Application of Airborne Geophysical Techniques to Salinity Issues in the Riverland, South Australia

A synthesis of research carried out under the South Australian Salinity Mapping and Management Support Project [SA SMMSP]

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EXECUTIVE SUMMARY

Background

This document is one of a series of final site reports for the South Australian Salinity Mapping and Management Support Project (SA SMMSP) and synthesises the findings for the Riverland site.

In the Riverland region of South Australia natural inflows of highly saline groundwater to the River Murray have been exacerbated by irrigation development in the riverine corridor. Future irrigation development and dryland agricultural land use will continue to increase these inflows into the future. Salinity mitigation measures to maintain water quality in the river include groundwater pumping schemes, irrigation zoning, and improvements in irrigation water use efficiency and recharge control through revegetation and perennial plantings.

For both irrigation and dryland developments, there are long time delays between development and for the impacts on salt loads in the River to be fully realised. Similarly, for salinity mitigation options, there is a long time delay between the change in land use and salinity benefits in the river. These time delays critically affect the viability of land use salinity mitigation options. It is important to be able to estimate these time delays for any land use change on a given area in order to develop zones for irrigation development or prioritise areas for revegetation or technology transfer programs for water use efficiency.

These time delays are dependent on a number of factors, the primary one being distance from the river, but also depth to groundwater, hydrogeological parameters, groundwater salinity and soil hydraulic parameters. Some of these parameters, e.g. depth to water table, are easy to estimate by interpolating information between existing bores. However, some of these parameters are dependent on sub-surface soils and hydrogeology and can be too spatially variable to interpolate even in a regional sedimentary basin such as that in the Riverland. Previous work has illustrated that one of the key determinants of time delays is the Blanchetown Clay, an extensive, relatively shallow deposit of clays and silts. The primary objective of the SA SMMSP in the Riverland was to map the thickness of the Blanchetown Clay and then use the data in models that support land use planning in the area.

Mapping the Blanchetown Clay

The existing knowledge of the spatial distribution and variability (including thickness) of the clay layer was limited to scattered drillholes and outcrop. In a staged approach, the project first set out to establish whether airborne electromagnetics, (AEM) could map this near surface conductive clay unit at a resolution that would support better land use planning decisions. The challenges included its variable thickness, its proximity to the ground surface and the limited conductivity contrast with respect to underlying and overlying sedimentary units. Modelling work indicated that a helicopter mounted frequency domain EM system would yield the best results in mapping this unit, confirming the outcome of previous studies elsewhere in the Mallee. In particular, the RESOLVE helicopter EM (HEM) system was chosen and a limited field trial was undertaken, in an area just south of Loxton, to prove the system prior to commencing the full survey.

A 15–20 km wide corridor following the southern bank of the River Murray, between the border and Kingston-on-Murray (Lock 3), was flown with the EM system and a total of

11,500 line km of data collected. Flight lines were oriented north-south, mostly at a spacing of 150m, but also at 300m in parts. The study area from Lock 3 to the Border on the southern side of the river was chosen because of the new developments occurring there and the absence of current groundwater pumping schemes.

The survey data were re-calibrated after their conventional processing using independent ground-based geoelectric data. Conductivity depth sections were obtained through the process of inversion, which was based on a five-layer, 1-dimensional model of the earth. Reduction of the ambiguity in the unknown aspects of the geological section was sought by constraining the inversion with as much local geological and hydrological information as was available. Groundwater depth information was incorporated as an extra datum to constrain the upper layer thicknesses.

Results from the inversion compare well with available ground data and were further validated with additional drilling. The resulting detailed map of the distribution and thickness of the Blanchetown Clay is more detailed than previous compilations based on borehole logs.

Estimating Recharge

Fourteen soil cores were obtained beneath dryland agricultural land, from within the HEM survey area. Estimates of drainage since land clearance have been made from analyses of water content and chloride concentration on these cores. The estimated mean drainage rates at these sites range between 0.1 and 14.8 mm yr^{-1}, with an average of 2.7 mm yr^{-1}.

Empirical equations that relate drainage beneath dryland agriculture to soil texture and rainfall have been developed, based on the point estimates of drainage obtained in this and in previous studies. These equations have been made to extrapolate these data across the northeast Mallee (and across the entire South Australian Mallee region) using State soil landscape mapping data. The derived drainage map has been combined with the map of Blanchetown Clay thickness to produce maps of aquifer recharge in the years 2004, 2050 and 2100.

Where available, it may be possible to use airborne radiometrics and airborne electromagnetics data to assist in the generation of higher resolution soil maps. In the Loxton district, a comparison between an EM 38 ground survey conducted for soil property mapping purposes, and the apparent conductivity for the highest frequency of the RESOLVE HEM system indicated a high degree of correspondence between the two, suggesting that additional soils information may be forthcoming from the helicopter data set.

Better soil mapping is also important for estimating recharge, as measurements on soil cores taken during the Riverland work suggest that the drainage rate is related to the clay content of the top 2 metres of soil[1].

[1] This surface soil clay content influences moisture retention and water loss through evaporation/ transpiration, in contrast to the deeper Blanchetown Clay layer which influences time delays for recharge to the watertable.

Groundwater Modelling

The revised estimates of aquifer recharge and lag times have been incorporated into the SIMPACT/GIS and MODFLOW groundwater models for the Riverland region. Previous modelling exercises to predict the impacts of vegetation clearance on the river were carried out with the best recharge information available at the time, but were ultimately hampered by the use of broad landscape units and recharge rates derived from measurements carried out in other wetter areas of the Murray Basin. The SIMPACT/GIS model provides a framework for simulating land use changes and salinity impacts on the river. The revised estimates of root zone drainage derived from the clay map have been incorporated into the SIMPACT model and algorithms for better using this data have been included. The resultant model (SIMPACT II) has been used to generate high and low salinity impact zones and target areas for revegetation.

The complementary development of a revised MODFLOW groundwater model for the Riverland area, which has a smaller grid size and better calibration that the models used previously in the study area, has also been completed. This model has been used to predict the impacts of increased recharge following clearing on salt inflows to the river and floodplain. It has also been used to examine the efficiency of various management strategies undertaken to minimise salinity impacts to the river, including the targeted revegetation scenario derived from SIMPACT.

Unexpected Results

An image of the base of the Blanchetown Clay (and related materials) showed the ancient topography of the landscape prior to the development of a large lake that once flooded the Riverland region (Lake Bungunnia). This palaeo-landscape is dominated by the barrier-beach strandlines associated with the Loxton Sands. While knowledge of the depositional environment for the Loxton-Parilla Sands has been long established, the HEM data revealed details relating to these sediments that were not well understood. Results from the constrained inversion of HEM data have helped to better define the geometry of this sedimentary system and together with a hydrogeological interpretation have contributed to a more informed approach to the design, development and potential performance of the Loxton Sands Salt Interception Scheme borefields at Bookpurnong and Loxton, with potential to inform others that are being considered in the central Murray Basin, particularly when dealing with the Loxton Sands aquifer.

More recently, a limited investigation of available helicopter EM data where it covers the River Murray floodplain, suggests that the technology could be effective in providing valuable spatial detail on the salinisation of floodplain soils. While further work is required to better determine this potential, airborne geophysics such as that already acquired in the Riverland region, could help link run of river salinity determinations and river floodplain processes, thereby helping inform policy for floodplain protection and salinity mitigation.

Recommendations for further work

1) The current geophysical data should be further scrutinised to support the design of salt interception schemes at Murtho, Pike River etc.
2) Further work should be conducted to better understand the distribution of floodplain soils, recharge during floods and salt discharge to the river. Results here looked promising and run-of-river surveys using TEM have also proven to be useful.

3) Results show that airborne EM data could assist with siting further disposal basins.

4) Further investigations are warranted in the application of the current data for improving soil maps in the Riverland.

5) The maps of root zone drainage in areas unsuited for cropping e.g. SW of Waikerie should be reviewed.

6) Soil zone drainage processes in the vicinity of identified strandlines should be further investigated to determine whether such areas may be poorly suited for siting of new irrigation developments or whether water use efficiency measures should be targeted at these areas.

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INTRODUCTION

This report is one of a series of final site reports for the South Australian Salinity Mapping and Management Support Program (SA SMMSP). With investment provided by the Australian and South Australian Governments under the National Action Plan for Salinity and Water Quality (NAP), the project had the following aims:

- to test airborne geophysical techniques (in particular electromagnetics [EM], radiometrics, and magnetics) to determine their value in application to salinity management,
- to further refine and adapt the technology to suit this application, and
- to provide specific information to assist with salinity management in five key areas of South Australia.

The SA SMMSP adopted a pioneering approach compared to traditional research programs involving the application of airborne geophysical data to natural resource management issues. Instead of accepting data collected in an arbitrary manner, which may add to knowledge but be of little use for management, considerable thought went into how the data and derived products generated could contribute to the implementation of salinity management options applicable at each site.

By providing interpreted, appropriately targeted, spatial geophysical data and associated decision support tools, the program sought to reduce the impacts of salinity on land, surface water quality, groundwater quality and biodiversity.

Advancing considerably on existing knowledge, the outputs of the SA SMMSP offer:

- Detailed knowledge of the distribution and causes of dryland and irrigation-induced salinity.
- Potential land and water management solutions, using a multidisciplinary approach.
- Salinity and materials mapping, and on-ground calibration information, which will enable regional bodies to develop and refine their respective Integrated Natural Resource Management (INRM) Plans.
- More effective targeting of planning controls, development incentives, trading schemes and protection zones in INRM plans and subsequent investment under NAP.
- Identification of both current and future impacts of salinity on natural ecosystems, and biodiversity assets at risk.

The SA SMMSP involved the acquisition, calibration and interpretation of airborne and ground geophysical data, allied with field and laboratory work, as part of a strategy to produce meaningful products for salinity management. In addition, specific outputs from the geophysics were tailored to be used as model constraints in estimating aquifer recharge rates for inclusion in 2 and 3D groundwater models which provide the basis for regional planning to mitigate dryland and river salinity.

The Riverland site is one of five study areas in the SA SMMSP, and one of three located in the western Murray Basin. These sites were chosen on the basis of priority for salinity management as well as representing a range of different landscapes, assets at risk, potential management options and maturity of regional planning. The other 4 study areas are:

1) Tintinara (South East Region)
2) Angas-Bremer Plain (Western Murray Basin)
3) Jamestown (Mid-North) .
4) Bremer Hills.(Western Murray Basin)

The aim of this report is to synthesise study findings and outputs for project activities conducted at the Riverland Project site (a 15-20 km zone south of the River Murray between the SA / Victoria border and Lock 3 [near Kingston-on Murray]), located in the South Australian Mallee (Figure 1).

Current inputs from this reach of the river equate to around 30% of the salt load in the Murray measured at Morgan. This reach is predicted to contribute between 2 and 4 tonnes of salt per day per kilometre length of river in the year 2100 (Cook *et al*., 2001). Further downstream, between Kingston-on-Murray and Morgan, salt inputs are significantly lower due to deeper watertables and lower groundwater salinity.

Increased recharge from drainage under irrigated agriculture, and clearing for dryland agriculture, have increased hydraulic gradients driving naturally saline groundwater into the river. Management of the problem requires a range of approaches including more effective recharge control.

Airborne geophysics were employed in the Riverland to gather more detailed information on particular characteristics of the unsaturated zone, at a useful scale, important for understanding the dynamics of recharge and implementing appropriate salinity management measures in the region. As described in Part A, improved knowledge of the thickness and distribution of the low hydraulic conductivity Blanchetown Clay layer was required and this became the primary target of the airborne geophysics survey.

In summarising the findings from the SA SMMSP activities in the Riverland, this report:

1) Discusses the natural resource management issues for Riverland.
2) Defines the role of airborne geophysics in addressing these issues.
3) Reviews how derived products from the geophysical data are incorporated into hydrogeological models to predict aquifer recharge and lag times in the Riverland region.
4) Considers the additional benefits to emerge from a study of the airborne geophysical data including their role in the design, development and potential performance of salt interception schemes, mapping salt stores in the River Murray floodplain and improved mapping of soils in the region.
5) Examines the transferability of the results, including whether airborne geophysics should be considered as part of an integrated approach to inform policy for floodplain biodiversity protection and salinity mitigation.

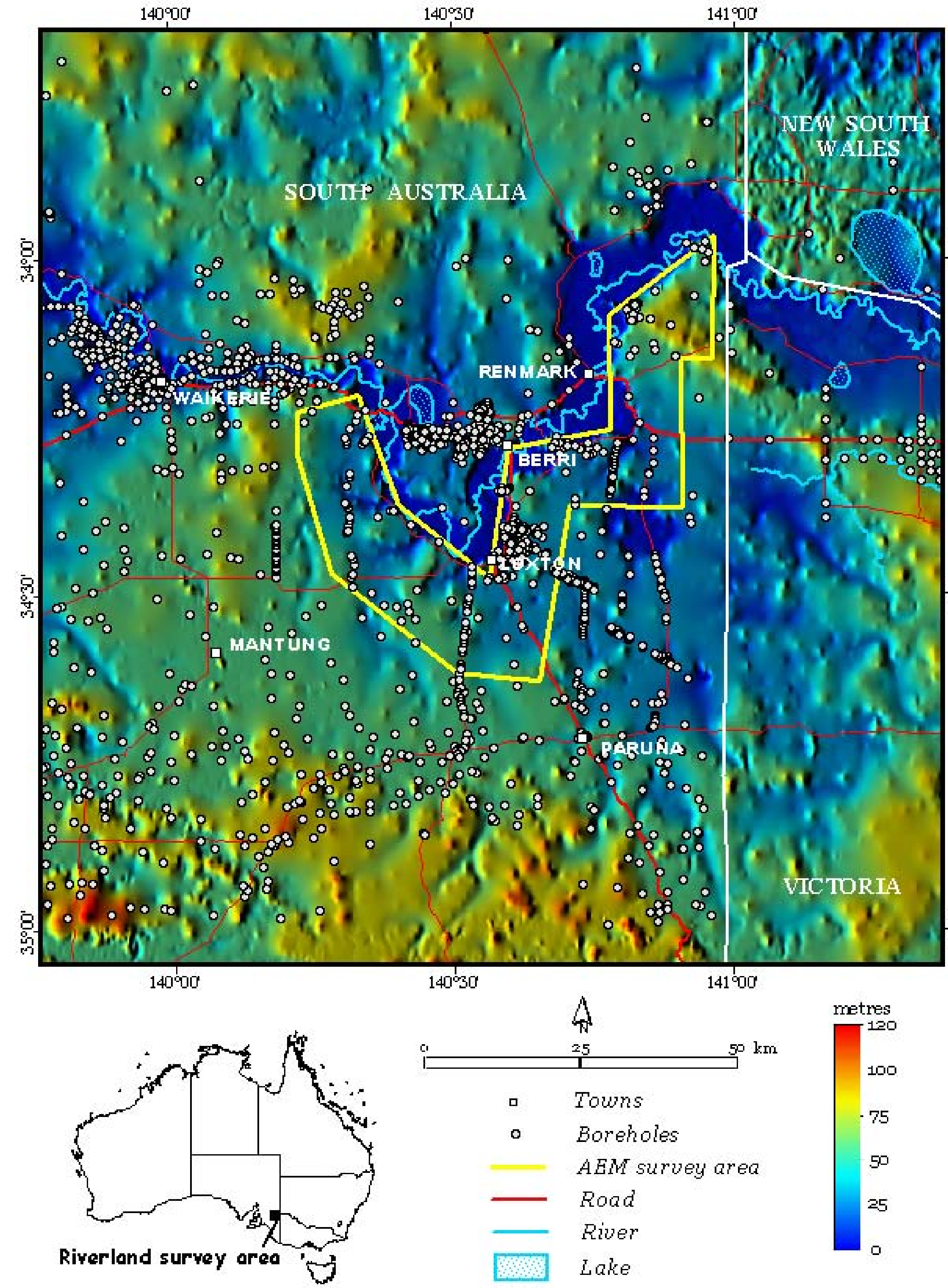

Figure 1. Central and eastern parts of the Riverland region with the HEM survey area (outlined by the yellow polygon), located on the southern bank of the River Murray between Renmark and Kingston upon Murray in South Australia. The wealth of borehole data available for this study is well illustrated, although the distribution and quality associated with this data base is variable.

1. Project Objectives and Outputs

The prime objective of the project in the Riverland region was to determine the depth, thickness and continuity of the Blanchetown Clay at sufficient resolution to enable:

- Targeting of recharge reduction options in dryland areas,
- Focus for improved irrigation efficiency and drainage works in irrigation areas,
- Zoning of irrigation development.

Contracted objectives for the Riverland project were:

- To develop techniques that use high resolution airborne electromagnetic (AEM) data in generating maps, for a 15-20 km zone of the River Murray from Lock 3 to the Border, detailing the spatial distribution and thickness of near surface clay-rich sedimentary units.
- To use this information with new models to predict the time delay between the increase in drainage due to clearing of the native vegetation and commencement of agricultural activity and the increase in groundwater recharge in the Mallee of South Australia.
- To incorporate the resulting predictions of the change in aquifer recharge over time as an input into new regional groundwater models that include the Riverland region, and examine the consequence of certain land management decisions on the projected rates of increase in Murray River salinity.

Contracted outputs included:

- A map detailing the spatial distribution and thickness of near surface clay rich materials determined from airborne EM data, and validated using ground information.
- Improved estimates of current drainage rates in the vicinity of the River Murray and estimates of the expected drainage if areas of native vegetation were to be cleared, or if irrigated areas were to revert to dryland agriculture.
- An Improved recharge map for underlying groundwater systems up to 100 years into the future for the entire South Australian Mallee region constructed using the soil-landscape data.
- Maps showing expected rates of groundwater recharge in the Riverland region for the years 2003, 2025, 2050 and 2100, produced by incorporating the map of clay thickness and drainage estimates.
- A floodplain attenuation model that simulates the impact of the floodplain on salt loads to the River Murray and impact of irrigation development on the floodplain
- Improvements to SIMPACT (irrigation planning model) and Border-to-Lock 3 MODFLOW model (used for land use changes and salt assessments) to incorporate improved recharge maps and floodplain attenuation model.

This synthesis is produced from the detail contained in the following papers and reports that were compiled in the course of the SA SMMSP.

- Barnett, S.R.and Munday, T.J. (2004) *Lessons from the application of airborne EM in the South Australian Murray Basin*. The 9th Murray-Darling Basin Groundwater Workshop, Bendigo Vic Feb 6-9th 2004
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- Fitzpatrick, A. (2004) *Calculation of conductivity depth images (CDI) S.A. AEM data using EMFLOW 5.30 (AMIRA-P407B): RESOLVE: Riverland & Tintinara (East & West); TEMPEST: Jamestown & Angas Bremer Plains*, CRC LEME Open File Report 176, Cooperative Research Centre for Landscape Environments and Mineral Exploration, July 2004
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- Leaney F.R., Barnett S.R., Cook P.G., Miles M., Munday T.J. and Tan K.P. (2004) *Field studies towards improving estimates of salt load to the river Murray due to dryland agriculture.* 9th Murray-Darling Basin Groundwater Workshop, Bendigo, Vic, Feb 6-9th 2004
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- McEwan, K.L., Holland, K.L., Smitt, C. and Jolly, I.D. (2003). *Results of a groundwater/soil survey to assess the impacts of land and water management on the River Murray floodplain.* CSIRO Land and Water Client Report to the River Murray Catchment Water Management Board and the National Action Plan for Salinity and Water Quality.
- Munday, T., Brodie, R., Green, A., Lane, R., Sattel, D, Cook, P., Barnett, S., and Walker, G. (2003) Developing recharge reduction strategies in the Riverland of South Australia using airborne electromagnetic data – a case study in tailoring airborne geophysics given a particular target and a desired set of outcomes. Extended Abstracts ASEG 16th Geophysical Conference and Exhibition, February 2003, Adelaide.
- Munday, T.J., Hill, A.J., Wilson,T., Hopkins, B., Telfer, A.L., White, G.J., and Green, A.A., (2004) Combining geology and geophysics to develop a hydrogeologic framework for salt interception in the Loxton Sands aquifer, central Murray Basin, Australia. 1st National Salinity Engineering Conference, 9–12 November 2004 Perth, Western Australia

2. Background

In the Riverland region of South Australia natural inflows of highly saline groundwater to the River Murray have been exacerbated by irrigation development in the riverine corridor. Future irrigation development and dryland agricultural land use will continue to increase these inflows into the future. The movement of water from below the root zone to the groundwater (root zone / deep drainage) increases once native vegetation is cleared or when irrigation commences. The additional water reaching the groundwater (recharge) causes water tables to rise and gradients in the groundwater surface to increase towards the river. This causes the saline groundwater to discharge into the river corridor, increasing salt loads to the river.

Salinity mitigation measures to maintain water quality in the river include groundwater pumping schemes, irrigation zoning, improvements in irrigation water use efficiency and recharge control through revegetation and perennial plantings. For both irrigation and dryland developments, there are long time delays between development and for the impacts on salt loads in the River to be fully realised. Similarly, for salinity mitigation options, there is a long time delay between the change in land use and salinity benefits in the river.

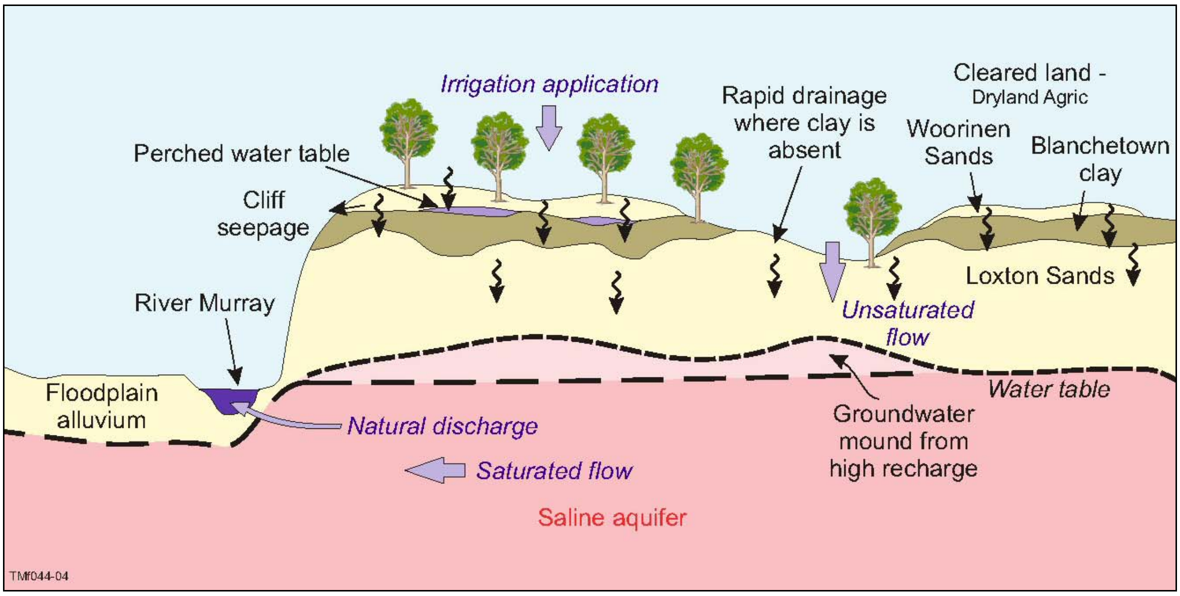

Figure 2. Schematic representation of the hydrogeological process operating in the Riverland region as a consequence of the clearing of native mallee and the development of irrigated agriculture. Increased recharge to the saline groundwater has caused an increase in the salt flux to the River Murray.

While improved irrigation practices and salt interception schemes (SIS) have helped reduce the salt input into the river, pressure for further development and the scale of the problem require additional strategies to minimise reliance on relatively high cost SIS and their “off-site” penalty, evaporative disposal basins. Low recharge agricultural practices are one option, but they require an improved understanding of soil characteristics at the local scale.

2.1 THE RIVERLAND STUDY AREA

The Riverland region is located along the River Murray between Morgan and the State border. In this study, only a part of the Riverland region was considered, extending from Lock 3 near Kingston-on-Murray to the Border (Figure 1), with particular focus given to a 15 - 20 km zone extending away from the southern bank of the river. This region is known to contribute significantly to the salinity of the river, much of it attributed to natural causes (eg. a very saline groundwater system). However, as mentioned above, recent increases in groundwater recharge from irrigation and dryland agriculture has seen a dramatic rise in the salt load reaching this stretch of the river. This study area is also of interest due to the potential for both future irrigation development and salt interception schemes.

2.2 HYDROGEOLOGY

The regional groundwater flow is from the south-southeast towards the River Murray (Figure 3). Hence, the river receives groundwater input in the study area represented by the red polygon in Figure 3. Groundwater salinity increases from <500 mg/L under the Big Desert 100 km south of the study area to ~20 000 – 30 000 mg/L close to the river. In the Noora-Yamba groundwater discharge area, located SE of Berri, groundwater salinity can be well in excess of that of seawater (i.e. > 35 000 mg/L).

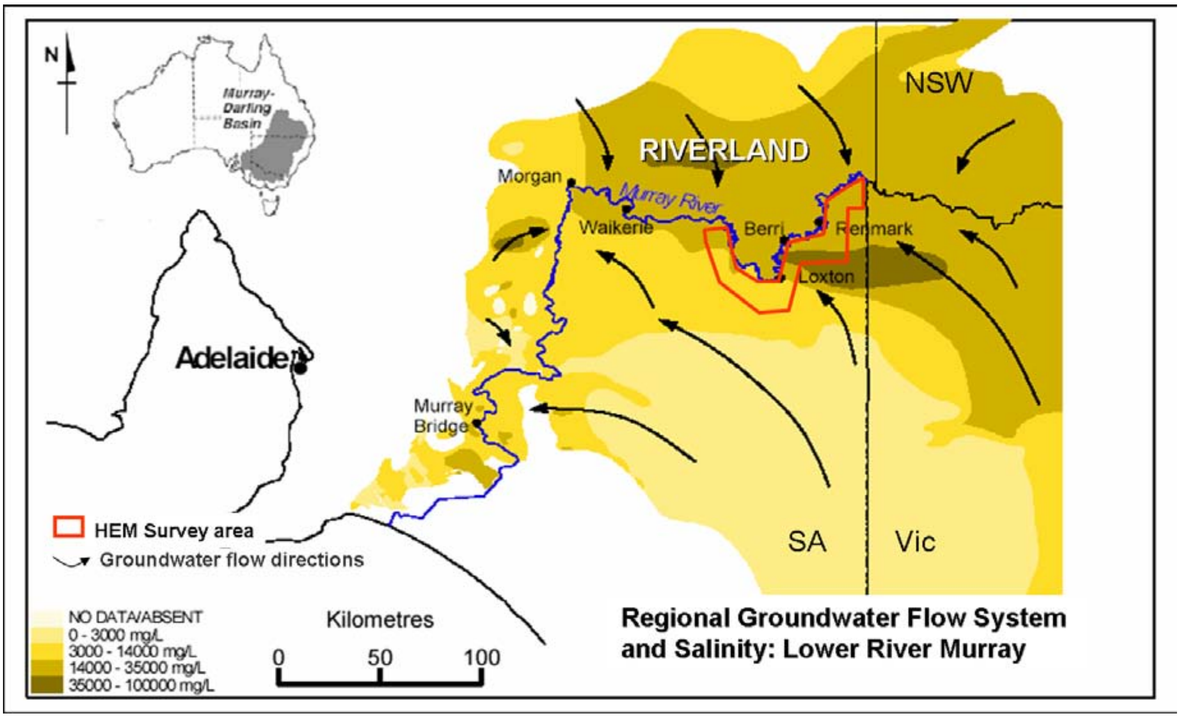

Figure 3. Map showing regional groundwater salinity variations and flow directions. The location of the Riverland study area is outlined in red.

3. Problem Identification

As mentioned above, the Riverland region is known to contribute significantly to the salinity of the river, with much of the salt load attributed to natural causes (eg. a very saline groundwater system). Recent increases in recharge from irrigation and dryland agriculture has seen a dramatic rise in the salt load in this reach of the river.

In addition, the native riparian vegetation communities on the floodplains of the lower River Murray in SA are suffering severe health decline, primarily due to salinisation of the floodplain soils caused by river regulation and highland irrigation.

Land use and land management changes (e.g. zoning for new irrigation developments, improvements in water use efficiency, revegetation) are being pursued (in addition to SIS) to address rising salinity trends however this requires an improved understanding of soil and regolith[2] characteristics. In particular, the Blanchetown Clay (and near-surface materials with a similar texture) are known to significantly inhibit drainage and natural recharge but information on their spatial distribution and variability (including thickness) is generally limited to scattered drillholes and outcrop.

Hydrogeological models have been employed to help support the decision making process regarding potential land use change and positive or negative impacts for river salinity, and the timeframes associated with these impacts. These models help inform policy and on ground work in the region and give the community a greater level of confidence that their actions will have the desired salinity management outcomes. However, such models also require greater spatial resolution information on soil and regolith characteristics, including the Blanchetown Clay.

Estimating drainage and aquifer recharge in the South Australian Mallee

The time delay between a change in land use and for the salinity impact to be realised in the river critically affects the viability of land use salinity mitigation options. It is important to be able to estimate these time delays for any land use change on a given area in order to develop zones for irrigation development or prioritise areas for revegetation or technology transfer programs for water use efficiency.

These time delays are dependent on a number of factors, the primary one being distance from the river, but also depth to groundwater, hydrogeological parameters, groundwater salinity and soil hydraulic parameters. Some of these parameters, e.g. depth to water table, are easy to estimate by interpolating information between existing bores. However, some of these parameters are dependent on sub-surface soils and hydrogeology and can be too spatially variable to interpolate even in a regional sedimentary basin such as that in the Riverland. Previous work has illustrated that one of the key determinants of time delays is the Blanchetown Clay, an extensive, relatively shallow deposit of clays and silts. The primary objective of the SA SMMSP was to map the thickness of the Blanchetown Clay and then use the data in models that support land use planning in the area.

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[2] Regolith is the material (soil and weathered rock) that lies above fresh (unweathered) bedrock.

Previous mapping of the Blanchetown Clay layer, interpolated from borehole data, is shown in Figure 4.

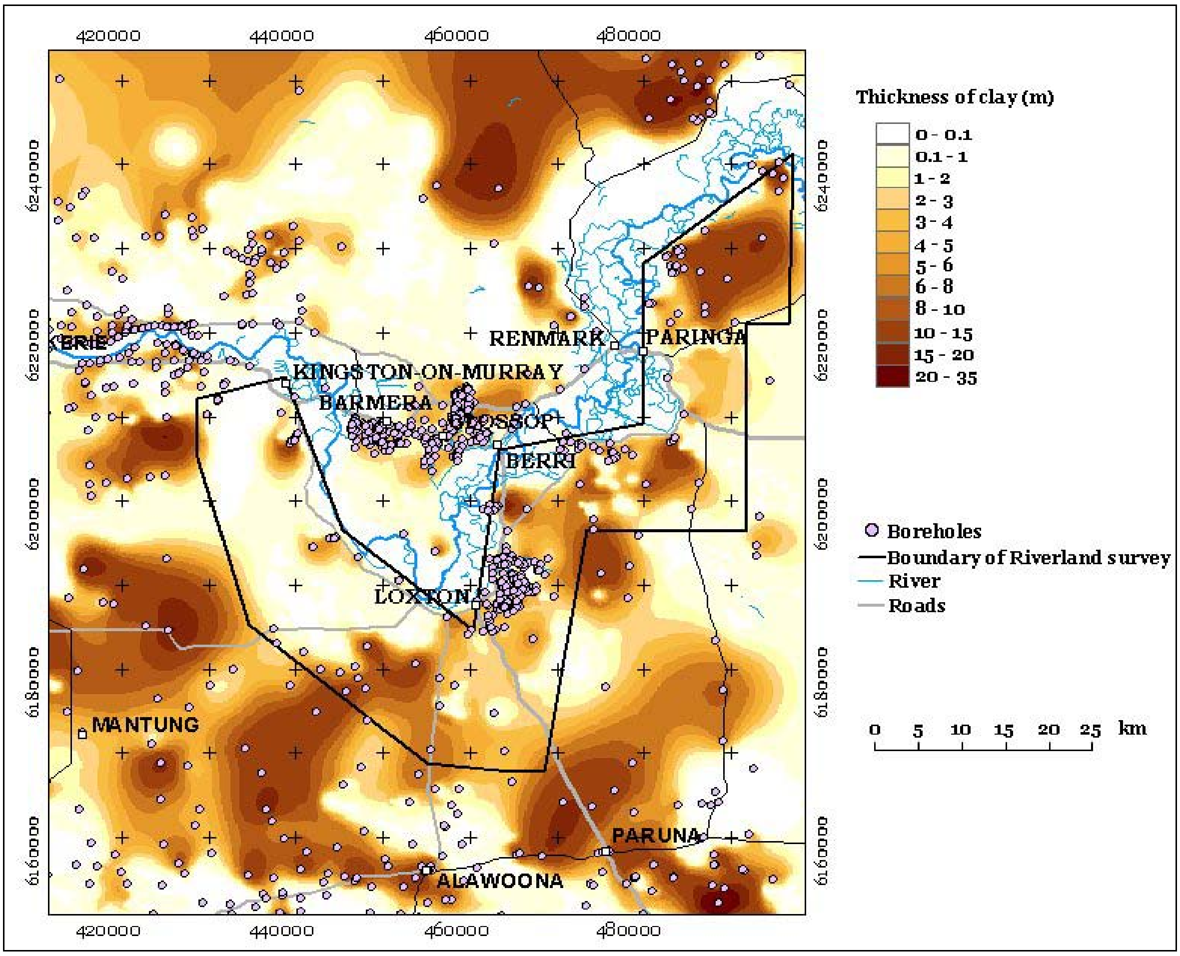

Figure 4. Map of Blanchetown Clay thickness from Riverland borehole data. (Barnett, pers. comm.)

The resolution of the existing borehole data was deemed inadequate for modelling the consequences of changing land use, which includes re-vegetation and the cessation of irrigation in areas adjacent to the River Murray. An airborne mapping technique was really the only means by which information on the clay could be acquired economically at an appropriate resolution and over a short period of time.

PART B. THE ROLE AND CAPABILITIES OF AIRBORNE GEOPHYSICS

When planning for the SA SMMSP survey work, there was a clear appreciation that airborne geophysics by itself was not likely to define salinity management strategies and that its value lay in better defining the physical attributes of the landscape at relevant scales to give greater confidence in planning and designing remedial action. Early studies which applied airborne geophysics in the Murray Basin in a salinity management context, particularly airborne electromagnetic (AEM) surveys, were carried out to assess their contribution to the "*understanding and management of dryland salinity"* by "mapping salinity", "salt stores" and "groundwater conduits". (e.g. Heislers, 1998; Lane *et al.*, 2001; Lawrie *et al.*, 2000; Dent *et al.*, 2002; among others). For the most part, the performance of airborne geophysics systems was reviewed and analysed within that context (George and Woodgate, 2002). While these surveys were targeted to answer specific questions related to salinity risk and catchment management, a failure to link derived products or information with the complexity of salinity and groundwater flow systems, and the viability of any remedial actions did not allow the true value or relevance of airborne geophysics to be determined. As a consequence, confusion and unfulfilled expectations have prevailed with catchment managers when these technologies are promoted as an option in developing effective land management change to mitigate salinity problems.

4. Developing the targeted approach

The SA SMMSP developed a strategy for the application of geophysics from an understanding of regional variations in landscape, hydrogeology, land use and the requirements of particular communities. In South Australia, the actual extent of dryland salinity in the Murray Basin has been mapped from ground survey and aerial photos (Barnett, 2000), and estimates made of future extents in 2025 and 2050 for the regional groundwater flow systems that underlie the Murray Geological Basin in SA. In these flow systems, effective recharge reduction to ameliorate dryland salinity would have to occur over at least 50 % of the total landscape area. Using AEM in this context to "map" salinity", "salt stores", or to determine where to plant trees, would be wholly inappropriate and uneconomic at best. Therefore, the blanket acquisition of geophysical data over particular catchments was not entertained.

At the outset of the project, recognition was given to benefits of acquisition by particular systems at particular scales, given cognisance of the target and the resource needs of the decision makers. In this regard, the SA SMMSP represents a significant departure from previous studies seeking to apply airborne geophysics in land management. It also reflects the thinking promoted earlier on the relevance of geophysics in land management (George and Green, 2000). Central to the SA SMMSP planning process was an acceptance that only the most appropriate geophysical system(s) were to be employed in each of the five strategically important catchments/areas within National Action Plan priority regions of South Australia.

Understanding the character and variability of the target (the clay) and defining an appropriate airborne geophysical system to map it at the required resolution, *prior to* the survey was also deemed critical. This approach allowed us to reduce the uncertainties (and risk) associated with acquiring these data. In targeting the survey objective and linking the project outputs to modelling aquifer recharge rates, and in turn in constraining a groundwater model, allows us to determine the effects of proposed recharge reduction options in mitigating River Murray salinity.

For the Riverland region, the considered use and application of airborne geophysics involved four components:

1) ***Target definition*** – to understand the nature and geometry of the material that had to be mapped and to define the resolution necessary for a mapping system.
2) ***Petrophysical characterisation*** – to determine whether a geophsyical system could realistically be used.
3) ***Forward modelling*** – to determine the most appropriate system to use.
4) ***Test survey and ground follow-up*** – to ensure the selected system met expectations in field conditions.

4.1 THE TARGET – THE BLANCHETOWN CLAY

The Blanchetown Clay is a near surface sedimentary unit, which was deposited in a large lake in the Lower Murray between about 2.4-0.7 million years ago (Brown & Stephenson, 1991). The unit has a patchy distribution constrained by palaeotopography and is of varied composition. Contrary to its label, this unit varies locally from silt to sandy clay, interbedded with thin beds of quartz sand, and locally some micrite lenses. It is overlain by younger aeolian sediments, and underlain by the Loxton-Parilla Sands (see Figure 2).

The geometry of the unit is partly a product of topography at time of deposition and partly due to post-depositional erosion. Both the lower and upper surfaces of the unit are irregular as a consequence. Locally the clay may attain thicknesses of 20m, but more commonly is only a few metres thick (Stephenson, 1986). The unit is generally thicker in the east. The overlying sediments are commonly up to 5m thick, exceeding some 20m where larger dunes are present.

4.2 PETROPHYSICAL CHARACTERISATION AND FORWARD MODELLING

Petrophysical study of the target materials using borehole electromagnetic (EM) induction / conductivity logging, confirmed that, where present, the Blanchetown Clay was characterised by elevated electrical conductivities relative to overlying and underlying sandy sedimentary units. Previous work in the South Australia Mallee (eg. Cook and Kilty 1992), demonstrated the potential of helicopter electromagnetics (HEM) data to help predict drainage to the deeper groundwater system by mapping the distribution of near surface, conductive clays. We were interested to determine whether a similar strategy could be employed effectively and economically in the Riverland region, and what, if any, airborne geophysical system was capable of mapping both the thickness and distribution of these clays. This was something not attempted before. To assist in answering these questions, we undertook a forward modelling exercise to determine which airborne electromagnetic (AEM) system might best define variations associated with this unit.

AEM systems map subsurface features through the transmission of electromagnetic energy, interaction of this energy with the ground, and reception of secondary, induced energy at a receiver. AEM technologies come in a variety of guises, but the majority have a source of electromagnetic energy (a transmitter) and a receiver to detect the response of the ground. Currents induced in the ground are a function of conductivity. By processing and interpreting the received signals, it is possible to make deductions about the distribution of conductivity in the subsurface.

Our forward modelling work indicated that high resolution frequency domain helicopter EM (HEM) data rather than fixed-wing time domain EM systems were most suited to the detection of the clay at a resolution appropriate for planning purposes (Green and Munday, 2004). The potential of several different EM systems (both time and frequency domain) was also examined, but the system best suited to mapping the clay was the Fugro RESOLVE HEM system (Munday *et al.,* 2003). Details of the RESOLVE HEM system used throughout the survey are contained in Table 1.

Prior to committing to a full survey, a limited test of the RESOLVE system in field conditions was conducted. Conductivity depth intervals (CDI's) for these data were compared with shallow drilling, EM31, EM34 and broadband ground TEM data. Results confirmed that near surface conductivity variations mapped by the RESOLVE HEM system were associated with the clay. Acquisition of some 12 000 line-km of data was then undertaken across the Riverland region (see Figure 1) at line spacings of 150 or 300m.

4.3 CONSTRAINED INVERSION OF HEM DATA

4.3.1 Mapping the Blanchetown Clay

In order to achieve the stated aim of mapping the distribution and thickness of the Blanchetown Clay and related materials, the HEM data were recalibrated with measurements from down-hole induction logs from bores scattered throughout the survey area. They were then inverted using a five layered 1-D parameterisation of the earth (Brodie *et al.*, 2004). The procedure involved in inverting HEM data is summarised in Figure 6.

Table 1. Details of the RESOLVE HEM system.

RESOLVE is a six frequency EM system mounted in a 'bird' towed beneath a helicopter (Figure 5). The bird contains horizontal coplanar coils, and in this survey, measured EM responses at 385 Hz, 1518 Hz, 6135 Hz, 25 380Hz and 106 140 Hz. It also has one coaxial coil pair which measured a response at 3323Hz. The transmitter-receiver separation was 7.86 m for the horizontal coplanar coil sets, and 8.99m for the vertical coaxial (3323 Hz) coil set. The towed bird assembly was fitted with a laser altimeter and GPS receiver, and nominally operated at 30 m above ground level.

The RESOLVE is a fully digital EM system, offering improved signal:noise characteristics, real-time signal processing as well as internal calibration coils for automatic phase and gain calibration in the air. These characteristics result in higher accuracy and a reduced drift. The very high frequencies help resolve very near surface conductors, as might be represented by the Blanchetown Clay units in the Riverland area.

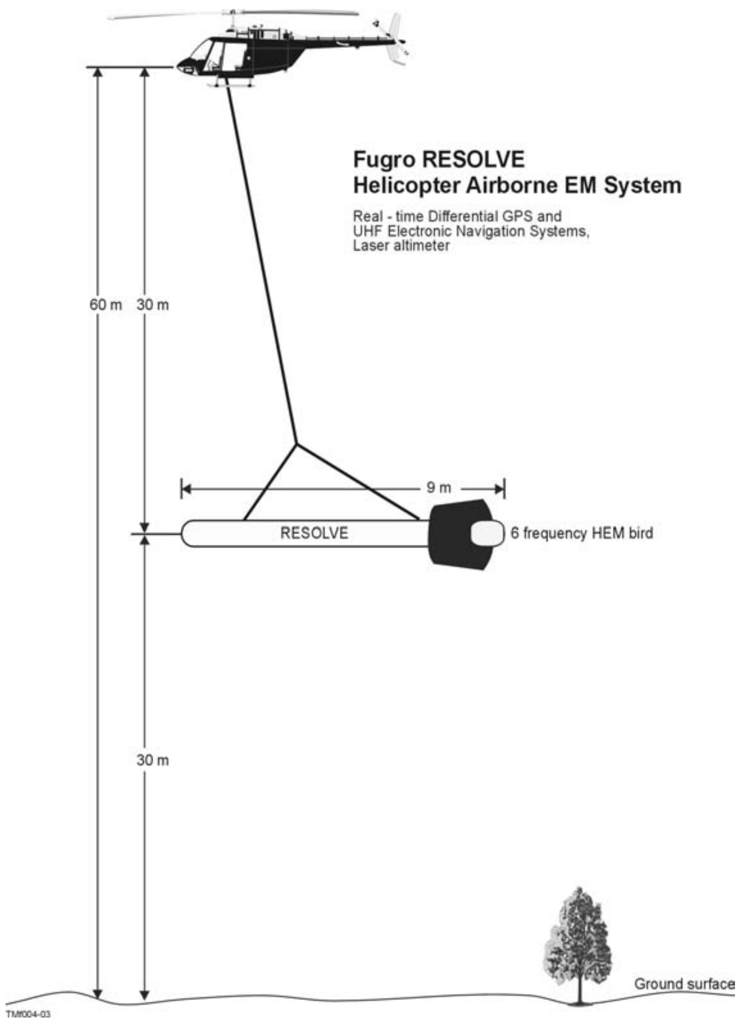

Figure 5. The RESOLVE HEM system survey configuration.

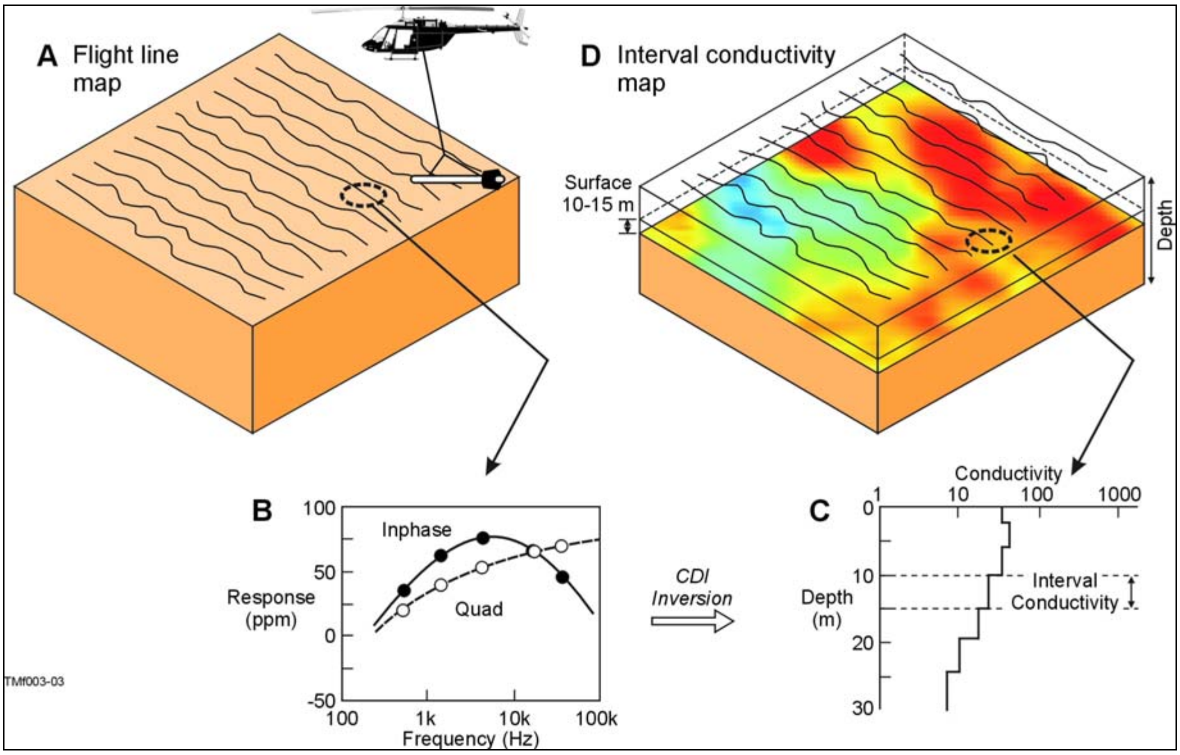

Figure 6. Schematic representation of Helicopter EM data acquisition and interpretation. A) Data are acquired along parallel flight lines; B) The receiver towed beneath the helicopter measures the inphase and quadrature EM response of the ground at several frequencies; C) The measured response is used to determine the conductivity-depth function by inversion. D) The conductivity-depth functions may represent layers and are combined to produce interpreted conductivity-depth intervals (CDIs) or stitched sections (eg. Figure 7) which map the spatial distribution of conductivity as it varies with depth (adapted from Fitterman and Deszcz-Pan, 2001).

To improve sensitivity to unknown aspects of the subsurface, the inversion was constrained with as much local geological and hydrological information as possible, including depth of the water table, conductivity of the groundwater, and information on the variability of the conductivity and thickness of three sedimentary units; namely the Woorinen Formation (aeolian sands at the surface), the Blanchetown Clay and the Loxton-Parilla Sands. An understanding of the geological and geomorphic history of the area was used to help define the probable geometry, distribution and disposition of relevant sedimentary units.

A map of the distribution and thickness of the Blanchetown Clay and similarly textured units was produced (Figure 8), with these data being the first of the contracted outputs for the Riverland site. While the map of clay thickness produced from bores (Figure 4) shows regional trends, the map generated from the constrained inversion shows greater local variability and an improved resolution, providing a product that can be used more effectively for modelling at both a regional and local scale.

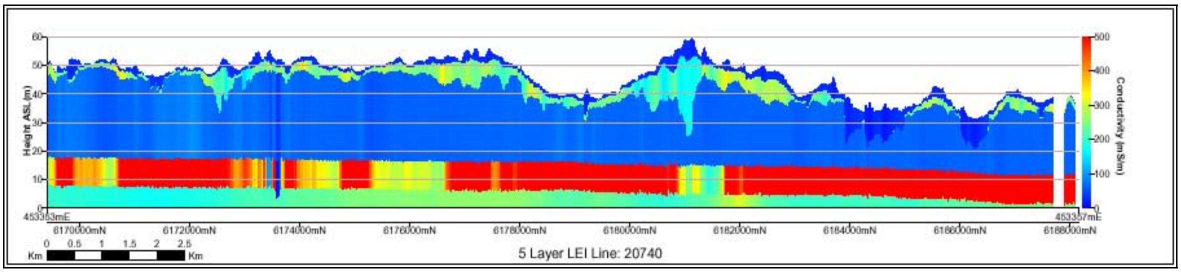

Figure 7. Stitched section illustrating the results from a constrained layered earth inversion for a typical flight line in the survey area. The sections shows layers with different conductivities which vary with depth below the ground surface.

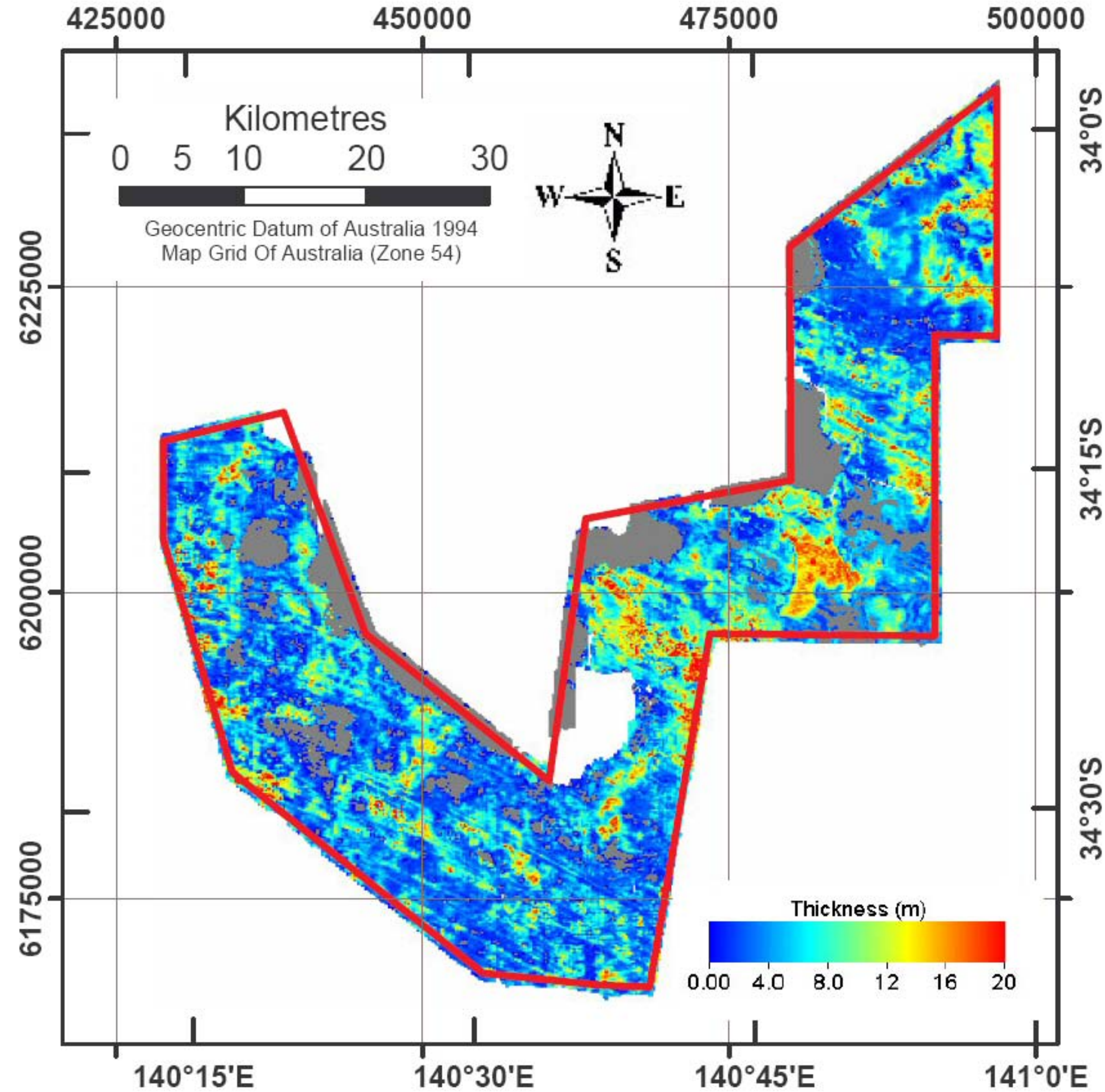

Figure 8. Map detailing the distribution and thickness of Blanchetown Clay and like materials in the Riverland region.

It is worth noting that the value of the airborne geophysics for the Riverland region has, in part, only been realised because of the wealth of hydrogeological data that exists in the area. It is highly unlikely that a “clay thickness” product could have been generated with a similar accuracy and fidelity without these ancillary data. In areas lacking spatial detail on depth of the water table and the conductivity of the groundwater, it is probable that a comparable airborne survey would yield information of a different nature and this would have to be given due consideration when considering their acquisition elsewhere.

The option of reducing line spacing might be examined in such circumstances. Somewhat contrary to the assertion that if a large pool of land management data exists at an appropriate scale, airborne geophysics in its current format is unlikely to be of sufficient value to warrant acquisition (eg. George and Woodgate, 2002), we would suggest that their application should always be examined, even in such instances, but only where the means exists to translate derived information into something of value.

4.3.2 Validation of the Clay Thickness product

In the analysis of all electromagnetic data of the type derived from the RESOLVE HEM system, it is always difficult to discriminate a change in layer thickness from a change in its conductivity. Moreover, as the layer becomes thinner, this difficulty increases. Thus, with thin layers, it is difficult to tell if an observed change in electromagnetic response has been caused by a layer thickening or by increasing conductivity.

In this project, we set up the inversion with a bias to cause changes in the high frequency data to appear as thickness variations in the clay layer. This was primarily achieved by stopping the clay conductivity from dropping below 100 mS/m and by providing an expectation that the clay conductivity will be approximately 240 mS/m. This is a reasonable enough assumption. After all, we might expect that very low conductivities would be better represented by an absence of clay in favour of either the upper or lower sands.

We have two ways of assessing the performance of the inversion. Both involve comparisons with drilling information. The first comparison is between the inversion results and induction logging of nearby drill holes. In general the inversion can be seen to match the logs as well as might be expected given the constraints of a simple five-layer model.

The other sources of comparative data are driller’s logs. Although they are more numerous, these logs are less reliable than the recent induction logging because they are generally of uncertain or inconsistent origin, having been collected over a considerable period by many different interpreters. Figure 9 shows a scatter plot comparing predicted clay thickness (from the inversion of the HEM data) and recorded clay thickness from drilling logs. Further discussion of these results is presented in Tan et al (2004), and Brodie et al. (2004).

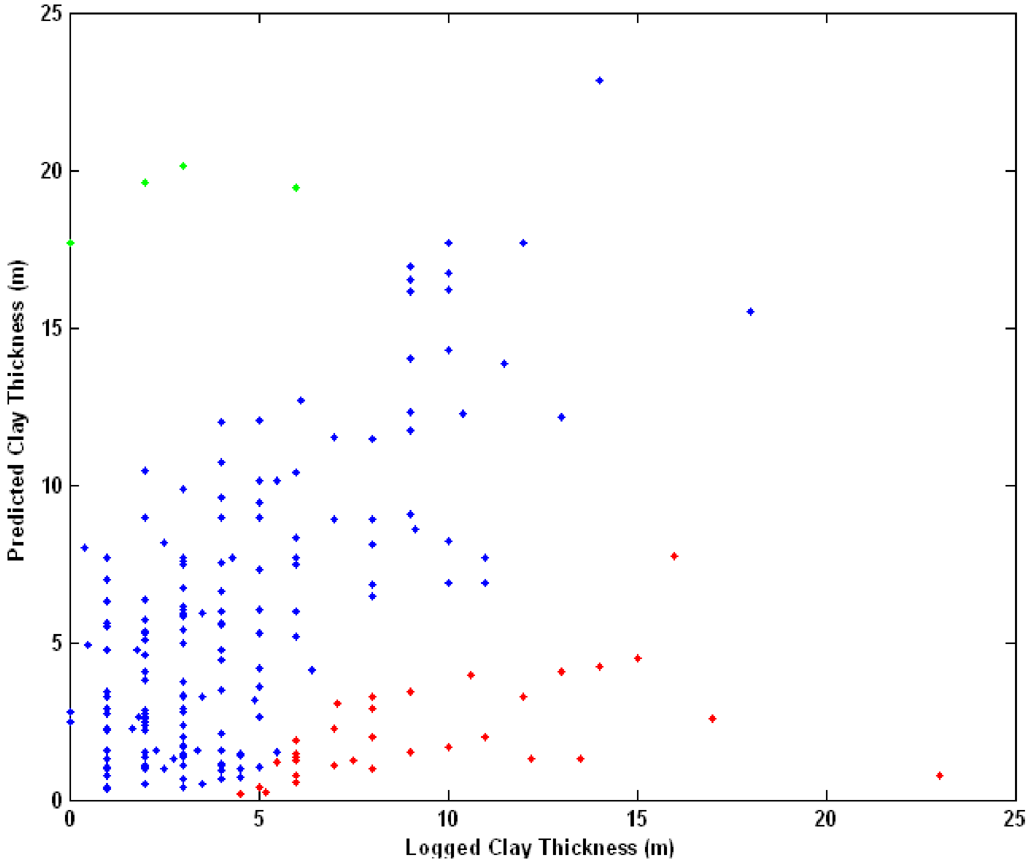

Figure 9. Scatter plot of clay thickness predicted form the inversion v's that from driller's logs.

There is considerable scatter on this plot. Our assessment is that the points plotted in blue represent the typical scatter for this data set. While those in red and green are probable outliers.

However, even accepting these outliers, there is still considerable scatter among the blue points. It would be interesting and useful to investigate the causes for this scatter in greater detail but at this stage we can only speculate about possible causes. Table 2 summarises some of the potential errors that may contribute to the observed relationship.

Table 2. Sources of error in the determination of clay thickness using HEM data

1) ***Inversion errors*** - Inappropriate constraints in the inversion may lead to errors in defining particular layers (eg the clay layer) from conductivity. Also in situations where the ground departs from 1D model, ambiguities and errors will arise – such as on the edge of the highlands.
2) ***Geoelectric properties*** - Given that the inversion relies on assigning a conductivity to a particular material type, no account can be taken of situations where non-clay materials exhibit clay-like electrical responses (eg. where they contain salty water)
3) ***Sampling differences*** - Airborne EM systems sample a large area (~2 x flight-height i.e. ~60m) in comparison with a drill hole (~10-15cm). In areas of variable clay thickness substantial discrepancies will occur.
4) ***Positioning differences*** - Drill holes are rarely close to flight lines and areas of variable clay thickness will cause differences.
5) ***Interpretation differences*** - The Blanchetown Clay often has appreciable sand content and interpretation of cuttings may produce quite different logs from those based on electrical conductivity. These problems are multiplied when, as in this case, different people have logged the cuttings over a long period.

5. *Unexpected Findings*

5.1 MAPPING LOXTON-PARILLA SANDS – INFORMING THE DEVELOPMENT OF SALT INTERCEPTION SCHEMES

Results from the constrained inversion of the HEM data have revealed information on the palaeo-landscape which existed prior to the development of Lake Bungunnia and the deposition of Blanchetown Clay. By imaging the base of the Blanchetown Clay as defined in the inversion (Brodie *et al*., 2004), we observe what is essentially the top of the Loxton Sands and a well developed beach strandline pattern that developed through the Pliocene as part of a prograding sedimentary sequence (see Figures 10, 11).

These strandlines were not apparent on the regional digital elevation model (the GEODATA 9 second DEM, http://www.ga.gov.au/nmd/products/digidat/dem_9s.htm), although they are much more clearly defined on the recently acquired elevation data generated as part of the Shuttle SRTM experiment conducted by NASA (Farr and Kobrick, 2000). The orientation of these strandlines is masked or obscured by the Quaternary dune systems which are orientated east-west as seen in a detailed elevation model derived from laser altimeter data collected during the geophysical survey. The nature and disposition of the Loxton-Parilla Sands, and the depositional setting for their development, is significant in the Riverland context, as these sediments represent an important aquifer that is to be pumped as part of the salt interception schemes (SIS) planned for Loxton and Bookpurnong.

Recent drilling and aquifer testing in the uplands adjacent to Lock 4, at Bookpurnong, identified high local variability in aquifer properties within the Loxton-Parilla Sands. The prevailing consensus is that the observed variation in transmissivity associated with the current bores is strongly correlated with the facies[3] variations in the Loxton-Parilla Sands. It has also been suggested that within the prograding strandline sequence (see Figure 11), there was likely to be a lateral persistence in permeability, particularly in the orientation of the strandlines themselves. In order to understand these observations better, Australian Water Environments, DWLBC, CRCLEME, and SA Water undertook a limited study of the sediments in the Bookpurnong area combining detailed interpretation of borehole geology, ground and airborne geophysics, with the analysis of sediments for the Loxton Sands and underlying Bookpurnong Beds (Munday et al., 2004). This was regarded as an important precursor to the development of a predictive model of groundwater hydraulic properties using available hydrogeological and geophysical data.

[3] Facies – sediment characteristics associated with particular depositional environments.

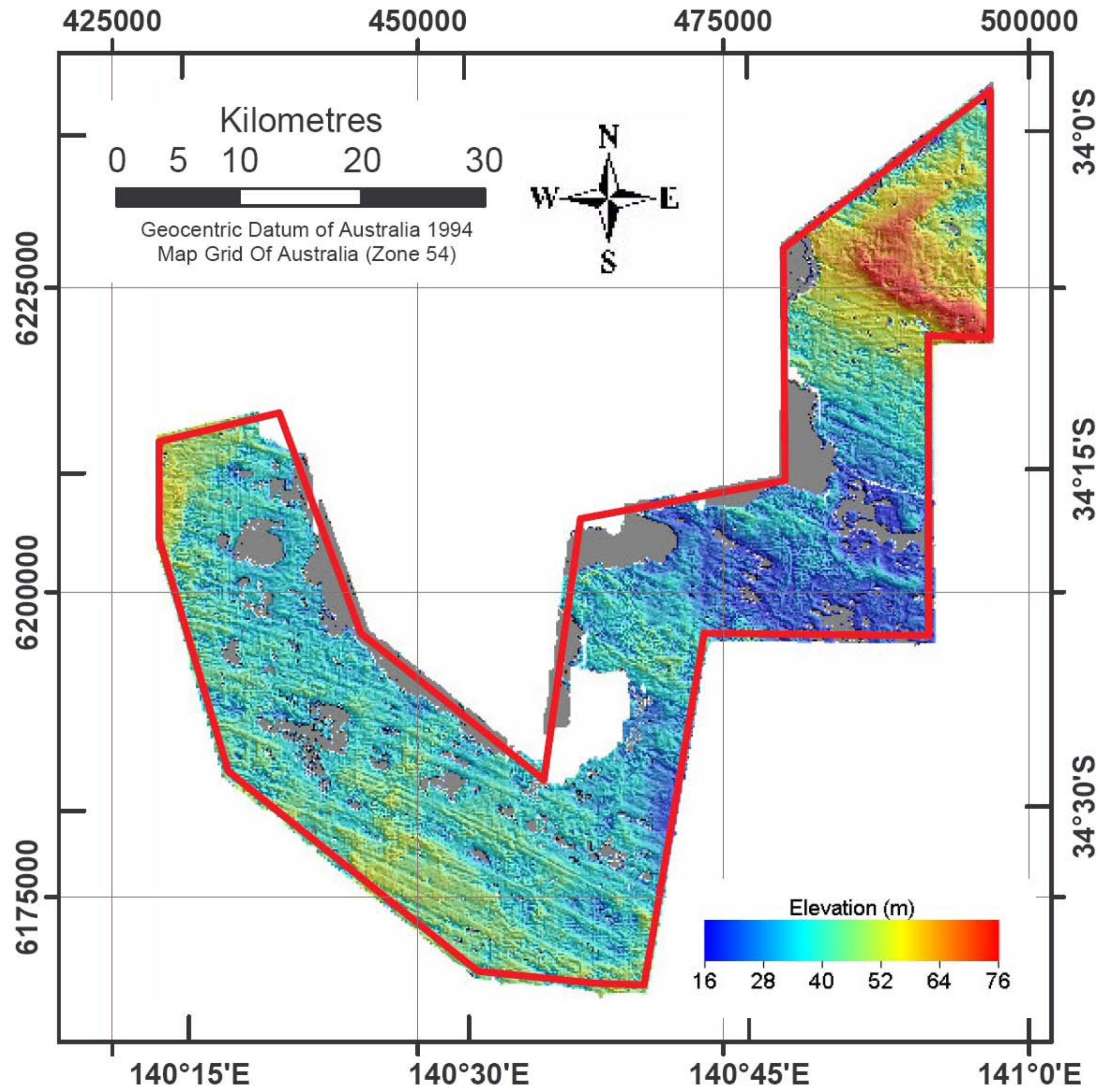

Figure 10. Map from the inverted Helicopter EM data showing the elevation of the Loxton-Parilla Sands across the Riverland region. Strandlines orientated NW-SE are clearly defined.

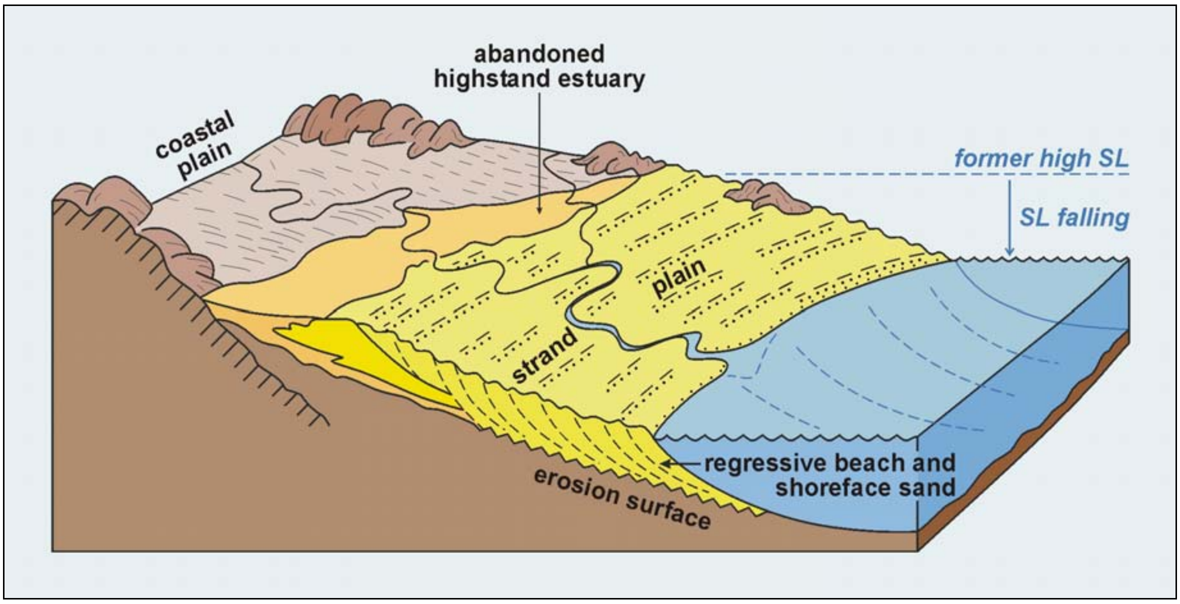

Figure 11. Schematic block model illustrating a regressive barrier sequence prograding under falling sea levels to produce a tabular, gently seaward-inclined sand deposit some 10-20m thick (Adapted from Roy *et al*., 1994). This describes the depositional model for the Loxton-Parilla Sands found in the Riverland region of the Murray Basin.

Results of this study have led to a refinement in our understanding of the sedimentological model that defines lateral and vertical changes in facies associated with the main aquifer system relevant to the SIS. Relatively narrow zones of high transmissivity, characterized by slightly reduced electrical conductivity response at the watertable, have been observed in ground and airborne electromagnetic data. The constrained inversion of helicopter EM data has helped to better define the geometry of this sedimentary system.

At Bookpurnong, in the vicinity of Western's Highland and Brand's Highland, a correspondence between transmissivity and zones of low electrical conductivity (coincident with the orientation of the strandlines) was noted (Figure 12). A similar correspondence was not apparent in the vicinity of Lock 4. These results suggest that, in places, EM techniques together with a hydrogeological interpretation may assist in developing a targeted scout drilling program as part of a broader strategy to identify potential SIS production bore sites.

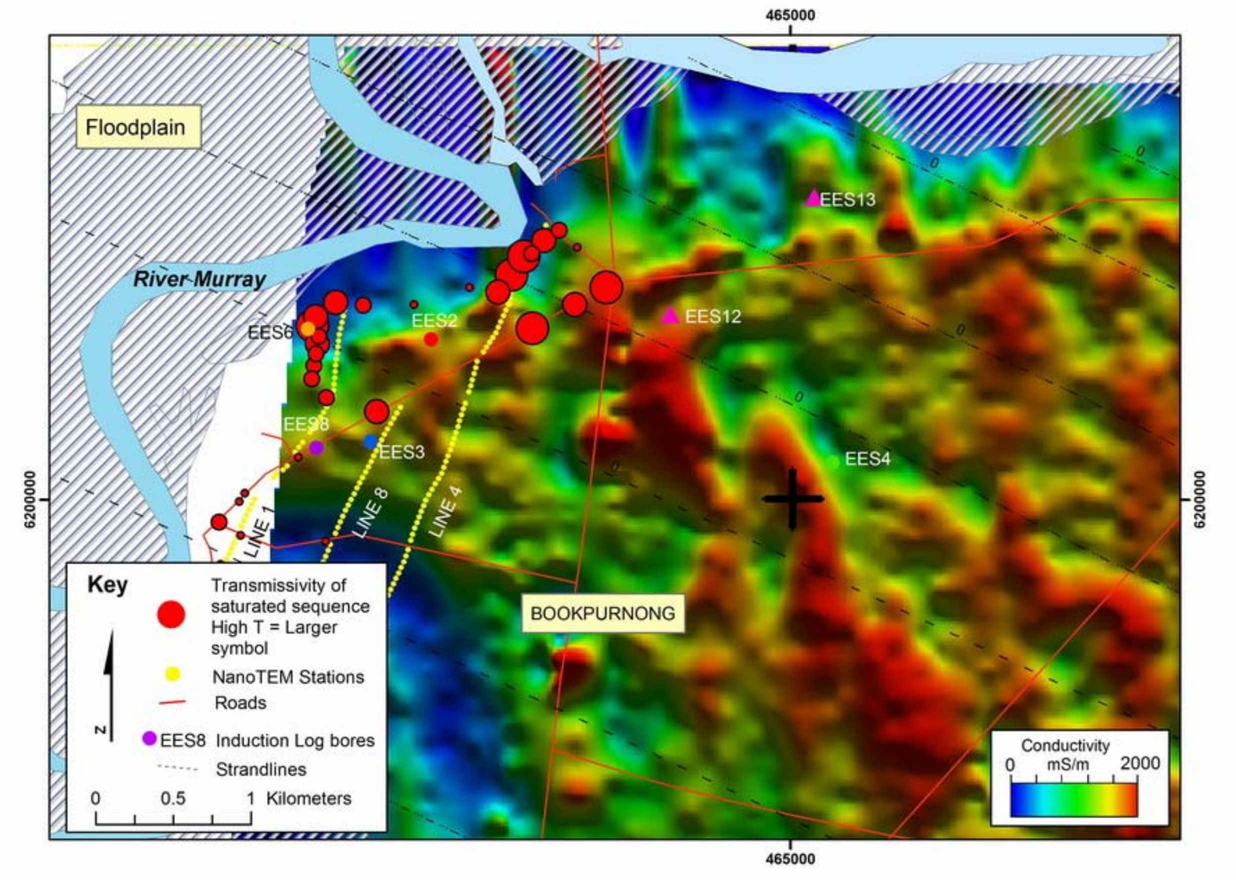

Figure 12. Bookpurnong Study area with pseudocoloured image of the conductivity of the 4th layer from constrained layered earth inversion of RESOLVE HEM data. Transmissivities of saturated materials from select pilot bores in the highlands are shown. Higher transmissivities have been recorded in holes straddling the HEM determined strandlines.

By providing further insight into the depositional environment of the Loxton-Parilla Sands, the HEM data, linked to further detailed ground work (AWE, 2004; Hill *et al*., 2004; Munday *et al*., 2004) have provided a framework that improves the conceptual model for the sedimentology and stratigraphy of the Riverland region. This has the potential to assist hydrogeological modelling for the SIS in the Central Murray Basin and is now being employed in developing the Loxton SIS (Hill *et al.*, 2004) (see Figure 13).

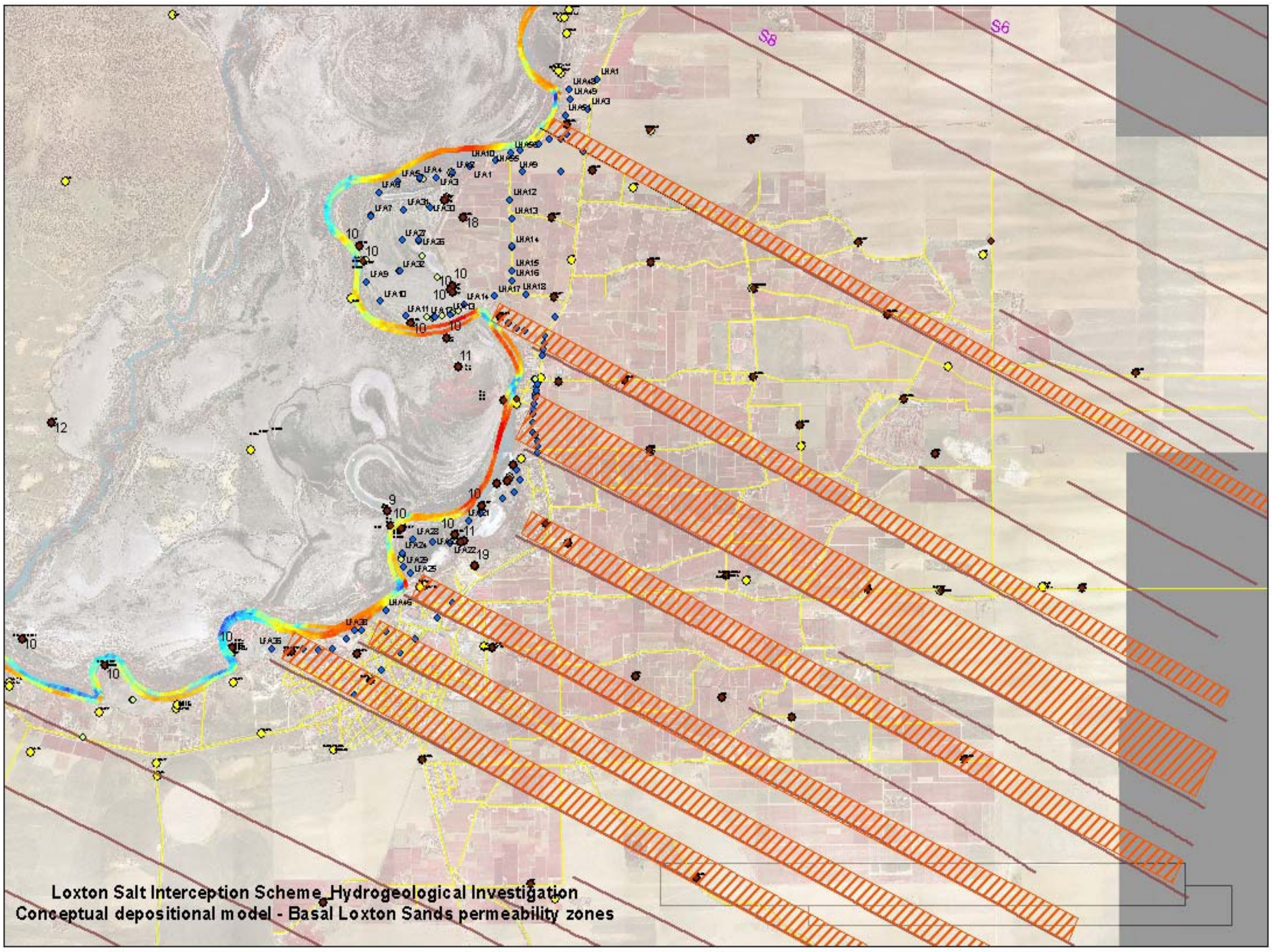

Figure 13. HEM derived strandline positions being used to inform the targeting of pilot production bores as part of the Loxton SIS investigation program (Hill *et al.*, 2004).

This unforseen outcome from acquisition and processing of the airborne geophysical data suggests that while having a clear objective for the geophysics is critical; value might also be gained in taking a more holistic look at salinity related issues when initiating projects of this type.

5.2 FLOODPLAIN PROCESSES

More recently, a limited investigation of available helicopter EM data where it covers the River Murray floodplain, suggests that the technology could be effective in providing valuable spatial detail on the salinisation of floodplain soils. While further work is required to better determine this potential, airborne geophysics such as that already acquired at Riverland, could help link 'Run of River' salinity determinations and river floodplain processes, thereby helping inform policy for floodplain protection and salinity mitigation.

An interval conductivity image for the depth interval 0-4m for part of Clarkes Floodplain near Bookpurnong showns a relatively good correspondence with groundwater conductivity sampled in bores (Figure 14). High conductivity areas in the image are shown as yellow and red colours. The conductivity data also indicate where the river may be a gaining system and a losing system in terms of salinity. Figure 15 shows that the observed ground conductivity mapped from airborne EM data correlates well with chloride content of floodplain sediments. These preliminary results suggest that these data could provide a basis for determining where the salt is stored in the floodplain sediments and how that may be linked to vegetation health.

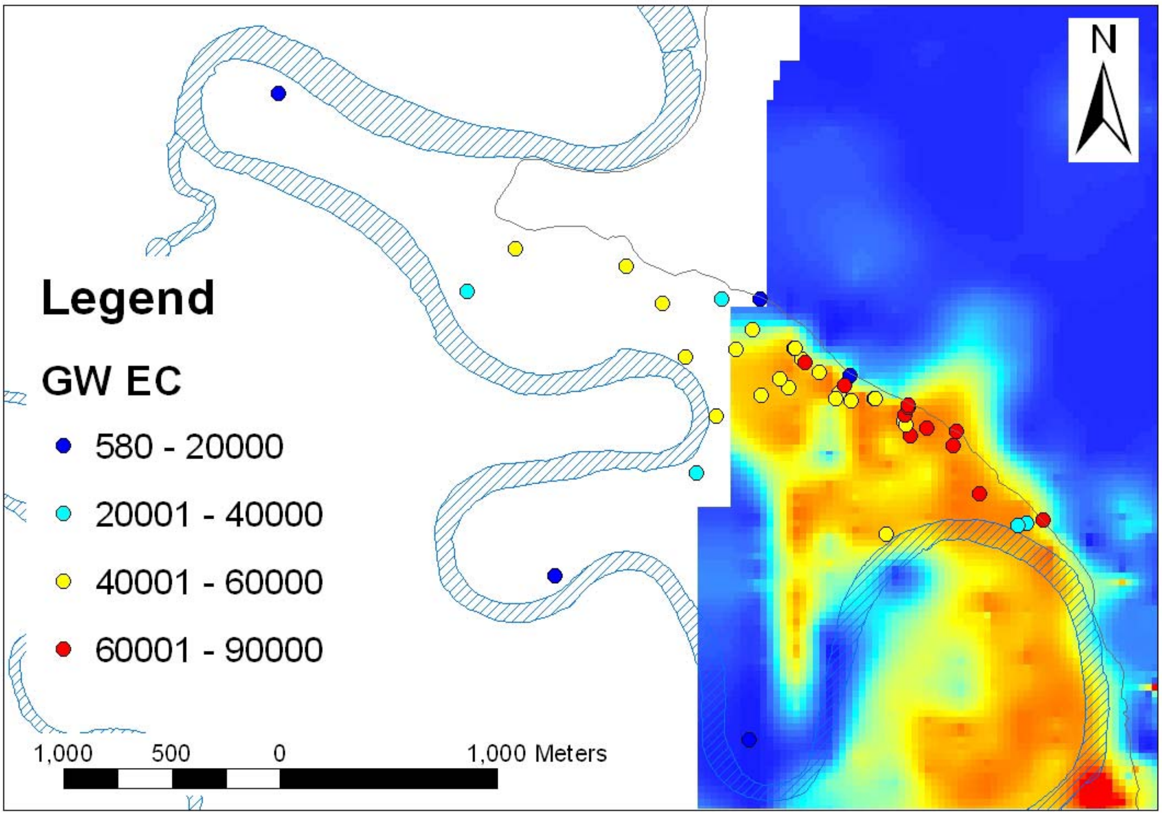

Figure 14. Clarkes Floodplain near Bookpurnong showing an interval conductivity image for 0-4m with borehole conductivities overlain (Rebecca Doble, pers comm.)

The challenge remains to determine how best to incorporate such data into management of river salinity and floodplain vegetation health. Floodplain vegetation requires periodic flushing of salts from the rootzone and steps taken to recover declining vegetation will need to account for additional floodplain salt entering the river.

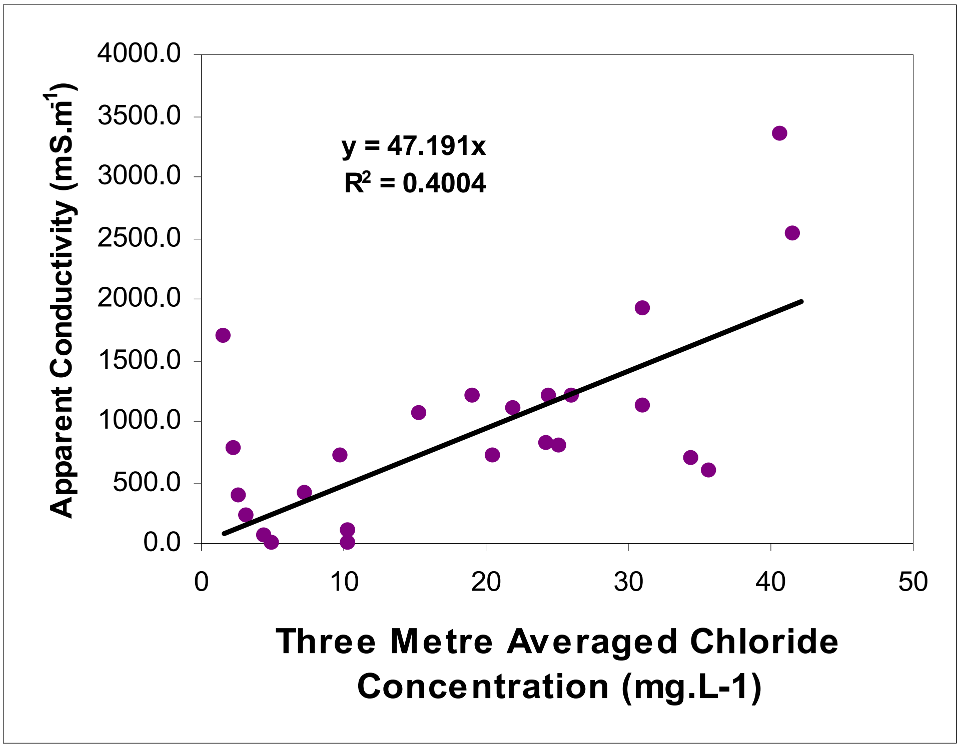

Figure 15. Relationship between the apparent conductivity derived for the 100kHz HEM data and the average chloride content of the top 3 metres of floodplain sediment.

5.3 SOIL LANDSCAPE UNITS

In the Loxton district, a recent comparison between an EM 38 ground survey conducted for soil property mapping purposes, and the apparent conductivity for the highest frequency of the RESOLVE HEM system indicated a high degree of correspondence (see Figure 16).

When Soil Landscape Unit (SLU) boundaries are draped over near surface conductivity data (0-2m) from the HEM survey (see Figure 17), this suggests there is potential for the HEM data to refine existing soil mapping. AEM data may not reduce the requirement for a high density of soil pits, routinely sampled when mapping soils in high value horticultural areas, however such data will significantly improve the understanding of soil variation between pits (Rod Davies, pers. comm.).

This suggests that additional soils information may be forthcoming from the helicopter data set. These observations confirm the work of Cook and Kilty (1992) who used high frequency helicopter EM data to map variations in drainage.

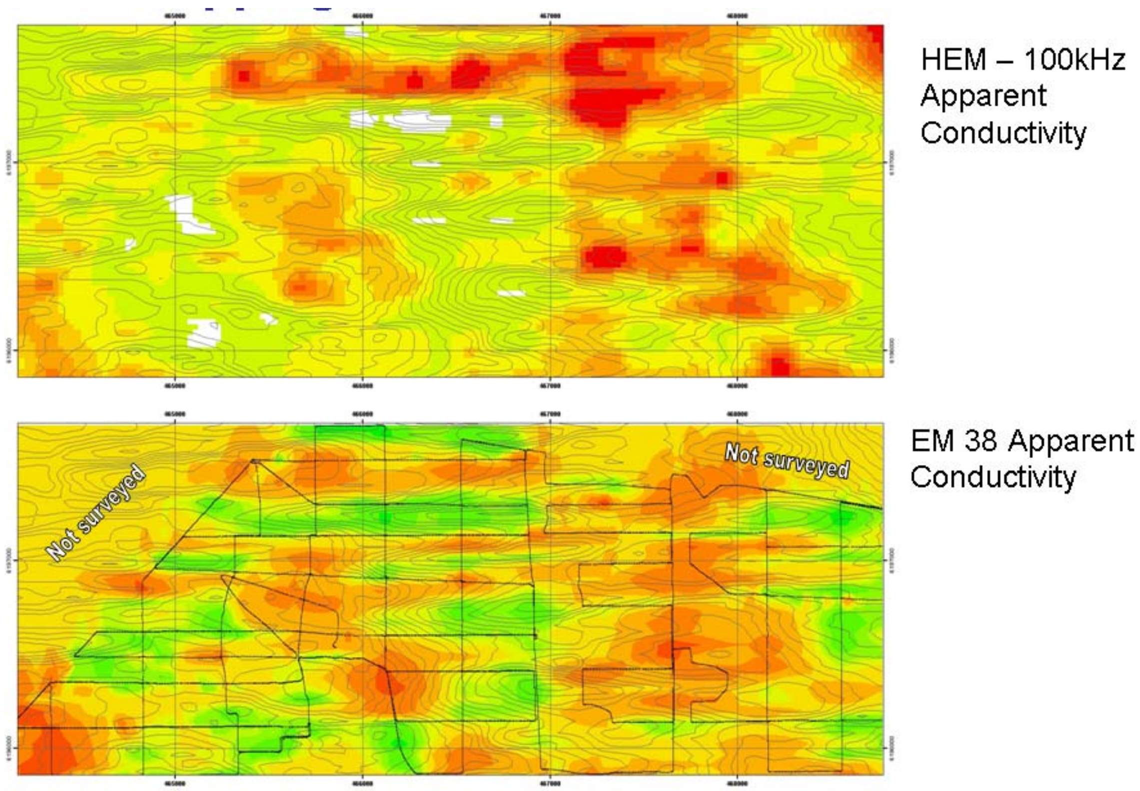

Figure 16. Comparison between EM38 and HEM apparent conductivity data for an area near Loxton. The results suggest that the high frequency airborne EM data may provide some general information about near surface soil character in the Riverland region (Rod Davies, pers. comm.).

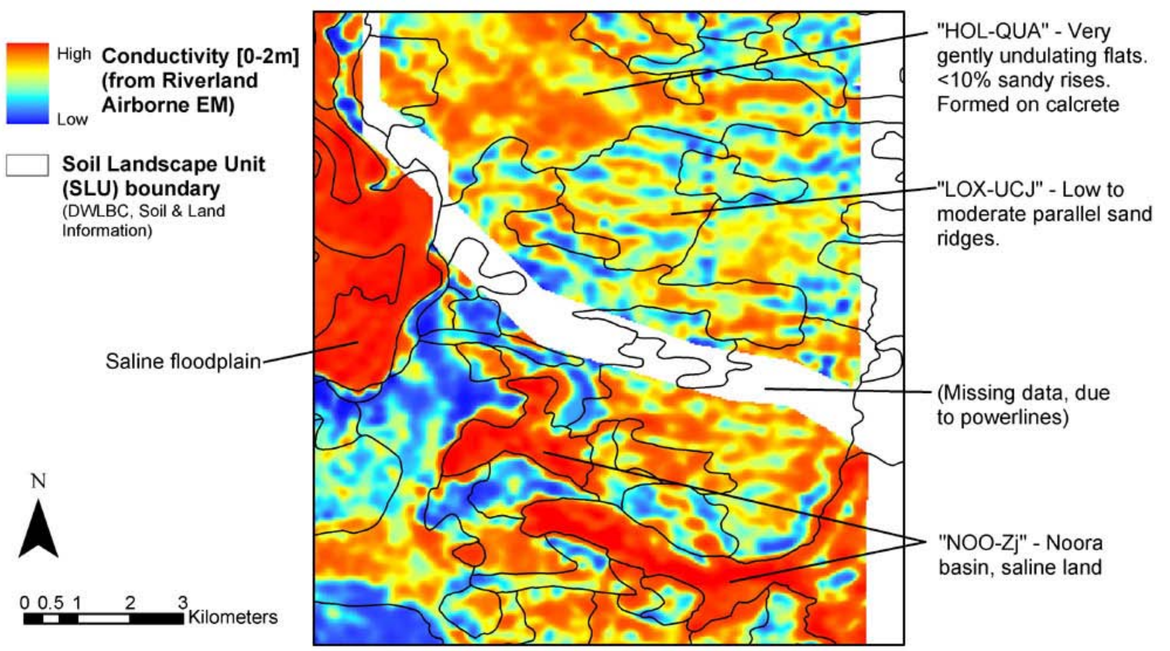

Figure 17. Overlay of Soil Landscape Unit boundaries (DWLBC, Soil and Land Information) on 0-2m interval conductivity image from the Riverland AEM survey, for an area south-east of Renmark. Examples of SLU descriptions are provided.

PART C. DEVELOPMENTS IN MODELLING AND DECISION SUPPORT TOOLS.

6. Estimating Deep Drainage

There are a number of different methods that can be used to provide point estimates of the rates of deep drainage following clearing of native vegetation. For this project, the chloride peak displacement method was used as it is most appropriate when drainage rates are likely to be less than 20 mm/yr. In summary, this method involves measuring the amount of water that has entered the soil profile since the land was cleared of native “mallee” vegetation (as recorded by the downward movement of the ‘salt bulge’ that in pre-clearing times would have remained directly below the mallee rootzone). The average rate of deep drainage is then determined by dividing this amount of soilwater by the time since clearing occurred.

Clearing of mallee vegetation results in an increase in the rate of deep drainage. This can be identified from soilwater chloride profiles, [Cl]SW, as a displacement in the depth at which the peak [Cl]SW occurs. Greater amounts of deep drainage will result in the peak [Cl]SW (or ‘salt bulge’) being located at greater depths. The theory for this method is described in more detail in Cook *et al*. (2004). In order to extend the point estimates of deep drainage to a regional scale, it has been necessary to invoke the use of a parameter that is more readily available as a proxy measurement of deep drainage. Over the last 15-20 years, the clay content of the top 2 m of soil, %C (0-2m), has been developed as such a proxy using an inverse relationship between %C (0-2m) and deep drainage for the 300-399 mm rainfall area in the Mallee (Kennett-Smith et al, 1994).

A total of fourteen cores were obtained as part of this study, to depths ranging between 12 and 57m. Estimates of drainage obtained from chloride and water content measurements on these cores ranged between less than 1 and approximately 15 mm/yr, although most estimates were less than 2 mm/yr. The empirical relationship between post-clearing drainage and clay content for areas in the 300-400 mm/yr rainfall area of the Mallee derived by Kennett-Smith et al. (1994) is presented in Figure 18 (open circles). Also shown in this figure is the relationship for data collected in the present study, where mean rainfall is approximately 260 mm/yr (closed squares). The only previous estimates of post-clearing drainage from Mallee areas with mean annual rainfall less than 300 mm have been at Maggea (5 estimates, rainfall =270 mm/yr) and at Murbko (1 estimate, rainfall =270 mm/yr) (also shown in Figure 18 as closed circles) .

When the data for all of the lower rainfall sites is overlain on the data of Kennett-Smith et al. (1994), it becomes apparent that drainage is significantly lower in these lower rainfall areas.

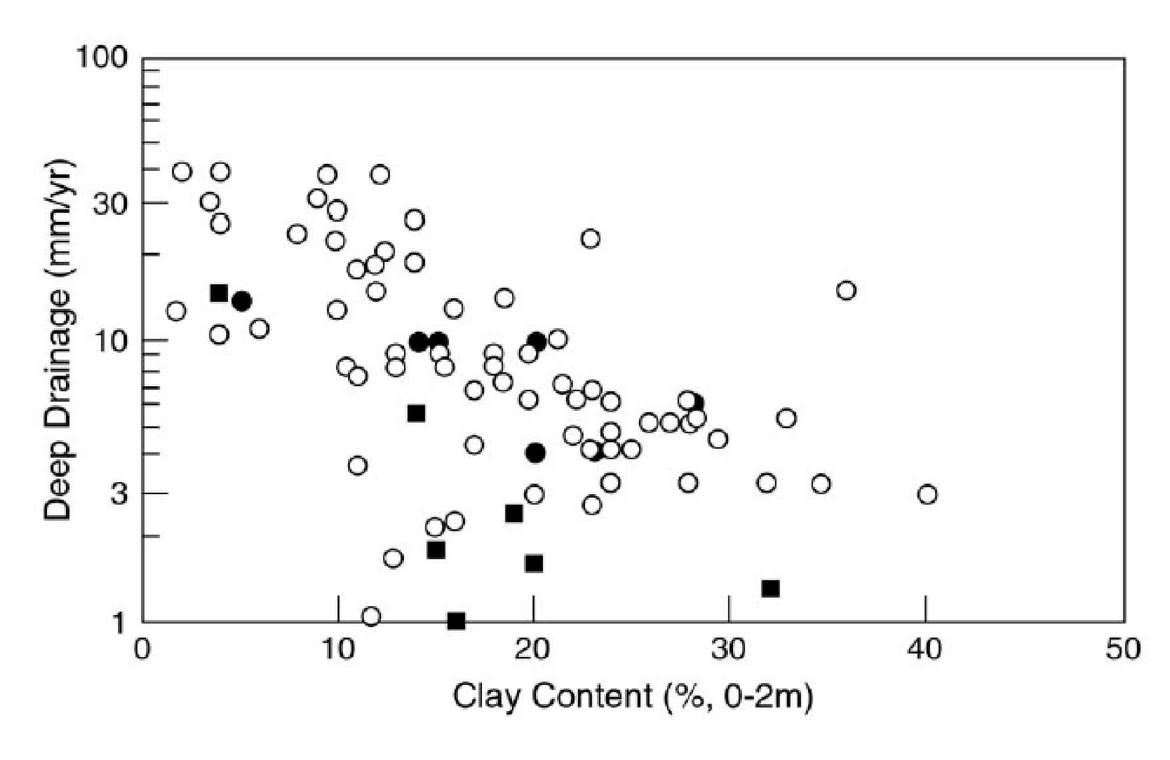

Figure 18. Relationship betweens soil texture and drainage under dryland agriculture in the 300-400 mm/yr mean annual rainfall zone (open circles), at Maggea and Murbko (270 mm/yr; closed circles) and for the study site (260 mm/yr; closed squares).

7. Regional Extrapolation

Estimation of aquifer recharge rates over time across the study area due to clearing of the native vegetation for dryland agriculture requires regional information on drainage rates, water table depths and unsaturated zone soil properties. For this regional mapping exercise, we have assumed that the unsaturated zone can be represented by two layers with uniform soil properties: a sandy loam and a clay layer. Variations in thickness of the clay layer have been determined from stratigraphic mapping and surface and aerial electromagnetic mapping (Brodie *et al.*, 2004). The watertable depth has been estimated as the difference between the potentiometric surface (interpolated from bore records) and the land surface elevation.

Drainage has been interpolated across the region using existing soil mapping and point estimates of drainage obtained during this study and previous investigations. Estimates of current rates of drainage assume:

- the revised methodology of Cook et al (2004), based on estimates of clay content in the top 2m of soil,
- that clearing has occurred and landuse is a uniform crop/ pasture rotation,
- areas currently under irrigation have reverted to dryland agriculture (crop/ pasture rotation), and

- mean annual rainfall.

The data have been combined using the SIMPACT GIS framework (Miles et al., 2001), which uses a 250 m × 250 m grid size. Figure 19 shows the expected current rates of drainage across the study area and Figure 20 shows expected deep drainage across the SA Mallee region.

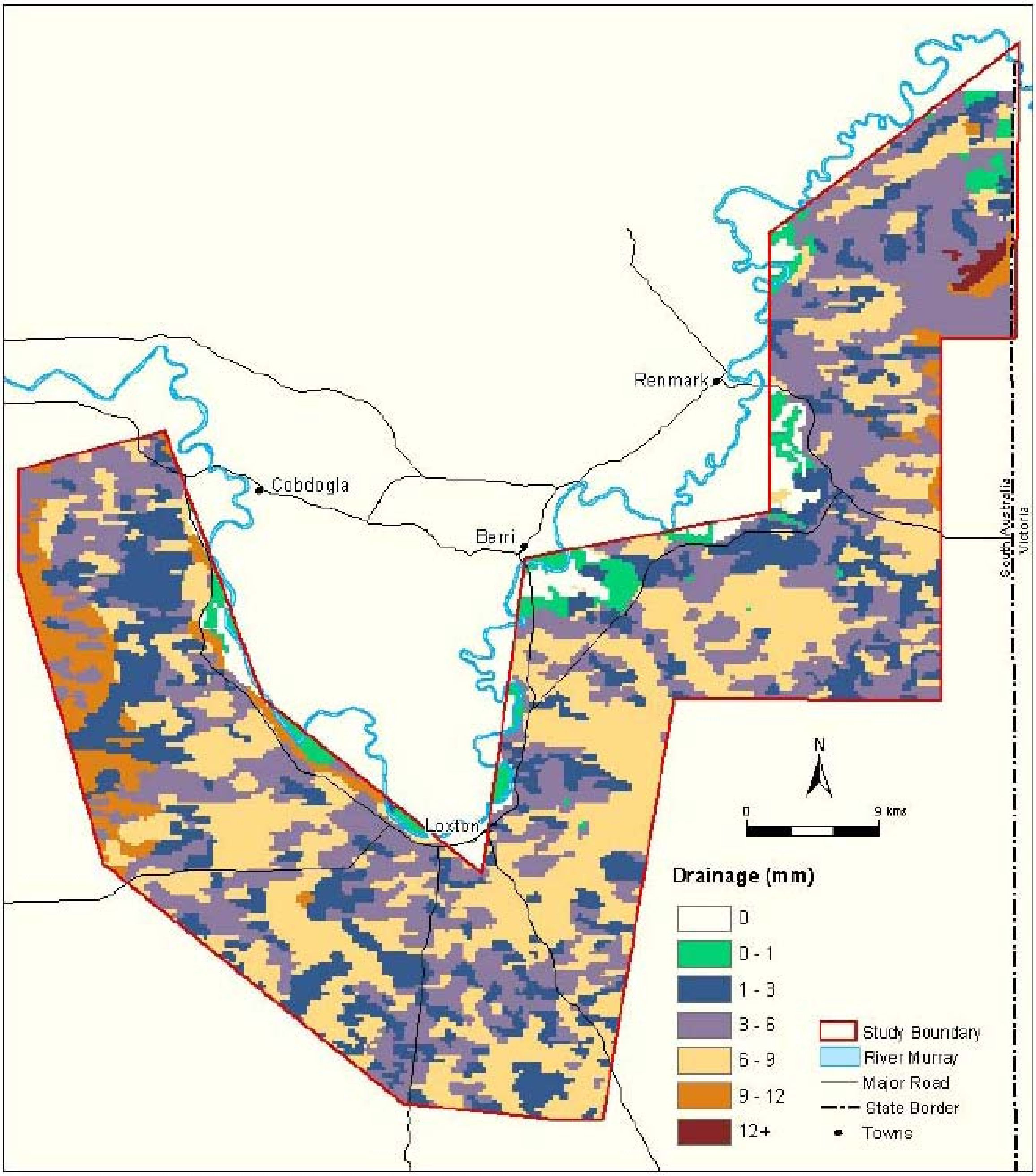

Figure 19. Estimated current rates of drainage in the study area based on a crop/pasture rotation system, mean annual rainfall and soil clay content in the top 2 metres (Cook *et al.*, 2004).

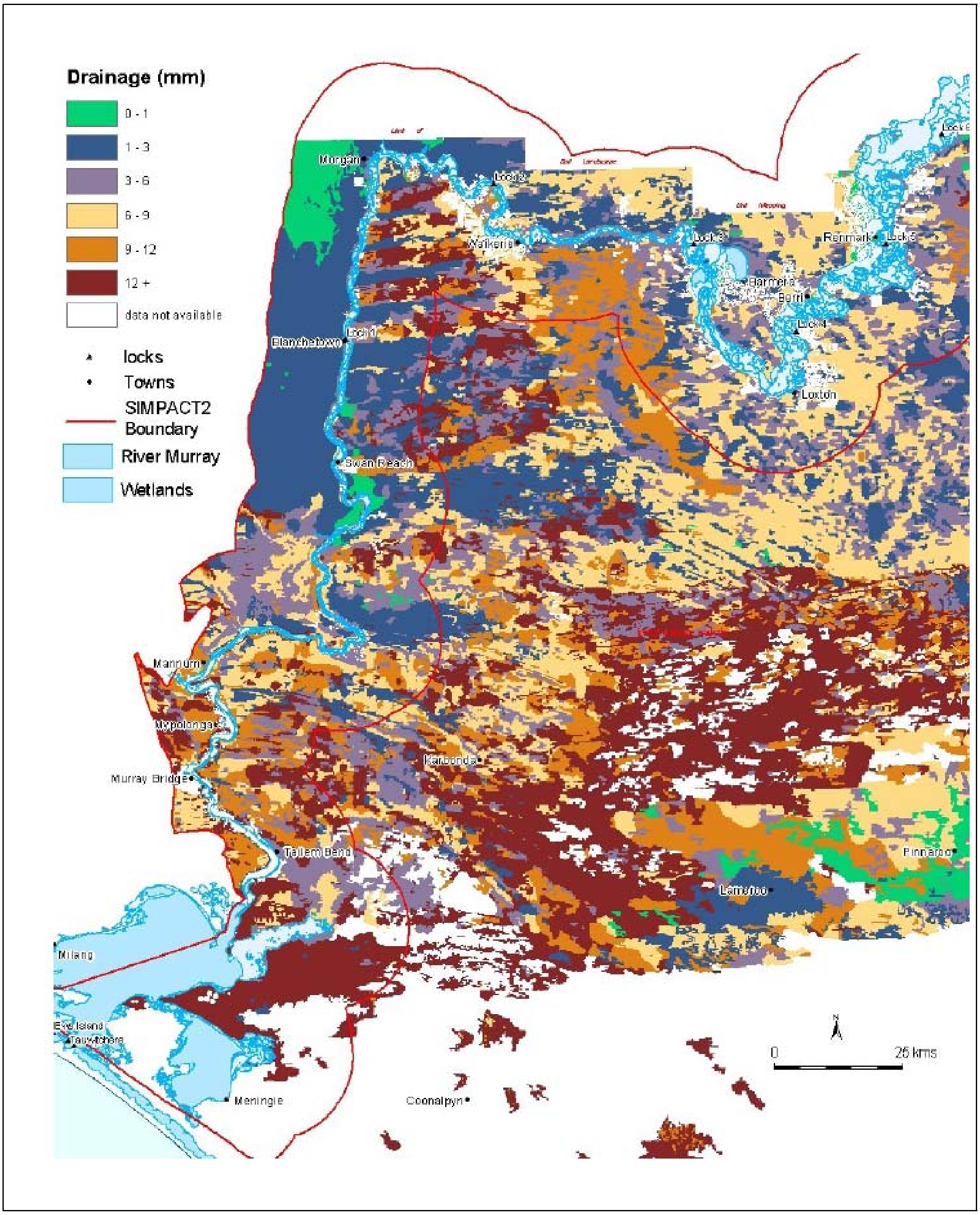

Figure 20. **Revised drainage map for the South Australian Mallee Region. Drainage passing the root zone of crop/pasture rotation system based on mean annual rainfall and soil clay content in the top 2 metres (Cook *et al.*, 2004).**

Maps are also presented to show expected rates of aquifer recharge today (2004), and in Years 2050 and 2100 (Figures 21-23). These replace the earlier recharge maps of Cook *et al* (2004), and reflect revised, lower estimates of deep drainage based on clay content in the top 2m (as discussed in the Addendum to Cook *et al* (2004) and Wang *et al* (in prep)).

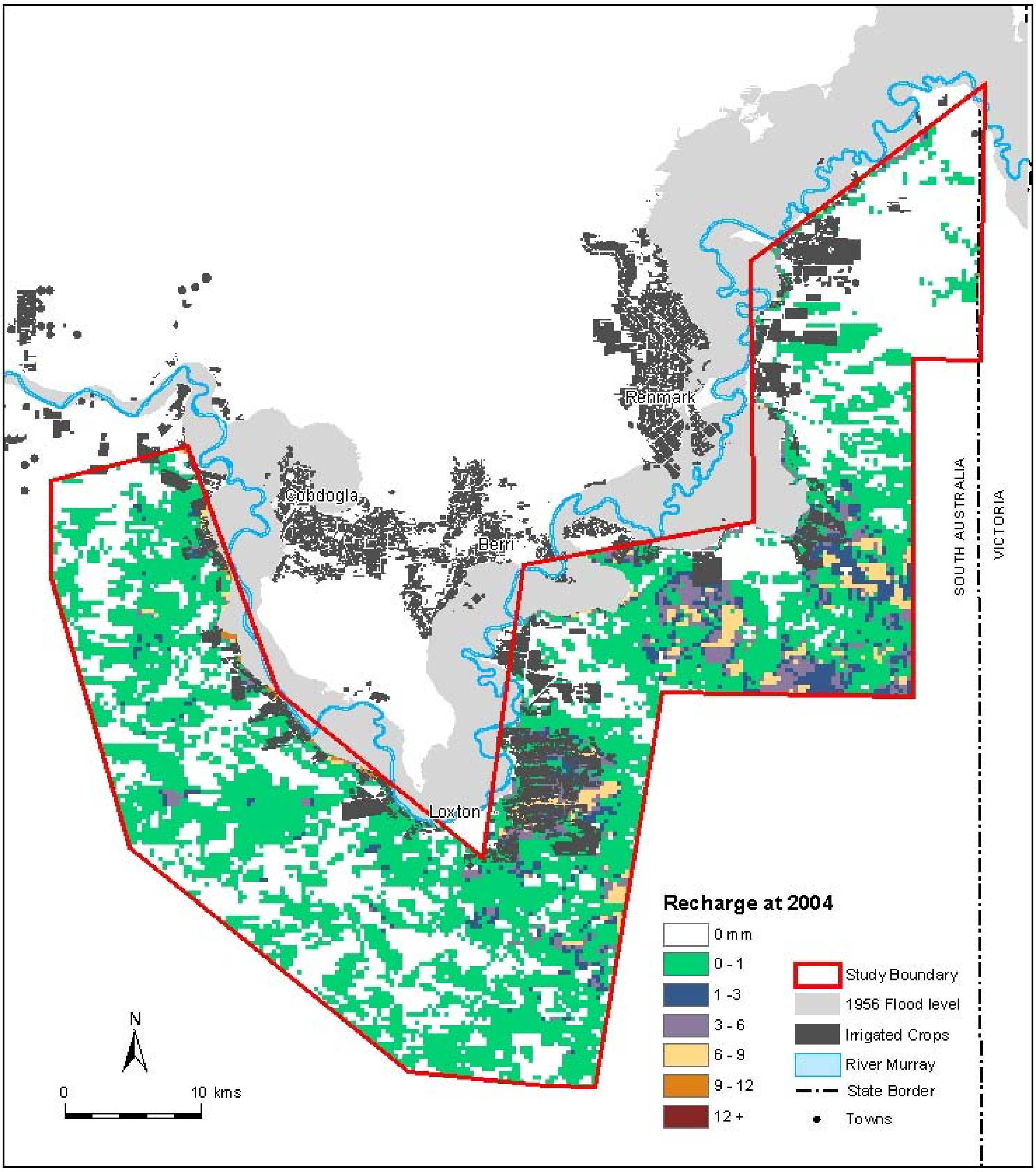

Figure 21. Map of predicted mean recharge rates for the study area in 2004 (84 years after the clearing of mallee vegetation) (Matt Miles, pers.comm.).

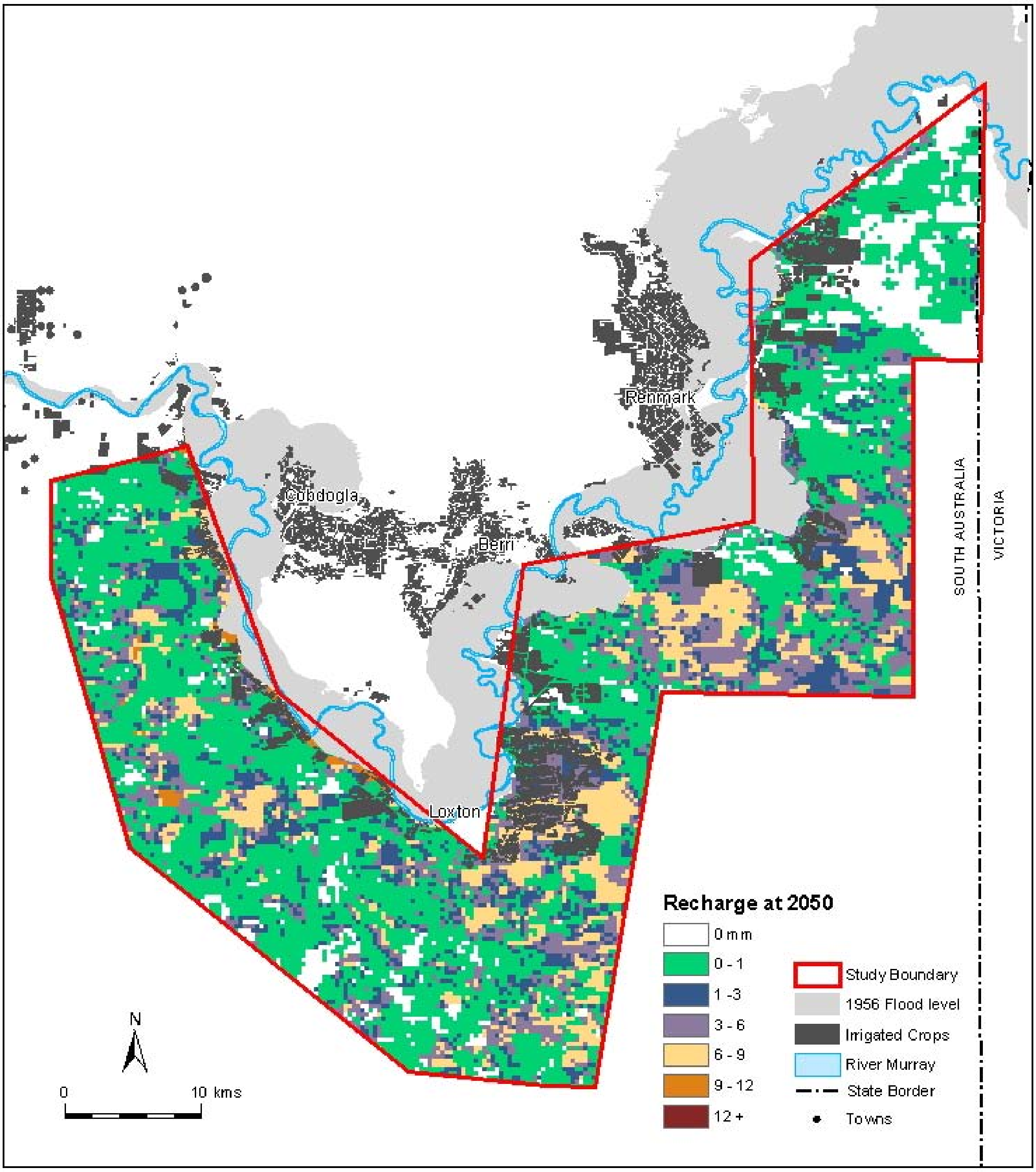

Figure 22. Map of predicted mean recharge rates for the study area in 2050 (130 years after the clearing of mallee vegetation) (Matt Miles, pers. comm.).

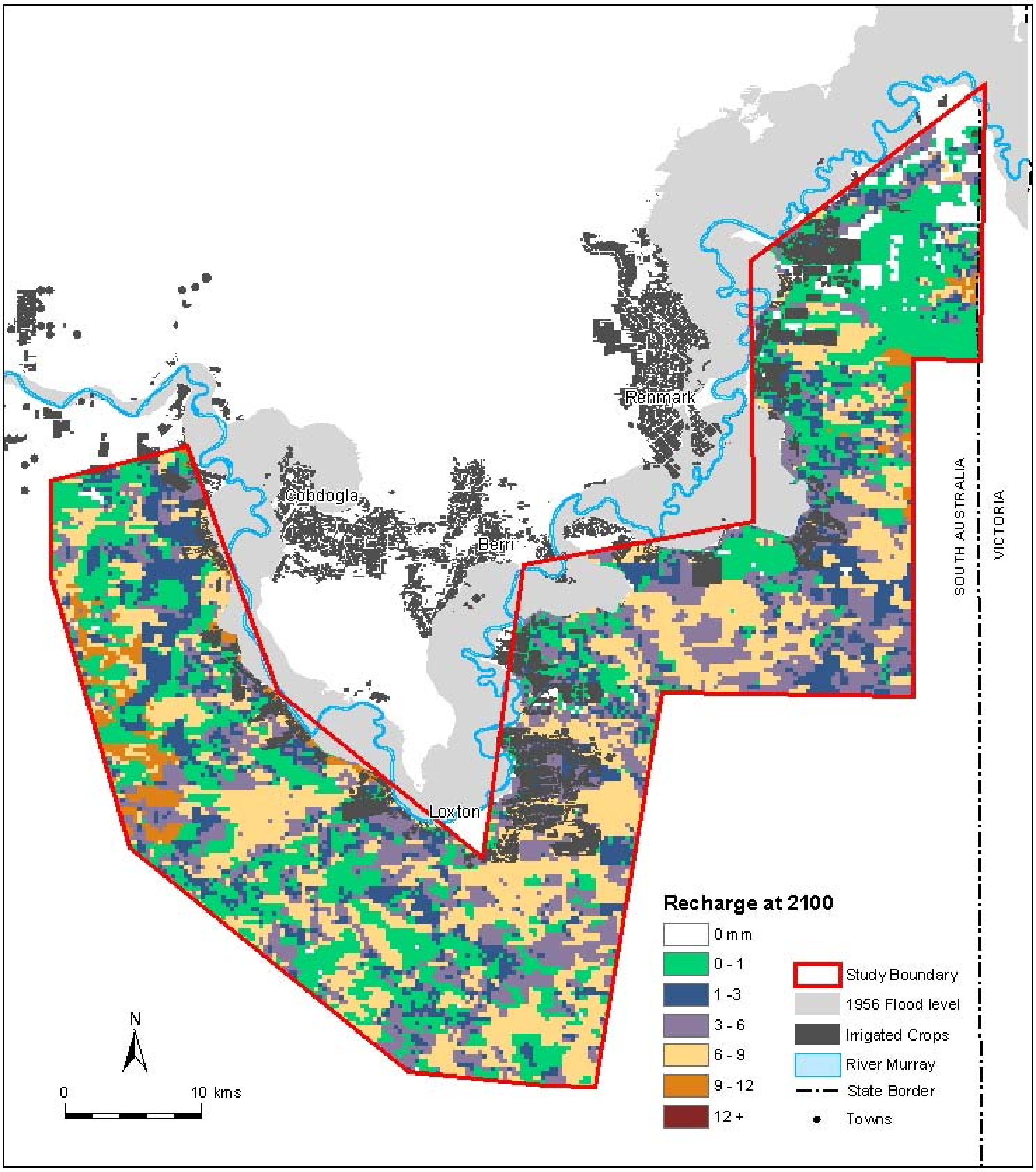

Figure 23. Map of predicted mean recharge rates for the study area in 2100 (180 years after the clearing of mallee vegetation) (Matt Miles, pers. comm.).

8. *Modelling Groundwater Processes*

Previously, it has been necessary to develop several groundwater models in order to:

1) determine the consequences of increased recharge to the groundwater on salt inflows to the Murray River and floodplain following land clearing,
2) assist in the design of cost-effective and efficient salinity mitigation management strategies, and
3) understand the impacts of future irrigation development.

In the Riverland region, current groundwater models are based on MODFLOW (eg. Barnett, 1990; Barnett *et al.,* 2001; Barnett and Yan, 2004), with others implemented in a GIS framework (eg. SIMPACT, Miles *et al.*, 2001, and Floodplain ImPacts (FIP), (Overton *et al*, 2003). The SA SMMSP contributed to the further development of three models which are summarized in Table 3.

8.1 RIVERLAND MODFLOW MODEL

The MODFLOW groundwater model described by Barnett and Yan (2004), was developed as part of the SA SMMSP to predict the effects of increased recharge arising from changes in land management on salt inflows to the river and floodplain. It examines the efficiency of various management strategies to minimise these impacts, using a smaller grid and better calibration compared with models used previously in the study area. The use of improved recharge estimates and lag times relevant to the local area, as described previously (Cook *et al.*, 2004), represents a significant improvement on previous model constraints.

The area covered by the model is shown in Figure 24.

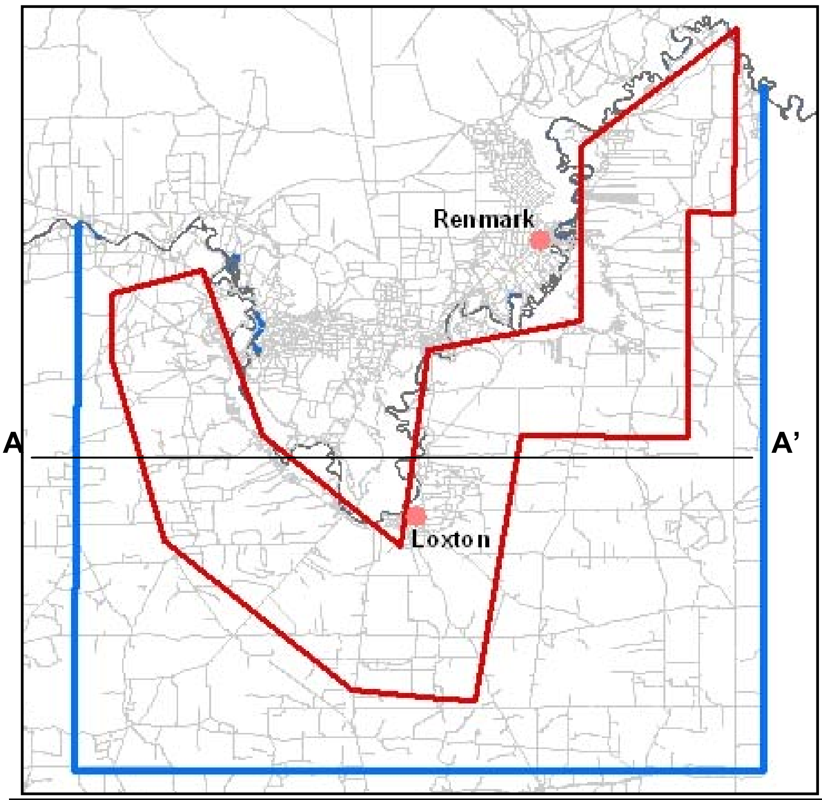

Figure 24. Riverland MODFLOW Model extent and survey area (in blue).

Table 3. Brief details of groundwater models improved through the SA SMMSP.

Riverland MODFLOW Model

The new MODFLOW model domain simulates an area 75 km (east west) by 78 km (north south). The rectangular model grid was divided into 359 rows and 398 columns. The minimum grid size is 125 x 125 m in the Loxton area. The maximum grid size is 250 x 250 m in the remaining model area. Vertically, the model was conceptualised as five layers (Loxton Sands and Monoman Formation; Lower Loxton Sands, Bookpurnong Formation and Part Pata Formation; Pata Formation; Glenforslan Formation; and the Mannum Formation).

The area modelled is considerably larger than the survey area flown by the Airborne EM system as shown in Figure 24. This was done to avoid boundary condition problems and because the model will be used for other larger scale projects. This model can be been used to predict the impacts of increased recharge following clearing on salt inflows to the river and floodplain. It can also help to determine the efficiency of various management strategies to minimise these impacts.

SIMPACT (SIMRAT) Model

The SIMPACT GIS framework was developed to assess the impact of increased drainage on the Murray River salinity. The first version of SIMPACT (Miles et al, 2001) was developed to identify salinity impacts of potential irrigation development in highland irrigation areas of SA. It focussed on comparing impacts at a regional scale by producing a river-wide perspective on where irrigation development would have higher and lower impacts. The model used a raster or ‘grid cell’ (500mx500m) approach to assess points on the landscape within 10km either side of the Murray River.

SIMPACT II and its offspring the rapid assessment tool SIMRAT (URS Australia, 2004), incorporated new unsaturated zone methods (Cook et al, 2004) to calculate lag times. It uses the drainage rate, together with depth to groundwater and clay thickness, as inputs and equations linking to subsoil moisture contents to estimate recharge over time. In addition, the unit response equation (Knight et al, 2002) was used to assess the impact of increased recharge on discharge to the river. Aquifer salinity at discharge is multiplied by the discharge over time to get the salt load into the river.

Floodplain ImPacts Model (FIP)

Regional scale models such as described above, cannot model floodplain processes at the resolution required to refine management strategies to the scale of the individual floodplain elements. The FIP was developed to address this. It is a steady-state analytical cross sectional model, implemented spatially within a Geographical Information System (GIS) framework. The model can predict areas of the floodplain at risk from salinisation and seepage at ~250 metre wide floodplain areas and salt loads to the river at 1 km intervals. It can also provide spatial floodplain attenuation estimates for use in regional and detailed salt load models such as the other models described above.

An East-West section A-A' shown in Figure 25 (location shown in Figure 24) illustrates the conceptualized hydrogeological model used in the Riverland MODFLOW model.

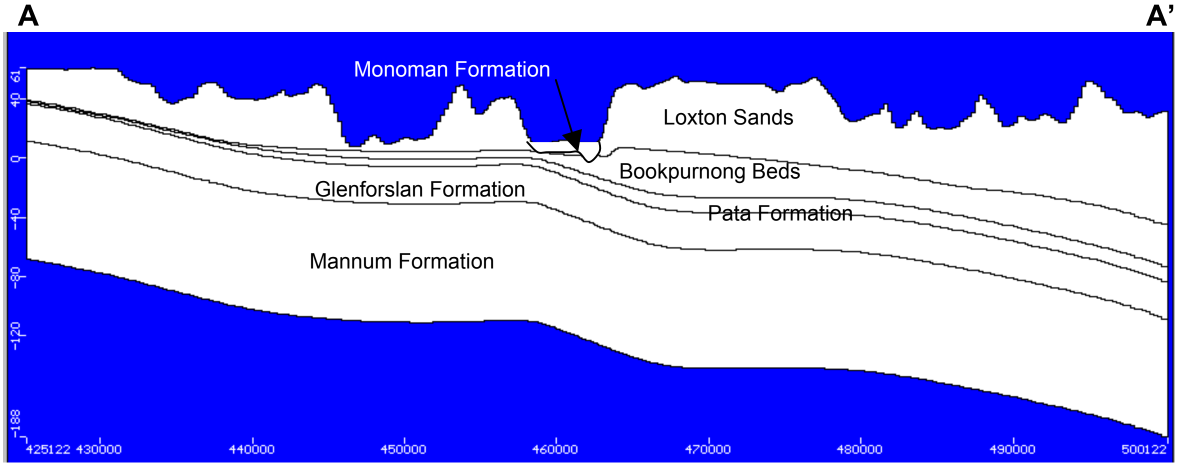

Figure 25. Conceptual hydrogeological section for line A-A' (shown in Figure 24) (Barnett and Yan, 2004).

As discussed earlier, the increase in recharge rates following clearing is the key process driving the increase in salt loads to the river. These rates are dependent on several factors: time since clearing, the depth to the water table, soil type and thickness of Blanchetown Clay. The recharge was applied in areas cleared of mallee (and outside irrigation areas), with values based on SIMPACT II modelling (Addendum to Cook *et al.*, 2004; Wang *et al*. (in prep)). Forty recharge zones were delineated in this investigation, but in order to make the modelling process workable, these zones were aggregated down to a total of seven (see Figure 26). Table 4 shows how the recharge rates (in mm/year) vary over time in these simplified recharge zones.

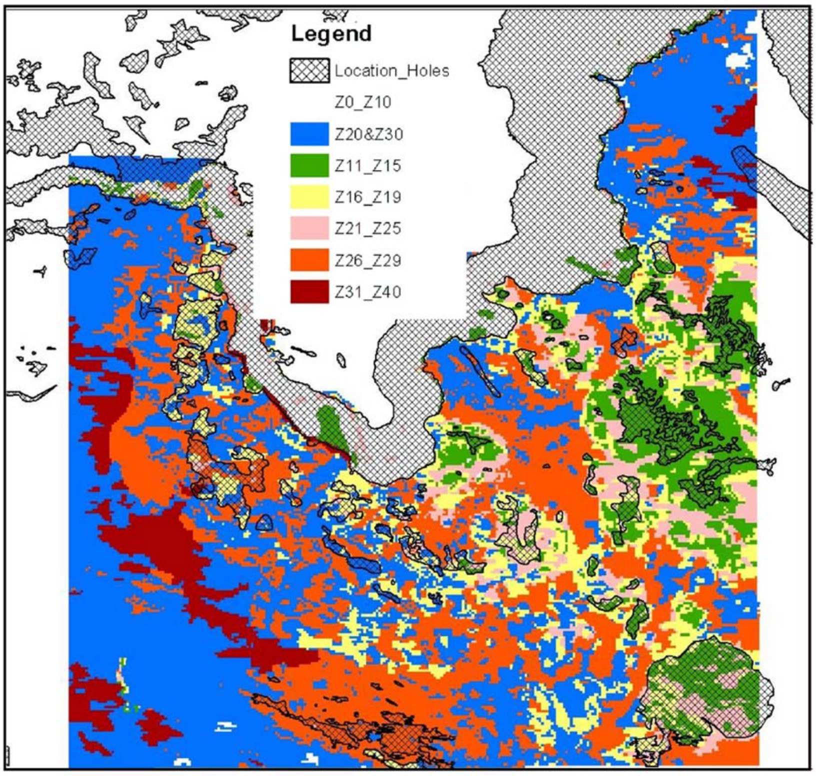

Figure 26. Location of simplified recharge zones in the Riverland MODFLOW model (Barnett and Yan, 2004).

Calibration

The model was initially calibrated for a steady state pre-irrigation situation, which aimed to reproduce the groundwater levels and estimated salt loads to the river thought to occur before irrigation commenced and after the river was regulated by locks. Pre-clearing recharge rates of 0.1 mm/year were applied throughout the model area. The simulated potentiometric heads in Layer 1 (Loxton Sands) and Layer 5 (Mannum Formation) of the steady-state model showed reasonable agreement with estimated pre-European regional potentiometric head away from the locks.

The model was also calibrated under transient conditions using data from some areas where there is an intensive investigation is occurring. A recent investigation by DWLBC and Australian Water Environments (AWE, 2003) has detailed the pre-irrigation and current salt loads to the river in Loxton and Bookpurnong areas. The calibration was based on the observed groundwater levels and the measured salt load from Run the River surveys.

Table 4. Variation in recharge rates (mm/year)

Year	Z0-Z10	Z20 & Z30	Z11-Z15	Z16-Z19	Z21-Z25	Z26-Z29	Z31-Z40
1920	0.00	0.10	0.14	0.10	0.10	0.10	0.10
1930	0.00	0.10	0.53	0.10	0.10	0.10	0.10
1940	0.00	0.10	0.80	0.10	0.10	0.10	0.10
1950	0.00	0.10	1.08	0.10	0.39	0.10	0.10
1960	0.00	0.10	1.38	0.10	1.32	0.10	0.10
1970	0.00	0.10	1.66	0.11	2.58	0.11	0.10
1980	0.00	0.10	1.99	0.13	3.84	0.12	0.10
1990	0.00	0.10	2.32	0.17	5.00	0.17	0.10
2000	0.00	0.11	2.58	0.29	5.96	0.36	0.13
2010	0.00	0.11	2.73	0.49	6.61	0.82	0.29
2020	0.00	0.13	2.81	0.80	6.95	1.53	0.76
2030	0.00	0.17	2.84	1.15	7.10	2.40	1.66
2040	0.00	0.22	2.85	1.52	7.16	3.34	2.94
2050	0.00	0.31	2.85	1.90	7.18	4.27	4.45
2060	0.00	0.46	2.85	2.25	7.19	5.13	5.98
2070	0.00	0.68	2.85	2.57	7.20	5.86	7.36
2080	0.00	0.99	2.85	2.83	7.20	6.45	8.46
2090	0.00	1.37	2.86	3.02	7.20	6.87	9.26
2100	0.00	1.81	2.86	3.16	7.20	7.15	9.78
2110	0.00	2.28	2.86	3.24	7.20	7.32	10.10
2120	0.00	2.28	2.86	3.24	7.20	7.32	10.10

In order to convert the groundwater discharge volumes calculated by the model into salt loads to the river, salinities were assigned to the groundwater in the various reaches. It is worth noting that the model calculates the discharge from the regional unconfined aquifers to the edge of the river valley. The rate and timing of salt loads entering the main river channel are determined by a range of complex processes within the river floodplain, including fluctuations in river flow and level, storage of saline groundwater discharge in floodplain aquifers and evapotranspiration from the floodplain.

Where the river flows adjacent to the side of the valley, it is assumed that all of the groundwater discharge directly enters the river. However where the river flows mid-valley, the discharge would have to travel beneath the floodplain at shallow depth before entering the river. In doing so, losses due to evaporative discharge and interception by lagoons could occur. While the discharge volumes to the river at low flows may be reduced by these processes which effectively store salt in the floodplain, high flow events will eventually mobilise this stored salt into the river. The issue of modelling floodplain processes is addressed more fully in the discussion on the Floodplain ImPacts (FIP) Model which follows.

8.2 SIMPACT (SIMRAT)

SIMPACT is a modelling framework for simulating time delays and changes in drainage, recharge to groundwater and discharge to the river which may result from a change in land use (eg clearing or revegetation) (Miles *et al.* 2001, Wang et al. *in press*). It provides spatial information on areas which will achieve the greatest salinity impact from revegetation. Model runs incorporating revised estimates of aquifer recharge for the Riverland region (which in turn have incorporated the clay map generated by the inversion of the airborne electromagnetic data) have resulted in spatial maps predicting the impacts of revegetation on salt load into the River Murray for a 100 year time frame.

SIMPACT is based upon a Geographic Information System (GIS) framework explicitly relating land use change on a given cell to its impact on the River Murray. The model assumes linearity and hence superposition of impacts that enables it to accumulate the the effects of individual actions.

As part of the SA SMMSP, SIMPACT was further developed to explicitly target areas for revegetation on the basis of salinity, by:

- incorporating measurements of deep drainage in areas closer to the river;
- adding information from the helicopter EM data on texture of the unsaturated zone below soils (ie the clay layer);
- incorporating derived relationships between deep drainage under dryland farming systems and rainfall as well as soil texture;
- embedding theory for time delays through the unsaturated zone upon a reduction or increase in recharge; and
- integrating a unit response equation for modelling discharge and salt load into the river.

'SIMPACT II' was the result. A schematic representation of the model is shown in Figure 27. Spatial data sets for the Riverland and beyond have been collated as base layers for the model. These represent the inputs required for the assessment of impact of land use change or revegetation on Murray River salinity. The degree of detail of the base layers varies considerably across the study area due to the variety of source data. For example the detail provided by the HEM data on the Blanchetown Clay is demonstrably better than that available elsewhere (note detail in Riverland survey area, Figure 28). A more detailed summary of the model and model results are presented in Wang et al (*in press*).

SIMPACT II and its derivative SIMRAT (URS, 2004) are not replacements for MODFLOW. They model a single layer system describing the dynamics of unconfined aquifers, so that the impacts of a change in recharge rates (e.g. from irrigation development) can be assessed. SIMPACT has flexibility to underpin any salinity assessment of change in recharge providing an effective regional tool for determining the likely impacts of new irrigation development; the effects of the historical development of irrigation, the potential benefits of revegetation across the Mallee and more recently the consequences of interstate water trading.

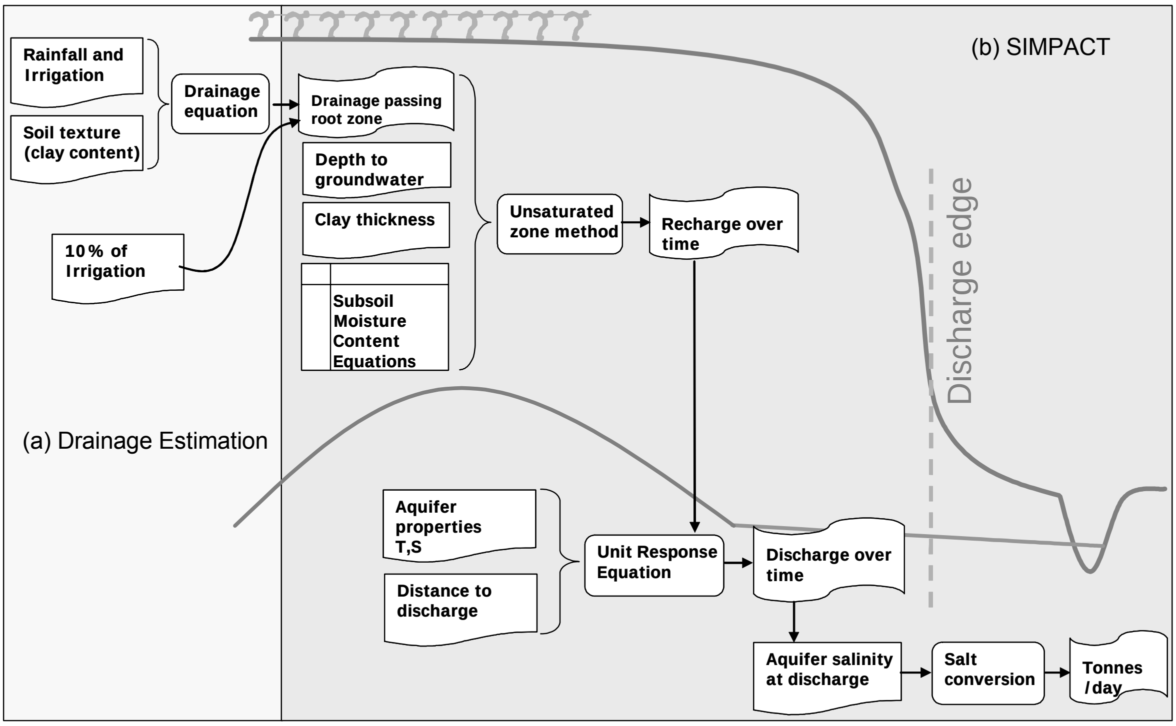

Figure 27. Schematic representation of SIMPACT II. Section (a) represents the drainage estimation; Section (b) represents SIMPACT II using drainage as input for simulating the recharge process (Matt Miles, pers. comm.).

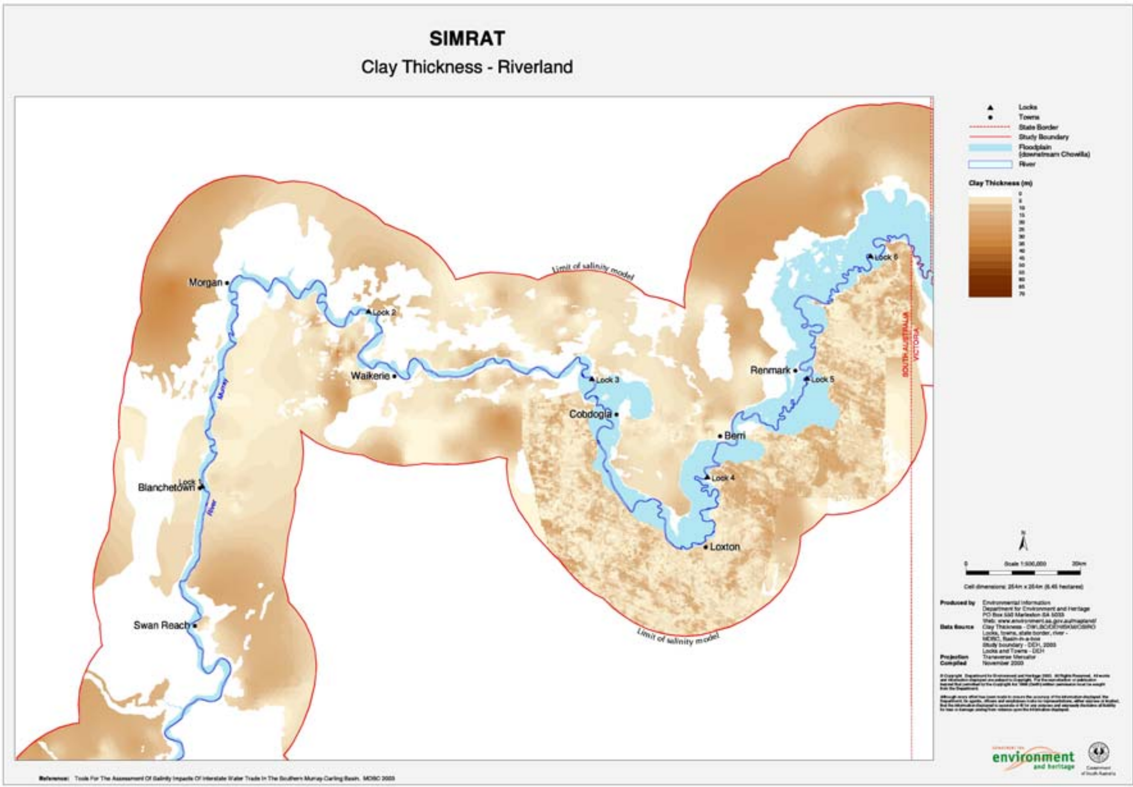

Figure 28. 'Blanchetown Clay thickness' input layer to SIMRAT, showing higher resolution data available from the Riverland AEM survey (Matt Miles, pers. comm.).

8.3 FLOODPLAIN IMPACTS MODEL (FIP)

The Floodplain ImPacts Model was developed as part of wider ranging project concerning the development of tools and the collection of baseline data relating to the floodplain of the Murray River (Overton *et al*., 2003). The model is a steady-state analytical cross sectional model (Walker and Holland, 2003), implemented spatially within a GIS framework. FIP predicts floodplain areas at risk of salinisation due to seepage at the break of slope of the highland / floodplain and evapotranspiration across the floodplain. It is sufficiently simple to be applied with GIS type applications, and yet powerful enough to determine the groundwater discharge patterns through cross-sections of the River Murray valley. The model can predict areas of the floodplain at risk from salinisation and seepage at ~250 metre wide floodplain areas and salt loads to the river at 1 km intervals. It can also provide spatial floodplain attenuation estimates for use in regional and detailed salt load models such as SIMPACT (Miles *et al*., 2001) and Land and Water Management Plan MODFLOW models.

The floodplain has been conceptualised in a simple cross sectional model, comprising a surface layer of Coonambidgal Clay overlying a layer of Monoman Sands (Figure 29). The highland area is represented by the unconfined Upper Loxton (Pliocene) Sands aquifer. Both the highland and floodplain are underlain by the Lower Loxton Sands, a relatively impermeable clayey sand formation. In the region downstream of Overland Corner, the water table beneath the highland is generally contained within the Murray Group limestone aquifer that underlies the Pliocene Sands. The arrows in Figure 29 represent groundwater flow directions and potential groundwater discharge sites. Groundwater flow in the Upper Loxton Sands (or Murray Group limestone in the region below Overland Corner) is a combination of irrigation recharge and regional groundwater flow. Groundwater from the highlands is discharged as either seepage at the break of slope if the groundwater level is above the surface, evapotranspiration through the floodplain when the water table is within the evapotranspiration extinction depth (vegetation rooting depth), or as base flow to the river.

The full mathematical description of the underlying analytical cross section model describing the above conceptualisation, including a number of important simplifying assumptions, is given in Walker and Holland (2003). In simple terms the model apportions the groundwater flowing into the River Murray valley into seepage at the break of slope, evapotranspiration from the floodplain or base flow to the river.

One of the important aspects of implementing the analytical model spatially in a GIS framework was the need for the floodplain to be discretised into a series of representative cross sections. This involved developing ~3500 floodplain divisions that discretise the floodplain into ~250 metre wide regions that represent the approximate groundwater flow lines (Figure 30). The floodplain divisions included areas where there is no floodplain (i.e. where the river abuts the cliff). Detailed MODFLOW modelling of Clark's floodplain by Doble *et al.* (2003) has shown that at the whole floodplain scale, as long as the slice divisions follow the groundwater flow lines, the simpler Walker and Holland (2003) model provides accurate predictions of the total volumes of seepage, floodplain evapotranspiration and base flow to the river.

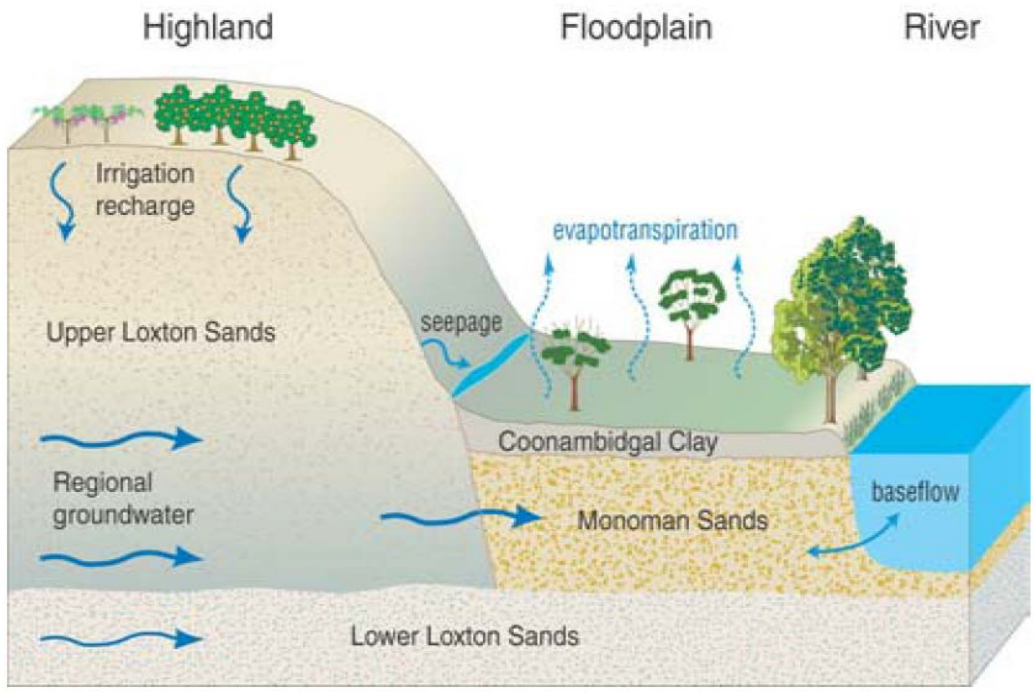

Figure 29. Conceptual model of groundwater inputs to the floodplain and potential groundwater discharge pathways within the floodplain (Overton *et al.*, 2003).

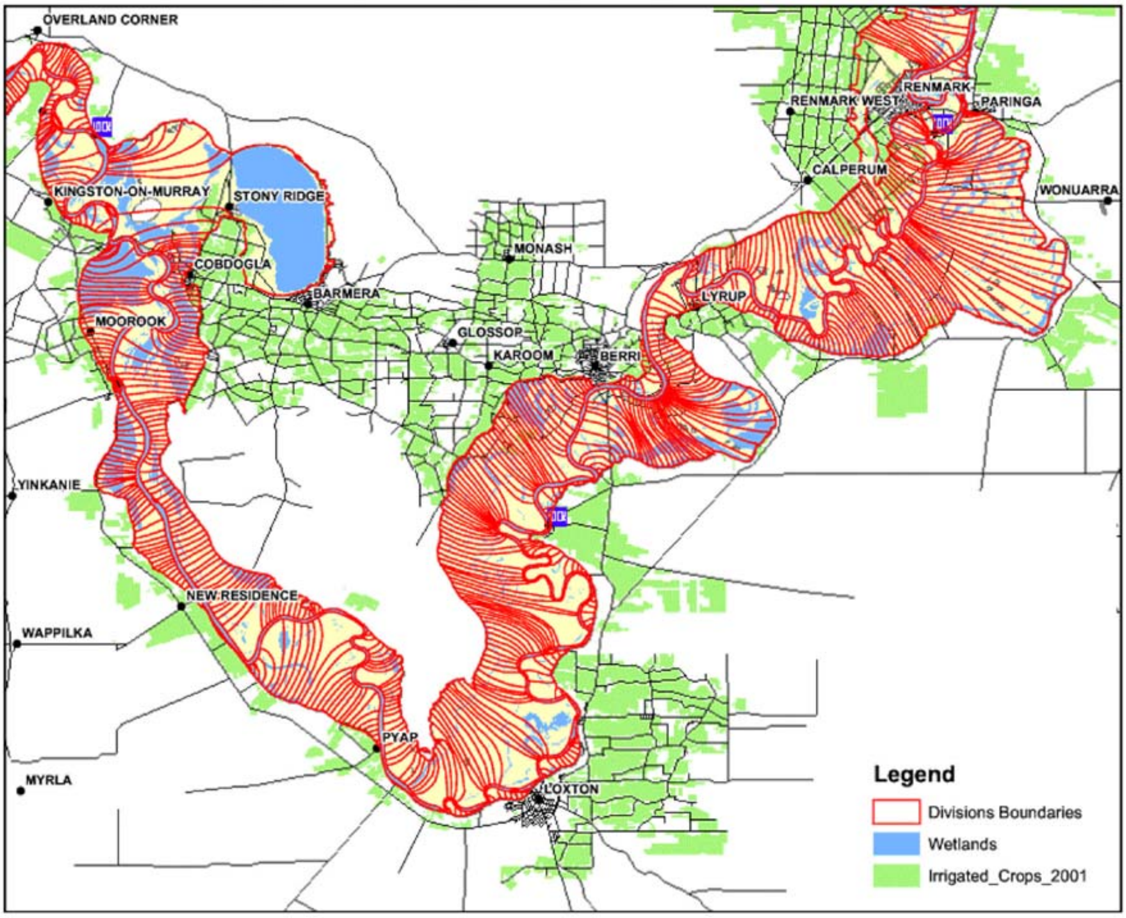

Figure 30. Map of part of the lower River Murray showing the floodplain divisions used to implement the spatial analytical FIP model (Overton *et al.*, 2003).

Calibration

The primary method of model calibration carried out to date has been comparing predictions of base flow to the river against 'run-of-river' salt load data, particularly that from 2001 which covered the whole length of the river in South Australia (Porter, 2001). Figure 31 shows the comparison of the run-of-river data and the model predictions under current conditions. There is a good comparison between the two datasets with some exceptions which are explored in Overton *et al*., (2003).

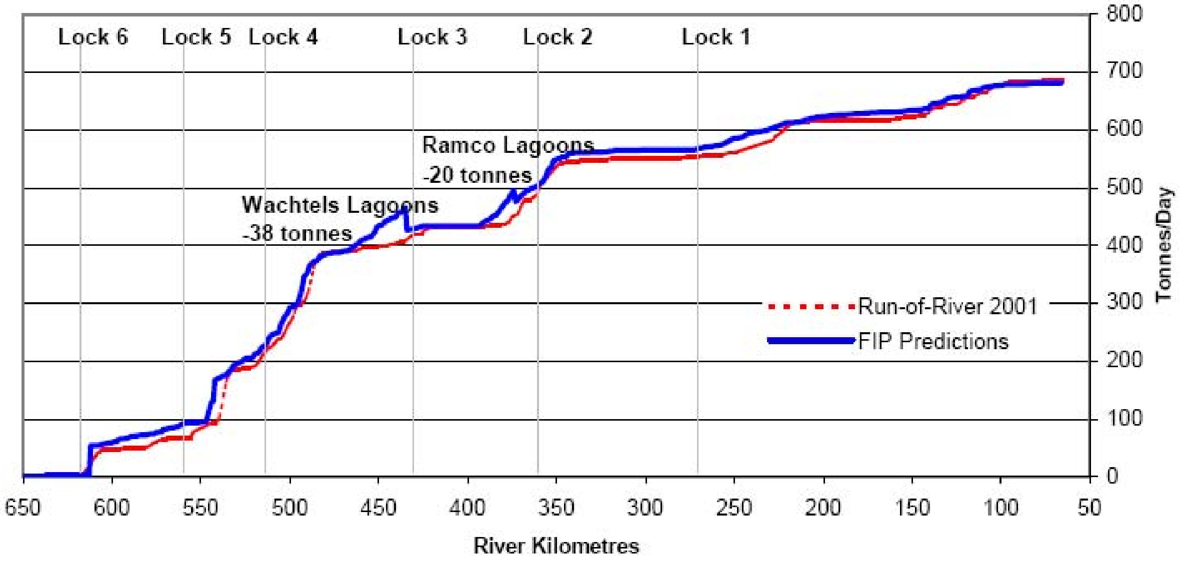

Figure 31. Preliminary FIP model predictions of cumulative salt loads to the river versus results of the 2001 run-of-river survey (Porter, 2001).

PART D. IMPLICATIONS FOR MANAGEMENT

9. *Riverland Land Management Scenarios*

9.1 RIVERLAND MODFLOW MODEL

The scenarios summarised in Table 5 were run with the Riverland MODFLOW Model, for the purpose of assessing potential river salinity benefits from targeted and larger scale revegetation options (Barnett and Yan, 2004). These scenarios do not include irrigation induced watertable mounds.

Table 5. Riverland MODFLOW Model land management scenarios.

Scenario 1: No intervention – this scenario takes into account the impacts of clearing only. Irrigation induced watertable mounds are not included, nor are any mitigation strategies.

Scenario 2: Revegetation over holes in Blanchetown Clay – this scenario assumes revegetation over holes in the Blanchetown Clay determined by aerial geophysics. No time lags are included, so that recharge rates are reduced immediately in 2004.

Scenario 3: Revegetation in priority areas determined by the River Murray Dryland Corridor Project (RMDCP) which used the Simpact GIS model. No time lags are included, so that recharge rates are reduced immediately in 2004.

Scenarios 4 - 6: Revegetation in corridors 5, 10 and 20km wide adjacent to the river valley to compare with results from a previous modelling exercise (Barnett et al, 2001).

The modelled total salt loads to the edge of the river valley from the south are presented in Table 6 and Figure 32. These figures have included an assumed time lag of 10 years between revegetation (which is assumed to have occurred in 2000), and the reduction of recharge rates as seen at the watertable in 2010. The decrease in recharge rates following revegetation have been estimated by the Department of Environment and Heritage.

As expected, the large scale revegetation would have most impact. Of the more targeted options, revegetation of the holes in Blanchetown Clay would reduce inflows by 14 tonnes/day after 100 years, whereas treating the priority areas delineated by the RMDCP would realize a reduction of 11 tonnes/day. The highest priority areas determined by the RMDCP were not within the Riverland MODFLOW model extent.

Results from a previous modelling exercise described in Barnett et al. (2001), for a region between between Morgan and the SA Border, using previously determined recharge rates from Cook et al. (1989), are included in Table 6 for comparative purposes.

Predicted increases in EC, measured at Morgan, for these modelled scenarios are shown in Figure 33.

Table 6. Total modelled salt loads to edge of river valley from the south (tonnes/day). Comparative figures for AWE (2001) [from Barnett *et al*., 2001] model estmates are shown in red.

Scenarios	Before Clearance	1995	2020	2050	2100
No intervention	154	160 (468)	171 (603)	193 (752)	254 (835)
Reveg clay holes	154	160	169	187	240
Reveg priority areas	154	160	170	188	243
Reveg 5 km	154	160 (468)	167 (591)	172 (620)	190 (659)
Reveg 10 km	154	160 (468)	167 (584)	168 (604)	170 (631)
Reveg 20 km	154	160 (468)	167 (578)	167 (593)	163 (620)

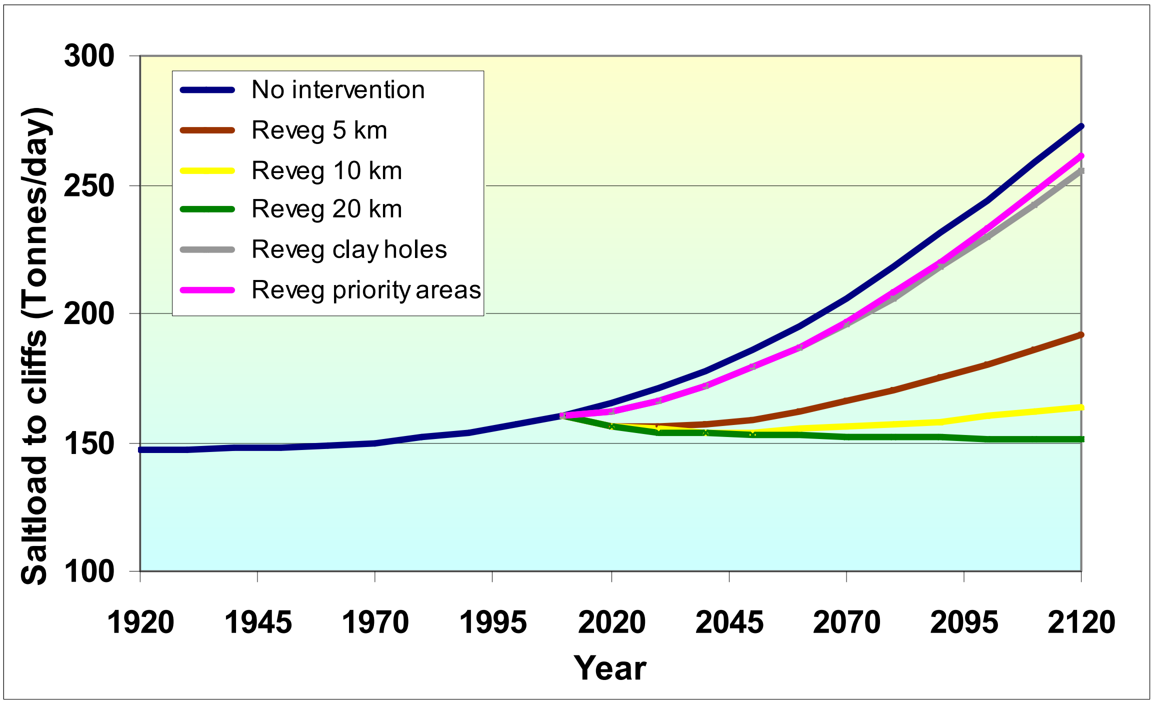

Figure 32. Saltload to cliffs for the modelled scenarios (Riverland MODFLOW model – Barnett and Yan, 2004).

For the no intervention scenario, the current modeling shows a 70 % reduction from the previous modelled prediction. This is due to several factors, with the most significant being improved (reduced) dryland recharge estimates and a more detailed and better calibrated groundwater model. Figure 34 compares graphically the two model results.

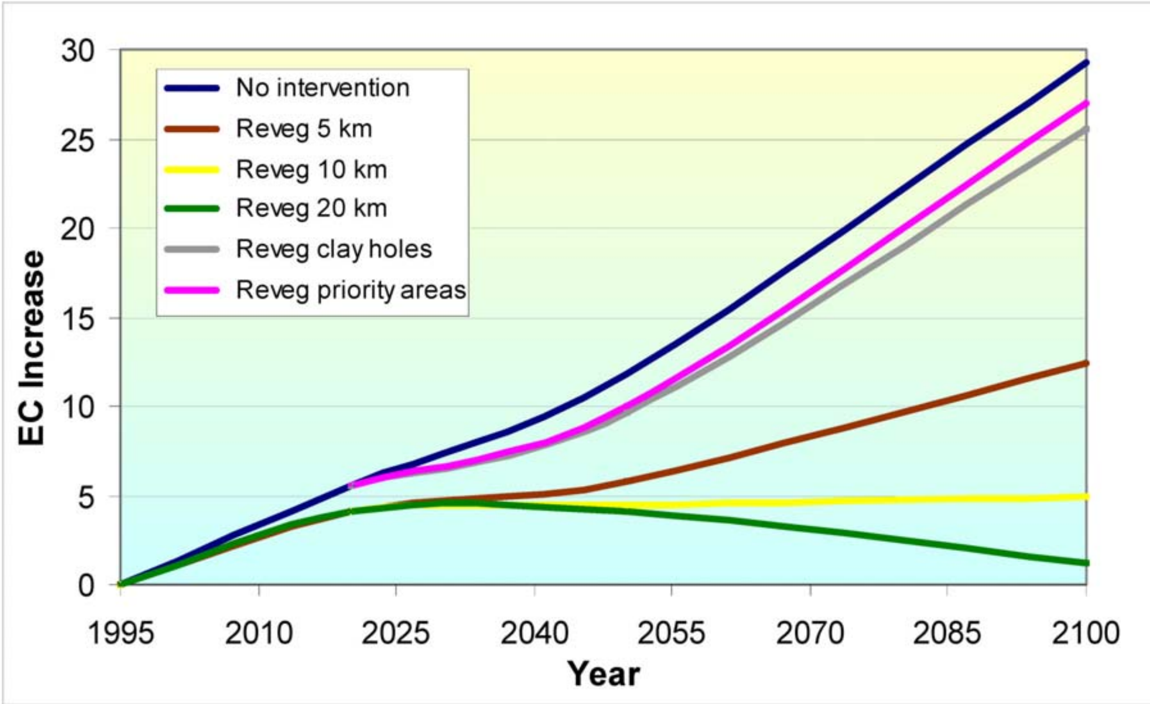

Figure 33. Increase in EC at Morgan for the modelled scenarios (Riverland MODFLOW model – Barnett and Yan, 2004).

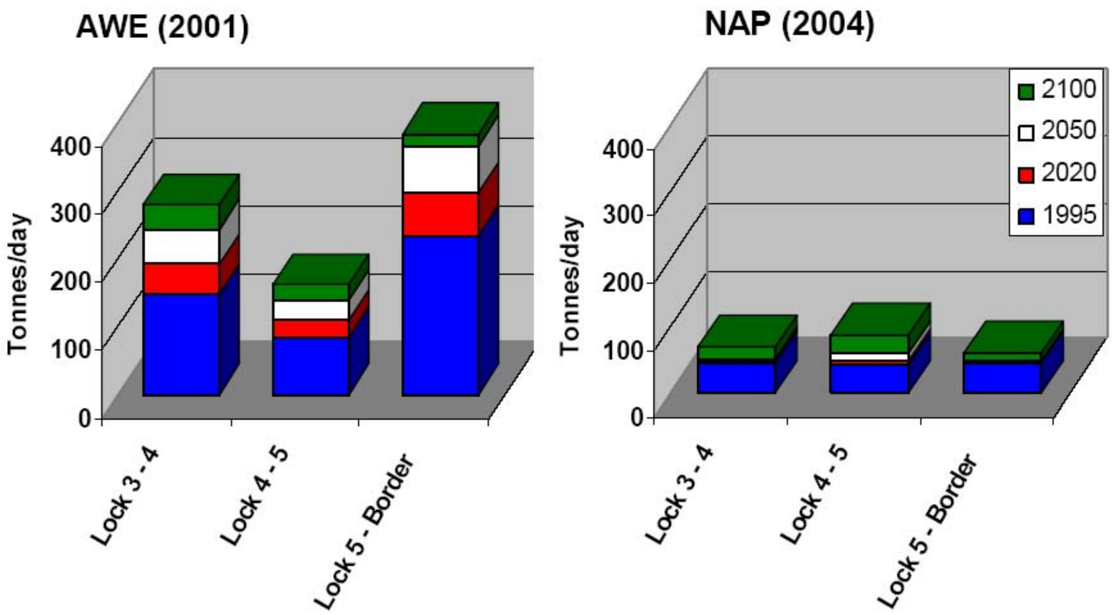

Figure 34. A comparison of the "No intervention" model results determined by AWE/ Barnett *et al* (2001) on the left, and Barnett and Yan (2004) on the right.

The main limitation of the new model appears to be the inability to effectively model the floodplain processes that reduce the final saltload that enters the river from that calculated to enter the edge of the floodplain. Further investigations are needed to quantify the amount of salt intercepted by the floodplain, and how it is later mobilised during high flow events. Recognition of these limitations led in large measure to an alternative approach to understanding and modelling floodplain processes as described earlier in a summary of the Floodplain ImPacts (FIP) model.

It is also recognised that in the model, the calculated inflows to the river valley are very sensitive to the chosen values of hydraulic conductivity for the unconfined aquifer close to the river. For instance, an increase of only 1 m/day in the Loxton Sands aquifer hydraulic conductivity from 1 to 2 m/day, would result in a doubling of the inflows. However, it is considered that the values chosen are consistent with current knowledge. Given the above uncertainties, the model's accuracy is considered to be within +/- 50 % at the current level of knowledge. Although this seems at first to be a large error band, it is still deemed sufficient to draw conclusions about priority areas and actions.

Clearly improved estimates of groundwater recharge that have emerged from the SA SMMSP study have significant consequences for land management in the Riverland region particularly in respect of predicted salt loads to the river.

9.2 SIMPACT II (SIMRAT)

With the clay layer as one input and with the unsaturated zone method of Cook *et al.* (2004) incorporated to calculate lag times for aquifer recharge, several scenarios have been run to estimate the impact of increases in drainage, recharge, discharge and salt load into the river and the impact of revegetation on the reduction of discharge and salt load into the River Murray (Wang et al. *in press*).

9.2.1 The wetting scenarios

Firstly, areas were assumed to be originally covered by native mallee vegetation, and then cleared, being replaced by an annual crop/ pasture rotation system in 1920. The drainage rate and rate of groundwater recharge under native mallee was assumed to be zero, and the drainage rate under the current dryland farming systems can be estimated using the results described by Cook *et al.* (2004). With these assumptions a drainage map was produced (Figure 19). Results from the effects of clearing and the increased drainage since 1920, have been presented earlier in Figures 21-23. They show the increase in recharge rate to groundwater predicted for the years 2004, 2050 and 2100, representing 84, 150 and 180 years after clearing. As a result of the increased recharge, the increased contribution from each area to discharge and salt load into the Murray River can be simulated for different years. An example of the predicted salt load entering the River Murray for the year 2020 is shown in Figure 35.

9.2.2 The drying scenarios

The effect of revegetating the whole South Australian Mallee region on discharge and salt load into the Murray River, assuming the whole area was revegetated with native mallee and that the mallee vegetation would immediately stop the increased drainage, has been determined for several years. Figure 36 shows a simulation for the year 2100. The influence of soil types can also be determined with these models.

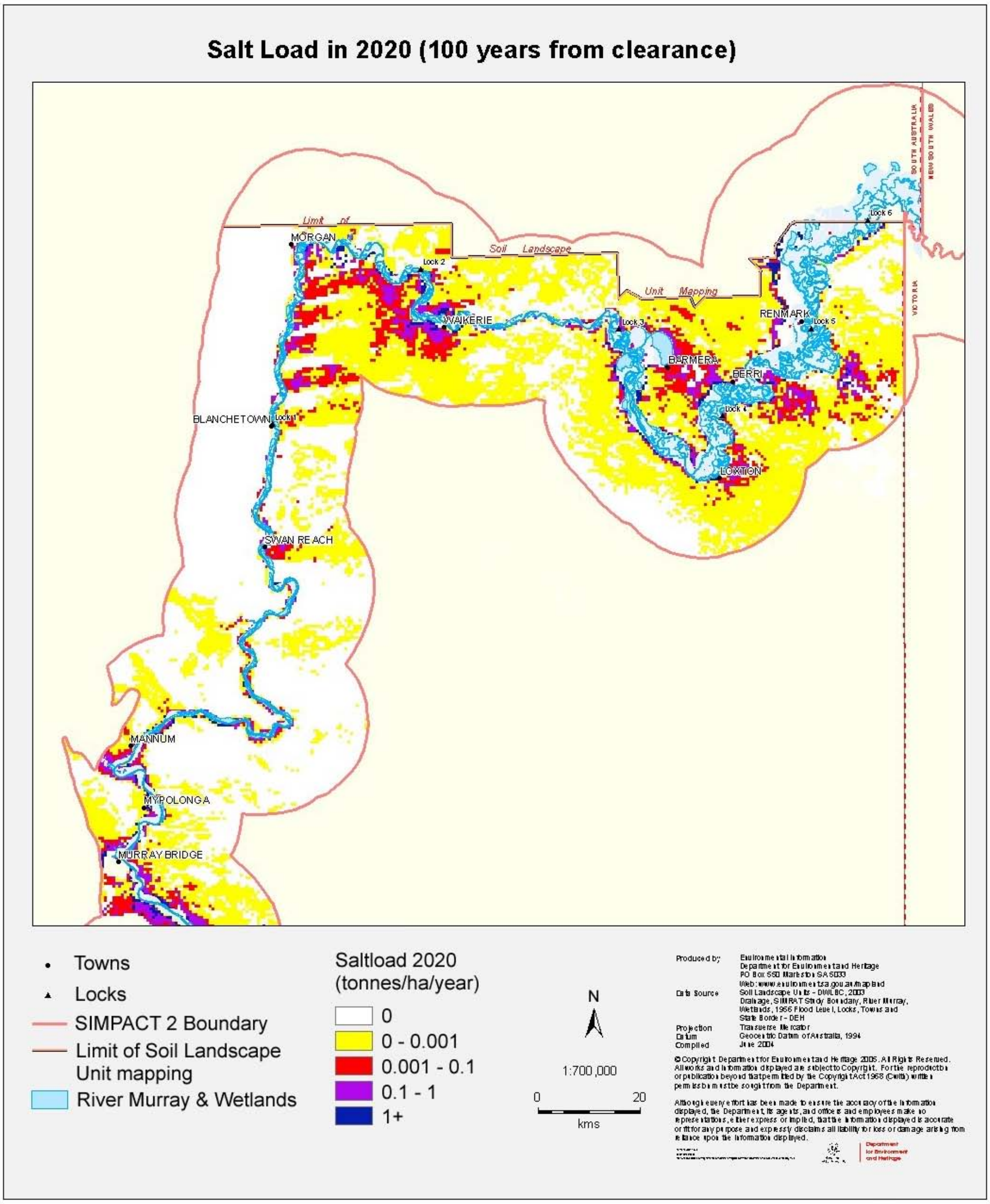

Figure 35. Simulated salt load to the river contributed from the Riverland region in year 2020, assuming total clearing of native mallee vegetation (Matt Miles, pers. comm.).

Predictions of regional impacts over 100 years will inevitably be couched with large error bars. The main outcomes being sought at present are to better determine the areas with likely salinity impacts on the river in 50-100 years and to better understand the magnitude of salinity benefits that could be obtained through recharge reduction in dryland areas. There is considerably more confidence in predicting these than determining exact time delays or the salinity benefit of an individual action.

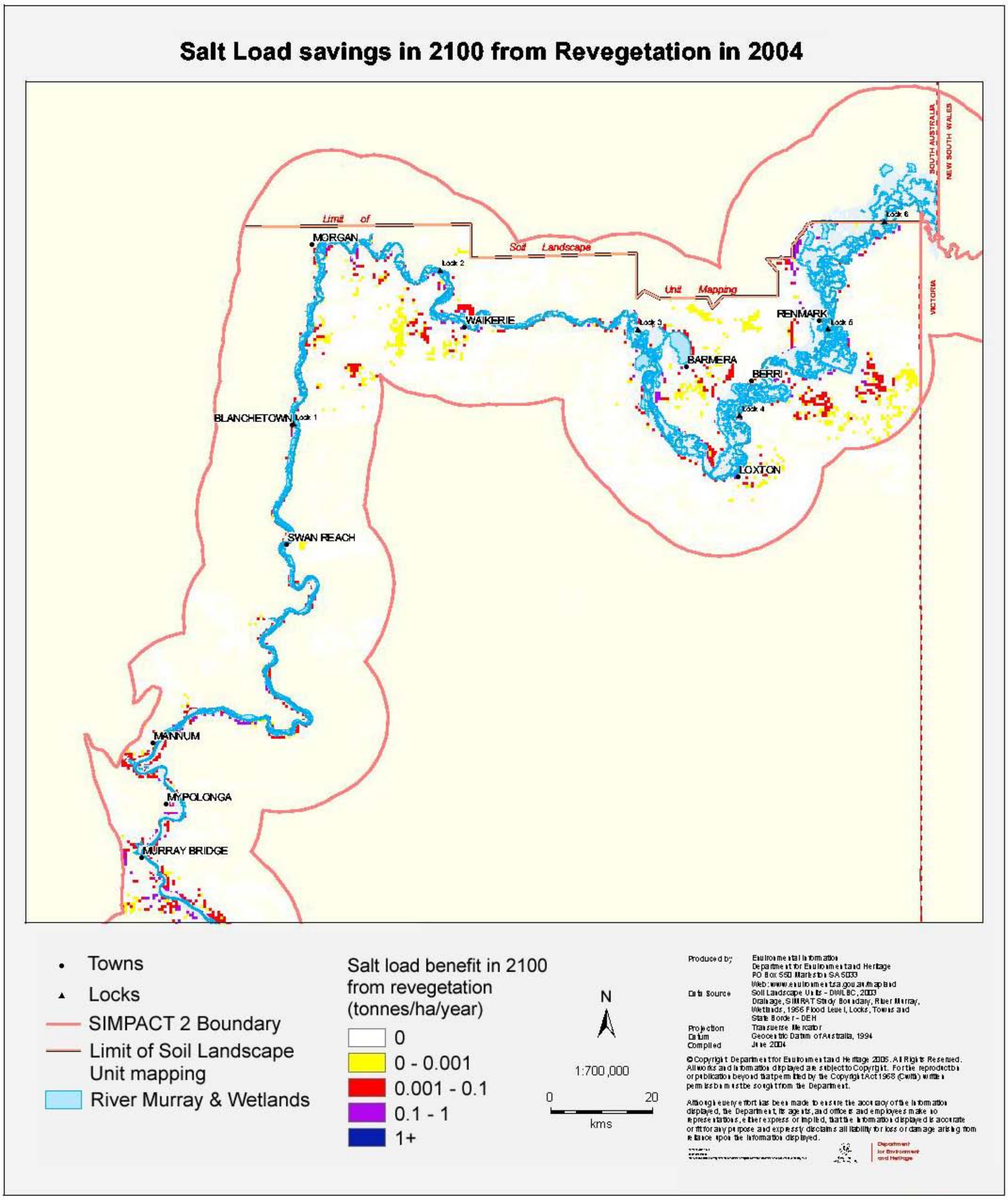

Figure 36. Simulated salt load saving to the river in the year 2100, assuming total revegetation with native mallee vegetation (Matt Miles, pers. comm.).

9.3 FLOODPLAIN IMPACTS MODEL

As described above, regional scale groundwater models based on MODFLOW or GIS approaches (eg SIMPACT - Miles *et al.*, 2001) are being used to estimate the flux of groundwater entering the river valley. However, within these regional scale models, floodplain processes cannot be modelled at the resolution required to refine management strategies to the scale of the individual floodplain elements. For example, the interception of groundwater by the floodplain is known to decrease the salt load to the river at low flows (Jolly, 1996), and leads to evaporative losses, storage of salt in the floodplain and declining vegetation health. This stored salt however can be released back into the river during high flows or flood events.

The Floodplain Impacts Project has involved the development of modelling tools, collection of baseline groundwater and soils data, and vegetation composition and health surveys. The final spatial calibration of the model will be undertaken once vegetation health maps are completed for the whole of the floodplain in South Australia. Prior to this, the model will be further developed to incorporate the impacts of flooding on vegetation health, and to improve prediction of risk areas where large wetlands and anabranches intercept groundwater flow across the floodplain. Preliminary field survey results illustrate generally how poor the terrestrial vegetation health is on the floodplains of the lower Murray, and shows the complex interactions between driving factors that lead to health decline.

The model predictions of salt loads to the river for each reach were compared to reported salt loads (Barnett *et al.*, 2001 (Table 6 - 1995 values) who assumed that 30% of groundwater inflows were attenuated by the floodplain) and measured 2001 'run of river 'salt loads. The FIP model results closely follow the published estimates and run of river values, with the exception of Lock 1-2, Lock 2-3 and Lock 5-6 where the published salt loads are much greater. FIP salt loads are comparable to run of river, but higher than the published estimates in the Wellington-Lock 1 and Lock 3-4 reaches.

While the average floodplain attenuation predicted by the FIP model is around 30% (as was assumed by Barnett *et al*., 2001), there is considerable spatial variability (see Figure 37). This needs be taken into account when using regional groundwater models to predict river salinity. The degree of attenuation at any given location is dependent on the rate of groundwater inflow and the floodplain parameters that control the rate of evapotranspiration and seepage (floodplain geometry - most notably width, floodplain aquifer depth and conductivity, evapotranspiration rate and river height).

The FIP model provides a means of determining floodplain attenuation at any location along the lower river Murray in South Australia for any rate of groundwater inflow to the river valley. The model can be used to predict areas at risk from future development and the impacts of management scenarios. Hypothetical scenarios that have been modelled (see Overton et al., 2003) include (i) a 20% increase in inflows due to new developments; (ii) a 40% decrease in inflows due to improved irrigation efficiencies; and (iii) a 1m lowering of the floodplain water table. It is important to note that these are broad-scale hypothetical scenarios to highlight the predictive capabilities of the model and should not be considered as likely management approaches.

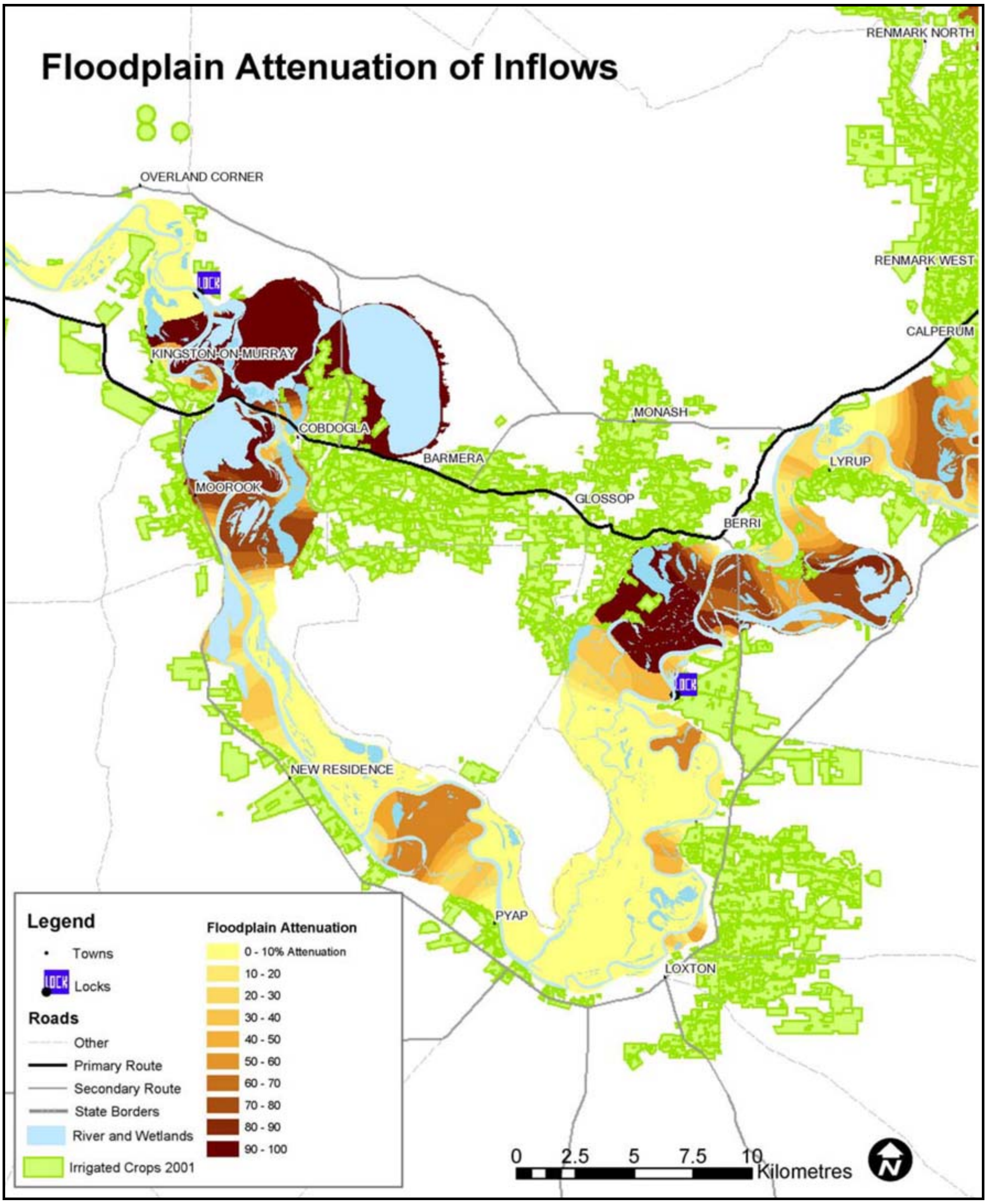

Figure 37. Predictions of the floodplain attenuation, as a percentage of inflows, for the area between Lock 3 and 4 under current inflow conditions. The degree of attenuation can be seen as a function of locking, floodplain width and of magnitude of groundwater inflow (Overton *et al.*, 2003)

9.4 SYNTHESIS OF RELATED DRYLAND STUDIES

A synthesis of findings, concerning dryland areas impacting on river salinity, from the related River Murray Dryland Corridor Project (RMDCP) and the SA SMMSP Riverland Study will be presented in Wang et al (in prep).

This report collates NAP funded work in the region aimed at identifying dryland areas to target for revegetation in order to achieve reduced salinity impacts in the River Murray. The RMDCP study area comprised a 15 km buffer from the 1956 floodplain, extending from the border to Lake Alexandrina. This area included the SA SMMSP Riverland study area.

Three main points emerge from this report:

1. Priority areas for targeted revegetation have been identified.
2. Salinity benefits achieved in the river (within a 100 year time frame) from targeted revegetation in these priority dryland areas are small (< 4EC (μS/cm) reduction at Morgan) and are not likely to meet expectations for a proposed salinity credits trading scheme.

   Conversely, this indicates that the predominant cause of human-induced salinity impacts on the river is due to irrigation activities, with some areas having greater impact than others.
3. The methodology used for estimating salinity impacts and benefits from changing land use (eg. dryland agriculture to native vegetation) can be adapted to other types of land use change (eg. irrigation to more efficient irrigation, or a change to native vegetation or some form of low recharge agriculture). Hence, the model used in this work can be further applied to examine potential salinity benefits from a change in land management for high salinity impact areas that are currently under irrigation.

10. *Transferability*

10.1 MAPPING THE BLANCHETOWN CLAY AND OTHER NEAR SURFACE CLAY UNITS

The effectiveness of the technology to map the distribution and thickness of near surface clay-rich units has applicability elsewhere in the South Australian Mallee to better determine recharge, and in the SE of the State where irrigation development has the potential to influence groundwater salinisation. If the focus is on asset protection and a more accurate determination of risk, then airborne EM should be considered.

The nature of the sedimentary system across the Murray Basin suggests the technology could be used at local and intermediate scales to map variability that might otherwise be missed in a drilling program. However, a combined ground and airborne investigation would be advocated in all instances. Shallow clay mapping using an HEM system might also be considered as part of preliminary site investigations for disposal basins in the Riverland and elsewhere.

10.2 INVESTIGATING VARIABILITY IN THE LOXTON-PARILLA SANDS AQUIFER FOR SALT INTERCEPTION SCHEMES (SIS)

The Riverland SA SMMSP and associated work has provided a framework that improves the conceptual model for the sedimentology and stratigraphy of the Riverland region. This framework has the potential to assist hydrogeological modelling for the SIS in the Central Murray Basin and is now being employed in developing the Loxton SIS.

10.3 GROUNDWATER MODELLING

Protocols for incorporating derived products from airborne geophysical data into decision management tools (eg. groundwater models) have been developed and demonstrated. The map of clay distribution and thickness has been used to derive new estimates of groundwater recharge in the Riverland region and in turn these estimates have been used to parameterise a 3D groundwater model.

These procedures have application to other areas where airborne geophysical data may be used to help parameterise groundwater models.

PART E. CONCLUSIONS

The SA SMMSP represents a significant departure from previous studies seeking to apply airborne geophysics in salinity management, in that it was the first occasion in Australia where geophysical data were deliberately acquired a*s part of* a broader natural resource management strategy. A carefully targeted approach was taken, giving due consideration to the problems being addressed. Particular importance was attached to ensuring that geophysical data could provide a product of value and perhaps more importantly, how that product could be incorporated into implementing appropriate management strategies. This approach reflected the thinking promoted earlier by George and Green (2000) on the relevance of airborne geophysics to land management.

In the Riverland region of the South Australian Murray Basin, the principal goal of the geophysical survey was to map materials *rather than* salinity. A derived map of the recharge-impeding Blanchetown Clay layer was used, in conjunction with other critical data, as a basis for estimating rates of groundwater recharge (see Cook *et al.*, 2004), and for input into a groundwater modelling exercise to determine the effects of proposed recharge reduction options in mitigating River Murray salinity.

Data acquisition was undertaken for a *data rich* area, with a clear understanding that this information was an essential input into generating an accurate map of clay rich materials through the constrained inversion of the HEM data. Without fundamental spatial constraints on depth to groundwater, groundwater salinity, and petrophysical / ground geophysical responses of the principal sedimentary units across the study area, it is unlikely that the inversion procedure would have successfully generated a useful product.

In conclusion we can say that:

1) The overall objectives of the Riverland projects have been achieved.

2) High resolution helicopter EM data were used to map the spatial distribution and thickness of a near-surface conductor associated with the Blanchetown Clay (and other related clay-rich materials) for a 15-20 km zone south of the River Murray, from Lock 3 to the Border.

3) A constrained layered earth inversion of the HEM data was an effective processing procedure for generating a map of clay distribution and thickness.

4) The clay map fits well with available drillhole data, and matches the distribution of fine grained-materials that was expected for a lacustrine deposit settling out on a palaeo-strandline sedimentary system (the Loxton-Parilla Sands).

5) The clay thickness data have been combined with other datasets and used to provide estimates of the drainage to the water table and, through groundwater modelling, predict salinity impacts to the river from various management scenarios.

6) For the no-intervention scenario, the current modeling shows a 70 % reduction from the previous modelled prediction. This is due to several factors, with the most significant being improved recharge estimates and a more detailed and better calibrated groundwater model.

7) New information on the sedimentary system (the Loxton Parilla Sands) that constitutes a significant aquifer has emerged, with implications for the development of salt interception schemes in the Riverland region and elsewhere in the Central Murray Basin.

11. Recommendations for Further Work

1) The current geophysical data should be further scrutinised to support the design of salt interception schemes at Murtho, Pike River, etc.
2) Further work should be conducted to better understand the distribution of floodplain soils, recharge during floods and salt discharge to the river. Results here looked promising and past run-of-river surveys using TEM have also proven to be useful.
3) Results show that EM data could assist with siting further disposal basins.
4) Further investigations are warranted in the application of the current data for improving soil maps in the Riverland.
5) The maps of root zone drainage in areas unsuited for cropping (e.g. SW of Waikerie) should be reviewed.
6) Drainage processes in the vicinity of identified strandlines should be further investigated to determine whether such areas may be poorly suited for siting of new irrigation developments or whether water use efficiency measures should be targeted at these areas.

PART F. LESSONS LEARNT

Other specific issues of note, particularly in respect of the airborne geophysics are summarised as follows:

- Critical to the successful application of geophysical technologies to salinity management in the Central Murray Basin was a well defined target and a set of derived products/information – in this case a map of clay thickness.
- It was also recognised that while focus on a specific target is important, the design of the survey should consider other targets that may be useful in a salinity management context. Unexpected beneficial results may emerge that warrant investigation. However, it was clear that the expectation of these additional benefits should not be the principal driver in carrying out the survey.
- The Riverland study demonstrated the value of using AEM to map the extent and character of materials *not* salt, or salt stores. The broader value of airborne geophysics may be realised by considering the technology as a means of mapping landscape elements that may assist in salinity mitigation.
- The success of the constrained inversion of airborne EM data was determined by a considerable wealth of existing hydrogeological information – the more data, the more accurate the product. The use of constraints with both airborne and ground electromagnetic data should be actively considered to derive more accurate products and better value.
- Contrary to a commonly held view which suggests that if a large pool of land-management data exists at an appropriate scale, airborne geophysics in its current format is unlikely to be of sufficient value to warrant acquisition, results from the Riverland study suggest that their application should always be examined even in such instances, *but only* where the means exists to translate derived information into something of value.
- Paradoxically, the value of airborne geophysical (particularly AEM) data in areas with limited hydrogeological information may be *more limited*, particularly in the generation of accurate products of the type produced in Riverland. In these situations, realising the true value of their biophysical information content is likely to require significant additional investment in ground programs.
- Acquisition of geophysical data at a high resolution (and high related costs) is warranted only if economic (and effective) options for salinity management exist (eg salt interception schemes).
- A critical part of the SA SMMSP project planning process was to ensure that any data generated would contribute to *implementing* salinity management plans (which are invariably economic only when protecting significant assets, such as the River Murray).
- Derived products only have value if they contribute to the planning of economic activities, including the location of future irrigation, recharge reduction etc.

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This report is only one component of a much larger project looking at the role and value of airborne geophysical technologies in managing salinity in a range of settings across South Australia.

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ABBREVIATIONS

AEM – Airborne electromagnetics

EM – Electromagnetics

FDEM – frequency domain electromagnetics

HEM – Helicopter electromagnetics

NAP – National Action Plan for Salinity and Water Quality

RMDCP – River Murray Dryland Corridoor Project (shortened version of Project Title: "Development of market based investment programs for NRM along the River Murray/ Mallee dryland corridor")

SA SMMSP – South Australian Salinity Mapping and Management Support Project

SIMPACT – Salinity Impacts Model

SIMRAT – Salinity Impacts Rapid Assessment Tool (derivative of SIMPACT)

TEM – Transient electromagnetics

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