



Final Report

On Farm Series | Cotton Research & Development Corporation

Part 1 - Summary Details

CRDC Project Number: **CRC44, CRC50 & CRC59**

Project Title: Understanding the salinity threat in irrigated cotton growing areas of Australia Part IV – Interpretation & Extension

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CRDC Program: On-Farm

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Part 3 – Final Report Guide (due 31 October 2008)

Background

Irrigation is an indispensable technology used to augment agricultural production in semi-arid and arid regions. However, due to poor water management, including unsuitable location of water reservoirs (Figure 1a) and supply channels, water logging, perched water tables (Figure 1b) and secondary soil and water salinisation is often the consequent land degradation. In some irrigated cotton growing areas of northern New South Wales and south east Queensland (Darling Basin), soil and or water salinisation has occurred (e.g. Darling River valley and lower Macquarie valley). However, in other districts there is little or no evidence (e.g. lower Gwydir and Namoi valleys). This is because soil and water salinisation occur as a function of complex interactions between various biophysical or causal factors. This includes;

- a) Agronomy,
- b) Geology,
- c) Hydrology,
- d) Climate, and
- e) Topography.



Figure 1. Water logging and soil salinisation is often the consequent land degradation issue in irrigated areas particularly near a) supply channels, and b) water reservoirs.

In order to determine where soil and water salinisation may arise, information which is related to each biophysical or causal factor (*i.e.* agronomy, geology, *etc.*) needs to be mapped. For example, geological and hydrological components can be represented, respectively, by estimates of salt storage and deep drainage across a given irrigated area. When these independent causal factors are stored in Geographic Information Systems (GIS), the interaction between factors can be related to where salinisation occurs, and therefore determine if and where these conditions may be met elsewhere. This is essentially the basis of Salinity Hazard mapping, where a Salinity Hazard is defined as the extent to which natural physical characteristics, excluding land cover, predispose a landscape to salinisation. However, consistent and repeatable methods of generating biophysical or causal factors is time consuming and expensive. This often makes extrapolation and comparison from area to area difficult. The underlying aim of this project is to use similar methods to generate independent maps of these causal factors, store the information in GIS format and generate Salinity Hazard maps at the district level.

Objectives

The project objectives as stated in the initial application were as follows;

1. On the field-scale deploy Mobile Electromagnetic Sensing System to determine cause and management of soil salinisation in Bourke, Trangie and Warren;
2. On the district-scale:
 - a. Conduct EM34/38 surveys to estimate groundwater recharge rate and identify shallow or deeper saline water tables on the Breeza Plains and Mallowa; and,
 - b. Use existing piezometer network, soil data and MODFLOW, model how saline groundwater interacts with the Darling River near Bourke.
 - c. Assess usefulness of Radiometric data for natural resource management (Namoi).
3. Extend and interpret the results and data from Phase III and IV for improved natural resource management through:
 - a. Development of a Geographic Information System (GIS) of data collected;
 - b. Development of a Webpage to allow extension officers and growers access and the ability to query the data stored on the GIS;
 - c. Publications in international and Australian soil and water related journals;
 - d. Publications in industry journals and periodicals (i.e. Australian Cotton Grower and ACGRA Cotton Conference Proceedings).

Owing to the shortage of CRDC funds, the three Australian Cotton CRC projects CRC40 (2002-2003), CRC50 (2003-2004) and CRC59 (2004-2005) were not fully supported to the extent requested in the initial application. In the last financial year only \$50,000 was made available as part of CRC59. In addition, a major funding stream that was previously available to researchers associated with the series of projects entitled “*Understanding the salinity threat in the irrigated cotton growing areas of Australia – Phases I-III*” was not renewed by the Australian Federal Government. That is, the Natural Heritage Trust that had previously been successfully used to leverage monies via joint funding applications between various community groups and the Australian Cotton CRC (See Question 7a) was discontinued and replaced with the NHT-Envirofund. This program was capped at a maximum project value of \$30,000.

Despite this many funding applications were submitted. This included applications to the Rural Industries Research and Development Corporation, Land and Water Australia and the NHT-Envirofund. Applications were also in preparation for the 2005 call for Australian Research Council Fellowships. In addition, various discussions were held with Government Agencies (e.g. DIPNR – Far-Northwest Region) in order to try and obtain the necessary funds to enable the Objectives outlined above to be carried out. Unfortunately, matching funds could not be attracted until April 2004, when a successful application for funding was made to the Natural Heritage Trusts – National Competitive Component and entitled “Web-GIS development for improved Natural Resource Management in the northern Murray-Darling Basin.

As a result of the short fall in funding and the inability to attract funds early in the project a couple of the objectives stated above could not be pursued. This included, Objective 1 and Objective 2, Parts a and b. Of the remaining objectives which were pursued, this report presents in detail the results achieved in relation to Objective 3. This is the main thrust of the series of the series of projects entitled “*Understanding the salinity threat.*” Objective 2, Part c was a minor aspect of this project with results presented in Appendix 3.

With regard to Objective 3, three major activities needed to be undertaken.

The first is the development of biophysical layers, which characterise various causal salinisation factors. This includes derived maps of:

- Agronomy (*e.g.* land use will be digitized from air photos and Landsat Thematic Mapper images);
- Geology (*e.g.* spatial distribution of salt stores will be developed from EM38 and EM34 signal data and root- and vadose-zone salinity information with clay content and saturated hydraulic conductivity maps derived from EM38 and gamma radiometric signal data and pedotransfer functions);
- Hydrology (*e.g.* maps of deep drainage risk will be generated from interpolation of calibrated EM38 signal data and salt-balance model estimates, and groundwater recharge maps derived from estimates of chloride mass balance modelling calibrated against EM34 signal data);
- Climate (*e.g.* maps of precipitation calculated by BIOCLIM); and,
- Topography (*e.g.* digital elevation model derived from RADARSAT and/or using ANUDEM).

The second major activity will be the incorporation of these biophysical data layers into Geographic Information Systems in several districts. The methodology proposed is equivalent to that outlined in National Resource Standing Committee's Technical Report on "Review of Salinity mapping Methods in the Australian Context."

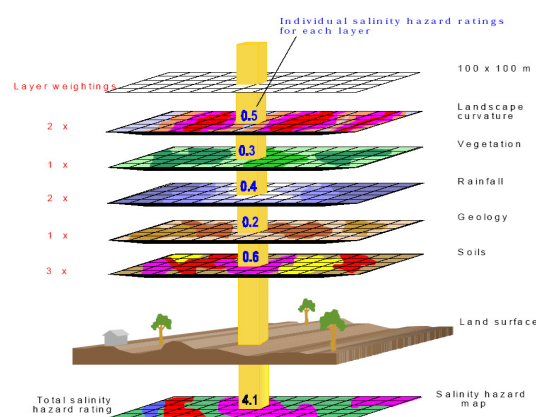


Figure 2a. Illustrative representation of how Composite Salinity Hazard model is applied (Searle and Baillie, 1998).

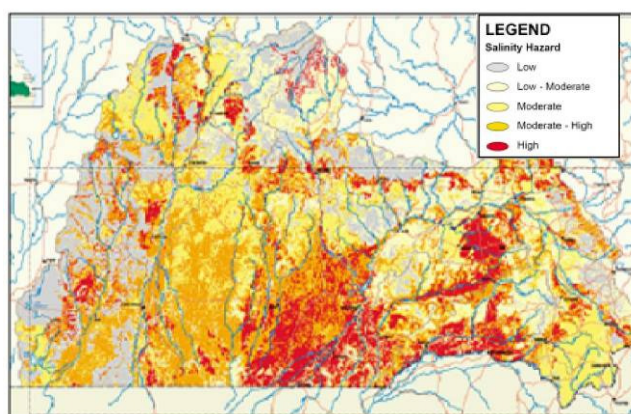


Figure 2b. The Queensland Northern Murray-Darling salinity hazard map (Queensland Department of Natural Resources and Mines, 2002).

The third activity will be GIS development, analysis and interpretation of these biophysical causative layers into for example Salinity Hazard or Risk maps.

Outcomes of the proposed research include:

- Clearly demonstrate how ground-based EM (*i.e.* \$0.50/ha), remotely sensed data and geostatistical methods can be used to develop bio-physical data layers relevant for Salinity Hazard mapping and assessment;
- Store and interpret biophysical data layers in a Geographic Information System (GIS) to identify natural resource management issues in key districts of northern Murray Darling Basin; and,
- Extend this information on the World Wide Web, research manuscripts and plain English extension material.

Methods

In order to prepare a Salinity Hazard map, hazard factors (*i.e.* biophysical features) for each location need to be assessed independently to determine susceptibility of an area to salinisation. Owing to the large amount of data generated and the need to spatially reference the maps produced, Geographic Information System (GIS) is increasingly being used to store the data. The spatially georeferenced information can be queried to assess Salinity Hazard for a given area. In general 5 classes of Salinity Hazard are shown, with classes varying from negligible to very high hazard rating (see Figure 3). In Queensland and New South Wales most layers of information are generated at a scale of 1:250,000. At this spatial resolution, such maps can only provide an indication of the potential Salinity Hazard over a regional area and can really only be used by Catchment Management Boards and at Policy Level to guide;

- a) Identification of priority locations for salinity management and investment,
- b) Underpin Action Plans, and
- c) Planning and funding allocations.

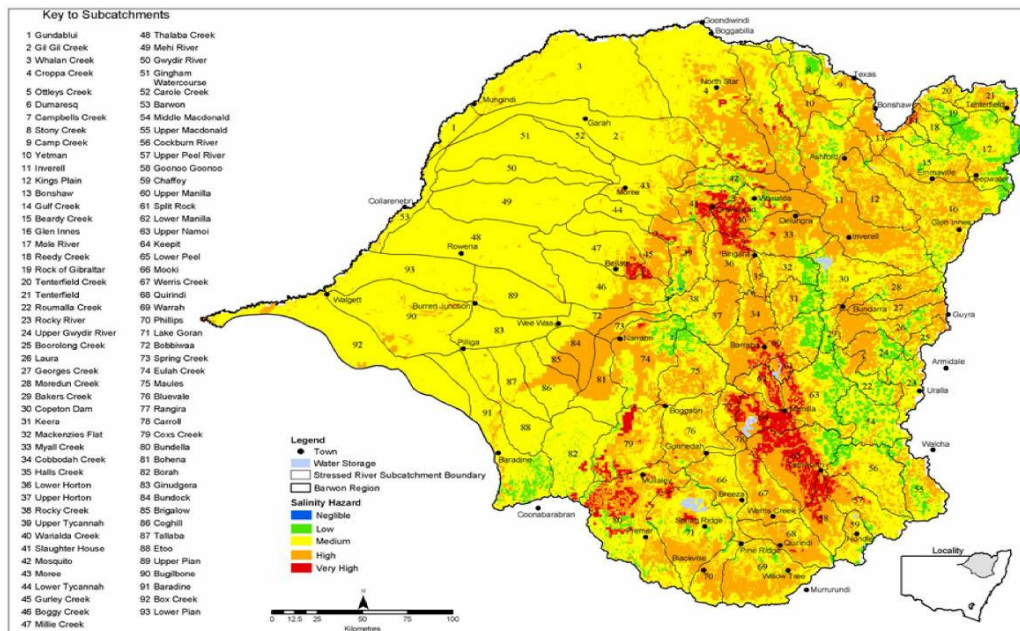


Figure 3. Barwon Salinity Hazard Map developed by the New South Wales Department of Infrastructure Planning and Natural Resources.

In specific irrigated cotton growing districts Salinity Hazard assessment needs to be carried out using a more rigorous assessment of the impact of landscape change (*i.e.* introduction of irrigation and concomitant change in hydrology). It is therefore necessary to obtain more detailed information.

Fortunately, and as part of an Australian Cotton CRC initiative, much of the information required to generate the necessary Salinity Hazard layers has been collected across seven irrigated cotton growing districts and in five valleys of northern New South Wales and southern Queensland. This has been achieved as part of a series of projects entitled “*Understanding the salinity threat in the irrigated cotton growing areas of Australia.*” The data collected includes over 7,500 EM measurement locations taken on approximate 500 m grids across 450,000 ha. To understand what the instruments are responding to, over 300 calibration holes have been drilled and sampled at 1 m intervals. The samples have been analysed for particle size fraction (*i.e.* clay, silt and sand), exchangeable cations (*i.e.* Ca, Mg, Na and K), electrical conductivity of a saturated soil paste extract (EC_e),

soil paste (EC_p), and a 1 part soil to five parts water ($EC_{1:5}$) extract. The chloride content on a mass basis has also been determined (Cl_m). LANDSAT and Radiometric data has also been acquired from Geosciences Australia and the New South Wales Department of Mineral Resources in many of these areas. This will provide complimentary information that can be used to determine and map land use type as well as characterise spatial variation of topsoil attributes.

Hydrological layers

Estimating deep drainage

Water that drains beyond the root zone and passes through the biologically inactive vadose-zone is classified deep drainage. Traditionally, estimates of DD have been based on soil hydraulic properties, whether measured directly or estimated as surrogates of soil morphological properties. Both approaches are difficult, time-consuming and expensive (Gee and Hillel 1988). Another approach is the use of salt/water balance models involving the use of the water balance equation (*i.e.* $DD = \text{Irrigation } (I) + \text{Rainfall } (R) - \text{Evapotranspiration } (ET) + \text{change in soil moisture content } (\Delta S)$). However, the approach requires measurement of many variables and as shown by Devitt *et al.* (1983), it is limited by uncertainties associated with ET . To resolve these problems chloride mass balance modelling can be used to estimate transient DD by comparing chloride profile differences between paired sites from profiles that a) lie in close proximity to each other but are managed differently (*i.e.* irrigation versus remnant vegetation) (Willis and Black 1996), and b) are collected from the same location but at the beginning and end of irrigation seasons (Willis *et al.* 1997).

However, a major problem with the approaches described is that they are site-specific and do not take into account the spatial variability of DD (Allison *et al.* 1994; Slavich and Yang 1990). In addition, they are not amenable to scenario studies where differences in volumes of water application can be evaluated to determine alternative irrigation regimes. An approach that resolves this problem is the application of the Salt and Leaching Fraction - SaLF (Shaw and Thorburn 1985; Shaw 1988) model, which was developed to provide DD estimates from soil databases for various water quantities and qualities. In addition, and combined with geostatistical methods, the SaLF model may overcome the spatial variable nature of DD . But large data sets are required for increased precision. This is particularly true because of the relatively large spatial variation (Odeh *et al.* 1998). Electromagnetic (EM) Induction instruments, such as the EM38, have been used extensively to assist in interpreting the spatial distribution of soil attributes that are related to DD . This includes changes in soil moisture (Hanson *et al.* 1997; Kkakural *et al.* 1998), clay content (Triantafilis *et al.* 2001a), soil mineralogy (Triantafilis *et al.* 2002) and salinity at the field (Lesch *et al.* 1992 and 1995), farm (Triantafilis *et al.* 2000 and 2001b) and district levels (Vaughan *et al.* 1995). This is because EM instruments measure bulk soil electrical conductivity (EC_a), which is related, to these properties (McNeill 1980). More recently EM signal readings have been coupled to estimates of DD to enable field- (Triantafilis *et al.* 2003a) and district-scale (Triantafilis *et al.* 2004) maps of DD risk to be generated. Results from some of these maps are shown in the Ashley irrigated district north of Moree in the lower Gwydir valley. Figures 4a and 5a show the results of DD risk at the district scale associated with the application of 600 mm (irrigation) and 1,800 mm (shallow reservoir) scenarios, respectively. Figure 4b and 5b show equivalent results for an irrigated field (*i.e.* "Auscott" Field 11) in the northern part of the district. In all cases a rainfall of 584 mm was assumed and DD exceeding 50 and 100 mm/annum was mapped for irrigated and shallow reservoir scenarios, respectively. The dark shaded areas indicate where DD risk is highest (*i.e.* Conditional Probability > 0.9). At the

district scale these higher risk areas are synonymous with sandier sediments of prior-stream channels associated with Marshalls Ponds and Carole Creek. Interestingly, anecdotal evidence suggests many of the reservoirs located near these channels lose significant amounts of water through DD. Some of the largest have been decommissioned or are used sparingly and only as short-term storage.

The field-scale maps indicate a narrow band of higher risk located in the southern and central parts of the field. Here again, sandy loams associated with a prior stream channel that has its origins in field to the south, dominate this part of Field 11. In these areas water logging is most evident. The methodology indicates where a more strategic approach may need to be implemented by management when considering options to improve irrigation efficiencies. This is particularly the case along the head ditch and supply channel, which are located on top of the prior stream channel. Here the supply channel might be lined or alternatively sprinkler irrigation systems could be installed and used.

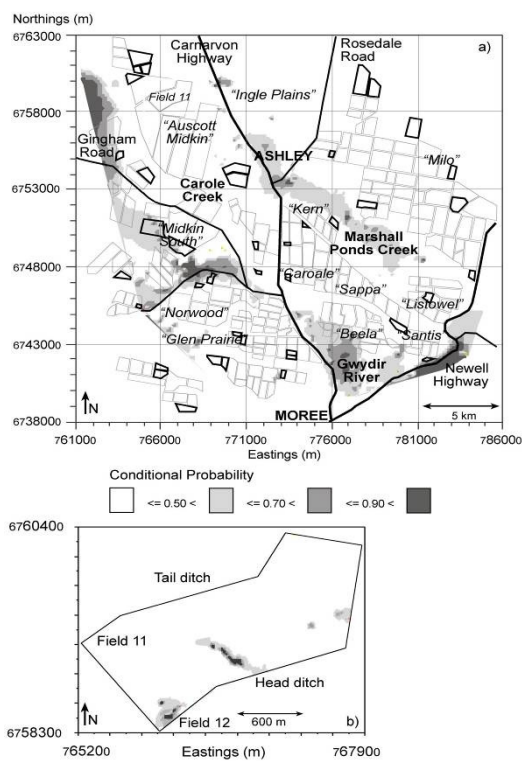


Figure 4. Maps showing conditional probability (risk) that soil at a particular site will exceed a deep drainage (DD) value of 50 mm/year a) at the district scale, and b) field scale if 600 mm of irrigation water was applied and 584 mm of rainfall is assumed in the lower Gwydir valley.

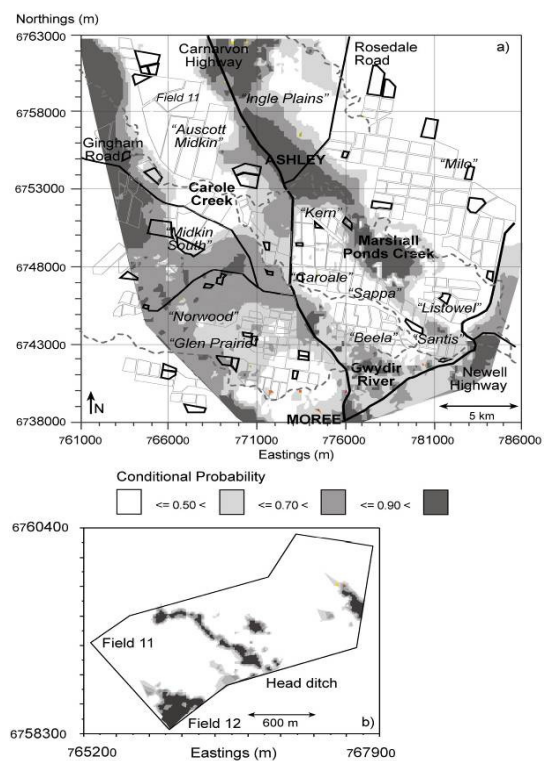


Figure 5. Maps showing conditional probability (risk) that deep drainage (DD) will exceed a value of 100 mm/year at a) district scale if 1,800 mm of irrigation water was applied, and b) field scale if 1,500 mm of irrigation water was applied and 584 mm of rainfall is assumed in lower Gwydir valley.

Estimating groundwater recharge rate

Deep draining water is said to contribute in large amounts to groundwater recharge, which is the process whereby the excess water of infiltration over evapotranspiration drains from the root-zone and continues to flow downward through the vadose zone toward the groundwater table (Gee and Hillel 1988). Past research has confirmed that excessive groundwater recharge can cause rising of the groundwater table which; can lead to soil and water salinisation in irrigated areas. This condition is evident across many irrigated cotton growing and irrigated rice-growing areas of southern NSW (Beecher and Hume 1996; Beecher *et al.* 2002).

The chloride mass-balance (CMB) model is an inexpensive method that can be used to approximate the rate of groundwater recharge under a steady state condition in the unsaturated zone of certain soil types (Allison and Hughes 1978). The technique only requires information of annual precipitation, chloride concentration in that precipitation, and the average chloride concentration in the vadose zone (*i.e.* 2-7...12 m). The chloride mass balance technique is based on the simple model

$$GWR = I \times C_i / C_z \quad (1)$$

where *GWR* is the recharge rate (mm/year); C_i is the concentration of chloride in the input water (rainfall and/or irrigation); *I* is volume of input water in the form of rainfall and/or irrigation (mm); C_z is the mean soil water chloride concentration below the root zone (mg/l) (Walker *et al.* 1992). The estimation of *GWR* rate across a district can be carried out by coupling estimates with more easily obtained information. This was the approach of Cook *et al.* (1989) who established a relationship between estimated *GWR* rate and soil EC_a as recorded using an EM34. In a later paper Cook *et al.* (1992) used the relationship to describe the spatial distribution of *GWR* rate from an EM34 survey. Both studies were undertaken on a farm scale. Triantafilis (1999) showed how this could be achieved with estimates of *GWR* rates obtained in the irrigated cotton-growing district around Wee Waa, lower Namoi valley. In that study a 3-parameter non-linear regression model enabled estimates of *GWR* rate to be coupled to electrical conductivity (EC_a) collected using EM34-10 signal data. In all some 24 soil cores drilled to a depth of 12-19 m and sampled at 1 m increments were analysed for chloride content on a mass basis. These were determined at 1 m increments from saturated soil paste extracts (USSSL, 1954).

Using equation (1), an estimate of *GWR* rate (mm/year) was made at each of the calibration soil cores. It was assumed that each of the profiles was in steady-state as irrigation at most sites has been carried out since the early to late 1960's. In addition, it was assumed that 600 mm of irrigation water was applied annually (equivalent to 6 mega litres/ha/annum, which is industry average irrigation volume) and that recharge as a result of precipitation was negligible. A one off measurement of Namoi River water produced a chloride concentration of 45.29 mg/L. These were used to estimate *GWR* rate using the chloride mass balance model.

Figure 6 shows the spatial distribution of *GWR* rate in the lower Namoi valley. Although not all areas are irrigated, it is evident that the areas associated with the prior stream channels, dissected low floodplains and Pilliga Scrub are most susceptible to excessive *GWR* rate (*i.e.* >150 mm/year). As a consequence any irrigated cotton farms located in these areas are likely to be water use inefficient and potentially could be adversely affecting groundwater levels. However, this does not appear to be the case as no widespread increase in water table levels has been reported. It is interesting to note that in these areas of higher *GWR* irrigated fields and water reservoirs are generally much smaller in run lengths and size, respectively. Nevertheless, more detailed investigations are necessary in order to understand the management required to minimise the threat of soil salinity and to understand the problems associated with water use inefficiencies and irrigation management in these parts of the landscape. Conversely, the clay alluvial plains generally contribute <150 mm/annum in terms of *GWR* rate.

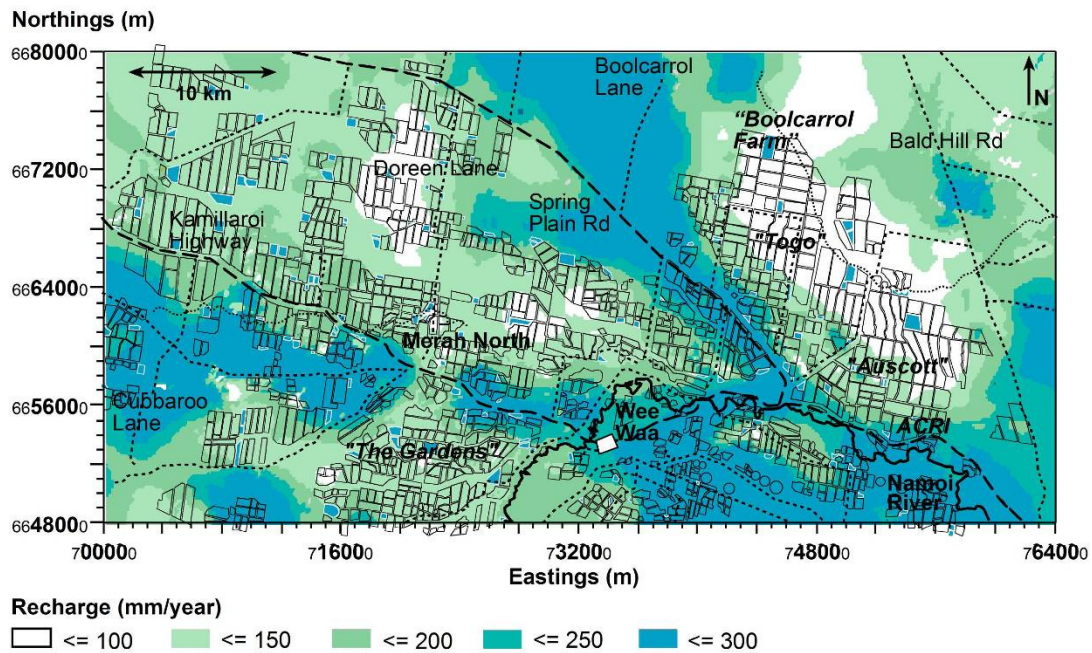


Figure 6. Spatial distribution of groundwater recharge (GWR-mm/year) in the lower Namoi valley.

Mapping spatial distribution of groundwater tables

Knowledge of where depth to groundwater in the soil and vadose zone is crucial for crop production and the long term sustainability of agricultural districts. This is particularly so in environments with high levels of primary salinity. The importance of understanding and mapping the depth to groundwater is highlighted by the fact that in Australia an estimated 17 million hectares is expected to be affected by dryland and irrigated salinity by 2050 (NLWRA, 2001). The vast majority of this will be as a result of salt transport through groundwater mechanisms. However, measuring and mapping depth to groundwater measurements is inherently expensive and time consuming. This is particularly the case during the installation of a well or piezometer. Consequently the number of groundwater measurements in a given area is often relatively sparse and generally does not reflect the actual level of variation (Olalla *et al.* 2003). Traditionally the mapping of groundwater levels has relied strongly on interpolation techniques such as inverse distance weighting (IDW) and ordinary kriging (OK) to extrapolate point measurements to a regionalised variable. Numerous studies have been undertaken comparing the performance of both IDW and OK as prediction methods (Kravchenko and Bullock 1999; Muller *et al.* 2001) however these concentrate on larger sample sizes (>60) which are often more than practically available. Neither method has been found to be universally superior as performance is largely based on sample size and spatial correlation. Where strong spatial correlation exists OK methods have been found to be superior as the ability to model the variogram increases.

Ancillary data have been used in numerous ways to improve the often sparse spatial resolution of soil and water related properties. Increasingly the same techniques are being used for depth to groundwater prediction. This has largely been through development of regression relationships which exploit the environmental correlations between groundwater depth and some easily measurable physical manifestation of this. One of the most commonly used ancillary data sources is aerial photographs (Edet *et al.* 1998; Metternicht 2001) and satellite data such as Landsat TM (Salama *et al.* 1994; Ringrose 1998; Salama *et al.* 1999; Neville *et al.* 2000). Digital terrain models as well as their derivatives have also shown to be very useful in hydrological investigations (Saraf and Choudhury 1998; Bixio *et al.* 2002; Betts *et al.* 2003) due to the natural relationship between landform and groundwater

conditions and height. Electromagnetic (EM) Induction techniques have been used widely in hydrological investigations however not generally as a direct predictor of groundwater depth but rather for associated processes. These include unsaturated flow characterisation (Scanlon *et al.* 1999), recharge (Cook *et al.* 1992) and salinity plumes (Hopkins and Richardson 1999). These predictions have been commonly derived through Multiple Linear Regression (MLR) analysis which have been widely used in prediction of soil physical properties (McBratney *et al.* 2003) and specifically ground water prediction (Shao and Campbell 2002; Bloomfield *et al.* 2003; Finke *et al.* 2004).

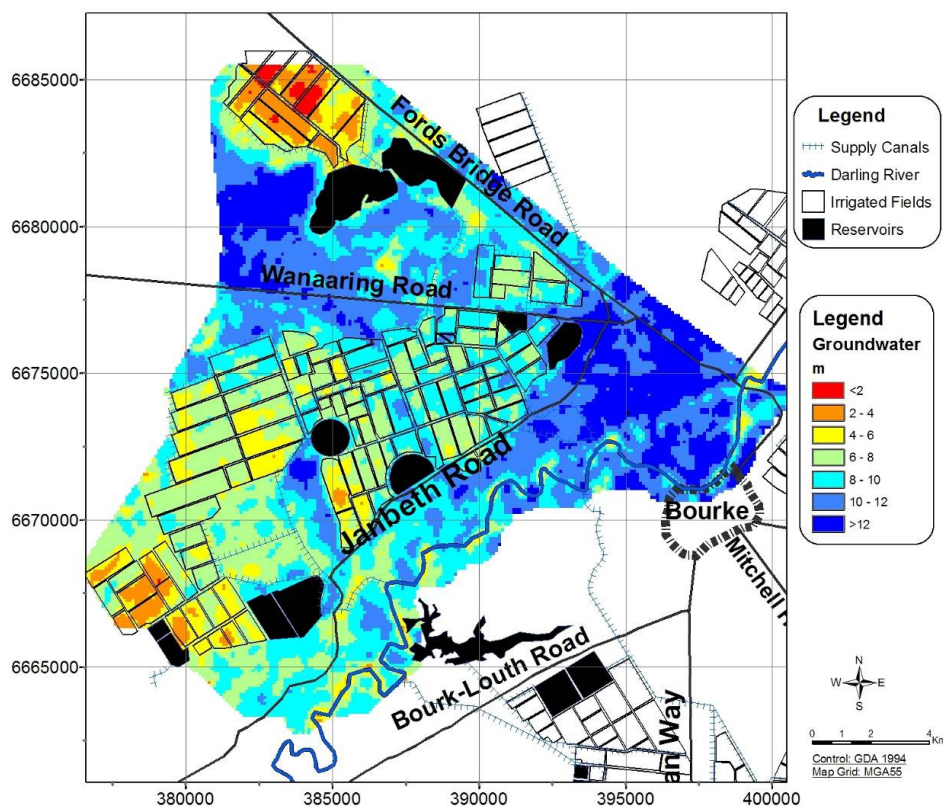


Figure 7. Spatial distribution of groundwater table height in the Bourke Irrigation District

Figure 7 shows the spatial distribution of ground-water table height as predicted in the Darling River valley within the Bourke Irrigation District (BID). The ground-water table height data was collected during the drilling phase of EM34 calibration. In all 36 cores were drilled and used to establish a calibration relationship. The ancillary data used included, DEM, plan curvature, ratio of EM38-h and EM38-v signal data and Eastings. The blue shaded areas indicate where the ground-water level is greater than 12 m below the surface, whilst the orange shaded areas indicate where ground-water is estimated to be within 2 m of the ground surface. Interestingly, the highest water-tables are predicted in the northern most area known as Gidgee Lake. Shallow water tables are also predicted in the south-western parts of the BID, but interestingly were not predicted in areas where shallow water tables and point sources of salinisation are evident. This includes the areas to the north, south and east of the three largest water reservoirs in the BID (*i.e.* respectively, circular, semi-circular and dual cell reservoirs). The reason for this discrepancy is due to the fact that no calibration sites were drilled in these locals.

Geological layers

Clay content

In order to manage the soil resource effectively basic information about its spatial distribution is necessary. One of the most important attributes required by landholders for effective soil use and management is that of clay content. From the hydrological perspective knowledge of the subsoil and vadose zone clay content is also important because large amounts can reduce permeability, inhibit deep drainage and potentially lead to waterlogged soil conditions. Conversely, subsurface coarse textured sediments allow water flow. Various geostatistical approaches have been employed to estimate spatial variation of clay content. These include, ordinary- (Kalivas and Kollias 1999), block- (Mapa and Kumaragamage 1996), intrinsic random function of order k- (McBratney *et al.* 1991), indicator- (Oberthur *et al.* 1999), co- (Zhang *et al.* 1992), universal- and regression- (Odeh *et al.* 1995) and compositional-kriging (Odeh *et al.* 2003). However, soil sampling for geostatistical mapping can be time-consuming and costly. This is particularly the case with respect to identifying and mapping subsurface clay content.

In light of this many studies have incorporated ancillary variables to enhance prediction. The most commonly used method is electromagnetic (EM) induction. In the Netherlands EM data was used to identify depth to a) boulder clay (Brus *et al.* 1992), and b) a soft layer in the western marine districts (Knotters *et al.* 1995). In the US, EM data have been used to estimate a) depth to clay pan (Sudduth *et al.* 1995) and b) depositional depth of sand after a large flooding event in the Midwest of the USA (Kitchen *et al.* 1996), whilst Gallichand and Marcotte (1993) mapped clay content for subsurface drainage in the Nile Delta. In Australia, average clay content was mapped using an EM38 at field level in the lower Gwydir valley (Triantafilis *et al.* 2001a), whilst Williams and Hoey (1987) used an EM34 to map clay content to 7 m.

Figure 8 shows the spatial distribution of average clay content to a depth of 7 m in the irrigated cotton growing area southeast of Trangie. In brief, the map was generated using a hierarchical spatial regression model (HSR) using a composite signal variable [*i.e.*, $\ln(\text{EM34}-10) + \ln(\text{EM34}-40) + \ln(\text{EM38}-h)$] and first-order trend surface components (*i.e.*, Easting and Northing). The final map of % clay generally reflects the known surface clay content and provides information about the spatial distribution of subsurface % clay variability. It is worth noting that most of the irrigated fields are located upon the clayier sediments, however some caution is required when interpreting this map, because as shown in detailed transect of clay content collected from Trangie to Rocky Point clay content at the surface is less than 30 % in the eastern part of the district and adjacent to the Macquarie River. Here water logging is problematic because of the increased clay content with depth.

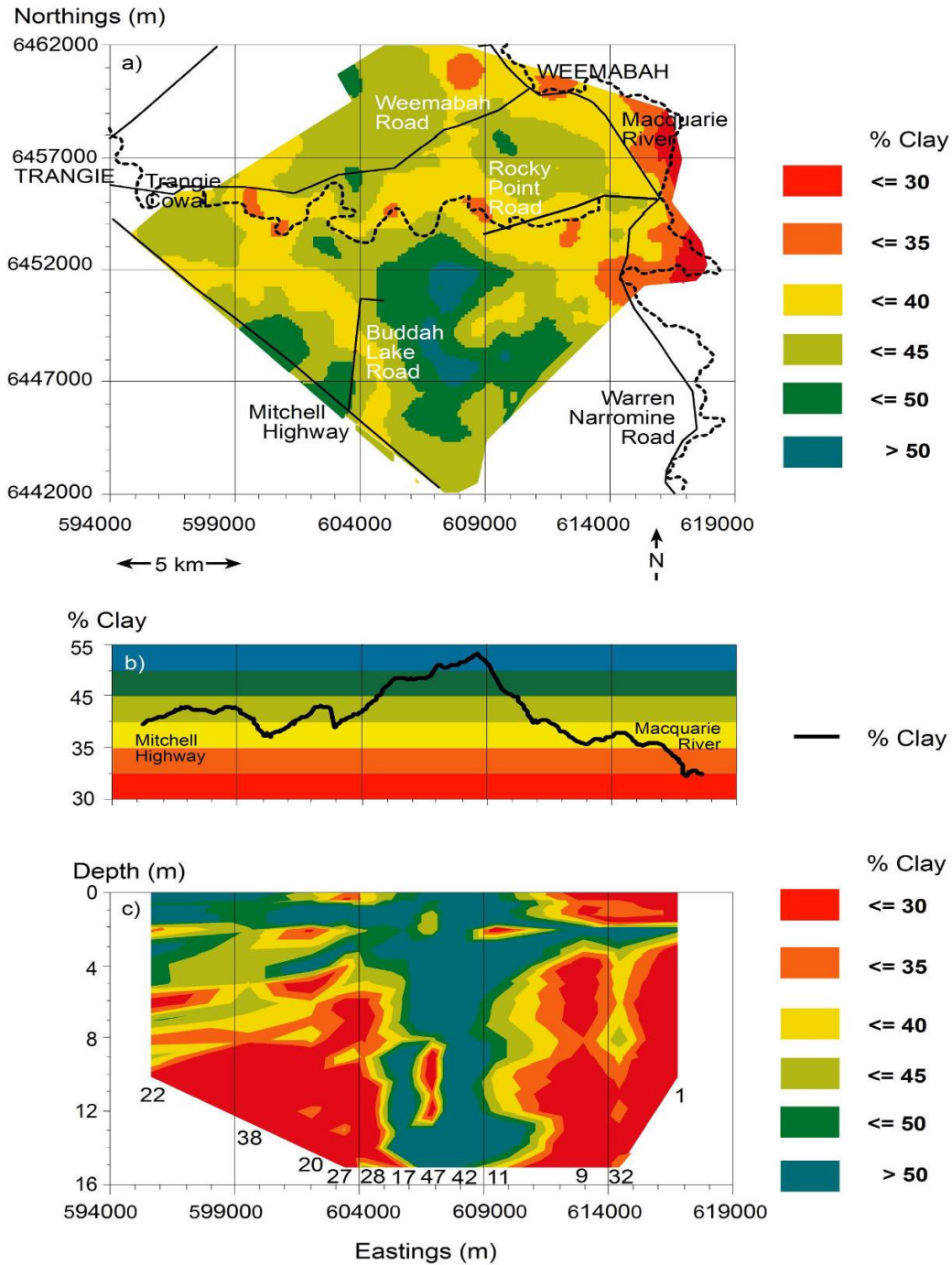


Figure 8. Spatial distribution of a) estimated average clay content (%) to a depth of 7 m, b) estimated average clay content along an East-West traverse at Northing of 6454000, and c) measured clay content at 1 m depth increments in 12 soil cores taken across the Trangie irrigation district in the lower Macquarie River valley (Triantafyllis and Lesch 2005).

Salt content

The use of electromagnetic (EM) induction instruments has similarly assisted in understanding the spatial distribution of soil and water salinisation. Various examples exist in the literature. With regard to soil salinisation EM instruments (*e.g.* Geonics Ltd. EM38) have been used for providing information on the nature, origin and spatial distribution of soil salinity at the field scale (*eg.* Cameron *et al.* 1981; van der Lelij 1983; Boivin *et al.* 1989, Lesch *et al.*, 1995b, Ceuppens *et al.* 1997). In irrigated areas of Australia research has also focussed on developing calibration models (Slavich 1990; Triantafilis *et al.* 2000) and using these to map soil salinisation at the field level (Triantafilis *et al.* 2001b).

EM instruments have also been used to detect the presence and map the spatial extent of saline subsurface material (*i.e.* groundwater and/or sediments) at the district scale. In New South Wales an EM34 was used by Williams and Baker (1982) to demonstrate a rapid reconnaissance method to identify soil salinisation hazard in the mid-Lachlan River valley. Similarly Williams and Hoey (1987) mapped the spatial variability of soil salinisation in the Murrumbidgee Irrigation Area. In Victoria Williams and Fiddler (1983) located subsurface saline material in the Major Creek drainage basin, whilst Potts (1990) reported that the EM34 was a useful tool in defining the location of shallow sand aquifers in the Shepparton Formation. Figure 8 shows the spatial distribution of saline subsurface material in the Bourke Irrigation District. The highest levels are located beneath most of the irrigated cotton growing areas. It is a function of mobilisation of salts associated with irrigation inefficiencies and ancient marine clays (*i.e.* Cretaceous mud stones).

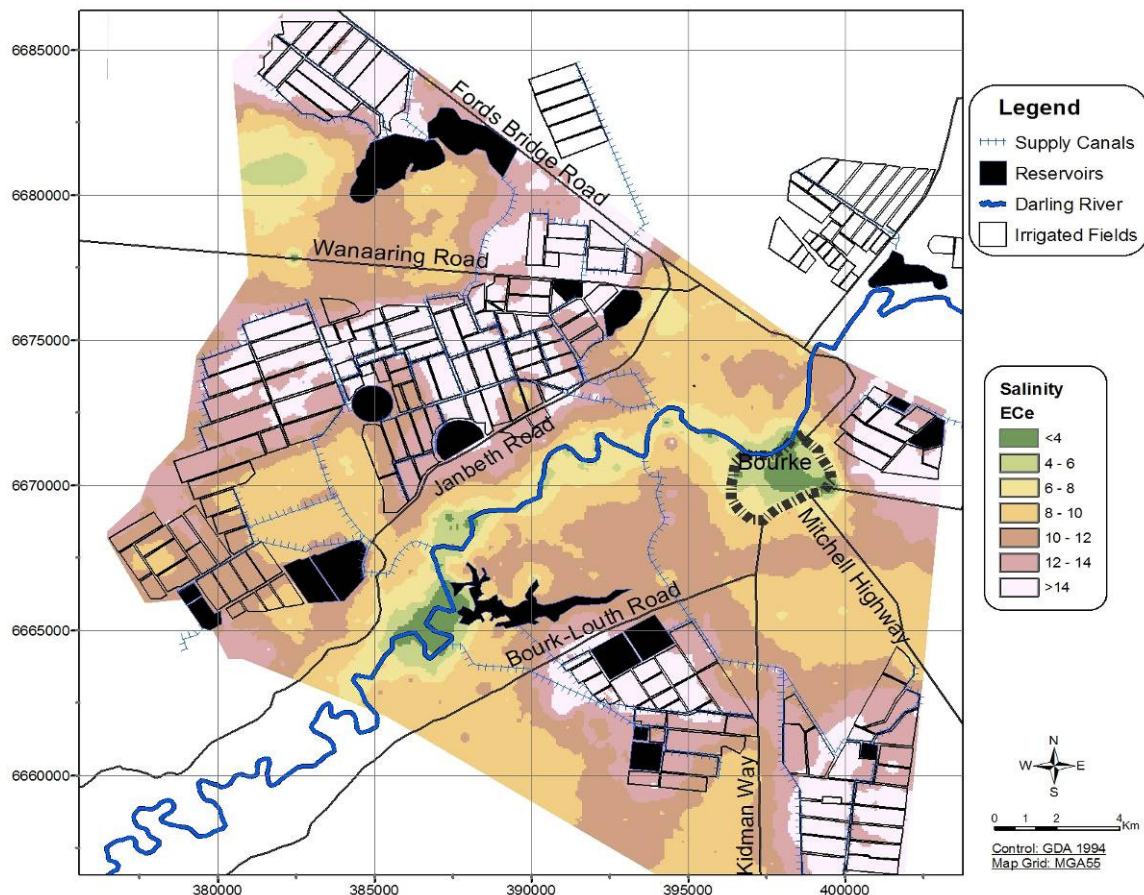


Figure 9. Spatial distribution of average saturated soil electrical conductivity (EC_e – dS/m) for 6-12m using entire EM34 signal data set and Multiple Linear Regression Kriging (MLRK).

Results

Determining salinisation potential in NSW Murray-Darling Basin

Irrigation is an indispensable technology used to augment agricultural production in the semi-arid and arid regions. However, poor water management (*e.g.* unsuitable location of reservoirs) can lead to the creation of perched water tables and secondary salinisation. In some irrigated areas in the northern Murray-Darling Basin, point-source salinisation has occurred (Triantafylis *et al.* 2003a) whilst in others there is little or no evidence. An example of where salinisation has occurred in irrigated cotton growing areas includes the lower Macquarie valley. Figure 10 shows water logging and outbreaks of soil salinisation associated with two water reservoirs in the Trangie and Warren irrigation districts. Water logging and salinisation in these areas has arisen as a function of interactions between various biophysical factors such as agronomy, geology, hydrology, climate and topography.



Figure 10. Water logging and soil salinisation a) within a drained water reservoir in the Trangie irrigation district and b) adjacent to a water reservoir in the Warren irrigation district.

In order to determine where these problems may arise, biophysical features (*eg.* salt stores) that are potentially influenced by agronomic practices, such as irrigation, need to be generated. Stored in Geographic Information Systems (GIS), they can then be retrieved, manipulated and interpreted to display processed and spatially associated data into composite maps. This has been the approach taken by various state government agencies to develop Composite Hazard Index maps of salinisation potential for various biophysical layers of information.

Figure 11 show some of the data collected and derived products developed by the NSW Department of Infrastructure, Planning and Natural Resources. Figure 12 shows the final spatial distribution of composite Salinity Hazard index across the NSW Murray-Darling Basin. The composite Salinity Hazard index map was generated by ranking the biophysical factors, shown in Figure 11, in terms of importance and weighting them accordingly. The final step involved simply summing these indices to produce a Composite Salinity Hazard index map (see Figure 2). A major problem with this approach is that hazard weighting assigned to particular biophysical layers is subjective (*i.e.* assigned by so-called experts) and may not be relevant at the management scale or in some locations as in others. In addition, in some areas data is available at higher spatial resolution than in others and the use of these maps to develop Salinity Investment Strategies across NSW may be inappropriate.

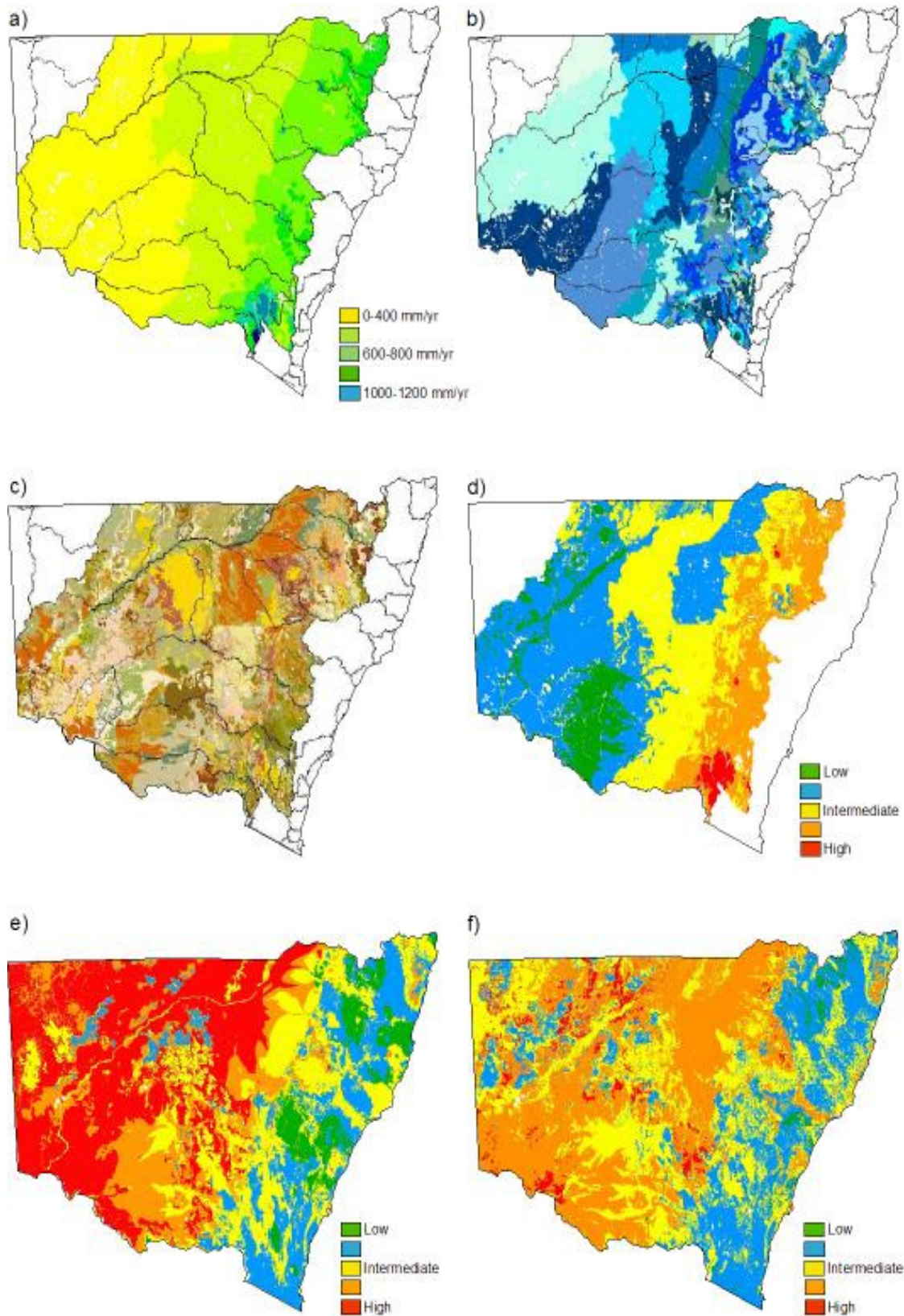


Figure 11. Spatial distribution of some of the biophysical data layers collected and generated by NSW Department of Infrastructure, Planning and Natural Resources, including a) rainfall, b) climatic zones, c) soil type, d) deep drainage (bare earth), e) groundwater salt store and f) total salt store.

What may be more appropriate, particularly in areas where incipient and points source salinisation are already in evidence, is the development of specific biophysical layers which are known to contribute to soil and or water salinisation. The justification for this is best explained by considering the final composite Salinity Hazard index map generated and shown in Figure 12. The orange and red shaded areas indicate intermediate-high and high Salinity Hazard, respectively. The yellow shaded area indicates, intermediate hazard. This is the rating designated for the Ashley (Gwydir), Wee Waa (Namoi) and Warren (Macquarie) irrigated cotton growing districts. The blue and green shaded areas indicate intermediate-low and low hazard ratings. Interestingly, in irrigated cotton growing areas where salinisation has occurred, for example Bourke (Figure 1) and Trangie and Warren (Figure 10), the hazard is considered low-intermediate. In reality Trangie, Bourke and Gunnedah have a higher salinisation hazard, given the larger salt stores inherent in each of these areas (see Triantafilis, 2002; Final Report “Understanding the salinity threat – Phase III”, respectively Figures 28, 34 and 25).

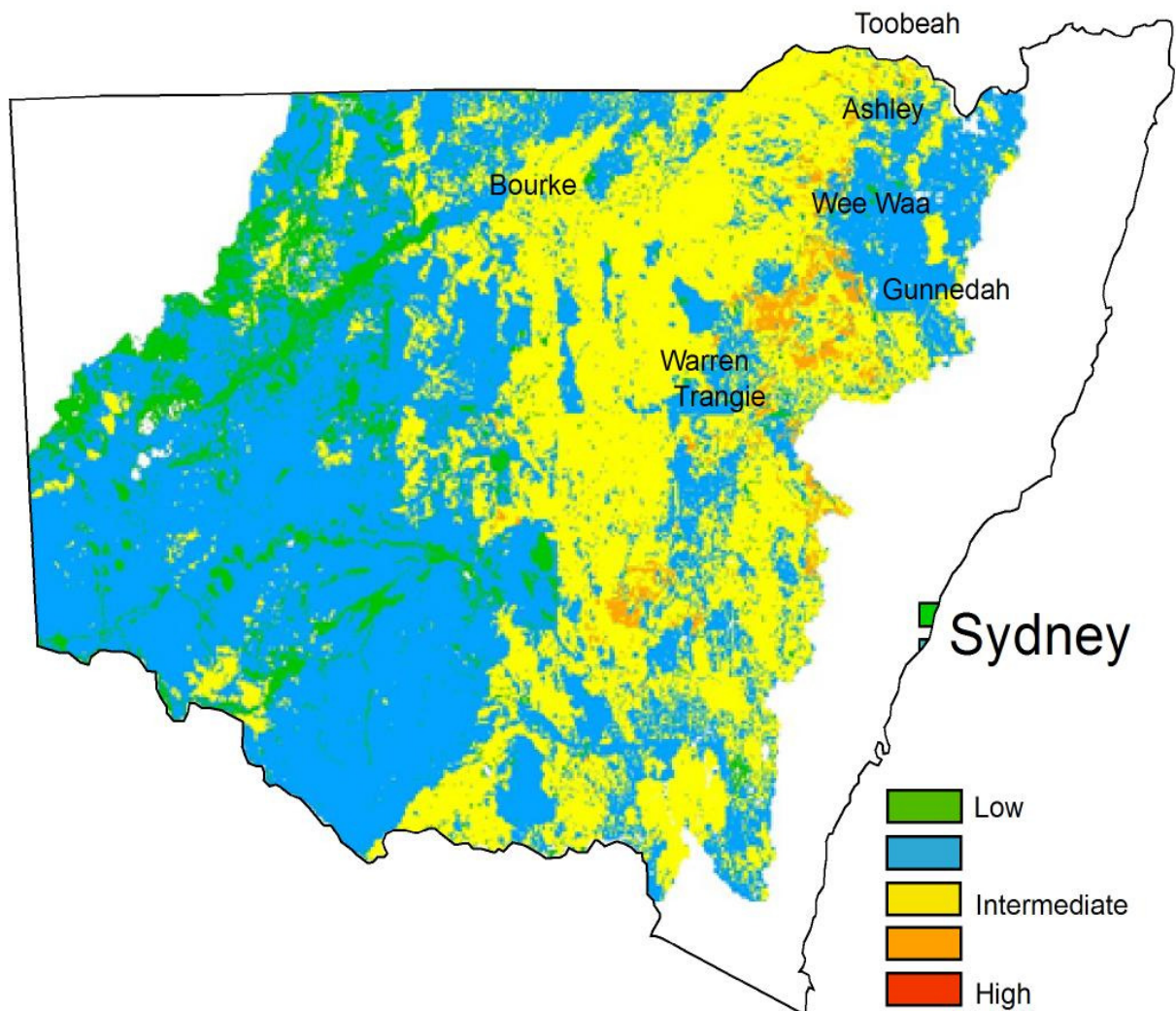


Figure 12. Spatial distribution of composite *Salinity Hazard* indices across NSW Murray-Darling Basin generated by NSW Department of Infrastructure, Planning and Natural Resources.

Determining salinisation potential of cotton growing areas in Macquarie valley

In order to minimise the onset of irrigation induced salinisation, biophysical information is required to map the various causal factors. This includes, land use, geology, hydrology, climate and topography. In the last 10 years this type of information has increasingly been generated and used in Geographic Information Systems (GIS) to identify Composite Salinity Hazard indices. Unfortunately and due to the high cost of acquiring quantitative information, Government Agencies rely upon qualitative maps generated at regional levels and catchment scales. The result is the production of maps of low accuracy and interpretability at the district and land management scale. In addition, the Composite Salinity Hazard maps are biased in that weightings are assigned based on expert knowledge about which biophysical factors are most significant in producing secondary soil salinisation. In irrigated agricultural districts more detailed information is required. This is particularly the case in irrigated cotton growing districts of the lower Macquarie valley (*i.e.* Trangie and Warren) where shallow water-tables and soil salinisation are evident.

In the following section a methodology is described for the development of a map of Composite Salinity Hazard associated with the construction of large earthen water reservoirs in the irrigated cotton growing areas southeast of Trangie and Warren. The final map is based on biophysical layers which show the spatial distribution of deep drainage (*DD*) risk associated with these reservoirs, average clay content (0-7 m) and average salt store (0-10 m). By doing this a Composite Salinity Hazard map based on the various causal factors thought to contribute to the creation of water-logging at can be mapped. Critical values were determined at a site where soil salinisation was first reported in the Trangie district in the early 1980's and include: a) *DD* risk greater than 0.5; b) average clay content (0-7 m) > 38 %; and, c) average salt store (0-10 m) > 2.5 dS/m. By doing this the element of bias is removed as local information is used to determine critical values. By using Geographic Information System type analysis a map was produced. This indicated where these three conditions may be met and hence creates a Composite Salinity Hazard map associated with construction of reservoirs across the Trangie and Warren districts.

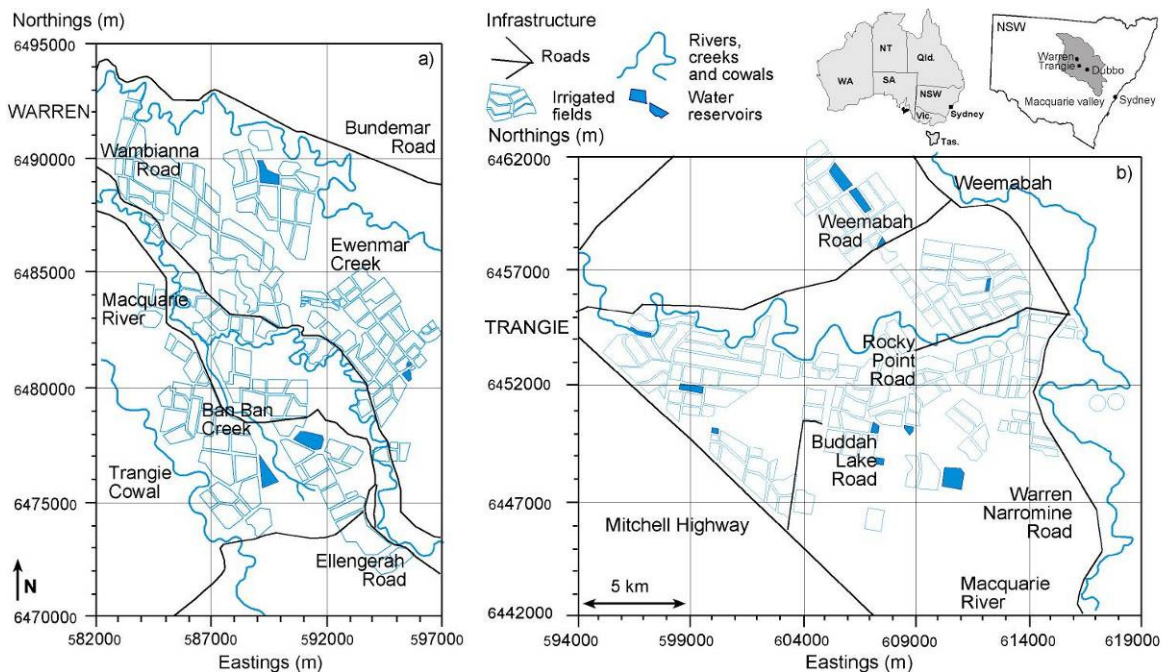


Figure 13. Location of lower Macquarie valley and major infrastructure a) Warren and b) Trangie.

Study area

The Macquarie River is a tributary of the Darling, which drains the northern part of the Murray-Darling Basin. The study area is located in the lower Macquarie valley southeast of the townships of Warren and Trangie (Figure 13) and includes both irrigated and dryland farms. The latter is mostly wheat production and native pastures. Irrigation is mostly for cotton production. The irrigated infrastructure (including major water reservoirs) of these areas is shown in Figure 14.

McKenzie (1992) identified several Pedoderms in the Macquarie valley (Figure 13). The Trangie Cowal Pedoderm is characterised by the Wilga red-brown profiles (Red Chromosol) and Byron red-brown earths (Red Chromosol). Both are characterized by distinct clay maxima between 0.30 and 0.80 m. The Gin Gin profiles (Red Dermosol) of the Gin Gin Pedoderm, are strongly weathered with a uniform to gradational texture profile. The Macquarie profile class (Stratic Rudosol) defines the Macquarie Pedoderm and is characterised by fine sand and silt fractions; moderately high cation exchange capacity and a permeable nature. The Mitchell profile class characterizes the Old Alluvium Pedoderm - Meander Plain, where the well-drained profiles (Red Chromosol) contain high coarse sand content. The poorly drained profiles (Red, Yellow or Grey Sodosol) are sodic by comparison. The Back plain is more variable and includes: Mullah - dark grey to black cracking clays (Black Vertosol); Snake - sodic grey cracking clays (Grey Vertosol); and, Buddah profiles (Red Vertosol) characterized by high clay content of which smectite and kaolinite is co-dominant with illite.

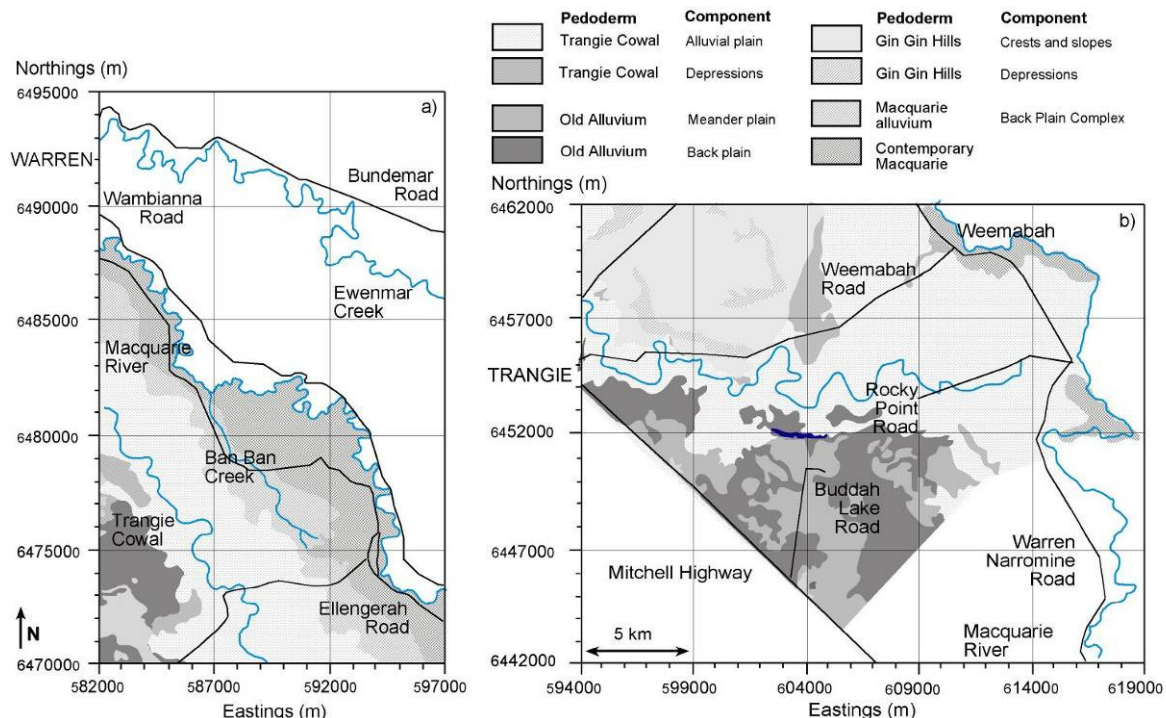


Figure 14. Pedoderms in the lower Macquarie valley (after McKenzie, 1992) southeast of townships of (a) Warren and (b) Trangie.

EM surveys

In order to confirm whether EM signal data could discern the soil patterns of McKenzie (1992) and potentially the spatial distribution of hydrological features in these landscapes, EM34 and EM38 surveys were undertaken. An EM survey is also a useful first step in identifying suitable locations to sample the various pedologic, geomorphic and geological units that may exist in a given area (Triantafilis and Lesch 2005). Briefly, EM instruments work by measuring the strength of electromagnetic fields (*i.e.* primary and secondary) induced into the soil and vadose zone. The strength of the secondary field is a function of: a) amount of negative charge; b) clay content; c) concentrations of salts in solution; and, d) moisture content (Triantafilis *et al.* 2000, 2001 and 2002). The more conductive the soil, the greater the secondary electromagnetic field produced (Williams and Hoey 1987) and the larger the measured soil electrical conductivity (EC_a -mS/m).

In both the Trangie and Warren districts 500-m grid spacing was used in irrigated cotton growing areas and 1 km survey spacing was adopted elsewhere. The Warren survey included 564 locations, whilst in the Trangie district 755 sites were visited. The EM34 survey consisted of taking three measurements in the horizontal mode of operation at coil spacing of 10, 20 and 40 m (*i.e.*, EM34-10, EM34-20 and EM34-40). The theoretical depth of measure for each coil spacing is respectively 7, 15 and 30 m (McNeill 1980). Therefore, the EM34 instrument can provide information about the shallow stratigraphy, vadose zone (biologically inactive zone between root zone and water table) and presence and location of deep saline water tables (Triantafilis *et al.* 2003b). In addition measurements were made with the EM38 in the vertical (EM38-v) and horizontal (EM38-h) modes of operation. The theoretical depth of measurement in these modes is respectively, 1.5 and 0.75 m (McNeill 1992). The EM38 instrument provides information in the agriculturally significant portion of the root zone and subsoil. At each site spatial coordinates were also recorded in the Australian Map Grid (AMG84) using a Magellan NavPro5000 GPS. The location of these survey points is shown in Figure 15.

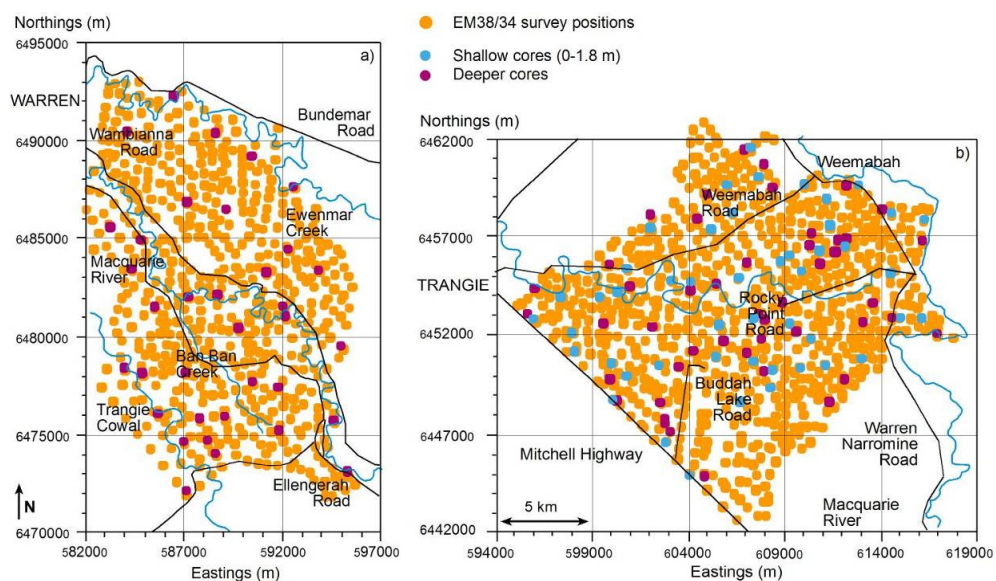


Figure 15. Location of EM34 and EM38 survey positions and shallow and deep soil sampling cores in (a) Warren and (b) Trangie districts of the lower Macquarie valley.

Soil and water data

Soil samples were collected at selected sites (Figure 15). This was done essentially at low, intermediate and high values of EC_a , with sites spread evenly. A total of 35 deep cores were drilled in the area southeast of Warren with samples collected to a maximum depth of 12 m and at 1 m intervals. In the Trangie study area 48 deep cores were collected to a depth of up to 15 m. In both surveys soil was collected at 0.30 m depth increments to 1.8 m. In the Trangie district 48 shallow cores were drilled and sampled every 0.30 m to a depth of 1.8 m. Prior to laboratory analysis samples were air-dried and ground to pass a 2-mm sieve. The samples were analysed for: a) particle size fraction using the hydrometer method; and, b) effective cation exchange capacity (ECEC- $mmol(+)kg^{-1}$) (Tucker 1974) using a mechanical leaching device (Holmgren *et al.* 1977). The latter method is preferred for estimates of exchangeable bases (Ca^{2+} , Mg^{2+} , Na^+ and K^+) and ECEC on alkaline soil containing solid phase carbonates (Loveday *et al.* 1972). Soil salinity was determined by EC_e : where 125 g of soil was weighed and made into a saturated paste according to procedure outlined by the U.S. Salinity Laboratory Staff (1954). The paste was left to stand for a period of up to 12 hours prior to extraction by suction. The EC_e of the soil solution extract was then measured directly. The EC of water samples (EC_{iw}) collected from the Macquarie River was also measured (*i.e.* 0.41 dS/m).

SaLF simulations

In order to simulate DD at each site, the soil attribute data was inputted into the SaLF program (Carlin and Brebber 1993). For Warren this included clay (%) and ECEC at depths of 0.0-0.3, 0.3-0.6, 0.6-0.9, and 0.9-1.2 m, and exchangeable sodium at 0.9-1.2 m. For Trangie, the first three depths were entered with exchangeable Na at 0.6-0.9 m. The EC_{iw} value for the Macquarie River (0.41 dS/m) was entered; along with Trangie's mean annual rainfall (*i.e.* $R = 494$ mm). One irrigation ($I = 1,800$ mm/year) simulation was carried out to estimate DD beneath a shallow reservoir, supply channel or head ditch (Triantafilis *et al.* 2003a and 2004a).

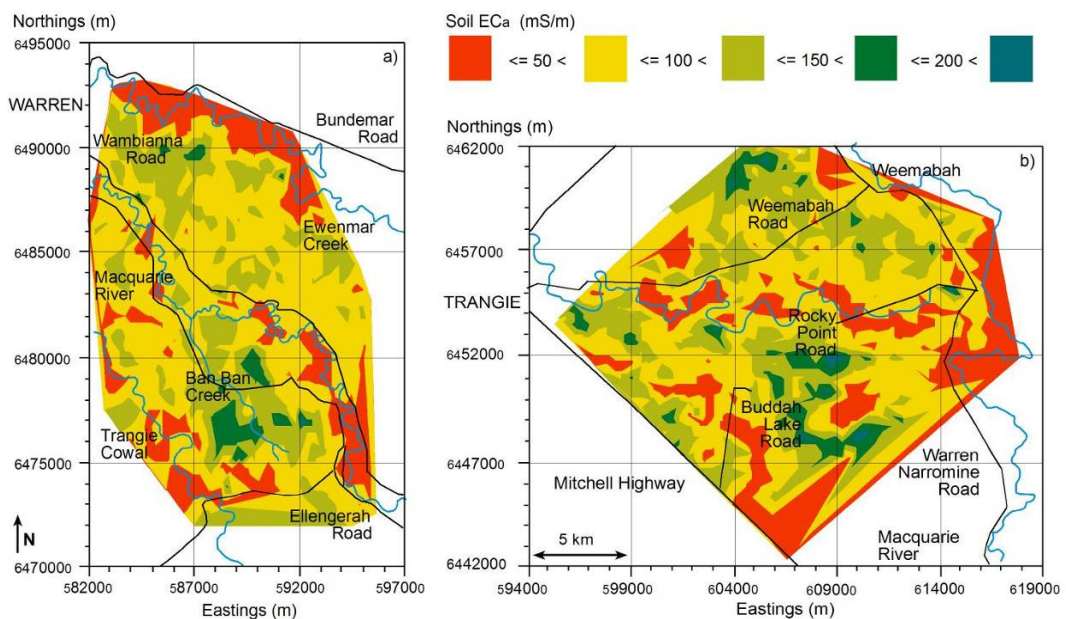


Figure 16. EM38 signal data (mS/m) in the vertical dipole (EM38-v) configuration as recorded in (a) Warren and (b) Trangie districts of the lower Macquarie valley.

Spatial distribution of root zone and subsoil EC_a

Figure 16 shows the pattern of EM38-v signal data collected for the Warren and Trangie districts. Low signal data readings (i.e. EC_a < 50 mS/m) are synonymous with: a) coarse sediment of the Trangie Cowal, b) Old Alluvium (meander plain) Pedoderm, which runs in parallel with the Mitchell Highway in the Trangie district, and c) Contemporary Macquarie Pedoderm, adjacent to the modern-day Macquarie River. Conversely, high signal data values (i.e. EC_a > 100 mS/m) are associated mainly with Old Alluvium (back plain) Pedoderm, which is clayey in nature. However, higher values of EM38-v signal data are also obtained on the Trangie Cowal Pedoderm in two locals: a) southern part of the Warren district between the Macquarie River and Trangie Cowal, and b) eastern part of the Trangie district in the area bounded by Weemabah, Warren-Narromine and Rocky Point Roads. This is evident around various reservoirs, where isolated instances of salinisation have been reported.

Spatial distribution of shallow stratigraphy and vadose zone (EM34) EC_a

Figure 17 shows the spatial distribution of EM34-20 signal data. As with the EM38-v signal data, the coarser sediments of the Pedoderms of the Trangie Cowal and the Old Alluvium (meander plain) are characterised by low values (i.e. EC_a < 100 mS/m), with the lowest signal readings (i.e. < 50 mS/m) associated with the Contemporary Macquarie Pedoderm. In the Trangie area the higher signal readings (i.e. EC_a > 100 mS/m) were recorded north of the Weemabah Road and in the central southern part of the district between Rocky Point and Buddah Lake Roads. The higher signal readings (i.e. EC_a > 150 mS/m) north of Weemabah Road are consistent with a known saline aquifer within 10-15m of the ground surface in this area. As with the Trangie area, signal readings generally increased with depth of instrument measurement (i.e. EM34-40 signal readings generally greater than EM34-10) in Warren, with the patterns similar to those achieved with the EM38.

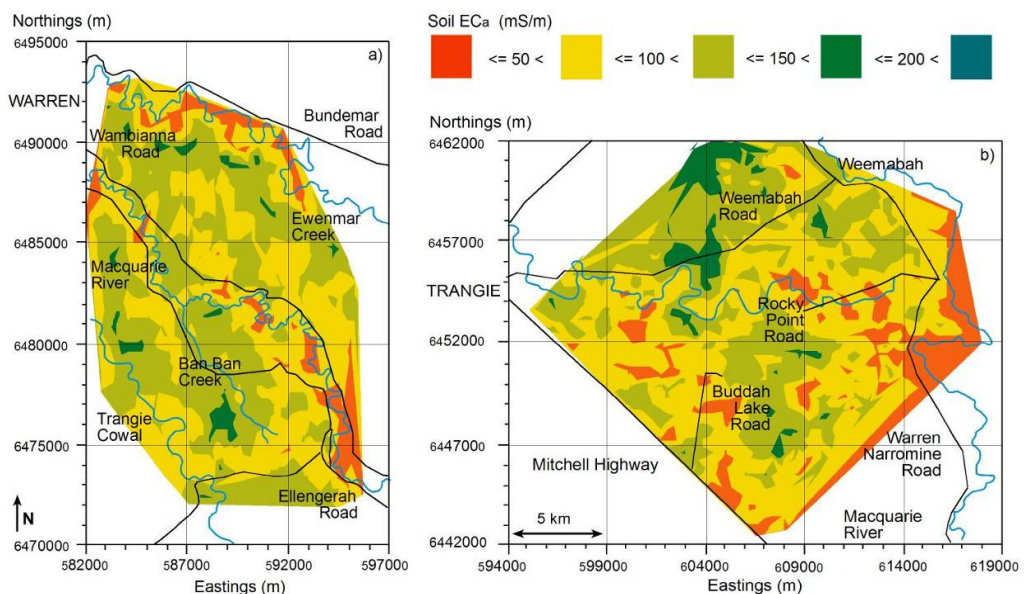


Figure 17. EM34-20 signal data (mS/m) in the horizontal dipole configuration and 20 m coil spacing as recorded in (a) Warren and (b) Trangie districts of the lower Macquarie valley.

Relationship between EC_a (EM38-v) and deep drainage (DD-mm/year)

Figure 18 shows the plot of EC_a versus DD (mm/year) estimated using SaLF at each of the soil sampling sites in the Warren and Trangie districts, when considering the water reservoir simulation (*i.e.* $I = 1,800$ and $R = 494$ mm/year). The low EM38-v signal values (*i.e.* < 100 mS/m) represent soil profiles where DD is high (*i.e.* > 200 mm/year). This includes soil types associated with: a) Trangie Cowal (Wilga soil); b) Old Alluvium (Mitchell soil); and c) Contemporary Macquarie (Macquarie soil) Pedoderms. Conversely, higher EM38-v signal data characterise soil where DD would not generally exceed 50 mm/year and relates to the clayier back plain soil of the Old Alluvium Pedoderm (Mullah, Buddah and Snake soils). These DD estimates are consistent with the results reported by McKenzie (1992) and Willis *et al.* (1997) using equivalent data sets in both areas.

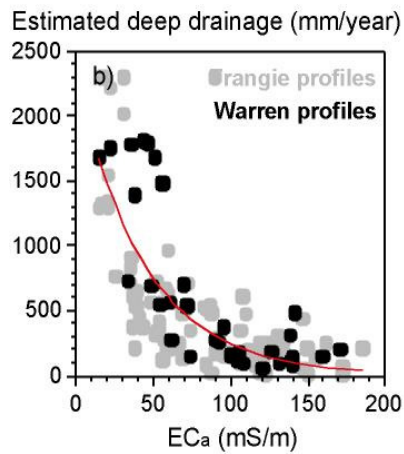


Figure 18. Relationship between EM38 signal data (mS/m) versus estimated deep drainage (DD-mm/year) if 1,800 mm/year of irrigation water (I) was applied and 494 mm/year of mean annual rainfall (R) assumed.

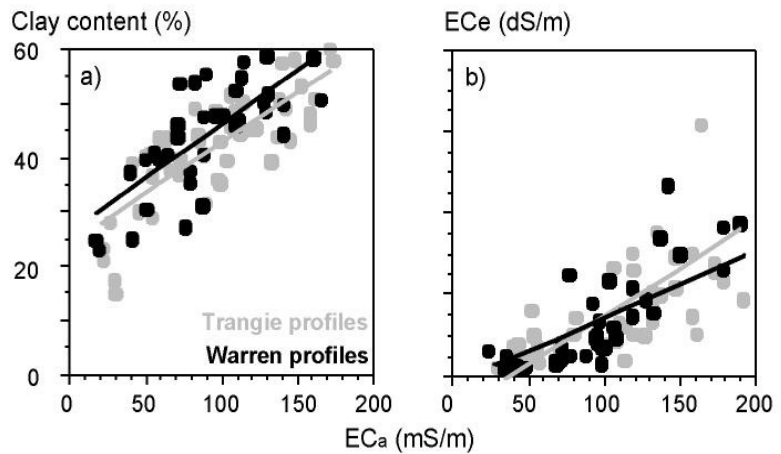


Figure 19. Relationship between; a) EM34 signal data (mS/m) in the horizontal dipole mode and 10 m spacing (EM34-10) versus average clay content to 7 m (%), and b) EM34 signal data (mS/m) in the horizontal dipole mode and 20 m spacing (EM34-20) versus average salt content (EC_e-dS/m) to 10 m. **NOTE:** Points collected in Warren and Trangie districts are shown in dark and light shades, respectively.

It is evident that the fitted or modelled curve (exponential) does not fit the data exactly, however. As such we would expect some errors in estimations of DD at EM survey sites using this relationship. Nevertheless a 4-parameter exponential decay model fitted best to the data shown in Figure 18. The equation derived is as follows: $2,532 \times e^{(-0.0294 \times EM38-v)} + 120.7 \times e^{(0.0006 \times EM38-v)}$, so that an EM38-v signal reading can be used to estimate DD at a site where an EM38-v measurement was taken. From a practical point of view and as a first approximation this equation can be used to estimate DD risk in an EM survey: possibly highlighting where further soil investigations may be appropriate. It is worth noting that the relationship between EM38-v signal data and DD is equivalent to that reported by Beecher *et al.* (2002), who assessed groundwater recharge rate beneath irrigated rice using an EM31.

Relationship between EC_a (EM34) and average clay (%) and salinity (dS/m)

Figure 19a shows the plot of EC_a (as measured with the EM34 at 10 m coil spacing) versus average (0-7 m) clay content (%) at each of the sampling sites in the Trangie and Warren districts. The regression relationships were similar in both areas (*i.e.* average Trangie clay content = $23.74 + 0.19 \times EC_a$ and Warren clay content = $26.25 + 0.20 \times EC_a$). The low values of EC_a (*i.e.* < 50 mS/m) represent profiles with average clay content of 30-35 %.

These equations were used to convert EM34 survey data at 10 m coil spacing into values of average clay content to a depth of 7 m. The data was interpolated onto a 150 m grid. The residuals of these equations of the line were similarly interpolated onto the same 150 m grid. The two values were added to produce the maps shown in Figure 23 of average clay content. This was the approach used in mapping average salinity (see Figure 24) to a depth of 10 m using the EM34 data at 20 m coil spacing (EM34-20). The regression relationships were slightly different (*i.e.* Warren salt content = $-1.71 + 0.05 \times \text{EM34-20}$ and average Trangie salt content = $-0.20 + 0.03 \times \text{EM34-20}$).

Maps of conditional probability (deep drainage risk)

In order to produce a map of where *DD* would be high (*i.e.* *DD* risk maps) the EM38-v measurements made in the Warren (564) and Trangie (755) districts, were converted into values of *DD* using the calibration equation (*i.e.* $DD = 2,532 \times e^{(-0.0294 \times \text{EM38-v})} + 120.7 \times e^{(0.0006 \times \text{EM38-v})}$) derived from the data shown in Figure 18. This gave *DD* estimates that ranged from as low as 3.5 mm/year to highs of 1,780 and 2,062 mm/year in the Warren and Trangie districts, respectively. This suggests that of the 2,294 mm/year applied (*i.e.* $I = 1,800$ and $R = 494$ mm/year) over 78 and 90 % of the water would be lost beneath a water reservoir located at these sites where *DD* is very high. Because these values are estimates derived, in the first instance from the SaLF model and secondly from EM38-v data collected under various moisture regimes (*i.e.* from dryland and irrigated fields) there is some uncertainty in the estimated *DD* value. Where there is such uncertainty a critical value can be selected instead, which indicates a level where *DD* may be problematic. In the Trangie district EM38-v signal readings are generally less than 100 mS/m adjacent to a water reservoir (Easting 613000, Northing 6560000) where a shallow water table and soil salinisation was first reported in the early 1980's.

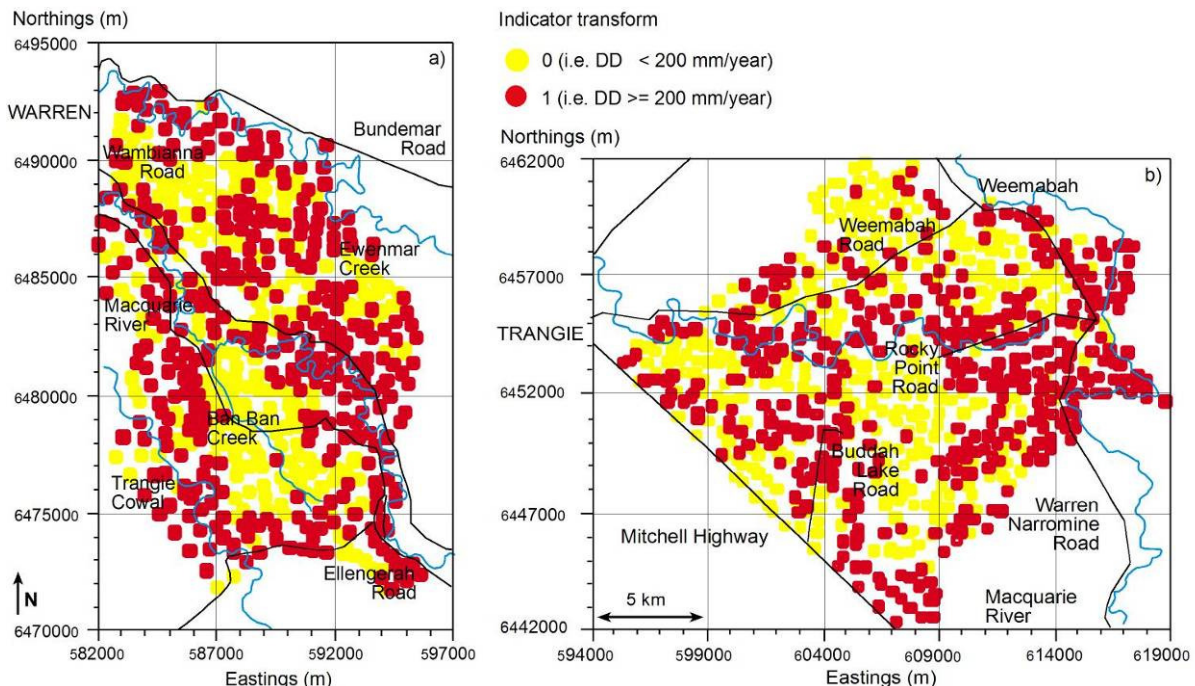


Figure 20. Location of EM38 survey positions where deep drainage (*DD*) is predicted to exceed critical cut-off value of 200 mm/year (red) if 1,800 mm/year of irrigation water (*I*) was applied and 494 mm/year of mean annual rainfall (*R*) assumed in (a) Warren and (b) Trangie districts.

On reviewing Figure 18 it is evident that 100 mS/m equates to a *DD* value of around 200 mm/year. Considering the fact that anecdotal evidence suggests losses are occurring from this particular reservoir, this value was used as the critical value to map. The estimated *DD* data was then transformed into values of 0 and 1. That is, if the estimated *DD* did not exceed 200 mm/year a value of 0 was assigned. Conversely, if estimated *DD* was equal to or exceeded 200 mm/year it was assigned a value of 1. Figure 20 shows a plot of where *DD* does (red shade) and does not (yellow shade) exceed the critical value of 200 mm/year if 1,800 mm/year of irrigation water (*I*) was applied and 494 mm/year of mean annual rainfall (*R*) assumed. With respect to where *DD* would be exceeded, approximately 53 and 51 % of the EM38-v measurement sites met these criteria in the Warren and Trangie districts, respectively.

In order to produce a map of the conditional probability (CP-or risk) that *DD* would exceed 200m mm/year at sites where EM38-v measurements were not made, we interpolated this data (*i.e.* 0 and 1) onto a grid of 150 m. The results are shown in Figure 21. The white areas indicate where the risk is low (*i.e.* CP < 0.5) and where *DD* is least expected to be greater than 200 mm/year. As such these areas indicate locations in the Warren and Trangie districts where the most suitable areas to locate a supply channel and/or shallow earthen water reservoir.

In the Warren district the largest contiguous area of low risk is located in the central southern part between the Macquarie River and Trangie Cowal. In the Trangie district low risk areas include the central northern and southern parts. Conversely, the red shaded areas indicate where *DD* is most likely to exceed 200 mm/year and where the risk (*i.e.* CP > 0.9) is highest. With respect to the water reservoir, where salinisation was first noted in the Trangie district, the results of *DD* risk is consistent with the experiences of management at this site. It should be noted that this reservoir is no longer used to store water long-term and is only used for collecting water from heavy rainfall events. This has mitigated the problem in most seasons, although in very wet years some areas are still affected.

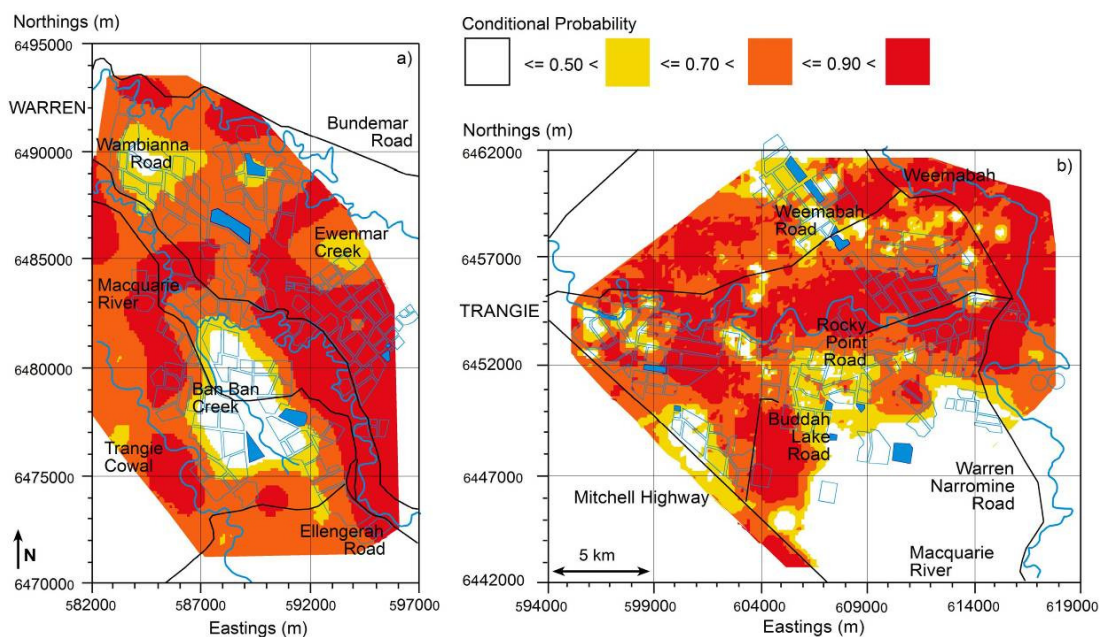


Figure 21. Map of conditional probability (CP) that soil at a particular site will exceed an estimated deep drainage (*DD*) value of 200 mm/year if 1,800 mm/year of irrigation water (*I*) was applied and 494 mm/year of mean annual rainfall (*R*) assumed in (a) Warren and (b) Trangie districts.

It is worth noting that areas where *DD* risk is highest may explain why certain landholdings, (eg. south of Rocky Point Road and adjacent to the Macquarie River in the Trangie district), were never developed for flood-irrigated cotton production. The risk map, shown in Figure 21b, also sheds light on the issue of water use efficiency. For example, south Rocky Point Road, some of the fields are potentially of high *DD* risk (*i.e.* $CP > 0.9$). However, two of the fields located in the high-risk zone were developed to apply water using centre pivots, hence maximising water use efficiency. In comparison, a larger portion of the Warren district falls within the category of highest risk (*i.e.* $CP > 0.9$). However, as with the Trangie district most of the irrigated fields appear to be located in areas where *DD* risk is lowest. Where this is not the case, field sizes are smaller than those located in other parts of the district and hence water use efficiency issues were considered during development.

The high-risk zones shown are also consistent with known areas of leakage, from supply channels and water reservoirs, where waterlogged and saline soil conditions have occurred. The best example of this in the Trangie district is adjacent to Rocky Point Road, where a major supply channel has produced these adverse conditions in the past. However, and in recognition of these problems, management strategies were implemented to minimize *DD* losses and hence groundwater accretion. For example, the supply channels in this part of the farm are only used during the irrigation (summer) season. In addition, saltbush has also been planted in strips parallel with the supply channel in order to use water that permeates laterally from the channel and hence prevent water logging and soil salinisation of the adjacent fields.

In the Warren district it is also evident that most of the area has a conditional probability exceeding 0.7. Where this is not the case is the area either side of Ban Ban Creek. In this area isolated point source salinisation has been problematic. As a consequence the EM values recorded here were the highest and influenced by the saline soil conditions. As a result the relationship established between EC_a (EM38v) and estimated *DD* (mm/year) may not valid in this area, because most of the sites used to establish the relationship were not affected by saline conditions. It is recommended that further work be carried out to ascertain the *DD* risk in this area using an alternate approach.



Figure 22. a) Soil salinisation evident in an irrigated cotton field in the Trangie irrigation district, b) groundwater table height indicator between Warren and Trangie irrigation districts and c) saline scald adjacent to a water reservoir in the Warren irrigation district.

Maps of average clay content and stored salt

The results shown above suggest deep draining water has the potential advantage of mobilising near surface salt stores, deeper into the vadose zone. Conversely, the deep draining water may interact with saline sediments laid down in earlier geological times and held in or associated with less permeable sediments. This is the case in the Bourke Irrigation district, which is underlain with Cretaceous marine mudstones. This may result in mobilisation of stored salts into the root zone via a rising water table. In order to understand where sufficient salts may be stored and where slowly permeable clay sediments may exist in the Warren and Trangie irrigation districts, maps of each of these attributes needed to be developed.

Figure 23 shows the spatial distribution of average clay content (0-7 m). The red and orange shades indicate where average clay content is less than 30 and 40 %, respectively. In both areas, this coincides with the Trangie Cowal and Macquarie River as well as the meander plain of the Old Alluvium Pedoderm in the southern part of the Warren district and southeast of Trangie (see Figure 14). Clay content is similarly low in the northern part of the Warren district (*i.e.* Ewenmar Creek). Conversely, clay content is higher (*i.e.* > 40 %) in the area southwest of Rocky Point Road in the Trangie district as well as the area either side of Ban Ban Creek in the central and southern part of the Warren district. In some places average clay content exceeds 50 % throughout. Overall it is evident that the Warren district is on average and to a depth of 7.0 m clayier in nature than Trangie. It should also be noted that whilst the map shown for the Trangie area below is equivalent to that of Figure 8, it was generated using a slightly different method. Nevertheless the results are not too dissimilar and either could be used to develop a Composite Salinity Hazard map as shown in Figure 25. From a practical soil/water management stand point it is worth noting that for the most part the large earthen water reservoirs have been constructed in locations where average clay content is greater than 40 %. However, in many instances these reservoirs are located in areas susceptible to *DD* risk (see Figure 21). This is the case near the small water reservoir, south of Weemebah Road in the Trangie area where soil salinisation was first reported.

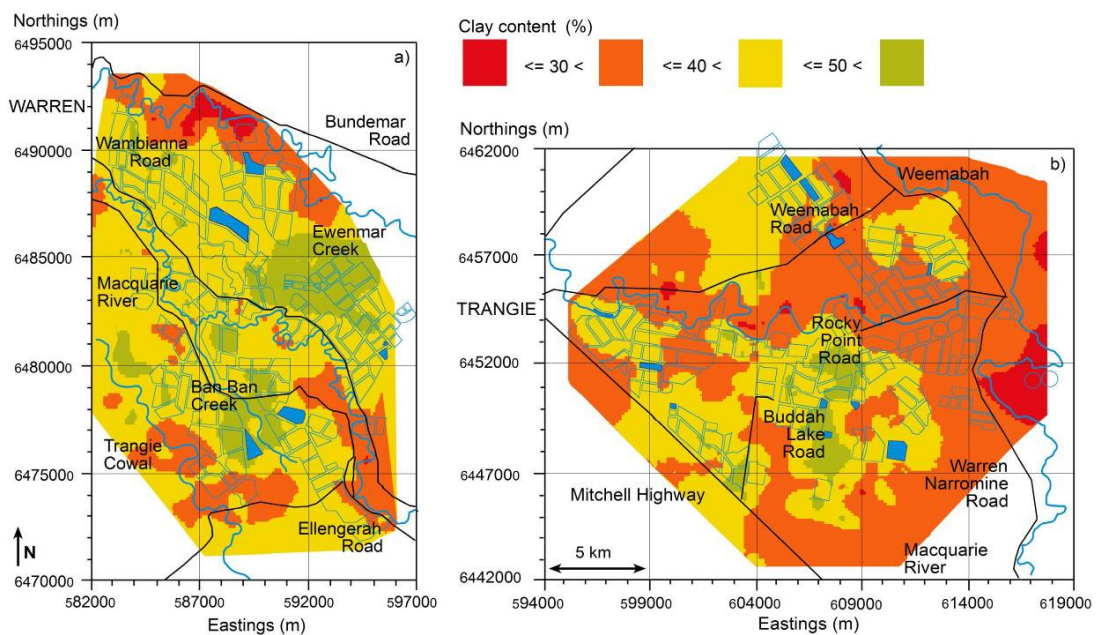


Figure 23. Map of predicted average clay content (%) to 7 m in a) Warren and b) Trangie areas.

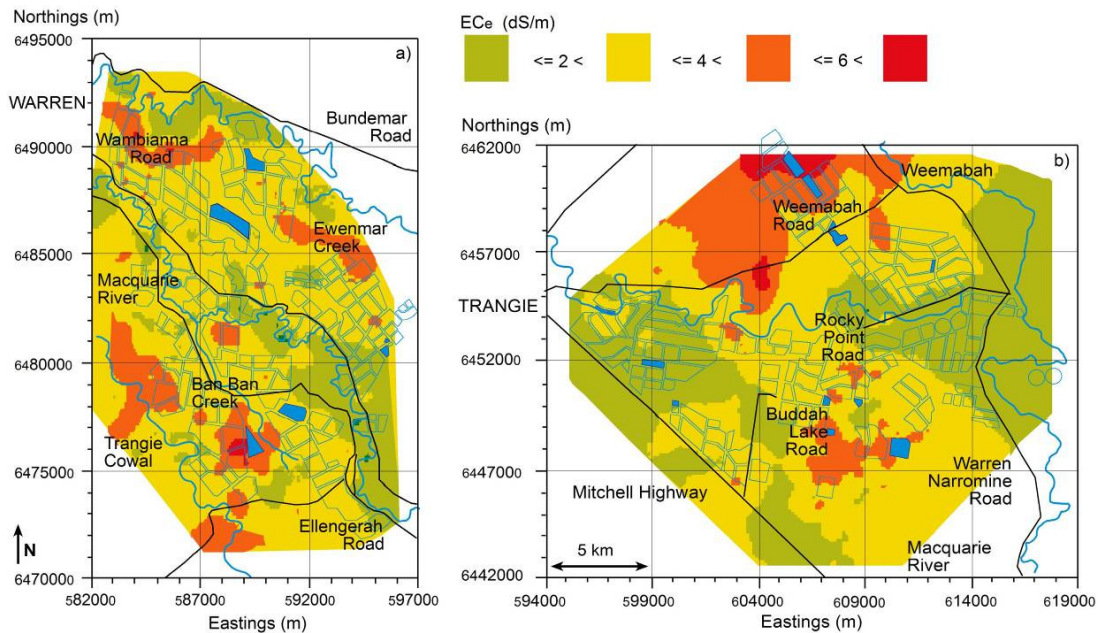


Figure 24. Map of predicted average EC_e (dS/m) to 7 m in a) Warren and b) Trangie study areas.

The areas of higher average clay content also contain the largest stores of salt. This is evident in Figure 24, which shows the spatial distribution of average EC_e content to a depth of 10 m. This is the case in the area southeast of Trangie and in the central northern and southern parts where average EC_e is greater than 4 dS/m (*i.e.* orange shaded areas). In the Warren area the largest concentration of EC_e is evident south of Ewenmar Creek and associated with the Trangie Cowal Pedoderm in the southern part of the district. This is particular the case adjacent to one of the major water reservoirs where isolated point source salinity has been problematic since in the early 1980's.

Predicting salinisation potential

The onset of soil salinisation in irrigated agricultural systems can arise as a result of poor water use efficiency and creation of shallow saline water tables. In the irrigated cotton growing districts southeast of Trangie and Warren it is thought that this occurs because of excessive *DD* from water reservoirs and supply channels. Impeding subsurface clay horizons impede groundwater recharge and lead to the creation of perched water tables and mobilization of stored salts into the root zone. In order to ascertain whether the biophysical maps produced in Section 4.2.2.6 could be used to identify where salinisation might occur the various layers of information generated were queried (*i.e.* *DD* risk map, clay content, *etc.*). The first step was intuitive and involved looking at the root- and vadose-zone attributes where perched water tables and salinisation are already problematic.

The best example of this is in the Trangie district near a small reservoir located between Weemabah and Rocky Point Roads. It was here that isolated instances of soil salinisation first became apparent in the early 1980's. At this site the risk (*i.e.* *CP*) of *DD* exceeding 200 mm/year beneath a water reservoir was between 0.7 and 0.9. However, a risk of 0.5 was considered a more suitable value of this data layer given that a nearby reservoir also has some minor risk of excessive deep drainage ($CP > 0.5$) associated with it and is known to lose significant amounts of water. The value considered critical in terms of average clay content and salt store were 38 % and 2.5 dS/m, respectively. That is, if the average clay content to a depth of 7 m was > 38 %, it can be surmised this might cause impeded drainage

and hence create a perched water table capable of mobilising stored soluble salts. Similarly, where $EC_e > 2.5$ dS/m sufficient salts are present in the profile (and above the perched layer) to concentrate in the root zone and result in soil salinisation. Again these conditions were consistent with those where soil salinisation first became evident in the Trangie district.

The orange shaded areas in the map shown in Figure 25 indicate where the above conditions have been met. That is:

- a) *DD* risk is greater than 0.5 when considering location of reservoirs
- b) Average clay content > 38 %
- c) Average salt store > 2.5 dS/m.

The maps are essentially Composite Salinity Hazard maps, but unlike those generated by State Government Agencies, were generated using biophysical data layers at the district scale and not using any weighting functions based on expert judgement. They indicate where soil salinisation may occur, based on the above criteria and if a reservoir is built in the Warren and Trangie districts. In the Trangie district the result is consistent with the water reservoir where the criterion was derived. That is between Weemabah and Rocky Point Roads. More significantly the map is validated somewhat by indicating similar problems of salinisation would arise in fields northwest of the leaking reservoir. Here losses from irrigation head ditches/supply channels may be the cause. In the Warren district the result is similarly consistent with localised point source salinisation. This is the case with respect to the reservoir in the southern part of the district. Here similar incipient salinisation was reported in the early 1980's. The map however, was not consistent with salinisation to the west of one of the reservoir. This is due to the EM38-v signal data being influenced by higher salinity (Figure 24) rather than low clay content. The result is similarly consistent with and validated by the isolated point source salinisation associated with a water reservoir in the central part of the Warren district.

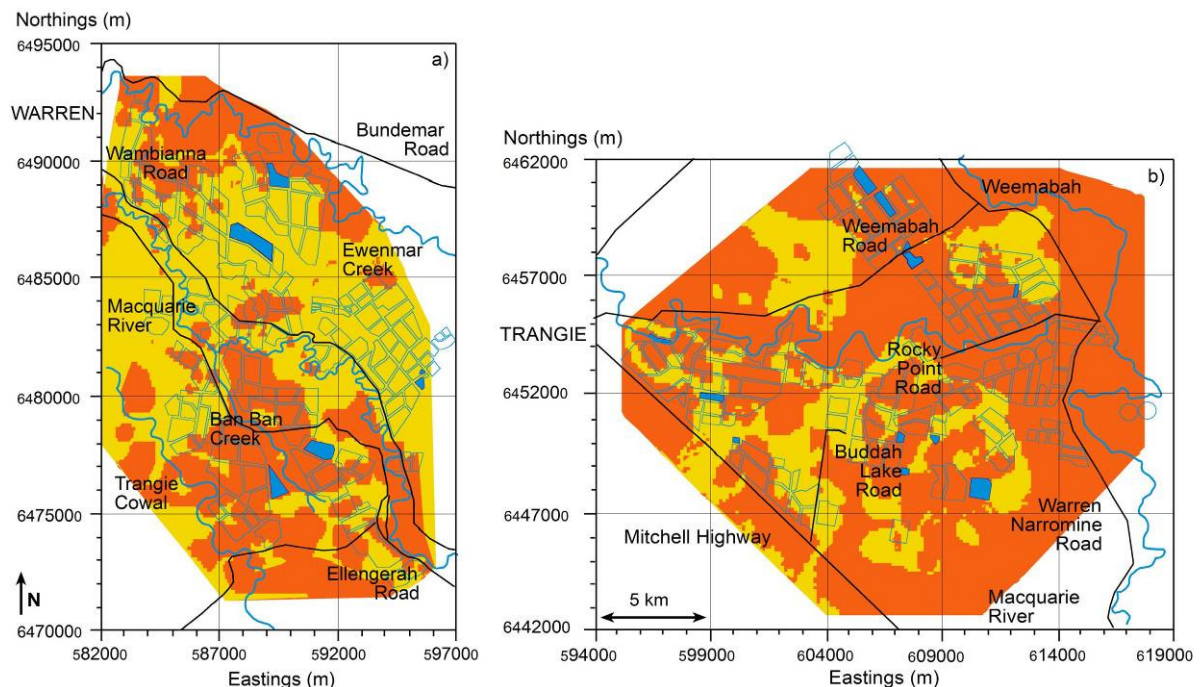


Figure 25. Map of predicted average EC_e (dS/m) to 7 m in a) Warren and b) Trangie study areas.

Outcomes

The project was heavily geared toward generating and interpreting natural resource management information in key districts for development of Salinity Hazard maps. These areas were studied because of the fact that each is indicative of the alluvial clay plain landscapes, which have been developed extensively for dryland and irrigated agricultural production in the northern Murray-Darling Basin and because of the extensive nature of irrigated cotton developments. The development of biophysical layers and the publication of GIS of the interpreted results will enable comprehensive delivery of results of this project to various end-users. The major beneficiaries will include:

1. Landholders, consultants and community groups (eg. Macquarie 2100), who can use the information for improved understanding of natural resource management issues relevant to each of the seven districts, with landholders able to incorporate results in developing Irrigation and Drainage Management Plans;
2. Extension officers, agency staff (eg. NSW Agriculture) and Catchment Management Boards, who can use the information to identify research priorities and in policy development; and,
3. Research organisations (eg. CSIRO Land and Water, CRC's and Universities) that can use the results generated or methods developed (i.e. spill over benefits).

Conclusion

The maps of conditional probability and associated conclusions drawn from the maps shown in Section 4.2.2.5 require some caution. In the first instance this is because the estimates of *DD* are based on a relationship established between a salt-water balance model (SaLF) and EM38-v signal data. The EM38-v signal data was collected at the height of summer in dryland and irrigated fields. Consequently, measurements were not made under uniform soil moisture conditions. This is significant in areas where EM38-v signal data lies between 75 and 125 mS/m. Here, and as shown in Figure 18, the 4-parameter exponential model used to establish a relationship between *DD* (SaLF estimate) and EM38-v signal data, increases exponentially. So that EM38-v signal data collected either side of a fence line that divides essentially the same soil type but is managed differently (i.e. dryland and irrigated), will result in slight to significant differences in instrument response. In some cases, this might suggest moist irrigated soil is clayier and hence less predisposed to *DD* than in adjacent dryland field. In reality, however, they are both likely to be susceptible to *DD*. In addition, and as alluded to above, in saline areas the EM38-v signal data response may be a function of higher salt content rather than high clay content. This would lead to an estimate of lower *DD*. If in fact, clay content is low the high risk in *DD* is masked by the saline soil condition. This is the case south of Ban Ban Creek in the Warren district. The result is a false positive. That is, the Composite Salinity Hazard would be low when in fact it should be high.

Secondly, there are some errors associated with the spatial variability of the EM38-v signal data collected and the sampling interval used (i.e. 500 m). In terms of decreasing the prediction variance there are several choices. The first is decreasing the ground-based EM38 survey interval from 500 to 250 or even 125 m. Although this would be a time consuming proposition, the information would be useful in improving the cause and management of soil and water salinisation in the irrigated cotton growing areas associated with the Trangie Cowl (alluvium). Alternatively, airborne EM systems could be deployed to increase the EM survey resolution, or other types of ancillary information (i.e. gamma radiometric, LANDSAT, RADARSAT, etc.) might be incorporated into the modelling process. In addition and where

appropriate a Mobile Electromagnetic Sensing System (MESS - Figure 26a) may be deployed to generate more detailed field or reservoir scale information to better discern the spatial distribution of soil types susceptible to *DD*. Figure 27 shows how EM31 signal data can be used to assist with identifying location of suitable sampling sites with the detailed methodology described by Triantafilis *et al.* (2001) and Triantafilis *et al.* (2004) for an irrigated cotton growing field in the lower Gwydir valley.



Figure 26. Assessing spatial distribution of root and vadose zone properties of sediments using a) Mobile Electromagnetic Sensing System (MESS), b) EM34 and c) direct electrical methods.

Nevertheless, the maps of conditional probability (Figure 20) produced using indicator kriging, illustrates at the district scale areas where problems with *DD* are most likely to be occurring. The areas exhibiting the largest probability of excessive *DD* (*i.e.* > 50 mm/year) using the various water application volumes (*i.e.* $I = 1,800$ mm), corresponded to permeable soil types associated with the Trangie Cowl, Contemporary Macquarie and meander plain of Old Alluvium Pedoderms (Figure 14). As a result the methodology developed here indicates where a more strategic approach may need to be implemented at the district and field scale when considering options to improve irrigation efficiencies and water delivery southeast of Warren and Trangie. This is particularly the case with the location of water reservoirs, head ditches and supply channels, which are currently, located in high risk areas. As alluded to previously MESS surveys can be carried out using in association with the equation derived from Figure 18 to estimate *DD* and map risk of exceeding a critical value (*i.e.* $DD > 200$ mm/year). Some caution is required when using these equations outside of the area studied as differences in clay mineralogy in particular would lead to the need for derivation of model and instrument calibration. In areas deemed to be at high risk, possible management options include lining channel in these areas with bentonite curtains to improve water delivery or rerouting infrastructure through areas that have lower risk. Otherwise these structures should only be used in conveying water during the irrigated season.

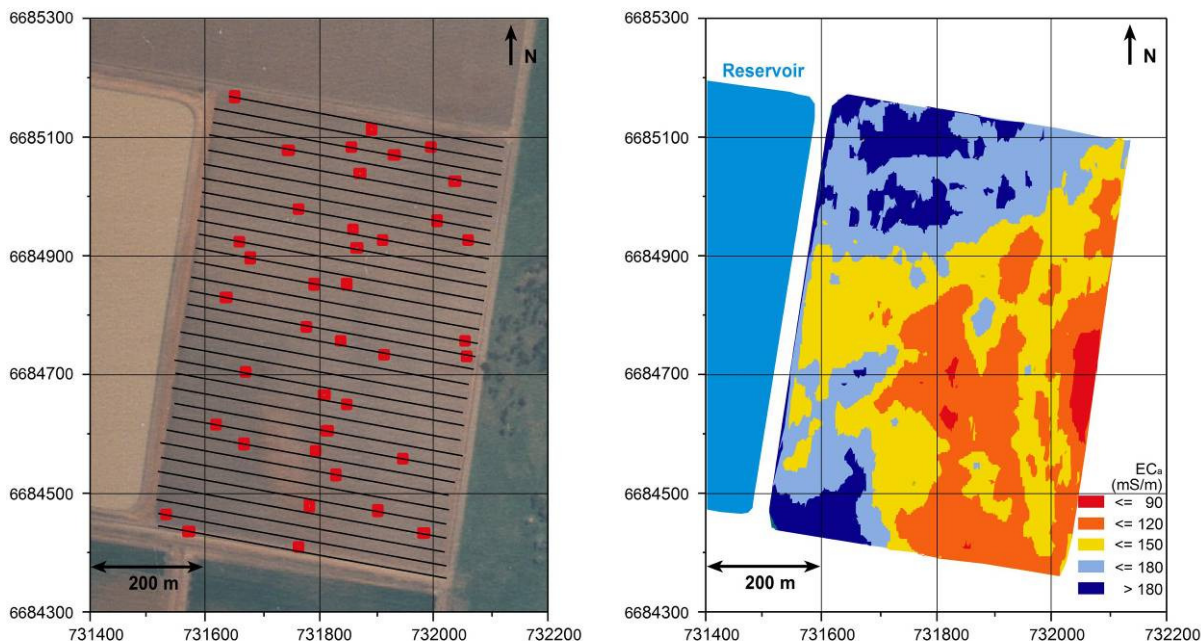


Figure 27. Map of a) air-photo, Mobile Electromagnetic Sensing System (MESS) transects and soil sampling sites required for calibration, and b) spatial distribution of EM31-v signal data in an irrigated cotton growing field in lower Namoi valley.

The spatial distribution of vadose zone properties such as average clay content (0-7 m) and stores of salt (0-10 m) were useful in identifying values consistent with presence of perched water tables (*i.e.* clay content > 38 %) and sufficient salt stores (*i.e.* $EC_e > 2.5$ dS/m) to cause soil salinisation. The production of a map where all these features occurred and developed from knowledge about the causes of salinisation at one site enabled a map of where storages might lead to salinisation being developed. The results were consistent with where salinisation has occurred in both Warren and Trangie districts. The final map also suggests that the cause of salinisation is similar and that the management practices developed to live with and manage salinisation in the Trangie district are most likely transferable to where salinisation has occurred in the Warren district. That is extension of best management practices developed in Trangie can be extended to Warren.

The final biophysical data layers and hazard map can be used as a guide to assist with decision-making with regard to location of water reservoirs.

In addition and where appropriate direct electrical methods (**Figure 26c**) and instrumentation (*i.e.* Zhong Electrical Device) could be used to discern spatial and temporal variation in groundwater height and salinity concentrations (Turner and Acworth 2004; Acworth *et al.* 2005; Acworth *et al.* 2006).

Extension Opportunities

Soil salinisation is the process whereby soluble salts accumulate in the root-zone. It results as a function of complex interactions between various biophysical factors, including agronomy, geology, hydrology, climate and topography. As demonstrated in the series of projects entitled “*Understanding the salinity threat in the irrigated cotton growing areas of Australia*” small and large quantities of stored salts are present in ancient sediments beneath several irrigated cotton districts. In the Bourke Irrigation District, irrigation inefficiencies have resulted in the mobilisation of some of these stored ancient salts into the root zone. This is similarly the case in the lower Macquarie valley. In both cases shallow water tables have developed in isolated instances and generally in association with water reservoirs and supply

channels. In comparison and although similar irrigation inefficiencies occur in the lower Macintyre, Gwydir and Namoi study areas, there are no multiple-field scale examples of soil salinisation despite the fact that water logging and in some cases shallow water tables occur in isolation in some of these districts.

The results shown in Section 4 and described previously in Final Report of “*Understanding the salinity threat in irrigated cotton growing areas of Australia - Phase III – Implementation and Management*”, point to the following recommendations:

To further develop or to exploit the project technology

- 1) On the field-scale:
 - a) Deploy a Mobile Electromagnetic Sensing System (MESS) to determine specific cause and management of soil salinisation in Bourke, Trangie and Warren districts;
 - b) Conduct detailed resistivity surveys adjacent to large earthen reservoirs and supply channels to assess changes in groundwater table heights as a function of seasons.
- 2) On the district-scale:
 - a) Extend existing piezometer network in the Bourke Irrigation District, and using MODFLOW, model how saline shallow groundwater interacts with the Darling River near Bourke and how irrigation may contribute to the problem;
 - b) Install a piezometer network in the Warren and Trangie Irrigation Districts in order to collect and then model how saline shallow groundwater interacts with the Macquarie River and how irrigation may contribute to the problem;
 - c) Estimate groundwater recharge rate in various irrigated cotton growing areas (eg. lower Macintyre, Gwydir and Namoi valleys) using a simple chloride mass balance model;
 - d) Extend the methods to Hillston, Collarenebri, Dirranbandi and St George where no detailed vadose zone (0-15 m) information exists.
- 3) Continue to value add to the information collected as part of the series of projects entitled “*Understanding the salinity threat*” by development of equivalent Salinity Hazard Maps for various cotton growing areas where soil and vadose zone information has been collected.

Future presentation and dissemination of the project outcomes

- 1) Extend and interpret the results and data from Phase III and IV for improved natural resource management through:
 - a) Development of a Geographic Information System (GIS) of data collected;
 - b) Development of a Web page to allow extension officers and growers access to demonstrated case studies and the ability to query the data stored in the GIS;
 - c) Publications in Australian and International soil, water and GIS related journals;
 - d) Publications in industry journals and periodicals (*i.e.* Australian Cotton Grower and ACGRA Cotton Conference Proceedings).

Publications

International Journals;

- i. Triantafilis J Ahmed MF and Odeh IOA 2002. Application of a mobile electromagnetic sensing system (MESS) to assess cause and management of soil salinisation in an irrigated cotton-growing field. *Soil Use and Management* 18, 330-339.
- ii. Triantafilis J Huckel AI and Odeh IOA 2003. Field-scale assessment of deep drainage risk. *Irrigation Science* 21, 183-192.
- iii. Triantafilis J Odeh IOA Minasny B and McBratney AB 2003. Elucidation of physiographic and hydrogeological units using fuzzy k-means classification of EM34 data in the lower Namoi valley. *Environmental Modelling and Software* 18, 667-680.
- iv. Odeh IOA Todd AJ and Triantafilis J 2003. Spatial prediction of particle size fractions as compositional data. *Soil Science* 168, 501-515.
- v. Triantafilis J Odeh IOA Warr B and Ahmed MF 2004. Modeling and mapping the impact of saline water use in the lower Namoi valley. *Agricultural Water Management* 69, 203-231.
- vi. Triantafilis J Odeh IOA Jarman AL Short M and Kokkoris E 2004. Estimating and mapping deep drainage risk at the district level in the lower Gwydir and Macquarie valleys, Australia. *Australian Journal of Experimental Agriculture* 44, 893-912.
- vii. Triantafilis J and Lesch SM 2005. Estimating clay content at the district-scale using electromagnetic (EM) induction survey data and geo-statistical modeling techniques. *Computers and Electronics in Agriculture* 46, 203-239.

Conference Proceedings;

- i. Triantafilis J Odeh IOA Short M and Ahmed MF 2002. Mapping deep drainage risk in the lower Gwydir and Macquarie valleys. (Ed. B.G. Sutton) *Irrigation Australia Conference Proceedings: Conservation or Conflict?* Darling Harbour-Sydney NSW, May 21-23. pp 322-329.
- ii. Odeh IOA Triantafilis J and McBratney AB 2002. The Australian Cotton Soil Database: a simple database assistant for managing soil information. Proceedings of the *11th Australian Cotton Growers Research Association Conference: "Field to fashion"*. Brisbane, Queensland, August 13-15. pp 491-494.
- iii. Triantafilis J Ahmed MF Odeh IOA and Warr B 2002. Soil salinisation risk assessment using saline water in the lower Namoi valley. Proceedings of the *11th Australian Cotton Growers Research Association Conference: "Field to fashion"*. Brisbane, Queensland, August 13-15. pp 495-508.
- iv. Triantafilis J Odeh IOA Huckel AI Short M Ahmed MF 2002. Mapping deep drainage risk at the field and district levels in the lower Gwydir valley. Proceedings of the *11th Australian Cotton Growers Research Association Conference: "Field to fashion"*. Brisbane, Queensland, August 13-15. pp 555-570.
- v. Triantafilis J Buchanan S Short M and Malik R 2002. Measuring and mapping subsurface salinisation in the Darling River Valley. (Oral paper 1806, Symposium 34 - Salinization, water management and policy). Proceedings of the *17th World Congress of Soil Science*. Bangkok, Thailand. August 15-21.
- vi. Buchanan SM Triantafilis J 2004. Wet Roots. Groundwater and salinity mapping in the Bourke Irrigation District. Proceedings of the *12th Australian Cotton*

- Growers Research Association Conference: "Quality Cotton-Not just another yarn". Brisbane, Queensland, August 10-12.*
- vii. Triantafilis J Odeh IOA 2004. Determine salinisation potential in the lower Macquarie valley. Proceedings of the *12th Australian Cotton Growers Research Association Conference: "Quality Cotton-Not just another yarn"*. Brisbane, Queensland, August 10-12.
 - viii. Odeh IOA Cattle SR Triantafilis J McBratney AB 2004. The Australian Cotton Soil Database and Geographic Information System. Proceedings of the *12th Australian Cotton Growers Research Association Conference: "Quality Cotton-Not just another yarn"*. Brisbane, Queensland, August 10-12.
 - ix. Triantafilis J Williams D 2004. Assessing and managing irrigation salinity: including EM surveying. In *WATERpak: a guide for irrigation management in cotton*. pp 235-258.

Magazine Articles;

- i. Triantafilis J Short M and Odeh IOA 2004. Identifying deep drainage risk areas in the lower Gwydir valley. *The Australian Cotton Grower*, Toowoomba, Queensland, Jan-Feb. pp. 19-22.
- ii. Triantafilis J Buchanan S Short M and Malik RS 2004. Mapping subsurface saline material in the Bourke Irrigation District. *The Australian Cotton Grower*, Toowoomba, Queensland, Jan-Feb. pp. 58-61.
- iii. Buchanan S Triantafilis J 2004. Wet Roots? Groundwater Mapping at the Farm Scale- A Case Study in the Bourke Irrigation District. *The Australian Cotton Grower*, Toowoomba, Queensland, Jan-Feb. pp. 58-61.

Online resources

The developed biophysical layers and Salinity Hazard maps for each of the seven districts will be incorporated into Arc-GIS. Using Arc-IMS software these individual GIS's will be published on the World Wide Web (*i.e.* Web-GIS). The proposed website address is www.soil.unsw.edu.au. The site is currently not active but it is envisaged that once placed online the address will enable comprehensive delivery of interpreted results of this project to various end-users. The web-GIS is being developed as part of an ongoing research project which is due for completion in 2007. The project is entitled "*Web-GIS development for Natural Resource Management in the northern Murray Darling Basin.*" It is funded through the Natural Heritage Trust's (NHT) – Nationally Competitive Component (NCC). The project is administered by the Australian Federal Government's Department of the Environment and Heritage. An example of the type of biophysical information being generated for each of the seven districts is exemplified by the two study districts in the lower Macquarie valley (*i.e.* Trangie and Warren). Figure 29, 30 and 31 show, respectively the location of the soil and vadose sampling sites, spatial distribution of EM38 signal data and irrigated infrastructure in both districts. Figures 32-34 show the various individual biophysical data layers developed (see Q4) to calculate a composite Salinity Hazard Map. This includes the deep drainage risk map (Figure 32), salinity stored in the vadose zone (Figure 33) and clay content (Figure 34). Question 11 shows equivalent information generated for the Toobeah district (lower Macintyre Reiver valley). Appendix B shows similar biophysical data layers that have been developed for the Bourke Irrigation District.

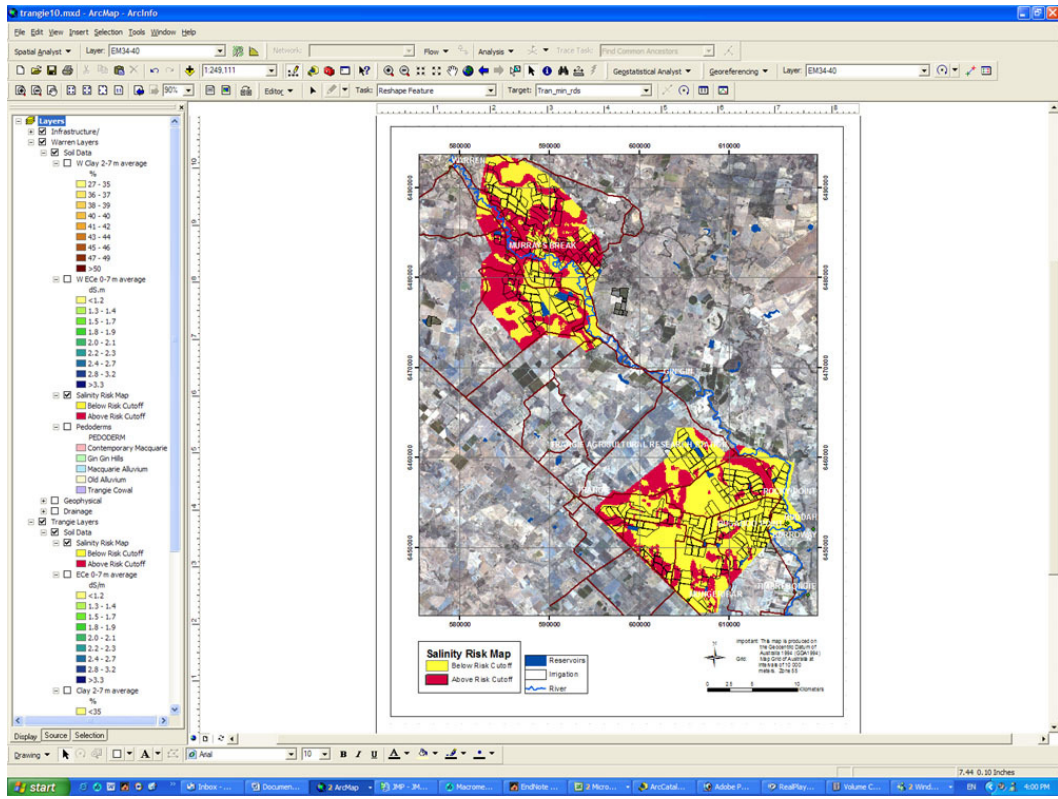


Figure 28. Spatial distribution of Salinity Hazard (red areas) across the irrigated cotton growing areas of Warren and Trangie districts in lower Macquarie valley, if

- i) Deep drainage (*DD*) risk for location of water reservoirs > 250 mm/annum
- ii) Average salt store to a depth of 0-7 m > 2.0 dS/m, and
- iii) Average clay content to a depth of 2-7 m > 35 %.

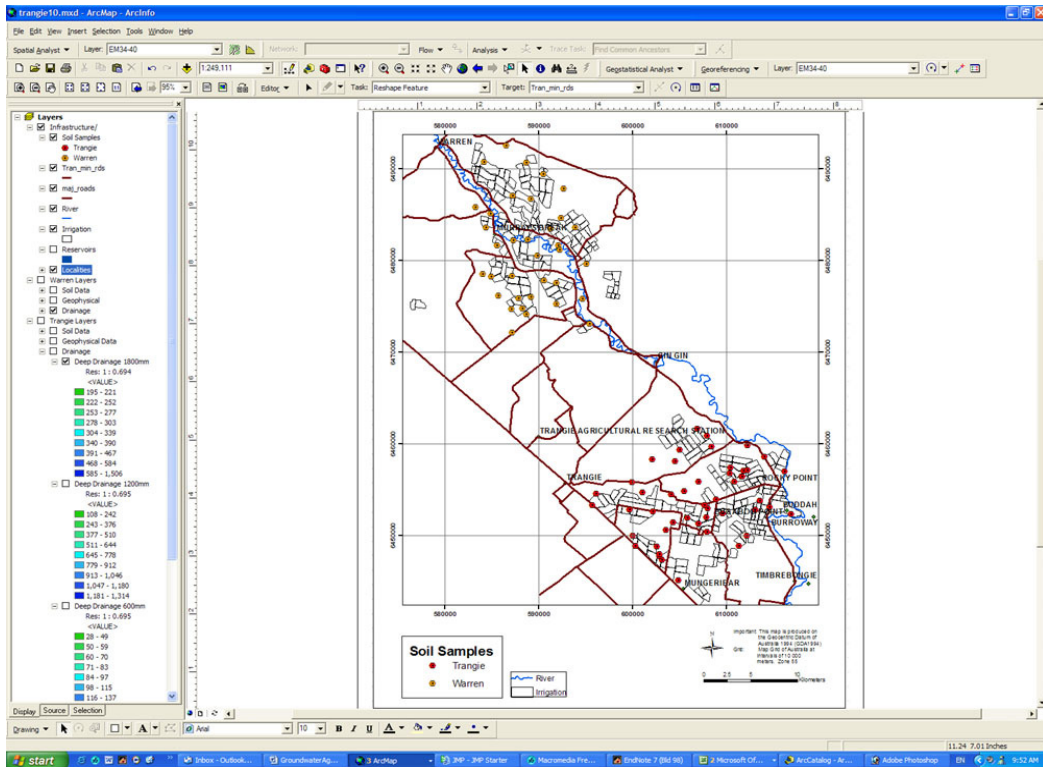


Figure 29. Spatial distribution of soil and vadose sample locations

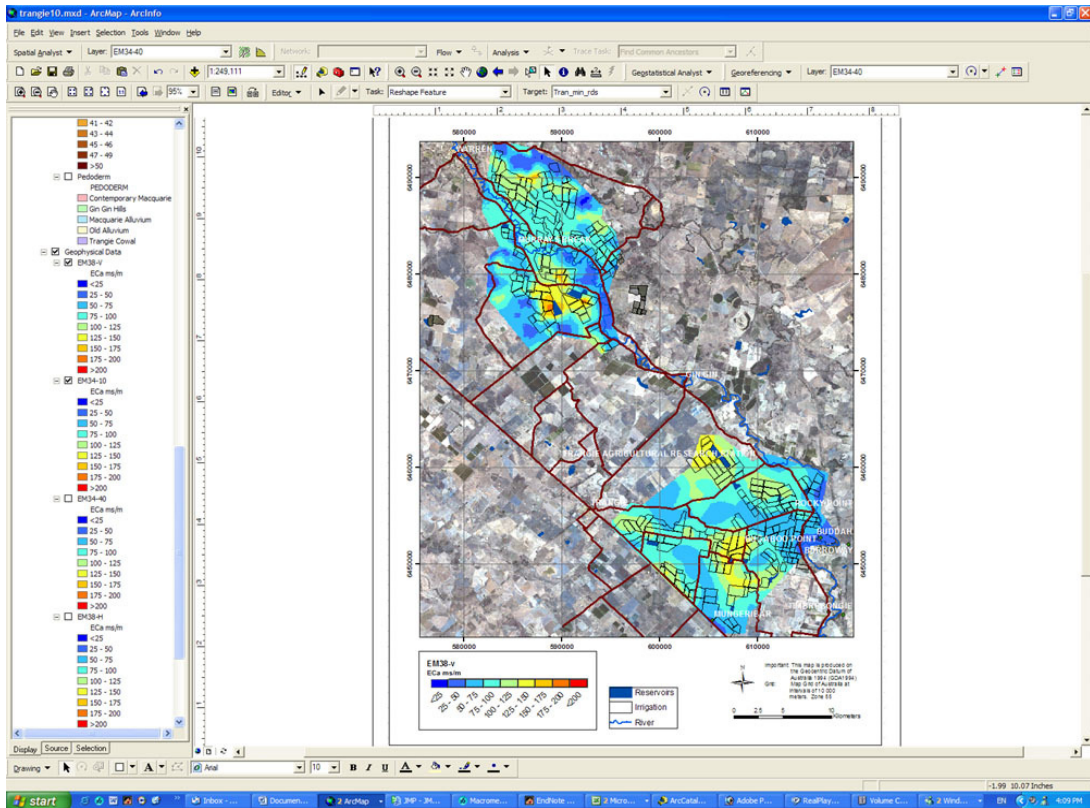


Figure 30. Spatial distribution of EM38 data (vertical mode) collected in lower

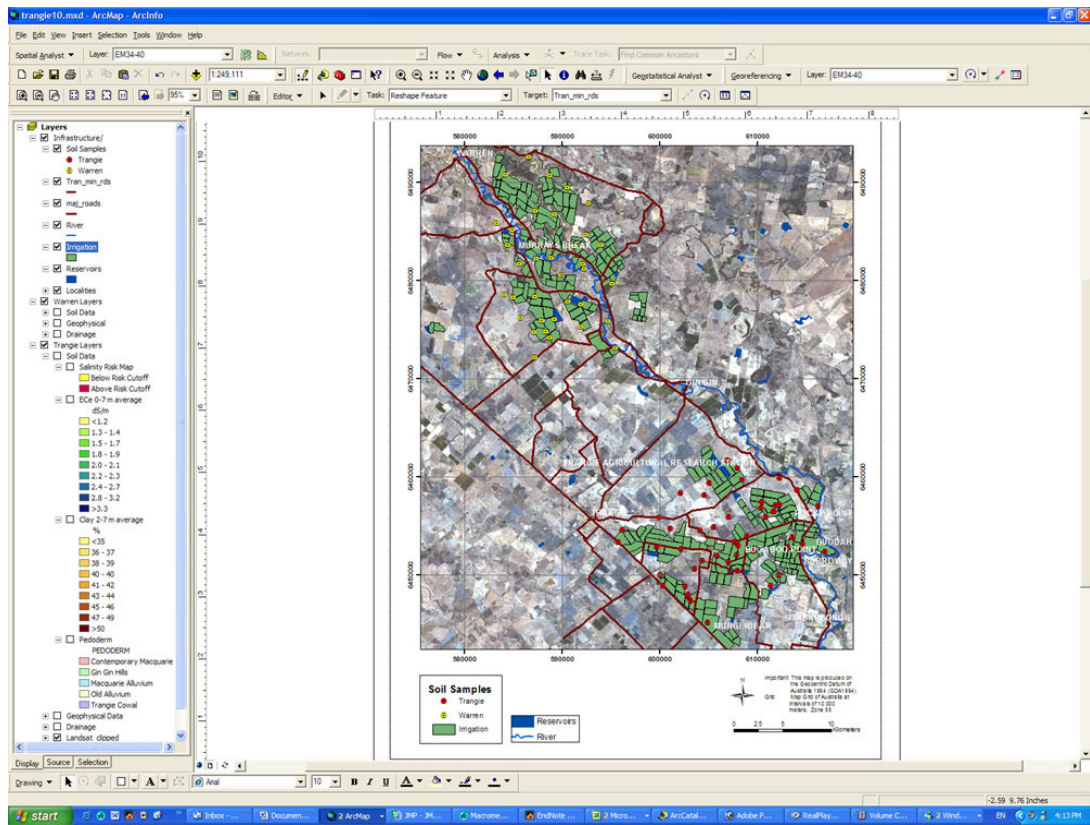


Figure 31. Location of irrigated infrastructure and cadastral data

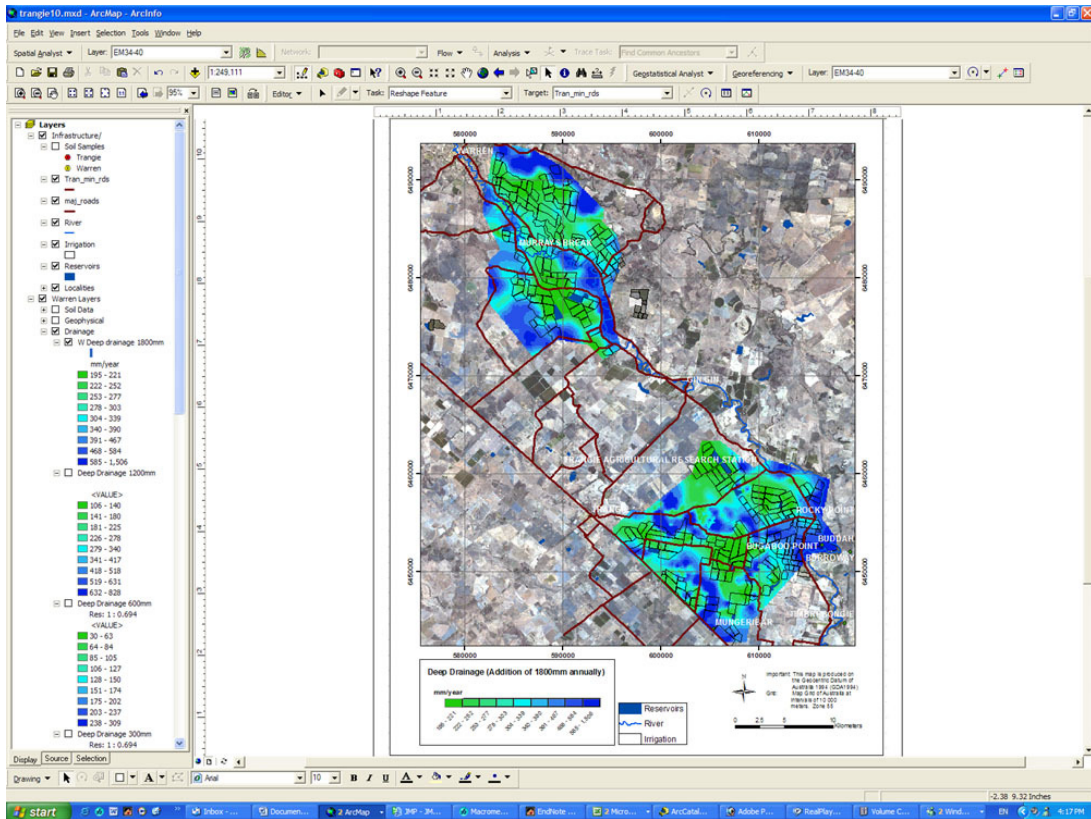


Figure 32. Spatial distribution of deep drainage risk for location of water reservoirs

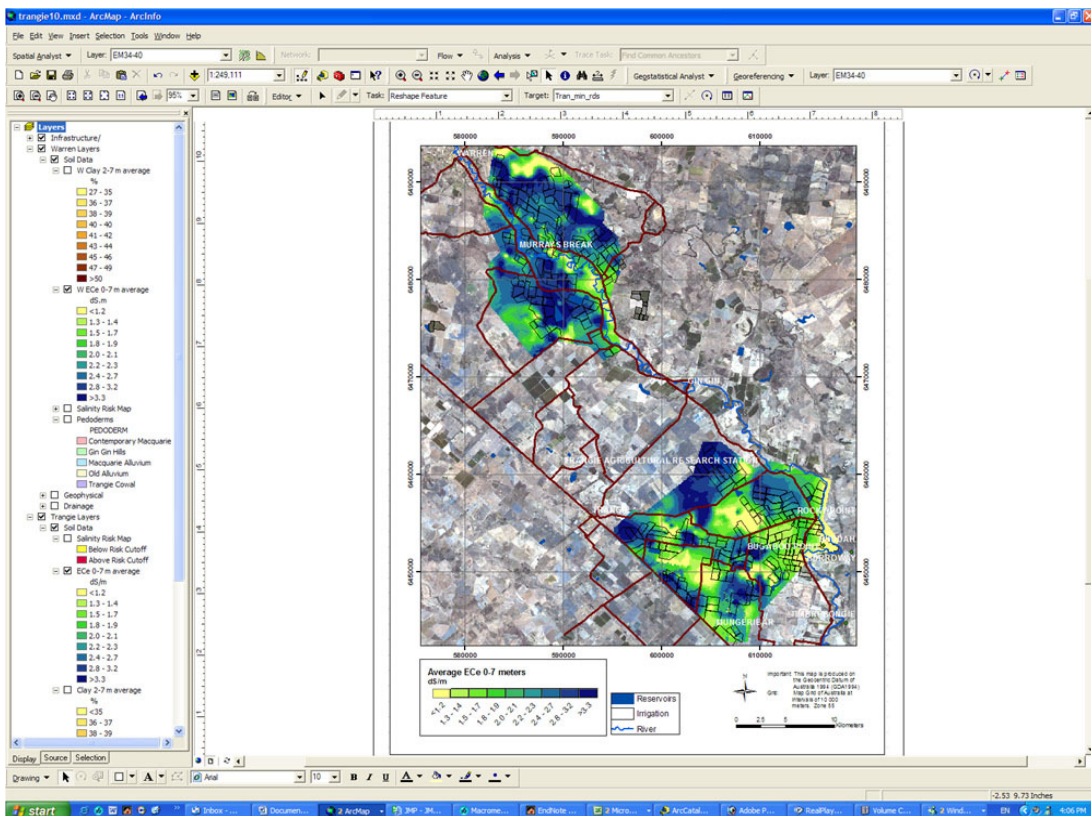


Figure 33. Spatial distribution of average salt store to a depth of 0-7 m

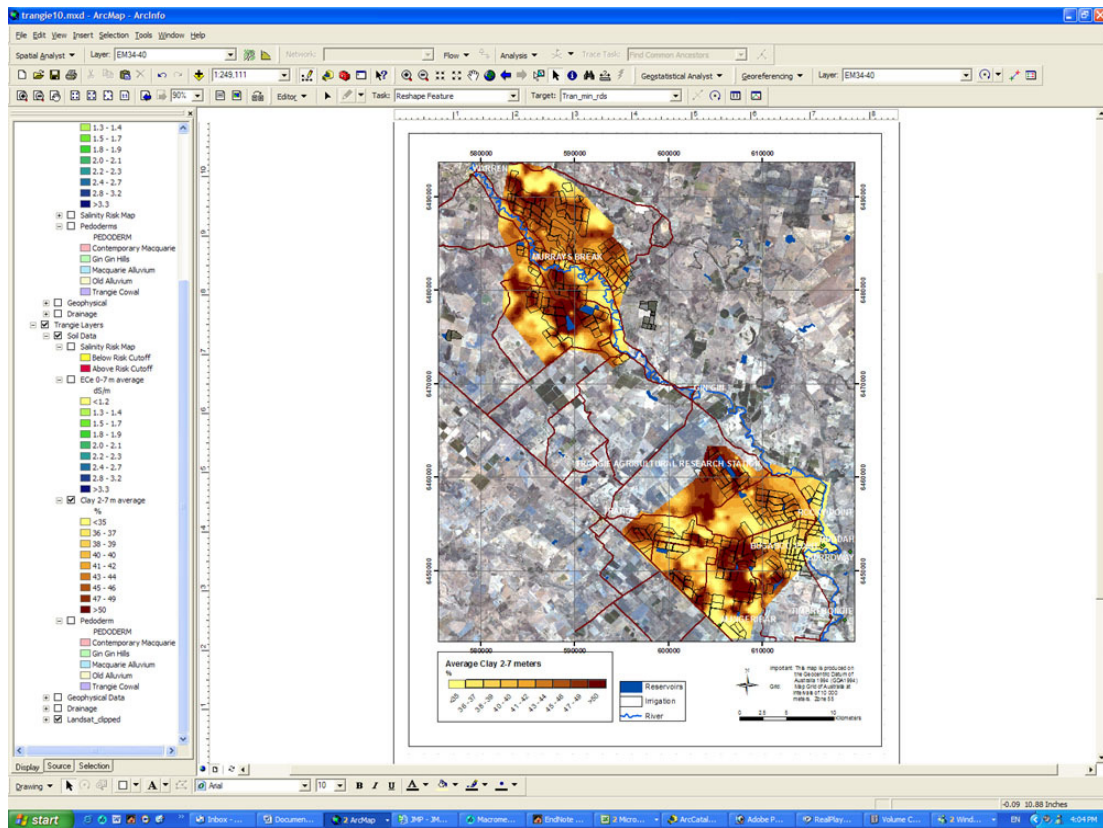


Figure 34. Spatial distribution of average clay content to a depth of 2-7 m.

Part 4 – Final Report Executive Summary

Salinisation as a consequence of irrigation can occur as a result of the application of poor quality (*i.e.* saline) water or mobilisation of salts from rising water tables (*i.e.* caused by excessive groundwater recharge). In order to determine the threat of salinisation a project entitled “*Understanding the salinity threat in irrigated cotton growing areas of Australia*” was established in 1991. Phase I (Preliminary Studies) involved testing existing field techniques (*i.e.* electromagnetic induction – EM) to assess cause and management of subsoil salinity at the field level, in the lower Namoi valley. Phase II (Methods and Techniques) was aimed at extending these techniques by i) automating EM instruments such as the EM38 and EM31 onto a Mobile Electromagnetic Sensing System (MESS), ii) developing district scale EM investigations (*i.e.* EM38 and EM34) and iii) carrying out regional scale modeling, in the lower Namoi and Gwydir valleys.

Phase III (Implementation and Management-CRC11C) was aimed at implementing the field (*i.e.* MESS), district (*i.e.* EM38 and EM34 surveys) and regional (*i.e.* reconnaissance soil surveys) methodology developed in Phase II, in each of the major cotton-growing areas of central (*eg.* Macquarie valley) and northern (*eg.* Gwydir valley) NSW and southeast (*eg.* Macintyre valley) Queensland. This was achieved by:

- a) initial consultation with various community groups (*eg.* Bourke Irrigators Association) to ensure research projects developed were consistent with natural resource management issues in each cotton-growing area;
- b) generate matching research funds through the Natural Heritage Trust and Salt Action Programs;
- c) collection of EM34/38 data and soil information in the root- (0-2 m) and vadose-zones (2-12 m) to measure, model, map, manage and monitor soil salinisation processes.

The main outcomes of the research carried out are the collection of over 7,500 EM34 and EM38 measurements and 350 soil profiles (0-12 m sampled at 1 m intervals) in the seven cotton-growing districts across five valleys. As shown in this report the data collected has been used at the district level to map a) deep drainage risk areas, and b) spatial distribution of subsurface saline material, whilst on the field level the cause and management of a) soil salinisation and b) water logging.

In order to consolidate the data collected in Phase III, for improved natural resource management, a follow up project is required (*i.e.* Phase IV-Interpretation and Extension). The main aim of Phase IV is to interpret the information collected and develop new methods (*i.e.* groundwater modeling from piezometric data) for understanding how point source soil salinisation occurs in irrigated cotton-growing areas. From the information collected and modelled it is expected that best management options can be devised for improved natural resource management. This is particularly the case in the Bourke, Warren and Trangie districts, where irrigation salinisation is problematic. In addition, detailed EM surveys are required to understand at the field level what the appropriate management options are required for improved natural resource management.



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