Application of Airborne Geophysical Techniques To Groundwater Salinisation Issues In The Tintinara Region, 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

The SA SMMSP represents a significant departure from previous studies seeking to apply airborne geophysics in land 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 that was already in place. 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 Tintinara study site in the Mallee region, the principal goal of the geophysical survey was to provide information to support management of the groundwater resource in the area. The quality of the groundwater is at risk from salt stored in the deep soil profiles being leached into the aquifer. Increases in horticultural development over the last decade have accelerated the processes of leaching. To the west of the study area, on the Coastal Plains, water tables are shallow and remnant native vegetation is at risk of stress from waterlogging and salinity. A combination of airborne geophysical techniques, rigorous field testing and modelling has shed light on these risks.

The prime objectives of the project in the Tintinara region are to:

(i) Map the shallow sub-surface clay within the Tintinara East region and adapt tools to use this information to predict the impact of land management decisions on the quality of the underlying groundwater resource. Sub-surface clay has contradictory effects on groundwater salinisation: more clay means more salt, but it also slows down the leaching processes.

(ii) Map zones of groundwater salinity on the Coastal Plain (Tintinara West) and use this information to study salinity impacts on native vegetation.

An additional objective that arose from an enquiry was to map the extent of shallow basement rock to the west of the study area.

The geophysics provided a reliable map of the thickness of sub-surface clay across the eastern study area. There was a good match with recent, carefully logged stratigraphic records. However, there was some discrepancy for large clay thicknesses with a few records, as extracted from the stratigraphic database. Previous experience from the Riverland, where there was a good match between recent logs and the spatial pattern that corresponded to a geomorphic understanding of the landscape, suggests that the maps are nonetheless reliable.

This information was used as input to a salt leaching model. This provided predictions of the impact of clearing native vegetation in the area for agriculture. The results showed that the amount of salt being leached into the aquifer increased as the effect of clearing reached the water table, and then decreased as the total salt store leached out. The time for this to happen was shorter for the shallow water table areas to the west, where there is evidence of this occurring already. To the east, the process may take 200 years. Superimposed on this east-west trend is a series of north-south trending linear features associated with the sub-surface clay.

The salt leaching model was also applied to simulate the impacts of horticultural development. The deep drainage flux under irrigated crops is likely to be dependent on the crop, irrigation management and soils. To produce a risk map, it was assumed that

the deep drainage was a flat 150 mm/yr. As a rule of thumb, this would cause the salinisation process to occur about 5 times more quickly.

A subsequent scenario with a spatially variable rate for irrigation drainage (where irrigation drainage was chosen to be 5 times that of clearing induced drainage) was used as an input to a groundwater model (see below) employed to determine aquifer salinity trends. A spatially variable rate was chosen for this subsequent work to give greater account of the influence of variation in soil texture on drainage rates and provide continuity between leaching under dryland farming and the introduction of irrigated agriculture.

These salt leaching model outputs, for both dryland and irrigation, were used as inputs to a MODFLOW groundwater model and the associated MT3D to predict impacts on groundwater levels, groundwater direction and groundwater salinity. A good calibration was achieved. The models predicted that even without irrigation, sufficient changes in groundwater salinity would occur in 50-100 years time to change the beneficial uses of the water (eg. threatening irrigation for some types of crops, or suitability for irrigation at all). These models should enable a prediction of the parameters of interest for a range of scenarios and should be used to consider the trade-offs between development and sustainability of the groundwater resource and between planning to optimise sustainability and equity issues.

Improvements in water use efficiency will improve the longevity of the resource. This would entail an understanding of deep drainage for combinations of irrigation management, crop type and soils. A sensitivity analysis suggests that knowledge of the clay content of the surface soils is a very important parameter when determining the rate of salinisation. Interpretation of previously surveyed radiometrics data for the area may improve the mapping of surface soils and hence provide enhanced estimates of clay content.

The geophysics was used to map groundwater salinity in the western site (Coastal Plain). Here the contrasts in groundwater salinity were so large as to over-ride any conductivity differences associated with spatial variability in materials. Even specific features such as irrigation recycling appeared to be detected. The groundwater salinity map was used to investigate the influence of salinity on the health of remnant native vegetation. Unfortunately, there was no clear correspondence between plant health measures and groundwater salinity, even though there were indicators of increases in plant stress over the study period.

Studies (described in Camp, 2003) showed that an estimated 605 ha of remnant vegetation was currently affected by salinity in the study area, with predictions that increasing salinity will impact a further 2 ha in 50 years and an increase of 51 ha on current levels in 100 years. While the spread of salinity is not predicted to be large, rising salinity levels will intensify the stress on already salt affected vegetation. Areas affected and at risk are also low because of the large areas of remnant communities already cleared for agricultural development, and because significant areas already have quite shallow watertables. A longer period of monitoring is required to really detect trends against the background. Because sites were selected before the geophysics became available, some are not ideal locations. Those, that are, should be continued to be monitored.

In the west of the Coastal Plain site, where the unconfined groundwater system becomes too saline for use, the confined aquifer is used. However, the basement becomes high in places causing this aquifer to be absent in places. An enquiry from a driller wishing to avoid this basement rock led to a mapping of the high basement elevations.

All of the set objectives were achieved, with an additional one also being completed. The flying at this site benefited from pre-flight testing in the Riverland. A much greater spatial definition of conducting layers has been achieved that would not otherwise be feasible using drilling alone or through any other remote techniques. The unusual processes associated with groundwater salinisation means that the whole methodology is unlikely to have wide application, although the individual components have wider applicability. Areas with underlying regional sedimentary aquifers will tend to benefit from geophysics applied to assets such as a water resource.

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INTRODUCTION

This report is one of a series of final site reports summarising results for the South Australian Salinity Mapping and Management Support Project (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 has adopted a pioneering approach compared to traditional research programs involving the acquisition of geophysical data. 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 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 seeks 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.

This report describes the component of the program conducted at the Tintinara site, one of 5 study areas in the SA SMMSP. 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. All the sites are shown in Figure 1. Apart from the Tintinara site, 3 of the study areas were in the western Murray Basin (Riverland [Lock3 to Border], Angas-Bremer Plains, and the Bremer Hills) with one in the mid-North (Jamestown).

In the Tintinara region, the lack of surface water means that the groundwater resource is an important asset. However previous studies have shown that the groundwater resource will become more saline over the next 100 to 200 years, as a result of clearing for non-irrigated agriculture. The growth in irrigation in the area has hastened this process and increased the need to consider planning processes to maximise the lifetime of the resource. To the west of the area, rising water tables have adversely affected the remnant vegetation.

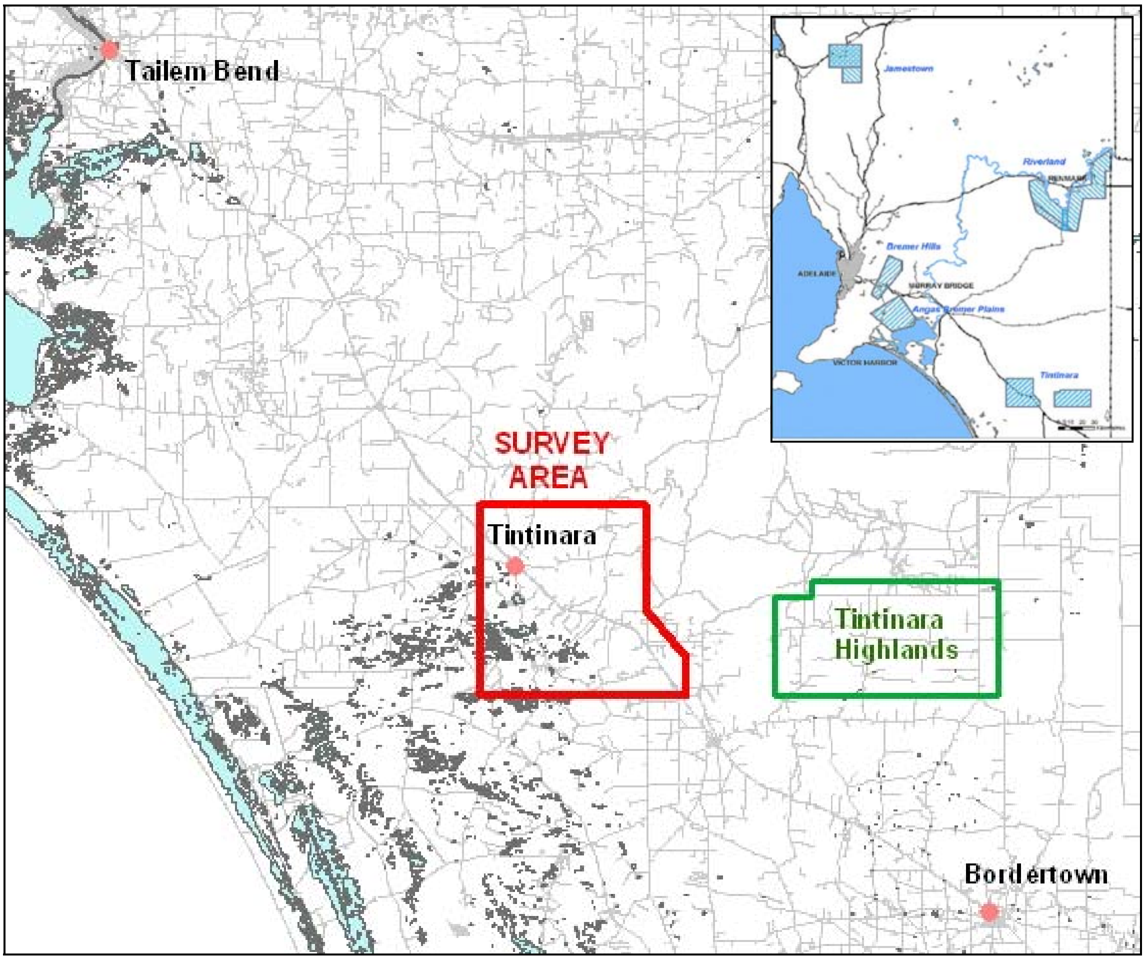


Figure 1. Location of the Tintinara site: east (mallee highlands) and west (coastal plain); inset: the 5 study areas.

The aim of this report is to summarise the study and main findings from the Tintinara site. Issues of extrapolation to other groundwater resources are also discussed. Similar reports have been written for each of the other study areas and a final report exists for the overall program. The report is divided into 4 parts, reflecting the staged approach taken throughout the SA SMMSP, comprising:

A. Discussion of the resource management issues

B. Definition of the role and capabilities of airborne geophysics in addressing these issues

C. Developments in modelling and decision support tools

D. Assessment of the lessons and outcomes of the project on future management decisions

The Tintinara site was divided into 2 parts (East and West) where different salinity issues were to be investigated (as outlined in Part A to follow).

Contracted objectives were to:

(iii) Map the shallow clay within the Tintinara East region and adapt tools to use this information to predict the impact of land management decisions on quality of the underlying groundwater resource.

(iv) Map zones of groundwater salinity on the Coastal Plain (Tintinara West) and use this information to study salinity impacts on native vegetation.

Contracted outputs included:

For Tintinara East (Mallee highland):

- A map of the clay across the main area of concern, as inferred from the EM conductance map and on-ground calibration
- Improved estimates of salt loads to the groundwater using the additional information from geophysics and drilling.
- Improved groundwater model of the area, incorporating the high resolution data obtained from the geophysics together with improved recharge data. The groundwater model is currently being used for water allocation planning.

For Tintinara West (Coastal Plain):

- Identify associations between vegetation health and salinity.

----------- And during the course of the program another output was derived: ---------------

- Define areas of shallow basement rock.

A number of detailed reports for the Tintinara site have been compiled under the SA SMMSP. Further information can be found in these reports:

- Brodie, R.C., Green A.A., and Munday, T.J. 2003. Calibration of RESOLVE airborne electromagnetic data, Riverland and East Tintinara, South Australia.. CRC CRC LEME Open File Report 173, Cooperative Research Centre for Landscape Environments and Mineral Exploration, December 2003.
- Cook, P.G., Leaney, F.W. and Miles, M. 2004. Groundwater recharge in the north-east Mallee region South Australia, CSIRO Land and Water Technical Report No. 25/04.
- Cowey, D., Garrie, D., and Tovey, A. 2003. Riverland and Tintinara, South Australia - RESOLVE Geophysical Survey, Acquisition and Processing Report. Report to the Bureau of Rural Sciences (available from Geoscience Australia), Fugro Airborne Surveys.

- Camp, A. 2003 Salinity and Native Vegetation Health – Tintinara and Angas-Bremer Plains, South Australia. Department of Water, Land and Biodiversity Conservation.
- Leaney, F., Barnett, S., Davies, P, Maschmedt, M., Munday, T. and Tan, K. 2004. Groundwater Salinisation in the Tintinara Highland Area of SA:: Revised estimates using spatial variation for clay content in the unsaturated zone. CSIRO Land and Water Technical Report No. 24/04. January 2004.
- Osei-Bonsu, K., Barnett, S., Leaney, F. and Davies, P. 2004. Modelling Groundwater Salinisation in the Tintinara Highlands area of SA, Department of Water, Land and Biodiversity Conservation, DWLBC Report 2004/ 44 (In Press).
- Tan, K.P, Munday T.J. and Leaney, F. 2004. The validation of RESOLVE helicopter EM data: Mineralogical and petrophysical results from field investigations for the Tintinara East survey area, in the south east of South Australia. CRC LEME Open File Report 174. Cooperative Research Centre for Landscape Environments and Mineral Exploration, September 2004.

PART A. RESOURCE MANAGEMENT ISSUES

1. *Groundwater Salinisation in the Tintinara East / Mallee Highland Region*

Increasing concentration of salts in groundwater can be as much a limitation to groundwater resources in semi-arid and sub-humid areas as the over-extraction of groundwater (i.e. removing more water than is being replenished). Increasing groundwater salinity is caused by mobilisation of salt into the fresh aquifer. Most often, salinisation of groundwater is caused by saline groundwater from above, below, or to the side being entrained into the fresh aquifer by groundwater extraction.

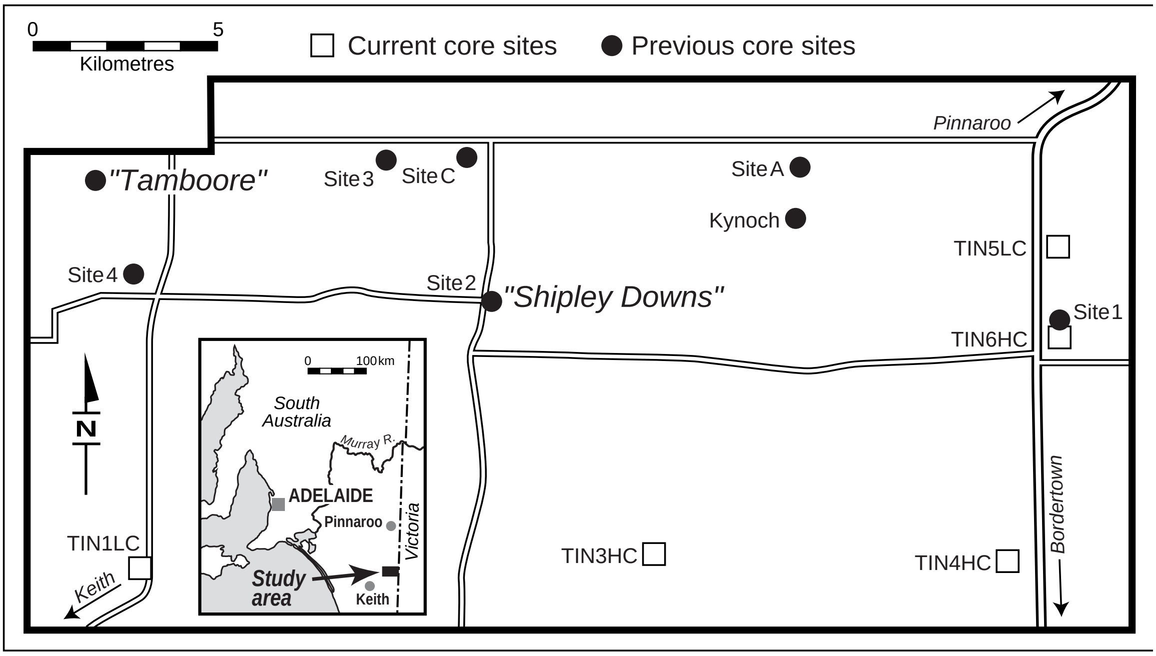


Figure 2. Location of the study site with sites where cores were collected during this and previous field investigations.

However, previous studies (Cook et al, 1993; Leaney and Herczeg, 1999; Leaney et al.1999) have shown that another mechanism operates in the southern Mallee groundwater resources, such as in the Tintinara area. In this case, the fresh groundwater resource (Murray Group Limestone aquifer) was recharged during a wetter period ~ 20,000 years ago. The lack of surface water resources in the area makes this an important regional asset.

The lower rainfall over the last 20,000 years has allowed plant roots to concentrate salt in the soil so that now large stores of salt exist in the deep Mallee soils. This store of salt forms a natural hazard. Increased recharge caused by clearance of native vegetation has led to leaching of these salts into the fresh aquifer and increases in the salinity of the groundwater. The recent increase in irrigation using groundwater has exacerbated this problem. In some areas the groundwater might be unusable for irrigation within the vicinity of the development activity within as little as ten to twenty years, and could lead to more general deterioration over the next 50 to 200 years.

The increased recharge under non-irrigated conditions also leads to rising water tables, but the water tables are sufficiently deep for land salinisation not to be a problem except in the very western areas. The extraction of groundwater for irrigation means that in irrigated areas, water tables should fall, but water quality will become an issue well before the groundwater store is depleted. Thus, salinisation of groundwater is the major risk to the water resources in the area.

There is now evidence of the water levels in some piezometers outside the main irrigation developments rising due to the increased recharge, others are falling due to the groundwater extraction, and for shallow piezometers, there is evidence of increasing salinity levels. There is also evidence of soils 'wetting up' and salt being leached in the soil profile. The question is not 'if' salinisation will occur, but 'by how much' and 'when'.

Both the magnitude and timing of salinity process will vary across the region, and any management will need to focus efforts on areas at greatest risk. There may be a need to encourage new irrigation developments away from these areas or improve irrigation efficiency in order to provide more security of the groundwater resource.

While the processes are understood, there is still a lack of sufficient data on the spatial patterns of these processes for land use planning for groundwater sustainability objectives. Better information about these spatial patterns will allow more reliable and detailed predictions of what management options are appropriate and the likely outcomes at various scales and over a range of times into the future. This in turn gives land managers confidence that their management choices are appropriate, which is particularly important in situations where the observed response of the groundwater system might be many years after the strategy is implemented.

Table 1 lists the factors that affect these spatial patterns. It can be seen from this Table that 2 key datasets are:

- Distribution of surface soils (0-2m depth), which affects the magnitude of the impact through soil salinity and timing through deep drainage rates under both non-irrigated and irrigated crops, and
- Distribution of sub-surface soils (2m to water table), which affects the magnitude of the impact through the size of the salt store and the timing through the size of the soil water store.

It should be noted that effects could be contradictory. For instance, the presence of heavier (more clayey) sub-soils will increase the store of salt, but will slow down the leaching of this salt. A sandier sub-soil may lead to salinisation occurring more quickly (say 20 years), whereas the magnitude of the impact will be greater under heavier soils, albeit slower (say 50 years).

Information on the texture of surface soils was provided through soil landscape mapping (1:100,000 scale) by the Soil and Land Information Group of DWLBC. They have collated data on proportions of defined associations of soils within each soil landscape unit. Unfortunately, information on sub-surface soils is much more sparse. Bore log data has provided only very general maps of the distribution and thickness of sub-surface clays, the resolution of which is insufficient for planning purposes.

Hence, the objective of this component of the study is to use airborne geophysical techniques to map the shallow clay within the Tintinara region at sufficient resolution and then to adapt planning tools to use this information.

Table 1. Factors that lead to regional variations in the magnitude and timing of salinity impacts:

– Magnitude –

(i) ***Size of the store of salt in soils.*** This is dependent on the salinity of soil water and the volume of soil water. Previous studies have shown that the salt concentration in the Mallee soils in this region is weakly dependent on the texture of surface soils varying from 14,000 mg/L soluble salts for sandy soils to 28,000 mg/L for clayey loams.

(ii) ***Volume of groundwater, with which it mixes***. This is a difficult parameter to assess until salinity processes become more evident.

– Timing –

(iii) ***Increase in deep drainage to leach the stored salt.*** Deep drainage under non-irrigated agriculture has been found in field studies to be dependent on the texture of the surface soils, being higher for sandy soils. Empirical relationships have been developed from these field studies. Deep drainage under irrigated agriculture is dependent on the irrigated crop, irrigation management and the soil texture.

(iv) ***Depth to water table.*** Depth to water varies from around 23-27m (OBSWELL bores MKN 008 and MKN 011, June 2004) in the west, to around 56m (OBSWELL bore SHG005, June 04) in the east.

(v) ***Store of water in the soils.*** The volume of soil water is strongly dependent on the depth to water table and the texture of the soils to the water table, increasing as the soils become more clayey.

(vi) ***Any impedances to salt mobilisation into the aquifer being used.*** There are no impeding layers between the limestone aquifer from which groundwater is extracted, although towards the Victorian border, this changes

2. Coastal Plain (Tintinara West)

The target for the geophysics for the western study area was the salinity of the shallow groundwater. Better knowledge will underpin groundwater management in order to:

- avoid unnecessary degradation of the resource through increases in groundwater salinity, and
- better understand the factors leading to decline in vegetation health.

The location of the survey area is shown in Figure 1 and a 3-D conceptual model of the groundwater systems is shown in Figure 3.

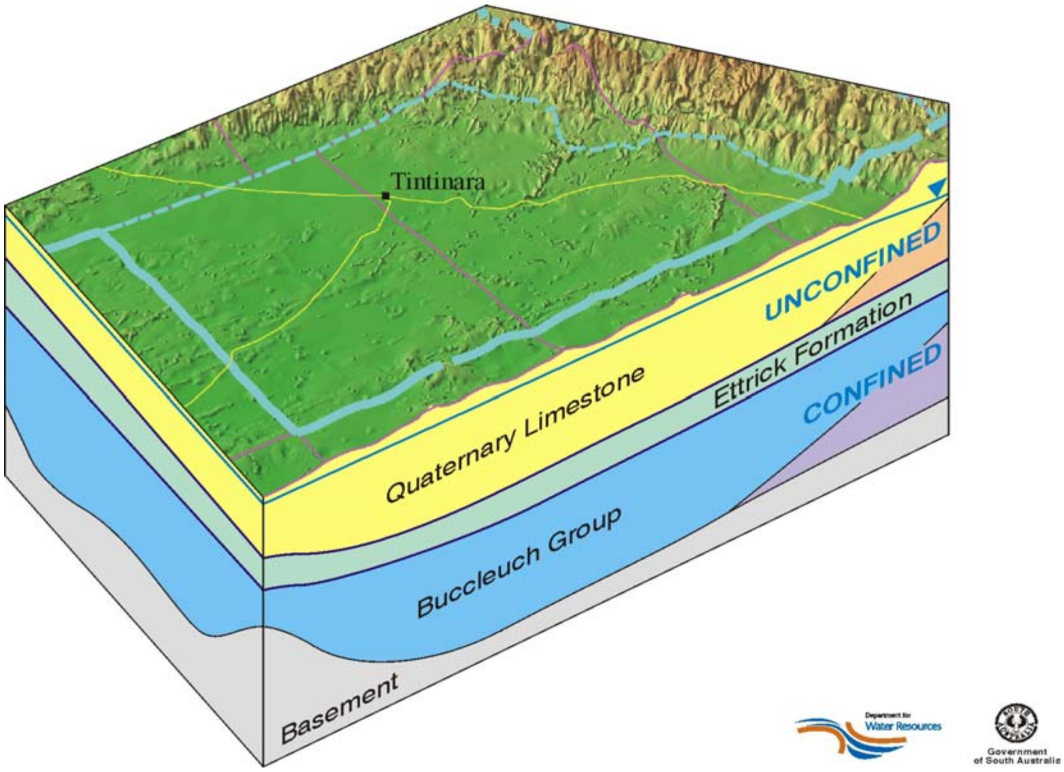


Figure 3. Conceptual model of groundwater systems underlying the Coastal Plains (Tintinara West) study area.

Groundwater flow, for both the unconfined and confined aquifer systems, originates from the topographic high of the Dundas Plateau located in western Victoria. From there, the groundwater flows westward beneath the study area toward the coast.

2.1 GROUNDWATER SALINITY PATTERNS - COASTAL PLAIN

The salinity of the groundwater increases to the west of the western study area and is associated with shallow water tables. This higher salinity determines the western limit of the unconfined groundwater resource, although some irrigation from the confined aquifer occurs further west.

Irrigation for lucerne has led to pronounced irrigation recycling and associated increases in groundwater salinity. To the west of the area, rising shallow water tables have led to increasing evidence of land salinisation and decline in vegetation health.

2.2 VEGETATION HEALTH RISK – COASTAL PLAIN

NLWRA (2001) showed that large areas of remnant vegetation were vulnerable to salinity and waterlogging caused by rising water tables. Many of these areas are fragmented, which makes them also vulnerable to a number of other risks. This component of the project aimed to assess salinity stress in remnant vegetation stands on the Coastal Plain and develop methodologies to predict areas of native vegetation at risk of salinisation into the future.

PART B. ROLES AND CAPABILITIES OF THE AIRBORNE GEOPHYSICS

3. *Airborne geophysics technologies and potential targets*

One of the prime objectives of the SA SMMSP was to assess the usefulness of airborne geophysics as an information gathering tool to be applied in addressing salinity and water quality issues. Four distinct geophysical techniques were employed, throughout the five key sites, each providing different but complimentary information. Variations and combinations of the techniques also provide the means to deliver a tailored approach to each particular investigation. The main features of the techniques are summarised in the box on the next page.

Airborne electromagnetics (AEM) can be used to define 3-dimensional conductivity structures of a region to describe the salt-water-materials relationships in terms of their defining electrical conductivity signal. This can potentially spatially define high (and low) salinity groundwaters and zones of high (and low) salt load. It may also indicate sub-surface variability in materials, specifically the clay: silt: sand contribution. AEM requires careful calibration to determine the relative contribution of conductive materials, but is the only geophysical technology that has the potential to map salt load directly in the sub-surface with good vertical resolution.

Radiometrics can give a spatially precise picture of soil and rock variability across a landscape. Flood plain, or alluvial sediments can be contrasted with the coarser slope, or colluvial, deposits and the bedrock on ridges.

Magnetics detects the presence of iron-rich minerals which are commonly associated with older sub-surface drainage lines – palaeochannels – that may act as conduits for groundwater flow. Geological structures (eg. faults, dykes, etc) are also often emphasised using this technology.

Altimetry / Elevation information is required to process the geophysics data but also can be of great value in helping to understand and / or model landscape processes.

3.1 LIMITATIONS

Airborne geophysical techniques have 3 significant limitations:

1. All surveys represent a snap-shot in time of the geophysical properties of the landscape. As such, they are only an approximate indication of the average ambient conditions across a region and the observations must be carefully evaluated with respect to their position in time and relative to ambient climatic conditions.
2. Careful, systematic and accurate ground-truthing, or calibration, is a vital pre-requisite for realistic interpretations of the airborne geophysical signals. This will add a cost of at least as much as that required to fly the surveys.
3. Each technology has its own strengths and weaknesses, and AEM, in particular, comes in a number of guises, each with peculiarities that allow it to be tailored to address the most prevalent issue for a given area. Forward modelling, or scenario-testing, is a useful exercise that should be carried out on dummy data sets representative of conditions expected to be met over the real survey.

Airborne Geophysical Technologies

AIRBORNE ELECTROMAGNETICS (AEM)

A pulse of EM radiation is emitted from the aircraft which interacts with conductive material in the ground. A modified, secondary signal ‘bounces’ back to a towed receiver that collects parcels of data in either time or frequency domains. These signals can then be modelled, or ‘inverted’, to define the 3-dimensional conductivity structure of the survey area. From the electrical conductivity signals and appropriate ground-truthing, the relative composition of salts, water and materials in the profile can be defined. Potentially, this can spatially define high (and low) salinity groundwaters and zones of high (and low) salt load. It may also indicate sub-surface variability in materials, specifically the clay: silt: sand contribution.

Vertical reliability and resolution is strongly dependent on the modelling routines used to convert the raw data into depth images and this is highly constrained by the interpretation of drill-hole data and pre-conceived ideas about the landscape and nature of the sub-surface (e.g. Hunter, 2001; Christensen, 2002). Interpreted data must, therefore, be treated with extreme care.

RADIOMETRICS (GAMMA)

Radiometrics detect the natural gamma radiation signal given off by near-surface (< 30cm) materials and can give a spatially precise picture of soil and rock variability across a landscape. The relative amounts of radioactive elements, namely potassium (K), uranium (U) and thorium (Th), are indicative of source minerals and hence soil and rock-types. This can help contrast regions of differing clay, silt and sand compositions. The ratio of different gamma intensities can give clues to a landscape’s development. For example, potassium depletion may indicate an older and hence thicker weathering profile which may be correlated with elevated salt loads (Wilford, et al., 2001). It should be noted, however, that, with existing technology, radiometrics can not measure salt directly.

MAGNETICS

Airborne magnetics detects the subtle variability in the earth’s magnetic field caused by the presence and absence of ferromagnetic minerals such as magnetite (Fe_3O_4), maghemite (□-Fe_2O_3), pyrrhotite (FeS) and ilmenite ($FeTiO_3$). These minerals are commonly associated with stream-bed deposits and have been used elsewhere (e.g. to the north around Jamestown (Wilford, 2004) and to the east across Honeysuckle Creek, Victoria (Cresswell, et al., 2004)) to pick-out sub-surface drainage lines – palaeochannels – that may act as conduits for groundwater flow (Cresswell, et al., 2004). Further, these minerals are common in many igneous rocks, both as primary and secondary minerals, and can often be used to depict geological structures (eg. faults, dykes) in the sub-surface from discontinuities seen in the airborne images.

ALTIMETRY

As a necessary by-product of flying the other 3 geophysical techniques, a precise digital elevation model (DEM) is generated from the radar and laser altimetry used to precisely locate the aircraft above the ground. The resolution is a function of the spacing of the flight lines and the signal repeat time, but generally this results in a spot measurement taken every 10m along the flight path, with flight paths 100m apart for the combined radiometrics and magnetics survey and between 100 and 400m for the AEM survey. The resultant data is interpolated to give an exact surface on which to “hang” the other data sets and provide a surface reference for other studies. The DEM also often gives new insights into the evolution of landforms and landscape relationships (Gibson, 2004).

Bearing these limitations in mind, airborne geophysics provides a suite of powerful tools that can give un-paralleled insights into landscape form and function, providing a quasi-continuous image of ground conditions and hitherto unprecedented spatial analysis of fundamental environmental features. Used without due diligence, however, the data can also give misleading, or even quite erroneous, results.

3.2 CHOOSING THE RIGHT TECHNIQUE

Given the relatively focussed nature of the investigations at Tintinara and the ability of airborne EM to detect both salinity in groundwaters and sub-surface clays, this was the only technique employed. Only recently did the project team become aware of the availability of coarse radiometric data.

4. Mapping Sub-Surface Clay – Tintinara East (Mallee Highland)

Airborne EM was flown across the area, targeting the sub-surface clay. Table 2 lists some of the key geophysical information related to the eastern Tintinara site. The dataset most sensitive to 8-10 m depth range, which corresponds to the sub-surface clay, is shown in Figure 4. Electromagnetic induction can detect clay both because of its inherent conductivity characteristics and the additional water (and hence salt) found in clayey soils. The expectation is that the red areas represent areas of clay for this depth range.

Table 2. Key geophysics information – Tintinara site

(i) For the Tintinara site, a helicopter-borne, fixed frequency electromagnetic induction device (RESOLVE) was flown with a line spacing of 300m.

(ii) Electromagnetic induction measures the conductivity of the earth is under the flight path. The bulk conductivity of the earth depends on a number of factors, but particularly the amount of water, the salinity of that water and the amount and type of clay.

(iii) A fixed frequency device measures some average of this property over depth with lower frequencies operating at greater depth.

(iv) Fixed frequency devices can allow greater sensitivity to near-surface properties than with the other main form of EM induction (time domain). Despite this, the top 1-2 m is outside the limits of detection and hence not used to map surface soils. The EM induction technique can also be used to estimate the salinity of the groundwater, although there is good information on this already. This groundwater data was used in the inversion of the geophysical data in order to limit the number of parmeters being derived in the inversion process.

(v) The line spacing determines the spatial resolution of the end-product with a general rule-of-thumb that to detect a feature that is 600m wide requires a line spacing of 300m.

(vi) A by-product of the geophysics flights is a high-resolution digital elevation model (DEM), to within a metre height.

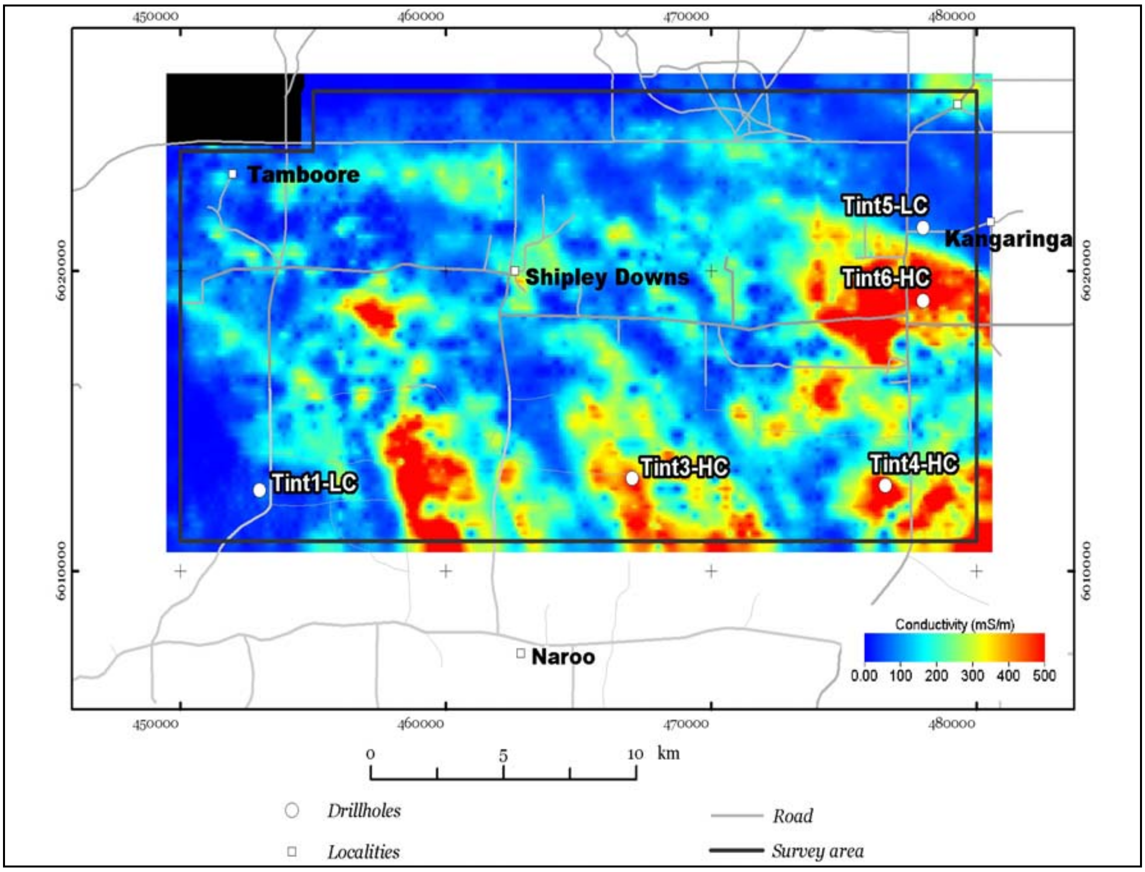


Figure 4. RESOLVE® HEM [Helicopter-borne EM] bulk conductivity for the depth interval 8-10m below the surface. The locations of drill holes used to validate the observed conductivity structure are also shown (Leaney *et al.*, 2004).

A number of sites were drilled (see Figure 4) to test whether these high conductivity zones actually corresponded to clays. An example is shown in Figure 5. As can be seen, elevated conductivities (4th column) are strongly correlated with percentage of clays within the sediment (1st column). This has been found true for the test-sites, as a whole (correlation coefficient, r = 0.88). These results also confirm that the airborne data should be most sensitive to the distribution of clays within the top 30 m.

4.1 DETERMINING CLAY THICKNESS

The RESOLVE® HEM [Helicopter-borne EM] survey generates data responses in the frequency domain, with lower frequencies penetrating deeper to characterise deeper materials. The process of converting this data into something representing variations in material properties with depth is called an inversion. To give the inversion process some meaning, the data is applied to a model of the sub-surface, often comprising of discrete geological layers with known parameters described. This constrains the output to agree as much as possible with what is known of the sub-surface.

The resulting map of clay thickness, as determined through this inversion of the AEM data is shown in Figure 6. This represents the first contracted output for this site.

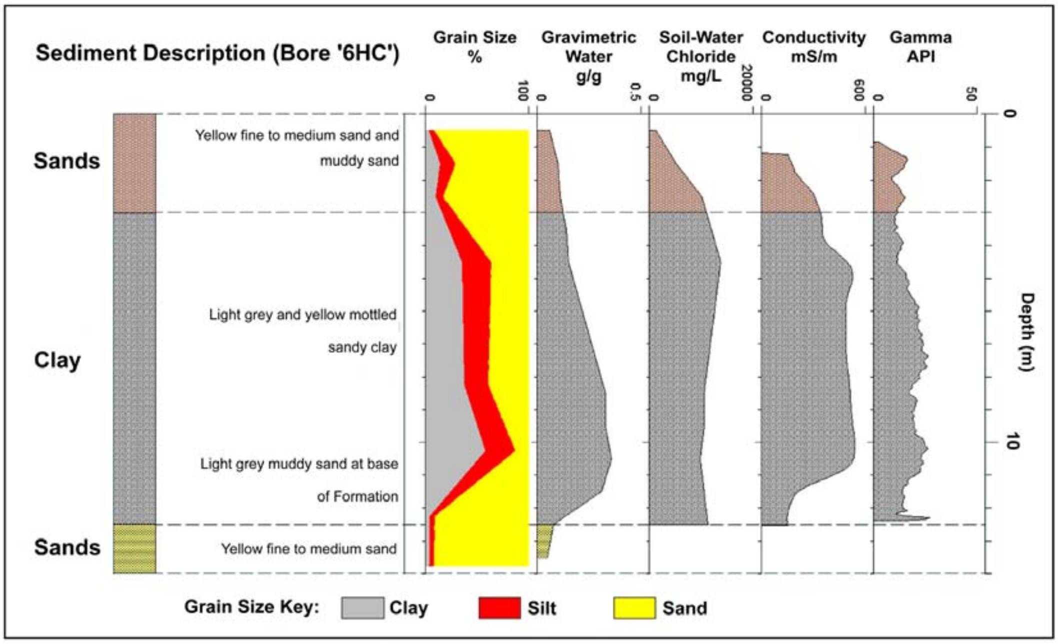


Figure 5. **Borehole geophysical, textural and soil-water chloride data for bore 6HC (location shown in Figure 2). Log shows thick sequence of clays with an elevated bulk conductivity (Leaney *et al.*, 2004).**

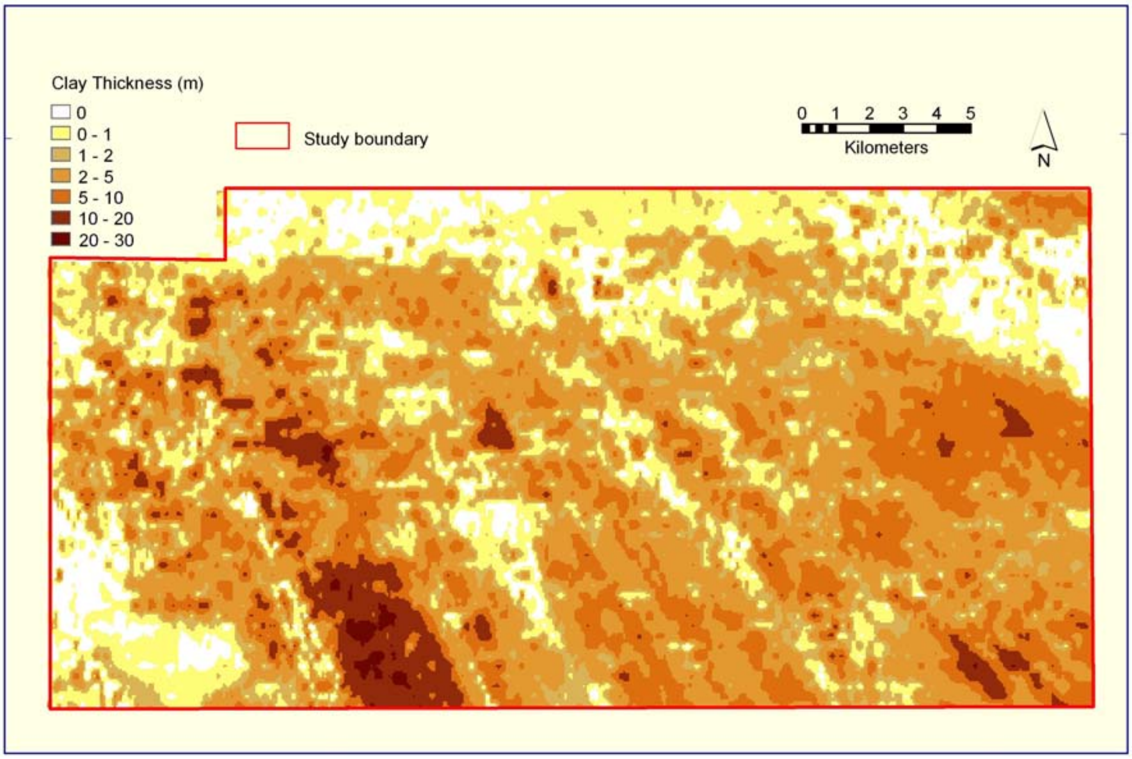


Figure 6. **Map of the clay thickness derived from the constrained 1D Layered Earth Inversion (LEI) of RESOLVE HEM data. (This is the direct equivalent of Layer 2 in the inversion.) (Leaney *et al.*, 2004)**

To determine the reliability of this map, the inferred clay thickness was compared with that derived from 53 drill-logs. In Figure 7, blue circles define the relationship between drillhole data from the DWLBC drill logs and the inversion result (r^2=0.47). The relationship defined by the red circles (r^2=0.8) is that determined for recent targeted drilling undertaken by CSIRO L&W, DWLBC and CRCLEME. In this exercise, greater care was taken in the geological logging of drillhole cuttings, with particular emphasis on detailing the true extent of the near surface clay-rich sedimentary units.

The errors associated with the process are summarised in Table 3. The wide scatter in the relationship shown by the blue dots is likely to reflect a combination of factors including the poor definition of clay-rich units during drilling, difficulties in correlating results from a drillhole with the average response from the helicopter having a footprint of between 30-50m, and errors associated with the underlying assumptions made in the inversion of the HEM data. Even so, the data from the blue dots show that where the clay thickness, was inferred to be greater than 4 m thick, the drill-logs supported this. On the other hand, where the thickness was inferred to be less than 4m, the range of thicknesses reported in the drill-logs varied up to 12m. If the dataset is restricted to the carefully logged bores represented by the red dots, the relationship suggests that the thickness of Layer 2 from the constrained inversion of the HEM data is a reasonable surrogate for the thickness of clay in the Tintinara East study area.

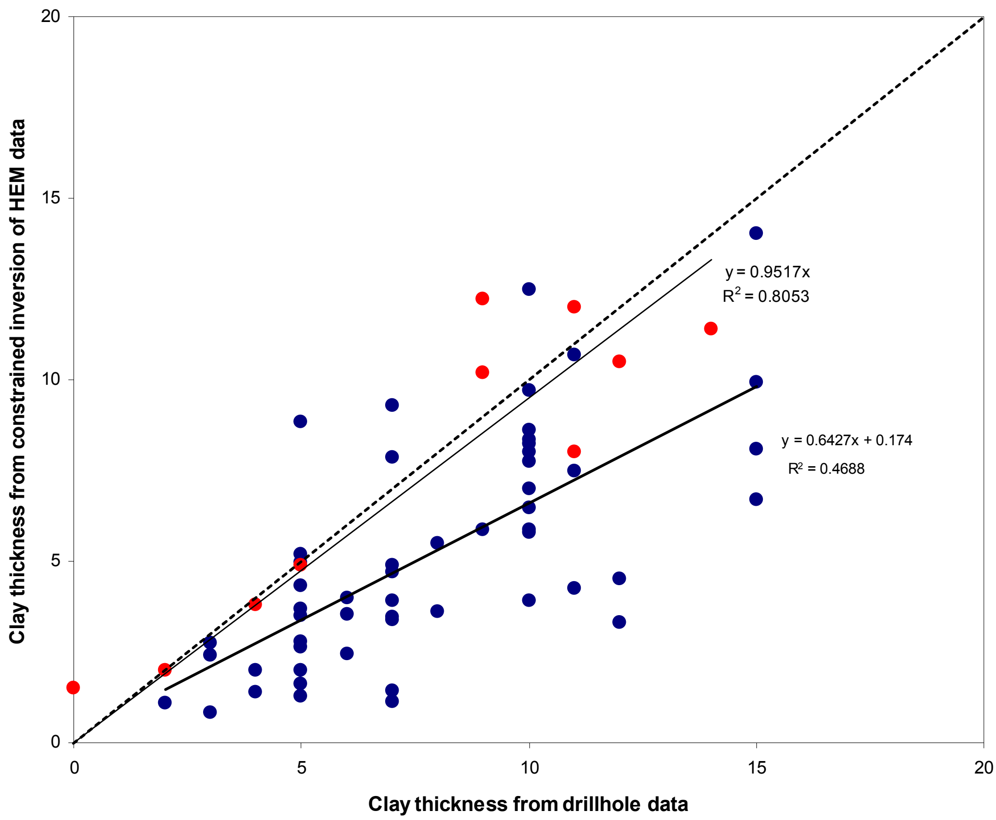


Figure 7. Relationship between clay thickness from drillhole data and clay thickness estimated from the constrained inversion of the helicopter EM data.

Table 3. Potential errors in mapping clay thickness

(i) ***Inversion:*** The main error introduced by using an air-borne EM device, rather than a down-hole device is in the inversion process: To obtain the bulk conductivity at different depth intervals requires interpretation of measurements taken at different frequencies. This process, called inversion, introduces its own errors even if measurements at some frequencies are sensitive to the conductivity at the desired depth interval. In this case, the sediments are assumed to consist of 4 layers of constant conductivity (a near-surface layer, a sub-surface clay layer, another sandy layer and the limestone aquifer).

(i) ***Footprint:*** This is the main error in comparing data from air-borne devices with drill-log data. The air-borne device averages over a given area; the so-called 'footprint'. In comparing data from drilling with that of air-borne EM, we are comparing data at a single point with that averaged over an area.

(ii) ***Positioning errors:*** due to errors in location.

(iii) ***Definition of a clay:*** Drillers' logs are often reliant on field interpretation. Reinvestigating drill-logs showed that drill-logs, especially from old drill-sites can often be erroneous.

(iv) ***Wrong Assumptions:*** While for detailed sites, the conductivity was sensitive to clay, but this may not be true for some areas e.g., if salinity of soil-water showed greater contrasts.

It is unclear why the errors are so large for lower conductivity readings. The lower inferred thickness reflects that this layer only represents a smaller fraction of the overall conductivity reading and hence may be prone to error. Also, thinner clays may vary over small distances, making the 'footprint' error larger. However, the only explanations for a 12 m thick clay layer having a small EM reading is that the soil water was not saline, the drill logs wrongly logged the clay or the area of thick clay was only small.

4.2 IMPROVED UNDERSTANDING OF GEOMORPHOLOGY

The spatial pattern of clay thickness clearly shows linear features running NNW. If these linear features could be related to an understanding of the geomorphology of the region, there perhaps can be a greater confidence in the overall patterns than in the individual point data.

Some effort was placed into better understanding the processes of ancient landscape formation and how the sedimentary profile has built up over time. Table 4 provides a brief description of the geomorphology and shows that the linear features may relate to an old dunefield with clay between these dunes. This dune field has since become covered with other material, including a more recent dune field with a completely different orientation. We would therefore expect reasonable confidence in predicting these linear features, which would generally correspond to clayey or sandy profiles, although there may be some variation within each of these features. This is re-emphasised in the cross-section shown in Figure 9.

Table 4. Brief discussion of geomorphology for the area

The geomorphology of the region is illustrated in a block diagram in Figure 8. The main aquifer used for groundwater extraction is the Morgan limestone. For our area of interest, the water table resides in this Formation. Above this is the Loxton-Parilla Sands, which were formed as the ocean retreated south-westward. As the shoreline retreated, the primary dune was stranded. Behind this would have been a lagoonal feature corresponding broadly to today's Coorong. Therefore, the recession of the shoreline left behind a series of parallel strandlines with clayey deposits nestled between the dune features. These NNW trending dunes are almost perpendicular to contemporary dunes, which mainly run east-west across the area. We would therefore expect reasonable confidence in predicting these linear features, which would generally correspond to clayey or sandy profiles, although there may be some variation within each of these features.

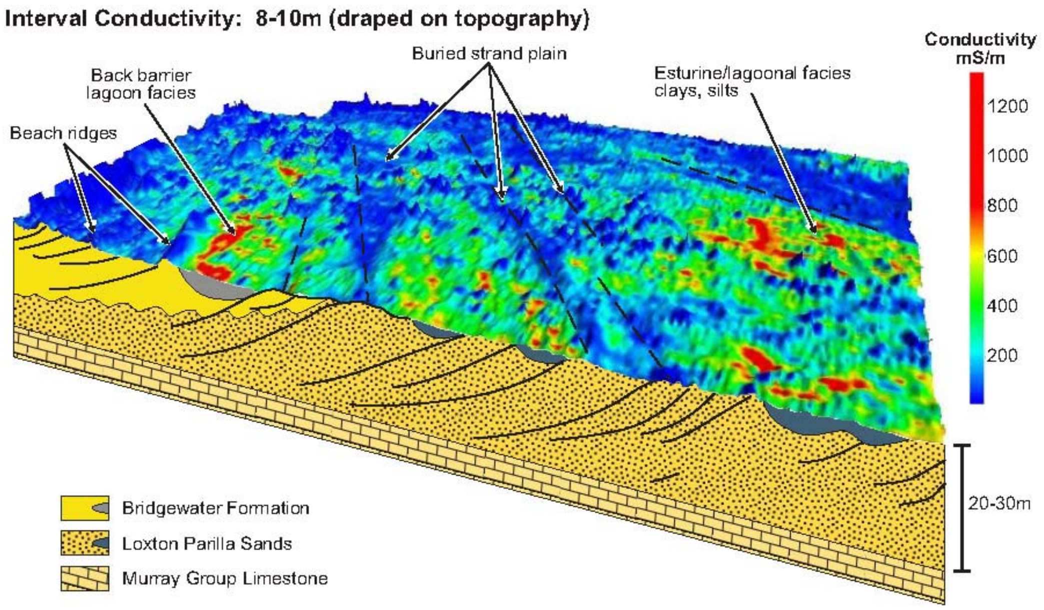


Figure 8. Block model of RESOLVE Interval conductivity for 8-10m draped on topography, with a geological interpretation of the observed conductivity structure (Leaney *et al.*, 2004).

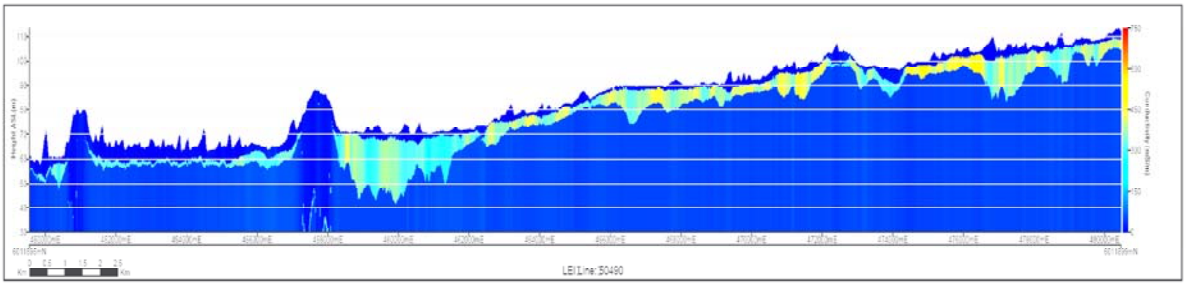


Figure 9. 1D Layered Earth inversion stitched section from the constrained inversion of one flight line running east-west. Clay rich sediments (the more conductive unit) occupy inter-barrier depressions and, in places, are in excess of 30m (Leaney *et al.*, 2004).

This data on the spatial patterns and thickness of clay rich units across the Tintinara East study area was then applied to models used to predict rates of recharge and salinisation of the groundwater resource. Results from these models are further discussed in Part C.

5. Findings on the Coastal Plains (Tintinara West)

5.1 MAPPING GROUNDWATER SALINITY

Figure 10 depicts the latest observed groundwater salinity distribution in the Tintinara area, with the irrigation areas also shown. The circular areas represent centre pivot irrigation of lucerne where application rates range from 5 – 7 ML/ha. The rectangular areas are where flood irrigation occurs, with much higher application rates in the range of 10 – 12 ML/ha. The increases of groundwater salinity, associated with recycling of salt contained in irrigation drainage water, is evident, especially beneath areas of flood irrigation. The strong east-west salinity gradient can be seen in Figure 10, with centre pivot irrigation occurring with salinities below 3,000 mg/L, and flood irrigation using higher salinities.

The flight details of the geophysics are similar in detail to that in the eastern study site. Those frequencies most sensitive to shallow depths should be responsive to groundwater salinity, although it should be noted that other factors will affect the signal.

Results from the AEM survey are shown in Figure 11, and show a very good correlation with the previously observed salinity patterns, particularly in the areas of shallow watertable associated with salinised land to the west. To the southeast, the “hot spot” beneath flood irrigation also appears to have been detected by the AEM.

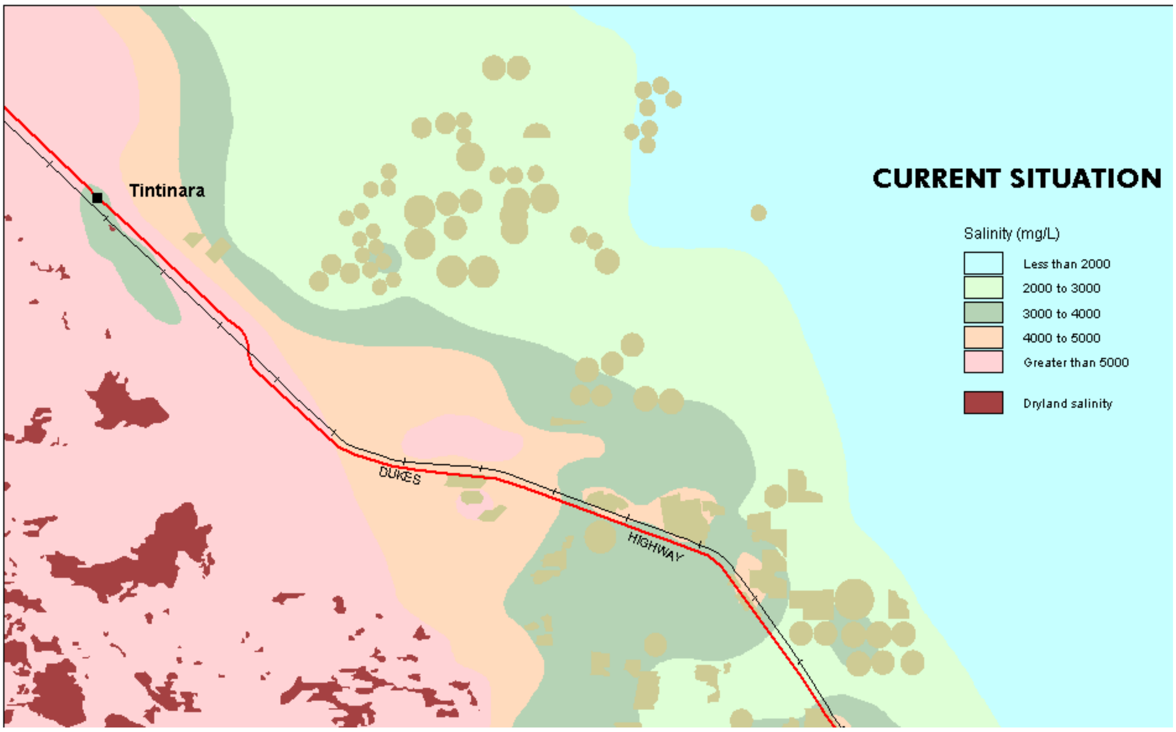


Figure 10. Recent observed distribution of groundwater salinities (limestone aquifer) in the Tintinara region (Barnett, pers. comm.)

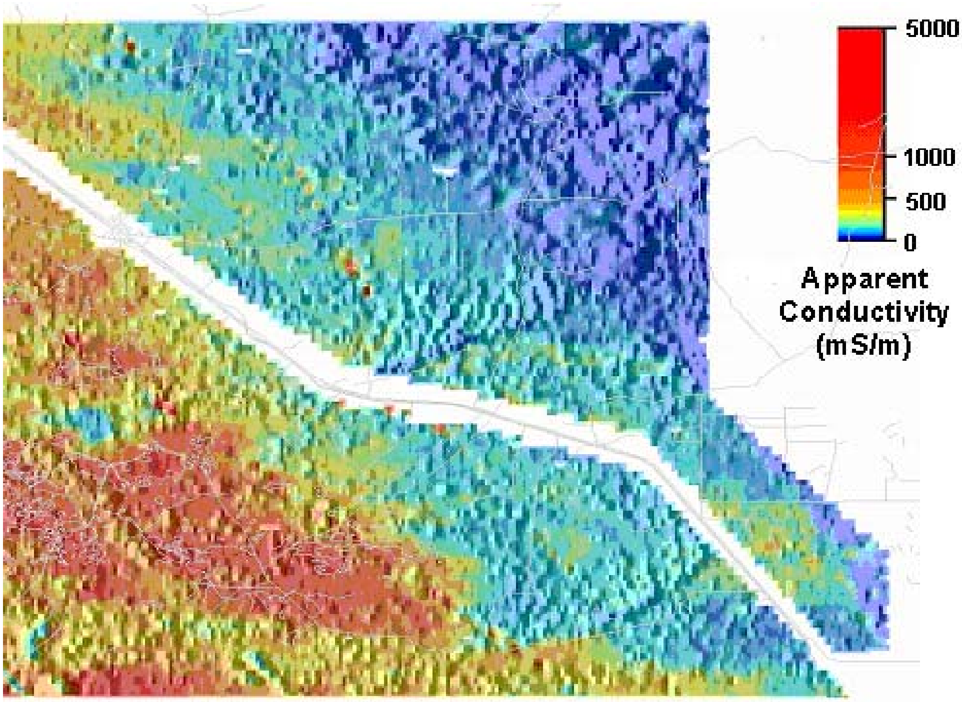


Figure 11. Coastal Plains (Tintinara West) Apparent Conductivity from the near surface, as measured by electromagnetic induction techniques.

5.2 ASSESSING VEGETATION HEALTH RISK

The methodology adopted to determine connections between shallow saline groundwaters and stands of native vegetation at risk is outlined in Table 5.

Table 5. Vegetation health methodology

(i)	8 sites were developed, 3 (T6, T7 and T8) of which were in areas of higher groundwater salinity.
(ii)	At each of these sites were conducted: botanical surveys, visual health assessments, chlorophyll fluorescence assessments of plant stress, soil sampling for salinity and isotopes, leaf ion measurements of salt accumulation within the plant and measurements of groundwater level.
(iii)	The vegetation health at each site was compared with a number of risk factors including depth to groundwater, soil and groundwater salinity. No obvious correlations were found. Different health assessment methods appeared to be contradictory,
(iv)	Native vegetation at risk of salinity were mapped using a combination of shallow water tables and high groundwater salinity.

There were a number of indicators at 3 of the sites that the stands of native vegetation were under stress from rising water tables.

However the monitoring was too short to detect any trends for some types of stress measurements. Surpisingly, there appeared to be little correlation between measured vegetation health and risk factors such as water table depth, groundwater salinity or soil salinity.

The area of remnant vegetation overlying areas of shallow saline water tables was estimated to be currently around 605 ha (Camp, 2003). Predictions were that increasing salinity will impact a further 2 ha in 50 years and an increase of 51 ha on current levels in 100 years. While the spread of salinity is not predicted to be large, rising salinity levels will intensify the stress on already salt affected vegetation. Areas affected and at risk are also low because of the large areas of remnant communities already cleared for agricultural development, and because significant areas already have quite shallow watertables.

The map showing areas of native vegetation superimposed on land currently affected and at risk of salinity is shown in Figure 12.

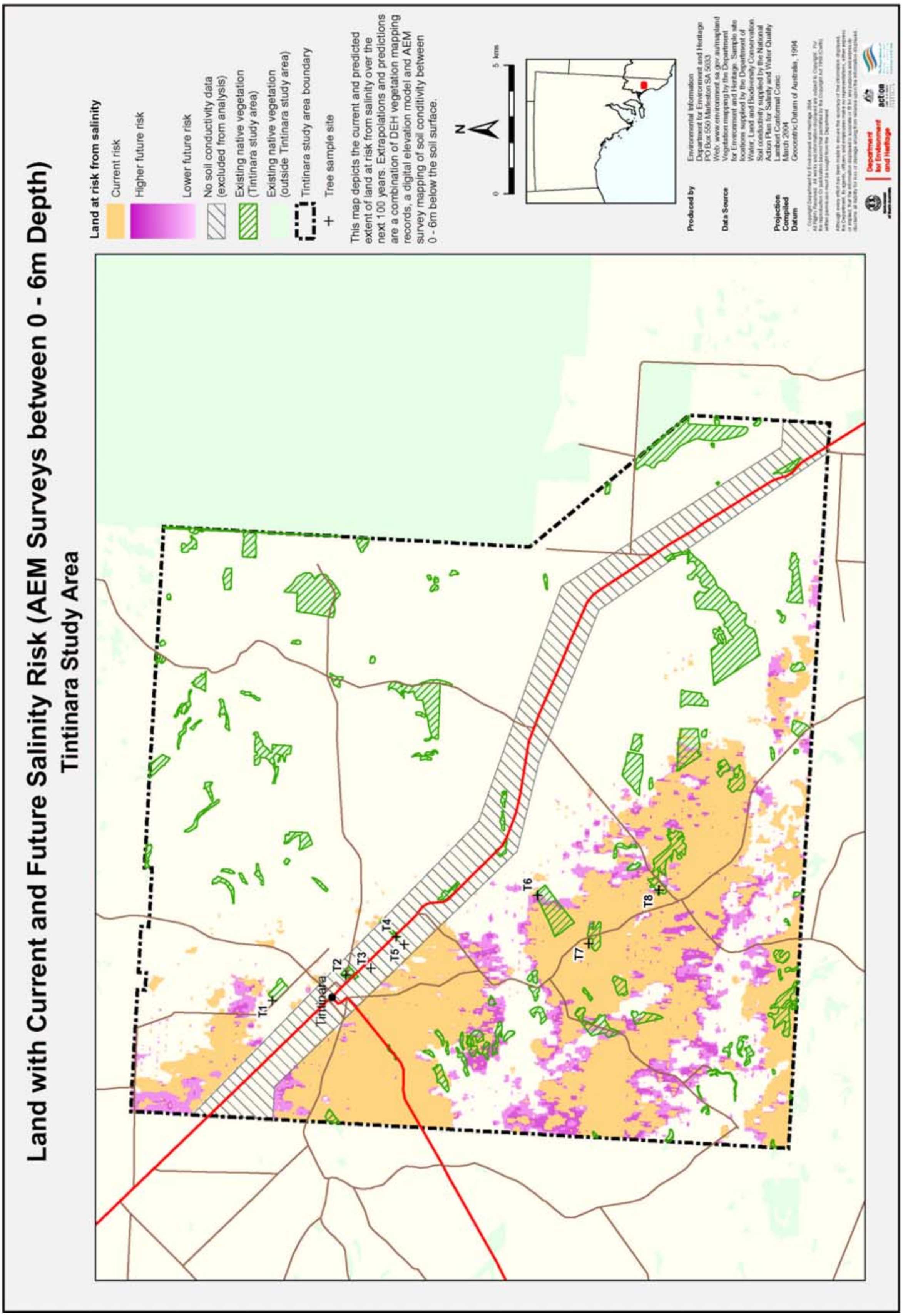


Figure 12. Areas of native vegetation overlain on land currently affected and at future risk of salinity (Camp, 2003).

5.3 DETECTING BASEMENT ROCK

In areas where the unconfined limestone aquifer is saline, the deeper confined aquifer is the only source of stock and domestic supplies. This aquifer wedges out against rising shallow granitic basement to the west of the survey area. Following a request for assistance from a driller who unexpectedly hit shallow granite south of Tintinara, the AEM data was processed to give a 40 – 50 m slice (Figure 13). One of these highly resistive dark blue areas correlates with the abovementioned drill hole and these almost certainly indicate areas of shallow granite.

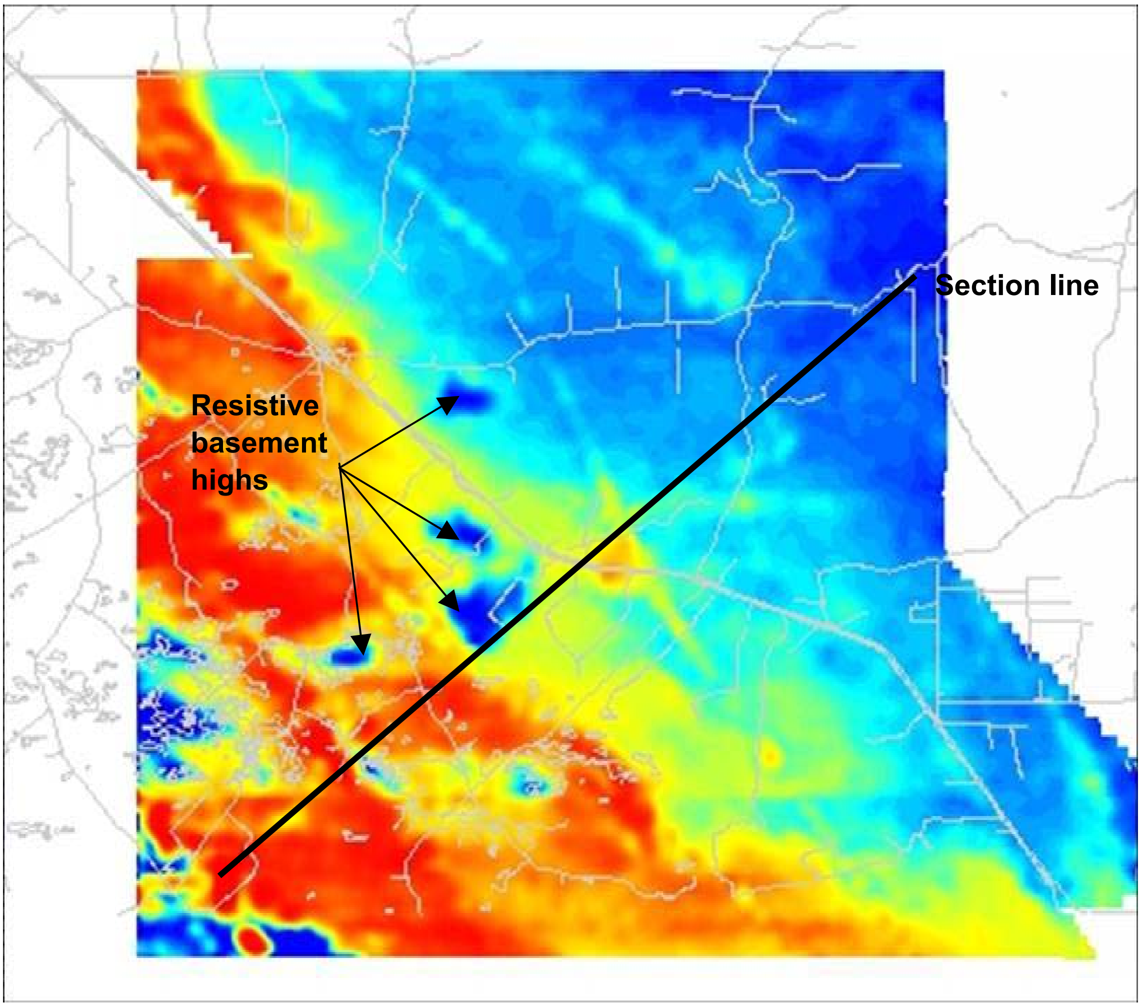


Figure 13. Conductivity depth interval for the depth range 40-50m below the ground surface, indicating areas of shallow granite (resistive basement highs).

The image depicts a conductive (saline) unconfined groundwater system (areas shown in red), with resistive highs representing areas where the underlying Early Palaeozoic granite is present at depth (See Figure 14 below). Deep drilling for groundwater in the confined Tertiary aquifers should avoid these areas.

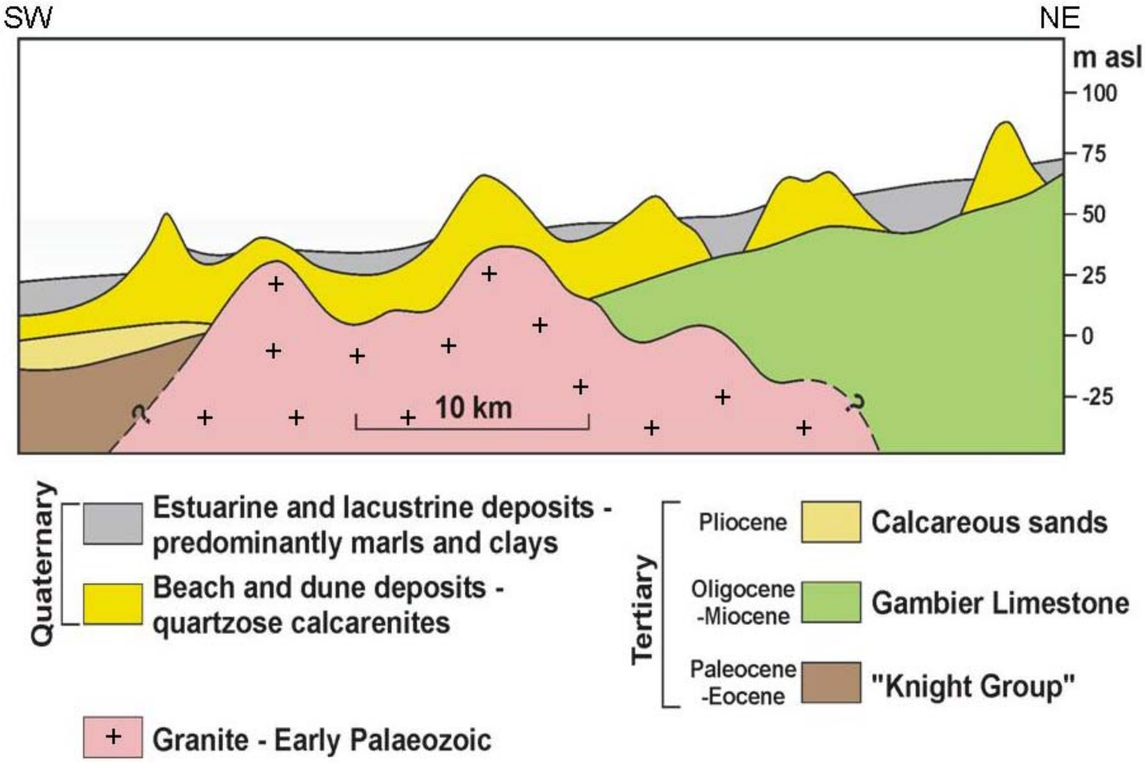


Figure 14. Geological section across the Tintinara West area (see Figure 13), indicating how the basement granitic rocks form basement highs which intrude into the tertiary aquifers.

PART C. DEVELOPMENTS IN MODELLING / DECISION SUPPORT TOOLS

6. *Modelling / Applying the data to decision support tools – Tintinara East*

Information, provided by the helicopter EM survey, on the spatial patterns and thickness of clay rich units across the Tintinara East study area was applied to models used to predict:

- rates of groundwater recharge.
- rates of salinisation of the groundwater resource (Murray Group Limestone aquifer) under dryland and irrigated scenarios.

6.1 PREDICTING SALINISATION PROCESSES UNDER DRYLAND AGRICULTURE

A model was developed within an ARCINFO Geographic Information System (GIS) in order to predict the amount of recharge occurring under dryland agriculture as well as the amount of salt being mobilised to the aquifer. This represents the second contracted output and will be used as input to the groundwater models described later. Some further details of the model are provided in Table 7.

Table 6. Brief description of the Dryland Model

The model consists of a number of components:

1. Estimating deep drainage under dryland agriculture through the following steps:
    a. Using previously developed correlation of deep drainage with surface texture based on previous field measurements to relate point measurements to mapped soil landscape units. Key dataset is correlation. See Leaney et al. (2004).
    b. Developing map of deep drainage using the mapped soil landscape units and spatially averaging over soils in each mapped unit. Key dataset is 1:100, 000 scale DWLBC Soil Landscape Mapping.
2. Recharge maps have been developed using the following methodology:
    a. It is assumed that all deep drainage will eventually become recharge. Key dataset: deep drainage map from component 1.
    b. Change in soil water storage estimated. Key datasets: Soil water database, Clay thicknesses derived from geophysics and DWLBC depth to groundwater map.
    c. Time delays between land use change and impact on water tables at any given point were estimated using the method of Cook et al. (2004) developed within the SA SMMSP. Clearing for agriculture is assumed to have taken place in 1960.

3. Estimating salt flux
    a. Estimation of salt storage: Estimates of soil water storage from step 2.
    b. Salt flux derived from recharge rate (component 2) and soil salinity estimates until entire salt storage has been leached.

The map products, illustrating estimates of spatial variation in deep drainage, salt flux and cumulative salt input, are shown in Figures 15 - 19. For this report, deep drainage is the amount of water percolating below the root zone (assumed to be within 2m of the surface). It is assumed that all of the deep drainage will become recharge - i.e. the amount of water input to the aquifer of interest. However, because of the long time delays between a change of land use (e.g. clearing) and the impact on groundwater, we need to map the recharge at various dates since most of the clearing took place (1950's). The time delays are longer towards the east, where water tables are deeper. On top of this east-west trend, there are local variations due to variability of either the surface or sub-surface soils. The salt load maps do indeed show a trend of slower leaching to the east, on to which is superimposed a NNW pattern related to sub-surface soils and another pattern related to sandy soils.

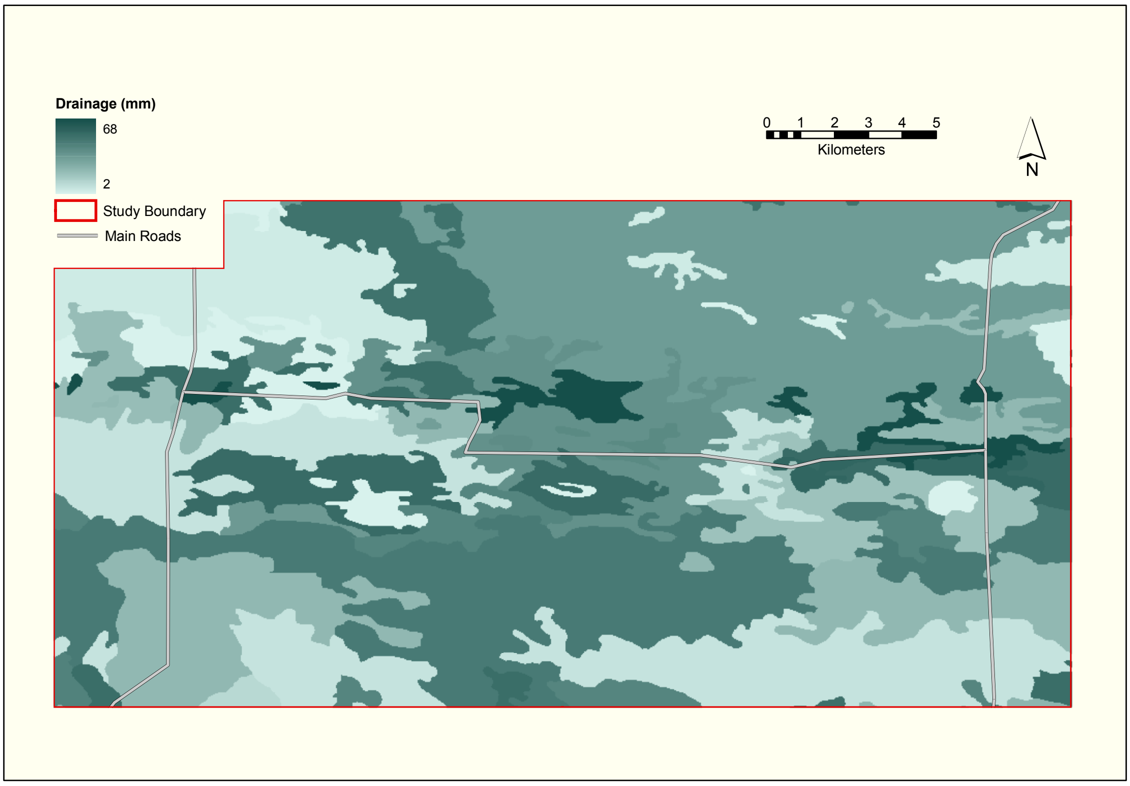


Figure 15. Estimated rates of drainage within the study region, under dryland conditions, based on the % clay content of sub-units of the Soil Landscape Units (SLUs) (Leaney *et al.*, 2004).

Across the region, we have areas, where there is little evidence of salt having been leached in 100 years; while for others, all of the salt has been leached. The map of cumulative salt shows how the total salt leached into the aquifer varies spatially.

Across the region, we have areas, where there is little evidence of salt having been leached in 100 years; while for others, all of the salt has been leached. The map of cumulative salt shows how the total salt leached into the aquifer varies spatially.

There could be significant errors in these predictions if each component is analysed separately. Confidence in the predictions is attained through comparisons with water table levels, groundwater salinity trends across the region and drill logs and as will be observed later matches appear to be good. The degree to which the results are sensitive to the geophysical data can be observed through any NNW patterns in the maps. Any errors, particularly for inferred sandy soils, will change the timing of impacts and the total amount of salt in the profile. The importance of these errors will depend on the decisions made on the basis of early results. This will be discussed in a later section.

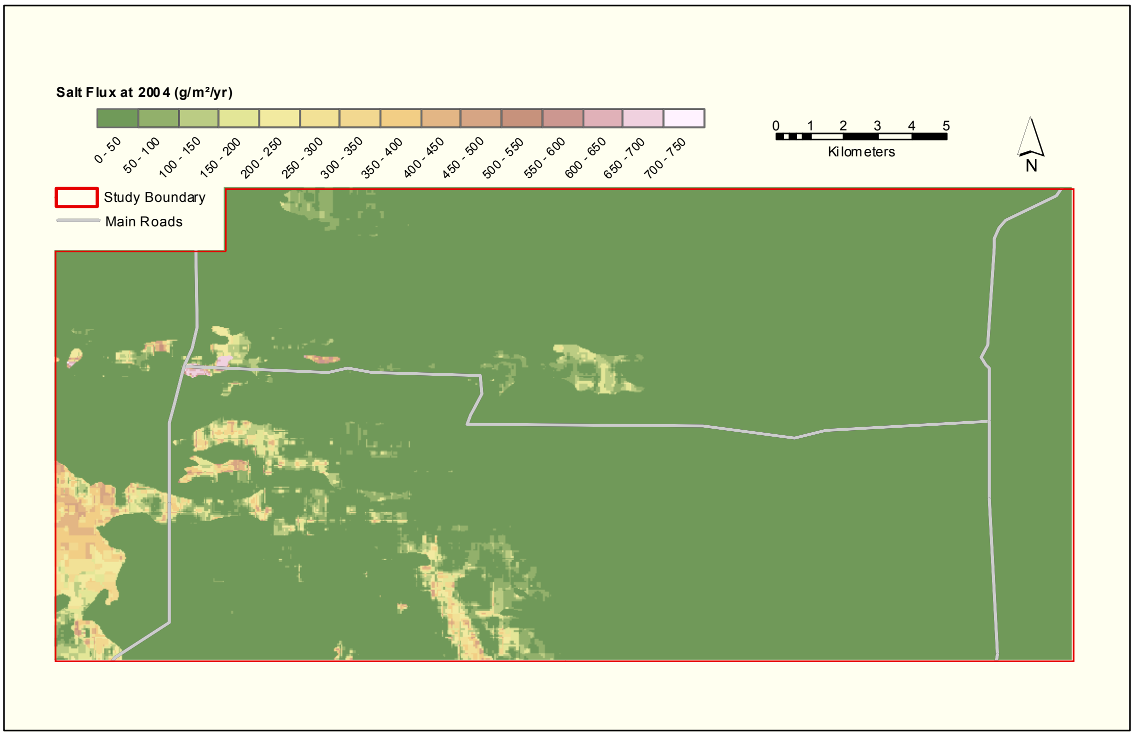


Figure 16. Predicted salt flux for the study area in the year 2004 (44 years after clearing), under dryland conditions (Leaney *et al.*, 2004).

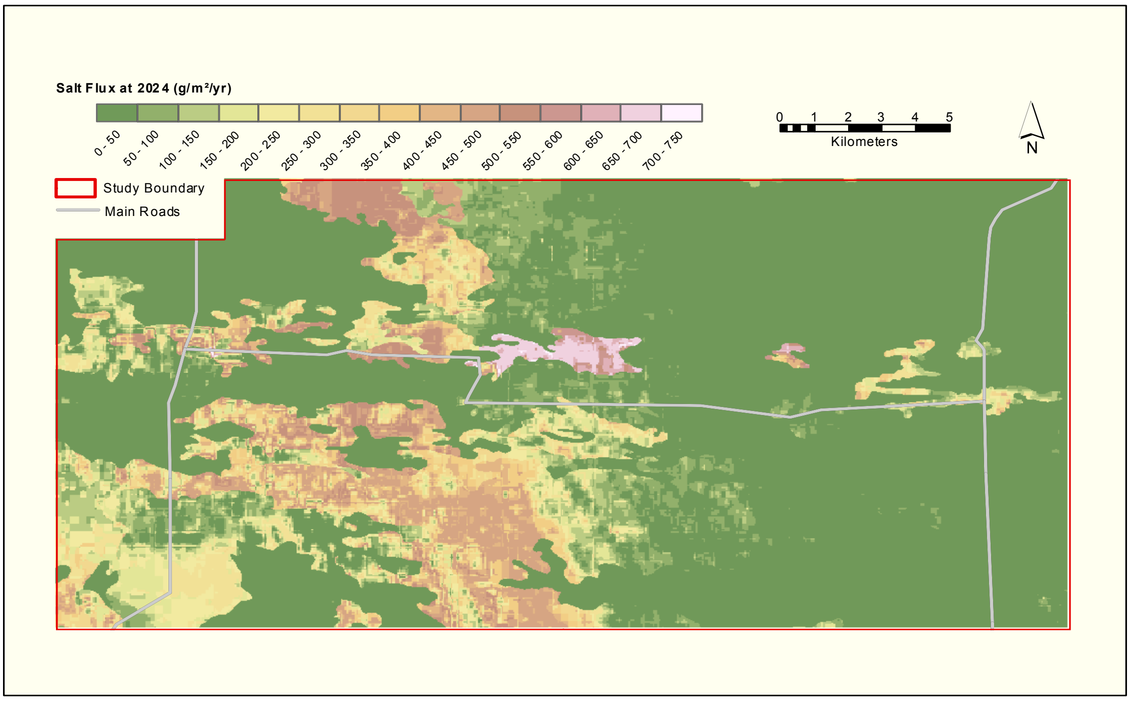


Figure 17. Predicted salt flux for the study area in the year 2024 (64 years after clearing), under dryland conditions (Leaney *et al.*, 2004).

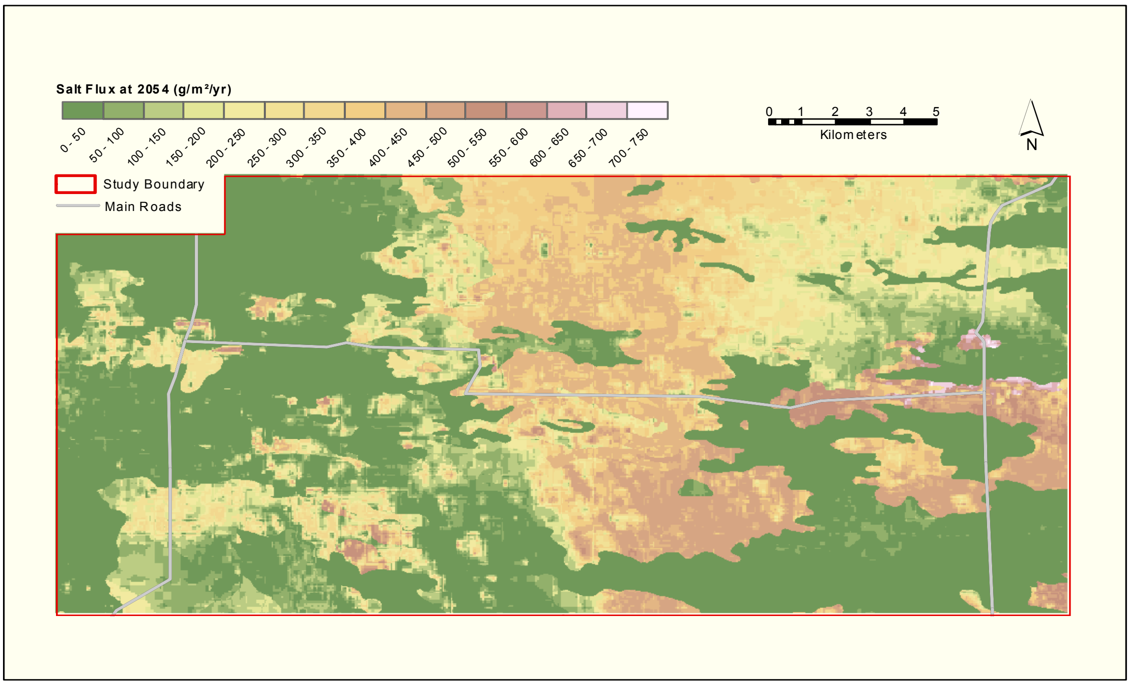


Figure 18. Predicted salt flux for the study area in the year 2054 (94 years after clearing), under dryland condtions (Leaney *et al.*, 2004).

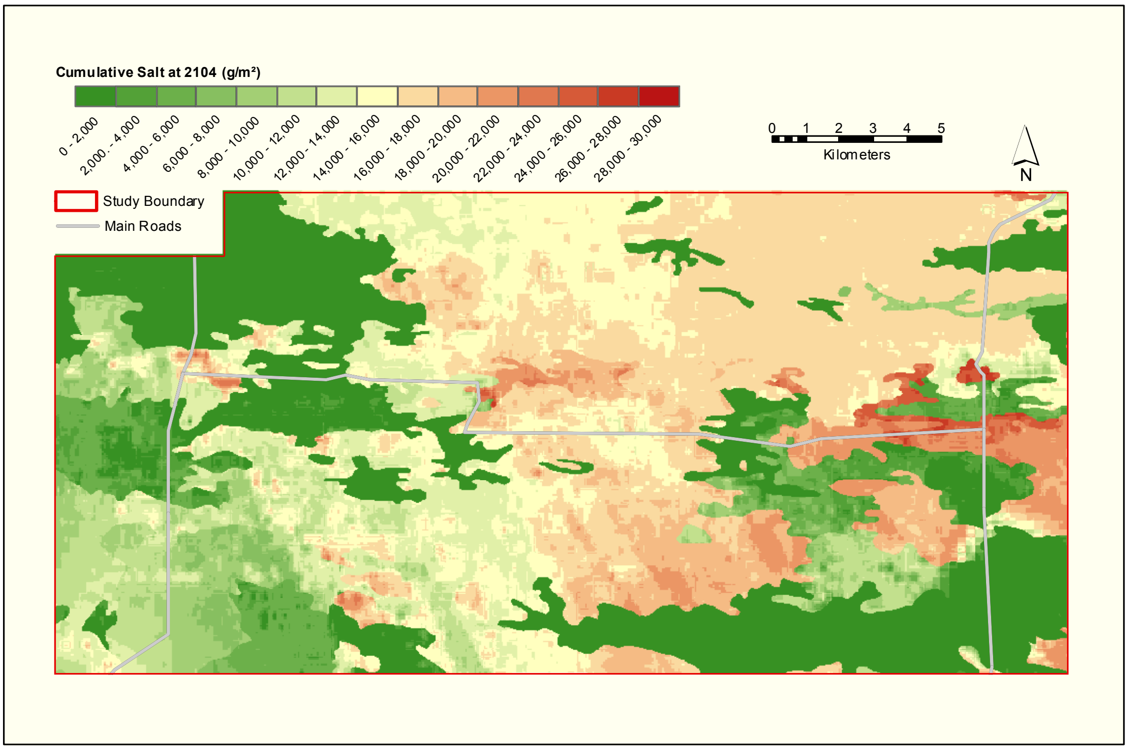


Figure 19. Predicted cumulative salt input for the study area in the year 2104 (144 years after clearing), under dryland conditions (Leaney *et al*., 2004).

6.2 SALINISATION PROCESSES UNDER IRRIGATION

There has been a large increase in the amount of irrigation development in the region. Salinisation processes under irrigation are the same as under dryland farming, except for variation in two significant ways:

- Rates of deep drainage are often much greater and hence processes occur much more quickly.
- Irrigation contains salt from groundwater and this salt begins to recycle back to the groundwater.

At present the area of irrigation is only a small fraction of the total area. However it is unclear what areas will develop into the future, what crops will be irrigated and the style of irrigation management. Hence, a salinity risk approach is used which indicates the likely risk attached if irrigation should immediately develop in any given area. A deep drainage rate of 150 mm/yr is assumed. Because this represents a relatively high estimate, the irrigation maps should be viewed as an upper estimate of impacts should irrigation occur. In interpreting the irrigation maps, one should note the deviation from the dryland predictions. As described above, the dryland process will eventually leach all of the salt. The irrigation quickens these processes and will eventually lead to recycling of salt.

Table 8 contains estimates for drainage in irrigated areas from previous work in the study area (Leaney, 2000 & 2001). Drainage estimates across the range of study sites varies considerably from 7-18 mm/yr at site 1 (2000) and site 2 (1999)) to in excess of 100 mm/yr at the other sites. Clearly, drainage rates in irrigation areas are dependent on many variables. No individual variable stands out from the limited amount of data that is available except that drainage rates tend to be less when the irrigation area has been operated continuously for several years and the surface soils have greater clay content. From this limited data, drip irrigation, at least during the earliest stage of irrigation development, does not necessarily ensure lower drainage than for center pivot irrigation.

Table 7. Drainage estimates, site details and irrigation practice in irrigated areas (from previous studies - Leaney, 2000 & 2001).

Site	Plant	Irrigation	Clay (%)		Years irrigated	Drainage rate
			(0-2 m)	(0-0.5 m)	yrs	mm/yr
1 (2000)	lucerne	CP	28	11	15	7-18
9 (2000)	olives	drip	30	8	1.5	130-420
A (2001)	olives	drip	15	1	3	125-500
C (2001)	lucerne	CP	22	5	2	125-500
1 (1999)	potatoes	CP	23	10	2	210-275
2 (1999)	potatoes	CP	42	47	15	12

[CP =Centre Pivot]

Figures 20 - 22 show estimates, over time, of spatial variation in salt flux and cumulative salt input to the groundwater resource (Murray Group Limestone aquifer) under an assumed irrigation drainage rate of 150 mm/year.

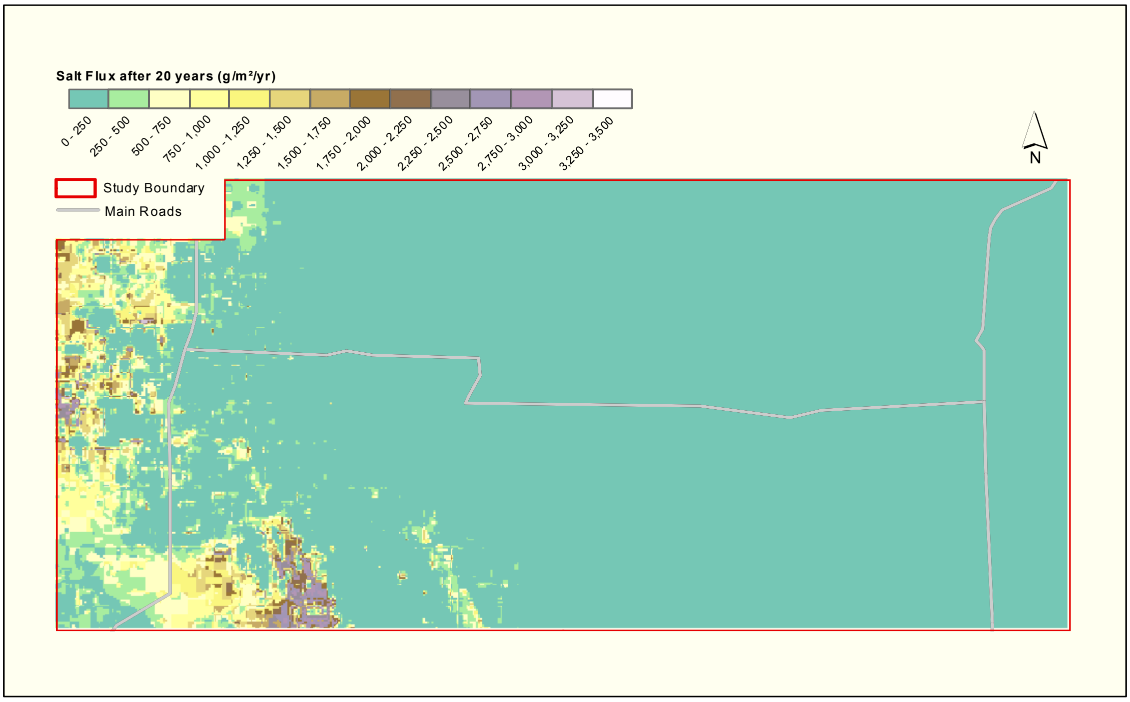


Figure 20. Predicted salt flux to the groundwater for the study area 20 years after the commencement of irrigation. (assuming uniform drainage of 150 mm/yr) (Leaney *et al.*, 2004).

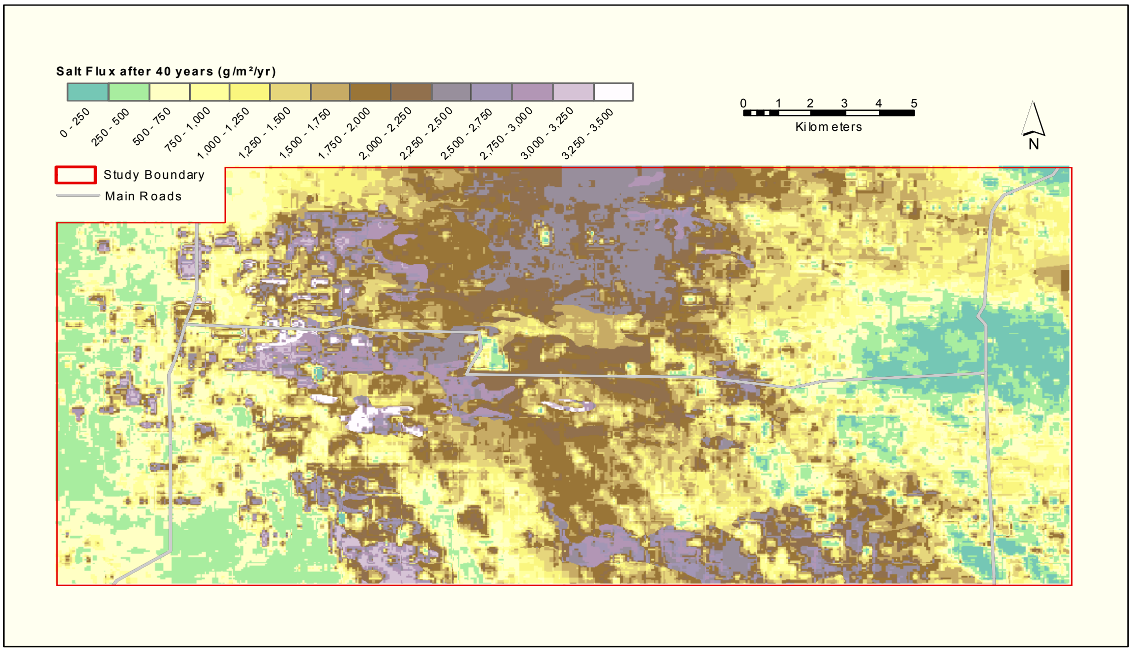


Figure 21. Predicted salt flux to the groundwater for the study area 40 years after the commencement of irrigation (assuming uniform drainage of 150 mm/yr) (Leaney *et al.*, 2004).

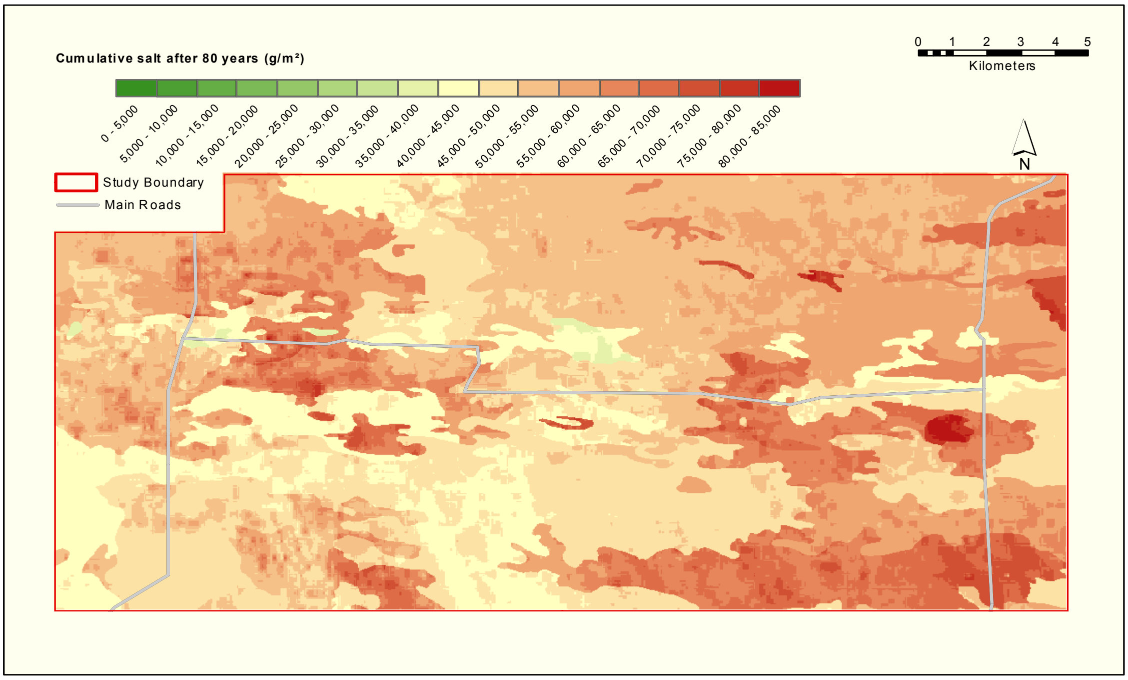


Figure 22. Predicted cumulative salt input for the study 80 years after the commencement of irrigation (assuming uniform drainage of 150 mm/yr) (Leaney *et al.*, 2004).

6.3 MODELLING GROUNDWATER PROCESSES

To make decisions with respect to land use planning and groundwater sustainability, it is important to understand trends in key parameters related to the groundwater resource. These include:

- Salinity of groundwater at different levels within aquifers,
- Directions of groundwater flow, and
- Groundwater levels.

To relate recharge and salt flux to the aquifer, to these key parameters, we need to use 2 types of groundwater models. The first is a traditional groundwater model utilising MODFLOW. This simulates the impact of recharge and groundwater extraction on water levels and groundwater direction. The second is a groundwater salinity model, which determines the trends in water quality. These are described in more detail in Table 9.

The calibration process provides a comparison between long-term groundwater level and salinity data. An example is shown in Figure 24. Part of this good fit can be attributed to the calibration process. The models also undergo a 'validation' process for the years 1997-2004, during which irrigation development occurred. However, the short duration of this period only tested some aspects of the model since there was insufficient time for some processes to occur.

Table 8. Brief details of groundwater models

Groundwater balance model

(i) A MODFLOW model was developed for the region, using the above recharge rates and compiled groundwater extraction rates. The model was initially calibrated under steady-state conditions for pre-clearing recharge (prior to 1960). The groundwater system was conceptualised as 5 layers (Pliocene Sands, Bookpurnong Beds, Murray Group, Ettrick Formation and Renmark Group). It covered a larger area than the study area so a broader range of groundwater issues than salinisation could be considered.

(ii) The model was then calibrated under transient conditions, using post-clearing recharge rates and records from 21 observation wells. This enabled the model to simulate groundwater responses to extraction and increased recharge resulting from land clearance. Good matches were found with observed data with reasonable calibration parameters.

(iii) The model was 'validated' during the 1997-2004. Groundwater extractions for the study area increased from 120ML in 1990/91 to 5135 ML in 2000/01.

(iv) The model was run.

Groundwater salinity model

(v) An MT3D salinity model was developed for the region using the outputs from MODFLOW. The model was validated for the 1997-2004 period and then a prediction scenario was run over the next 50 years for a comparison between dryland and current irrigation.

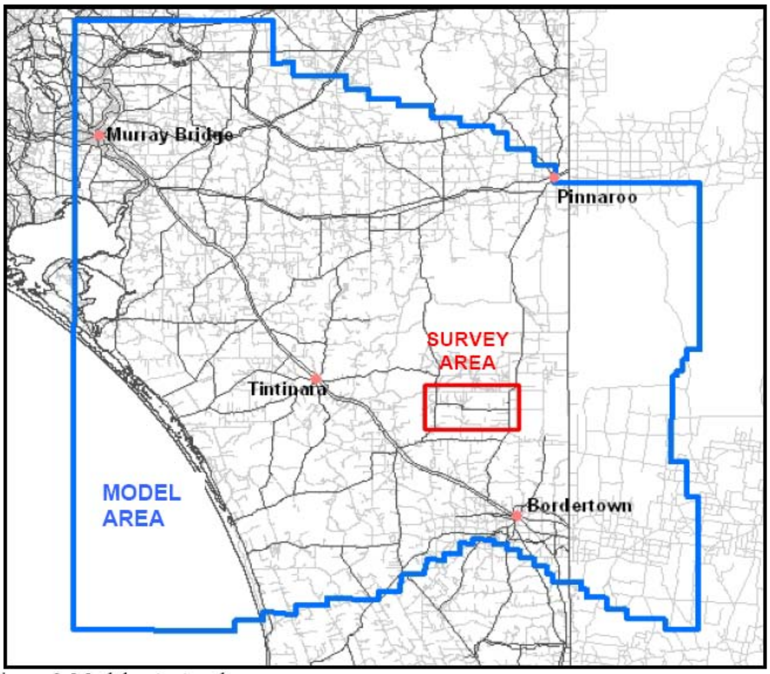
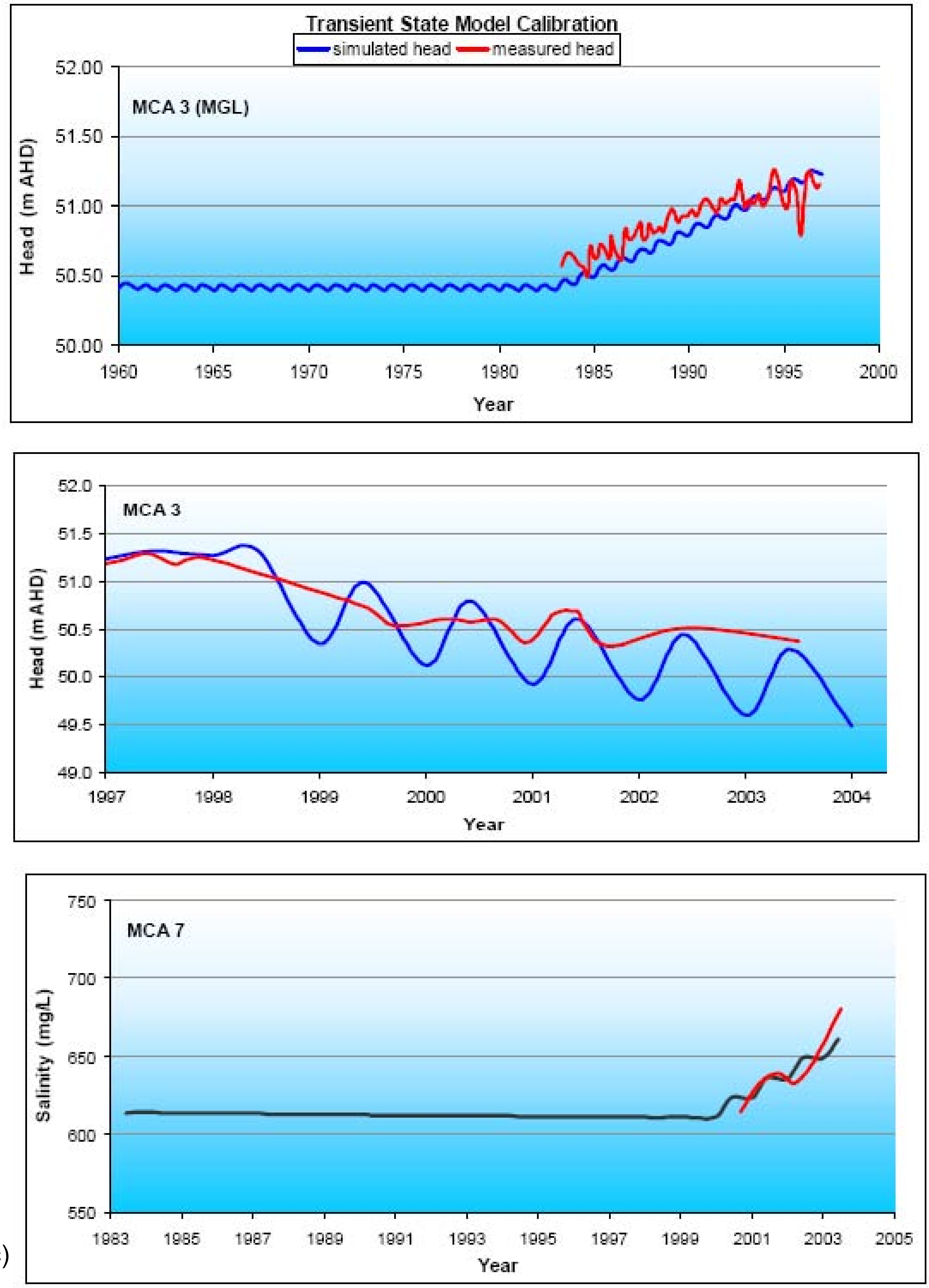


Figure 23. Model extent and survey area (Osei-Bonsu *et al*., 2004).



(a)

(b)

(c)

Figure 24. Example data for calibration and validation of groundwater models: (a) shows calibration against piezometric head; (b) is a validation test for the year 1997-2004, using the same parameters obtained from the calibration period. (c) is the modelled change in groundwater salinity. (Osei-Bonsu *et al*., 2004)

6.4 GROUNDWATER SALINITY PREDICTIONS – NO IRRIGATION

Figure 25 shows the predicted trends in groundwater salinity in the Murray Group Limestone aquifer, for a number of observation wells in the area, in response to salt flux from non-irrigated (dryland) areas. The location of these bores is shown in Figure 27.

Figure 26 shows the modelled spatial salinity patterns for 2004.

Figure 27 shows the spatial changes in 50 and 100 years time. As can be seen, the groundwater will change the status of beneficial use in many areas, i.e. from good quality irrigation water to marginal irrigation water quality to stock and domestic water. The impact in the next 50 years will only be felt in the western part of the study area, whereas the impact is more widespread in 50-100 years.

These increases in groundwater salinity will result in unsuitability for new vegetable irrigation (in areas not previously irrigated), in about 50 years time. Significant areas will not have groundwater suitable for domestic consumption in about 80 years, while lucerne irrigation in new areas and stock supplies will be able to be maintained indefinitely (Osei-Bonsu *et al*., 2004).

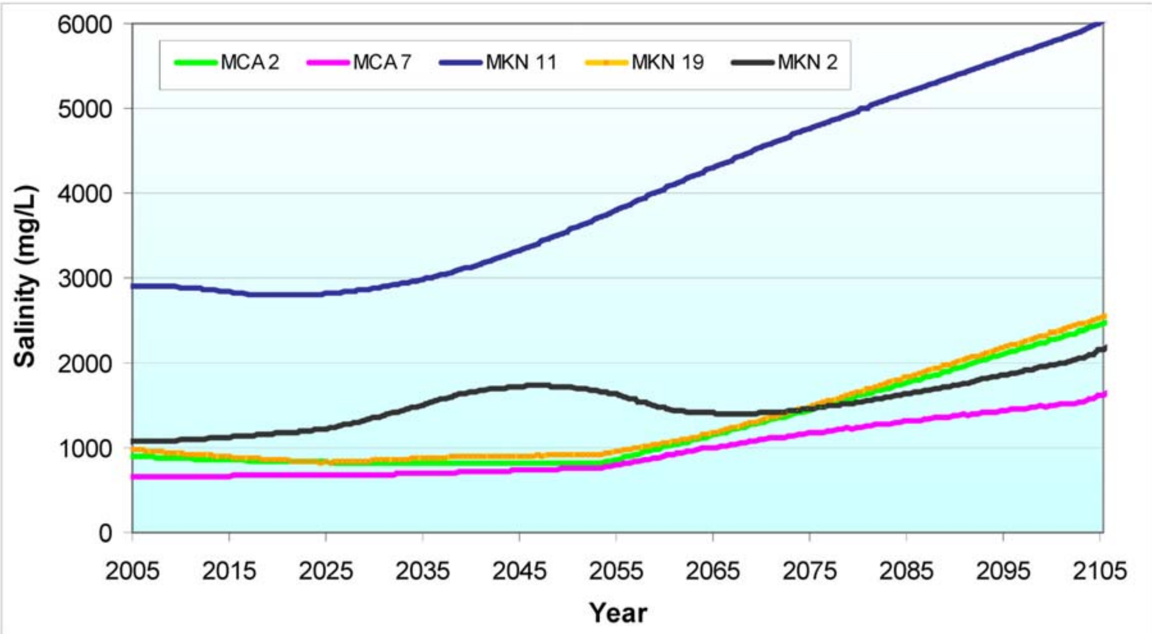


Figure 25. Predicted groundwater salinity trends for a number of observation bores under dryland conditions (no irrigation) (Osei-Bonsu *et al*., 2004).

Figure 26. Modelled spatial salinity patterns in the MGL aquifer in 2004. (Osei-Bonsu, pers comm.)

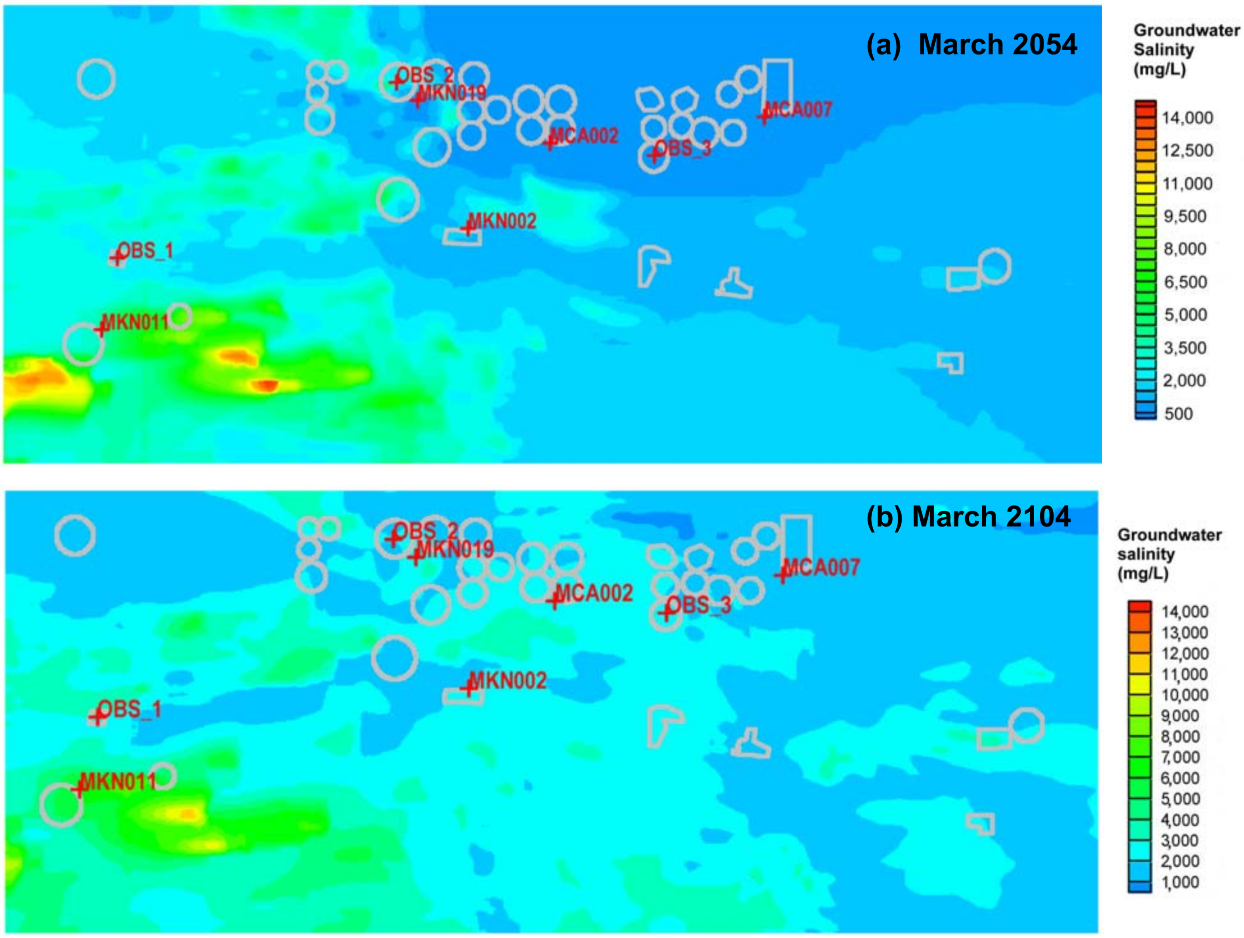


Figure 27. Modelled predictions for groundwater salinity in the MGL aquifer, under dryland conditions, in (a) 2054, and (b) 2104. The location of the survey area (displayed here) is shown in Figure 23. (Osei-Bonsu, pers. comm.)

6.5 GROUNDWATER SALINITY PREDICTIONS – WITH IRRIGATION

The impact of potential irrigation activities on groundwater salinisation has also been modelled. Estimated groundwater extraction rates since 1990 for the modelled area are shown in Figure 28. The MGL aquifer provides about 88.5% of the total usage. Within the smaller (airborne geophysics) study area estimated extractions increased from 120ML to 5135ML over the same period (Osei-Bonsu *et al.*, 2004). These figures indicate the rising trend in groundwater usage.

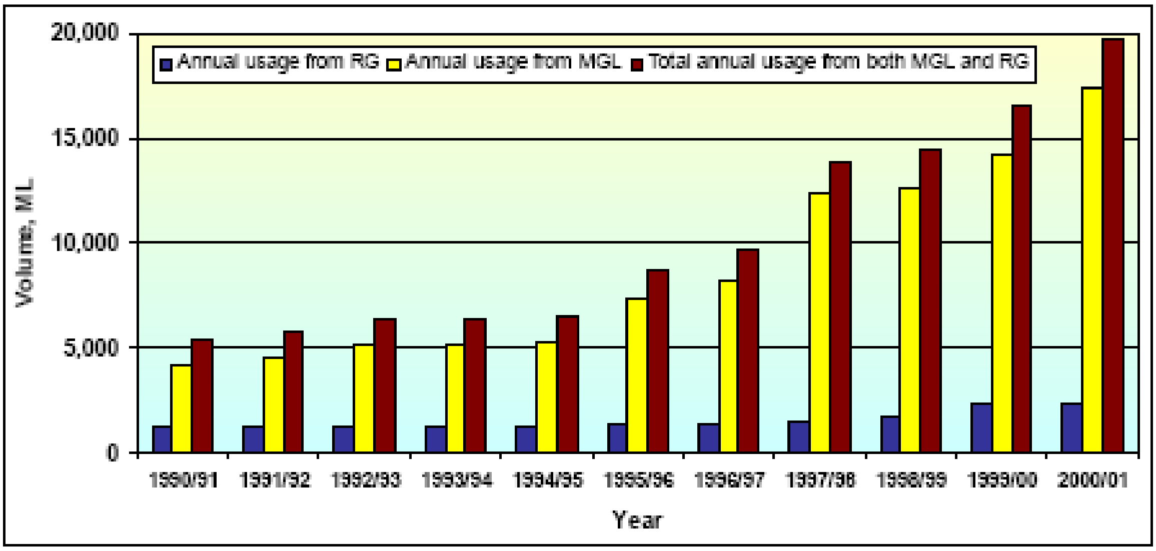


Figure 28. Estimated groundwater extraction rates assumed for the irrigation scenario. [RG = Renmark Group; MGL = Murray Group Limestone.] (Osei-Bonsu *et al.*, 2004).

New salt leaching figures were generated for the groundwater salinity model based on a spatially variable rate for irrigation drainage (where irrigation drainage was chosen to be 5 times that of clearing induced drainage). This was done to give greater account of the influence of variation in soil texture on drainage rates and provide continuity between leaching under dryland farming and the introduction of irrigated agriculture.

Figure 29 indicates the predicted spatial changes to groundwater salinity under irrigation, in 50 and 100 years time. The green and yellow zones in this figure correspond to areas of high recharge and sandy soils where salinities beneath irrigated areas have reached over 5000 mg/L by 2050. However this is only a modelled output as, in reality, irrigation would have stopped as soon as salinities exceeded 3000 mg/L.

The movement of plumes of salinised groundwater in a westerly downgradient direction from beneath irrigated areas (moving a maximum of about 500m after 50 years) can also be seen in Figure 29. The direction of groundwater movement may be modified by pumping in some areas. This model may be used to refine the buffer distances currently enforced between new and existing irrigation (Osei-Bonsu *et al.*, 2004).

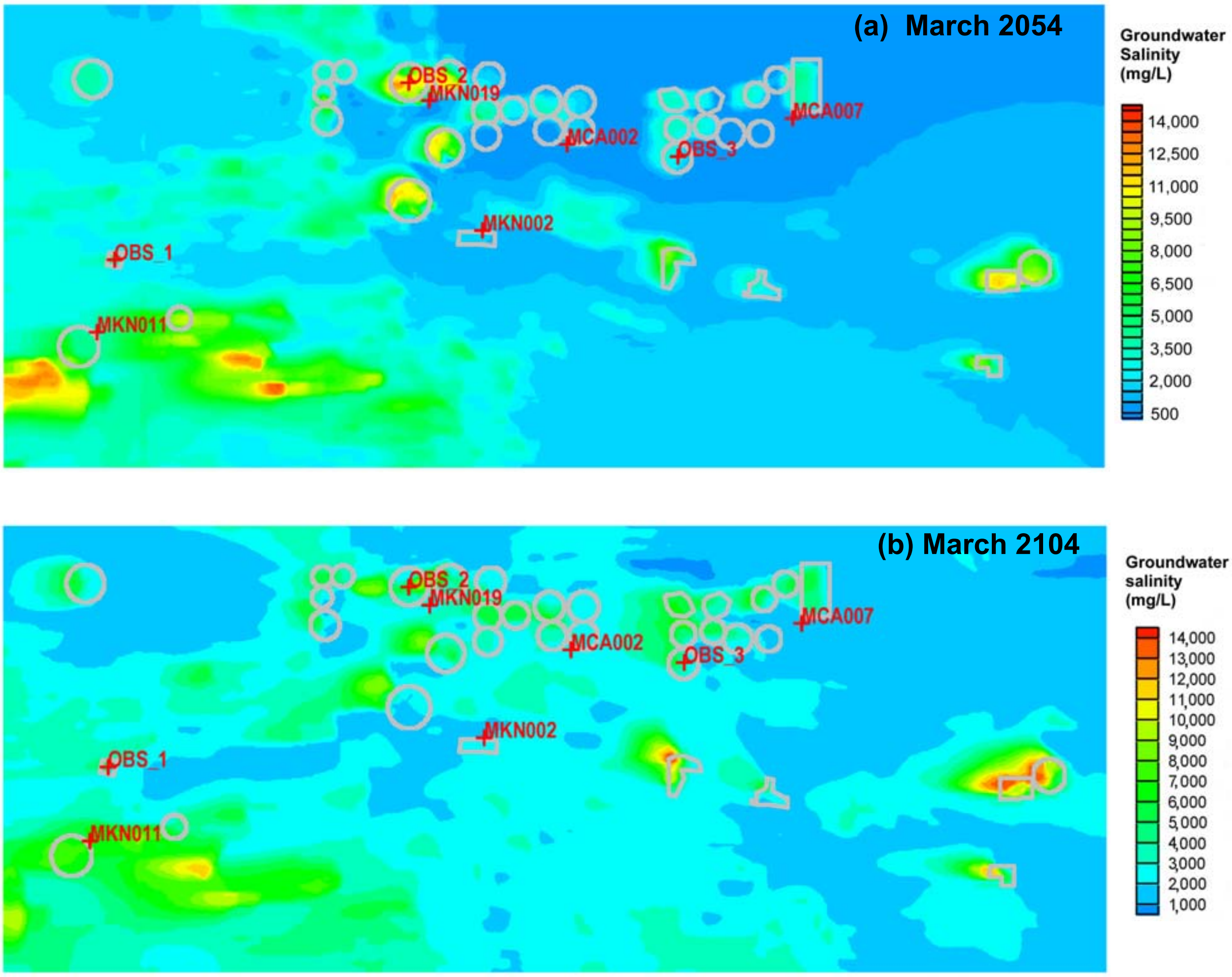


Figure 29. Predicted spatial variability in groundwater salinity in the MGL aquifer in (a) 2054, and (b) 2104, in response to salt flux under uniform irrigation (Osei-Bonsu, pers. comm.).

In addition, some different irrigation scenarios were modelled at selected sites to help understand the potential changes in groundwater salinity over time, directly under irrigation developments. Three sites were chosen, each coinciding with the centre of a selected existing irrigation plot (locations are shown in Figure 27, 29):

- OBS_1 – This site takes into account impacts since the beginning of irrigation in the area (irrigation started in 1993 at OBS_1). Here summer irrigation is carried out every year.
- OBS_2 – Summer irrigation is carried out every year, having commenced in 1999.
- OBS_3 – Summer irrigation is carried out every 4 years, having commenced in 1998.

Modelling results at the 3 observation points (OBS_1, OBS_2 and OBS_3) allow a comparison of predicted salinity trends under alternative irrigated and dryland conditions. Figures 30-32 show simulated changes in salinity with time, in the MGL aquifer, at the three monitoring sites. Differences in groundwater salinity under summer irrigation and in the absence of summer irrigation are substantial at all sites.

Without irrigation there is no net change in groundwater salinity at OBS_1 in 100 years. Salinity falls from about 2900 mg/L (in year 2004) to about 2400 mg/L (in year 2054) before rising to about 2900 mg/L (in year 2104). Irrigation over a period of 100 years would lead to a net increase of groundwater salinity from 2900 mg/L in year 2004 to about 3700 mg/L in year 2104.

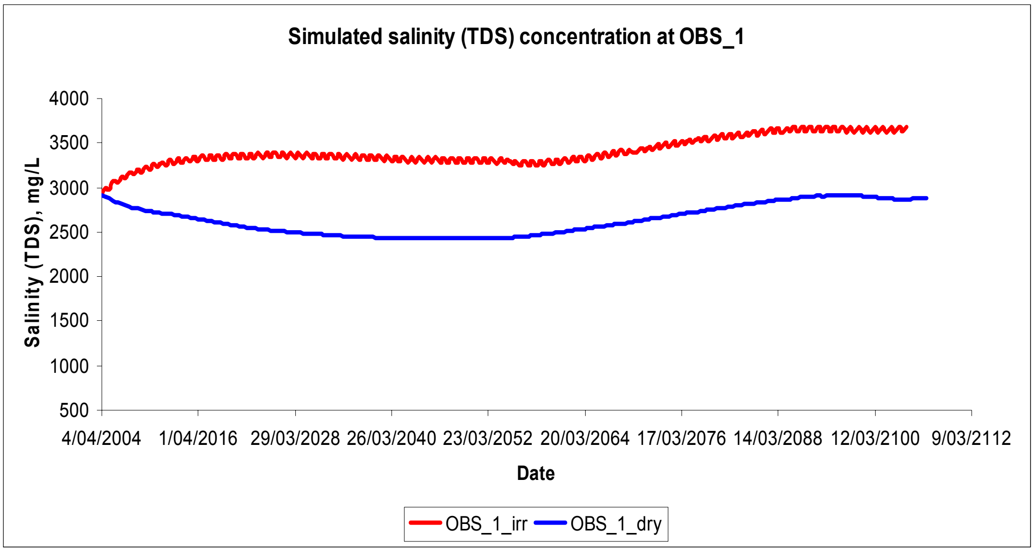


Figure 30. Simulated groundwater salinity in the MGL aquifer at OBS_1 for dryland and irrigated agriculture (summer irrigation applied every year) (Osei-Bonsu, pers. comm.).

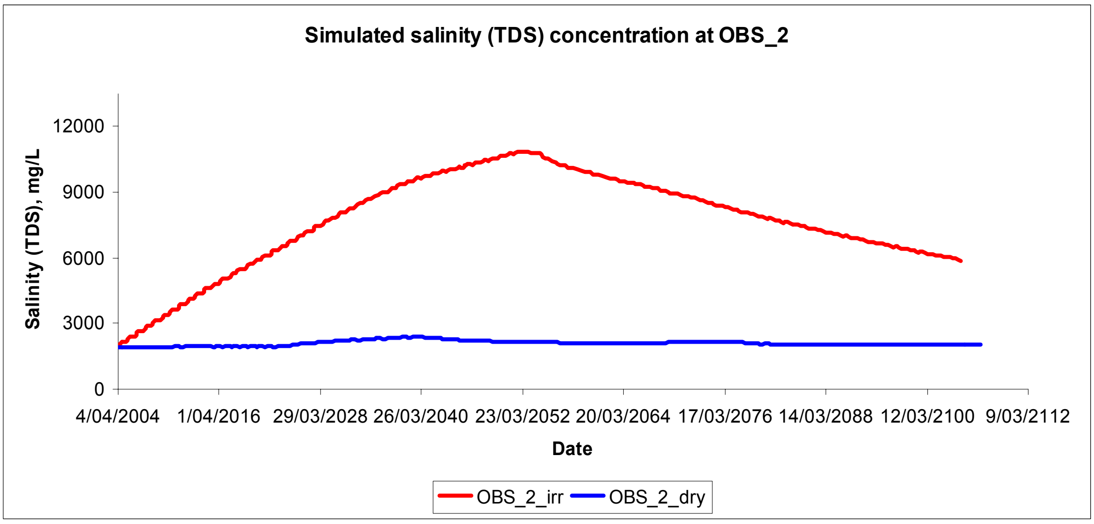


Figure 31. Simulated groundwater salinity in the MGL aquifer at OBS_2 for dryland and irrigated agriculture (summer irrigation applied every year) (Osei-Bonsu, pers. comm.).

For OBS_2, without irrigation, salinity would increase only slightly from about 1900 mg/L to 2000 mg/L over 100 years. With irrigation, groundwater salinity would increase from 1900 mg/L in 2004, peaking at about 11,000 mg/L (in 2051) before dropping down to about 5900 mg/L in 2104. At the peak in salinity this groundwater becomes unsuitable for use as a stock and domestic supply.

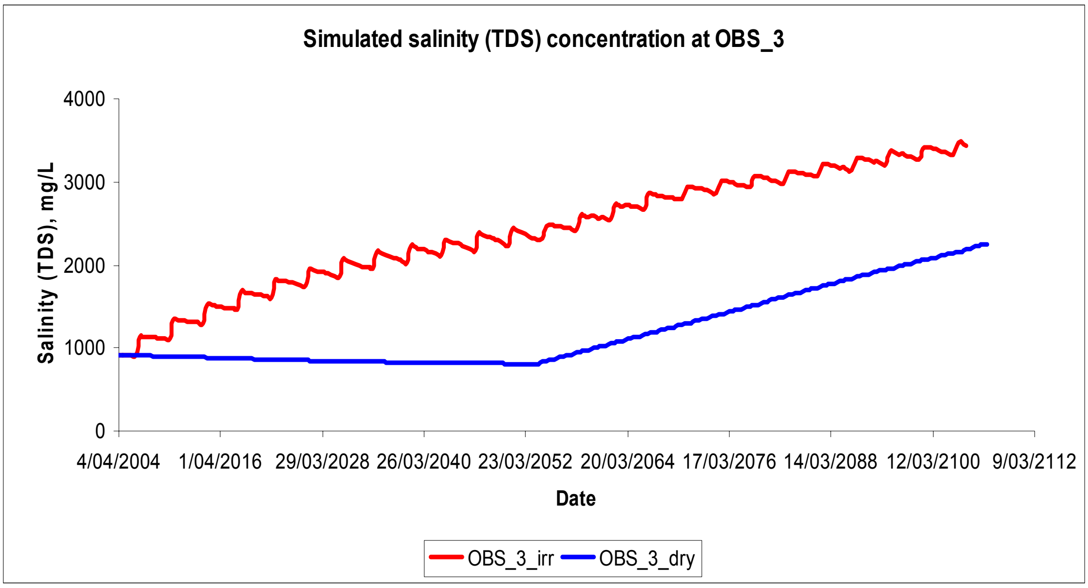


Figure 32. Simulated groundwater salinity in the MGL aquifer at OBS_3 for dryland and irrigated agriculture (summer irrigation applied every 4 years) (Osei-Bonsu, pers. comm.).

At OBS_3, from a groundwater salinity of 900 mg/L in 2004, without irrigation this is expected to rise to about 2200 mg/L in 100 years. With irrigation, groundwater salinity is predicted to rise from 900 mg/L to about 3400 mg/L in 100 years.

The results indicate that the effect of irrigation is to change the salinity of the groundwater to the extent that it may change its use for irrigation. This impact occurs over the next 25 to 40 years.

Existing observation wells are not able to detect the impacts directly beneath irrigation sites, however should the modelled sites (OBS_1, OBS_2 and OBS_3) be replaced with actual observation wells, these can be used to validate the model predictions in the future.

PART D. IMPLICATIONS FOR MANAGEMENT

7. *Transferability of the Techniques and Results*

The type of groundwater salinisation occurring in this region is somewhat unusual, although unlikely to be unique. The combination of a fresh groundwater resource overlain by saline soil water will occur elsewhere, but it is unlikely that the results will be directly transferable to such areas.

The techniques used here to detect sub-surface clay have been used in the Riverland and could be used elsewhere, where water tables are deep, there is sufficient contrast between the clay and other soils, the noise from soil salinity contrasts are not such to confound the signal from the clays. It is *imperative* that on-ground work is done before using air-borne surveys to 'prove' that the target will be detected. The modelling work done for the Riverland site showed the efficacy of fixed frequency devices for detecting shallow targets.

Geophysical techniques should be suitable for detecting groundwater salinity contrasts for areas where salinity patterns may be complex, provided the signal from these contrasts is greater than the noise from regolith variability. For regional groundwater systems, which tend to have a pan-cake structure, the spatial variability of the geological structure tends to be less significant than elsewhere. Nonetheless, the salinity contrasts still need to be large to overwhelm the variability of materials.

The application of geophysics focussed on an asset at risk rather than the aquifer as a whole. We see this generally applying to regional sedimentary systems. The pancake structure of regional sedimentary systems means that a drilling program will pick up many of the features of a regional aquifer, but may miss out on local variability. Despite the high costs of flying, the importance of groundwater management in areas of high resource value will increase the likelihood of geophysics significantly adding value to decision-making through detection of local variations in geological structure and water salinity.

8. *Lessons Learnt*

The objectives of this study have been achieved. An additional objective related to the resistive basement on the Coastal Plain was achieved in response to an enquiry.

Selection of sites for the vegetation health was the only logistical difficulty. The short timeframe of the project meant that monitoring was required to begin before geophysical datalayers were available. Consequently, 5 of the 8 field sites could have been better placed.

For the Tintinara site, we were able to take advantage of the test site and pre-flight modelling in the Riverland. This, together with the previous studies of Cook and Kilty (1992) gave a degree of confidence in the methodology despite no staging.

The modelling had been specifically designed for the issues for the area. The logic of the modelling based on recharge estimates and salt balances enabled the geophysical data to be used directly.

9. Future Work

The models developed are ready for use. Scenarios need to be developed to run with the model. This would lead to a better understanding of the risks associated with various levels of development, siting impacts and inefficient irrigation practices.

The actual planning for more efficient irrigation requires better information on:

1. deep drainage under different management practices and irrigation types in relation to the soil type,
2. soil mapping, and
3. interpretation of shallow geomorphology to show the interrelationships between soils and underlying sediments.

Radiometrics may be able to provide better information on soils at reasonable cost. The cost per length of flightpath is about an order of magnitude cheaper than electromagnetic induction techniques. The strength of the signal will be related to the chemistry, and hence clay content, of the surface soils.

10. Conclusions

1) A map of sub-surface clays has been produced for the eastern site, which reliably shows areas of varying clay thickness. The spatial pattern of clays matches the expectation from an understanding of the landscape history.
2) This information has been used to provide estimates of salt fluxes to the underlying aquifer under both dryland and irrigated agriculture over the next 200 years. Under dryland agriculture, the leaching of salt takes 50 to 200 years with quicker times in the more shallow water table areas to the west. The leaching under the assumed irrigated agriculture takes 20 to 50 years again with the same pattern. Superimposed on the east-west water table trend is a linear pattern running NNW associated with the clays.
3) This data has been used as input to groundwater models. The salinity of groundwater is expected to increase under current irrigation by 1000-6000 mg/L over the next 25-40 years. This is sufficient to make some groundwater unsuitable for irrigation and in some cases, for stock and domestic water supply.
4) The spatial patterns of groundwater salinity of the western site were reliably mapped. The mapping even indicated areas of increasing groundwater salinity caused by irrigation recycling.
5) The geophysics also showed areas of high basement to the west of the study area. This information will support drilling for scant water resources in this area.
6) There are a number of indications of increasing stress on vegetation in the western study area. The area of native vegetation currently at risk in this area is 605 ha.

11. Recommendations for Management

Tintinara East / Mallee Highland

There are no obvious current economic measures to prevent salinisation processes under dryland conditions. This suggests that there may be a finite lifetime for the groundwater resource. Horticultural development will exacerbate this salinisation process. Thus, there are trade-offs between profitable irrigation and the lifetime of the groundwater resource.

Data suggests that efficient irrigation on appropriate soils may lead to deep drainage rates comparable to that of dryland conditions. Thus, adaptation to more efficient irrigation can lead to a better overall outcome. Modelling results can provide the basis of a more sensible public discussion of these issues.

To better inform management strategies, Osei-Bonsu *et al.* (2004) recommend that modelling of salinity responses to varying irrigation drainage rates be undertaken, to simulate the variation in irrigation efficiencies under different crop types. Also, regular salinity monitoring of all irrigation bores and some dryland stock bores should be continued to assist with the groundwater model calibration and validation.

Tintinara West / Coastal Plains

Monitoring of vegetation sites affected by, and at risk from, salinity should be undertaken (or continued) using mapped shallow groundwater salinity and vegetation (Figure 12, taken from Camp, 2004) as a guide to appropriate future monitoring sites.

Potential salinity impacts from irrigation activities should also be monitored, particularly in salinity ‘hotspots’ as indicated by the AEM survey. Where elevated conductivities in the shallow AEM data coincide with irrigation activities, this suggests the presence of higher groundwater or soil salinity zones (‘hotspots’), which can be confirmed by on-ground investigation.

Drilling for groundwater resources in the western study area should be undertaken in locations which avoid the newly mapped shallow granite basement.

ACKNOWLEDGEMENTS

This report was produced for the Department of Water, Land and Biodiversity Conservation as part of the South Australian Salinity Mapping and Management Support Project funded by the National Action Plan for Salinity and Water Quality. The National Action Plan for Salinity and Water quality is a joint initiative between the Australian, State and Territory Governments.

This report is but one of component of a much larger project looking into the value of airborne geophysical techniques in gathering information to assist with salinity management.

Successful results came from the combined skill base of the assembled multidisciplinary team. Team members came from the following organizations: CSIRO Land and Water, CSIRO Exploration and Mining, Bureau of Rural Sciences, the Cooperative Research Centre for Landscape Environments and Mineral Exploration (CRC LEME), Geoscience Australia, (SA) Department of Water, Land and Biodiversity Conservation (DWLBC), Rural Solutions SA, and consultants.

Valuable local input and insight has resulted in a more meaningful study and special thanks should go to the landholders in the area who gave access to properties, and to the Tintinara-Coonalpyn Water Allocation Planning Committee.

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