand is in direct connection with the river (either via the Channel Sands with no intervening aquitard, or where the Parilla Sand is at surface) and a response to flood events is seen.

The Parilla Sand aquifer is mostly confined over the area of the study, with the confining layer being the Blanchetown Clay or the weathered upper Parilla unit. There are significant areas, however, where the Parilla Sand is unconfined.

The responses in the aquifers indicate that for some time of the year the Murray River recharges the aquifer systems along its banks. On an annual basis, in most areas however, the situation is either near neutral or the aquifers have a net discharge to the river. There are exceptions, near Nyah for example, where the river recharges the aquifers for the entire year. An opposite example is near Merbein where there is groundwater discharge for the entire year into the river, hence, the need for the Mildura-Merbein Groundwater Interceptin Scheme.

With the varying hydrogeological environments and water quality along the river there are a number of possible aquifer responses to irrigation. For this reason eight groundwater models have been developed that covered the eight type-cases of hydrogeological environments encountered.

GROUNDWATER MODELLING

Models covering the eight type cases were developed using a finite element, quasi-3-D multi-layer groundwater model (AQUIFEM-N, Townley, 1987). In all cases the Murray River is modelled as a third-type boundary (partial penetration). The models are calibrated against observed piezometric responses in bores. In general the models cover areas about 20 by 20 kilometres. Within the models are both irrigated and non-irrigated areas. The irrigated areas contain both tile-drained and non-drained areas with the drainage water disposed of by a variety of methods.

Irrigation input in the models is treated as recharge direct to the aquifer. This means that a proportion of the applied volume of irrigation water has actually accessed the water table. Calibration runs were done assuming 10% of the applied volume accessed the water table. Production runs were done with accessions at 1%, 10% and 30% of applied volume as these values were expected to cover the range of all possible values. Within the modelled areas are allotments that have applied for extra irrigation water. These were incorporated into the model as extra irrigation with 1%, 10% and 30% of applied volume accessing the water table. The increase (or otherwise) in flow of groundwater to the river was calculated for each model.

The modelling is being used in conjunction with hydrogeological sections to develop indications of the sensitivity to irrigation in relation to effects on the river. This work is still in the preliminary stage but when completed, it will assist the assessment of the potential effect of extra irrigation applications in the Nyah-border Region.

CONCLUSIONS

There are different areas of susceptibility to irrigation-induced saline groundwater displacements along the Murray River between Nyah and the South Australian Border and these are being delineated and quantified. This information will be used to plan future irrigation, both new and existing irrigation transferred to new locations. This will enable better planning or irrigation in the region to reduce the irrigation effects on the Murray River quality.

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IRRIGATION RECHARGE

W. Trewhella

Rural Water Commission of Victoria, Tatura

INTRODUCTION

Water table levels have risen throughout the irrigation areas in the Murray Basin as a result of the clearing of the natural vegetation and the introduction of intensive irrigation of relatively shallow rooted crops. The processes causing increased recharge are generally well understood at the macro scale, but knowledge of the actual rates is still relatively imprecise. The paper discusses the processes and gives typical recharge rates for the Mallee Zone and the Riverine Plains areas. The problems of getting more accurate information are discussed for both the regional scale and the local scale. It is suggested that what is known is adequate for making decisions on priority regional issues, with the understanding that continual monitoring and review will allow refinement of current estimates, and enable the effects of future changes in land use and management to be incorporated.

THE MALLEE ZONE

In the Mallee Zone the most intensive irrigation occurs mainly on the sandy soil types of the Woorinen Formation. These have been developed predominantly for high value horticultural crops and vines. Because of their light texture and generally undulating topography recharge rates are potentially high. Rainfall is generally only about 200mm/yr, and recharge is dominated by direct irrigation recharge, and also by channel seepage in areas where unlined open channels are in use.

The sandy topsoils are often underlain by heavy subsoils, but sometimes have almost unrestricted connection to the underlying Parilla Sands or alluvial aquifers in the river flood plain. Where the subsoils are heavy a local recharge/discharge pattern occurs, with little nett recharge at the regional scale unless the irrigated areas are subsurface drained. Where tile drains have been in use for many years, leaching of the subsoils is often well advanced and an approximate salt balance exists. Where the subsoils are relatively light, significant nett recharge occurs and major rises in regional water table levels result. As the underlying groundwater is almost universally very saline, large amounts of salt can be displaced to the land surface or the Murray.

With poor irrigation management recharge rates of 300 to 500mm/yr can occur. There is therefore great potential to reduce these accessions by the use of improved management, particularly better irrigation scheduling or microjet or drip irrigation. Artificial lining or piping of irrigation supplies also allows significant reductions in recharge, and particular care is required in the siting of water storages or evaporation basins.

RIVERINE PLAINS AREAS

It is likely that little recharge occurred on the Plains prior to development. The regional 'deep lead' aquifers were predominantly recharged in the highlands and discharged to the western parts of the Plains and the Mallee. The 'shoe string' sands of the Upper Shepparton Formation were probably unsaturated to about 30m below surface over much of the Plains. In the Kerang and Wakool Regions, however, water tables were closer to surface prior to development. Regional water table levels would have been similar to the piezometric levels in the 'deep leads'.

Intensive irrigation has been accompanied by the rapid development of high water tables and soil salting. Local recharge from rainfall and irrigation has caused the complete saturation of the most shallow aquifers and the overburden soils. Local high water table mounds have merged to form almost continuous sub-regional water tables associated with these aquifers. While water table levels were low unrestricted recharge occurred from all the overlying soils. However, as water table levels rose close to the surface, a complex pattern of local recharge and discharge has developed, with the shallow aquifers linking the recharge and discharge areas. The distribution of recharge and discharge is determined by many variables at the local scale, but in many cases the nett recharge over such areas is small. Part of the water entering the groundwater body continues downward as nett recharge to the Lower Shepparton Formation aquifers, and the 'deep leads', where present. However, the groundwater flow budget is commonly dominated by transfers occurring within the shallow aquifers at a local or subregional scale.

Observation of water table behaviour and of government and private pumping has lead to a workable knowledge of the groundwater budget for the more shallow aquifers. However, although it is clear that a proportion of the recharge water is dissipating to the deep aquifers, and raising pressures in them, the processes are less well understood. This leakage may be due to lateral dissipation of water table mounds away from the shallow aquifers; through interconnection of aquifers at various levels; by direct recharge of those deeper aquifers which are not overlain by the shallow aquifers; or (most likely) by all these processes. Little is known about the aquitards between these aquifers, and it is not even certain that they are all fully saturated. Although there are reasonable data about salinities in all the aquifer systems, there are virtually no data about the aquitard salinities at depths below 20m. This may prove to be a very significant data gap if development of the underlying deeper aquifers is encouraged.

The 'deep lead' aquifers are also believed to be receiving increasing recharge from the highlands and foothills. It is assumed that the persistent piezometric level rises occurring on the Plains are due to increased recharge from both the upland areas (dryland) and the Plain (irrigation areas). Improved modelling of these regional aquifers is needed to quantify the interaction between the irrigated and dry land areas. There is also a need for more detailed investigation and modelling at a sub-regional scale of the bed rock aquifers in those areas which lack any significant alluvial aquifers e.g. east of the Goulburn River and adjacent to the foothills near Rushworth in the Shepparton Region.

The Kerang Region clearly demonstrates the need to maintain both a regional and a local perspective of the recharge processes. Much of the region is a regional discharge zone but there are many local recharge areas which are profitably farmed, and are in reality recharge areas. The salinisation process is dominated by the local rather than the regional groundwater flows, with the major groundwater inputs resulting from local irrigation and rain largely balanced by local discharges to the land surface or by seepage to the drainage system, even though local transfers of groundwater may sometimes occur via the deeper Parilla Sand aquifers as well as through the Shepparton Formation. However, the real significance of the regional groundwater discharge lies in its high salinity, such that even 1mm/yr at 30000 EC units introduces a salt load comparable to that introduced with 300mm/yr of irrigation water at about 100 EC units.

The paper briefly discusses the methods used to obtain estimates of both direct recharge to the shallow aquifers and the residual leakage to the deeper aquifers. These include water balance studies, soil chloride leaching studies, artificial tracers and lysimeters for surface recharge estimates; and geochemical and isotopic analyses to estimate vertical fluxes through the deeper aquifers. These studies provide representative point values for various soil types and land uses, and allow some broad regional estimates to be made. However, it is still impossible to make accurate estimates at the local scale without intensive data collection because of the variability of the key factors determining recharge.

Groundwater modelling has recently been used in Victoria to estimate the major components of the groundwater flow budget. Results and limitations of this modelling are discussed in the paper.

The paper will contain a table of typical values for recharge and 'deep seepage' drawn from all the work discussed. These will include representative values for common Victorian soil types under perennial pasture irrigation, together with integrated recharge values for several localities based on chloride leaching studies and groundwater modelling. The limitations of these values will be discussed. The significance of rice cultivation in the New South Wales regions will also be discussed.

OPTIONS FOR REDUCTION OF RECHARGE IN THE RIVERINE PLAINS

Options for reduction of recharge include:

- channel sealing or seepage interception
- extending surface drainage to additional areas
- improved irrigation management
- within farm restructuring and/or changes to agronomic practices.

Each of these options has the potential to reduce the magnitude of the salinity problem and must be implemented where appropriate. In some specific locations reduction of channel seepage or introduction of surface drainage may relieve acute local problems. However, at the regional or sub-regional scale the resulting reduction of recharge is likely to be small, although surface drainage clearly provides other benefits as well. Changes in irrigation management and within farm restructuring can be important at the local level, and may in some cases have effects at the sub-regional scale. Selection of suitable soil types for rice growing is clearly an important issue in New South Wales, while a shift from extensive annual pasture irrigation to intensive perennial pasture irrigation may reduce recharge in Victoria. Changes in agronomic practices offer some scope for reducing gross recharge through the introduction of commercially attractive deep rooting crops, and for reducing nett recharge by utilising saline water from sub-surface drainage to irrigate salt tolerant crops. However, it seems inevitable that the combination of intensive irrigation and moderate (but variable) rainfall on the Riverine Plains will continue to produce much higher recharge rates than the local and regional aquifer systems can safely accommodate. The alternatives are atificial subsurface drainage or the acceptance of permanent high water tables, saline areas, reduced agricultural productivity, and continuing environmental destruction.

THE EFFECT OF TREE REMOVAL AND AFFORESTATION ON DRYLAND SALT DISTRIBUTION IN THE MURRAY-DARLING BASIN

B. Williams[1], J. Walker[1] and J. Ive[2]

[1] CSIRO, Division of Water Resources, P.O. Box 1666, Canberra, 2601

[2] CSIRO, Division of Wildlife and Ecology, P.O. Box 84, Lyneham, 2602

The excessive removal of native and forest vegetation for agricultural and pastoral development has been identified as a major cause of rising groundwater tables and salinisation of surface soils in the Murray-Darling Basin and elsewhere in Australia.

The time taken for these adverse effects to become apparent depends on the climatic regime of the particular region, the type and intensity of land-use implemented, depth to the water table, groundwater salinity and aquifer properties.

In an attempt to ameliorate the undesirable salinisation effects of clearing vegetation, particularly in areas of high groundwater recharge, there are presently numerous Departmental and Community reafforestation projects in operation. However, because of the long-term nature of groundwater responses to tree planting there is yet no generalised solution to questions of the appropriate tree densities required, the geographical locations most likely to benefit and the likely time response of salinity profiles to tree planting.

An alternative approach to this problem is to examine what effects of various degrees of tree clearing and/or natural regeneration in areas of native vegetation has had on salt redistribution in the landscape. In other words the long-term 'experiments' are already in place in most, if not all, parts of the Murray-Darling Basin. By careful selection of sites with known land-use histories it is possible, in a relatively short time period (2-3 years), to identify areas that would most benefit from a reafforestation program.

There are a number of independent observations which support this hypothesis.

1. Greig & Devonshire (1981) obtained quite a reasonable relationship between stream salinity in Victoria and three variables – rainfall, sedimentary geology and degree of forest cover.
2. Ive & Walker (1987, in press) modified the Greig & Devonshire approach and developed a dryland salinity hazard map of Victoria based on 1595 grid cells, each of about 40km^2 (Figure 1). This map correlates extremely well with the dryland salinity map for Victoria (Boruvka & Matters, 1987) which was produced on the same 1/8 degree grid cell basis. Also the Ive & Walker model has been used to predict those areas which can sustain further clearing without increasing the salinity hazard.
3. Walker & Williams (unpub.) used electromagnetic induction (EM) near Goondoowindi to estimate the relative salt concentration to a depth of 7.5m in areas having known histories of tree removal and/or regeneration. For that geo-climatic environment it was apparent that salt concentrations in the upper profile increased markedly, over a 20 year period, if the number of trees was reduced to less than about 90 stems/ha (Figure 2). Also areas of natural regrowth required periods of 20 to 40 years to reverse the salt accumulation process (Figure 3).

It would be rash to extrapolate this present evidence to form definite statements for the whole of the Murray-Darling Basin but it does point the way to an improved methodology for tackling such a large area. In the first instance Carnaghan's (in press) vegetation map can be used to update the percentate tree cover for all parts of the Basin. Similarly climate data can be interpolated from the surface fitting MAPCON

Dry land salinity hazard estimates

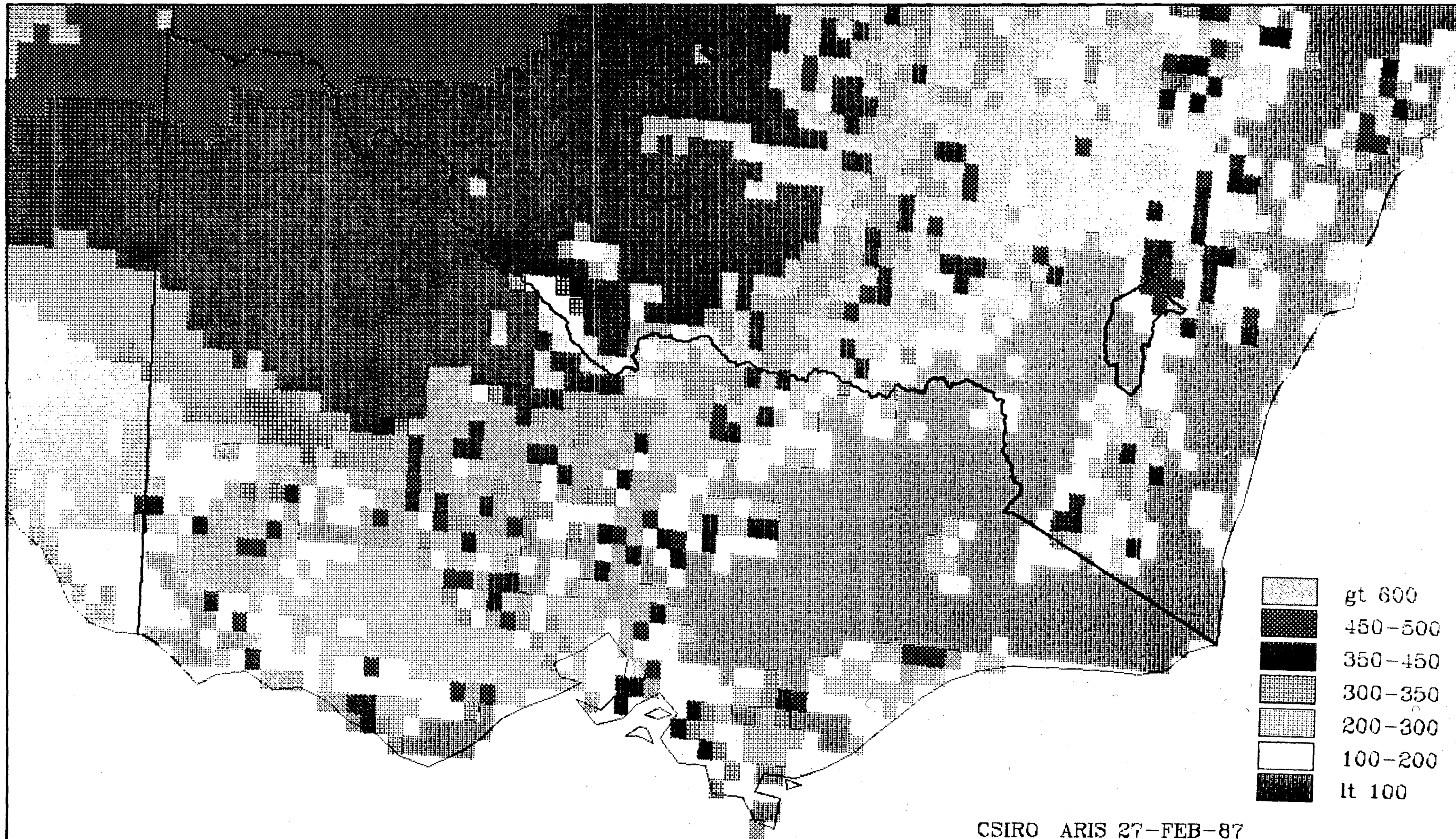

FIGURE 1

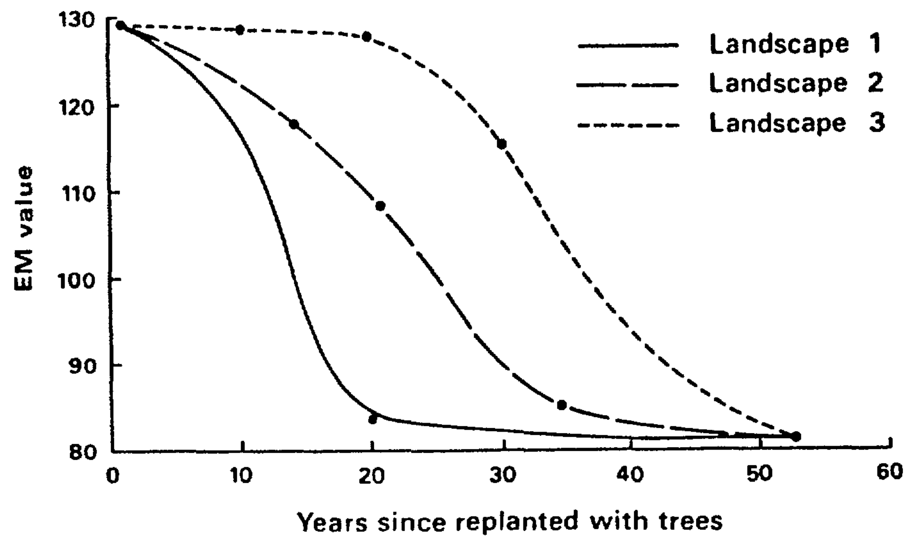

FIGURE 2

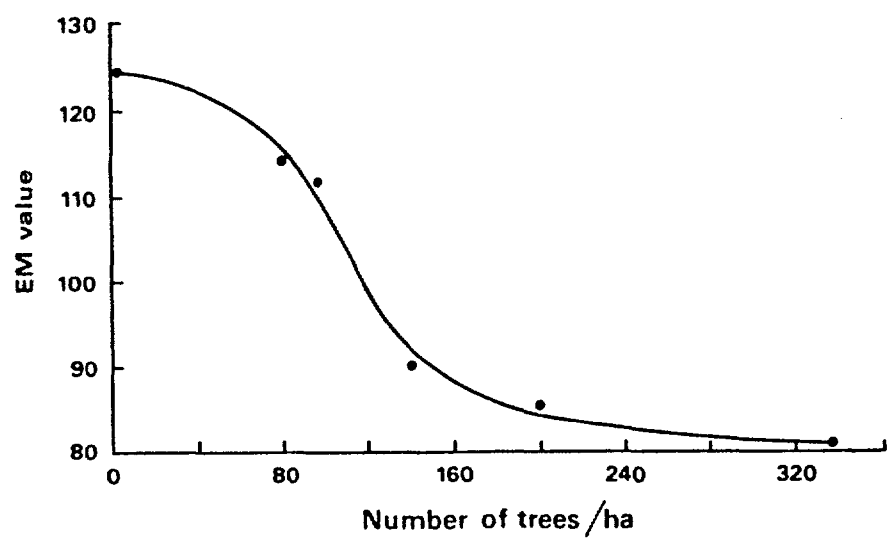

FIGURE 3

program (Hutchinson, 1984) to provide more accurate estimates on a 40 km^2 grid cell basis. The resulting salinity hazard map should then provide a sound basis for targetting 20-25 test areas, each of about 10km^2 size.

A physiologically-based plant community model such as RESCOMP (Penridge & others, 1987) would be applicable to such test sites and would provide a more realistic description of the water balance. In doing so it is expected that a 'salt flushing potential' (SFP) could be calculated in order to describe the effectiveness and dynamics of the plant community/rainfall interaction in halting or reversing adverse salt redistribution. Also the geological factor used in the Ive & Walker model would be considerably improved by using the EM technique to provide actual salt concentrations to a depth of about 15m.

The final grid-cell size produced by re-iteration of this procedure is yet undecided but would be expected to be in the order of hectares rather than square kilometres.

Undoubtedly modifications to this proposed research program will be required in the light of field experience. However in a period when, by necessity, the 'best-bet' syndrome has become firmly established in the fight against salinity we believe that this approach has considerable potential for providing a rational framework for future investments in reafforestation programs.

EVALUATION OF THE SUITABILITY OF AQUIFERS IN THE GOULBURN/BROKEN REGION FOR GROUNDWATER PUMPING

Dr Robert Williamson
Victorian Department of Water Resources

It is understood that the salinity problem in the Goulburn/Broken region of the Murray Basin is a consequence of an increase in groundwater pressures, with the associated rise in water tables. It therefore follows that the salinity problem could be mitigated if groundwater pressures were to be reduced. There are two possible methods of achieving this end, either reduce the inflow (recharge) rate, or increase the outflow (discharge) rate.

We will concentrate on the latter possibility, and consider some of the issues associated with direct pumping of groundwater. In some cases the water will be suitable for irrigation uses, either by itself or mixed with less saline water. Otherwise the saline water would have to be disposed of in some manner. It is conceivable that tax-payers' money could be used to facilitate groundwater pumping. It is thus necessary to evaluate the suitability of areas for groundwater pumping.

Any such evaluation would have to consider both the groundwater salinity and the existence of aquifers suitable for pumping. There is considerable data relevant to both of these components available within the Victorian Government; in the Department of Water Resources and in the Rural Water Commission. Data from both sources was used here.

A standard 2.5 km square grid mesh has been utilised in the regional groundwater modelling that has been undertaken in recent years by the Department of Industry, Technology and Resources and is being continued within the Department of Water Resources. The same areal grid was used in this study.

Stratigraphic data had already been compiled, it was summarised as the proportion of sand, a sand classification and an estimated transmissivity for each five metre interval at each recorded bore. This data was translated to the standard mesh.

Salinity data was available for a number of points in space and time from both the Department of Industry, Technology and Resources and the Rural Water Commission. These data were checked and a single salinity level was assigned to each measured bore. In turn, these data were also transferred to the standard mesh.

Each horizontal grid unit was subdivided into five vertical sections; three within the Shepparton Formation, one representing the Calivil and Renmark Formations and the fifth representing the basement rocks. There was considerable data near the surface, interpolation was not a major issue, however, more interesting issues arise with interpolation where there is little data.

The collated date permit the evaluation of various operational rules that might be established for the implementation of groundwater pumping schemes. Areas with medium to high permeabilities and low salinities are obvious candidates for the encouragement of private pumping. On the other hand areas with higher salinities and higher permeabilities are suitable for public schemes that concentrate on the removal of saline groundwater for subsequent disposal.

GROUNDWATER USE IN THE MURRAY BASIN

D.R. Woolley
Department of Water Resources, NSW
PO Box 3720, Parramatta NSW 2150

Groundwater usage in the Murray Basin has been closely linked with the development of the agricultural industry in all States into which the Basin extends. The linkage began during the 19th century, and has continued through changes in emphasis in agricultural production, developments in borehole and pumping technology, and changing living standards. Quantitative data are only available, however, for the most recent two decades.

The earliest use of groundwater in the Basin is not extensively recorded, but it was certainly in use prior to 1860 when wells near Broken Hill were mentioned by Burke & Wills. Wells, and to an increasing extent bores, were common in extensive parts of the Basin by the 1880's. While the number of individual watering points may not have been great because of the size of landholdings, groundwater provided the only reliable source of water for stock over much of the arid and semi arid country in Western N.S.W. and Victoria and in South Australia.

In Victoria, subdivision of large tracts of land in the 1880's gave an impetus to groundwater use. Gold mining in the deep leads also led to considerable activity in the groundwater area, and very large quantities were pumped in mine dewatering schemes. Use of groundwater for town water supply purposes also became important at about this time. Drilling technology was advancing, and cable tool drilling rigs powered by steam engines were able to construct bores to considerable depth. This technology was put to use further north in N.S.W. and Queensland, in the rapid development of groundwater from bores in the Great Australia Basin after the first flowing bore was drilled in 1884. As a sidelight, it is worth noting that this discovery led to a great search for artesian flowing bores over much of the northern and western parts of N.S.W., but the first flowing bore in the Murray Basin was not drilled until much later, in the Lake Victoria area.

From these early times, the use of groundwater appears to have increased gradually, as the land became fully settled and the size of holdings tended to decrease, resulting in the need for more watering points. The emphasis was still, however, very much on stock watering.

This development was recorded by a number of notable authors, generally associated with the State Geological Surveys. These early workers developed a very substantial understanding of the geology of the Basin, and of the occurrence and movement of groundwater within its formations. Their reports recorded details from many of the bores and wells, and in many cases constituted the only such record. Some of the more notable of these are Gloe (1945), Kenny (1934), Mulholland (1940), O'Driscoll (1960) and Barnes (1951).

A quantum leap in groundwater pumpage began in the late 1950's when its use for irrigation was contemplated and implemented. This development arose from a number of factors. Firstly, the occurrence of groundwater in quantities sufficient for irrigation had been suggested by a number of people (e.g Barnes, Gloe, O'Driscoll). Their ideas, the rapid expansion of knowledge about the hydrogeology of the Basin, and the concurrent development of new bore construction technology, were crucial.

The major technological breakthrough was the introduction of the continuous-slot, wedge-wire sandscreen. This development enabled the construction of stable and efficient bores in the unconsolidated sand and gravel aquifers so common in the Basin. Such bores were then capable of being pumped at rates of tens of litres per

TABLE 1

GROUNDWATER ALLOCATION AND ESTIMATED USE
MURRAY BASIN - MID 1980'S

NSW	L. Lachlan (Hillston) (8)	46,500	9,000	4,000
	L. Murrumbidgee (Darlington Pt) (8)	140,500	57,000	13,000
	L. Murray (Deniliquin/Corowa) (8)	54,400	9,000	4,000
	Sundry (8)	1,700	1,700 (2)	small
	Stock/Domestic (1)	-	14,000	-
	SUBTOTAL	243,000	91,000	21,000
VIC	Shepparton (5)	3,782	130	(4)
	Rodney (5)	22,196	3,599	
	Rochester (5)	29,902	5,678	
	Murray V. (5)	111,160	30,822	
	Tongala (5)	18,925	6,133	
	Campaspe (5)	7,897	4,280	
	Border Area (6)	10,705	7,000	
	Stock/Domestic (1)	-	12,000	
	SUBTOTAL	197,000	70,000	
S.A.	Tatiara Proc. Region (7)	83,000	57,000	13,000
	Mallee Proc. Region (7)	13,000	5,000	1,400
	Marne River Proc. Region (7)	1,000 (3)	1,000	small
	Tintinara (7)	1,000 (3)	1,000	small
	Other Border Areas (6)	9,700 (3)	9,700	700
	Other Stock/Domestic (7)	-	1,000	-
	SUBTOTAL	107,000	74,000	16,000 (say)
	TOTAL	548,000	2,35,000	-

(1) Stock and domestic bores generall do not have an allocation. The volumetric use has been estimated from the number of licensed stock and domestic bores and the assumption that the average use per bore is 5 ML/year.

(2) Usage figures uncertain, and assumed to be the same as allocation.

(3) Allocation figures uncertain, and assumed to be the same as usage.

(4) Areas irrigated in Victoria not readily available or separable from areas irrigated with surface water.

(5) From RWC internal report by A. Webster 1986.

(6) From "Management Proposal for Groundwater Resources along the State Border of S.A. and Vic. 1982".

(7) From E. and W.S. data supplied by S. Barnett.

(8) From DWR NSW Groundwater Data Bank.

(9) Stock use in Victoria based on 2ML/bore per year.

second, sufficient for irrigation purposes on a small scale. The concurrent introduction of the deep well turbine pump provided the means by which the bores could be pumped efficiently. Much pioneering work was carried out in the Riverine Plains in Victoria by F.N. Bethune, during these years.

The development of groundwater use during the next two decades was hastened by investigations funded through the Australian Water Resources Council and the work of a new generation of groundwater professionals, for example, Lawrence and Macumber in Victoria, Bleys and Shepherd in South Australia and Williamson and Griffin in N.S.W.

Developments in technology were also rapid. Rotary drilling rigs using mud circulation and techniques adapted from the oil drilling industry, and the use of geophysical logging techniques provided opportunities for faster and more controlled exploratory drilling. Developments in sandscreens led to the ability to construct larger diameter bores, and the use of close-coupled submersible electric motors on borehole turbine pumps provided the capacity for much larger pumping rates. So there are now numerous bores in the Darlinghurst Point area in N.S.W., for example, with casing and screen diameter of 600 mm or more and depth of 150 m with pumps powered by electro submersible motors of 250 HP, producing water at the rate of 350 - 400 L/S from a pumping depth of 25 - 30 m. Although the cost of such water is moderately high, the efficiency of the bore/pump combination is such that profitable irrigation on a large scale is feasible.

Information about the volume of groundwater actually being used within the area of the Basin is incomplete, and what is available is dealt with differently in each State.

A summary, showing the groundwater allocation to license bore, and the estimated actual usage, is shown for the three States in Table 1. The figures are based on information provided during discussions with relevant people in the water agencies, together with some published reports and unpublished internal reports. They have been forced into a consistent format, and in doing this they may have lost some precision. They should not be taken as absolute, therefore, but as an indication of the order of magnitude and relativities. In general, the data shown are representative of the situation in the mid 1980's but are not consistently specific to one year.

Some information in the Table is relatively "hard", for example, allocation amount; usage amount in NSW where all irrigation & TWS bore licenses must report volume used annually; area irrigated. Other information is quite "soft", for example, the usage attributed to stock and domestic bores, and the irrigation usage in Victoria where a variety of ways of determining usage has been attempted.

The major points which come from the tabulation are the magnitude of the groundwater allocation and the difference between allocation and actual use. Use is commonly as low as 30% of allocation or less.

A map has been prepared showing the distribution of groundwater use in the Basin. There is a large central area occupying much of western Victoria, a large part of south-west NSW, and small pockets in SA, in which there is effectively no groundwater used because of its high salinity. However, stock requirements are met from groundwater over 60-70% of the Basin's area, and as such it is a major contributor to the agricultural industry in this part of Australia. More intensive use, primarily for irrigation and to a lesser extent for town water supplies, is concentrated in the Shepparton-Avoca region in Victoria, the Deniliquin-Corowa, Darlington Point and Hillston regions in NSW, and in a zone close to the Victorian border in SA. Irrigation in some of these areas is quite intense.

ACKNOWLEDGEMENTS

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