Faculty of Science and Engineering
Department of Exploration Geophysics

Application of Geophysical Techniques for 3D Visualization of Regolith Hydrogeological Architecture and Use of this Information for Management of Dryland Salinity in Western Australia.

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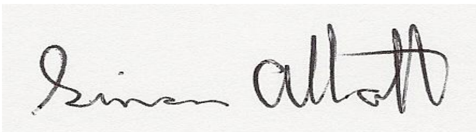
Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.



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Contents

List of Figures

List of Tables

Abstract

This thesis demonstrates the use of geophysics to identify the hydrogeological structures and mechanisms responsible for the salinisation of land and water in three different case studies. In addition, it demonstrates the critical importance of the interpreted information products being relevant to the land managers and the management tools and strategies available to them. Three case studies are examined. The common requirement for each study area was the acquisition of detailed sub-surface information on the location of hydrogeological features that could not be interpreted from surface observations or obtained from isolated drill holes. The spatial coverage of the geophysical data is shown to be critical to the quality of location information produced. The interpretation of these data and presentation of information products in terms of the current management tools available to land managers are shown to be essential for successful and cost effective adoption.

At Broomehill, the geophysical and other data were interpreted to produce information products that indicated the location of salt stores, sources of water, mechanisms that brought water and salt together in the landscape and mechanisms that brought saline groundwater to the surface. Using these information products, the spatial plan took the form of a farm plan that clearly mapped the location and design of surface water management earthworks, areas of revegetation, water storages, roads and fences such that the salinising processes in each paddock were directly impacted through the considered location of the proposed works. One such plan at Broomehill was promptly implemented in 1996 and the results have been monitored since that time. The farm plan is shown to be more cost effective than comparable farm plans on nearby properties that did not use information from geophysics.

At Tammin, ground geophysical surveys (gravity and time domain electromagnetics) were used to identify the location of sedimentary fill in a buried inset valley. This was to provide information on which to base the siting of a production bore such that it would intersect hydrologically transmissive sediments. This bore was used to test the effectiveness of groundwater pumping to lower the watertable and recover agricultural land from salinity.

The bore failed to pump an adequate volume of water and the groundwater pumping aspect of the trial was considered a failure. However, the value of this case study lies in observation of the characteristics of the geophysical information collected.

The geophysical data were collected along four transects 0.8 km to 2.0 km apart. The processed geophysical data revealed cross-section profiles of the buried valley and the production bore was located on the transect that showed the steepest "V" profile. Given only four transects of information and the difficulty of interpolating over up to 2 km between them, this choice is understandable. The failure of the interpretation of the geophysical transect data to locate a suitable bore site calls into question the usefulness of geophysical survey transects up to 2 km apart. The geophysical information (although it was cheaper) was not much better than having four transects of closely spaced bores. It failed to adequately reveal the hydrogeological architecture of the study area. This case study revealed the importance of survey design and scope to ensure that the data are suitable to produce interpreted information products that are suitable for the purpose.

A helicopter-borne, time domain electromagnetic survey was flown over the Lake Warden Wetlands near Esperance. The data were processed and interpreted to reveal potential groundwater flow paths in the main aquifers underlying the wetlands. This information, along with salt storage distribution maps derived from the conductivity product, was provided to the Department of Environment and Conservation (DEC) in the form of the maps shown in this thesis. This information enabled the DEC to formulate a catchment management strategy that focussed on the eastern sub-catchments of Bandy Creek and Neridup Creek as the main sources of saline groundwater. Surface water management plans prioritised diversion of waters contaminated by discharging saline groundwater and could be designed without active discharge occurring at the time. Prior to this survey, the DEC and South Coast Natural Resource Management were promoting generic management strategies, such as revegetation to reduce groundwater recharge, over the whole catchment area.

The information products developed in this study enabled the DEC and community to understand mechanisms causing high water tables and salinisation in the wetlands and consequently, to be much more targeted and effective in their investment of limited land conservation funding.

In all these case studies, the use of geophysics was essential to identify the hydrogeological architecture and mechanisms responsible for the salinisation of land and water. Furthermore, the interpretation of the data and design of information products is critical as to whether the information is successfully acted upon. The interpretation of the data and design of information products based on location of aquifers and other geological structures is critical to adoption by land managers and the impact and effectiveness of the actions taken.

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1. Chapter 1: Introduction

In Western Australia, very few geophysical surveys undertaken for natural resource management have resulted in implementation of remedial works on the ground. This thesis examines the use of airborne and ground geophysical surveys to help facilitate the design of cost effective land management measures that reverse or reduce the environmental damage resulting from the salinisation of land and water. It examines case studies where management decisions and works have proceeded on the basis of the information obtained. It examines the analysis of the data and the characteristics of the information products that lead to effective decisions and on-ground works. It investigates and identifies the critical factors for cost effective use of geophysical surveys for management of dryland salinity in Western Australia.

1.1 Background and Literature Review

Salinisation can be defined as:

"the increase in total dissolved solids in soil and water. Land and water resources can be salinised by natural physical and chemical processes or by human activities such as irrigation (secondary salinisation)" (Ghassemi et al., 1995).

Dryland salinity is the term used for the salinisation of soils in areas of dryland agriculture driven by changes in the hydrological balance in a landscape. An example is the Western Australian wheatbelt where rainfall is the primary or sole source of water and irrigation is minimal or absent.

The salinisation of land and water has long been considered a problem in Western Australia. Soon after the settlement in Perth the explorer Dale (1830) noted the natural salinity of inland streams and lakes. As clearing of natural vegetation for agriculture progressed, settlers began to observe salinisation of previously fresh water supplies (Bleazby, 1917). Mann (1907) was the first to publish a possible link between clearing and dryland salinity in a Journal of Agriculture article. However it is usual to credit Wood (1924), who published a comprehensive paper in the Journal of the Royal Society of WA in which he described the mechanism of accumulation of atmospheric salt in Western Australian soils. He also described soil and regolith profiles and the mechanism of salinisation as a consequence of land clearing.

Nearly 80 years later, in spite of the significant efforts of land owners and natural resource management agencies, dryland salinity continues to expand and the area at risk in WA was predicted to double in the next 50 years (Anonymous, 2001). Failure to effectively manage dryland salinity has been blamed, at least in part, on a lack of political will (Beresford et al., 2001).

In Western Australia, farming communities are most directly affected by salinity and are those whose livelihoods are most closely allied to the condition of the land. They have observed the commencement and expansion of soil and water salinisation. Most members of the farming community are not trained in understanding hydrological systems at the scales at which salinisation processes work. To the layman, the hydrological factors that produce dryland salinity at any particular location are underground, invisible and mysterious. The knowledge gaps pertaining to dryland salinity have resulted in management actions that are empirically based. That is, management has been based on treating symptoms. Where success has been achieved, the strategy has been promoted for other sites without necessarily having full understanding of why it was successful at the original site. An example of this is the Whittington Salt Affected Land Treatment System reviewed by Henschke (1989) (Figure 1).

On the other hand, much effort has been put into attempts to treat the cause. Rules for decision-making about remedial actions have been developed that attempt to mimic pre-agriculture natural systems Stirzaker (1999). This is based on the assumption that the system was in 'equilibrium' before clearing and a return to a similar vegetation assemblage will return the system to such an equilibrium. This approach does not recognise that natural systems are dynamic, constantly evolving and that there have been changes in the landscape that may not be reversible (Hatton, 1999 Coram et al., 2002). Some of these changes have occurred since European settlement and perhaps even prior to that, as a consequence of aboriginal settlement and vegetation burning

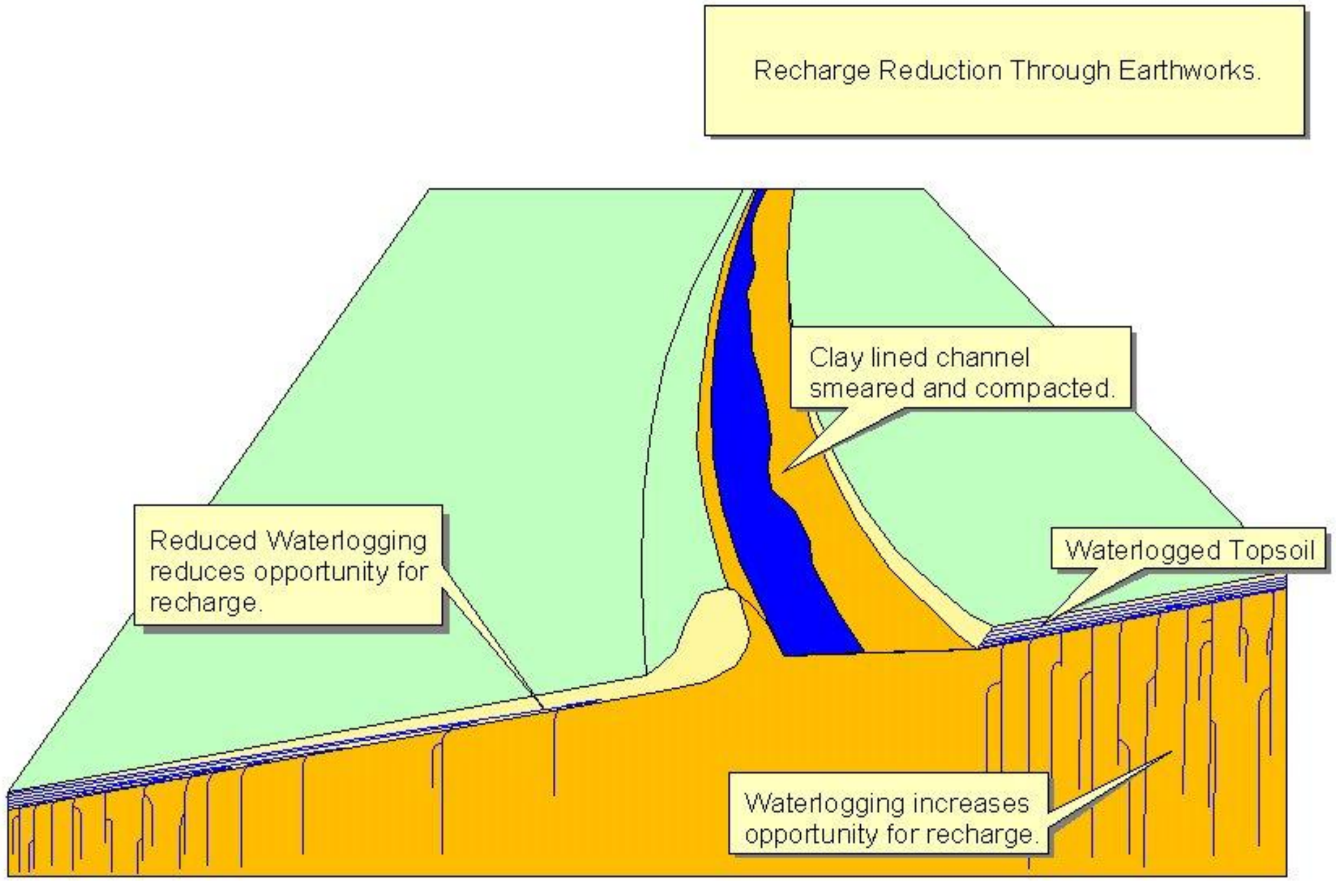

Figure 1. Schematic of a 'Whittington' interceptor bank showing how it reduces surface waterlogging. In lower slope areas also affected by salinity, the reduction of waterlogging significantly improved pasture growth but did not lower the water table.

In addition, the geology of the agricultural areas of Western Australia is highly variable at both small and large scales. In most of the wheatbelt region, the bedrock is comprised of crystalline igneous and metamorphic rocks. Deep weathering of this geology has resulted in a regolith that is also highly variable in hydrogeology. The variation in soils apparent to the observer on the surface is far exceeded by the complexity of hydrological characteristics beneath (Clarke, 2005).

The hydrogeological characteristics of the agricultural areas of Western Australia that are highly variable include: regolith thickness, hydraulic conductivity, water storage, specific capacity, specific yield, salt storage, basement topography, parent rock geology and geomorphological history (George, 1990). These characteristics can vary significantly over distances of a metre or less.

The salinisation process at any site is controlled by the hydrogeology at that site. Therefore, a salinity management plan for site X may not be fully or even partially transferable to site Y (Nulsen, 1991). Extrapolation and generalisation cannot produce solutions for other sites, although they may assist in developing general guidelines. There was recognition of landscape differences at regional scales and this resulted in a national hydrogeological classification of catchments for salinity management (Coram, 1998); but this still left variability at farm and paddock scale un-mapped.

Recognition that recharge of the deep saline watertable was occurring across the entire landscape logically required increased water use by agricultural systems. However, agricultural systems that are economically viable and that mimic the hydrological function of the native vegetation do not exist (Pannell et al., 2001). Revegetating the agricultural area to a sufficient extent to halt or reverse the salinisation process is considered a politically impractical and unrealistic proposal, as it would displace most of the agricultural industries (George et al., 2001).

The majority of the land in the agricultural areas of Western Australia is privately owned and managed as commercial farming enterprises. Land management decisions are the responsibility of individual landowners who make their decisions at a farm or paddock scale. Converting this to mapping scale equates to scales of 1:10,000 (farm scale) or larger, 1:5,000 (paddock scale). There is a disparity between the scales at which landowners make decisions and the scales at which decision support information is provided, particularly in the area of natural resource management. Most mapping products are at scales of only 1:250,000, with some as detailed as 1:25,000 (Abbott, 2003).

At 1:10,000 scale, 1 mm on the map is equivalent to 10 m on the ground. The influence of regolith variability on groundwater hydrology over distances of 30 m or less and its importance for salinity management planning has been well documented (George, 1990). In the 1980's the development of geophysical technologies along with Differential Global Positioning Systems and digital data recording capacity made high resolution (<30 m pixel) airborne geophysical surveys feasible and cheap (see definition of "resolution" and "pixel" in section 1.4). High resolution geophysical surveys were quickly adopted in mineral exploration to map spatial variation in bedrock geology and the regolith. The potential for the application of the geophysical data to natural resource management issues was also recognised (Engel et al., 1987). However, as was the case in the early stages of development of other remote sensing technologies, such as satellite imagery, the process of knowledge extraction was not clear or well understood. While geophysicists saw the potential for geophysical information to assist in the management of dryland salinity, they did not recognise the gap that existed between the outputs of the technology and the knowledge that was required by agriculturalists. The geophysicists did not understand what the agriculturalists required and the agriculturalists did not understand what the geophysicists could deliver. Consequently, there has been controversy about the value of geophysical data since the surveys of the 1980's (De Broekert, 1996 George, 2000). Nulsen et al., (1996) recognised that a suite of data (including geophysical data) could be assembled that would contain sufficient information to effectively design remedial actions, and there was an increase in the development of survey systems for these purposes, such as SALTMAP and TEMPEST.

The National Airborne Geophysics Program was undertaken in an effort to objectively assess airborne geophysical technologies and information outputs in various parts of Australia. The report of this project (George et al., 1998) made a recommendation for the systematic and coordinated collection of geophysical data over land at risk of dryland salinity. This recommendation was:

> *"To maximise the potential for sound decisions when preparing salinity management plans, it is recommended that a minimum core suite of data sets be used. These data sets include bore hole data, aerial photos, satellite imagery, maps of terrain, maps of geology and meteorological data with the airborne geophysics data used to value-add these data where appropriate."*

In the 1980s and 1990s, when the landcare movement was at its peak, land managers were attempting to manage dryland salinity by planting trees in what they hopefully believed were strategic parts of the landscape in order to lower saline water tables. They focused on strategic location of trees in the landscape and the information they used to define these strategic locations was surface soil and topography data, and some interpretation of hydrogeology from this surface information. For example, topographic break of slope zones were interpreted as groundwater accumulation/discharge zones. The theory behind break of slope groundwater discharge (Bulman, 1995 McJannet et al., 1998) is described in section 1.4.3. Unfortunately, many plantings died due to lack of water and surviving plantings failed to reduce the spread of dryland salinity as was hoped (Figures 2 and 3).

The extrapolation of surface information into quasi-hydrogeological information failed to provide effective decision support for this strategic approach. The subsequent failure of this approach and the results of broadscale modelling studies (Campbell et al., 2000) caused strategic approaches to fall out of favour. Instead of strategically located management actions, the recommendation focussed on changing the entire farming system to a perennial agronomy based system applied across the whole landscape (George, et al., 2001). It is interesting how broadscale modelling using broadscale inputs produces broadscale results and recommendations.

In supporting the strategic approach to salinity management, I suggest that the **local spatial factors** in salinity management may be more highly sensitive to the relative location of hydrogeological features that control groundwater movement than was previously thought. The interpretation of subsurface hydrology from surface soil and topography data was not adequate to accurately locate or identify important hydrogeological features.

Clarke (2005) made the following observation in respect of dryland salinity and the decision support information used to manage it in the Western Australian wheatbelt:

> *"The presence of inverted Eocene valley floors, incipient inversion of younger sediments and major shifts in position of valley floors all indicate that modern morphology is a poor predictor of regolith thickness in general and sediment thickness in particular. However, despite the problems with such methodologies, use of surface data, both soils and digital elevation models (DEMs) as the prime predictors of subsurface fill thickness continues to be recommended (George and Coleman, 2001; Commander et al., 2001). While such approaches are a partial solution, exclusive reliance on them must be abandoned if significant progress is to be made in understanding and mapping groundwater flow and salinity in the WA wheat belt".*

The three case studies presented here cover the main hydrogeological settings found in the Western Australian wheat belt, the in-situ weathered gneissic regolith and the in-filled valley sediments. Detailed descriptions of these hydrogeological settings are given in each case study. Geophysical data, primarily from airborne surveying systems, was viewed by many as a potential source of hydrogeological information that could fill the information gaps left by the shortcomings of interpreting surface data (Engel et al., 1987 : Nulsen et al., 1996). The application of geophysics to the management of dryland salinity in Australia has been a contentious issue for more than 20 years (O'Brien, 1998; George et al., 1998; George et al., 2000). This is due to the apparent failure to apply the information to successful implementation of management actions (George et al., 2000). Land managers need to know what to do and where to do it. This is a fact that I have learned over more than twenty years working with farmers on their natural resource management and farm planning issues. Interpreted information from geophysical investigation should fill the "where to do it" information gap. However, most of the geophysical information acquired for managing dryland salinity in Australia has not resulted in improved salinity management on farms (Table 1).

George et al. (2000) commented:

> *"....the data have largely failed to alter either the current trajectory of salinity or the plans that have ensued in any catchment in which it has been used. Why, when we acknowledge that the technology has developed and now provides unparalleled insights into soils, geology and regolith structure, have we failed to use it successfully?"*

George et al. (2000) note that data processing and interpretation capability have much improved but claim that nobody is applying it to land management problems. They also made the following observation:

> *"Information and forecasting tools are critical to any salinity program. While an understanding of land and water processes will not deliver salinity management, a failure to recognise landscape attributes, accommodate them with options and reflect them in designs will cause unnecessary failures. Landscapes work differently, respond differently and require collection and interpretation of biophysical data at paddock level to help design and predict the impact of options."*

I contend that too few geophysical studies have been carried through to implementation of management actions for there to be a sufficient weight of positive evidence to counter the negative impression of the numerous geophysical studies that have not been carried through to management actions.

In attempts by scientists to explain the lack of management action, it has been postulated that this is due to the lack of economically viable management options. In a review of the effectiveness of past attempts at management of dryland salinity, Pannell et al. (2001) state:

> *"It is remarkable the extent to which one hears the view expressed that there must surely be sufficient information out there and all we need to do is make sure it gets to the farmers. In reality, the problem is not lack of information but the lack of management options."*

Pannell demonstrated, from a review of hydrological research in WA, that in the in-situ weathered landscape of the Yilgarn Block, there is not massive movement of groundwater and salt from the top of a catchment to the bottom. Rather, the effects of groundwater recharge are expressed as rises in water-table or piezometric head relatively close to the site of recharge. Thus, the land manager at the bottom of the catchment cannot pass on the responsibility for his salinity problem to the land manager at the top of the catchment. Cause and effect are spatially close together, mostly within the one property (Pannell et al., 2001). So having disproved externality (see definition of externality in section 1.4) as an explanation for lack of application of salinity information, they suggest there is a lack of economically viable management options. Working from this conclusion, Pannell et al. (2001) characterise the issue in terms of recharge control at the farm scale and notes the lack of profitable perennial agronomic options available to farmers. I do not believe farmers are particularly looking for perennial agronomic options, especially on a large scale. They are more inclined to use management practices and infrastructure works that they are familiar with and that are available to them today.

The land manager dealing with dryland salinity needs to know WHAT to do and WHERE to do it. The WHAT-to-do information sought by land managers consists of the range of land management practices suitable for the particular parcel of land. The WHERE-to-do-it information sought by land managers consists of a spatial plan for the location and design of those management practices such that they exert maximum impact on the salinising processes relative to the cost of implementation. This could be as simple as changing the land use, or more direct measures, such as constructing surface water control earthworks.

Pannell, et al., (2001) cites the lack of profitable perennial agronomic options as the explanation for airborne geophysical surveys not being taken through to improved salinity management actions on the ground. There are, however, existing best practice infrastructure and management actions that impact on the salinising processes, especially where they can be strategically located to obtain maximum impact. I contend in this thesis that the reason for airborne geophysical surveys not being taken through to improved salinity management actions on the ground is the lack of a spatial plan based on site-specific hydrogeological information. The majority of airborne geophysical surveys commissioned for dryland salinity management did not provide land managers with detailed spatial plans describing remediation measures (Abbott, 2003).

The standard processed geophysical images and technical and interpretation reports provided by geophysical survey contractors are not suited to supporting natural resource management decision-making. Geophysical surveys for natural resource management in Western Australia, that delivered only standard geophysical images and reports to clients, have not been followed by on-ground application of the knowledge gained (Table 1).

Of all the airborne geophysical surveys undertaken for dryland salinity management in Western Australia, only five have been used to produce spatial plans for land management actions (Abbott, 2003). These were at Broomehill, Trayning/Wyalkatchem/Nungarin, Moora, Toolibin Lake and Lake Warden (Table 1). The Broomehill project in which I worked as the farm planner using geophysical information, was the first of these to be undertaken and is examined in detail in this thesis. The research question that this thesis seeks to answer is:
Does the use of geophysics in farm and catchment planning produce cost effective environmental and economic benefits?

1.2 Aims and Scope of this Study

Aims:

- To describe methodologies that I used to produce information products that can be understood and applied in the context of current management options in farm and catchment management.
- To demonstrate the need for an information outcome focus in geophysical survey planning.
- To demonstrate that these methodologies facilitate cost effective environmental and economic outcomes from using geophysical data.

Scope:

- These aims are achieved by presenting two case studies where these methods were used and one where they weren't used, thus demonstrating the different outcomes.

SURVEY	YEAR	MAGNETICS	ELECTROMAGNETICS	RADIOMETRICS	HYPER SPECT RAL	HECTARES	CLIENT	PRODUCTS	Management actions resulting
Perenjori	1984		INPUT				Department of Agriculture	Contours of resistivity - homogeneous half-space model	Unknown
Kent	1986		INPUT			50,000	Department of Agriculture	Contours of conductance	Unknown
Yornanning	1988 - Mad/VLF 1989 - EM/Mag 1990 - Thermal IR 1991 - Mad/Rad	YES x 3	VLF, QUESTEM	YES		15,000	Department of Agriculture	Geophysical images, interpretation of magnetics, interpretation report and report by Department of Agriculture (Patabendige, 1992)	Unknown
Cartmeticup	1988 - Mag/VLF	YES	VLF			20,000			Unknown
Boscabel	1993	YES	QUESTEM			2,000	Farmers	Geophysical images, catchment plan and report.	Unknown
Kent/Frankland	1992	YES	QUESTEM	YES		60,000	Department of Agriculture	Geophysical images	Unknown
Carnamah	1992	YES	QUESTEM			35,000	Department of Agriculture	Geophysical images and interpretation report (WGC)	Unknown
Neridup	1994	YES	QUESTEM			15,000	Department of Agriculture	Geophysical images and interpretation report (WGC)	Unknown
Keep River		YES	QUESTEM			100,000	Government	Geophysical images	Unknown
Broomehill	1995	YES	SALTMAP	YES		50,000	Farmers	(1 farm plan, 7 maps, 1 report) x 14 clients. Unpublished reports by WGC, 1 PhD thesis (Anderson-Mayes, 2000), 2 reports by Water and Rivers Commission, George and Smith, (1998) and Leonhard (1999).	YES
Towerinning	1985 - Mag/Rad 1987 - SALTMAP	YES x2	SALTMAP	YES		35,000	Murdoch University ARC project	PhD Thesis	Unknown
Trayning	1997	YES	SALTMAP	YES		15,000	Farmers	(1 farm plan, 7 maps, 5 digital datasets, 1 report, 1 CD ROM) x 30 Clients	YES
Wyalkatchem	1998	YES	SALTMAP	YES		40,000	Farmers	(1 farm plan, 7 maps, 5 digital datasets, 1 report, 1 CD ROM) x 30 Clients	YES
Nungarin	1997	YES	SALTMAP	YES		40,000	Farmers	(1 farm plan, 7 maps, 5 digital datasets, 1 report, 1 CD ROM) x 30 Clients	YES
Moora	1998	YES	SALTMAP	YES		25,000	Farmers	(1 farm plan, 7 maps, 5 digital datasets, 1 report, 1 CD ROM) x 30 Clients	YES
Mobrup	1998	YES	GEM3a				Water and Rivers Commission		Unknown
West Dale	1997	YES	Geophex	YES		10,000			Unknown
Morbinning	1998	YES		YES		25,000	Farmers	Geophysical images and magnetics interpretation	Unknown
South Tammin	1999	YES				40,000	Farmers	Geophysical images and magnetics interpretation	Unknown
Collie	1999	YES		YES		30,000	Water and Rivers Commission	Geophysical images	Unknown
Warren	1999	YES		YES		40,000	Water and Rivers Commission	Geophysical images	Unknown
Kent	1999	YES		YES		40,000	Water and Rivers Commission	Geophysical images	Unknown
Chapman Valley	1998	YES	DIGHEM	YES		20,000	NDSP and Department of Agriculture	Interpretation Report by SKM	Unknown
Toolibin Lake	1998 - Mag/SALTMAP 1999 - TEMPEST	YES	SALTMAP, TEMPEST	YES	YES	50,000	NDSP and Department of Agriculture	Survey scale interpretation maps and interpretation report	YES
Elashgin	2000	YES		YES			CSIRO	Report by CSIRO	Unknown
Dumbleyung	2007	YES		YES		100,000	Departmenbt of Minerals and Energy	Geophysical images	Unknown
Lake Warden	2005		HoistEM, TEMPEST			20,000	Department of Environment and Conservation	Detailed interpretation report and map products indicating groundwater behaviour in each of 3 main aquifers	YES

Table 1. List of geophysical surveys conducted for Natural Resource Management purposes in Western Australia. Information products and land management outcomes are listed in the two right hand columns. Those resulting in land management actions are coloured green.

1.3 Thesis Overview

Three case studies are examined. Each study area had different physical characteristics and technical challenges. The scales at which the information was to be collected and used were different as were the potential land management tools and actions to be applied in response to the information obtained. However, the common requirement for each study area was the acquisition of detailed sub-surface information for the spatial location of hydrogeological features that could not be interpreted from surface observations or obtained from isolated drill holes.

At Broomehill, the geophysical and other data were interpreted to produce information products that indicated the location of salt stores, sources of water, mechanisms that brought water and salt together in the landscape and mechanisms that brought saline groundwater to the surface. Using these information products, the spatial plan took the form of a farm plan that clearly mapped the location and design of surface water management earthworks, areas of revegetation, water storages, roads and fences such that the salinising processes in each paddock were directly impacted through the considered location of the proposed works. One such plan at Broomehill was promptly implemented in 1996 and the results have been monitored since that time.

This was part of the "SALTMAP" farm planning project at Broomehill, the first of the three studies to be examined in this thesis. It was undertaken at a time of technical and political controversy regarding the use of airborne geophysics to aid in the management of dryland salinity. The aim of this project was to apply current management practices guided by hydrogeological information from geophysics to target and manage the salinising process. The project was commissioned by the Broomehill Land Conservation District Committee with the intention of obtaining farm plans that, when implemented, would effectively impact the causative processes of salinisation on their farms. This project began in 1993 and was completed in 1996. It is one of the few airborne geophysics based NRM projects to use the geophysical data and information products to design and implement land management actions at the farm scale. It used the information products to target the hydrological mechanisms that bring water and stored salt together, that control their movement in the regolith, and that cause groundwater discharge.

In the second study to be examined in this thesis, the importance of the spatial factor was also demonstrated at Tammin in a trial of groundwater pumping as part of the Western Australian Government's Engineering Evaluation Initiative. The aim of the project was to investigate the technical and economic feasibility of groundwater pumping from the coarse alluvial aquifers known to make up the basal layers of the in-filled valley systems of the Western Australian wheatbelt. The valley sedimentary system is 2 km to 4 km wide at the study site, yet the location within that width of the in-filled basement structures could not be detected or approximated from any available surface information.

Ground based geophysical surveys were conducted along four ground transects. This involved collecting gravitational anomaly data and time domain electromagnetic data.

This case study examines the effectiveness of the geophysical survey information in selecting a site for the production bore in the light of the results of testing of the bore by the Department of Water.

In the third study in this thesis, the Lake Warden wetlands study, the **"spatial location"** factor was created by the inaccessibility of much of the study area to surface-based investigations. Knowledge of the hydrogeology of the Lake Warden Wetlands was based on a small number of widely dispersed drilling sites. On-ground methods of obtaining hydrogeological information between these sites were ruled out by inaccessibility due to thick vegetation or inundation. The variable and precipitous nature of the basement topography in the area meant that basement topography would be a major information type required to better understand groundwater hydrology. Its variability over short distances dictated that data collection would have to be spatially dense to capture this variability. The requirement for detailed hydrogeolgical information was to facilitate better understanding of the relative contributions of salt and water from surface water and groundwater in the Lake Warden wetlands system.

The helicopter-borne time domain electromagnetic system known as HoisTEM, operated by Worley GPX, was chosen to conduct the survey. During the survey, there were substantial technical issues including a failed altimeter and interference from commercial radio transmitters degrading the electromagnetic data. Some data processing work-arounds had to be devised and some parts of the study area data were un-salvageable, mostly in the shallow regolith area to the north of the Lake Warden Wetlands. In spite of these difficulties, the remaining EM data were calibrated using EM39 and gamma downhole logs collected from the existing bore network using the method of Hashemi and Meyers. (2004). This depth and conductivity calibration enabled basement topography information as well as intermediate aquifer layers to be generated from the electromagnetic data.

Analysis of these information products revealed the main groundwater barriers and flow paths into and beneath the Lake Warden wetlands. This is information critical to the effective management of the area and it is information that could not be obtained cost effectively by any other means. However, without this thorough analysis and interpretation of the data and production of information products relevant to the stakeholders, they would have derived little added value from the standard products delivered by the geophysical survey contractor.

Historically, standard geophysical survey technical products with little interpretation or relevant derived information products have been delivered to stakeholders wishing to better manage dryland salinity. This is the reason, the majority of geophysical surveys for dryland salinity management have not resulted in effective on-ground works.

1.4 Concepts and Terminology Employed in This Project

A multidisciplinary project such as this uses a range of technologies and associated language from different disciplines. For the reader's benefit, sections 1.4.1 to 1.4.13 summarise the most important concepts and terminology.

1.4.1 Dryland Salinity

This is the term used to describe salinisation of soil and/or water in areas where the principal source of water in the landscape is from rainfall and there is no significant importation of water by human activities such as irrigation. Naturally saline deep aquifers rise to the surface as a consequence of increased recharge resulting from the replacement of deep-rooted native perennial vegetation with shallow-rooted annual crops and pastures. Concentration of salt in the surface soil by evaporation reduces agricultural yield and can render the soil completely unsuitable for conventional agricultural use.

1.4.2 Recharge

Recharge is that portion of rainfall that is not used by vegetation, evaporated or run off into stream flow. It is soil water that percolates beyond the reach of plant roots and enters the deep groundwater aquifer, thus recharging it.

1.4.3 Break of slope theory of dryland salinity

This is based on the assumption of basement topography mimicking surface topography (Bulman, 1995, McJannet et al., 1998) and the behaviour of groundwater within this model (See Figures 2 and 3).

1.4.4 WISALTS

This is an acronym for **W**hittington **I**nterceptor **S**alt **A**ffected **L**and **T**reatment **S**ystem. This system utilises soil embankments built level or on a slight grade upslope of salt affected areas. The theory is that these embankments intercept groundwater and salt and keep them from accumulating in the lower parts of the

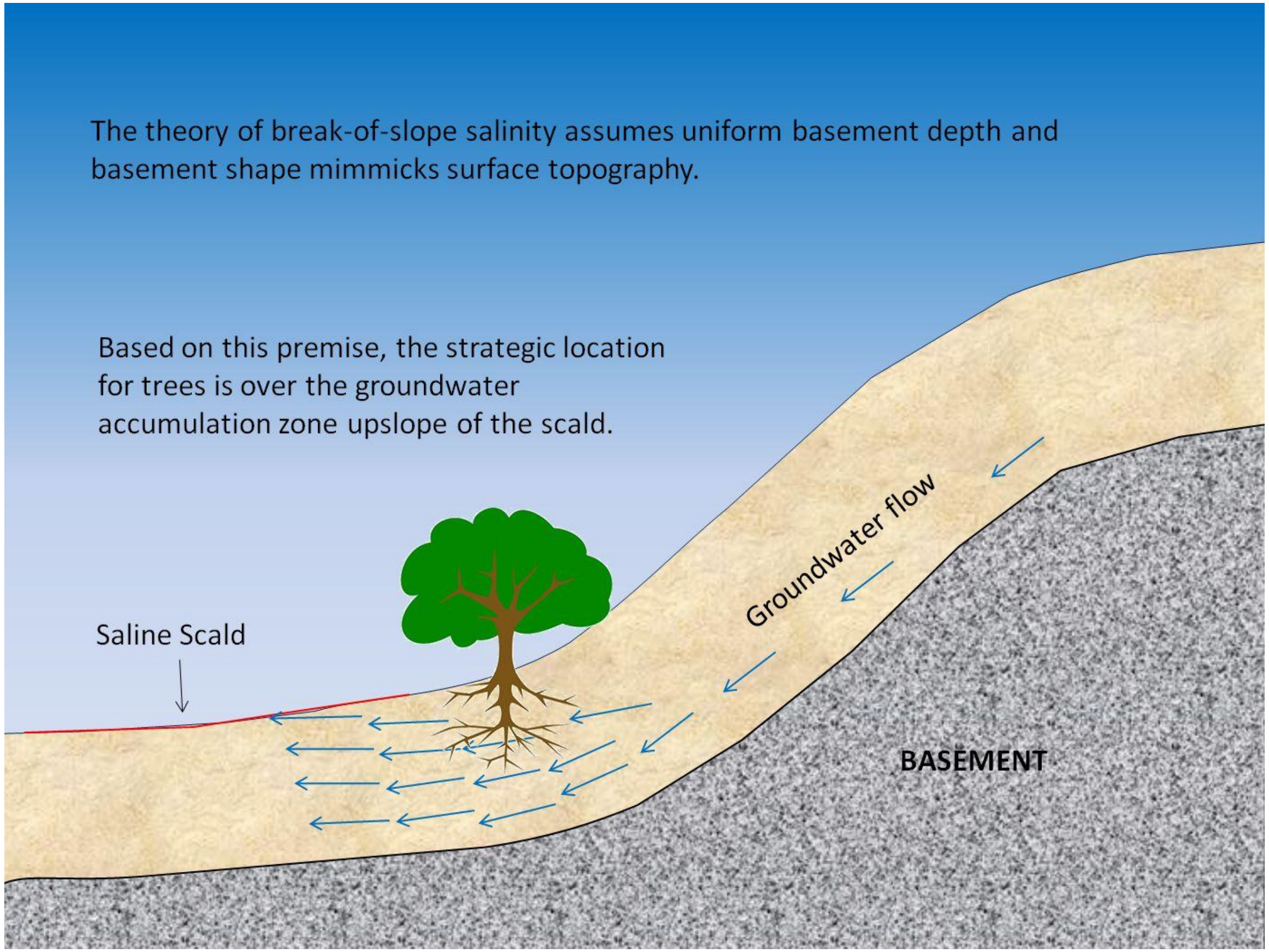

Figure 2. Break of slope theory of dryland salinity.

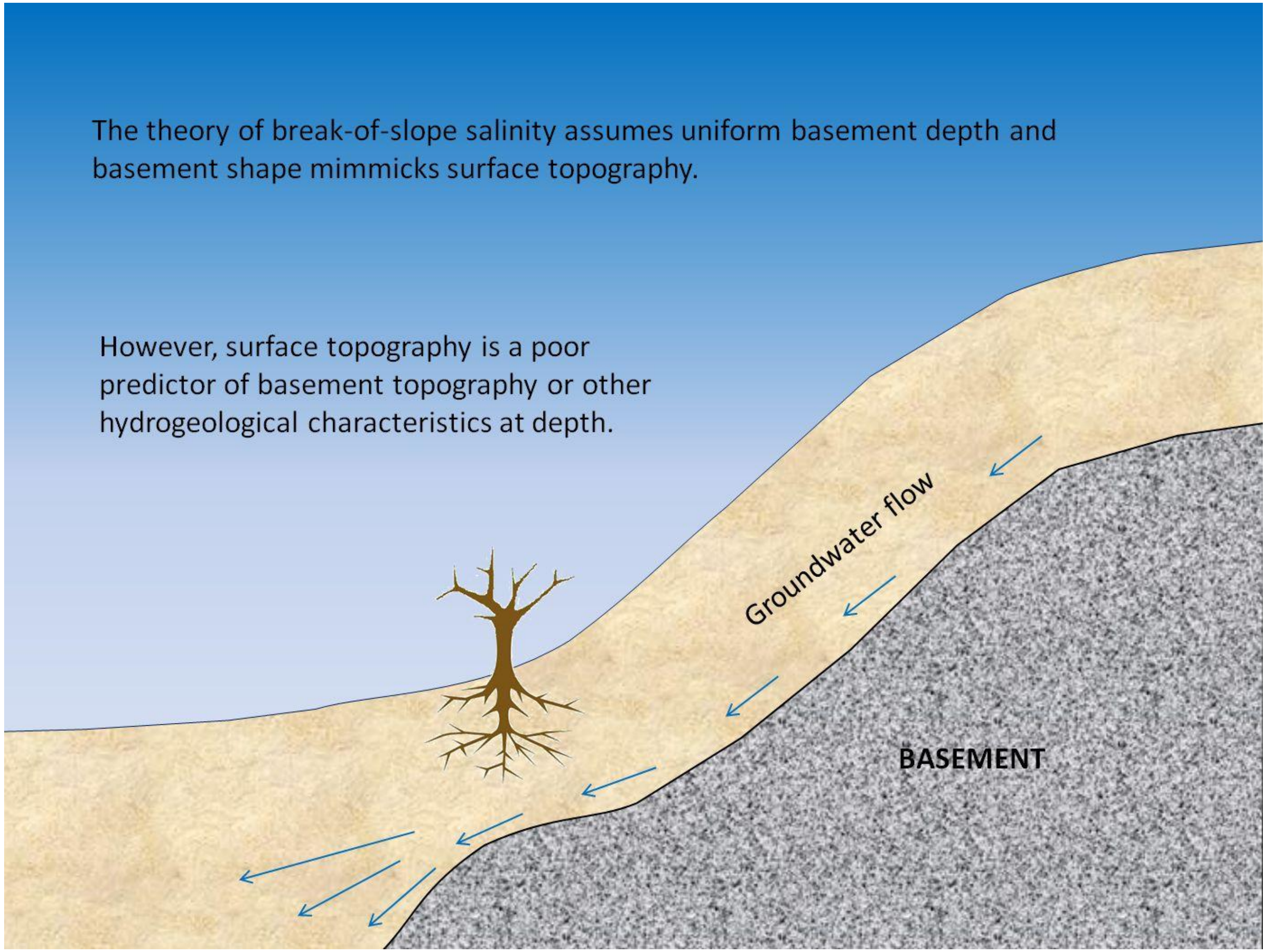

Figure 3. Example of mismatch between break of slope theory and site conditions.

landscape. They are built by bulldozer or excavator, and this makes them relatively expensive compared to other surface water management earthworks. It has been proven that the effect of this treatment is a reduction of surface waterlogging in the lower landscape, but not lowering of the saline water table (Cox and Negus, 1984) (see Figure 1).

1.4.5 Other surface water management earthworks

Grade banks: These are similar in cross section to that shown in Figure 1. However, the difference is they are not cut as deeply into the clay subsoil, they have a smaller spoil bank, occupying a narrower swath, and they are constructed on a grade of approximately 0.5 m fall every 100 metres using a road grader. Seepage interceptor banks are cut deeper into the clay by a road grader, but not as deep as WISALTS banks (Keen, 2001).

1.4.6 Modelling

Hydrologic models are simplified, conceptual, mathematical representations of the hydrologic cycle within a geographic boundary such as a catchment. They are primarily used for hydrologic prediction and for understanding hydrologic processes. Models are often used for generating outputs in response to "what if" questions such as:

- What if rainfall is increased?
- What if transpiration by vegetation is increased?
- What if vegetation is removed and transpiration is decreased?

Because most models are simplifications of the real world parameters, their accuracy is determined by the assumptions made in the simplification process. The truism "garbage in, garbage out" not only applies to the inputs to each run of a model. It also applies to the parameters embodied in the model design.

1.4.7 Geophysical Techniques

The mapping of subterranean soil characteristics using non-invasive techniques based on the different physical properties of different materials and their sensible outputs (such as density or natural gamma radiation) and responses to different physical inputs such as sound waves, electrical currents or the earth's magnetic field.

1.4.8 Pixel

The smallest discrete component of an image or dataset. The greater the number of pixels per unit of distance the greater the resolution.

1.4.9 Voxel

The smallest discrete component of a dataset representing a 3D volume. The greater the number of voxels per unit of distance (in X,Y and Z dimensions) the greater the resolution.

1.4.10 Resolution

Spatial resolution refers to the sensor's ability to sharply and clearly define the extent or shape of features within the subject area. It describes how close two features can be within the subject area and still be resolved as unique (NAC Image Technology, 2011)

1.4.11 Externality

An economic term: when the person who causes a problem (or a benefit) is not the same person who experiences it. Landowners experiencing the effects of dryland salinity often blamed upslope neighbours and used this as a reason not to take action themselves. They see the cause as something that is external to the things they can control so have no reason to attempt to control the problem (New South Wales Department of Environment, Climate Change and Water, 2011).

1.4.12 EM39 down hole logging

This is an instrument using a conductivity probe, lowered down a borehole that records the electrical conductivity of the surrounding regolith at regular depth intervals.

1.4.13 Gamma logging

With a Gamma probe (Geiger counter) substituted for the conductivity probe, the instrument records the natural Gamma radiation of the regolith at the same regular depth intervals. These readings can differentiate between clay and sand strata.

1.4.14 Gravity survey

Where there are deep deposits of sedimentary material that is less dense than surrounding bedrock, the reduced average density of the substrate results in a reduced gravitational pull which can be measured by a gravity meter. This can be used to map the location and shape of sedimentary deposits lying in granitic terrain.

2. Chapter 2: Broomehill Farm Planning Project

2.1 Introduction

The assumption that a European style of agriculture would work in the Australian landscape was historically applied without any knowledge of Australian geology and geological history. The change from native vegetation to annual crops and pastures in the wheatbelt of Western Australia has resulted in widespread land degradation due to soil acidification, compaction, erosion and in particular, dryland salinity (Wood, 1924, Ghassemi et al., 1995).

The salinisation of land and water in Western Australia has been accelerated by increased recharge of groundwater that has occurred since European settlement. This increased recharge is the result of the replacement of deep rooted, perennial, native vegetation with annual crops and pastures that use less water than the native vegetation.

The development of dryland salinity is thus driven by a source of water, a source of salt in the regolith, a mechanism that brings the water and salt together and a mechanism that brings the saline groundwater to the surface.

To prevent or manage the spread of dryland salinity in Western Australia, farmers and land managers have been encouraged to reduce recharge to the groundwater. Widespread tree planting is often the populist approach, such as the One Billion Trees Program (Hawke, 1989). Rather than a widespread or piecemeal reactive approach, many farmers have developed 'farm plans' to guide future land management change. Typically these plans have used rule-of-thumb guidelines for surface water management (Keen, 2001).

Land management occurs at the paddock scale and farmers acquire their paddock scale information over many years of observation. They use this paddock scale information to adapt to landscape niches that provide farming opportunities that suit local climate, soils and water availability. For the effective management of dryland salinity, less readily observable underground information is also required at paddock scale.

Effective land management planning that deals with the subsurface mechanisms that drive salinity requires a level of information of the subsurface that is not provided by most readily acquired land information, such as regional soil maps, and the limited understanding of groundwater that comes from widely spaced groundwater bores.

In 1995, a group of farmers in the Broomehill area commissioned a study to develop farm plans based on a wide range of biophysical data as proposed by Nulsen et al. (1996). Inherent in this approach is the use of geophysical data. Previous work in WA had shown that airborne geophysics has great promise for revealing subsurface landscape information at a scale close to that needed for on-farm and in paddock decisions (Street, 1992[a]; Street, 1992[b]).

Despite this promise, prior to the Broomehill study, no farm plans had been devised and implemented based on information derived from airborne geophysical data. Spies (2001) noted:

"One major issue encountered was that while the data very accurately described the landscape, they could not routinely be used to better define management options".

This chapter describes the Broomehill process and methodology of land management planning at the paddock scale (Street et al., 2007). It describes the interpretation of the geophysical data and my role in designing the information products that were produced to support the farm planning. I started work on this project in 1993 and finished in 1996. I performed the role of intermediary between the land owners and the geophysicists and I was responsible for the design of all the farm plans. I have used The Meadows property as a case study for this thesis. This chapter goes on to review the physical and economic monitoring of the fully implemented farm plan on The Meadows (Figures 4 and 5). In this chapter, I have also analysed the influence of the information derived from geophysics on the design outcomes in the farm plan.

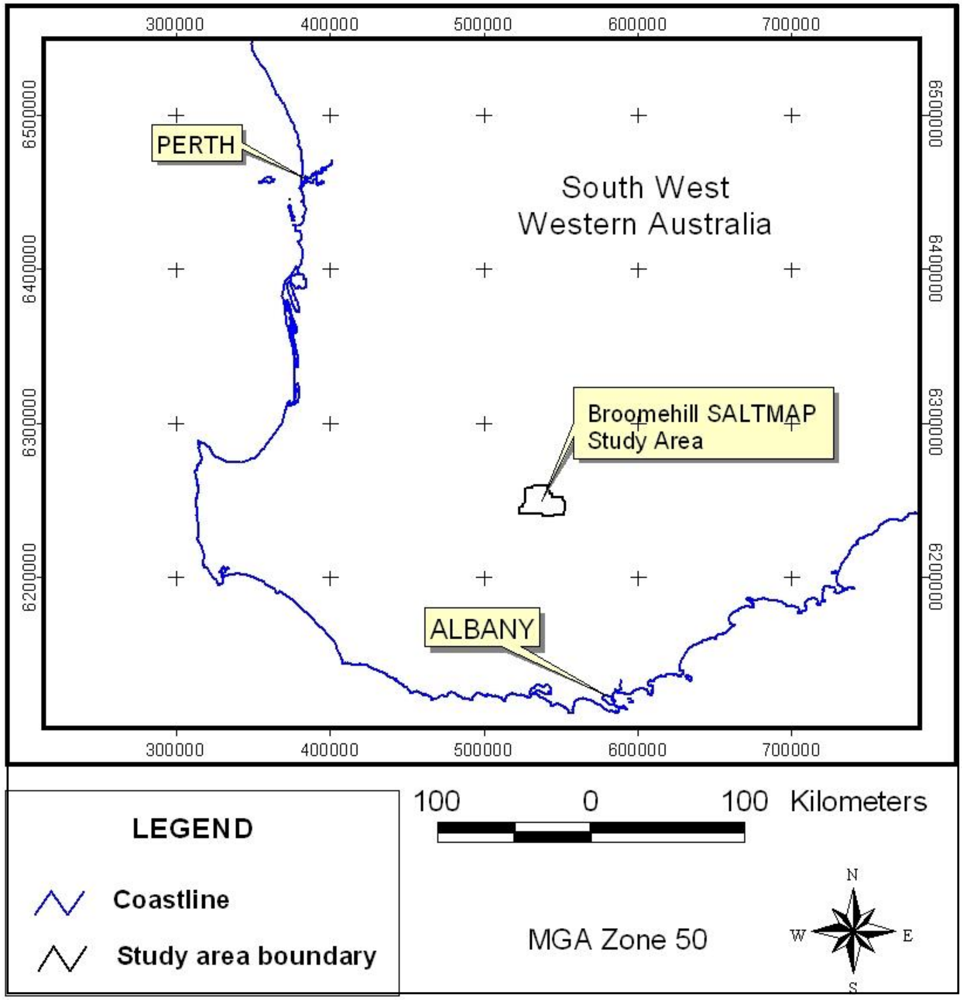

Figure 4. Location of Broomehill SALTMAP survey area.

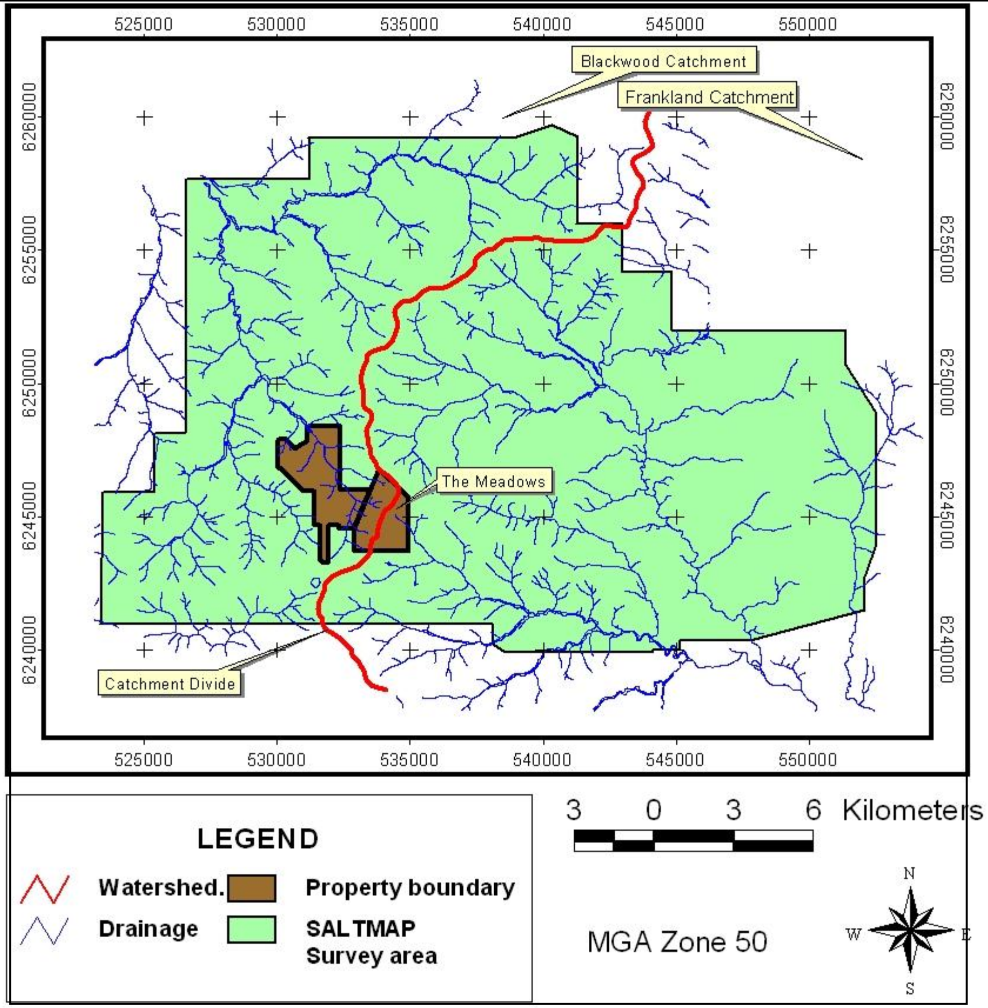

Figure 5. Broomehill SALTMAP study area and location of The Meadows property.

2.2 Previous Work

Previous attempts at integrating geophysics into land management decisions at Yornanning (Street, 1992[a], Buselli and Williamson, 1994), Carnamah (Speed, 2002) and Kent River (Salama et al., 1997) were carried out by specialists in narrow disciplines within the broad land management sphere. Results of airborne geophysical surveys (magnetic data and QUESTEM electromagnetic data) were used for catchment planning on a study area at Boscabel in the south west of Western Australia. The geophysical data provided a good explanation of the geological and hydrogeological reasons for the surface expression of salinity in this catchment and provided a guide for some catchment scale land management recommendations (World Geoscience Corporation and Read, 1992). Anderson et al. (1995) prepared a land management plan for a large property at Frankland in the south west of Western Australia, also using QUESTEM fixed wing airborne electromagnetic and magnetic data. This study concluded that the geophysical data, used in conjunction with other datasets, had significantly improved the understanding of hydrogeology in this property and assisted in planning management actions to control salinity.

2.3 Method

The Broomehill SALTMAP survey area is shown in Figures 4 and 5. The Broomehill project used a multidisciplinary project team in an approach developed from mineral exploration methodology. This required the farmer and planner to learn about geophysics and it required the geophysicists to learn about land management and the types of information products required to inform land management planning. Every week, the interpretation and planning team would meet and discuss the project and progress towards land management recommendations.

Dryland salinity was the priority issue to be addressed in the planning, so groundwater processes had to be well understood. Prior to this, property plans were based on surface information, sparse drill-hole data and extrapolation of this information into crude regolith models.

A literature review was implemented in order to obtain all available land information pertaining to the study area. The types of information acquired were similar to those described by Nulsen et al. (1996). This meant that at least 14 data sets would be used as an information source for property planning decision-making. With the geophysical and interpretation data sets included, there were 22 different types of datasets and information products (Table 2). These data sets were brought

No.	DATASET/INFORMATION PRODUCT
1	Cadastre/land tenure
2	Topography 10 metre interval contours
3	Surface Geology – scanned 1:250000 scale maps
4	Drainage lines
5	Aerial photography – scanned mosaic
6	Satellite imagery – Landsat 7
7	Road and rail networks
8	Vegetation
9	Land use information
10	Climate – rainfall and evaporation data
11	*Soil maps*
12	*Waterlogging prone areas*
13	Digital elevation model from SALTMAP (50 m grid)
14	SALTMAP channel 4-5 conductance (salt storage) 200 m line spacing, N-S
15	Magnetic images from 200 m line spacing, north-south survey
16	*Magnetic interpretation linework*
17	Regolith thickness data processed from SALTMAP
18	Basement (bedrock) topography from SALTMAP
19	*Basement geology interpretation of magnetic data*
20	Radiometric ternary image
21	*Integrated regolith interpretation map*
22	*Salinity (groundwater discharge) hazard map – this was called a hazard map at the time but it is more correct to call it a risk map.*

Table 2. List of data sets and information products used to support property planning decisions at Broomehill. Those listed in italics are value-added or derivative information products.

into a digital Geographic Information System (GIS). It was necessary to compare features of one image with those of another at the same location. This required interpretation in the form of lines, points or polygons that could be displayed over the other images. For example, linear trends in the magnetic image were interpreted using lines (Figure 13). This line data could then be displayed over (for example) an aerial photograph mosaic. Features in the aerial photographs, in some areas, reflected basement geology as interpreted from the magnetic data, but in other areas they did not. This data comparison identified the strengths and weaknesses of any particular dataset. With this knowledge, use of a particular data set can be constrained to its strengths. Likewise, features in any data set can be represented in the form of lines, polygons or points for comparison with any other data set. Thus there are primary data sets and derivative or interpreted data sets. Of the 22 data sets used at Broomehill, 16 were primary and 6 were interpreted data sets (Table 2).

2.3.1 Airborne Electromagnetics

The electromagnetic (EM) technique involves the transmission of an electromagnetic pulse into the earth from a transmitter loop suspended around the extremities of an aircraft (Figure 6). As the generated electromagnetic field enters the earth, conductive materials such as moist saline saprolite will develop their own secondary electromagnetic field in response and this is detected by the receiver antenna trailed behind the aircraft. A time domain EM system (TEM) operates by sampling the induced response signal at discrete time intervals (called ‘channels’ in the dataset) after the shut-off of the transmitter pulse. As the transmitted electromagnetic pulse penetrates the earth, early time responses are from shallow conductors and late time responses are from relatively deeper conductors. The AEM data provides information on the lateral and vertical distribution of salt stored in the regolith.

SALTMAP is a fixed wing, time domain airborne EM (TEM) system that differs from conventional airborne TEM systems in that it is a 100% duty cycle (on-time) square wave system. The transmitter waveform is a 495-hertz (Hz) alternating polarity square wave, with a pulse width of one millisecond. The receiver has a bandwidth of 50 KHz and samples each waveform 100 times (Duncan et al., 1992; Munday, 2001). For the Broomehill survey, the data were binned in a geometric sequence into 8 channels. Line spacing for the survey was 200m and flown in a N-S

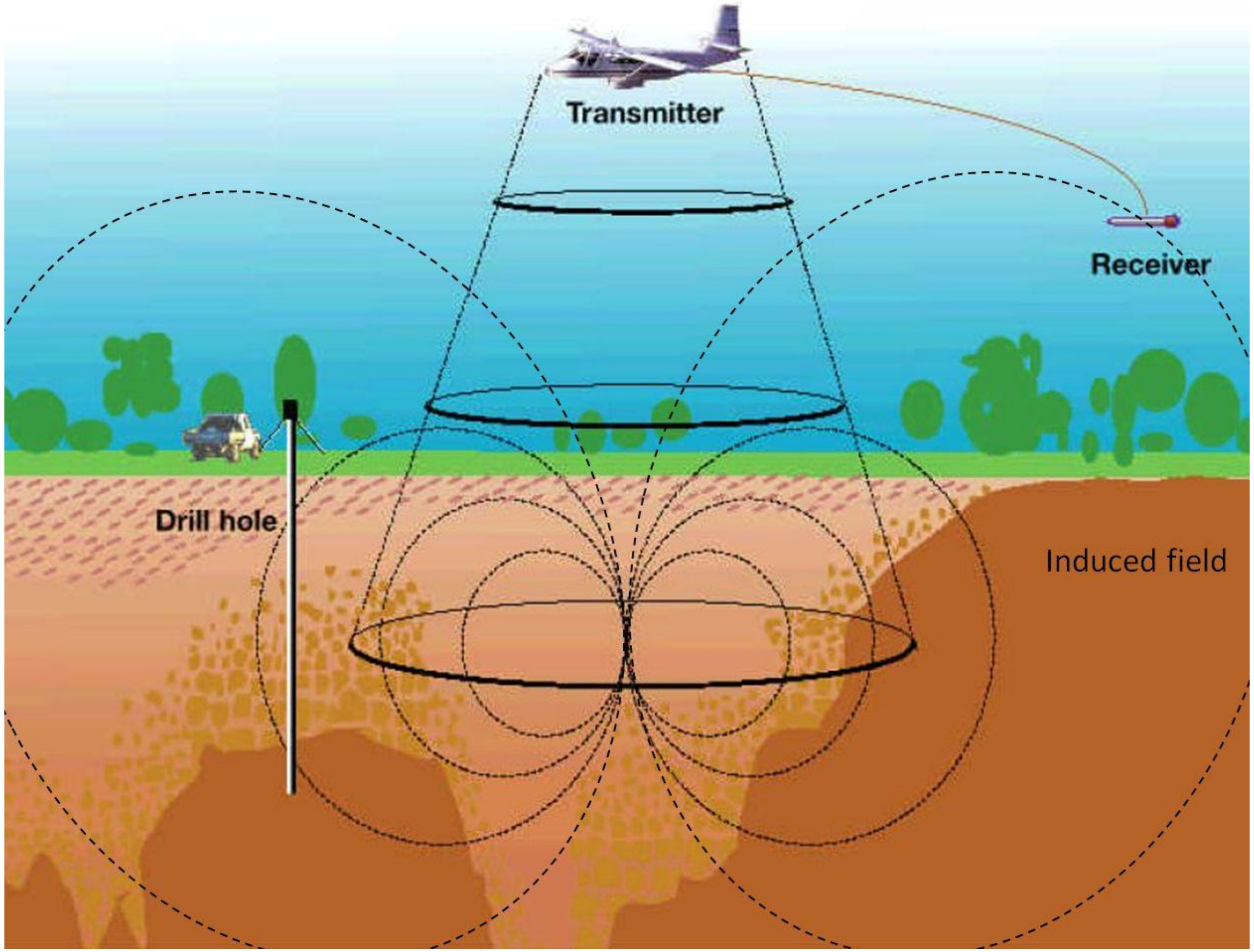

Figure 6. Schematic of Airborne Electromagnetic Survey system (after George et al., 1998)

direction with a nominal ground clearance of 60m for the receiver bird. In the geological setting of the Yilgarn craton, the SALTMAP system can discriminate three separate layers. Thus the whole data set was inverted to a 3-layer earth using a Layered Earth Inversion algorithm developed by Sattel (1998). Layer 1 is the (mostly) resistive surface layer of colluvium/alluvium, Layer 2 is the conductive saprolite, mottled clays, and saturated sedimentary valley fill. Layer 3 is the resistive basement. The LEI products can be represented as conductivity-depth sections (Figures 53, 54, and 55), conductivity-depth slices (Figure 62 showing depth slice at 45 metres) or as layer-specific parameter grids.

A composite of channels 4 and 5 conductance was chosen as the best representation of the lateral distribution of salt storage in the conductive saprolite layer when compared with drilling information. This is the direct measurement of the induced electromagnetic field at time steps 4 and 5 representing layer 2 (saprolite layer). This is dataset 14 in Table 2. Basement topography was another important dataset derived from the SALTMAP data. This was calculated by subtracting regolith thickness from surface elevation. Regolith thickness is measured in the SALTMAP data by identifying the time channel (depth) at which the 3rd (resistive) layer appears. This is where the induced electromagnetic field falls away as the transmitted field enters the resistive basement.

2.3.2 Airborne Magnetics

The earth's magnetic field is affected by the presence of magnetic minerals in the crust and secondary fields generated by magnetically susceptible minerals. An airborne magnetic survey measures the earth's magnetic field plus the subtle variations caused by the geology (Figure 7). The earth's magnetic field and variations caused by sunspot activity can be removed by subtracting data collected from a stationary magnetometer located in the same area. Data processing leaves only the variation caused by magnetic minerals, particularly magnetite. Relative abundance of magnetite is related to different rock types so geology and structures seen in the magnetic image can be interpreted. Interpretation of magnetic data provides mapping of faults, shear zones, dykes and volcanic and metamorphic features in the basement rock. Magnetic data reflects the geology and structure of basement rock revealing the location and alignment of faults, shear zones and dykes (Engel et al., 1987).

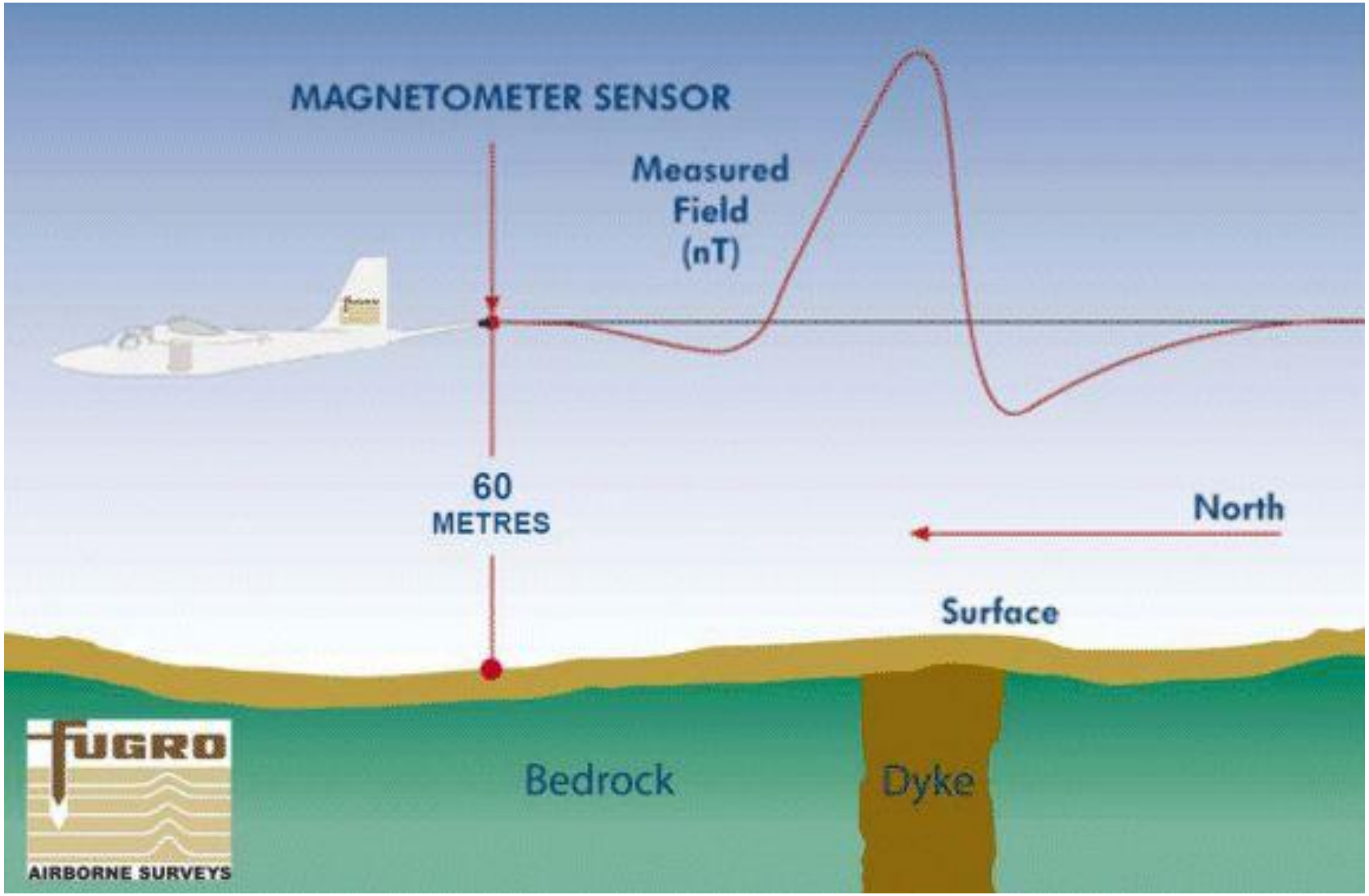

Figure 7. Schematic of airborne magnetic survey system, image supplied courtesy of Fugro Airborne Surveys.

In the agricultural areas of Western Australia, the relatively thick weathered zone over basement makes conventional surface geological mapping difficult. Magnetics has been an important tool in improving the quality and accuracy of geological mapping(George et al., 1998). The information products from airborne magnetic surveys are grids and images and interpreted linear and polygon features. For non-geologists the most useful product is an interpretation map. Interpretation map products clearly display significant geological features such as dykes, shears and faults. Dykes generally contain a higher concentration of the principal magnetic minerals (magnetite, ilmenite and pyrrhotite) relative to granite, and therefore have a higher magnetic susceptibility and a greater intensity of induced magnetism. Measurements of the earth's magnetic field in the vicinity of a dolerite dyke that intrudes granite will produce an anomaly in the earth's magnetic field. Therefore magnetic survey methods have the potential to locate and delineate magnetic dykes (Reynolds, 1997). The linear hydraulic barrier caused by the clay-rich doleritic saprolite can result in the impeded flow of groundwater and the forcing of saline groundwaters into surface soils (Engel et al., 1987). For this reason, it is important to know the locations of these features at the farm and paddock scale to facilitate infrastructure and agronomic planning to minimise the risk of groundwater discharge.

2.3.3 Using the information from geophysics to map the hydrogeological drivers of dryland salinisation.

The airborne geophysical surveys at Broomehill provided information on salt storage, basement and regolith structures, and basement depth. This resulted in better understanding of the location and impact of surface management actions with respect to hydrogeological structures that were for the first time represented on a site specific basis. This information changed the approach to designing surface water management earthworks, such as grade banks and storage dams. These types of earthworks redistribute surface water that is destined to become either runoff or groundwater. For example, it has been shown by McFarlane and Cox (1990) that grade banks and seepage interceptor banks significantly reduce waterlogging down-slope of the bank (Figure 1). Collecting this water and directing it to a watertight storage dam results in improved crop and pasture production through reducing the negative effects of waterlogging. It also increases the on-farm storage of water, thus reducing summer water carting costs. The additional knowledge of the spatial distribution of salt storage enables the farm planner to directly influence the interaction of surface and groundwater with stored salts in the regolith. This information guides the planner's decisions about where water is collected from and where it is placed.

The basis of the property planning for salinity management at Broomehill was hydrological risk management. For salinity to occur at any particular site there are four primary risk factors which are described in Table 3.

Factor No.	**Risk factor description**
1	A source of salt
2	A source of water
3	A mechanism that brings the salt and water together
4	A mechanism that brings the saline water to the surface.

Table 3. The four primary risk factors for the development of dryland salinity.

This was the basis for interpretation of the geophysical data for farm planning on 24 properties at Broomehill. This thesis focuses on The Meadows property as the detailed example of how the methodology was applied.

The Broomehill area and The Meadows property in particular, has good relief with slopes in the range of 5% to 3%. The valley floor has a minimum slope of 0.6%. Even though most of this landscape should be classed as well drained, farmers identified winter waterlogging as a significant productivity-limiting issue. This appeared to be more due to the duplex nature of the soils rather than lack of slope. Most soils were loamy sands or sandy loams over heavy clay subsoil. This texture and permeability contrast predisposes such duplex soils to waterlogging (Gardner, 1989). Groundwater recharge can occur in any part of the landscape, however the groundwater recharge process is most active in areas of soil waterlogging (George, 1993). In these areas, water is retained in saturated surface soils and has maximum opportunity to percolate into deeper groundwater via preferential flow pathways or "macropores" (Johnston et al., 1983). This is illustrated in Figure 1. The importance

of waterlogging prone areas as a strategic target for managing salinity is highlighted by the findings of George (1993) who concluded from 9 years of research into the nature and roles of groundwater aquifers in the western Australian wheatbelt that:
“Throughout the wheatbelt, significant recharge to the deep aquifer takes place down macropore channels following saturation of surface soil materials after major rainfall events. This is evidenced by rapid water table responses in the deep aquifer following saturation of the shallow aquifer…”

Waterlogging prone areas can be mapped quite accurately from aerial photography, provided the photography is captured at the right time of year. That is usually in springtime when differential rates of soil drying are reflected by the condition and maturity stage of crops and pastures. At Broomehill, springtime aerial photography was available. Areas that remained green in spring relative to those that had senesced, and showed more of a straw colour, were the areas prone to winter waterlogging. The aerial photography was interpreted with the assistance of farmers’ local knowledge and used to produce a transparent hatched waterlogging polygon theme in the GIS (Figure 8). The SALTMAP channel 4-5 conductance image identifies the distribution of salt storage in the landscape (Figure 9).

By combining the channel 4-5 conductance image with the map of waterlogging prone areas (Figure 9), it was possible to identify the highest risk areas for the first three requirements for the development of salinity – a source of salt, a source of water, and a mechanism that brings the water and salt together (Table 3). These areas were given highest priority for surface water management earthworks designed to minimise the severity and extent of waterlogging. These areas were also given a high priority for revegetation as a means of drying out the sub-soil.

The fourth requirement for the development of salinity is identified by the groundwater discharge mechanisms most commonly found in the granite/gneiss terrain of the Broomehill area and represented in the form of six hydrological models (Figure 10) (Leeming et al., 1994). Model C in Figure 10 also applies to roads where they traverse drainage lines. Compaction of the subgrade (saprolite clay) for road building reduces the hydraulic conductivity of the clay directly below the road. The reduced permeability of the compacted clay causes groundwater to accumulate on the

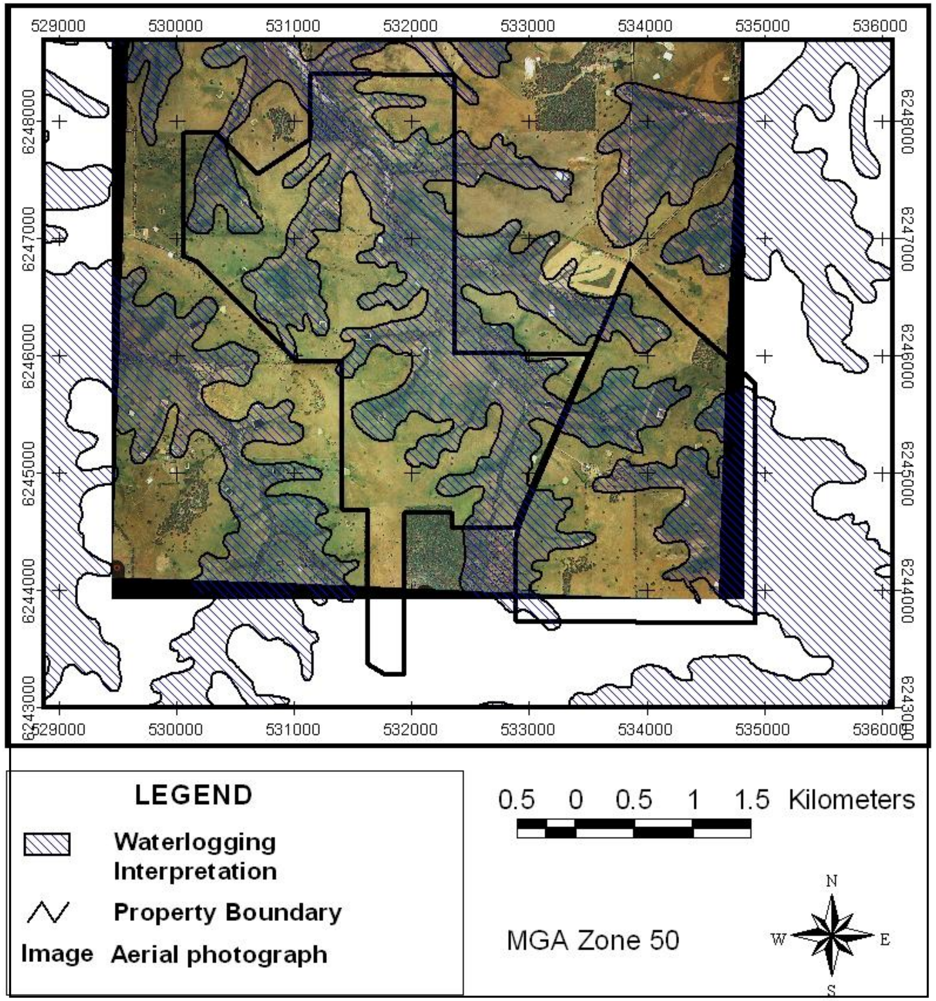

Figure 8. Aerial photograph interpretation of waterlogging on The Meadows property.

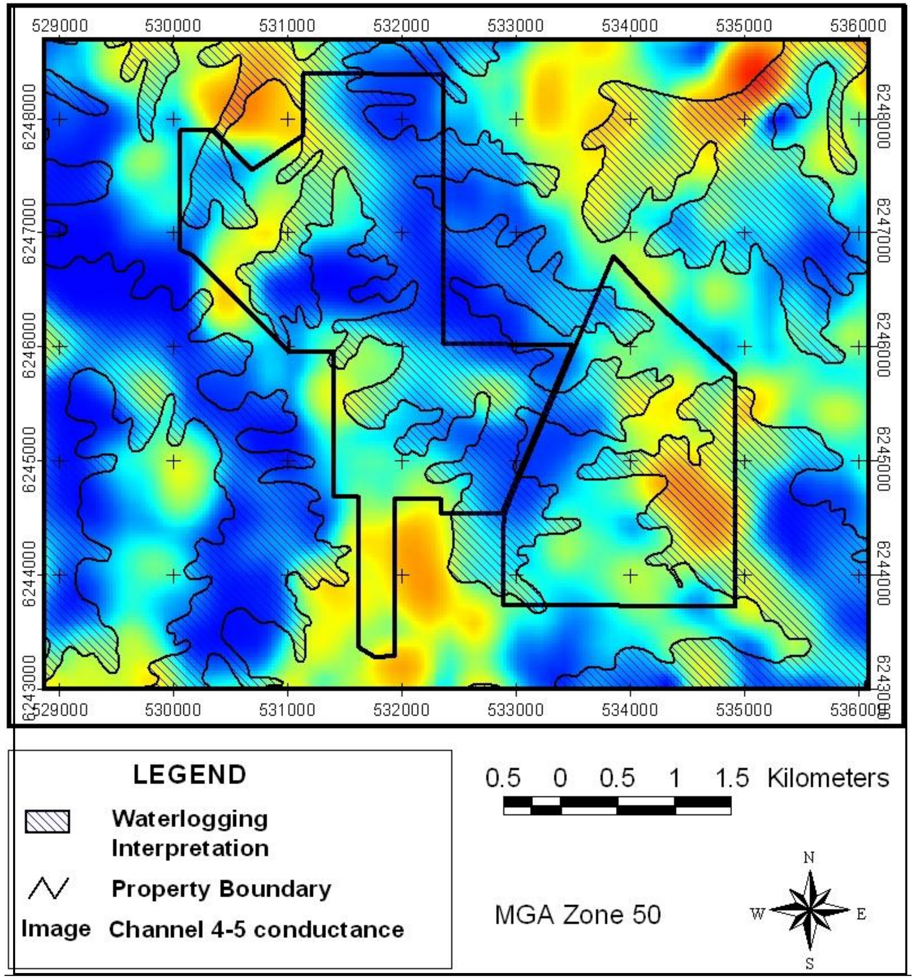

Figure 9. Water logging prone areas overlaid on SALTMAP channel 4-5 conductance image. High conductance is red/orange, low conductance is blue.

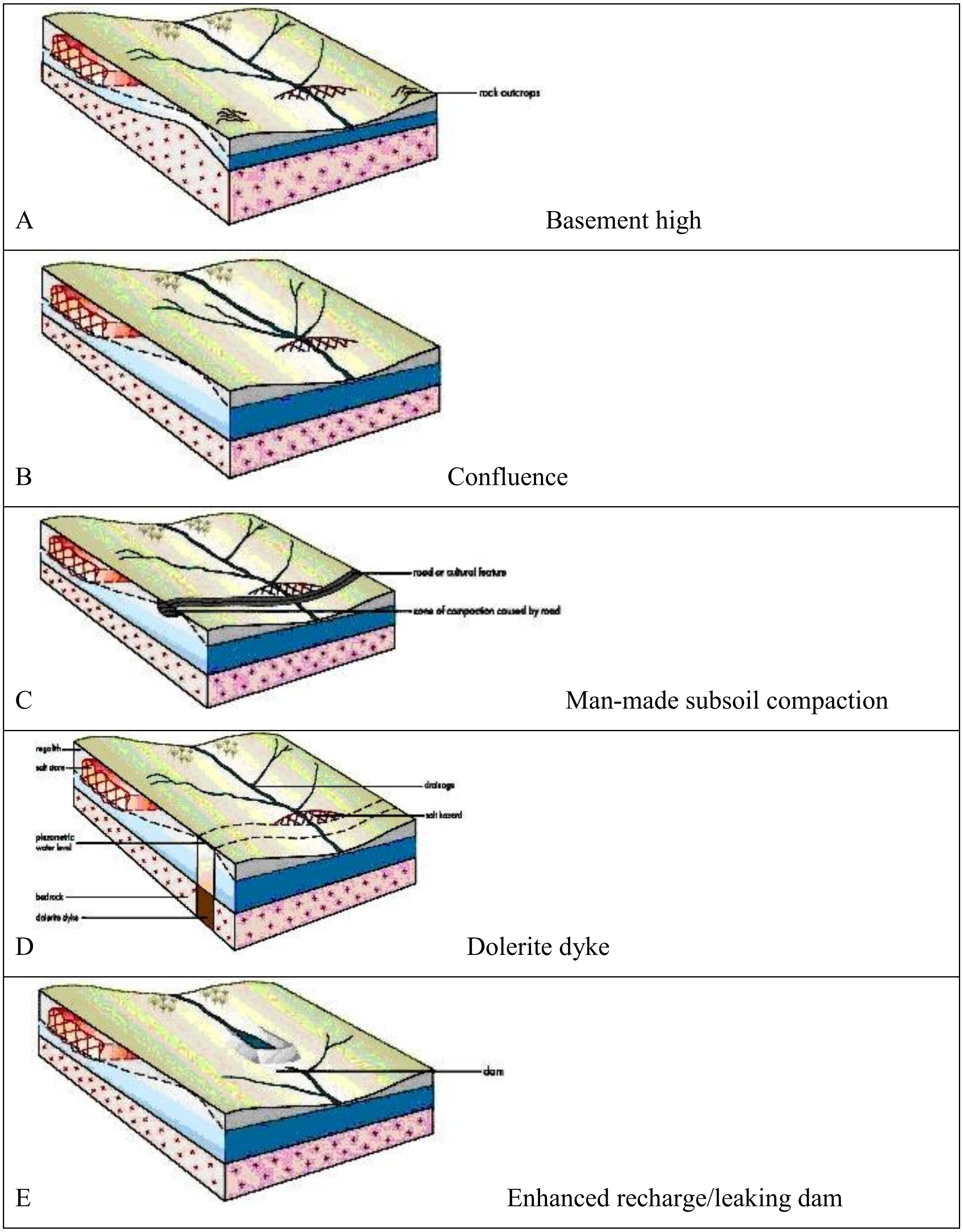

Figure 10. Groundwater discharge models used to identify groundwater discharge risk forsalt hazard sites (reproduced from Leeming et al., 1994). Model 'C' also applies to roads, where subsoil compaction creates a man-made risk site.

up-slope side of the road in the same manner as it does on the upslope side of a dolerite dyke (Engel et al., 1987), resulting in increased discharge at the surface.

The models in Figure 10 were the basis for the interpretation of existing and potential saline discharge sites (salt hazards) in the area (Figures 12 and 13). The basement topography image in Figure 11, although coarse, enabled interpretation of basement catchments to salt hazard sites. The magnetic and electromagnetic data were interpreted to identify the locations at which the hydrological conditions defined by the models occurred. For example, dolerite dykes are known to present barriers to groundwater movement (Engel et al., 1987). The first pass of this interpretation of magnetic and electromagnetic data was manual interpretation using a series of map overlays on a light table.

Each salt hazard site has a surface water catchment and a groundwater catchment. These catchments often differ from each other in shape and area, because impermeable basement topography often differs significantly from the surface topography (Figure 12). The main pathway for lateral movement of groundwater in in-situ weathered regolith of the Yilgarn Block in WA is within the saprock zone, which is the gritty interface between fresh, unweathered basement rock and the overlying saprolite clay (George, 1990). The groundwater catchment is determined by basement topography at Broomehill (Figures 11 and 12). Therefore, basement topography is the principal driver of lateral groundwater movement in this geological environment. The basement topography dataset derived from the SALTMAP data was therefore used to fill a major knowledge gap in the information base for land management planning at Broomehill. The basement topography dataset is a product of a 3-layer constrained inversion of the SALTMAP data and represents the surface contact of the third layer (resistive basement).

Salt hazard sites were ranked based on the size and bulk conductivity of the groundwater catchment feeding each site (World Geoscience Corporation, 1996). This produced 18 salt hazard sites on The Meadows property (Figures 12 and 13). In 1996, three of these sites did not display evidence of groundwater discharge or salinity. There were four existing saline sites on the property that were not identified by the manual interpretation method.

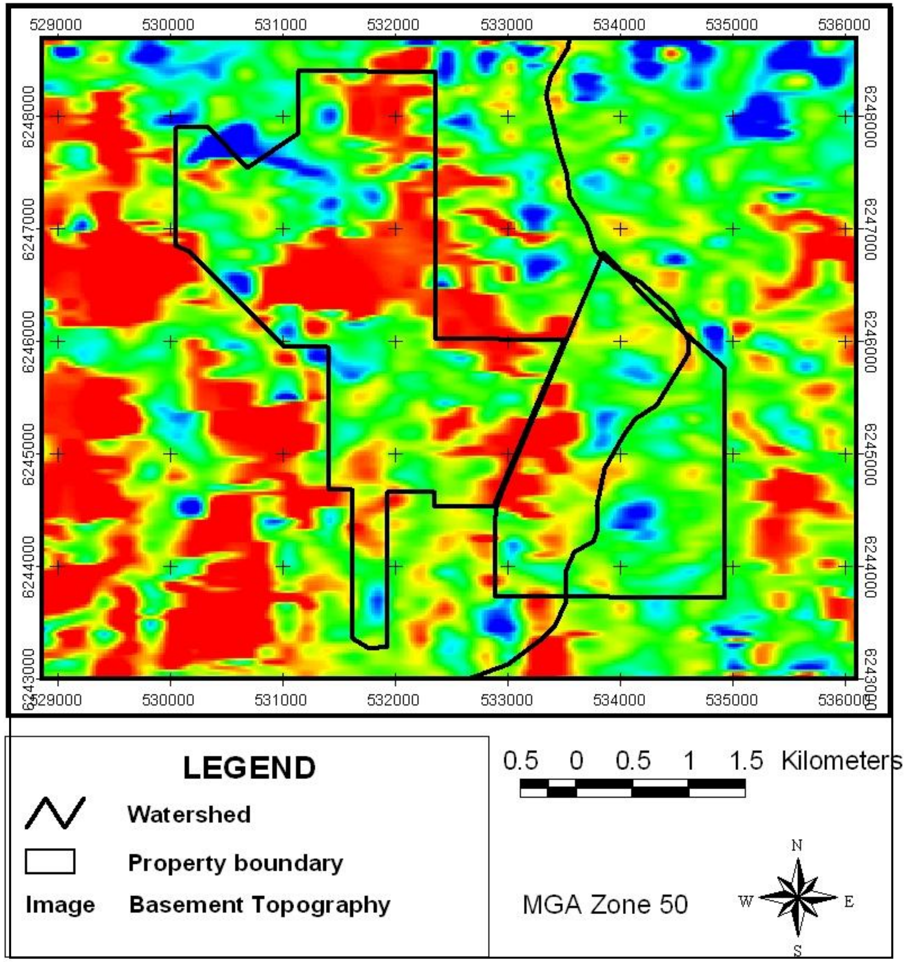

Figure 11. SALTMAP basement topography image. Note that the basement topographical high (red) is west of the surface topographical high represented by the drainage divide marked as "watershed" in this figure.

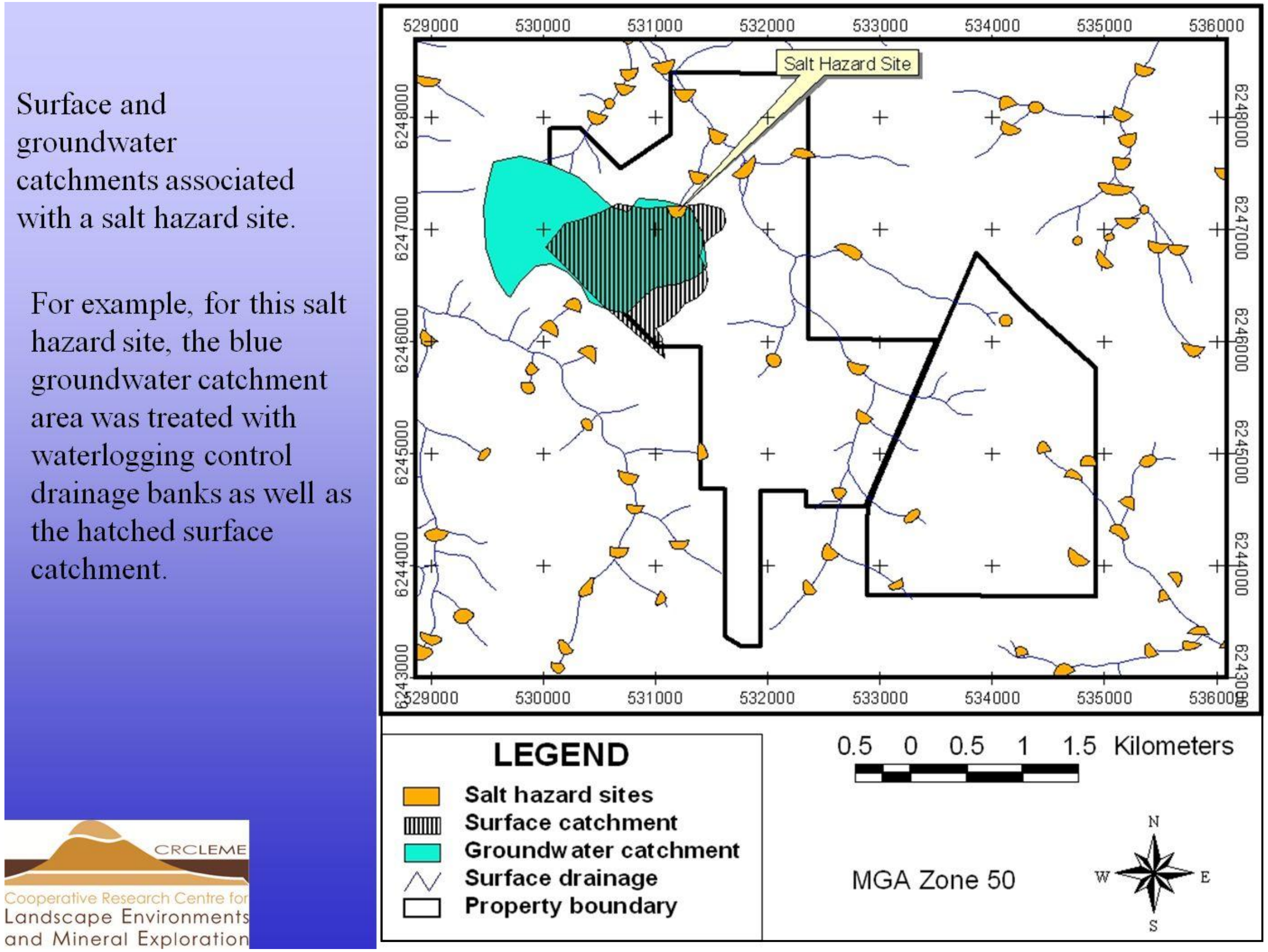

Figure 12. Salt hazard sites on and surrounding The Meadows property. Note the difference between groundwater and surface water catchments to the marked salt hazard site.

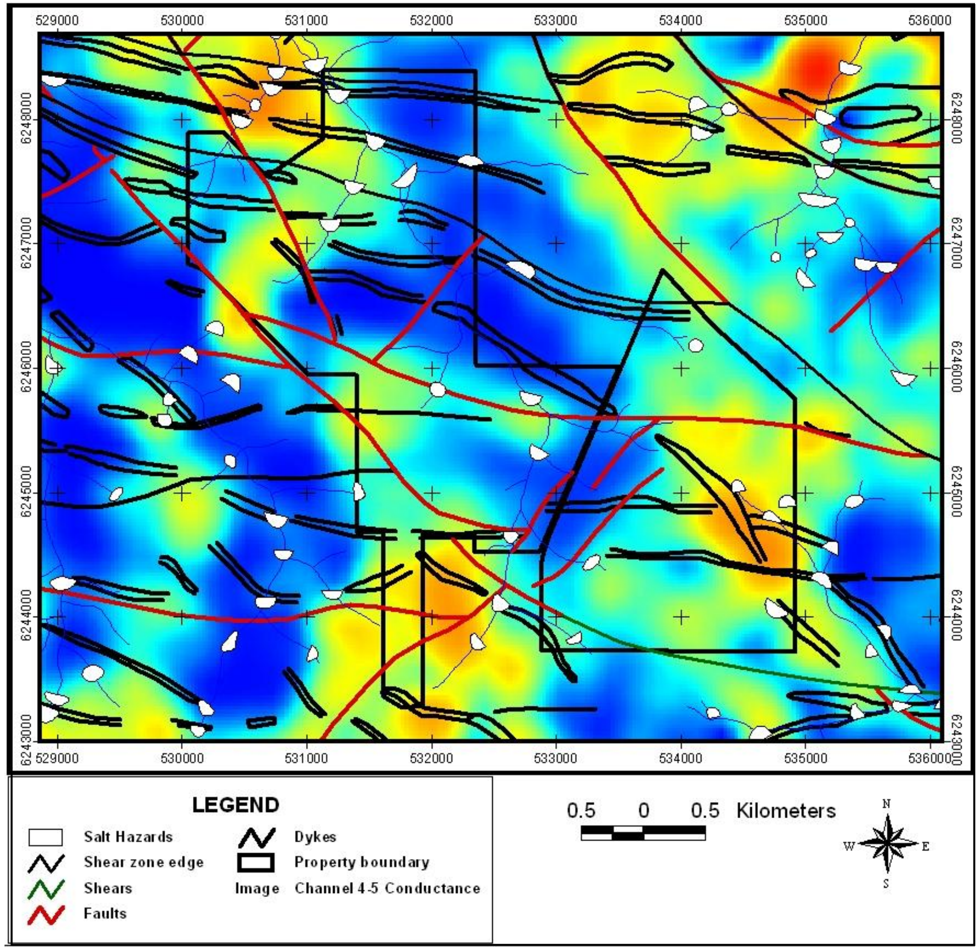

Figure 13. The use of the magnetic interpretation in conjunction with SALTMAP channel 4-5 conductance image, surface and basement topography to identify potential groundwater discharge (salt hazard) sites.

At these locations, salinity (identified by interpretation of satellite imagery) extended more than 50 metres upstream of an identified salt hazard site and a groundwater discharge mechanism was not identified in the data to explain the full upstream extent of the discharge. The process of identifying dyke intersections with streamlines and valley floors was later automated in GIS by Anderson-Mayes, (1997).

2.3.4 Applying the hydrogeological information to farm infrastructure planning.

Knowledge of basement topography enabled a better understanding of subsurface water movement. This enabled informed decisions to be made about the diversion of surface and shallow seepage water by surface water management earthworks to take account of both the surface and the groundwater catchments to the salt hazard sites (Figure 12). It was then possible to design surface water management earthworks that would prevent or substantially reduce waterlogging over high salt storage zones, within not just the surface catchments, but also the groundwater catchments of these sites. This information also enabled the planning of earthworks to be cost-effective. Earthworks infrastructure is expensive both in terms of construction cost and the productive land sacrificed (3.8% of total area of The Meadows property). Areas that did not need treatment did not receive treatment.

These earthworks consisted of grade banks and seepage interceptor banks. Grade banks are earth embankments built with a road grader to a maximum height of 0.5 metres on the downslope side of the excavation (Figure 1), and intended to collect and divert surface runoff. They are constructed to have a fall of 0.5 metres in 100 metres which is a gradient of 0.5%. Seepage interceptor banks are cut deeper into the clay subsoil than grade banks and are designed to intercept shallow seepage water from the interface between the permeable surface soil layers and the less permeable subsoil (saprolite clay). The macropores and preferred pathways in the clay base of the bank are sealed by smearing and compaction to prevent leakage. Without geophysical information, it would have been necessary, by virtue of the precautionary principle (Anonymous., 1998), to design the earthworks in a blanket approach according to conventional rule-of-thumb guidelines (Keen, 2001). For example, if a slope is x% and soil type is y, then earth banks must be no less than z metres apart and deliver water to the nearest natural waterway. This can result in investment in earthworks where they are not needed. This approach considers only soil type and slope. Earthworks designed on this basis, without knowledge of location of salt storage and regolith thickness from geophysics, can discharge water onto areas of high salt storage and relatively shallow regolith. The consequence of this is raising the saline watertable at the discharge site, thus creating or, aggravating salinity at that site. This is described in a case study in my Masters dissertation (Abbott, 2003) and the same case study was published in Spies and Woodgate (2005).

Prior to the Broomehill SALTMAP project, a reliable basement topography data set had not been used in salinisation analysis and property planning. Basement topography was used in producing a property plan for The Meadows at Broomehill. The mechanisms and pathways of groundwater movement were interpreted and used in decision-making at the paddock scale in this property plan. However, management of mechanisms driving salinity were not the only design criteria. Other design criteria that applied to this planning process include;

- Fencing to soil type
- Fencing to allow efficient livestock and machinery movement
- Surface water management to provide all-weather access around the farm
- Surface water management to control storm water erosion
- Surface water management to control waterlogging
- Surface water management to harvest fresh water
- Surface water management to concentrate waterlogging control over high salt storage areas
- Revegetation to protect soils from wind erosion
- Revegetation to dry out subsoil over and upslope of high salt storage areas
- Revegetation to moderate paddock microclimate
- Ensuring there is a livestock water supply in every paddock

Farm planning is a process guided by multiple design criteria of which, in this case, salinity management had a high priority. Another criterion is the need to fence the property according to soil type, but there are compromises. For example, it is beneficial to locate earthworks close to soil type boundaries, so that fencing follows the earthworks and serves a dual purpose of protecting associated tree belts. This criterion is often compromised due to the location of high salt storage and waterlogging areas, because they are addressed as a higher priority. Earthworks must deliver water to predetermined points, such as storage dams, thus requiring further compromise. This means that in the "low conductance (low salt storage)" parts of the property, where salinity management had a lower priority, the other criteria, listed in dot points above, often required infrastructure proposals.

2.4 Farm planning methodology using geophysics

The basis of the farm plan was water management. The farm had a history of water deficiency during summer, requiring the farmer to cart water for stock every summer. Consequently, there was a requirement to harvest winter run-off and to direct it into storage dams throughout the farm. Salinity management was also a very high priority and was the farmer's main motivation for undertaking the re-design of his farm infrastructure. The drains proposed for water harvesting were also designed such that they addressed the salinisation risk factors listed in Table 3. This was achieved by giving priority to locating drainage banks upslope of, and on areas prone to waterlogging and overlying high salt storage zones. This strategy directly addressed risk factor 3 – the main mechanism that brings water and salt together.

Proposed revegetation mostly took the form of belts of native trees planted immediately downslope of the drains. This strategy has been shown to reduce water storage in the root zone of the trees and reduce groundwater movement down the slope (White et al., 2002).

To address salinity risk factor 4 (mechanisms that bring saline groundwater to the surface) both the surface water catchment and the groundwater (or basement) catchments of each salt hazard site (Figure 12) were taken into consideration in designing the drainage banks and revegetation areas. The basement catchment was interpreted from the basement topography dataset.

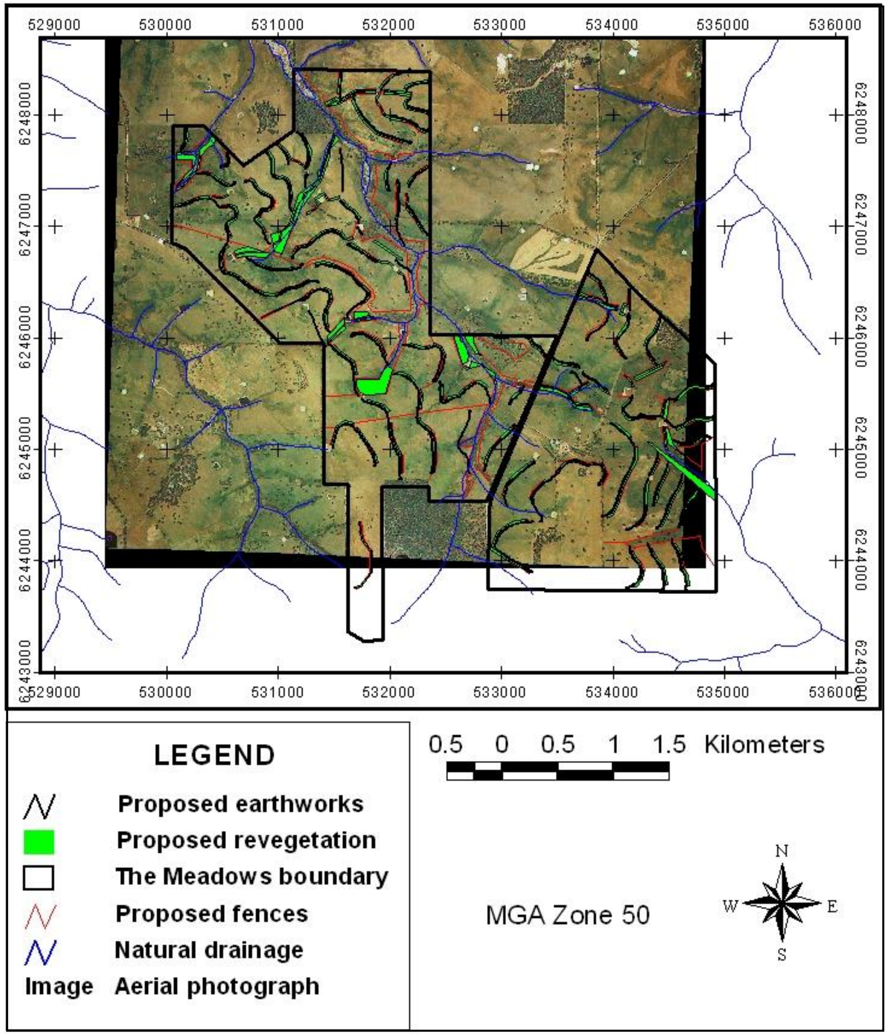

Figure 14. Plan showing proposed drainage, revegetation and fencing works on The Meadows property

Figure 15. Newly constructed grade bank on “The Meadows” in 1996.

Figure 16. Photograph taken from approximately the same location (point “A” is reference point) in 2006.

In addition, the salt hazard sites interpreted from the magnetic data were used as pour points to define surface and groundwater sub-catchments to each salt hazard site. This facilitated a check on drainage bank and revegetation area design such that there was waterlogging control coverage of both surface and groundwater catchments for each salt hazard site.

2.5 Results

Ten years after the Broomehill SALTMAP project five key results for The Meadows property can be noted. They are:

- The plan for The Meadows (Figure 14) including fencing, earthworks, roadworks, revegetation and construction of new water storages was implemented in 1996 (Figure 15), driven by the land holder's conviction that the proposals in the plan were based on the most comprehensive set of supporting data available at that time. This is significant because less than 5% of the hundreds of property plans prepared in Western Australia are implemented. This was reported by Robinson et al., (1996).

- The property became water efficient. Prior to implementing the plan, the landholder frequently had to cart up to 20,000 litres of water per day for stock during summer. This was at a significant cost in terms of fuel and time. He has not carted water since the surface water management earthworks were constructed (Chadwick, personal communication), even in the face of declining average rainfall, because runoff and shallow seepage water that was previously causing degradation and/or going to waste, is now directed into storage dams.

- During the farm planning process, the benefits of realigning paddocks to soil type and along the land contour, between drainage banks were discussed with the farmer. The Farmer reported that, in the re-aligned paddocks, stock used less energy walking up and downhill between water and feed so production of meat and wool per unit of feed is improved. They were less inclined to "camp" in one spot so nutrients from faeces and urine were more evenly distributed thus improving soil fertility and crop productivity. The plan was a catalyst for restoring the farmer's enthusiasm for farming and changing the way the farm was managed. It is now ranked in the top 5% of properties in the regional farm productivity benchmarking group (Chadwick, personal communication).

- Implementation of the plan was followed up by independent economic assessment and physical monitoring. The economic analysis (Chamarette and Robinson, 1999) examined the cost benefit of the implementation of the plan compared to two other implemented farm plans in the same geographical area. All the farm plans used the same "trees on banks" strategy but the Meadows plan was the only one based on geophysical information in its design. This analysis revealed that the Meadows was the only farm to have a positive cost benefit from the implementation of the plan. Further analysis in this thesis demonstrates that the positive cost benefit can be attributed to the use of the geophysical data.

- The physical monitoring continues in the form of monitoring of piezometers by the Department of Agriculture. This monitoring shows continuing rise in piezometer levels on all 3 properties (in un-published bore data) (Paul Raper, personal communication) that were compared by Chamarette and Robinson (1999).

2.5.1 Influence of geophysical information supporting the farm planning process

Visual examination of The Meadows property plan (Figure 14) reveals no obvious difference to any other property plan using similar strategies. To discover if there was a significant difference in the spatial distribution of works due to the use of the SALTMAP data, the property was coarsely classified into "high conductance" and "low conductance" areas (Figure 17). This classification was then further subdivided using the waterlogging dataset producing a classification map showing high conductance with waterlogging, high conductance without waterlogging, low conductance with waterlogging and low conductance without waterlogging (Figure 18).

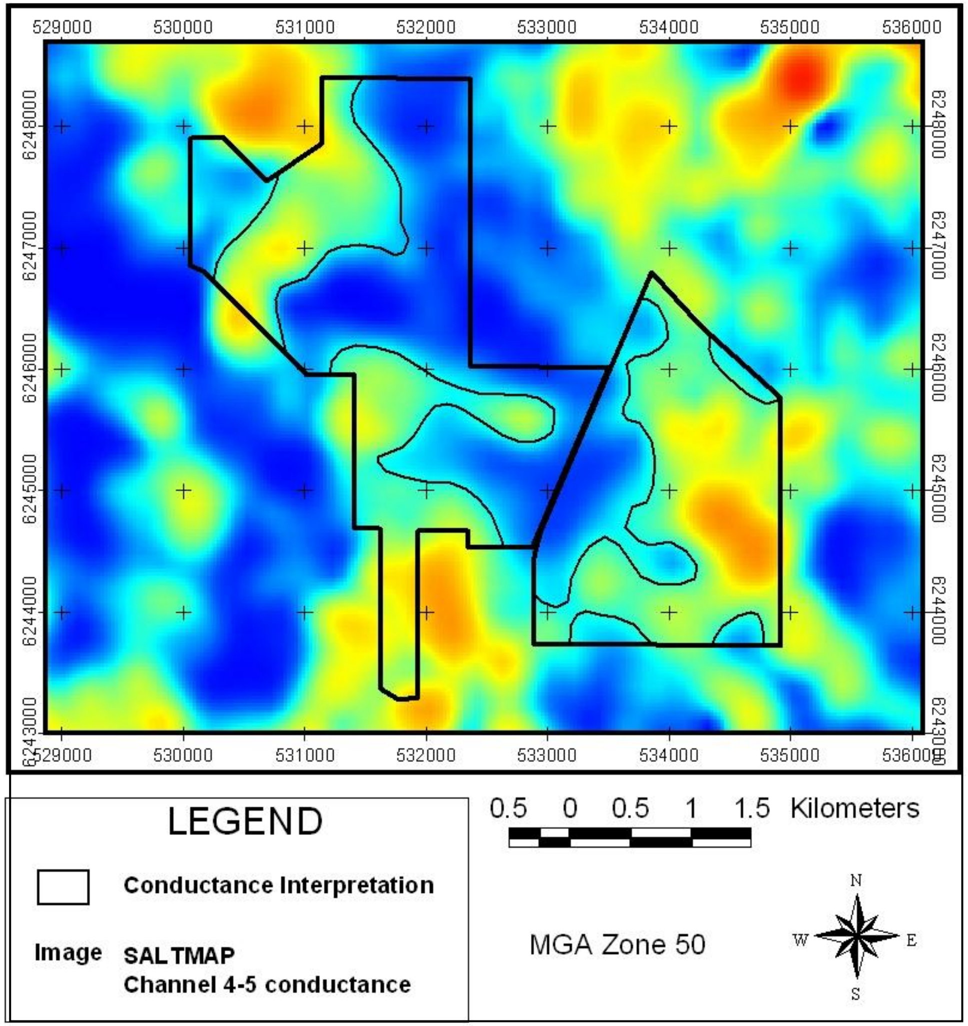

Figure 17. Manual classification of conductance image into high conductance and low conductance classes.

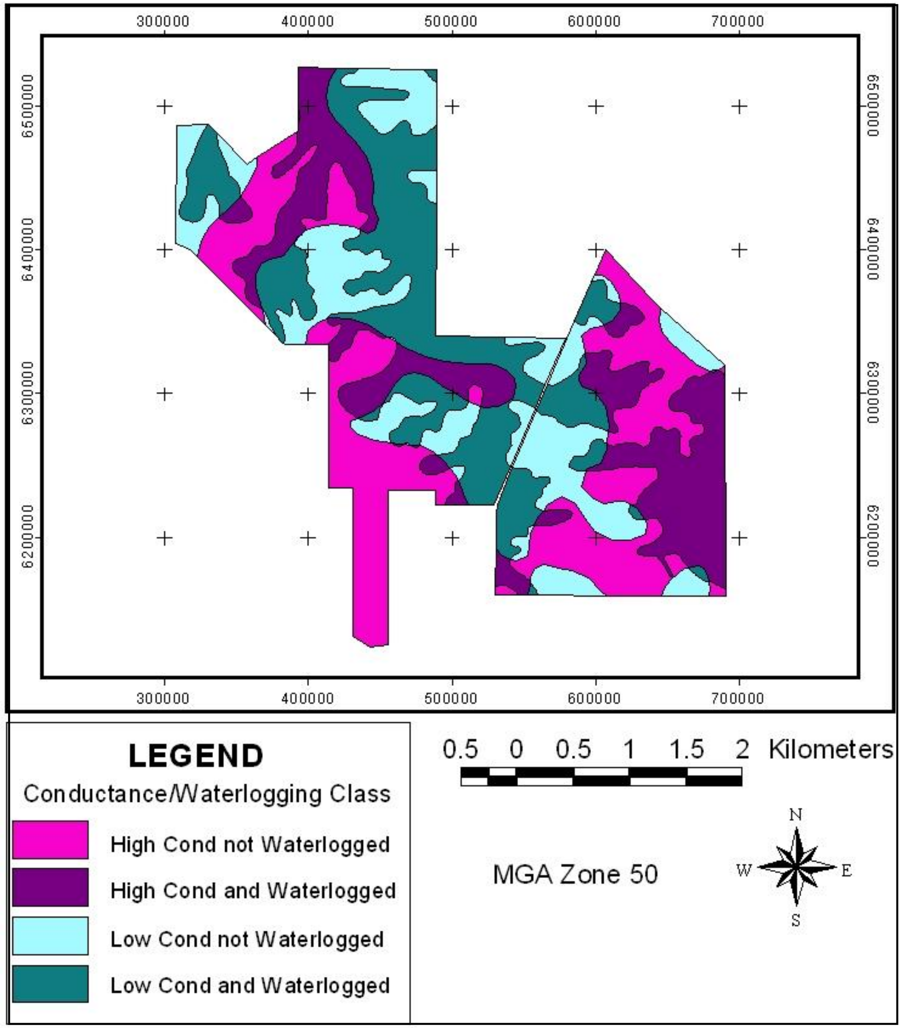

Figure 18. Classification of the Meadows on the basis of interpreted conductance and waterlogging.

It was then possible to measure the amount of farm plan infrastructure (hectares of revegetation and kilometres of earthworks) located on each class. The farm plan infrastructure (hectares of revegetation and kilometres of earthworks) were allocated to the land class on which they are located as listed in Tables 4 and 5.

CLASS	AREA (ha)	REVEG (ha)	% of CLASS	% of TOTAL
High-Dry	335.78	12.51	3.7	17.5
High-Wet	278.48	27.43	9.8	38.4
Low-Dry	255.52	10.63	4.1	14.9
Low-Wet	322.69	20.84	6.5	29.2

Table 4. Farm plan revegetation by SALTMAP conductance/waterlogging class.

CLASS	AREA (ha)	Earthworks (km)	km/ha	% of TOTAL
High-Dry	335.78	7.97	0.024	25.6
High-Wet	278.48	7.67	0.028	24.6
Low-Dry	255.52	7.56	0.030	24.3
Low-Wet	322.69	7.96	0.025	25.5

Table 5. Farm plan earthworks by SALTMAP interpreted conductance/waterlogging class.

The distribution of proposed revegetation is closely related to interpreted conductance/waterlogging class (Table 4 and Figure 19). This indicates that interpreted salt storage (from SALTMAP conductance) and susceptibility to waterlogging were strong influences on the location of proposed revegetation in the farm plan for The Meadows. Concentration of proposed revegetation is directly related to salinity risk factors 1, 2 and 3 (Table 3).

The distribution of proposed earthworks shows an even distribution relative to interpreted conductance/waterlogging class (Table 5 and Figure 20). The concentration of proposed earthworks is not directly related to the interpreted conductance/waterlogging class on which it is located.

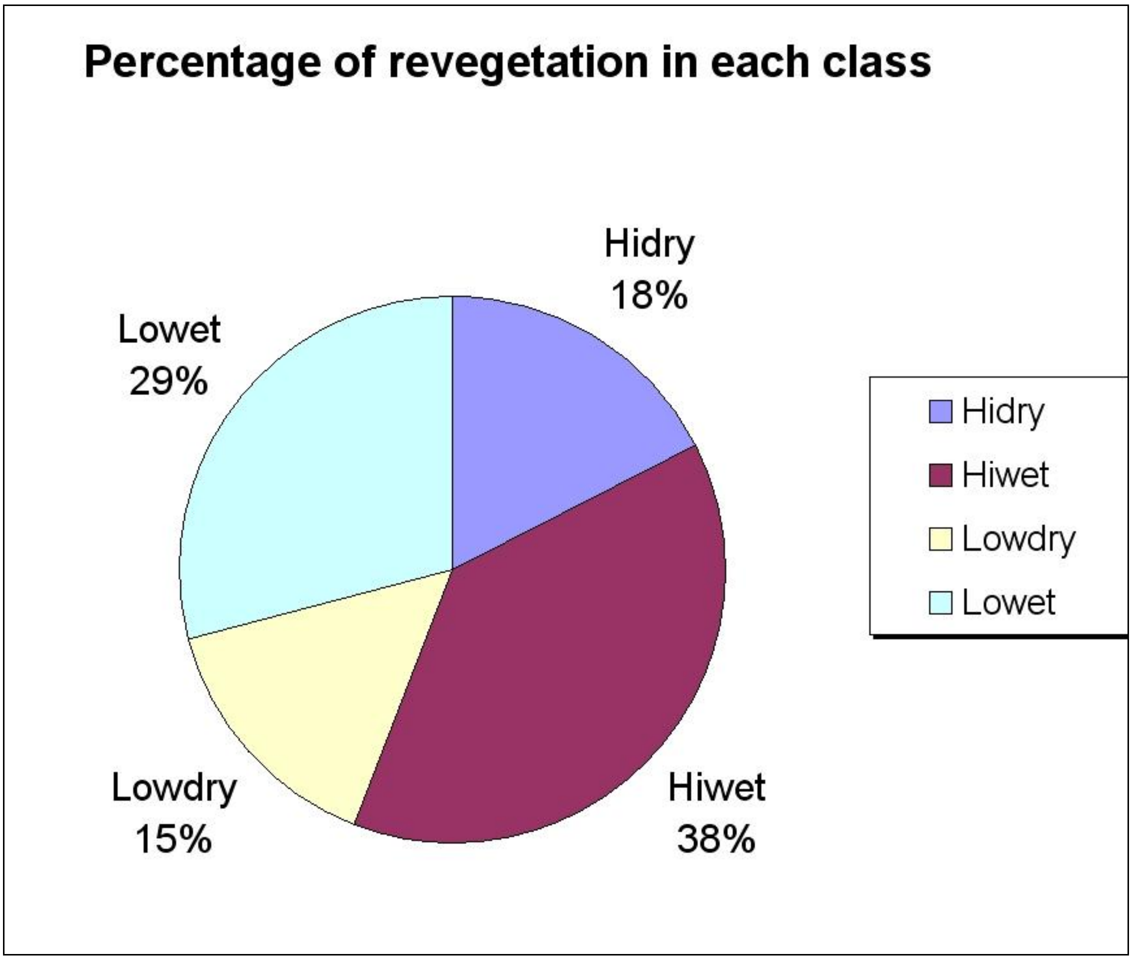

Figure 19. Graphical representation of distribution of proposed revegetation (% of total revegetation) located on the interpreted conductance/waterlogging class.

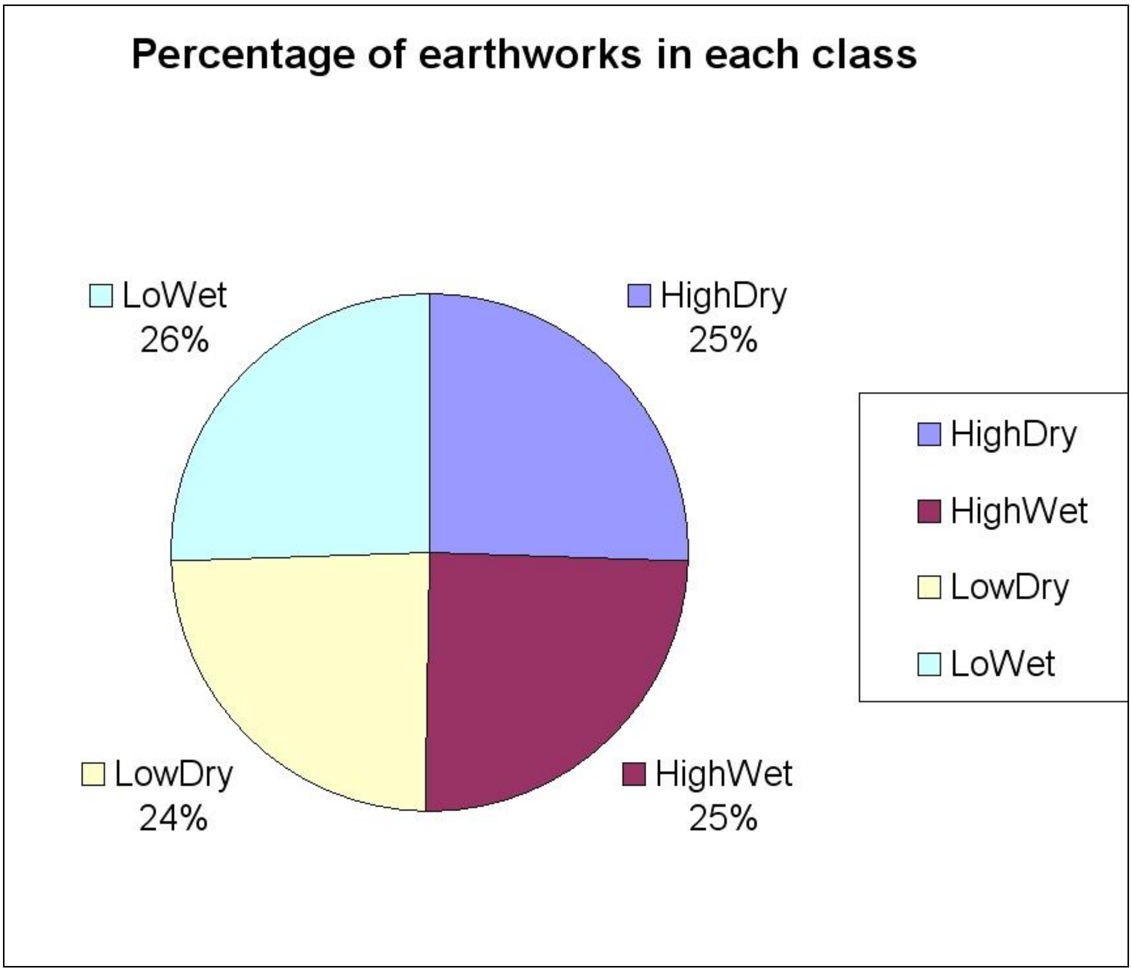

Figure 20. Graphical representation of distribution of proposed earthworks (% of total km of earthworks) located on each interpreted conductance/waterlogging class.

The Department of Agriculture Western Australia undertook a comparison of this property plan with two other property plans that used similar biophysical strategies in the same region (Chamarette and Robinson, 1999). The implemented plans were compared on the basis of Cost Benefit Analysis (CBA). This took into account implementation costs, estimates of the productivity benefit resulting from implementation of the farm plan, the likely decline in arable area and the gross margin if no farm plan was implemented. The Cost Benefit Ratio (CBR) was calculated for each property. If the CBR < 1, the costs exceed the benefits. If the CBR > 1, the benefits exceed the costs. The most profitable farm plan was The Meadows (Table 6).

	The Meadows	Property A	Property B
BCR	1.41	0.89	0.08

Table 6. Benefit cost ratios of the three properties examined by Chamarette and Robinson (1999).

This was due to the cost per hectare of implementation being the lowest of the three properties.

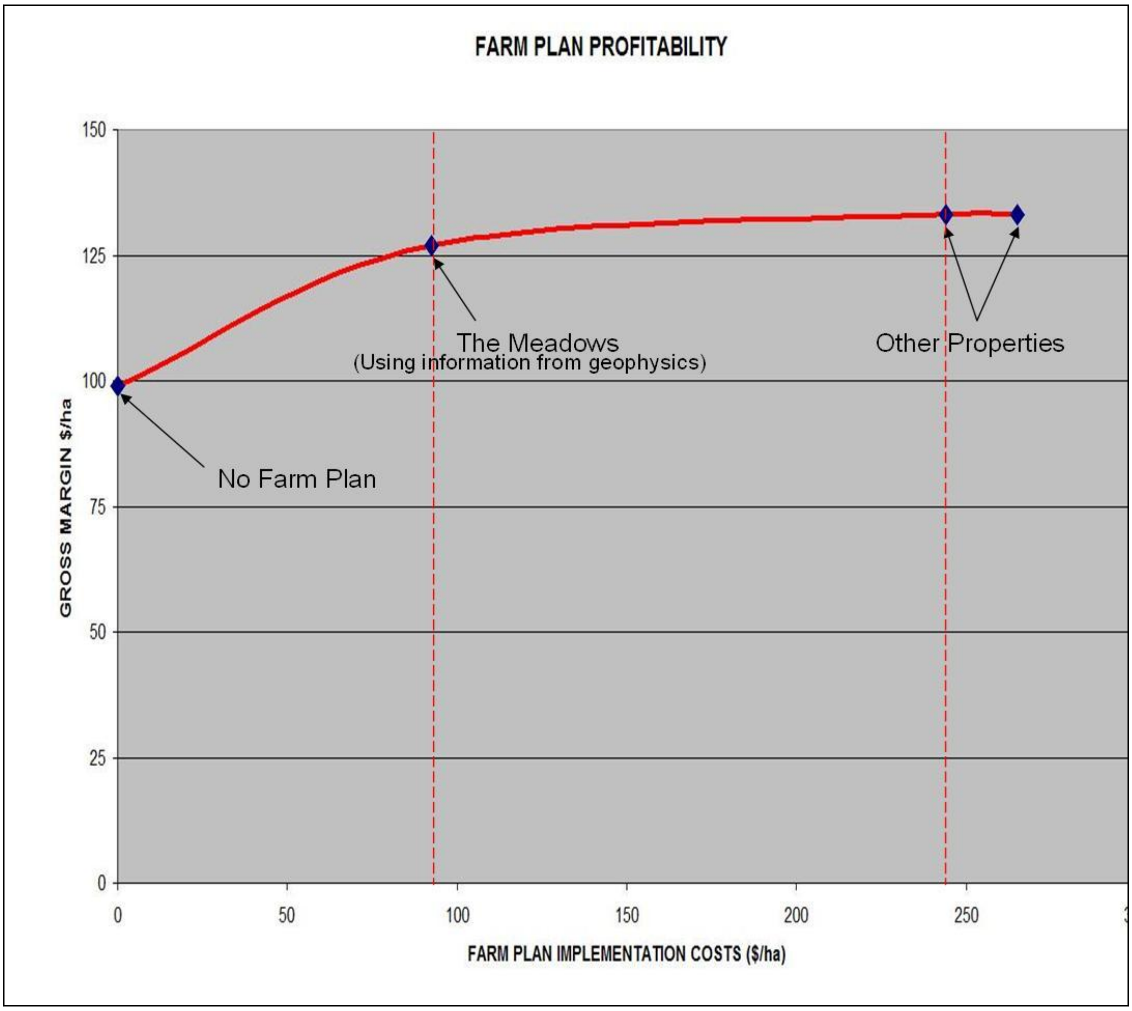

Figure 21. Graphical comparison of farm plan implementation costs. All three properties started from the same "No Farm Plan" production base and production increases are the result of implementation of the farm plans.

The return on farm plan investment function in Figure 21 is very flat. The importance of flat payoff functions in natural systems and natural resource management decision making is discussed in detail by (Pannell, 2006[a]). He points out that finding the top of the production curve in these circumstances has very little influence on return or profitability and, therefore, the value of information used to find the top of the curve is low. At Broomehill, however, the use of information from geophysics was not intended to find the optimum economic return, but to achieve the optimal biophysical impact for a given investment. Thus, the implementation cost per hectare was reduced without greatly reducing the return (Figure 21). So in this case, the flat payoff function has provided the opportunity for a very high value of information by reducing farm plan implementation costs by more than 60%; yet still achieving most of the potential productivity increases, and thus facilitating a positive cost benefit ratio. The saving of more than $150 per hectare in farm plan implementation costs was achieved through investment of $7.25 per hectare for geophysical data acquisition, interpretation and farm plan preparation.

The Meadows property plan had the lowest implementation cost per hectare, because the use of information from geophysical data facilitated a strategic approach to the location and quantity of proposed works. There had to be a hydrological or hydrogeological justification, based on the site specific data, for any infrastructure proposal. The positive benefit cost ratio reflects the importance of water management to the productivity of this biophysical system.

2.6 Discussion

The objective of the Broomehill SALTMAP project – at the request of the principal clients and stakeholders – was to produce “better” farm plans. The term “better” refers to how well the farm plans address the salinity risk. Reviews of the project focussed on the technology in their criticisms and failed to review the farm planning outcomes (George and Smith, 1998, Leonhard, 1999). They focussed on how well the SALTMAP data matched data models from other sources such as boreholes. It did not match very well at all. It provided a different kind of information that addressed the primary weakness of borehole data – its spatial distribution. It was agricultural economists Chamarette and Robinson (1999) who eventually reviewed the cost effectiveness of the farm planning, who made no reference to airborne geophysics, and possibly had no knowledge of its use in the farm planning process.

The usefulness of airborne geophysical data at Broomehill was questioned by (Leonhard, 1999) and George and Smith (1998) because there was a variance about the mean of 40% when comparing individual borehole measurements against individual Broomehill SALTMAP data points. This is because the SALTMAP data is an averaged measurement of a "footprint" sampling area in the order of a hectare of land whereas the borehole is sampling a very small ($1m^2$) area in a highly variable landscape. Nevertheless, Leonhard (1999) concluded:

"However Broomehill SALTMAP survey channel 4-5 conductance displays a positive and close association to bedrock depth, groundwater salinity and salt storage."

This was precisely the information required to manage salinity risk. There is more information provided by the spatial pattern revealed in the data than there is in the actual numbers measured at any particular point. Unfortunately, this is where reviewers of the Broomehill project left the discussion. They did not comment any further on the value or potential use of this spatial information in the farm planning process.

In his report on the use of geophysical data at Broomehill, O'Brien, (1998) notes that the Salt Hazard sites were identified at least as effectively by experts during field inspection using the "Bunbury rules" (George and Smith, 1998). These were a set of rules designed to quantify hydrological knowledge of the causes of dryland salinity devised at a workshop in Bunbury, Western Australia, in 1994. How these sites are identified is not as important as whether or not they are identified. The automated interpretation of Salt Hazard sites is cost effective compared to detailed assessment by experts. It is a means of applying expert knowledge over a large area without requiring the expert man-hours. The important point is these sites need to be identified, because they determine the groundwater and surface water catchments that are the foci for management actions.

The Department of Agriculture produced a technical report that examined the effectiveness of farm planning at the Byenup Hill catchment using a groundwater model (Raper and Guppy, 2003). The Byenup Hill catchment is situated in the western part of the Broomehill SALTMAP study area (Figure 5). This study used a regolith model based on soil/landform units. They concluded that modelling the implementation of farm plans resulted in a reduction of only 1% in the area of land at risk from salinity by 2012. They also noted that the impacts of farm plan implementation would be localised and at a spatial scale that would not be well represented by the model. This would indicate that the model and/or the input data are not at an appropriate scale for the system being modelled.

The Meadows study at Broomehill has important features that differentiate it from simplified model studies. That is, measured, site specific paddock scale variations in regolith parameters derived from airborne geophysical data were used to plan land management actions. These land management measures have been fully implemented and actual results have been measured by the farmer and independently assessed by the Department of Agriculture.

The main influence of the SALTMAP data on the property plan was on the location and quantity of earthworks and revegetation proposals. The location of proposed revegetation was influenced by the data in a different manner to the location of proposed earthworks (Figures 19 and 20). The influence of revegetation is on the regolith directly beneath it plus perhaps a 10 metre buffer area surrounding it, (George et al., 1999). Therefore, proposed revegetation was placed directly over areas of soil water accumulation and interpreted high salt storage. Surface water management earthworks, however, have an area of influence on surface water and shallow seepage extending down-slope of where they are located. This means that the location of proposed earthworks is not directly related to the interpreted conductance/waterlogging class directly beneath them. The additional design parameters of water harvesting, erosion and waterlogging control over non-conductive areas also resulted in the proposed earthworks being distributed more evenly over the farm than might be suggested by the interpreted conductance/waterlogging classification.

For any infrastructure proposal in this plan there had to be a hydrological or hydrogeological justification based on the site specific data. Once the salinity risk had been addressed, for example by a proposed grade bank, the water harvesting requirement was often satisfied as well. Where there was no requirement for earthworks for salinity management, water harvesting, or erosion control, no earthworks were proposed. This approach reduced the spatial density of proposed works compared to other property plans not guided by site-specific hydrogeological information.

Scientists evaluating airborne EM using 200 m line spacing at Broomehill as a tool for natural resource management did not find a strong numerical/statistical correlation between SALTMAP data and borehole data (Leonhard, 1999). Mechanical application of statistical measures of significance in this case, concealed the most important attribute, of the SALTMAP data, that is, the spatial distribution of the interpreted principal salinity risk factors (Pannell, 2006[b]). Criticism of AEM based on statistical analysis was focussed on proving that AEM was inaccurate relative to data obtained from boreholes. Such comparisons also ignored the complementarity of the two data sources.

To understand the strengths and weaknesses of these information sources, the minimum grid distance necessary to reproduce the same salt storage distribution information represented in the classification in Figures 17 and 18 using (for example) boreholes, was assessed. The smallest spatially significant class variations occurred over a distance of approximately 150 metres. A smaller grid spacing than this would be needed to map it accurately, but if 150 metres is accepted as the conservative minimum resolution or maximum grid spacing, then it would require 530 boreholes to basement on this property to provide equivalent information on the spatial distribution of salt storage. The Broomehill drilling by Water and Rivers Commission cost $175,000 for 35 bores on 14 transects under SALTMAP flight paths. This included analysis of 552 regolith samples from drill core to measure salt storage. Using an average drilling depth of 18 metres (Leonhard, 1996) this was an average cost of approximately $276 per lineal metre. The cost of 530 drill holes 18 metres deep at $276 per metre amounts to $2.63 million or $2,204 per hectare.

George and Smith (1998) recorded the results of a field workshop where expert participants examined salt hazard sites in the field and assessed their own use of airborne geophysical data in devising management proposals to address salinity risk at those sites. They concluded that AEM data was used in only 55% of the sites and that its use improved management decisions by a factor of 15%. This is a valid assessment. A piecemeal focus on individual salt hazard sites would not allow any leveraged benefit from integrated planning where items of infrastructure (revegetation areas or surface water management earthworks) address salinity risk for more than one salt hazard site. Measurement of the costs and benefits of a fully integrated farm plan that has been implemented on The Meadows, (Chamarette and Robinson, 1999) shows a 37% greater cost benefit ratio than the nearest comparable property (property A) (Table 5). That is, with a benefit cost ratio of 1.41, The Meadows returns an additional 41 cents for every dollar spent on the farm plan from higher gross margins due to the implementation of the farm plan. This is 37% greater than the nearest comparable farm planned property that was planned not using airborne geophysics in its information base.

The Meadows farm plan cost $96 per hectare to design and implement. The SALTMAP airborne geophysical data cost $3.25 per hectare to acquire and interpret. This is an additional 3.4% of the cost of design and implementation. This extra 3.4% cost returned a 37% additional benefit relative to a comparable farm plan not using geophysical data.

If we accept George and Smith's (1998) 15% benefit this is still a significant improvement for a 3.4% additional cost.

The drilling program cost $4.38 per hectare and did not yield information suitable for farm planning. To achieve this on The Meadows would require a drilling project costing $2,204 per hectare. This is an unfair requirement that drilling provide the same type of data as airborne geophysics. Just as reviewers of the Broomehill project criticised airborne geophysics for not providing the same type of data as drilling. This is a fruitless argument. The information technologies and their datasets are complementary and neither can be used to its full potential without the other.

There were minimal borehole data available at Broomehill and the Water and Rivers Commission drilling program occurred after the farm planning was completed. Therefore, the airborne geophysical data was not used to its full potential, yet its inclusion in the information suite at Broomehill still yielded a positive return on investment.

2.7 Conclusions

The analysis of the spatial distribution of property plan infrastructure showed that, distribution of proposed revegetation was strongly influenced by the salinity risk information derived from the airborne geophysical data, but distribution of proposed earthworks was relatively uniform. This is a consequence of the lateral shift of the area of impact of earthworks and the multiple design criteria that apply to the property planning process. If an element of infrastructure is not required for the first priority it is often required for the next but not necessarily in the same place.

Piezometer levels continue to rise on all three properties compared here (Raper, Personnal communication). Some would argue that this represents a failure of the farm planning. However, modelling has shown that it would require revegetation of at least 80% of the landscape to cause a reversal of the salinising process (George et al., 2001). The important point demonstrated in this case study, is that existing land management tools can be applied in a hydrologically targeted manner, cost effectively, facilitated by geophysical information.

There were no new or novel land management tools used, just conventional best practice. The use of these information products enabled the land management planner to break away from the constraints of the "*precautionary principle*" that apply where information is limited or absent. The precautionary principle is principle 15 of the Rio Declaration on Environment and Development made at the United Nations Earth Summit 1992. It states:

"Where there are threats of serious or irreversible environmental damage, lack of full scientific certainty should not be used as a reason for postponing cost effective measures to prevent environmental degradation."

Use of the precautionary principle is implied in the demonstration of due diligence in agricultural land management planning. Consequently, in the absence of site-specific information that shows the location of hydrogeological features and risk factors, the planner must disperse management actions throughout the paddock to ensure nothing has been missed and in order to demonstrate due diligence. The result of this approach has been the recommendation of greater investment in management actions and infrastructure than may have actually been necessary. The use of the spatial information in the geophysical information products enabled the targeting of the hydrogeological salinising mechanisms, at the paddock scale, with appropriate location and density of management actions. This reduced the spatial density and total amount of works and thus the cost of implementing the farm plan. This was achieved whilst also demonstrating due diligence in addressing the hydrogeological issues. The farm plan is shown to be more cost-effective than comparable farm plans on nearby properties that did not use information from geophysics.

The strategies employed in The Meadows property plan were not new, nor did they require massive revegetation and changes in farm enterprises. The infrastructure proposed in the plan was, however, current practice, enthusiastically implemented by the land holder, and site-specifically targeted. In designing the plan there had to be a hydrological or hydrogeological justification, based on the site specific data, for any infrastructure proposal. Property planning using airborne geophysics at Broomehill was an education process for the land holder, the planner and the geophysicists. Everyone involved felt the discomfort of setting aside familiar ways of doing things. This is why previous attempts at using airborne geophysical information for land management planning had failed. The geophysical images were handed over to people who had specialist expertise in some aspect of land management and they were asked to use them to design management options. In the absence of an interactive learning process, the experts retreated to their familiar areas of expertise and the geophysical information was not used. Due to the rigour of this methodology used in designing the property plan for The Meadows, independent economic analysis of the implemented plan has demonstrated that the landholder has obtained a high biophysical and economic return on a level of investment that is significantly less than is common for fully implemented farm plans in this area.

In a short article on the history of airborne electromagnetics in Australia, Spies (2001) noted:
"*one major issue encountered was that while the data very accurately described the landscape, they could not routinely be used to better define management options.*"

This was true in a large part due to the disconnection between scientists and land managers. In his overview of the Broomehill SALTMAP project, O'Brien (1998) made this comment:
"A major strategic and technical challenge which appears largely in default is filtering of land elements through layers of different methodology to yield reliable and cost effective land management outcomes."

The interactive learning that took place in the multidisciplinary team at Broomehill overcame that technical challenge. The Meadows property plan is a demonstration that the strategic and technical challenge referred to by O'Brien (1998) was met and reliable and cost effective outcomes were achieved.

The Broomehill project demonstrates that the application of airborne geophysical information to land management is not a technical issue but an information product/representation issue. The technology for interpreting and producing information products from airborne geophysical data has developed greatly since the Broomehill project. The benefits of disciplined interactive interpretation of an integrated land information base, facilitated by GIS technology, has been demonstrated in the Broomehill project. The information product issue is one of training and teamwork. The Broomehill SALTMAP based farm planning demonstrates due diligence in acquiring and using appropriate land information products and formulating products for the land holder in terms of current land management tools, and strategies.

The reason that little reliable and cost effective land management resulted from airborne geophysical data in the past is there was not the methodology to overcome the gaps in understanding between disciplines involved in land management. Regardless of the source of data (drilling or geophysics), the derived knowledge will not be applied unless it is presented to the land managers in an appropriate form.

The methodology employed at Broomehill resulted in the production of appropriate information products that supported the farm planning and encouraged its implementation. It demonstrated due diligence and produced cost effective land management outcomes.

In terms of the thesis question, this work has demonstrated that the use of geophysics in farm planning has produced cost effective environmental and economic benefits.

3. Chapter 3: Tammin Groundwater Pumping Project

3.1 Introduction

My involvement in this project consisted of conducting the topographic survey of geophysical survey lines, conducting the gravity survey, assisting with the electromagnetic survey and interpretation of the data. I also reviewed the drilling investigation data and the hydrological pumping test data with Shawan Dogramaci of the Department of Water.

The Tammin study site is located approximately 3 kilometres north west of Tammin townsite. Tammin is located 184 km east of Perth on the Great Eastern Highway (Figure 22). It is an area of subdued relief at approximately 250 metres elevation. The elevation difference between local valley floor and ridge top is less than 50 metres. It has a Mediterranean climate with winter dominant average annual rainfall of 370 mm. Winter maximum temperatures range between 15^{o} C and 20^{o} C and in summer they range between 30 C and 40 C. Landuse is agriculture, growing annual crops and grazing sheep and cattle. The area was first settled in the 1890s.

Regional geological mapping and interpretation of drilling logs made available by CSIRO (Norman et al., 2006) indicate the presence of an extensive, north-south trending, sedimentary channel system (inset valley) in excess of 1500 metres in width and 50 metres in depth. The southern limb of this channel system appears to pass close to Tammin town site. Saturated duricrust and surficial alluvial deposits overlie the inset valley aquifer. Approximately 1800 ha are currently affected by groundwater discharge in the surficial alluvials.

In the Tammin area, some of the most productive agricultural land is being lost to salinisation. A range of solutions designed to halt, and possibly reverse the process of salinisation of high-value land at Tammin have been proposed. One method to be trialled is to lower the water table over a long time (years) by pumping water out of the basal sands in inset valleys believed to exist below the salt-affected land.

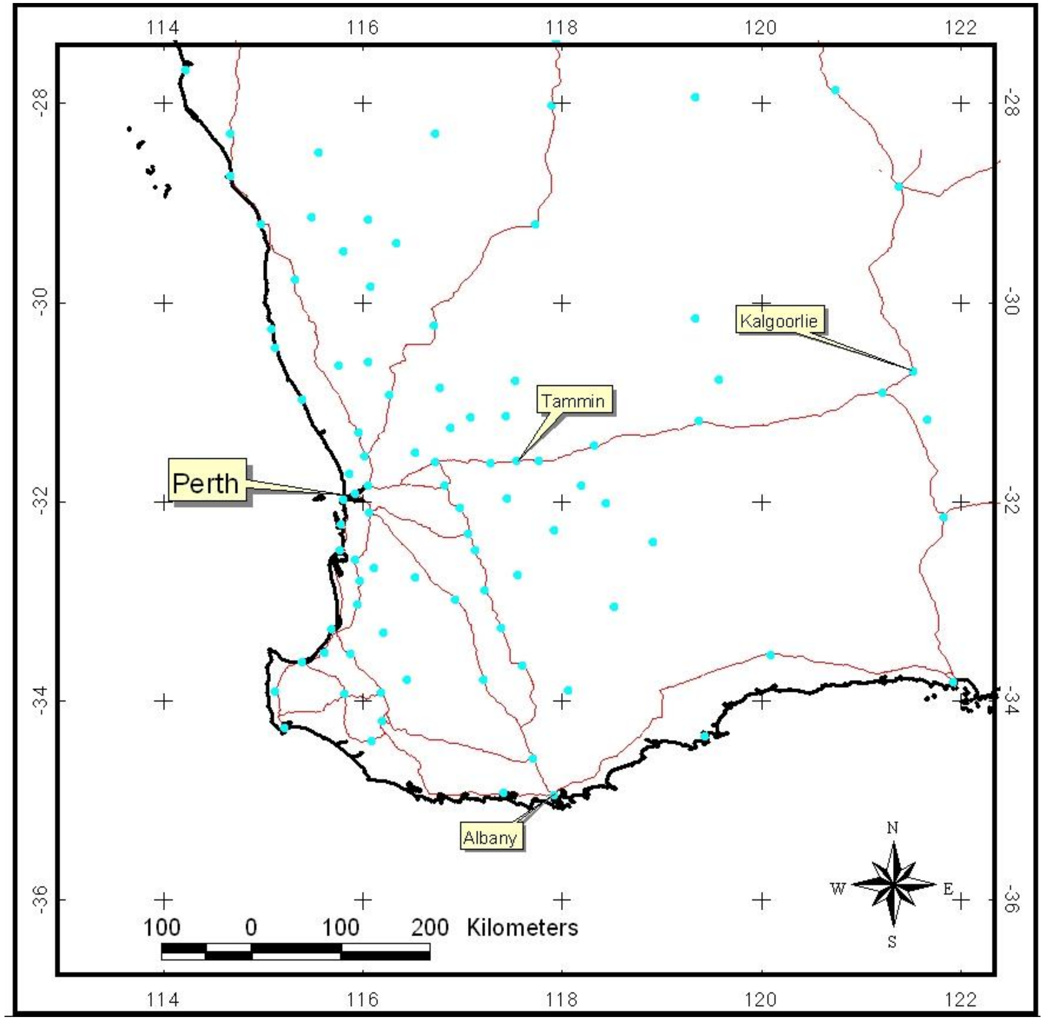

Figure 22. The Tammin study site is located approximately 3 km north of Great Eastern Highway at Tammin. The blue dots represent towns.

Groundwater extraction from similar inset valleys in the Eastern Goldfields has produced significant watertable draw-down (Johnson, 2003). However, before any such method can be assessed, the location, size, geometry and hydrogeology of the inset valleys needs to be rapidly and cost effectively determined. Although similar inset-drainage systems have been studied in detail in inland Australia (Van De Graaff et al., 1977; Salama et al., 1997; DeBroekert, 2002), , there have been very few studies into the depth, geometry and hydrogeologic characteristics of inset-drainage systems in the Wheatbelt of Western Australia (Salama, 1997; Johnson et al., 1999; Commander et al., 2001).

The broad valley floors of the Wheatbelt in Western Australia are relict drainage systems filled with alluvial, colluvial and aeolian sedimentary deposits. Van De Graaff et al. (1977), Waterhouse et al. (1995) and Salama (1997) showed in palynological studies that these in-filled valleys developed during the late Cretaceous and Eocene, flowing westward into the Indian Ocean (Beard, 1998). The tectonic uplift of the Darling Range and the Yilgarn Craton caused loss of topographic gradient that resulted in filling of these drainage systems with transported sediments. The low gradient rivers became chains of salt lakes due to the loss of gradient creating internal drainage (Van De Graaff et al., 1977).

These primary salt lakes acted as evaporation basins and repositories of salt accumulated from salt introduced to the landscape via rainfall and the weathering of crystalline bedrock (Ghassemi et al., 1995). Following clearing of native perennial vegetation for annual agriculture over the last 150 years and the change in the hydrological balance, most of the drainage lines, in the zone of ancient drainage east of the Darling Scarp, have developed secondary salinity (Figure 23).

The first land to be cleared for agriculture in the Wheatbelt valleys was that with red-brown loamy soils supporting salmon gum and gimlet eucalypt forests. These soils are on the valley floor, adjacent to the primary salinity in the drainage lines and the salt lakes. Therefore, the development of secondary salinity adjacent to and up-gradient of the primary salinity, as a consequence of clearing has impacted most on these more naturally fertile soils.

Figure 23. Ancient drainage system of the southwest of Western Australia, reproduced from Commander et al., (2001).

Secondary salinity occurred first on these soils, in many cases only a few years after clearing, and it affects a greater proportion of them.

It is likely that the inset channels are important to the management of dryland salinity in the Western Australian Wheatbelt, as most salinity occurs in the valley floors and on their margins.

The inset valley sands of the Eastern Goldfields have been shown to be continuous along the main trunk drainages with the possible exception being where they cross greenstone belts. They have been shown to act as regional drains (Johnson et al., 1999) and to receive groundwater flow from the surrounding bedrock and in-situ weathered regolith. Johnson et al., (1999) also demonstrated that long term pumping of the inset channel aquifers of the Eastern Goldfields approaches a steady state condition where downward leakage and groundwater movement from the weathered bedrock profile into the inset channel balances the groundwater extraction (Johnson, 2003). Natural groundwater discharge from the inset channels occurs mainly through salt lakes which act as evaporation basins. As these valley systems are full in terms of groundwater, discharge is increased during times of rainfall and recharge. Heavy rainfall events cause the saline lakes to link and once more become a river system that drains to the sea. It is only such exteme events that remove both salt and water from the valley systems.

These drainage systems now sit on valley floors that consist of very wide plains as much as 20 km wide. The inset valleys of the eastern Goldfields have been studied extensively as a source of water for the mining industry. The inset valleys of the Western Australian wheatbelt have not been so thoroughly studied. However, work that has been done indicates that the wheatbelt inset valleys are similar in geomorphology and hydrological characteristics to those of the Eastern Goldfields (Salama, 1997; Johnson et al., 1999; Commander et al., 2001). They consist of valleys cut into basement rock and weathered basement materials. They have been filled with coarse alluvial sediments at their base and these have been overlain by finer, riverine and lacustrine sediments (sands, silts and clays). This has occurred as the ancient river valleys lost their gradient due to tectonic uplift and tilting of the

Yilgarn craton and changes in climatic conditions from wet to arid (Van De Graaff et al., 1977) (Figure 23).

The valley floors of the Wheatbelt are the sites of most of the primary and secondary salinity in agricultural areas of Western Australia. If the hydrogeological characteristics described above are also features of the Wheatbelt inset valleys, then these inset valleys could present opportunities for more effectively managing valley floor groundwater levels and dryland salinity in the Western Australian Wheatbelt. Encouraging results were obtained by Salama et al. (1989) who showed that groundwater pumping at a rate of 360 m^3 per day (4.2 litres per second) can be sustained and produce measurable effects on groundwater levels as much as 2 km along the inset channel system of the Salt River in the Avon catchment. Using these short term pump test data, hydrogeological information from the drilling and geophysical transects, Salama et al. (1989) modelled the effect of long term pumping. This modelling indicated the potential to generate a significant drawdown as far as 20 km along the valley from the production bore.

To test this theory, the Department of Water proposed to install a production bore in the north Tammin area. The north Tammin site comprises a significant area of approximately 1800 ha of degraded agricultural land resulting from secondary salinity. It is located on the floor of a broad valley that is a tributary to the Mortlock River. The underlying groundwater systems comprise an inset valley aquifer with overlying saturated sandy clay alluvials. This has been determined from geological logs of piezometer boreholes installed in the area by CSIRO (Norman et al., 2006). The depressurising of the deep sedimentary aquifer via pumping allows dewatering of the surficial alluvial deposits and is seen as a potentially effective means to improve agricultural production.

The object of drilling in the Tammin area is to establish a productive pumping site with a minimum of unsuccessful drill holes. Success equates to intersecting the sand/gravel sediments that are often located at the base of these inset valley structures. These relatively coarse sediments can be sinuous and aligned along the valley structure (Johnson et al., 1999) and thus offer the potential to influence the groundwater over a relatively large area. The interpretation of the location and cross-sectional form of the inset valley from geophysics offers the opportunity to accurately target the inset channel aquifer and reduce the cost of drilling.

Engineering intervention to manage groundwater discharge requires information about the sub-surface features of the landscape. This information is very different from the types of information used in attempting to address recharge. In addressing recharge the effort has been to control it at the soil surface, so the land information required was surface information. In attempting to manage discharge through groundwater pumping the information required relates to the physical characteristics of the basement and the sedimentary layers between basement and the surface. The land surface over these features is very flat and consists of relatively uniform low gradient alluvial deposits (clays) in the order of 10 metres thick, variably overlain by more recently deposited aeolian and/or alluvial sand deposits. Therefore, surface data in these areas do not provide the sub-surface information necessary for effective engineering intervention for the management of groundwater and dryland salinity. To locate, design, install and manage a groundwater production bore, information on basement topography, regolith stratigraphy, permeability, hydraulic conductivity and groundwater chemistry is required. The first three of these information types can be provided by geophysical techniques.

Gravimetric and Time Domain Electromagnetic (TEM) methods are frequently used methods for defining inset channels. Gilgallon (2002) showed that the use of gravity and TEM methods over the valley floor environment at Lake Bryde was successful in identifying inset valley structures. Harris (2001) demonstrated the integration of TEM methods, hydraulic testing, and groundwater flow modelling for the rapid delineation of high volume water resources in the Eastern Goldfields of Western Australia. Williams and Stevens (2002) showed that TEM methods were useful in defining potential water-bearing aquifers in western Tanzania. Abbott (2002) used airborne TEM data to interpret the inset drainage pattern of the Upper Kent River in the South of Western Australia. The sedimentology and nomenclature used to describe the shallow inset valleys that have formed above the Yilgarn Craton of Western Australia are well described by Salama (1997) and DeBroekert (2002).

The combined use of gravity and TEM methods was proposed for Tammin. Both methods are discussed in detail in Reynolds (1997). Their combined use for detecting inset valley structures in the Yilgarn Block of Western Australia is described by Smyth and Barrett (1994). However, such methods are not uniformly effective. The mobilisation cost of airborne systems can be expensive, as can the collection of ground geophysical data over large areas. Also, if the basement is highly weathered or the regional gravity gradients are steep, the data may be extremely difficult to interpret.

At Tammin, the first priority was to establish the existence of an inset valley system. The second priority was to see if a relatively small number of ground based geophysical transects would adequately describe the basic geometry of such inset valley systems (Figures 24 and 25).

3.2 Methods

The gravity method relies on density contrasts between the sediments contained within inset valleys and the surrounding regolith and bedrock (Reynolds, 1997; Tracey and Dirreen, 2002). The TEM method (Harris, 2001) is used to detect the distribution of electrical conductivity beneath the earth. The inset valleys are generally highly conductive compared to the fresh basement rock. Note that in some circumstances basement that is strongly weathered (saprolite) can be electrically conductive due to its high porosity and saturation with saline groundwater. Gravity stations were established on lines A, B, C and E at 25 m intervals (Figure 25). Each line was approximately 2 km in length. Location of these lines is shown in Figure 25 which shows their location superimposed on an aerial photograph.

3.2.1 Gravity

A Scintrex CG3 gravity meter was used for this work. This is capable of 0.01 mgal resolution, does automatic tidal corrections and stores the gravity data digitally for download at the end of each day to a portable computer. Two 60 second gravity measurements were made at each station. The gravity and survey data were acquired in the period 16–20 March 2004.

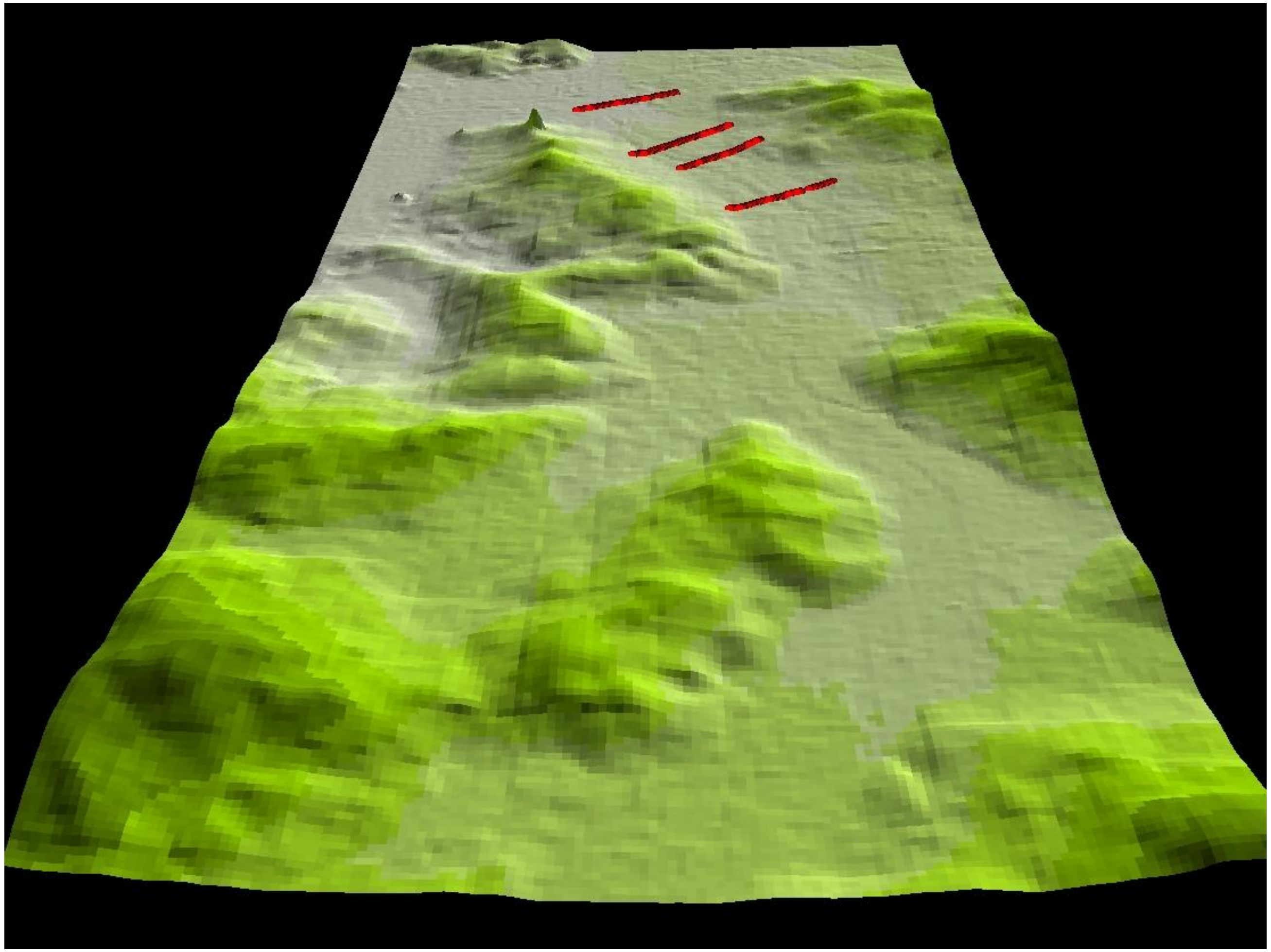

Figure 24. Exaggerated surface elevation rendering of the Tammin study site looking due north and showing the geophysical survey transect lines. These lines are approximately 2 km long.

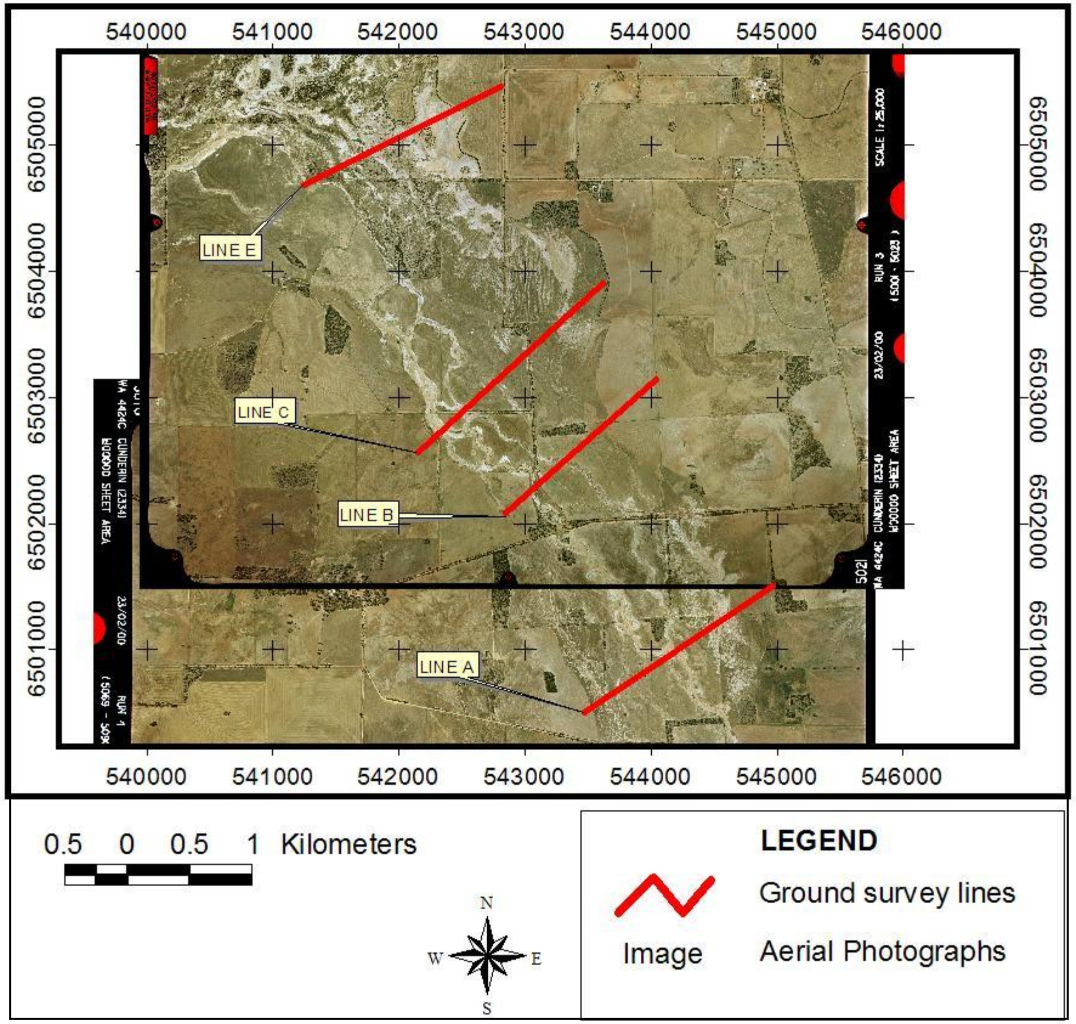

Figure 25. Location of the four ground survey lines across the salt affected valley floor at Tammin.

Heights were obtained by optical levelling to the nearest millimetre. Horizontal coordinates were obtained from handheld GPS measurements using Garmin GPS units. The stations were laid out by tape measure on pre-determined lines. Heights are required to better than 5 cm accuracy and horizontal positions to better than 10 metres to provide 0.01 mgal Bouguer gravity data.

Both of these objectives were easily achieved in this survey. The likely repeatability of the GPS horizontal position measurements was within +/– 5 metres. Gravity data were processed to obtain Bouguer gravity results with densities of 2.20 and 2.67 g/cc. Topographic heights were established by assuming an absolute height of 250.00 metres above sea level at a selected point on each line. This is approximately correct from comparison with the 1:100 000 topographic map. The GDA 94 projection has been used throughout the processing and map production.

3.2.2 TEM

TEM data were acquired on the same lines as the gravity survey, along lines A, B, C and E, with 50 m transmitter loops and 50 metre station spacing. Zonge equipment was used for this work. This consisted of an NT 20 transmitter which produces about 9 amps, a TEM 3 vertical receiver antenna, positioned at the centre of each loop, and a GDP 32 electronics receiver. This equipment enabled the acquisition of 32 channels of decay windows after current switch off. Each measurement stacks the data for approximately 3 minutes to ensure low noise results. TEM data were acquired in the period 27–30 April 2004.

3.2.3 Processing

Initial data processing was done in the field to control data quality and to enable any changes in survey specifications to be readily made. Data processing and interpretation was completed at Curtin Exploration Geophysics offices, in Perth. ModelVision software was used to do gravity modelling and EM Vision software for the TEM modelling. The EM Vision software was used to convert transient voltages measured in the field to apparent conductivity versus diffusion depth sections for the four transects.

3.3 Results

Figure 26 shows the Geoscience Australia gravity data for the Kellerberrin 1:250 000 map sheet. This shows a major gravity low over the Kellerberrin granite to the east of the study site, and this is important in establishing the regional trend to be used in the gravity modelling over the survey lines.

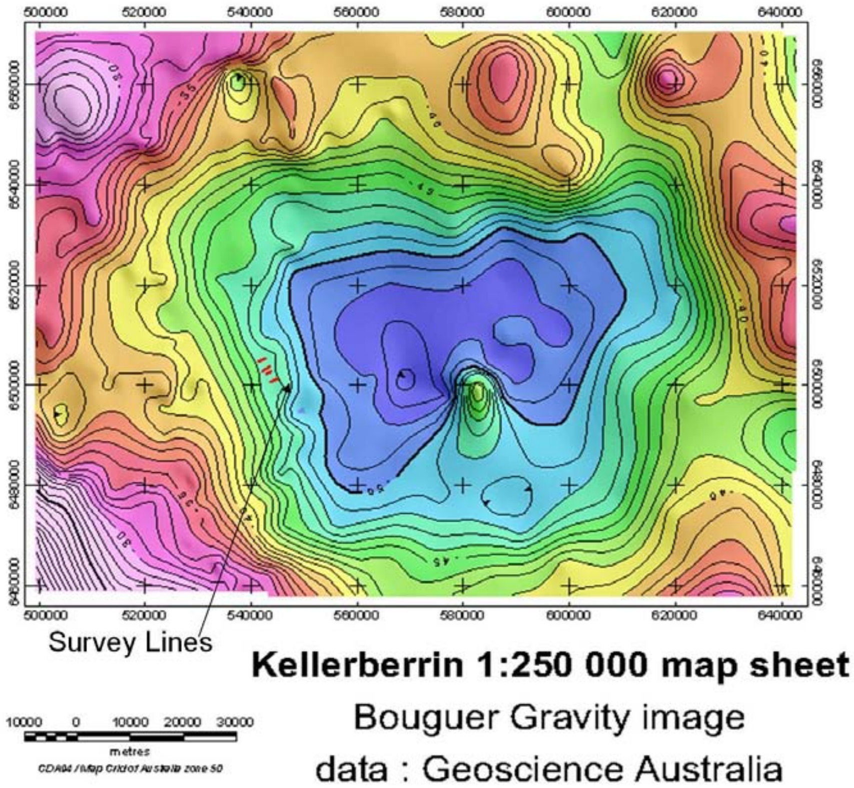

Figure 26. Geoscience Australia gravity data for the Kellerberrin 1:250 000 map sheet. At the location of the survey lines there is a regional gravity gradient from high in the west to low in the east.

After processing, the gravity and EM data were displayed as section diagrams for each transect. These section diagrams were then set at the same horizontal scale and their common data points aligned for comparison. Bouguer gravity (using densities of 2.2g/cc and 2.67g/cc) and TEM survey conductivities are shown for each line. (Figures 27 to 30). The apparent conductivities representing the transition from conductive valley sediment to resistive basement are less than 350 mS/m. For this reason the 350 mS/m contour was taken to represent the basement profiles. Also note the complex three-dimensional shape of the inset valleys makes the application of any strict one-dimensional inversion or approximation to a one-dimensional inversion problematic (i.e. they all produce severe artefacts that are difficult to interpret).

Both gravity and TEM results show clear evidence for an inset valley trending approximately 330 degrees and with the deepest part of the valley close to the minima in the gravity profiles. The inset valley appears to be asymetric in lines A and C, with gentler base slopes on the south west side of the channel. Line B shows a narrower symmetric cross section in both gravity and TEM section. Naturally, the orientation of the geophysical transect compared to the orientation of the channel will affect apparent width of the channel. However, the symmetry of the channel at line B suggests a genuinely narrow section of subsurface valley that may contain higher energy sand/gravel deposits similar to those intersected by CSIRO bores (Norman et al., 2006) located approximately 1.5 km downstream.

The cross sectional profile of the inset valley basement has been drawn in on the conductivity cross sections included in Figures 27 to 30. This was interpreted from previous drilling and the conductivity measurements from the TEM transects. Interpreted maximum depth at each transect ranged from approximately 50 metres at line A to 65 metres at line E. Maximum conductivity in the inset valley ranges from 425 mS/m at line A to 550 mS/m at line E, downstream.

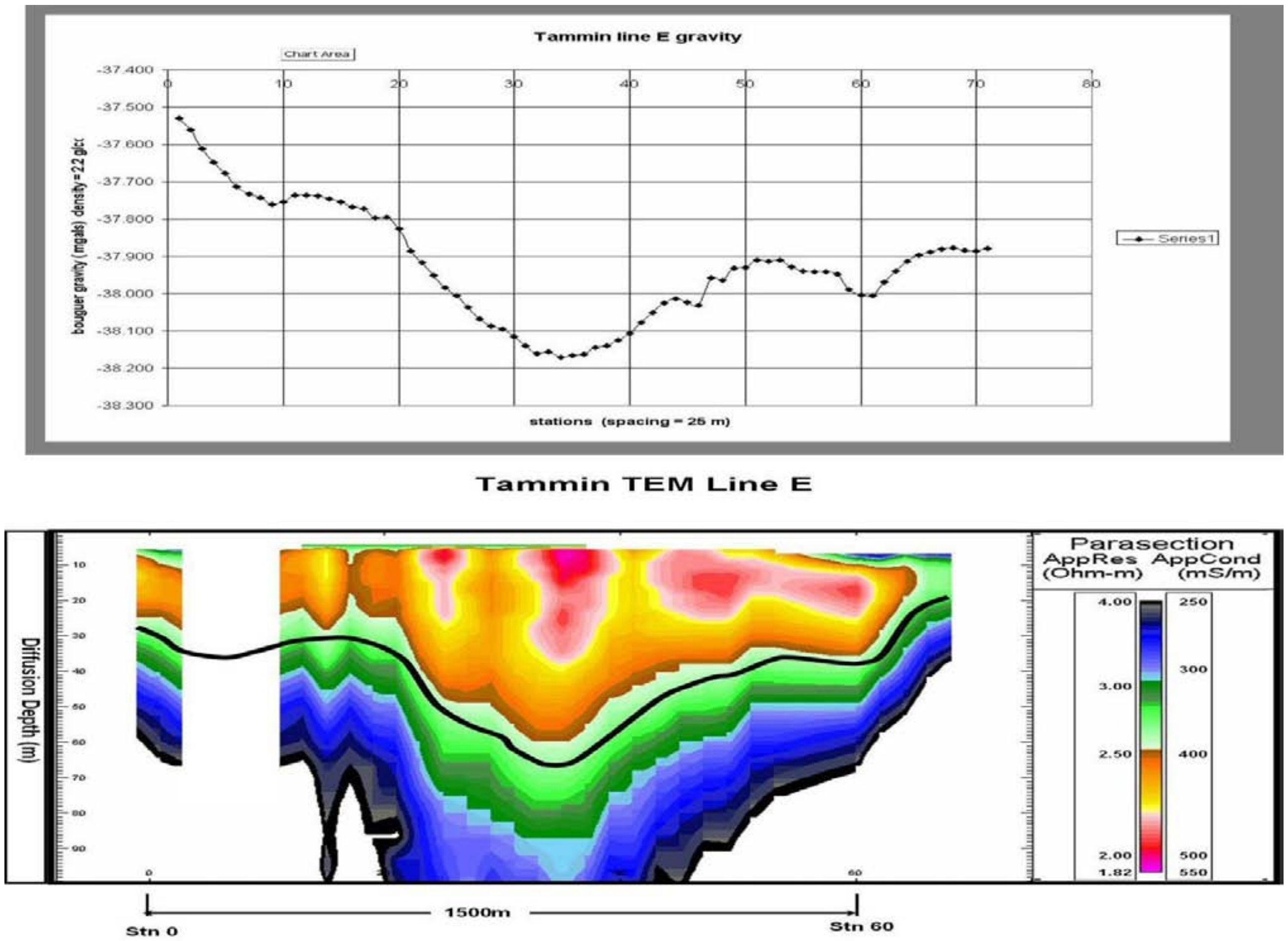

Figure 27. Co-located gravity profile and conductivity parasection of line E. Interpreted valley base is represented by the heavy black line on the conductivity parasection.

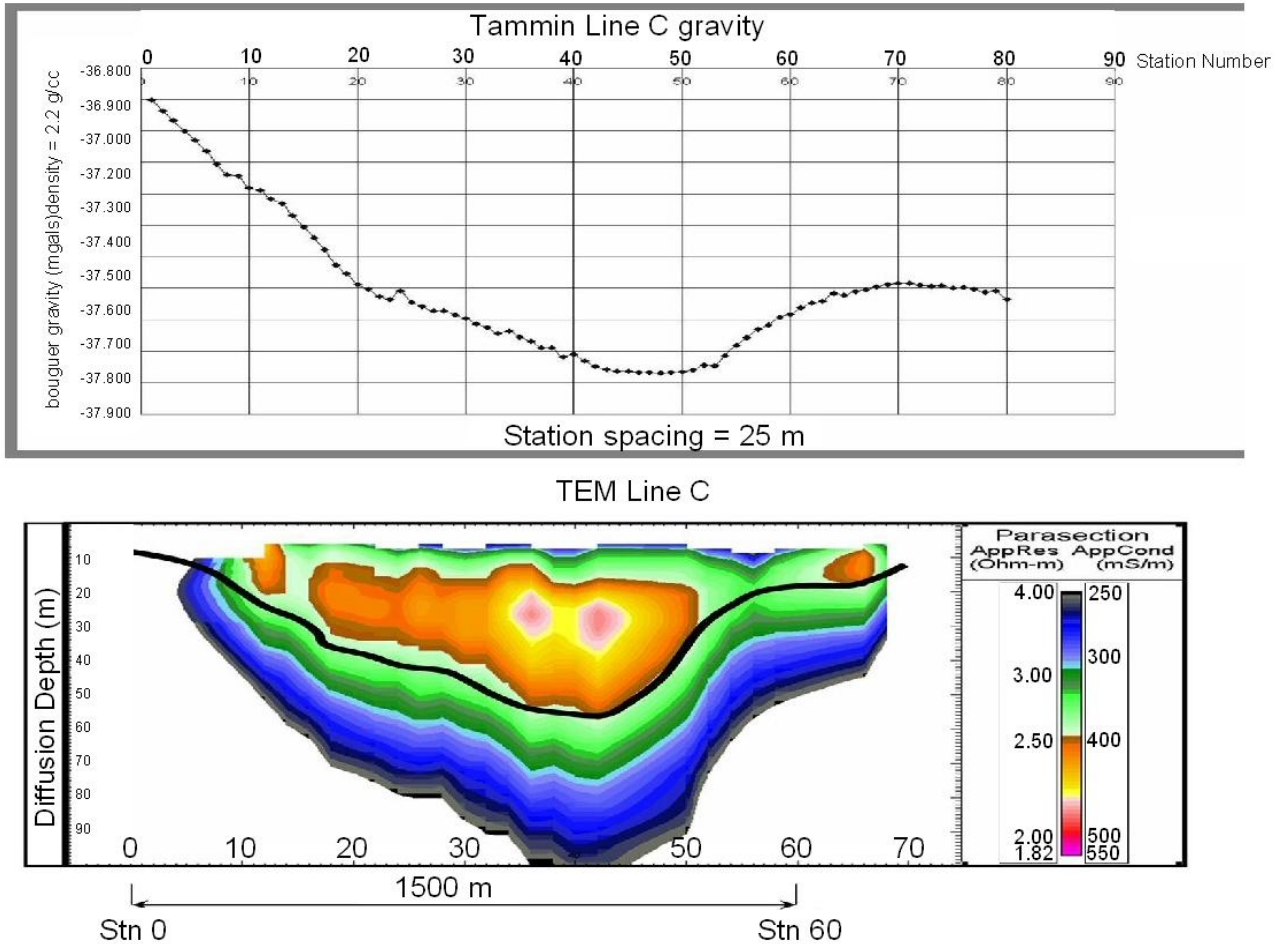

Figure 28. Co-located gravity profile and conductivity parasection of line C. Interpreted valley base is represented by the heavy black line on the conductivity parasection.

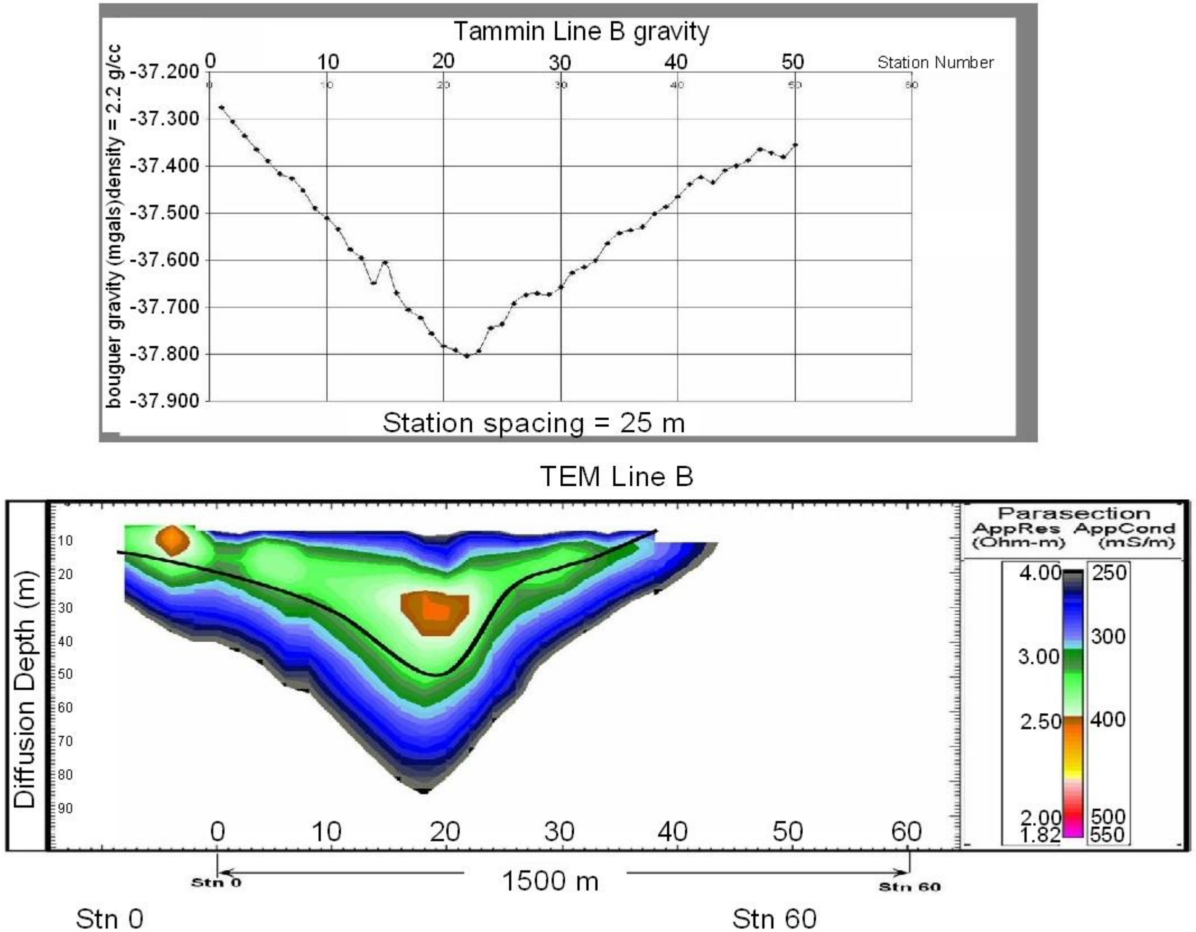

Figure 29. Co-located gravity profile and conductivity parasection of line B. Interpreted valley base is represented by the heavy black line on the conductivity parasection.

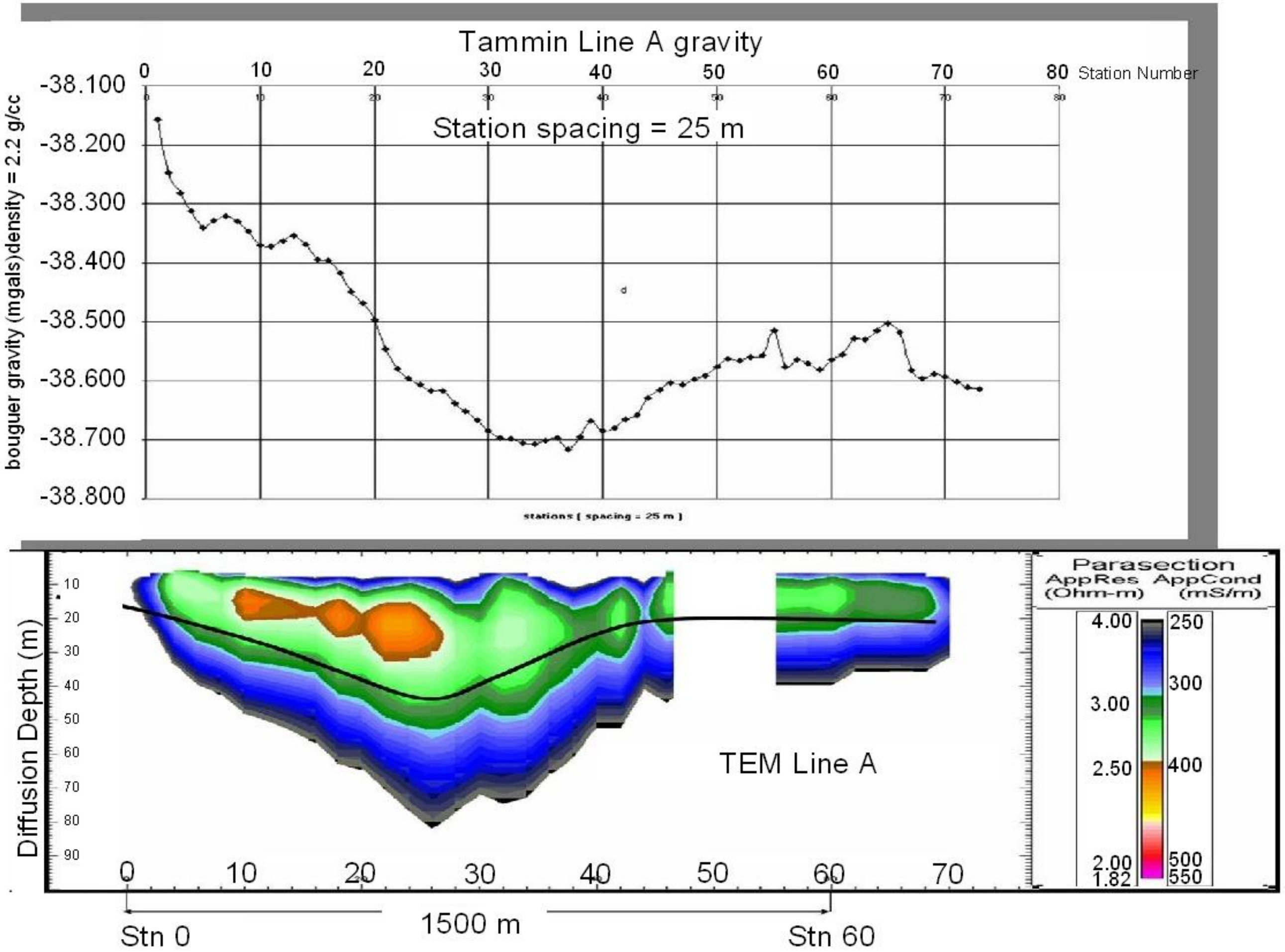

Figure 30. Co-located gravity profile and conductivity parasection of line A. Interpreted valley base is represented by the heavy black line on the conductivity parasection.

Hydrograph data provided by CSIRO for the deep sedimentary aquifer and overlying saturated duricrust and surficial alluvials exhibit very similar seasonal responses at similar head elevations. A similar seasonal hydrograph response, albeit much more muted, is observed for the adjacent saturated weathered granite bedrock (Norman et al., 2006). A high degree of hydraulic connectivity is indicated between the inset valley aquifer and the saturated surficial alluvials.

The inset valley aquifer is assumed to have moderate permeability, estimated to be up to 2 m/day, whilst the sandy clay materials of the surficial alluvials are estimated to have lower permeability, with an upper limit likely to be no greater than 0.5 m/day.

The processed gravity data and the TEM inversions provided geophysical sections that were interpreted for the purpose of selecting a site for a production bore. The primary site selection criterion was to maximise the chance of intersecting coarse alluvial sediments at the base of the inset valley. This aquifer was targeted because it is likely to extend longitudinally along the valley and it has the highest hydraulic conductivity. For these reasons, groundwater extraction from this gravelly part of the aquifer is likely to yield the most water per unit of pumping energy expended and the area of influence is likely to be maximised.

The relatively narrow 'V' shaped section of the inset valley at line B (Figure 29) indicates potentially higher energy, coarser, alluvial deposits at this point in the inset valley. This is because water velocities would have remained relatively high due to the constriction of the flow channel, thus only coarser material might be deposited at this location. The narrowness of the inset valley at line B was also interpreted to indicate the potential for the coarse alluvials to be relatively deep. It was considered that they may have a similar cross sectional area to coarse alluvials in other parts of the valley, but because they are constrained to a narrower channel, they might also be deeper. This was supported by the interpretation of basement surface in the EM transects.

The drilling contractor drilled 7 bores to basement along the valley between lines A and C (Figure 31). Only the production bore and bore number TM004 were located on geophysical transect lines. The production bore was positioned over the interpreted deepest point of the inset valley on line B and went to 53 m depth before striking basement. This agreed very well with the predicted depth to basement indicated in the TEM interpretation illustrated in Figure 29. TM004 was located on Line C also over the interpreted deepest part of the inset valley on that line. The bore locations and depths are given in Table 7.

EASTING	NORTHING	DEPTH TO BASEMENT (m)	BORE NAME	DISTANCE FROM PRODUCTION BORE (m)
543210	6502414	53	TMPRODN	
543187	6502452	59	TM001D & TM001S	50
543160	6502499	50	TM002D & TM002S	100
543043	6502650	47	TM003D & TM003S	300
542951	6503276	48	TM004D & TM004S	900
543251	6502317	50	TM005D & TM005S	100
543437	6502015	49	TM006D & TM006S	400

Table 7. Bores and depths drilled.

Bore TM001D struck basement at 59 m and was located only 50 m downstream of the production bore and Line B. A photograph of the coarse sandy alluvial sediment intersected below 41 m in the production bore is shown in Figure 32. Photographs of the production bore installation are shown in Figures 34, 35 and 36.

The production bore on Line B was gravel packed with 8/16 grade gravel from 5 m below ground level to the bottom of the hole at 53 m. It was concrete sealed from ground level to 5 metres. The PVC casing was slotted from 41 m to 53 m and an electric submersible pump was installed inside the casing (Figure 33). Photographs of the pump installation are in Figures 34 to 36. The pump capacity was 1.5 litres per second. However, the pumping rate varied a great deal early in the trial due to the pump exceeding bore capacity to deliver water into the casing, causing automatic shutdown of the pump.

During the period of pumping, 15,000 m^3 of saline groundwater were discharged by pumping from the basal inset valley aquifer. The deep aquifer showed a drawdown up to 300 m away from the production bore. The cone of depression in the deep aquifer was continuing to expand with on-going pumping.

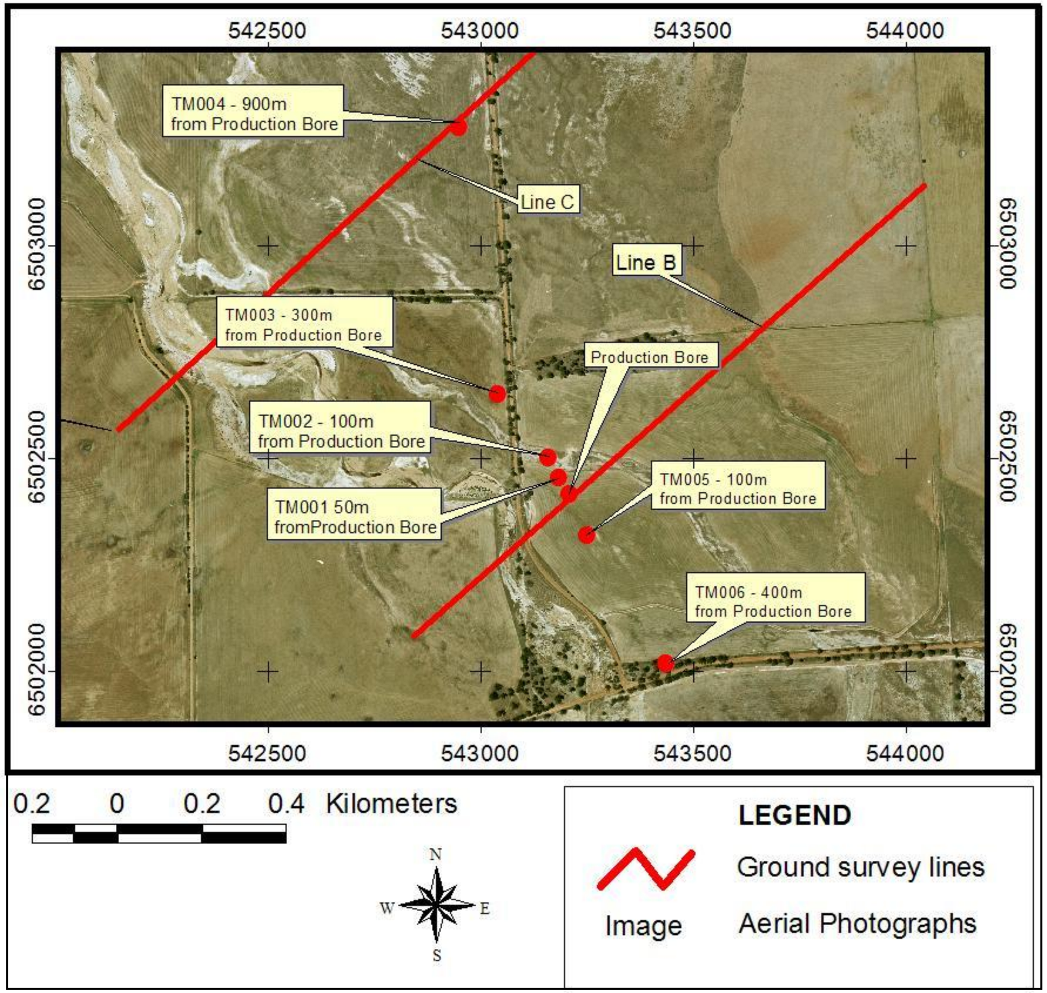

Figure 31. Positions of the production and monitoring bores.

There was a slow response in the shallow aquifers, showing only a 1 m drawdown after 6 weeks of pumping. This indicates the creation of a head difference between the deep and shallow aquifers producing leakage from the shallow to the deep aquifer through a partially permeable aquiclude. Department of Water modelling indicated the potential to impact an area up to 30 hectares with longer term continuous pumping at a low pumping rate of 60 m^3 per day (Dogramaci et al., 2009).

3.4 Discussion

The primary mechanism of soil salinisation in Western Australia is capillary rise of saline groundwater in situations where the groundwater table is less than 2 metres from the surface (Nulsen, 1981). The purpose of engineering actions for salinity management is to reduce the salinity of the surface soils – generally the top 2 metres, by lowering the water table to below 2 metres and thus preventing capillary rise. The success of engineering efforts is, therefore, most often measured in terms of the degree to which the water table has been lowered.

When the pumping at Tammin was terminated, the recovery of the water table in the production well (from 20 m to approximately 5 m in just a few hours) was considered to be disappointing. However, hydrological systems are often significantly “damped”. Removal of a certain volume of water from an aquifer may not be fully reflected in the measured drawdown of that aquifer. In a confined or semi-confined aquifer, groundwater extraction may reduce the potentiometric head (pressure) without lowering the water table. This was the case at Tammin. The potentiometric head in the deep aquifer was lowered by 20 metres at the production bore during pumping. However the overlying surficial aquifer, separated from the deep aquifer by a semi-permeable aquiclude, recorded a drawdown of 1 m after 6 weeks of pumping. The surficial aquifer is partially isolated from the deep aquifer by clay layers in the sedimentary fill. This caused the “damping” of the response to pumping. The response of the system was slow but it did produce accelerated leakage from the surface aquifers toward the deep aquifer.

This, in fact, is reversal of the salinising process and therefore the trial can be considered proof that this hydrological system responds in a satisfactory manner to groundwater extraction from the inset valley aquifer. Department of Water measurements indicated that at this rate of pumping, the surficial aquifer could be drawn down over an area of approximately 30 ha.

The pumping rate achieved in this trial was low (0.69 L/s) relative to those reported by Salama et al., (1997). There are two reasons for this. Firstly, the pump that was installed was capable of a maximum pumping rate of only 1.5 L/s. Secondly the bore was very inefficient in terms of its ability to deliver water through the screens to the pump. The gamma log and driller's log of the production bore (Figure 33) does not show a significant thick intersection of coarse sediments (Figure 32) which are the ideal material in which to construct an efficient bore. In this bore, there are numerous thinner intersections separated by clay bands. The pump did not sustain its optimum pumping rate during this trial. The cost of installation and operating the pump, however, is not decreased by the low pumping rate achieved. Conversely a higher pumping rate can be achieved for a similar cost. The annual pumping cost in this trial was approximately $15,000. The landholder indicated that an economic cost of effective pumping would be approximately $80 per hectare per annum. This is the economic cost of obtaining land to farm by lease. Therefore to obtain land (recover land) by groundwater pumping, the cost must be close to this figure to be viable.

If a higher pumping rate can be achieved for a similar pumping cost, then the area that must be recovered (at $80 per ha per year) is $15,000/$80/ha which amounts to 187 ha. The volume of the cone of depression with a surface area of 187 ha and 20 m drawdown at the pump can then be calculated. From this, using the specific capacity of the aquifer calculated from the Tammin trial, the volume of water that must be pumped can be calculated. From this figure, the required average annual pumping rate is determined. The required pumping rate to recover 187 ha amounts to 5.2 L/s. This is a pumping rate closer to that reported by (Salama, 1997) in the inset valley of the Salt River near Quairading in Western Australia. This illustrates that there is order of magnitude difference between the capacity of this trial pump installation and the capacity of bore and pump required to affect a large area. This trial did not achieve an adequate pumping rate.

Figure 32. Material retrieved from below 41m in the production bore during drilling.

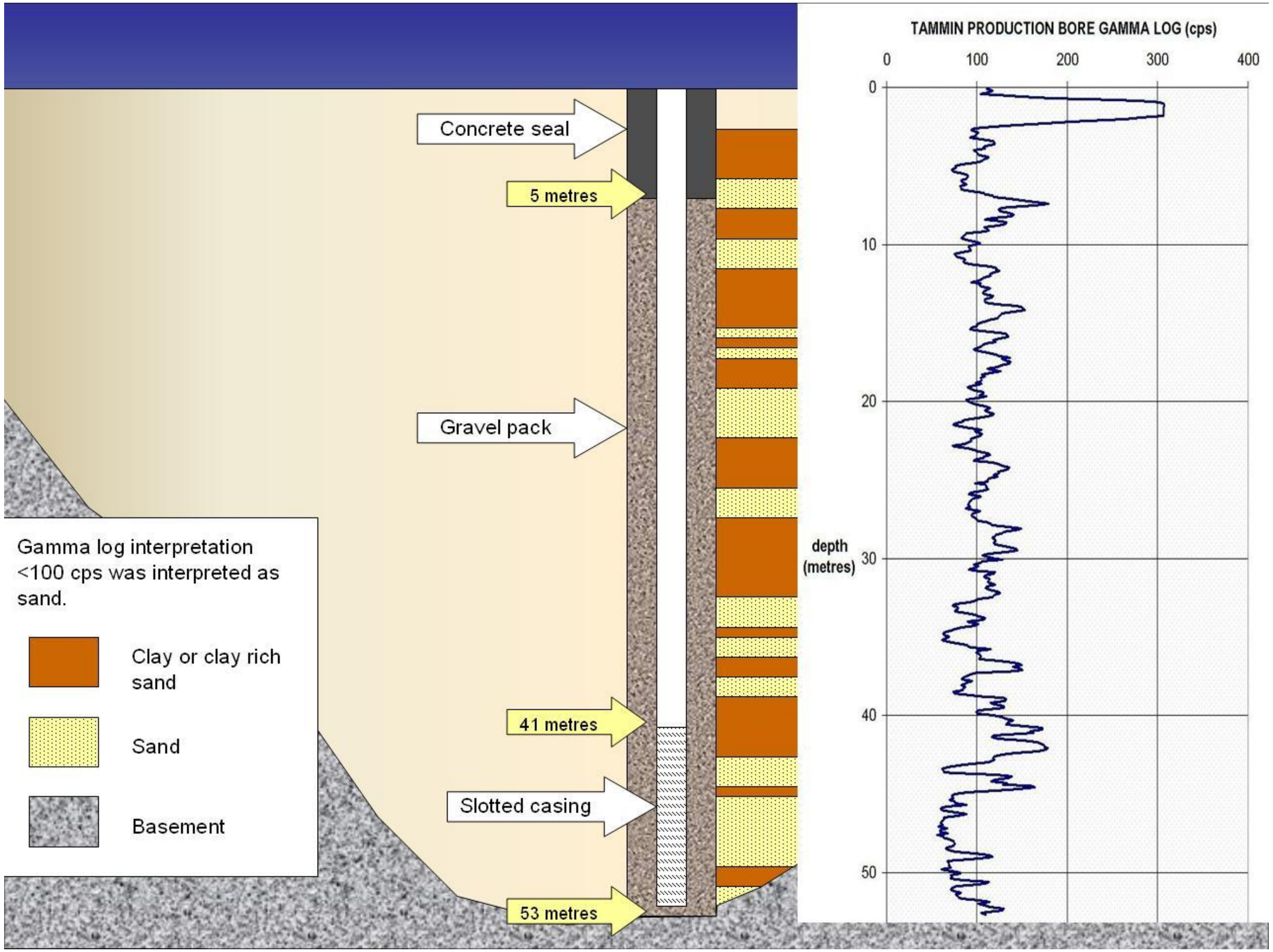

Figure 33. Schematic diagram of the production bore with stratigraphy interpreted from the Gamma log.

Figure 34. Production bore site looking along route of discharge pipeline which discharges into a natural creekline approximately 50 m beyond the road visible in the background (photograph courtesy of Department of Water).

Figure 35. Head works at the production bore (photograph courtesy of Department of Water).

Figure 36. Site of discharge from the production bore (photograph courtesy of Department of Water).

3.5 Conclusions and Recommendations

Both gravity and TEM clearly indicate the existence of an inset valley system below the high value land that has been degraded by salinity at Tammin. The inset valley ranges from a very discreet narrow inset valley in the order of 250 metres wide at line B to a broader, less well defined inset valley system downstream at line E as it enters the trunk inset drainage of the Mortlock River. The bulk electrical conductivity was shown to increase downstream.

There was no obvious correlation between surface drainage or other surface features such as saline scalding with the location of the inset valley system. The use of both gravity and TEM methods at Tammin has proved to be an effective first step in assessing the potential for engineering techniques to recover these high value lands from secondary salinity. This process has provided sufficient information to site boreholes with some confidence. Much of this confidence comes from the confirmation of information provided by data sets derived from completely independent technologies. The integrated use of gravity and transient electromagnetic methods has demonstrated the existence of a discrete inset valley below or adjacent to salt-affected land at Tammin. The axis of the inset valley does not follow the path of current surface drainage neither can its location or orientation be interpreted from any surface information. The geophysical methods are shown to be effective in providing information that facilitates targeted drilling. This has reduced the cost of the project by greatly reducing the need for exploratory drilling. Geophysical investigation is therefore an essential step as it facilitates due diligence in the planning and design process for developing an engineering method for salinity management at Tammin and other areas where inset valley aquifers are likely to exist.

The geophysical information did not, however, ensure the construction of an efficient production bore. The measured aquifer responses to this low pumping rate trial indicate that an economically viable cost of pumping per hectare of land impacted may be achieved. This would require a hydraulically efficient bore equipped with a pump capable of sustaining >5L/s rate of pumping.

In order to obtain a more efficient well, the information about the inset valley morphology provided by the geophysical data should be reviewed. The data from line B is interpreted to reveal a narrowing of the inset valley in the vicinity of Line B. After the completion of this trial, the interpretation of the sedimentological implications of the geophysical transects was revised. Information on stream flow and sediment dynamics in Bursik and Woods (2000) indicates greater deposition of sediment loads upstream of flow constrictions. This disagrees with the original interpretation used to site the production bore and may explain why the bore performed so poorly.

The failure of the interpretation of the geophysical transect data to locate a suitable depth of coarse sediments calls into question the usefulness of transects up to 2 km apart. The information (although it is cheaper) is not much better than having four transects of closely spaced bores. The ground geophysical surveys of these transects cost $15,000 which amounts to $8.30 per hectare over the 1800 hectare study site. At 2005 prices, an airborne electromagnetic survey could have been procured for $80 per line kilometre. At 200 metre line spacings, this would be equivalent to $12.00 per hectare. This calls into question whether the ground geophysical surveys were value for money.

I consider this trial is inconclusive and that it failed to produce a definitive result for a number of reasons. These are:

- low spatial resolution of hydrogeological data from geophysical surveys;
- incorrect interpretation of hydrogeological structures and consequent incorrect siting of production bore due to low spatial resolution of data; and,
- poor production bore performance as a consequence of poor siting which caused it to be constructed into an insufficient depth of porous gravel.

In respect of the first two dot points, interpreters favoured the installation of the production bore directly on transect B because it was the only transect that showed a steeply defined channel and interpolation between these widely spaced (0.8 to 2 km) transects was considered too risky.

The pump was only capable of a maximum pumping rate of 1.5 L/s. It pumped the bore casing dry when first installed due to the inefficiency of the bore. Water could not flow into the casing fast enough for the pump. This means the bore was either poorly sited (in a stratum not capable of yielding sufficient water) or the bore was poorly constructed/developed resulting in blockage of the screens and/or gravel pack. The material retrieved from below 41 metres in the production bore (Figure 32) appears angular to sub-angular with only a few rounded or sub-rounded particles visible. Transported palaeochannel material should be predominantly at least sub-rounded. The particles in the sample are more typical of what would be found in the saprolite grit zone (the zone of in-situ weathering just above fresh basement). This suggests the bore may not have been installed into a palaeochannel gravel stratum and indicates poor siting rather than poor construction. Site selection was poor because it was dependent on a poor spatial resolution of hydrogeological data. Higher resolution data could have been obtained for 44% higher cost. This 44% higher cost would provide more than 400% greater area surveyed (1800 ha). The possibility of identifying suitable drilling sites would be greatly enhanced by this. The primary cause of failure of this trial was inadequate spatial extent of hydrogeological data to support production bore site selection.

4. Chapter 4: Lake Warden Hydrogeological Mapping Project

4.1 Introduction

The Lake Warden wetlands airborne electromagnetic (AEM) study was undertaken with the purpose of better understanding the detailed hydrogeology of the Lake Warden wetlands near Esperance in Western Australia. To achieve this, it was necessary to overcome the spatial information shortcomings of traditional hydrogeological data sources based primarily on topography and widely spaced drilling. My role in this study was to interpret the geophysical data and provide information from this interpretation to guide catchment management works. However, I also undertook data processing in order to overcome the noise issues in the HoistEM data. In addition, I used this data to produce digital elevation models of the aquicludes that separate the aquifers underlying the study area. I also carried out the down-hole geophysical logging of bores in the study area.

Driller's notes, geological drill spoil logging, down-hole geophysical logging and hydraulic testing are the basis for traditional drainage basin hydrogeological investigations. In areas like Lake Warden, where the number and distribution of drill holes is restricted, hydrogeologists and hydrologists must interpolate between drilling sites. Interpolation between drill holes does not capture the substantial variability that exists in nature over relatively short distances. In complex hydrogeological environments, it is unreliable to assume gradational change in hydrogeological characteristics between widely spaced drill holes. AEM survey data yields detailed images of the spatial distribution of conductivity.

Beneath the Lake Warden wetlands, AEM data provided parameters for the location and form of hydrogeological structures within the regolith at and between the existing drilling sites. Even with major challenges to the quality and quantity of the data, its spatial nature and resolution gave new insight into the hydrogeology of the Lake Warden wetlands system. This enhanced the understanding of hydrogeological units and facilitated the formulation of better-targeted strategies to manage the wetlands in the future.

The Lake Warden wetlands are of international significance as defined by the Ramsar Convention to which Australia is signatory. This convention is the basis of the international treaty for protection of wetlands of environmental significance, particularly as migratory waterfowl habitat. There are 8 other "Ramsar" listed wetlands in Western Australia. The Lake Warden wetlands are located on the coastal plain adjacent to and north of the south coastal town of Esperance in Western Australia (Figures 37 and 38). Esperance is approximately 700 km south east of Perth. Four catchments contribute surface and groundwater to the Lake Warden wetlands. They are the Western Lakes, Coramup Creek, Bandy Creek and Neridup Creek catchments (Figure 39). The combined catchment area is approximately 157,000 hectares (Salama et al., 2000). The largest of the lakes is Pink Lake at the western end of the wetlands. It is an hypersaline lake that is famous for its pink colouration attributed to high concentrations of salt tolerant algae, *Dunaliella salina*. Commercial salt harvesting by solar evaporation of brine is undertaken at the eastern end of Pink Lake. This is made possible by the lake having low water levels and frequently drying out. However, in recent years there has been increased frequency of filling and higher water levels.

The Department of Environment and Conservation (DEC) is charged with the management of the wetlands. Rising water levels and increasing salinity have been cause for concern, because the high water levels in lakes other than Pink Lake have destroyed much of the sedge and low shrub foreshore habitat that is the preferred breeding ground for many species of waterfowl (Figure 40). The higher water levels have also reduced the area of shallow water suitable for wading birds. For example, the increase in water volume of between 5 and 8 GL in Lake Warden from 1980 to 2003 has resulted in a decline in the wading zone habitat from 68 hectares to 3 hectares (Robertson and Massenbauer, 2005). The catchments that contribute surface and groundwater to the Lake Warden wetlands (Figure 39) have been substantially cleared for agriculture and other development, and this has increased the amount of groundwater recharge and surface runoff, potentially contributing to the increasing salinity and other hydrological issues such as frequency of flooding at Lake Warden.

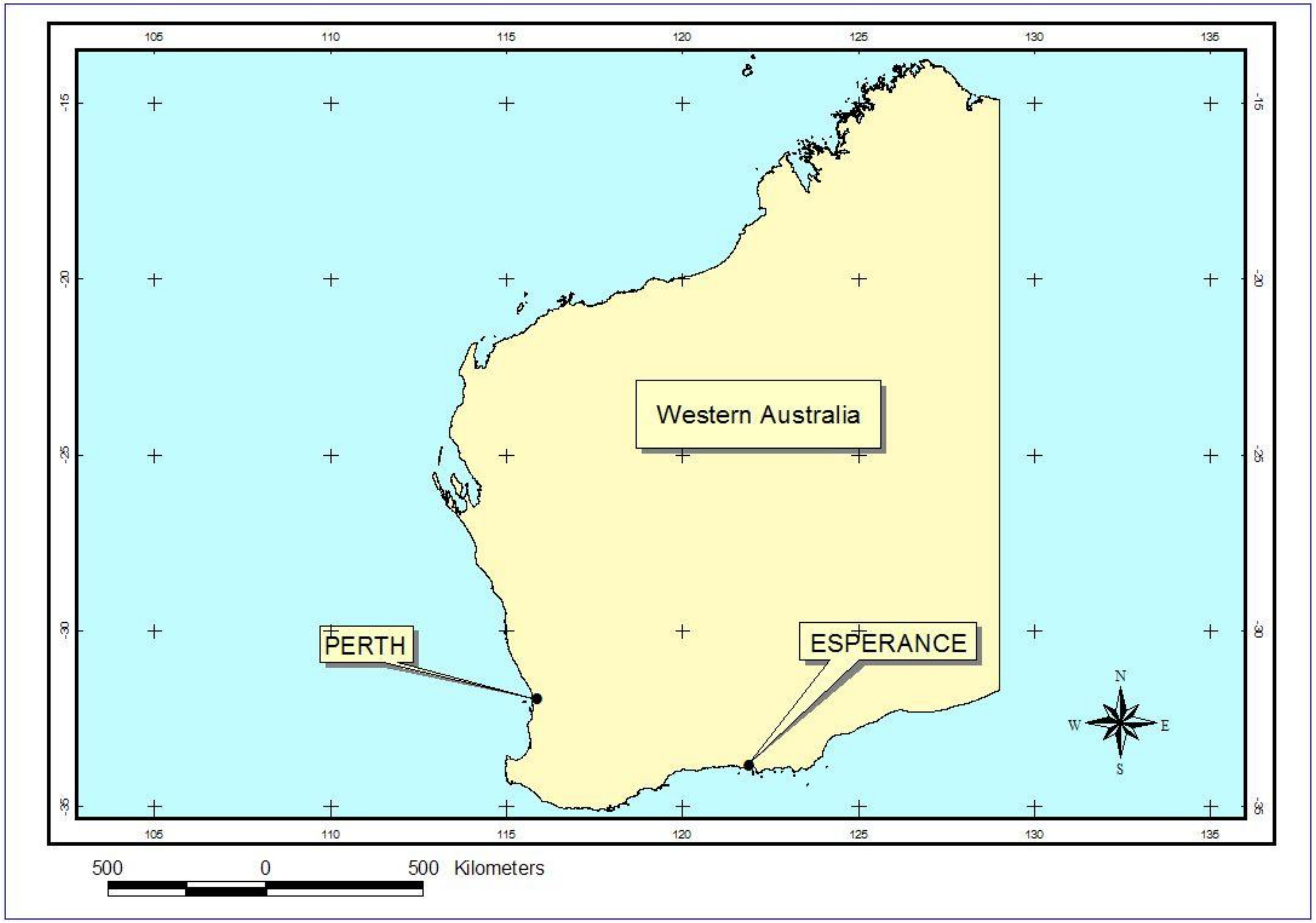

Figure 37. Location of Esperance in Western Australia.

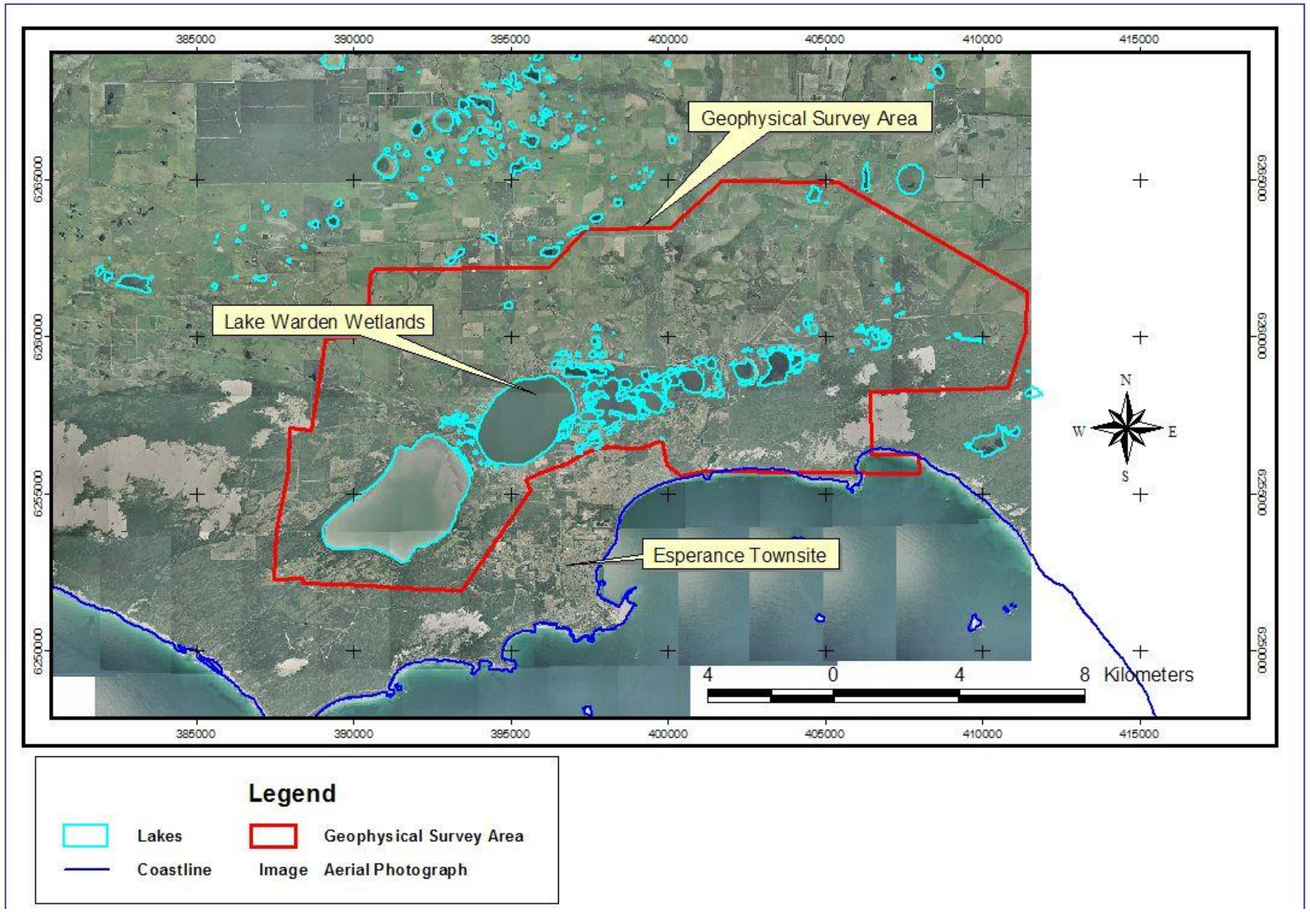

Figure 38. Aerial photograph mosaic image showing the location of Lake Warden wetlands in relation to Esperance Townsite.

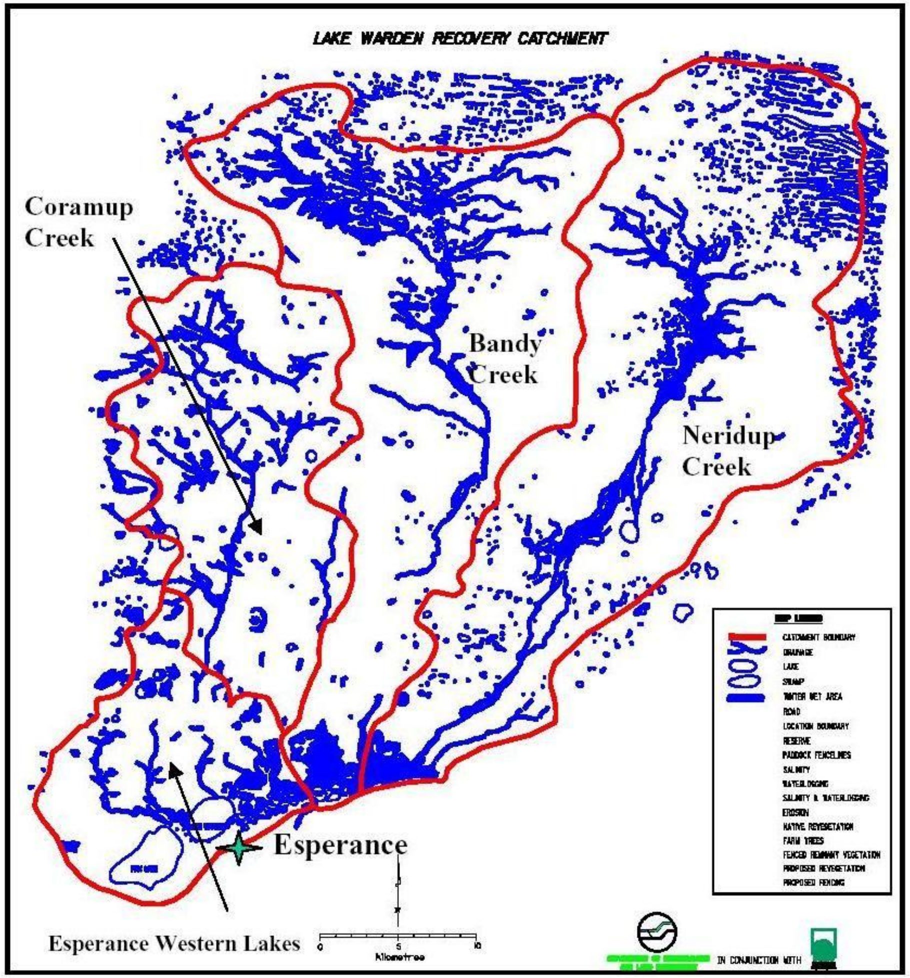

Figure 39. Surface water catchments that drain into the Lake Warden Wetlands (image courtesy of Department of Environment and Conservation).

Figure 40. Inundation and drowning of fringing vegetation in the Lake Warden wetlands.

4.2 Geological Setting

The geology of the Esperance area has been mapped at regional scale (1:250,000) by the Geological Survey of Western Australia with explanatory notes (Morgan and Peers, 1973).

Hydrogeological mapping was done in the late 1990s (Johnson and Baddock, 1998). The Bureau of Mineral Resources (BMR), now known as Geoscience Australia, flew regional airborne magnetic surveys over most of Australia including the Esperance and Ravensthorpe 1:250,000 sheets. These surveys were conducted on a 1600 metre (one mile) line spacing. The image in Figure 41 comes from this airborne magnetic survey and illustrates the regional structural contrast between the granulites, gneiss and amphibolite of the Biranup Group and the granite/gneiss of the Nornalup Group. The interpreted divide between the two geological groups effectively bisects the Lake Warden Wetlands. The Nornalup Group exhibits hilly topography, forming steep-sided basement highs expressed as numerous outcrops in the land surface and, offshore, forms the islands comprising the Recherche Archipelago. Whereas to the west, the Birranup Group has a much more subdued topography with fewer, low, relatively flat outcrops.

The south west to north east gneissic banding evident in the magnetic image is visible in the basement outcrops and in the location of the basement outcrops relative to each other. The position of the Lake Warden wetlands and the arrangement of the lakes within them appear to be strongly controlled by this basement geological structure. The regolith overlying this basement structure, moving upwards from basement surface, consists of in-situ weathered saprolite grit and saprolite clay, Werillup Formation, Pallinup siltstone and Quaternary sands at the surface (Figure 43). There are basement outcrops in the divides between lakes and the lakes appear to sit between outcrops aligned along the south west to north east lineaments as shown in Figure 42.

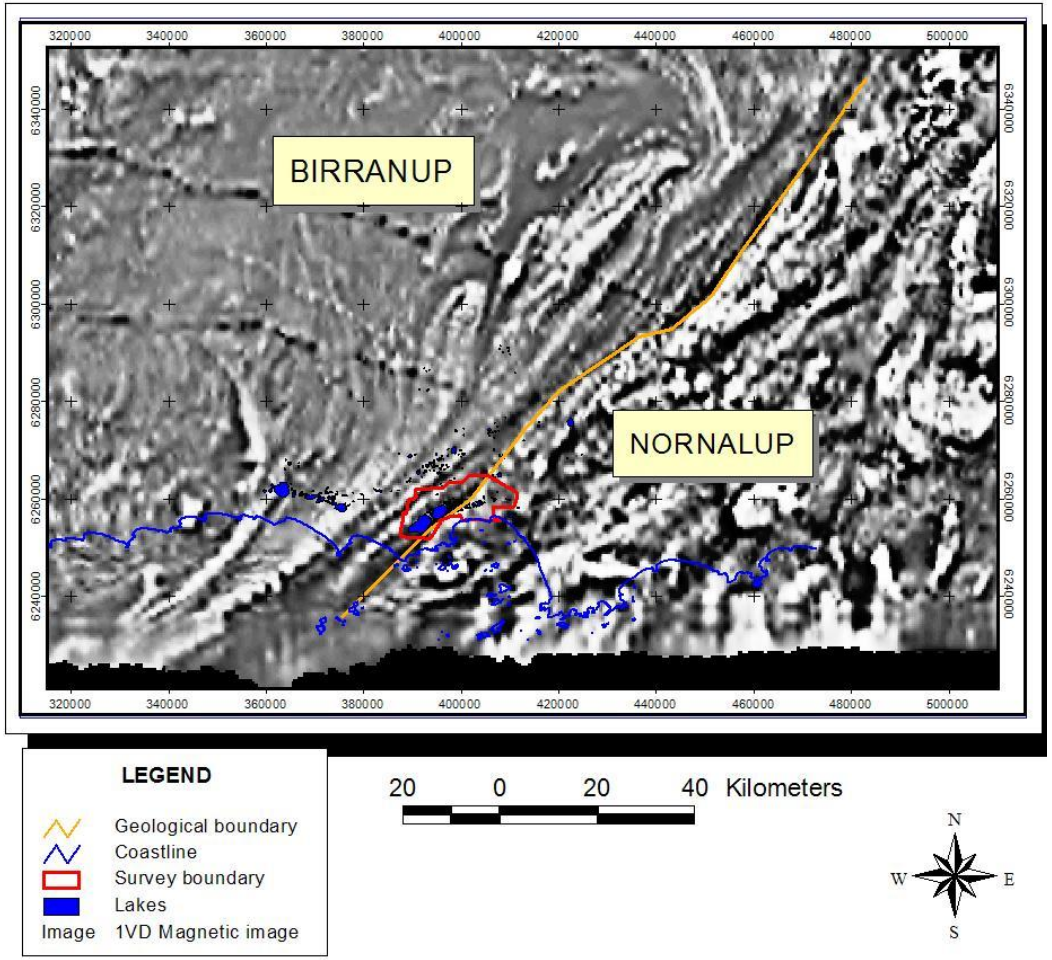

Figure 41. Regional aeromagnetic image (courtesy Geoscience Australia) showing that the Lake Warden study area sits on the divide between the granulites gneiss and amphibolite rocks of the Biranup group in the west and the granite gneiss of the Nornalup group in the east.

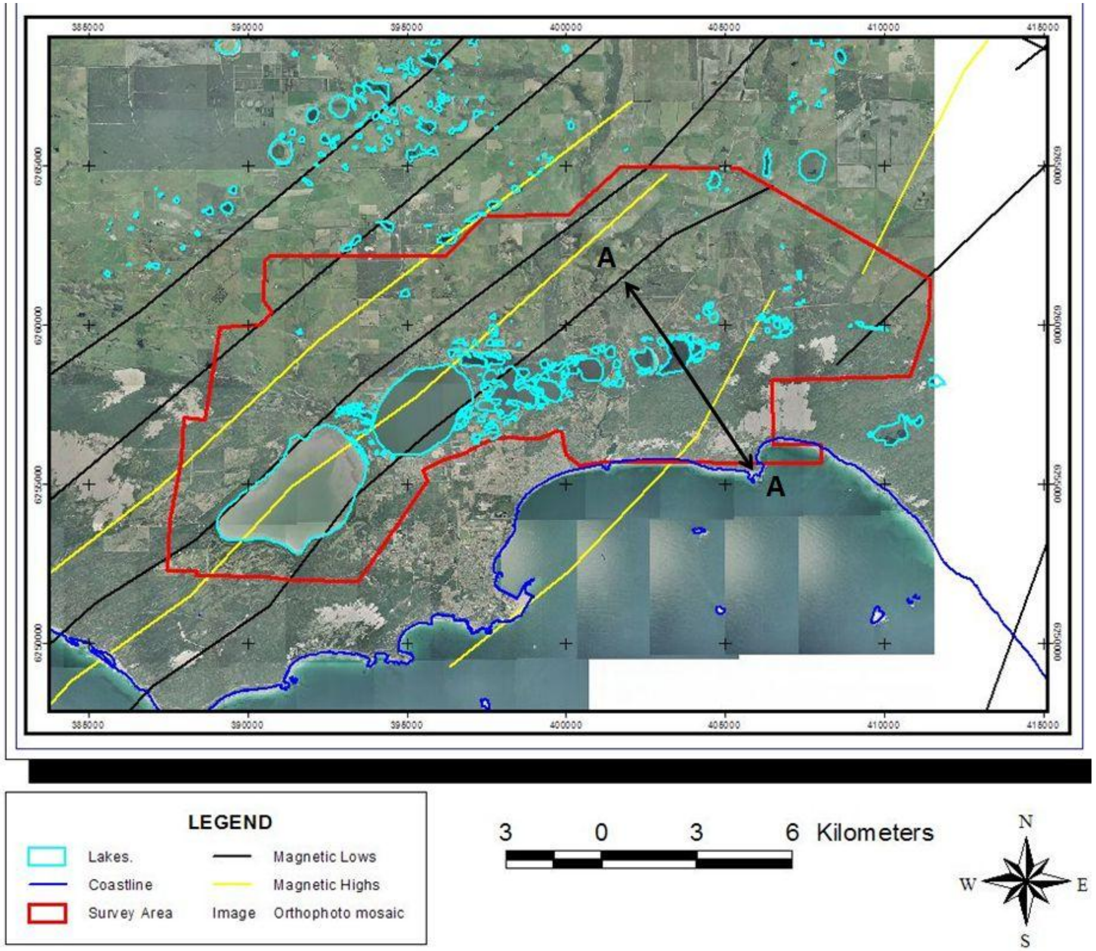

Figure 42. The position of the Lake Warden wetlands in relation to the major geological structural lineaments superimposed on an aerial photograph mosaic. The schematic cross section ‘A-A’ is shown in Figure 43.

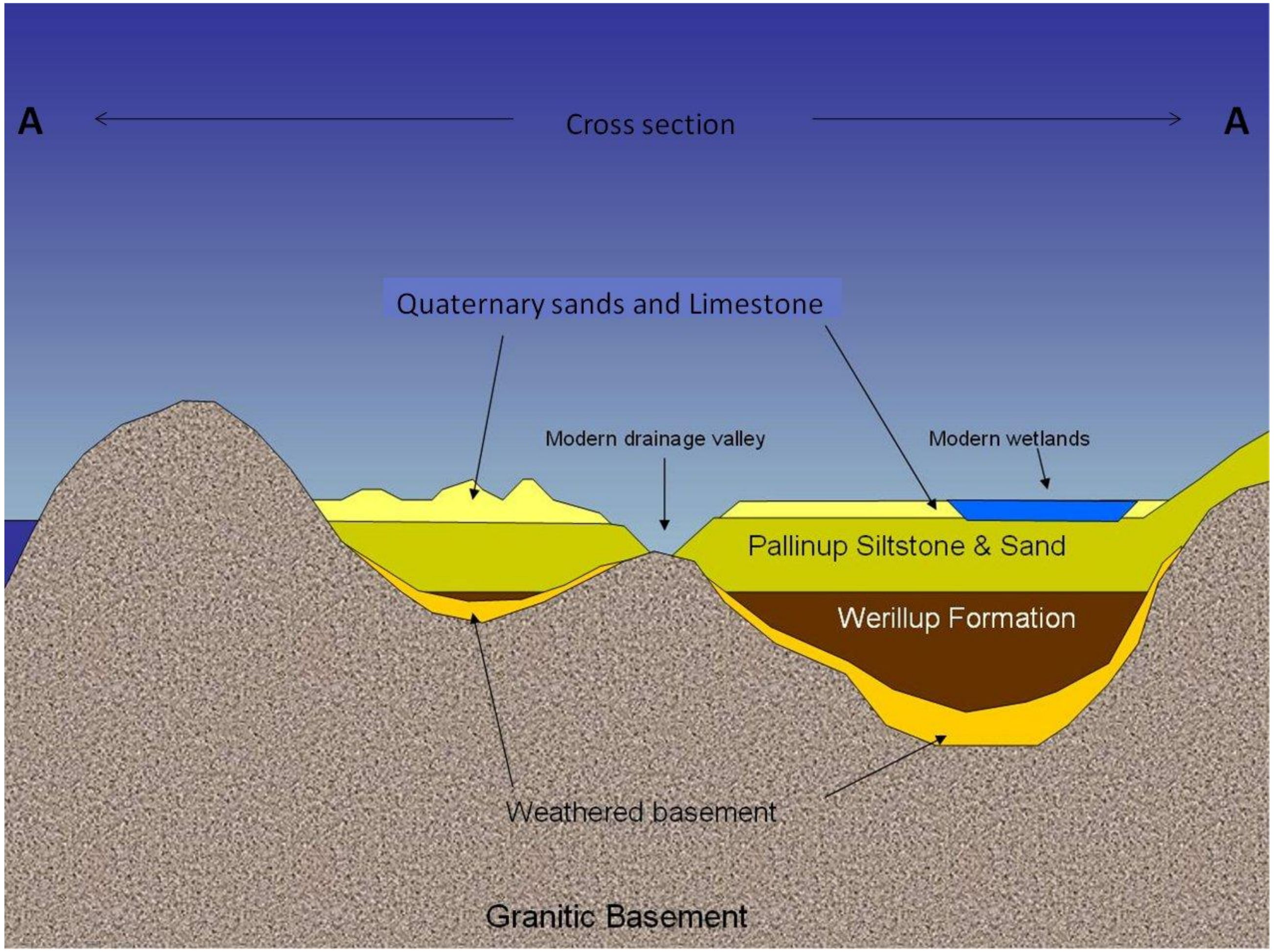

Figure 43. Schematic cross section A-A from Figure 42 showing relationship between the main geological formations in the Lake Warden Wetlands study area.

The Werrilup Formation occupies depressions in the basement (Figure 43) and was formed during marine transgression in the Eocene (Morgan and Peers, 1973). Terrestrial woody organic material and carbonates were deposited in valleys and swampy depressions. When the marine transgression reached its peak, the submerged valleys became shallow, relatively warm embayments in which sponge life flourished and the deposition of the Pallinup siltstone began. Wind-blown material also contributed to this depositional formation (Morgan and Peers, 1973). A stratigraphic column based on mapping by Morgan and Peers (1973) and Johnson and Baddock (1998) and Water Corporation drilling in the Esperance area (Anonymous, 2004) is shown in Figure 45.

Dryland salinity is most often understood in Western Australia under the well established paradigm of a simple, single aquifer with rising groundwater levels (Wood, 1924). However, the background hydrogeological information reviewed here and that which was obtained from the limited drilling in the wetlands (Figure 44) identified a more complex assemblage of aquifers (Figure 45) than is encountered in most of the agricultural areas of Western Australia. This suggested that a more detailed, site-specific study would be required to accurately understand the hydrology and hydrogeology of the Lake Warden wetlands. There was good knowledge of groundwater aquifers to the south west of the wetlands from drilling associated with water resource exploration for town water supply (Figure 44). Some hydrological investigation drilling was undertaken by DEC to the south and east of the wetlands. Hydrogeological information sourced from drilling was not available from directly beneath the wetlands due to the presence of dense wetland vegetation and poor accessibility for drilling equipment. There were several information gaps resulting from the low spatial density of data. The relative contribution of each of the four catchments in terms of groundwater and salt was not well understood. It was not clear if there was a store of salt beneath the wetlands that was being mobilised by groundwater movement or if salt stored in surrounding regolith was moving towards the wetlands.

Questions requiring answers were:

A. Does groundwater move between Lake Warden and Pink Lake?
B. In what direction does it flow?
C. What factors influence this movement?
D. What is the architecture of the groundwater aquifers and what are the significant groundwater flow paths?
E. What is the horizontal and vertical distribution of salt storage in the wetlands and surrounds?
F. Is there a significant hydrological connection between the wetlands groundwater system and the Southern Ocean?

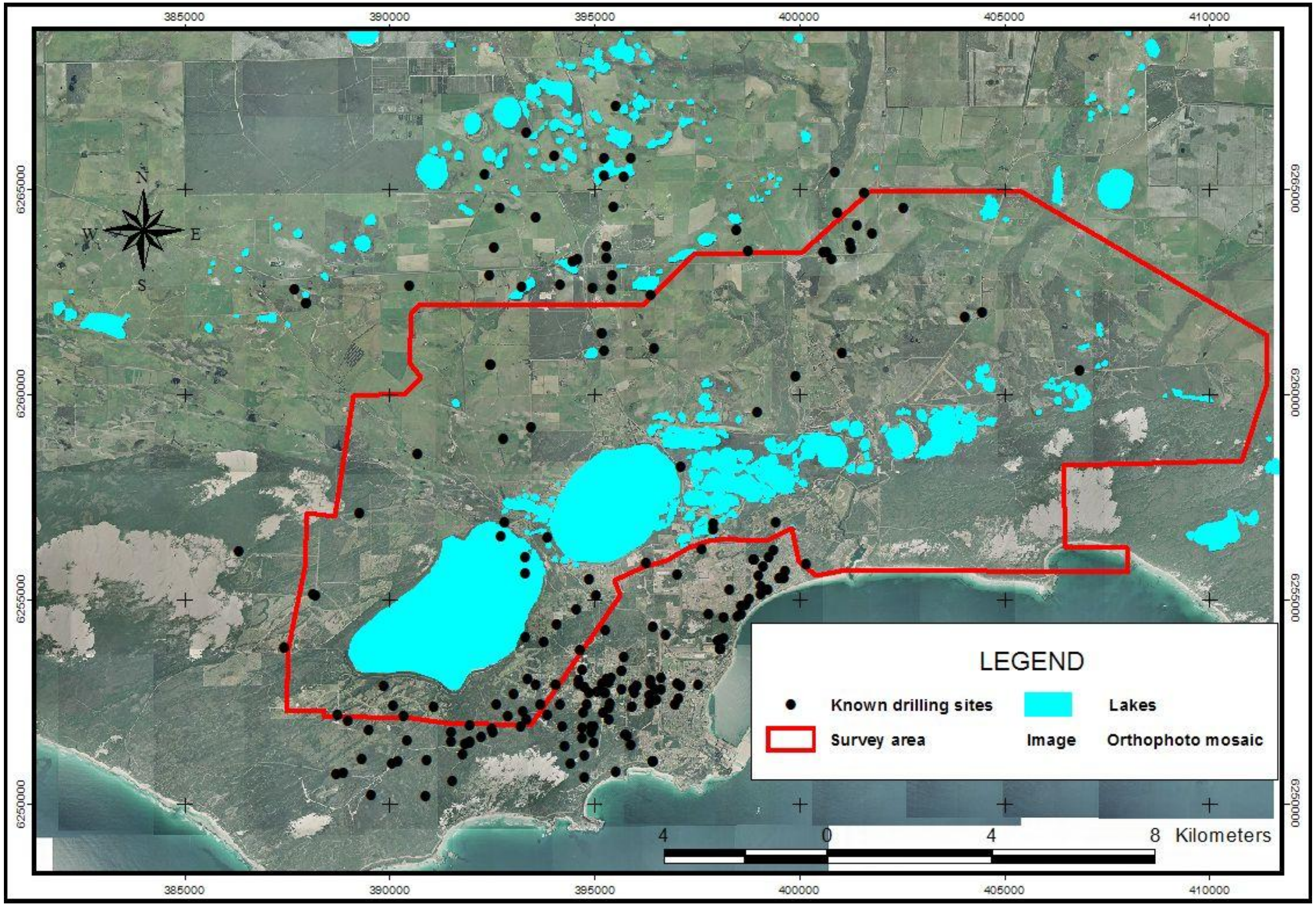

Figure 44. Location of existing drilling sites showing low density of drilling in the wetlands.

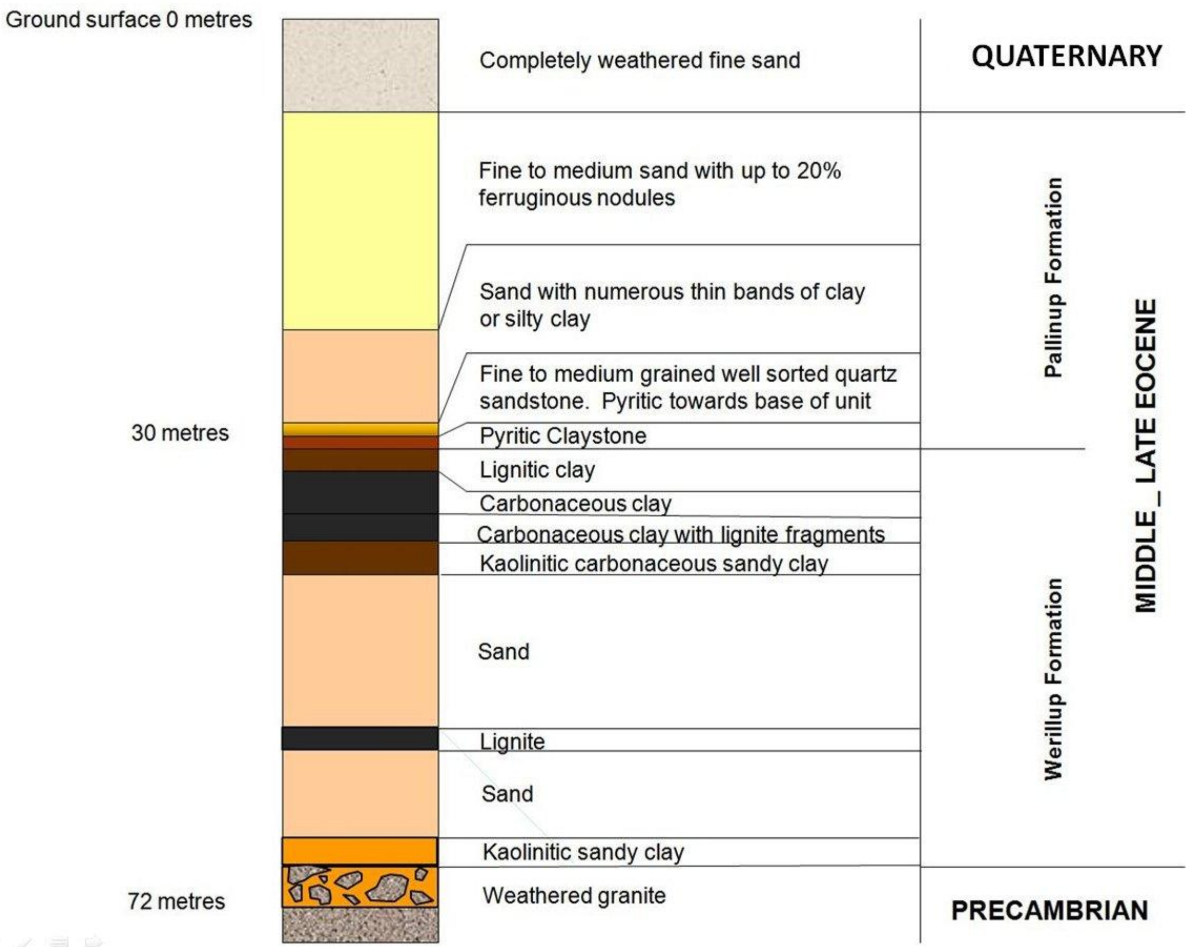

Figure 45. Typical stratigraphic column with geological formation notes, adapted from (Morgan, 1973; Johnson, 1998; Anonymous, 2004)

4.3 Helicopter EM Survey

In response to these knowledge gaps, the community and DEC developed a proposal to acquire high resolution airborne electromagnetic (AEM) data over the entire wetlands area and parts of the surrounds. The electromagnetic technique involves the transmission of an electromagnetic pulse into the earth. Conductive materials such as moist saline saprolite will develop their own secondary electromagnetic field in response and this is detected by the receiver antenna of the EM instrument. The Time Domain EM system operates by sampling the induced response signal at discreet time intervals after the shut-off of the transmitter pulse. As the transmitted electromagnetic pulse penetrates the earth, early time responses are from shallow conductors and late time responses are from relatively deeper conductors. The AEM data provides information on the lateral and vertical distribution of salt stored in the regolith. However, interpretation of the geophysical data requires understanding of the geological setting of the survey area.

4.4 Method

The request for tender for the airborne EM survey required 200 metre flight line spacing with flight lines oriented east–west. A helicopter-borne system was preferred as the helicopter has capacity to sharply deviate flight lines around built-up areas and to rise or descend vertically as it traverses obstacles, whereas a fixed-wing platform has to climb, descend or turn at a rate that puts it too high or off line for long sections of survey line, thus losing detailed data. GPX Airborne Geophysical Surveys was chosen as the successful tenderer with the HoistEM time domain system.

HoistEM has the receiver and transmitter coil concentrically mounted within a carbon fibre framework known as “the bird” which is at a position of only 30m from the ground. The bird being closer to the ground signal source produces greater received signal strength than fixed wing systems. Due to the rapid rate of induced signal decay which increases with distance from the ground, closer proximity of the receiver to the ground enables recording of a stronger induced signal. Due to the relatively slow speed of the helicopter, a reading is taken every 5 metres along survey lines. This is one of the principle advantages of helicopter-borne systems. This is an advantage with rapidly decaying conducting bodies because the end of the response is being emitted from the body while the receiver is still in the vicinity and able to record it. Another advantage with the HoistEM system is that the transmitter and receiver are in a concentric, coplanar configuration, which significantly improves the signal to noise ratio. It is effectively an in-loop ground EM system suspended from a helicopter. In fixed wing systems, the transmitter is around the aircraft and the receiver is on a towed bird up to 150m away. If the wind currents change or the aircraft alters course, the bird shifts relative to the aircraft causing the transmitter/receiver geometry to change, producing errors. Fixed wing systems such as Fugro's TEMPEST use GPS receivers in both the aircraft and receiver bird to facilitate real-time correction of errors due to such variations in system geometry. With a coincident configuration this source of error and need for corrections is eliminated. Figure 46 shows the system during surveying over Pink Lake.

HoistEM Data were recorded, stacked, cleaned of the system response, and then binned into 27 channels. Data were filtered using a nonlinear filter having a narrow window to reduce noise and increase resolution. Decay channels were saved as ASCII data and imported into Geosoft Oasis Montage software. The main data columns included are:

- data point easting
- data point northing
- transmitter current
- fiducial
- line number
- helicopter radar altimeter
- helicopter GPS elevation
- Tx laser elevation
- twenty seven EM response channels with time delay from 0.078 to 11.724 milli-seconds.

The HoistEM data were converted to a format suitable for EMFlow software for processing and interpretation.

Figure 46. HoistEM surveying over Pink Lake.

EMFlow has generated a high level of interest for diamond exploration, mineral exploration and environmental purposes (McNae, 1998). It can provide readily interpretable 3D depth images of ground conductivity structure, and has made it practical to process data gathered by modern AEM systems.

Several difficulties were encountered by the contractors in the course of conducting the airborne survey. The laser altimeter was not returning readings over still-water surfaces, so this instrument had to be replaced with a radar altimeter. There was a high level of noise in the received EM signal. This noise originated from broadcast radio transmission towers in the vicinity of the northern boundary of the survey area. The additional area of survey on the north west corner of the study area was flown for the Shire of Esperance for another purpose. Due to the dominance of noise in this area, it was not used in this study (Figure 47). At least one of these transmitters is known to be one of the most powerful of its kind in the southern hemisphere. Anomalous signals were also received from metallic infrastructure features such as pipelines, railways and power transmission lines. As this occurred at quite discreet locations affecting only a few data points on any particular survey line, the spurious signals from these sources were removed by deleting affected data points. Gridding of EMFlow conductivity-depth horizons is useful for imaging the spatial distribution of conductivity with increasing depth. The "depth slicing" technique is based on the work of Lane and Pracilio (2000). EMFlow was set to output conductivity depth interval images (CDI) conductivity values at 10 metre depth intervals to a depth of 100 m. These images are like a vertical section of the landcape representing conductivity at calculated depth intervals

All attempts to process out the radio transmitter noise proved fruitless. It was however, possible to identify the noise affected areas and mask them out of the dataset. Fortunately, the wetlands area was relatively unaffected by the noise (Figures 47 and 48). The radio transmitter noise had most impact close to the transmitter and over resistive shallow basement areas. This was a consequence of the strength of the noise signal relative to the returning ground signal in these resistive areas.

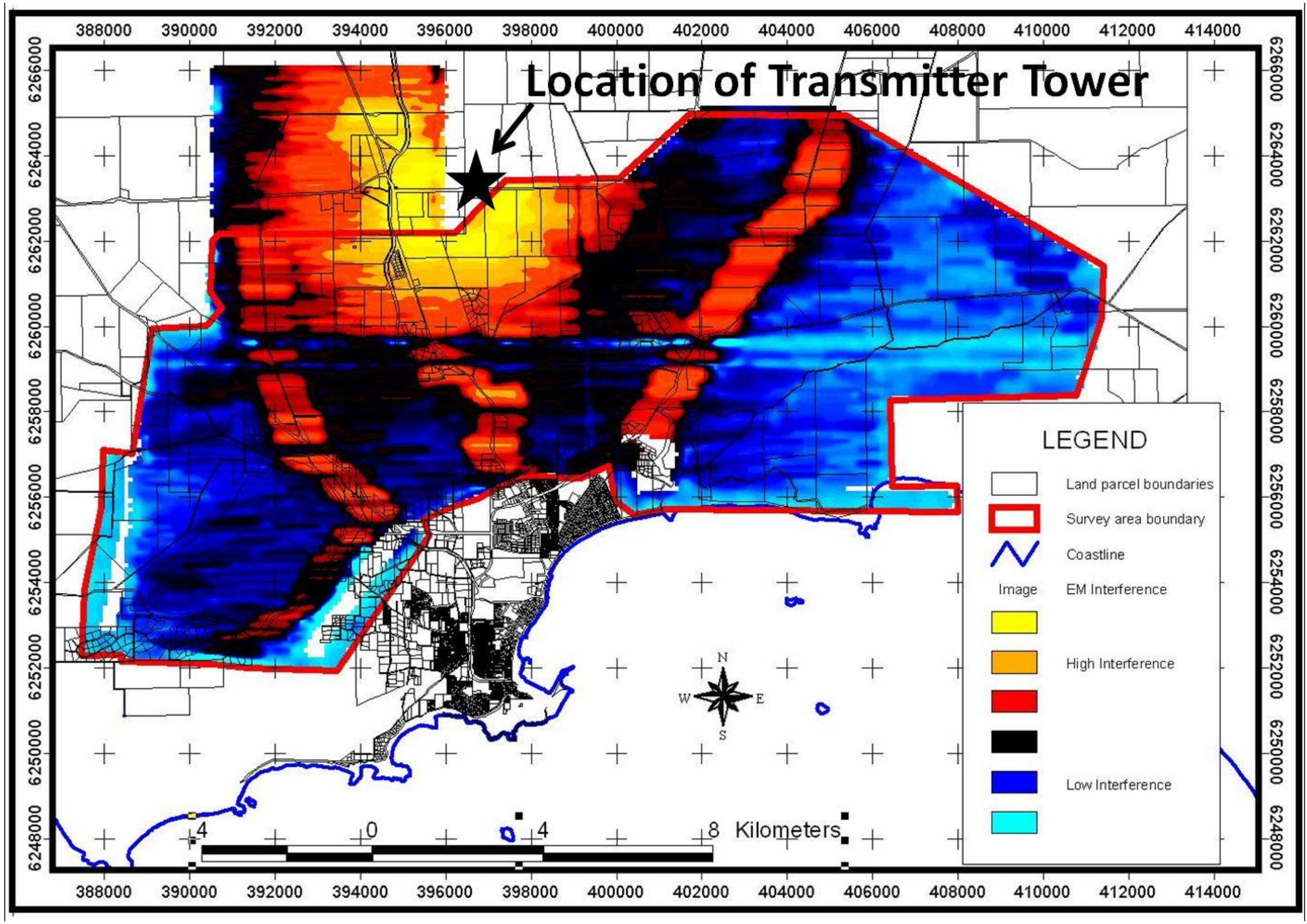

Figure 47. Noise map of the Lake Warden survey area. The additional area of survey on the north west corner of the study area was flown for the Shire of Esperance for another purpose. Due to the dominance of noise in this additional area, it was not used in this study.

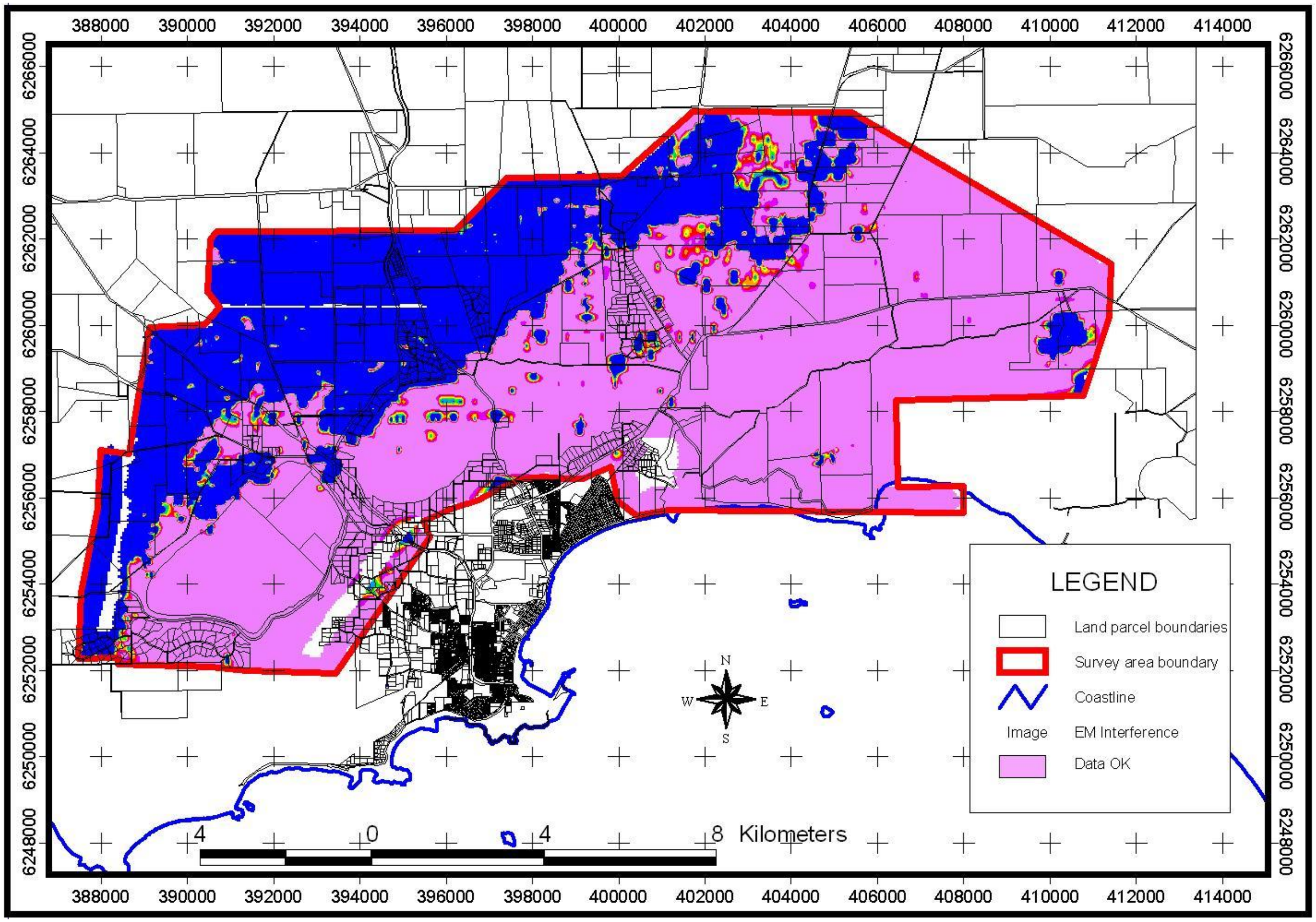

Figure 48. The pink area in this image identifies the parts of the survey area where the data was sufficiently free of noise to be reliable.

4.4.1 Basement Topography From Drilling Information

Most of the regolith underlying the Lake Warden wetlands consists of sediments of the Werillup and Pallinup groups (Figures 43 and 45). These are sedimentary aquifers critical to the understanding of the hydrology of this study area as they are both more hydraulically transmissive than the saprolite clay of in-situ weathered granite-gneiss terrains. However, weathering of basement has proceeded since these sedimentary depositions and the existence of the saprolite grit zone beneath sedimentary deposits was confirmed by drillers logs and notes (Anonymous, 2004).

The main pathway for lateral movement of groundwater in in-situ weathered granite-gneiss regolith in WA is within the saprolite grit zone or saprock zone, which is the gritty interface between fresh, unweathered basement rock and the overlying saprolite clay (George, 1990). Groundwater flow direction close to basement surface is thus determined by fresh bedrock topography. For this reason, it was important to derive basement topography from the available data. Before the HoistEM data was available, the topography of the bedrock beneath Lake Warden was estimated by extracting the depth from surface at which bedrock was struck from drilling logs. Only confirmed bedrock strikes were used in this analysis. Weathered basement or saprock was not interpreted as a bedrock strike. The topographical heights of the drilling sites were used to reduce these bedrock depths to relative levels (heights above or below sea level). An inverse distance weighting interpolation process was used to construct a topographical grid of basement elevation. This produced a very smooth and generalised grid of basement topography (Figure 49) and this showed general agreement with known structures and the interpretation of regional magnetic data (Figure 50).

4.4.2 Basement Topography From Hoistem Data

Additional depth to basement information was obtained from the part of the HoistEM data not affected by noise. However, a further problem was found in the HoistEM data. When the surface topography channel was gridded, it appeared lumpy as shown in (Figure 51).

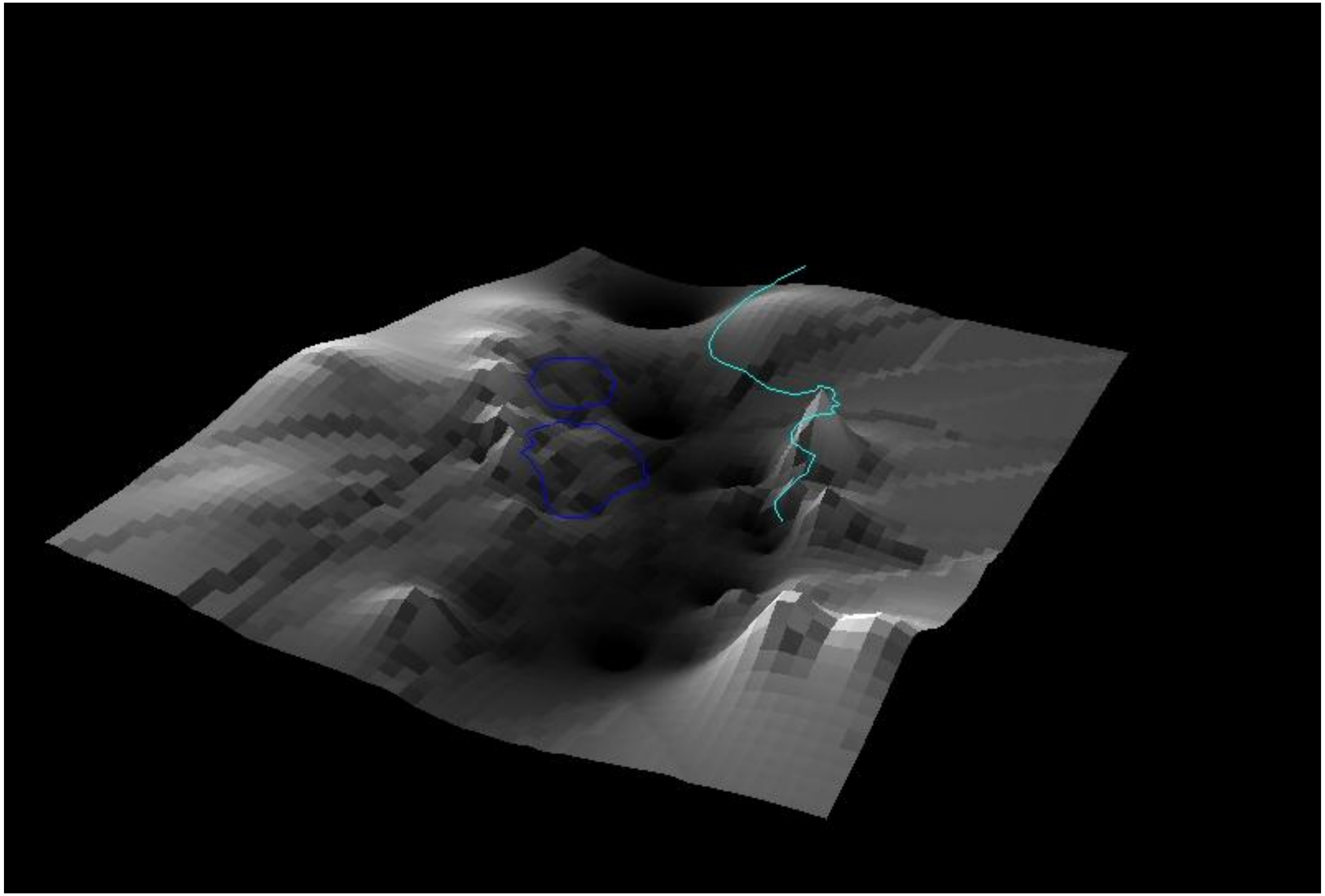

Figure 49. Oblique view, looking ENE, of basement surface interpolated from confirmed basement strikes in drilling logs.

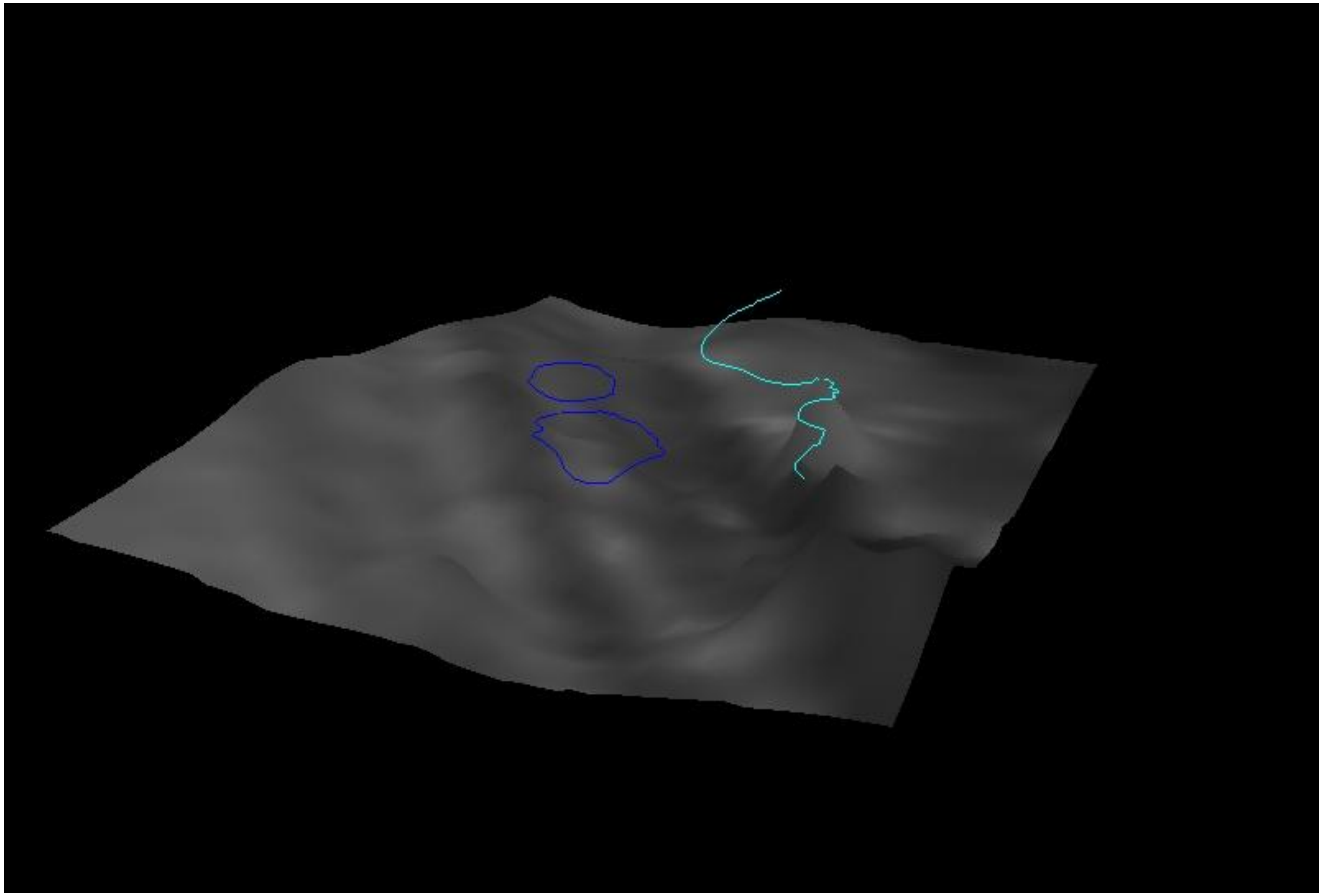

Figure 50. Same basement surface, from Figure 49, looking east, with magnetic image draped over it. Although very fuzzy at this scale, the main SW to NE magnetic lineaments are visible.

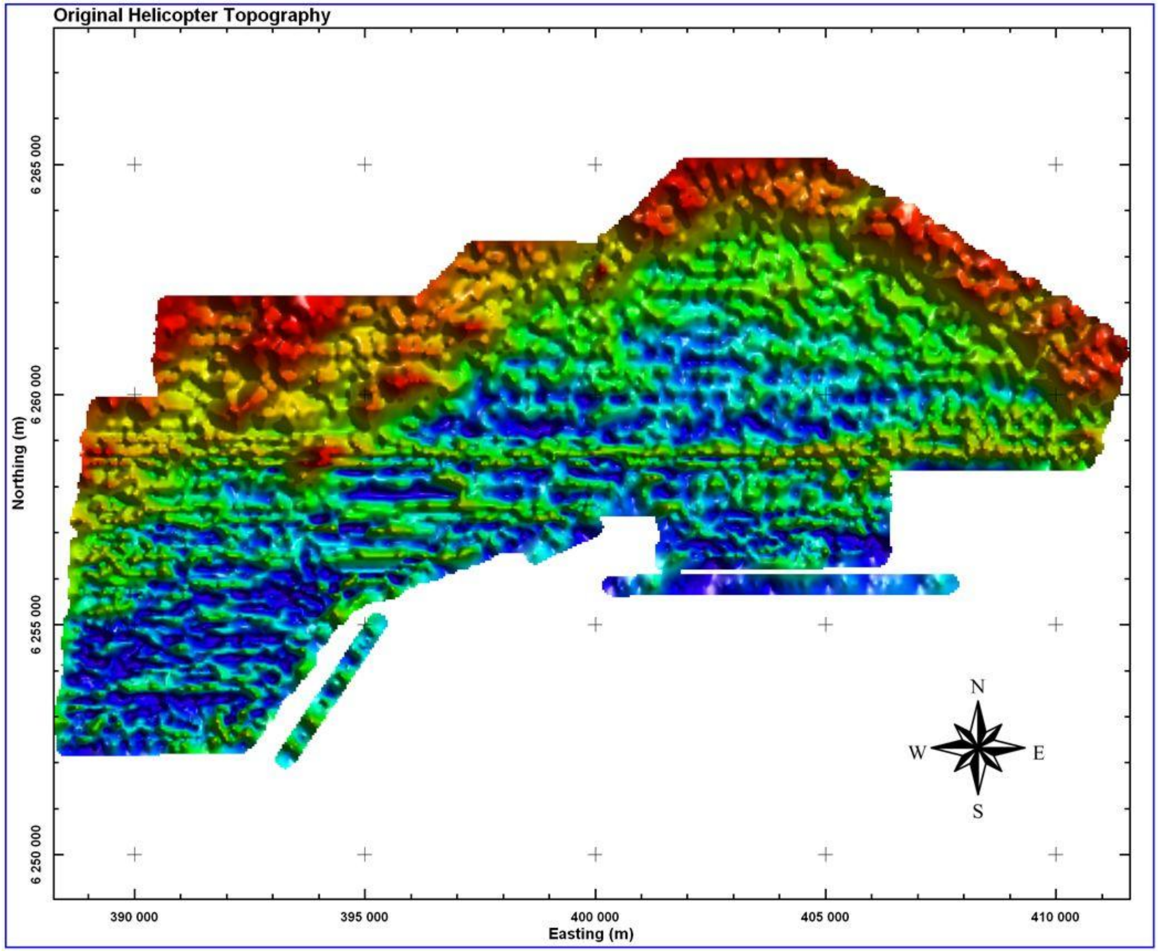

Figure 51. Surface elevation data gridded from HoistEM survey data.

There is very poor correlation between the HoistEM elevation data and the digital elevation data produced from photogrammetry by the Department of Land Administration (now Landgate) Land Monitor project (Cacetta et al., 2000) (Figure 52). The processing of the electromagnetic data using the topography channel from the survey was seriously compromised. Because the elevation of the land surface was incorrect, all other depths in the outputs of the data processing were affected. Figure 53 shows hills and troughs caused by bad HoistEM elevation data along flight lines and this is most obvious over the flat salt lakes. As it was not possible to re-fly the survey, a means of replacing the faulty topographic data had to be devised.

The Land Monitor DEM was used as the topography data source. This dataset was imported into Oasis Montage software and sampled at each HoistEM datapoint along every flight line. These height data were copied into the topography channel in the HoistEM dataset before it was re-processed. The results of the processing using accurate topography data showed a great improvement. Figures 54 and 55 show the CDI results before and after the topographic correction.

4.5 Results

4.5.1 Basement Topography From Drilling and Hoistem Data

With correct topography data inserted into the topography channel of the HoistEM dataset, basement depth could be calculated from the data by identifying the depth at which conductivity dropped to a threshold consistent with resistive basement. The threshold conductivity value chosen to identify the beginning of basement surface was less than or equal to 100 mS/m. The top of the conductive layer was calculated in a similar manner by selecting a conductivity threshold of greater than or equal to 200 mS/m. This was determined from drillers notes and EM39 down hole condictivity logs. The grid of basement topography from HoistEM was converted to points, each with a Z value for depth to basement (Figure 56). To these points were added the points representing depth to basement from drilling. Also added to this set of points were the points derived from topographical contours of bedrock outcrop. An additional set of drilling data was obtained from the Water Corporation and points of basement contact were added from this

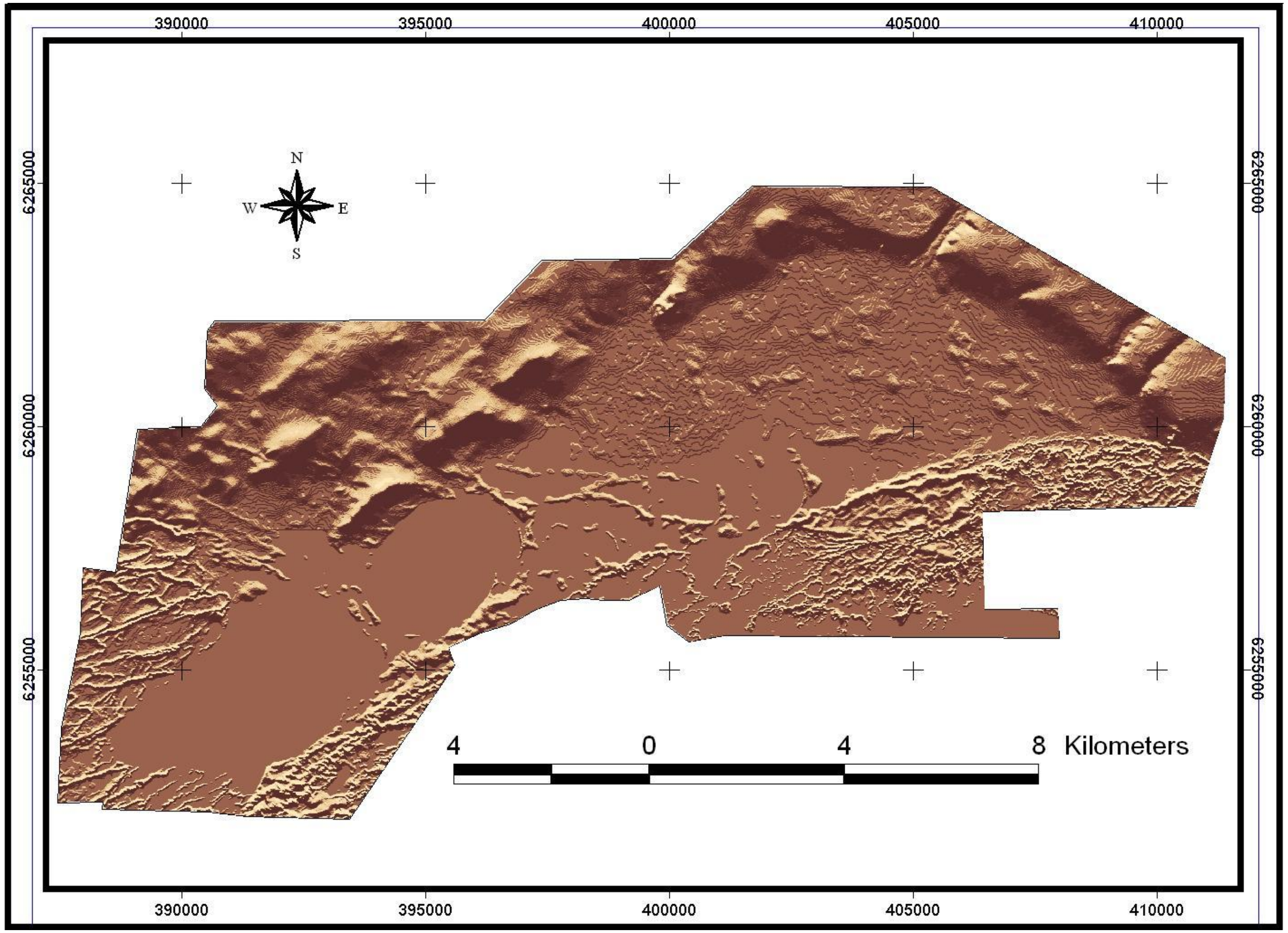

Figure 52. Surface digital elevation model (DEM) derived from Land Monitor photogrammetric project.

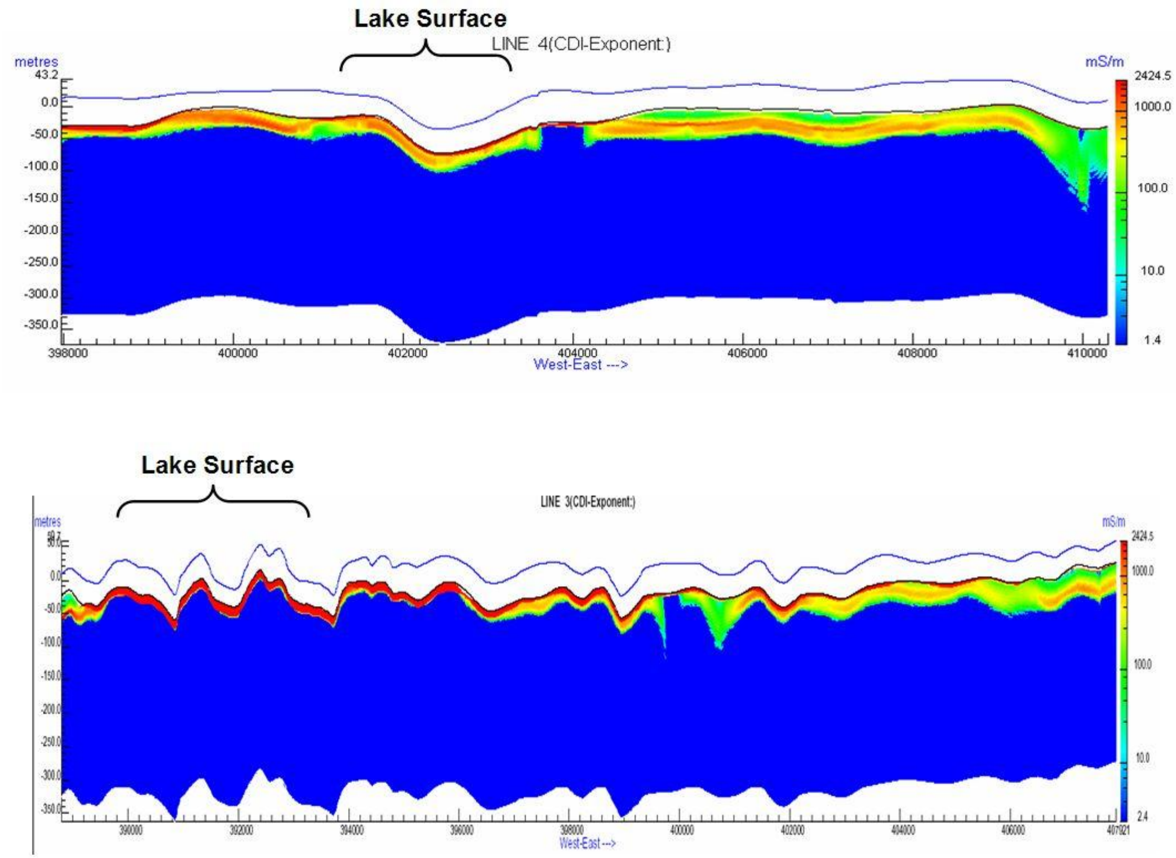

Figure 53. Conductivity depth images (CDIs) produced using the HoistEM survey topography channel. Note the false topography of the lake surfaces.

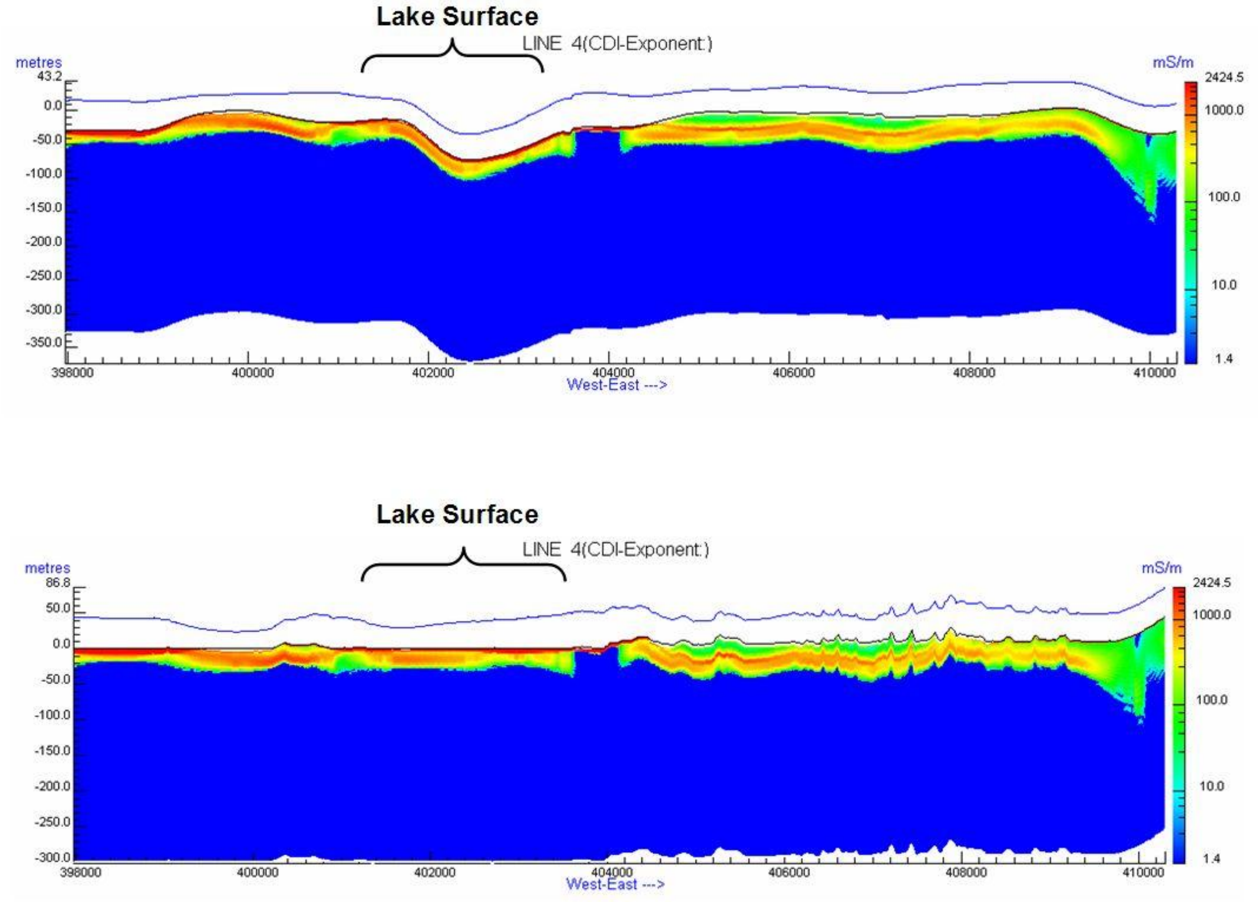

Figure 54. The bottom image shows the CDI of the same flight line as the top image after reprocessing with correct surface elevation data.

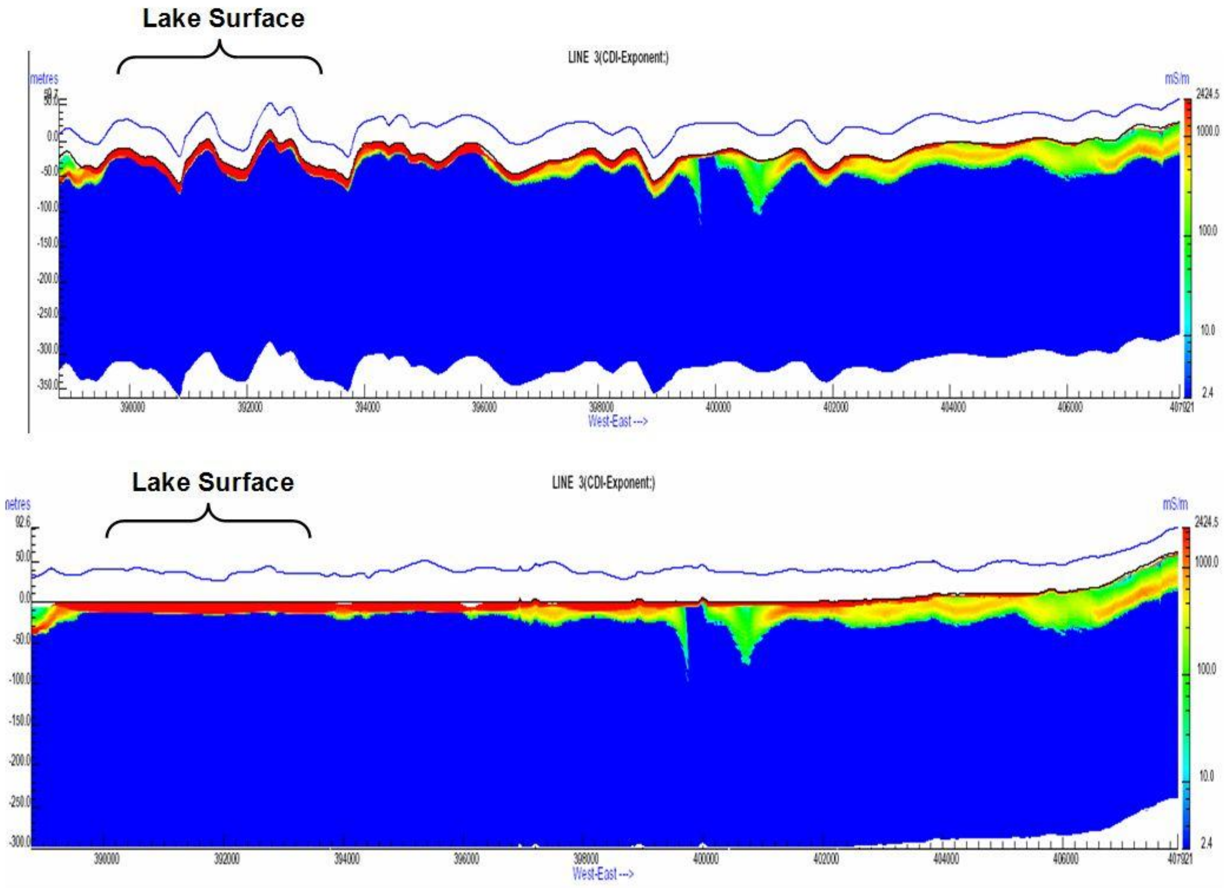

Figure 55. The bottom image shows the CDI of the same flight line as the top image after reprocessing with correct surface elevation data.

ArcView Spatial analyst was used to construct a basement topography grid from these points (Figure 56). This new grid was much more detailed, especially in the eastern area where the HoistEM data was the main source of depth information.

4.5.2 Groundwater Flow Lines

ArcView 3.2 was used initially to identify potential groundwater flow directions over the fresh bedrock surface. An automated water accumulation program was run but the results were complicated by the large number of sinks in the surface. Generated flow lines were very short. Manual analysis of spot elevations each side of sinks facilitated interpretation of this product to extract the key trend lines of potential flow across the basement surface (Figure 57).

Using ArcGIS 9.3, which has automated sink-filling capability, the basement surface was analysed again using the flow accumulation tool. The new flow accumulation analysis shows good agreement with the original, more subjective, interpretation. There are, however, some interesting exceptions. In the western half of the study area, most basement surface flow lines trend in a south easterly direction all the way across the survey area. One exception to this is in the extreme west of the survey area where the flow direction is due south. In the eastern half of the study area, the dendritic pattern of the original interpretation in the north and south was confirmed. However, in this new analysis, the northern set of flow lines does not join the southern system but appears to be truncated possibly by a basement ridge (circled in Figure 58).. In addition, some of the most northern flow lines flow northward out of the study area which is contrary to the assumption of the original interpretation that all slope must have a general southerly trend. Similarly, some of the eastern flow lines do not connect to the south west flowing system in the south but exit the survey area in a south easterly direction (Figure 58). Compare this with the original interpreted flow accumulation lines (shown in red) added to the same flow accumulation image in Figure 59.

Although there are some differences between the two sets of flow lines, the overall trend of basement slope is shown to be in a south, south easterly direction but with a basement “ridge” beneath the wetland lakes. The predominant slope trend is perpendicular to the structural trend in the basement geology (Figures 41 and 42).

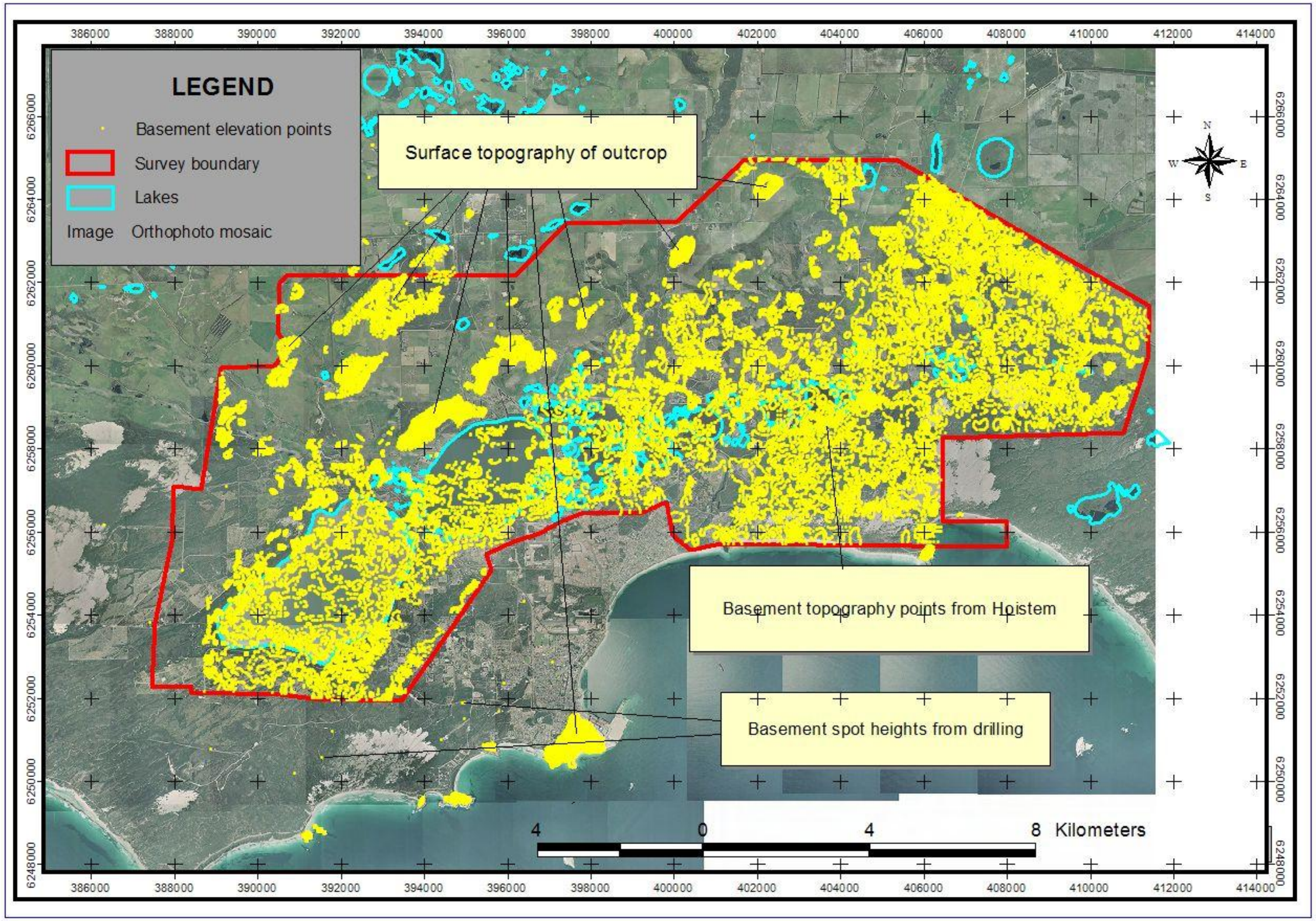

Figure 56. Points representing basement elevation from Hoistem, drilling and outcrop topography.

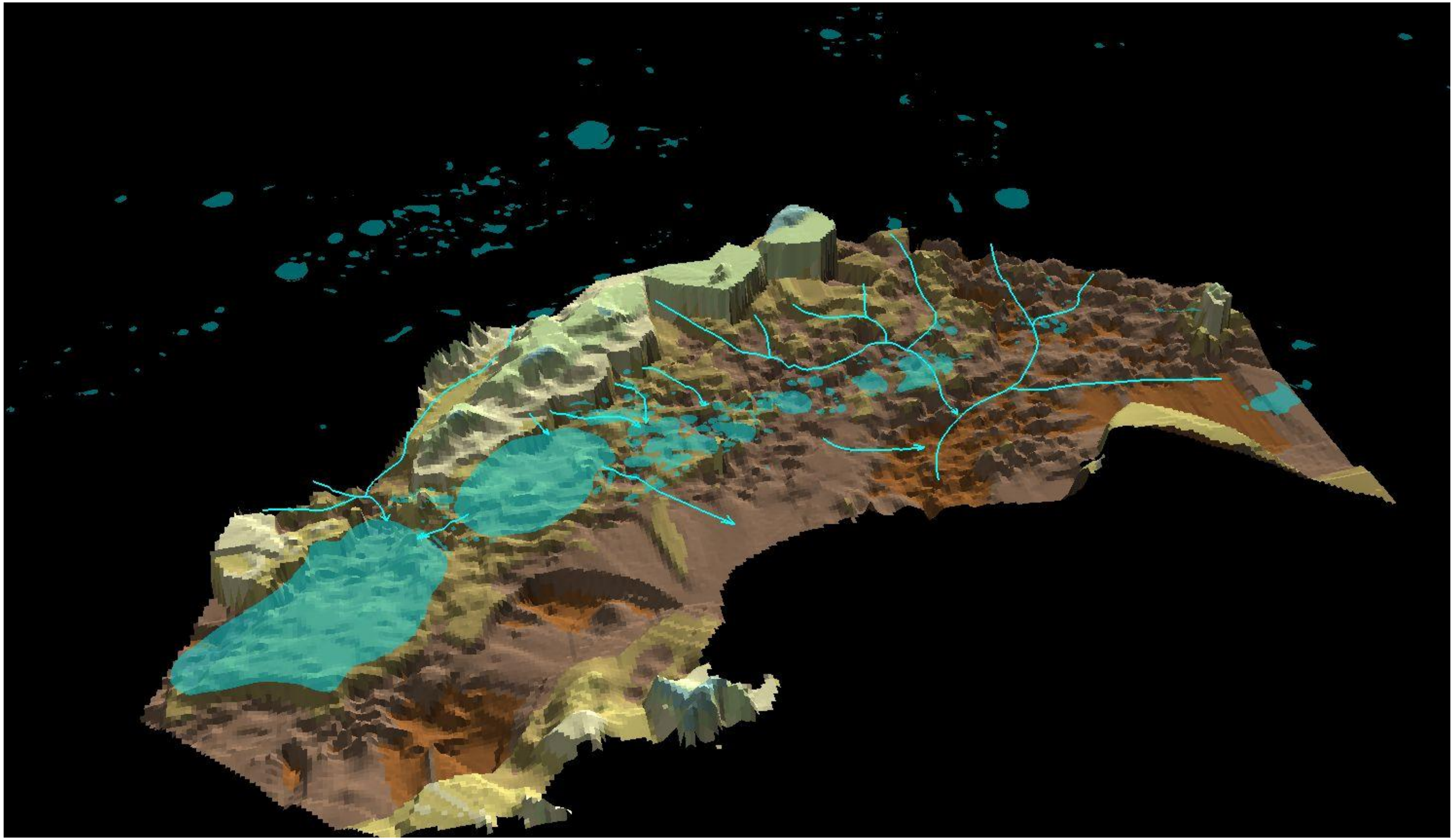

Figure 57. Oblique view of basement surface, looking north east, with simplified basement slope flow lines.

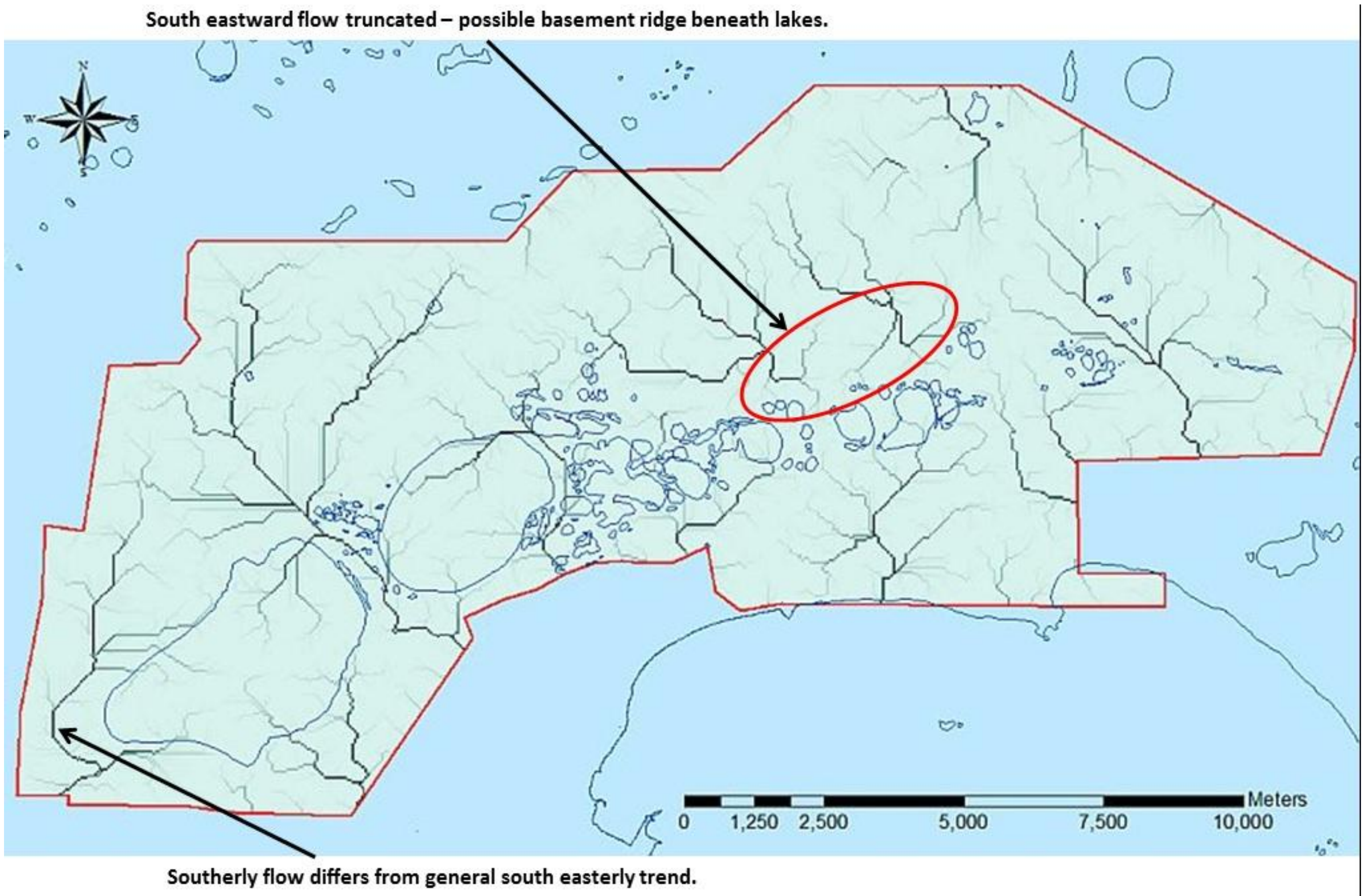

Figure 58. Revised flow accumulation of basement surface derived from Hoistem data and produced using ArcGIS 9.3.

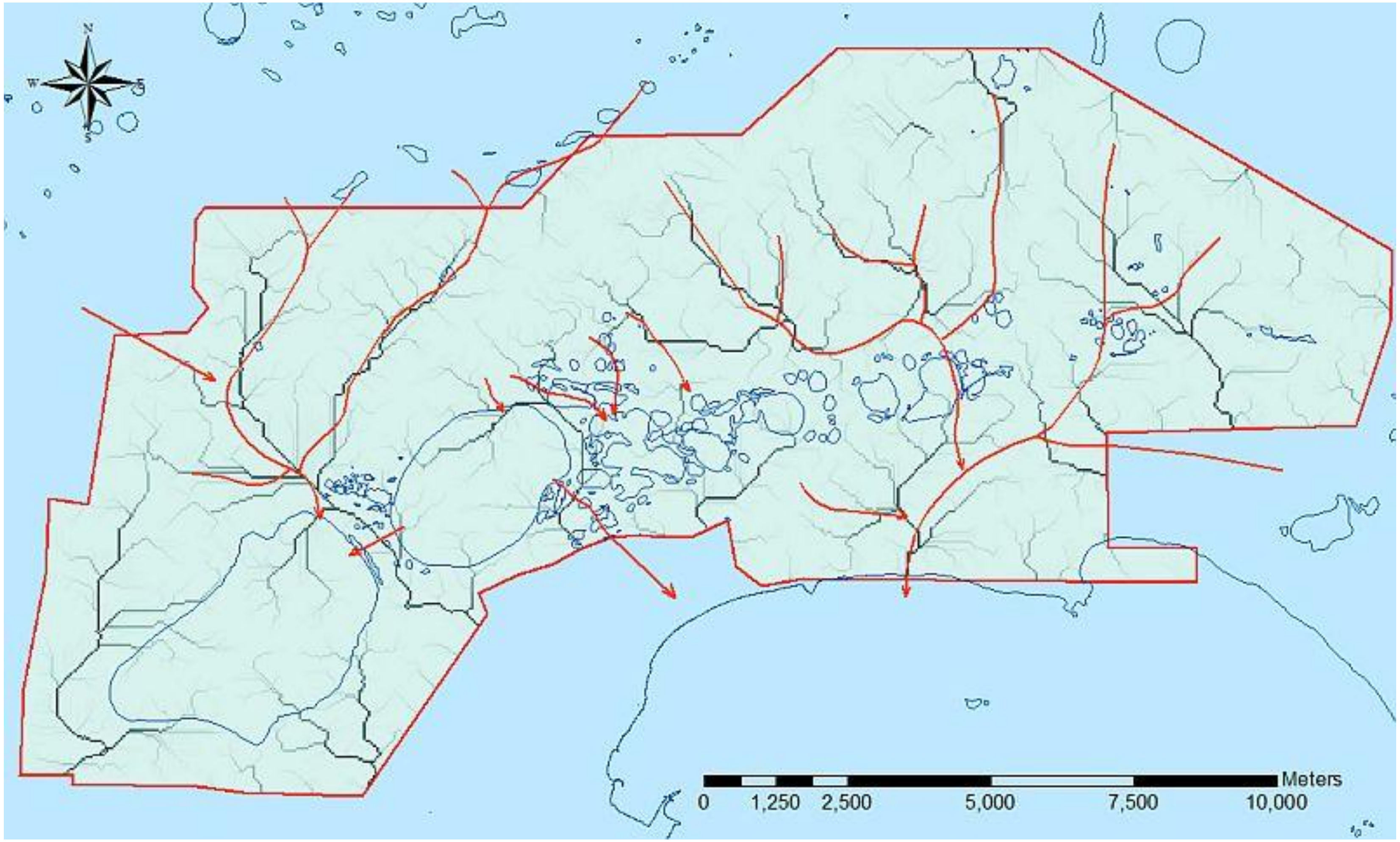

Figure 59. Original basement flow accumulation interpretation shown in red for comparison with the revised basement flow accumulation shown in black.

Conceptually, it may be the southward flow of groundwater over-topping the basement ridge that is hydraulically supporting the wetland lakes.

4.5.3 Representation of Aquifer structures between basement and ground surface – identifying the base and top of the Werillup Formation

Layered earth inversions (LEIs) were used to identify the spatial distribution of the deepest conductive layers. From drilling, it is known that the Werillup Formation is a highly conductive and often thick stratum and that the top of the Werillup represents the top of the conductive layers in this area. As Werillup Formation was not encountered universally in drill holes across the study area, it was necessary to identify the horizontal spatial extent of known Werillup Formation. Areas where drilling did not encounter Werillup were excluded, as were basement outcrop areas. Due to the spatial limits of the Hoistem survey, the interpreted northern boundary of Werillup Formation is based on the EM data and drilling logs, whereas the southern boundary is probably outside the survey area and is extended beyond the survey area only on the basis of evidence from drill holes. This interpreted boundary identifies the main body of Werillup Formation of hydrogeological significance to the Lake Warden wetlands.

Drillers notes and EM39 conductivity logs (Figure 60) were used to calibrate the HoistEM data for depth using the method of Hashemi and Meyers (2004). Within the Werillup Formation boundary, the LEI for depth 25 m agreed with the shallowest interceptions of the conductive layer in drilling notes and down-hole EM39 conductivity logs. The top of the conductive layer varied between 25 m and 45 m (Figure 61). The LEI image for depth 45 m was used to define the spatial extent of Werillup Formation in the survey area (Figure 62).

The Hoistem data indicated a highly conductive layer extending to 70 m. Drill logs suggest 55 m may be more correct, but also show weathered basement below Werillup in many instances. This may explain deeper readings in LEIs. LEIs were used to place interpreted spot heights of base and top of Werillup throughout the Werillup footprint. Drillers notes were used to differentiate between conductive Werillup sediments and conductive saprolite.

Figure 60. EM39 down-hole logging at Esperance.

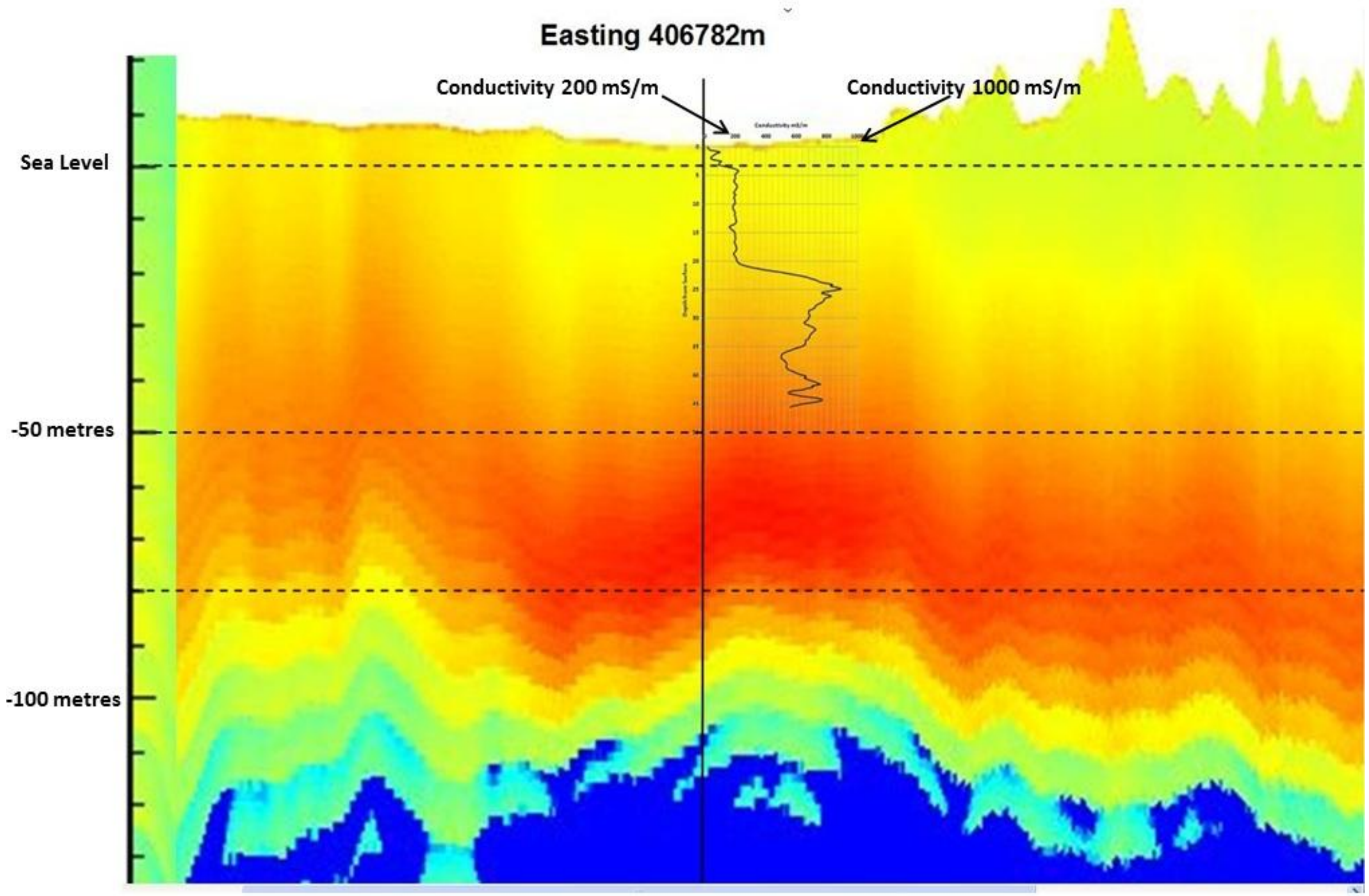

Figure 61. Down-hole conductivity log of DEC bore LW18 located on CDI image of TEMPEST line 20 which overflew this bore.

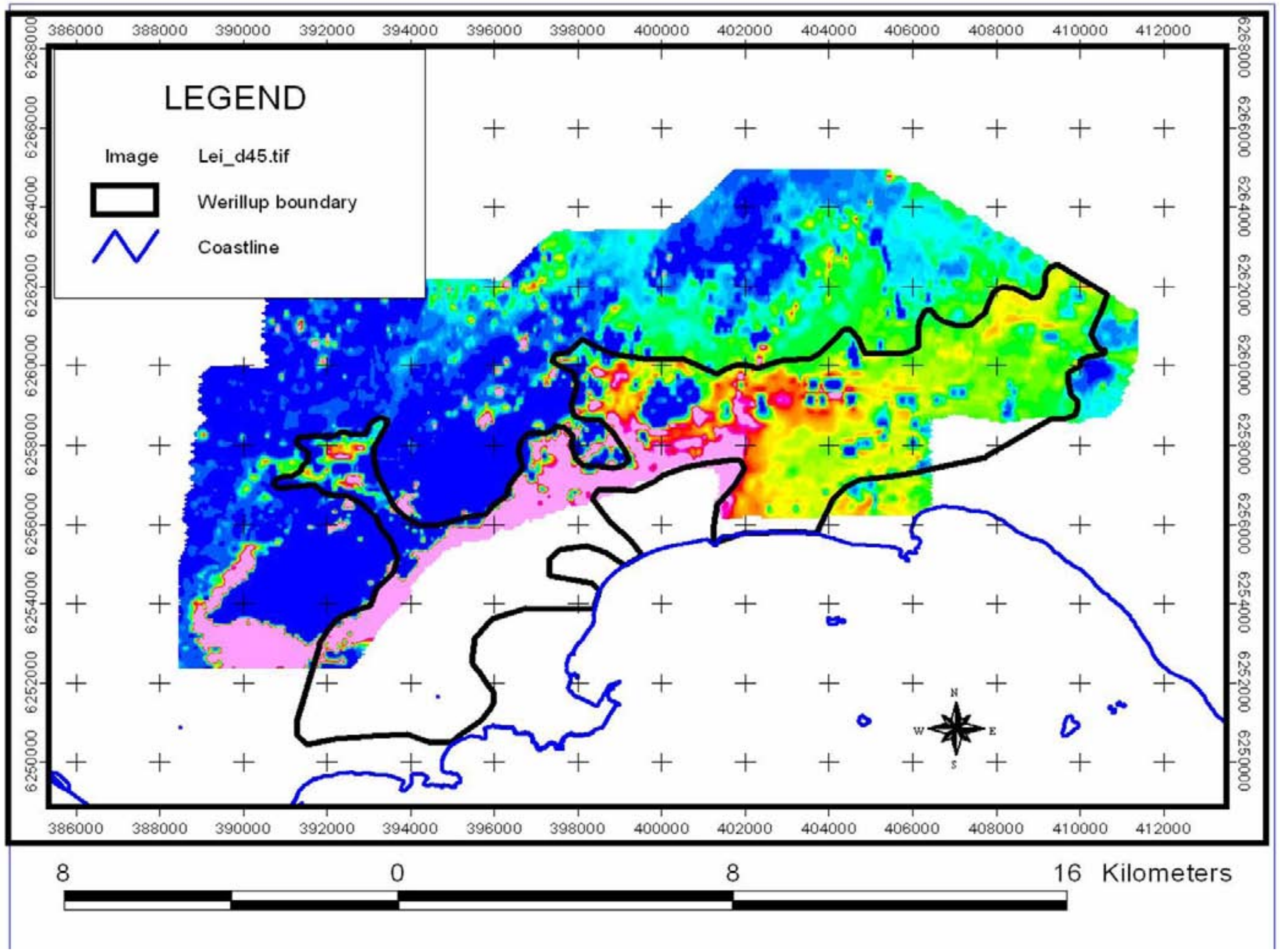

Figure 62. Interpretation of main Werillup extent from layered earth inversion images and drillers notes.

Two grids were created, one for the top of the Werillup, one for the bottom. These were reduced to relative levels by subtracting them from the surface topography grid.

The bottom of the Werillup sits on either basement or in-situ weathered saprolite clay. Both materials behave hydrologically as an aquitard. The flow accumulation and direction generated on the surface representing the base of the Werillup indicates a potential influence on groundwater movement within the Werillup Formation close to this surface. Figure 63 shows the flow accumulation generated on this surface. The south south east trend seen on the basement surface is largely repeated on the base of the Werillup except in the east and north where there are some significant north-trending flows potentials. These northward flow directions support the interpretation (from basement topography) of a basement ridge beneath the wetland lakes.

A grid representing Werillup thickness (Figure 64) was generated by subtracting the elevation of the bottom from the elevation of the top. This showed the thickness of the Werillup to vary from less than 1 metre to more than 54 metres. The thickest parts were in the eastern part of the study area in the vicinity of the southward flowing basement slope flow line close to the coast.

4.5.4 Identifying the Base and Top of the Pallinup Formation

The top of the Werillup and the bottom of the Pallinup are considered to be conformable (Morgan and Peers, 1973; Johnson and Baddock, 1998). Therefore, the top of the Werillup was used as the bottom of the Pallinup wherever the Pallinup overlies the Werillup. Where Pallinup does not overlie Werillup, it sits on either in-situ weathered saprolite or basement. The same procedure as was used to define the top and bottom of the Werillup was used to define the top and bottom of the Pallinup. This was achieved by selecting appropriate depths from the LEIs guided by gamma logs where available, drillers logs and drillers'notes. Known outcrops were "cookie cut" out of the areas defining the spatial extent of each stratum. This process produced a spatial extent for the Pallinup Formation that was somewhat more extensive than that of the Werillup Formation (Figure 65).

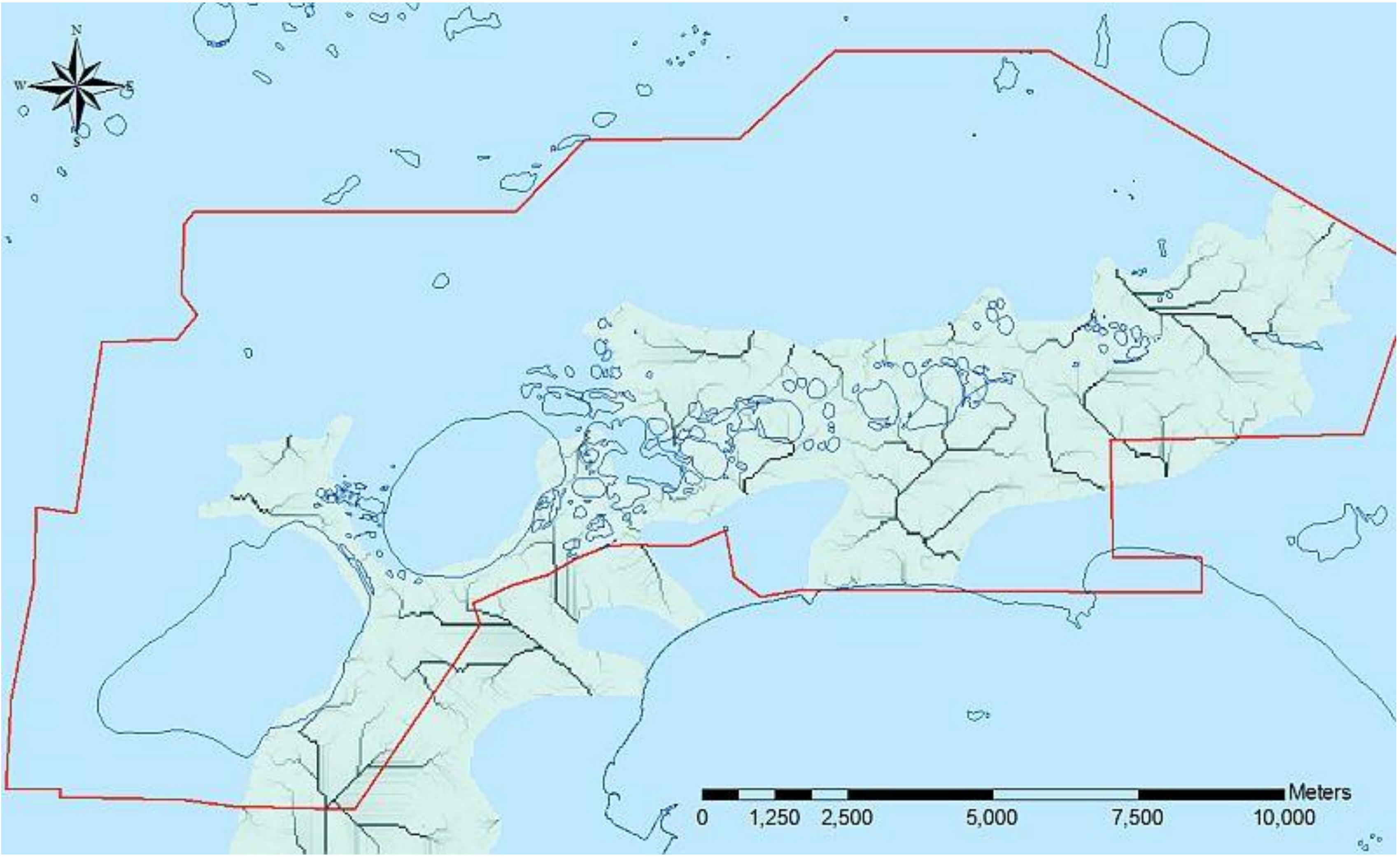

Figure 63. Flow accumulation on base of Werillup Formation.

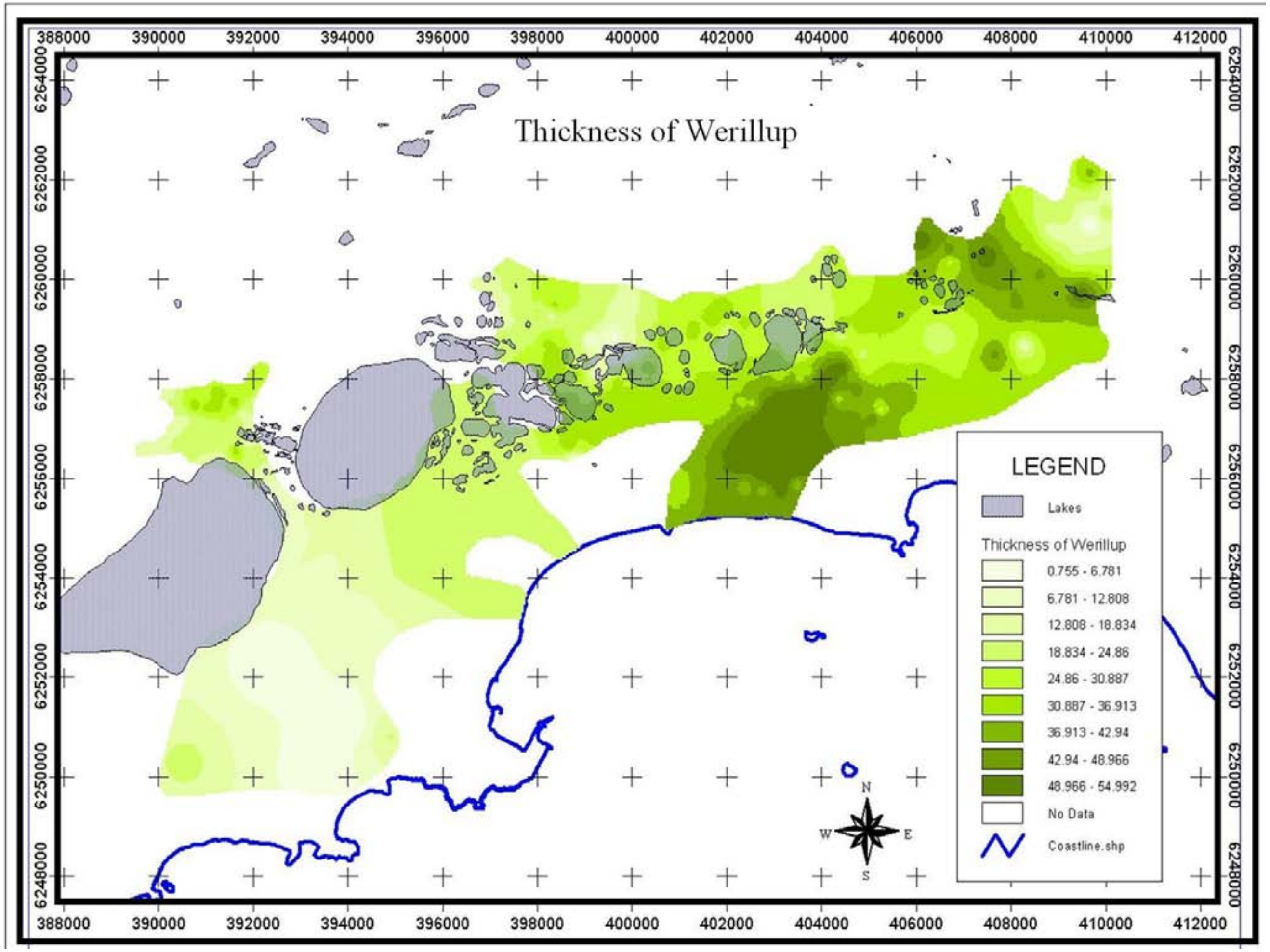

Figure 64. Werillup thickness map generated by subtracting the elevation of the bottom from the elevation of the top based on drillers notes and layered earth inversions.

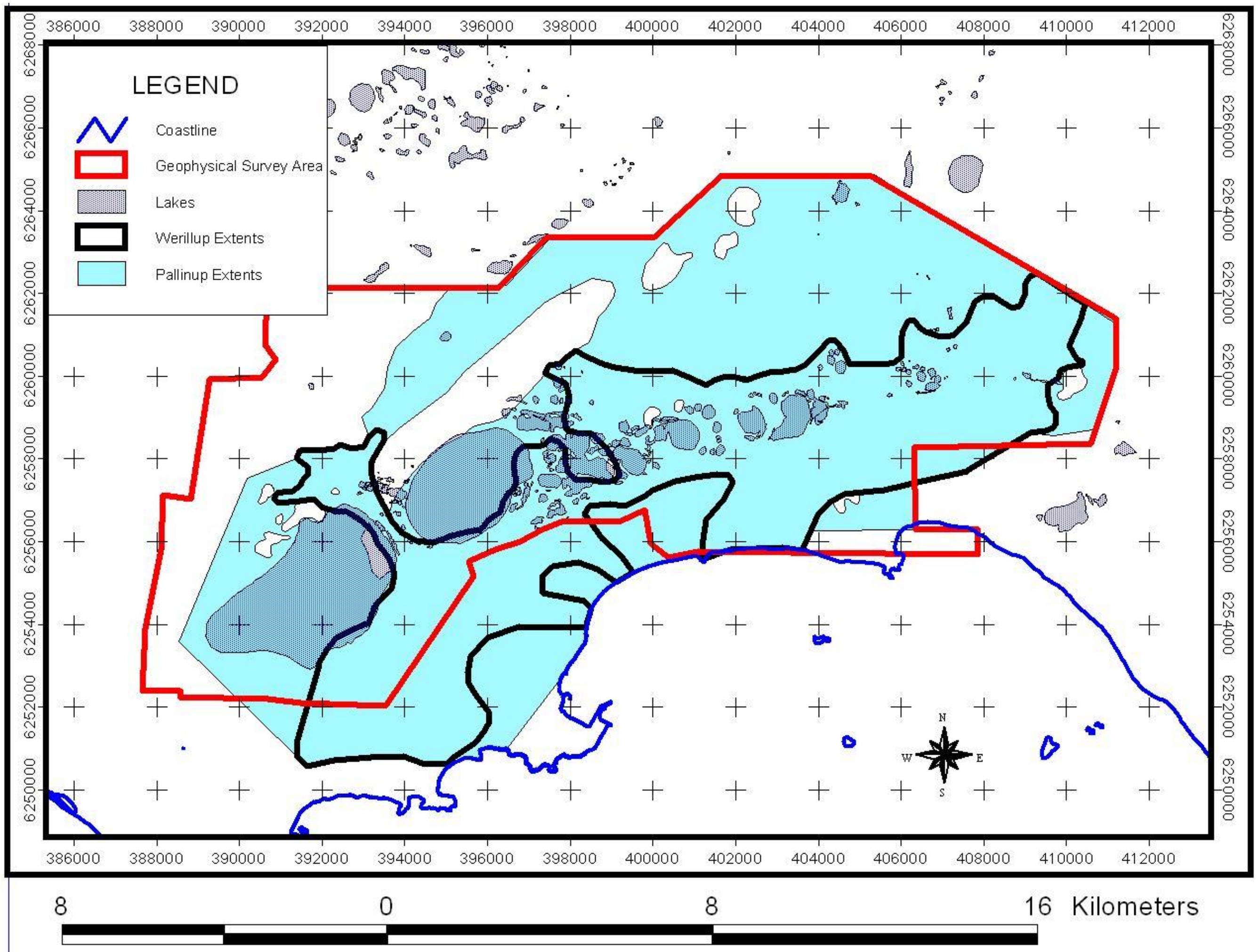

Figure 65. Light blue area represents verified extent of Pallinup Formation with the Werillup extent shown in black for comparison.

The bottom of the Pallinup ranged in depth from 17 m to 45 m with the majority of points in the mid to high 20s. Where the Pallinup overlies Werillup, there is a clay aquitard forming the top of the Werillup. Where the Pallinup does not overlie Werillup, in-situ weathered saprolite or the basement surface also behave as an aquitard. Flow accumulation modelling of the base of the Pallinup thus provides some insight into possible gravitational flow paths over these aquitards and within the Pallinup formation (see Figure 66). The top of the Pallinup ranged from being exposed at ground surface to as deep as 17 m with most depths between 5 m and 10 m.

The groundwater flow patterns on the base of the Pallinup also reflect a ridge along the axis of the wetland lakes. As with the Werillup, the thickness of the Pallinup was calculated by subtracting the bottom relative levels (RLs) from the top RLs to produce a grid of aquifer thickness (Figure 67). The greater thicknesses in the north and east reflect the limits of marine erosion that occurred after the deposition of the Pallinup Formation (Morgan and Peers, 1973)

4.5.5 Defining the Base and Top of the Quaternary

The top of the Quaternary is the natural land surface. Everything from natural land surface to the top of the Pallinup was defined as the Quaternary except where Pallinup is exposed at the surface. The Quaternary and the top of the Pallinup have similar conductivity in the study area so there is no conductivity contrast in the EM data to define their interface. High resolution surface mapping of Pallinup and Quaternary was not available. The most reliable and authoritative source of this information was from drilling logs which are quite spatially isolated within the study area. The Pallinup is exposed at the surface in many places and thus where this occurs we would expect the Quaternary to have a zero thickness. This is evident in the 3D rendering of the surfaces (Figure 68) but some of this may be due to the interpolation between isolated data points across steeply changing surface topography. This product requires revision using high resolution surface geological information to differentiate real exposure of Pallinup at the surface from artefacts of the interpolation. The thickness of the Quaternary was calculated by subtracting the bottom relative levels (RLs) from the top RLs to produce a grid of Quaternary thickness (Figure 69).

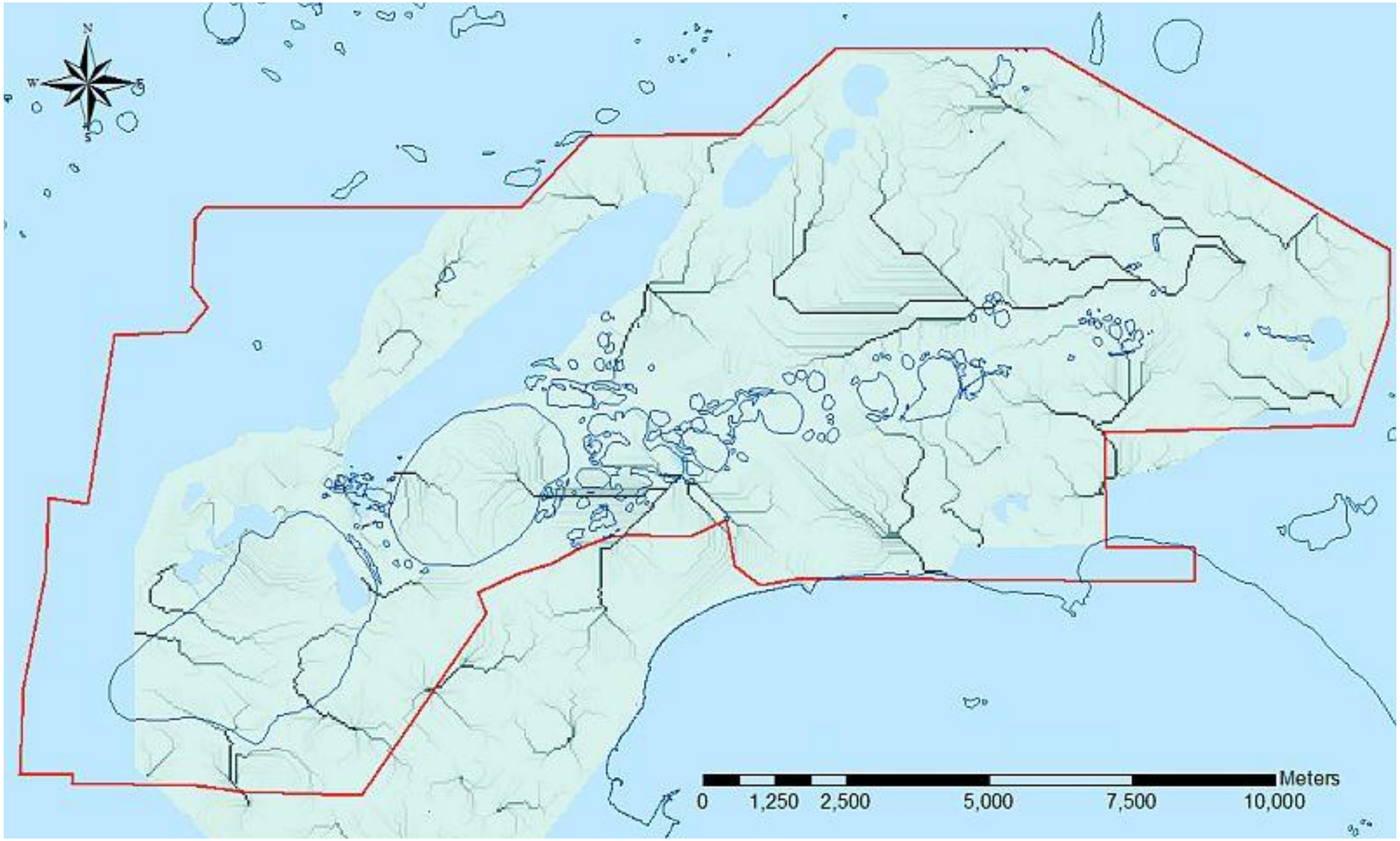

Figure 66. Flow path potentials at the base of the Pallinup Formation.

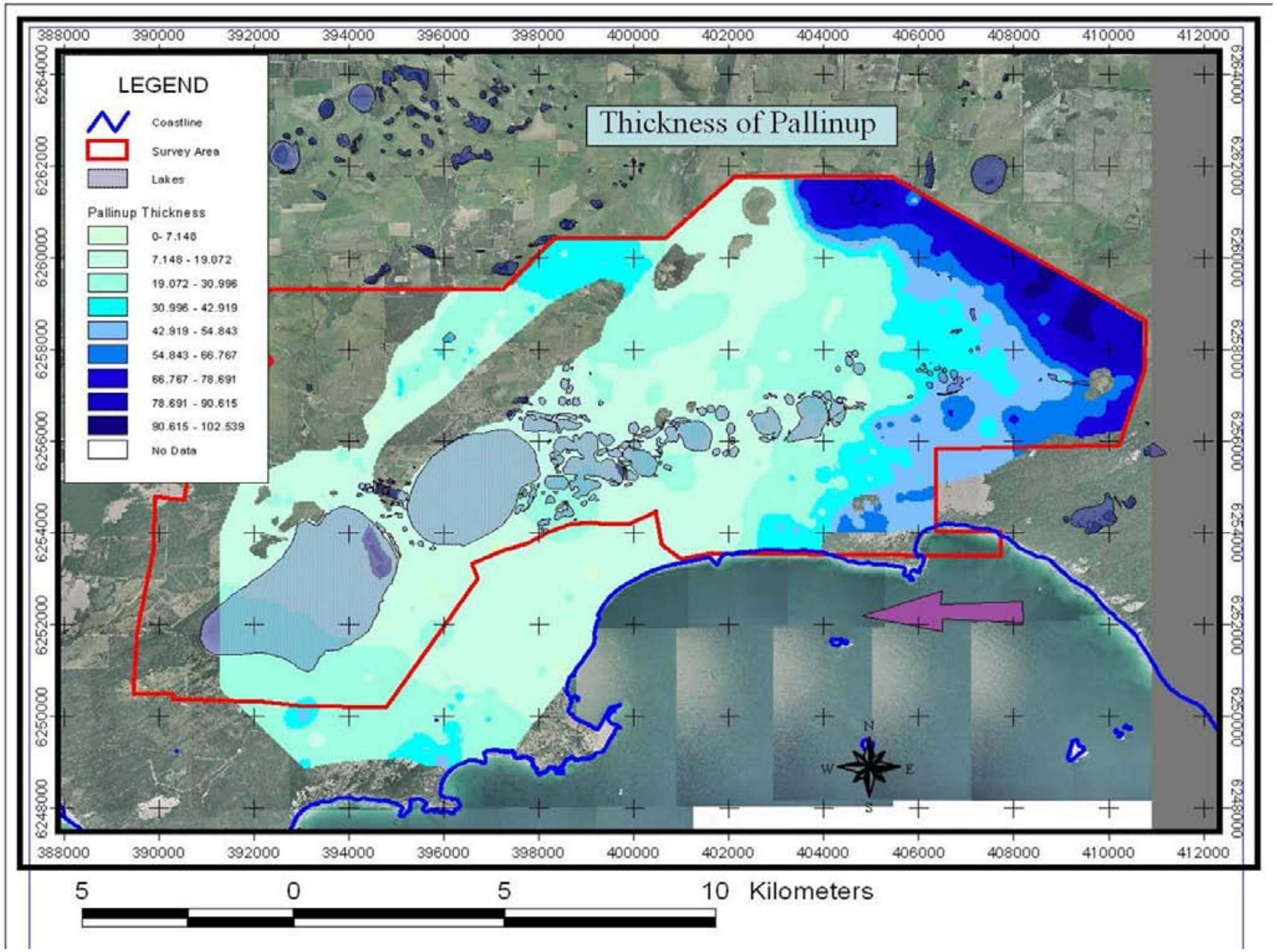

Figure 67. Map of Pallinup thickness generated by subtracting the elevation of the bottom from the elevation of the top based on drillers notes and layered earth inversions.

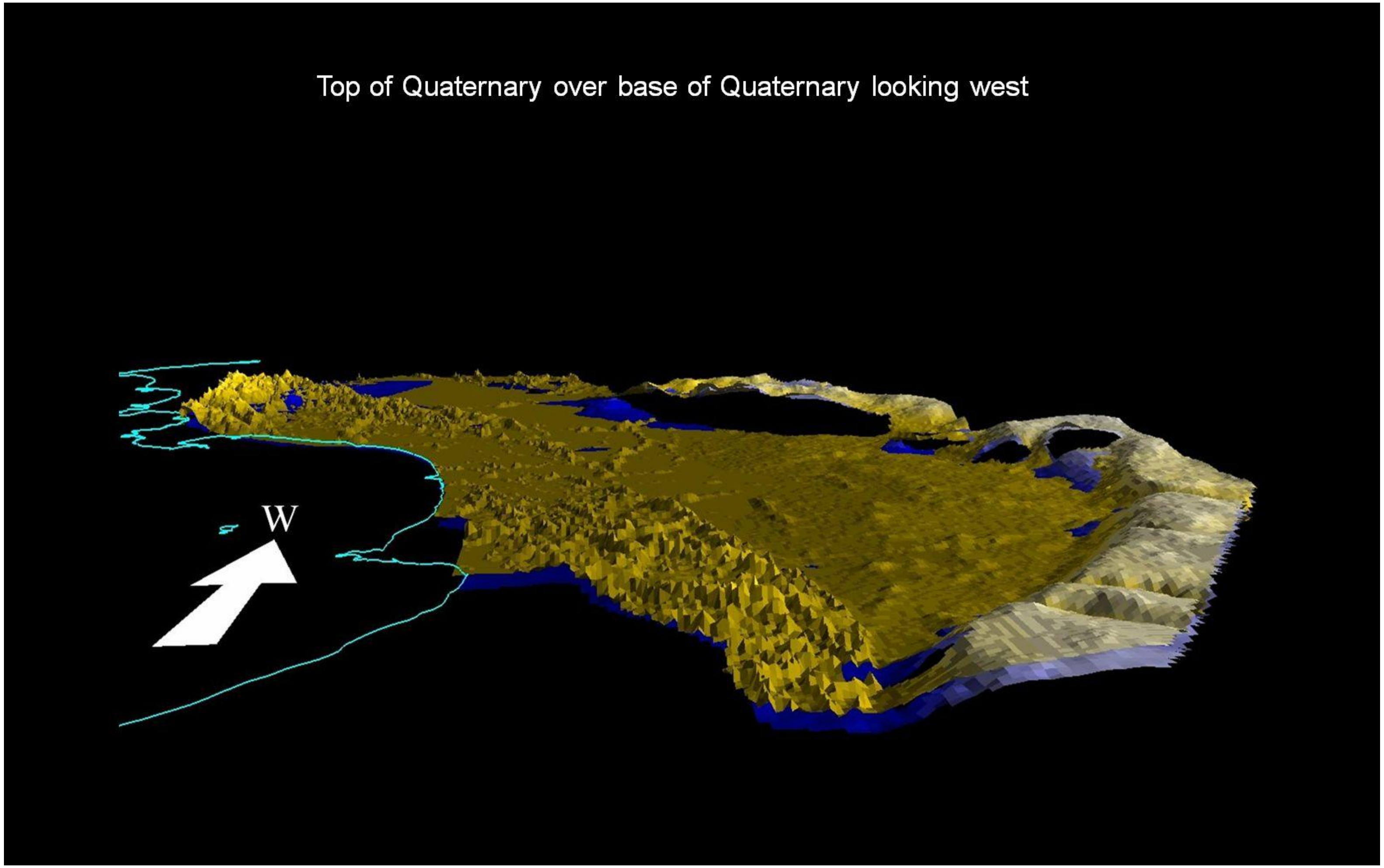

Figure 68. Top of Quaternary (brown) and base of Quaternary/top of Pallinup (blue)

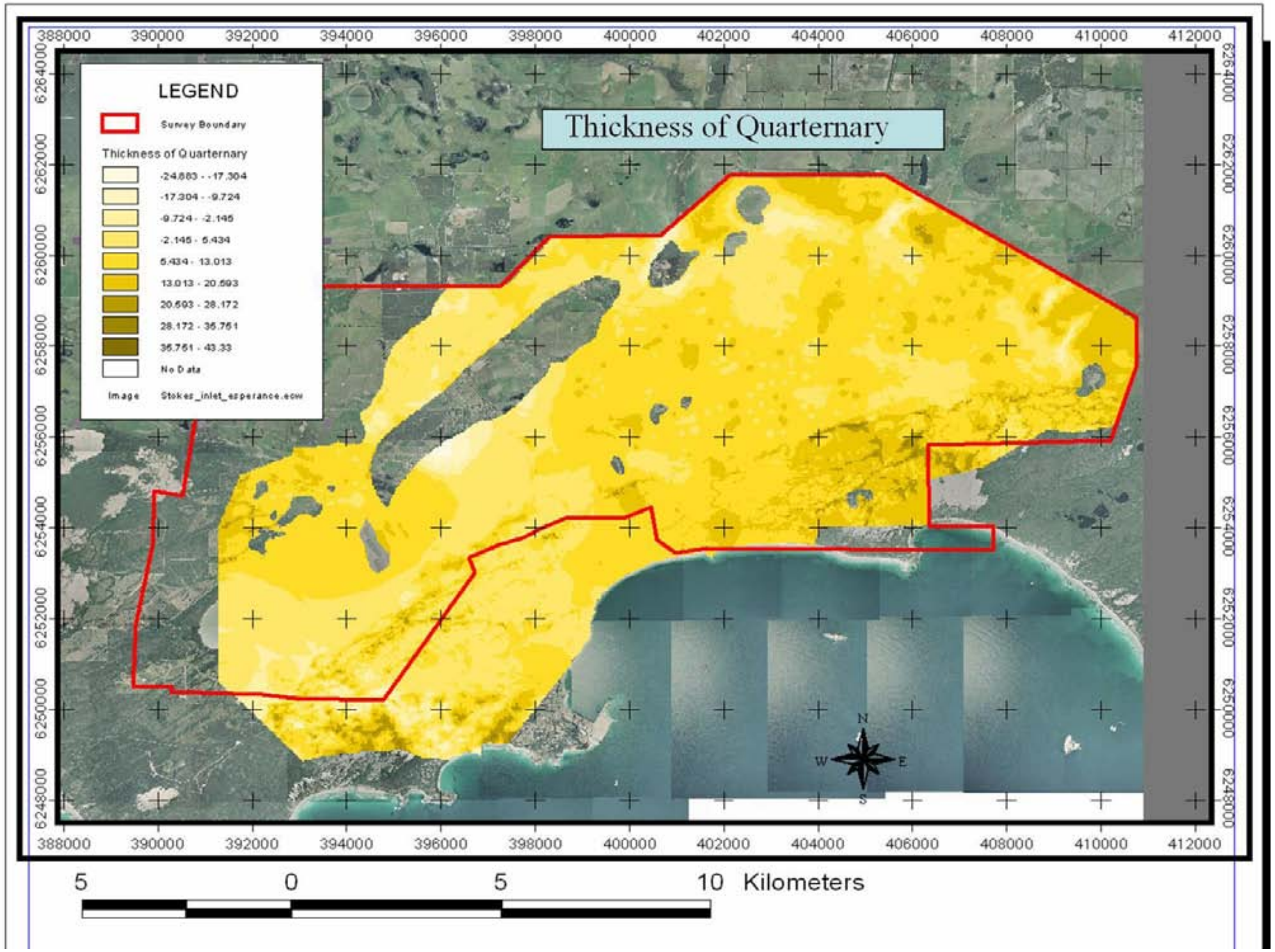

Figure 69. Map of Quaternary thickness generated by subtracting the elevation of the bottom from the elevation of the top based on drillers notes and layered earth inversions.

Areas in Figure 69 with negative values are where the Pallinup surface is exposed or where the interpolation of elevation is erroneous as described above.

4.5.6 Fugro 'TEMPEST' Fixed Wing Airborne EM Survey

After the HoistEM processing and analysis was completed, the opportunity arose to fly some lines of TEMPEST (Lane et al., 2000) fixed wing airborne EM survey. This would be useful for comparison and as a check on the results from the reprocessed HoistEM data. All lines were chosen to traverse known conductive or resistive features in the landscape. A single east-west line was selected as a repeat survey of a HoistEM line. A total of seven lines were proposed for the TEMPEST survey (Figure 70).

The actual lines flown deviated slightly from those proposed (see Figure 71) and due to flight height restrictions over built-up areas, the aircraft was unable to cover the southern half of line 70 low enough to record meaningful data, however, the rest of the lines were flown to survey specifications, although not necessarily exactly on the prescribed course. Line 20 was flown on two different alignments so the additional line was called Line 21. Line 20 directly overflew the deep bore LW18 from which were collected conductivity and gamma logs to 47 m (Figure 61).

The TEMPEST flight line data were processed by Fugro Airborne Surveys into Conductivity Depth Images (CDIs) for each flight line. To help understand what these images were showing, they were placed in their correct locations as a fence diagram on the map of the study area (Figures 72 and 73). The TEMPEST fixed wing AEM system did not appear to be affected by electromagnetic interference unlike the HoistEM system.

Line 60, the East-West survey line (Figure 73) accurately mapped high conductivity in the regolith on the northern shore of Pink Lake. It detected the shallow basement known to outcrop between Pink Lake and Lake Warden. It accurately mapped the saline water bodies of Lake Warden and Lake Windabout as well as the exposed basement between Lake Windabout and Woody Lake. Eastward, away from the lakes, TEMPEST clearly maps the deep conductive regolith interpreted to be part of a palaeodrainage system. This deep conductive regolith is seen in lines 10, 20, 21, 30 and 40 as a south west to north east trending feature (Figure 72).

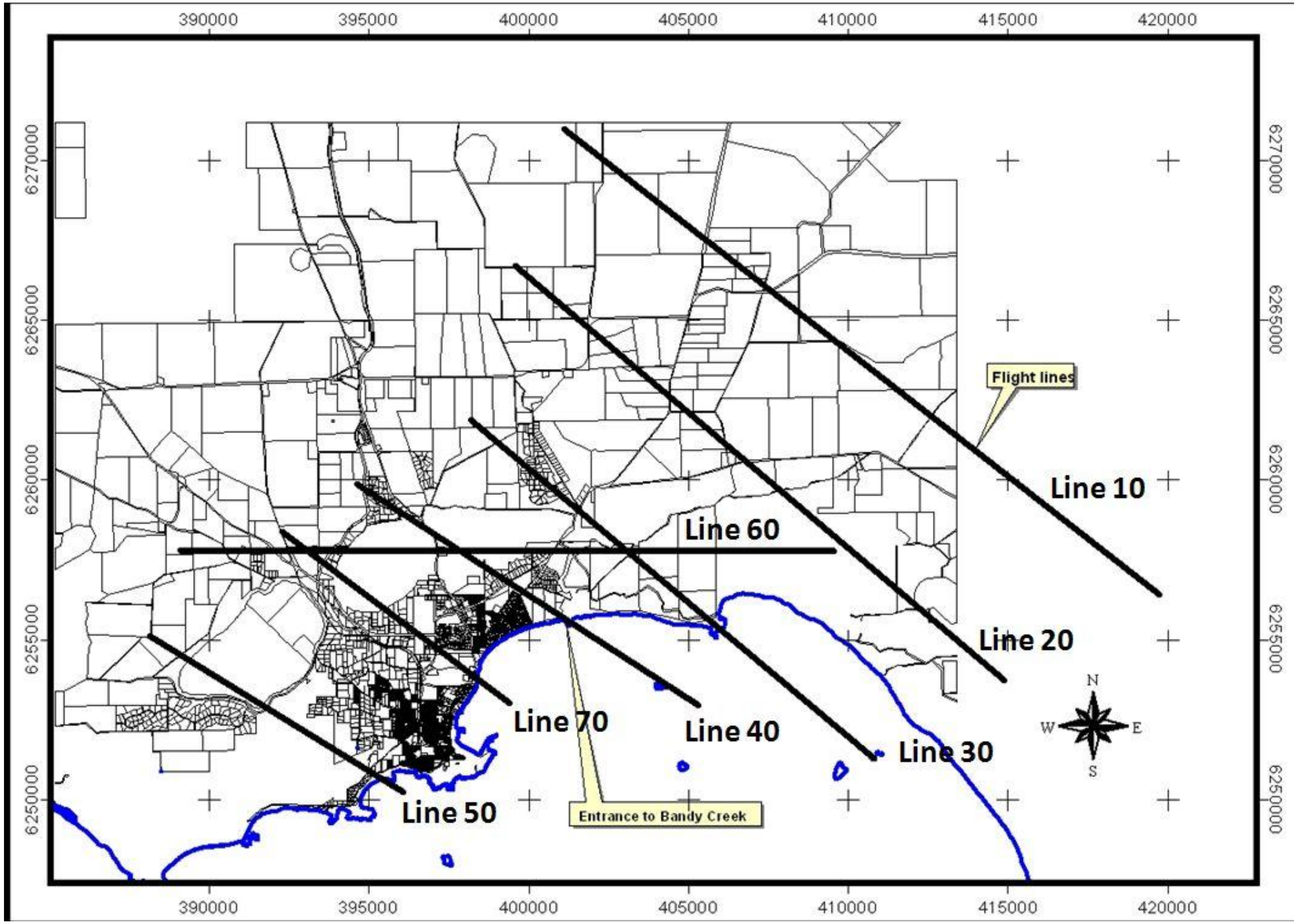

Figure 70. Proposed TEMPEST survey lines.

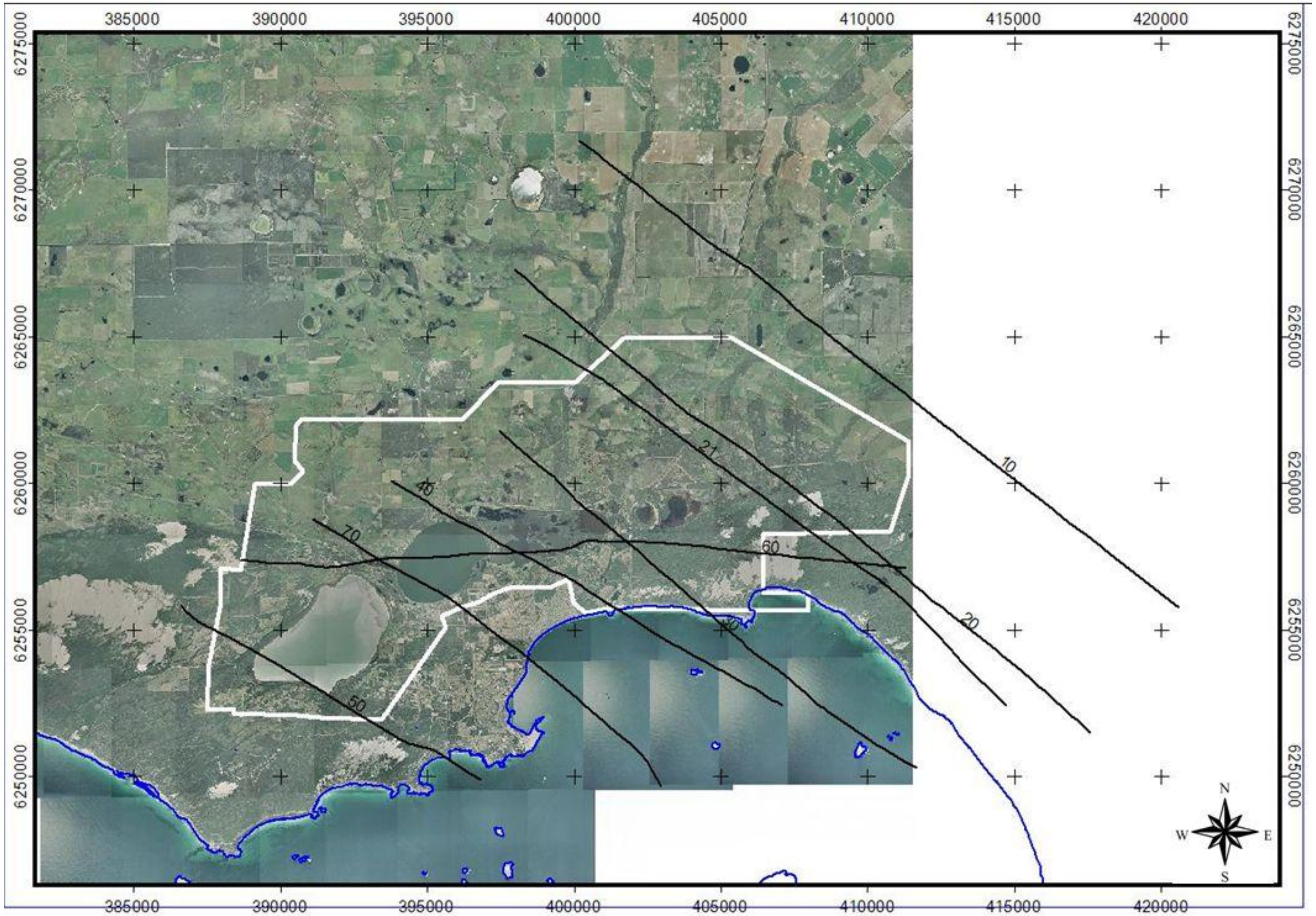

Figure 71. Actual lines flown by TEMPEST survey aircraft.

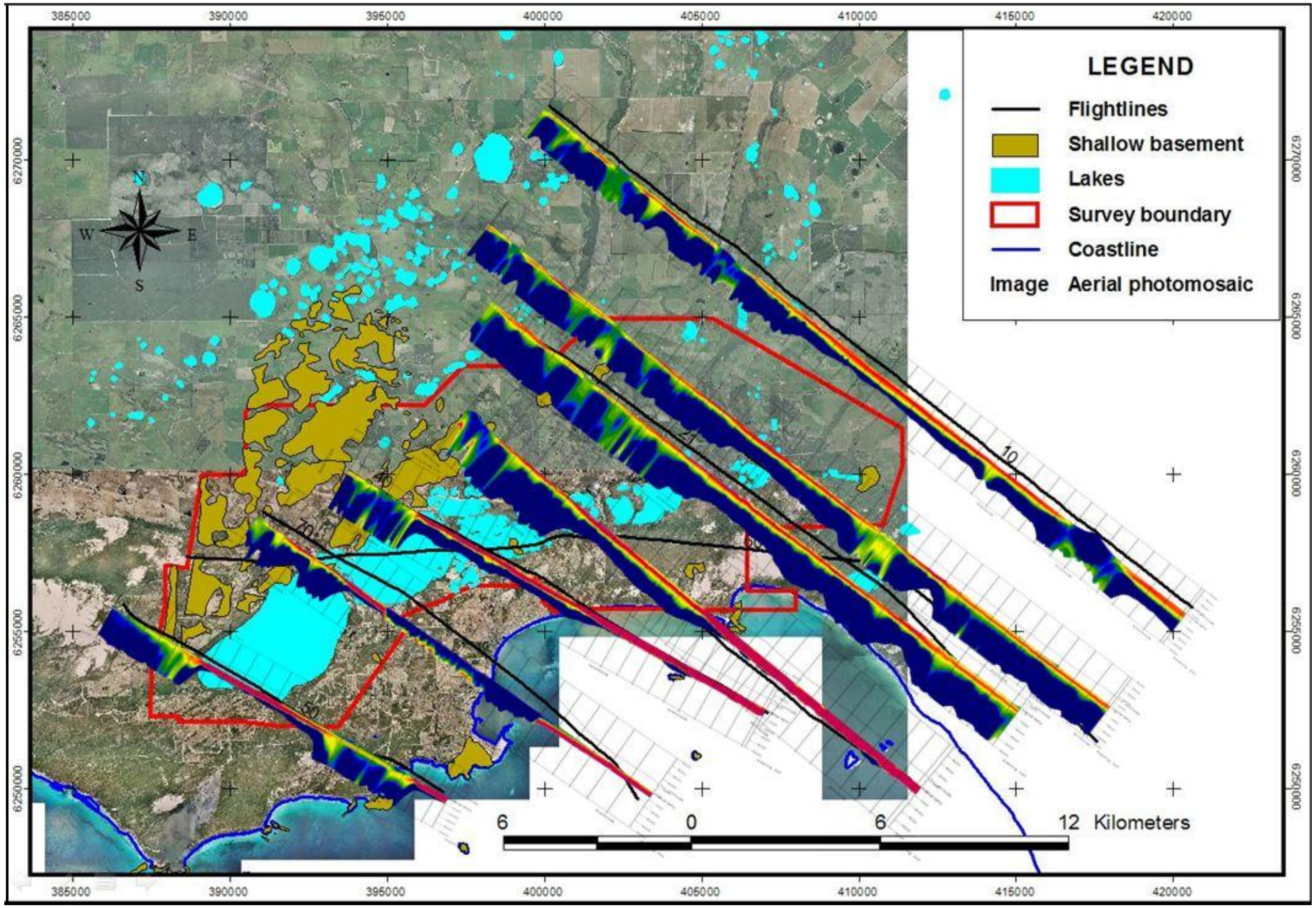

Figure 72. TEMPEST CDI profiles located on their respective flight lines as a fence diagram.

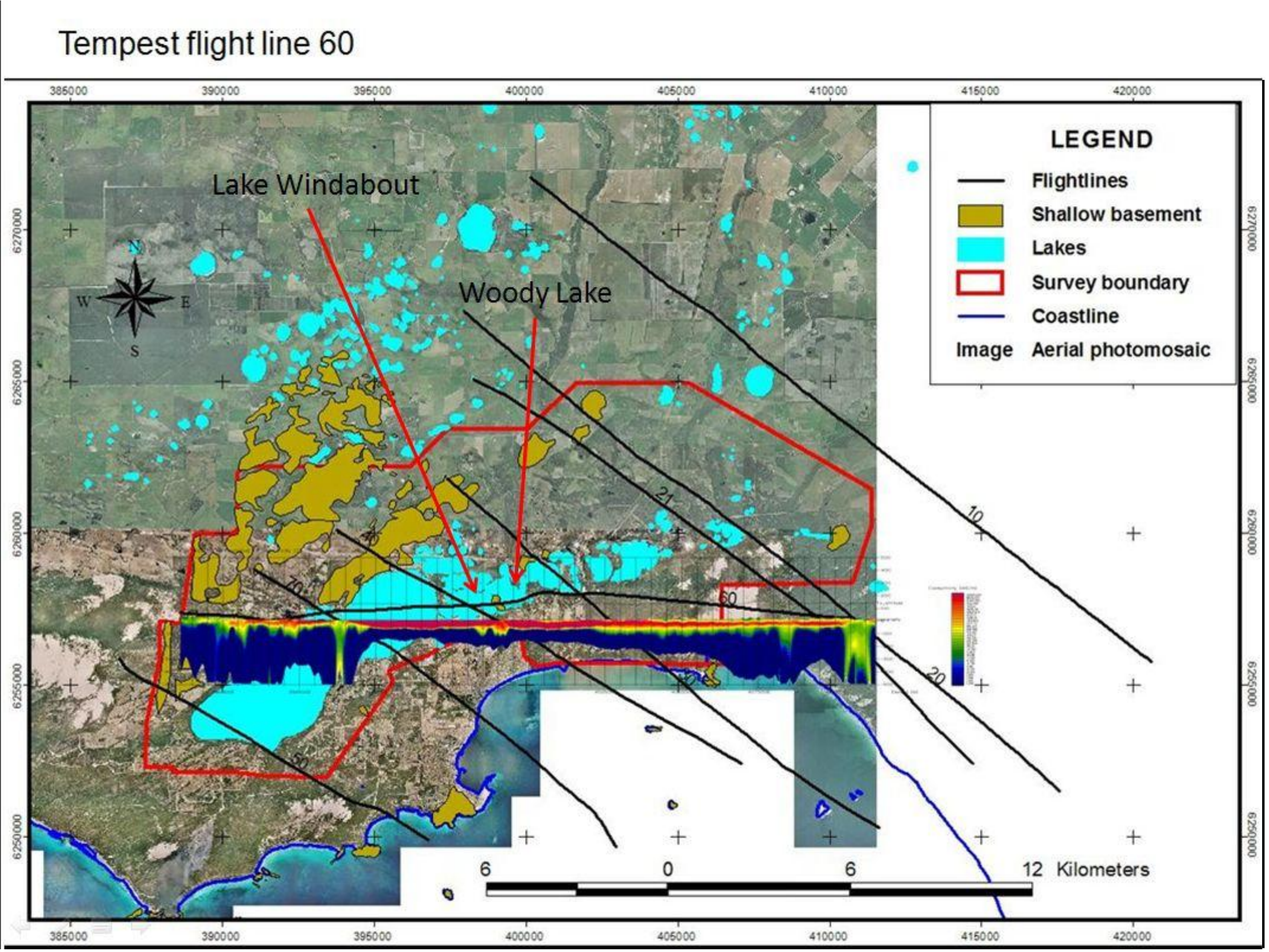

Figure 73. TEMPEST CDI for Line 60

4.5.7 Results Summary

At the commencement of this project, six questions were required to be answered. They are repeated below with their answers which were obtained from analysis of the geophysical data.

A. Does groundwater move between Lake Warden and Pink Lake?

Yes, however, groundwater movement is restricted by shallow bedrock between these lakes. There is some potential for groundwater movement from Lake Warden towards Pink Lake in the shallow Quaternary and Pallinup aquifers.

B. In what direction does it flow?

From east to west. This is supported by visible surface discharge into the eastern end of Lake Warden and no contradictory evidence in the data examined.

C. What factors influence this movement?

High water levels in Lake Warden providing hydraulic head westwards in the Pallinup and Quaternary aquifers.

D. What is the architecture of the groundwater aquifers and what are the significant groundwater flow paths?

Groundwater flow potential vectors were generated for the three main hydrogeological surfaces (aquitards):

- Basement surface (Figures 57 and 58)
- Base of Werillup (Figure 63)
- Top of Werillup/Base of Pallinup (Figure 66)

All of these aquifers showed a general north to south south east groundwater flow trend. Because the lakes are aligned above and along a basement ridge, hydrostatic pressure of groundwater overtopping this ridge as it moves south south east is likely to be supporting high water levels in these lakes.

E. What is the horizontal and vertical distribution of salt storage in the wetlands and surrounds?

This was mapped horizontally and vertically by the layered earth inversion product from HoisTEM. The groundwater flow potential pathways identified in the aquitard slope analyses may help to explain differences between individual lakes in water chemistry which was identified by (Marimuthu et al., 2005)

F. Is there a significant hydrological connection between the wetlands groundwater system and the Southern Ocean?

Yes, the survey area has a north to south south east groundwater gradient on most of the aquitard surfaces revealed in the data. However, the northern half of the wetlands area appears to be separated from the southern half by a bedrock ridge. This ridge is an impediment to groundwater flow towards the southern ocean from the northern half of the Lake Warden Wetlands. This ridge may be supporting discharge of relatively fresh groundwater into the wetlands as they overtop the bedrock ridge under pressure of the southward hydraulic gradient.

4.6 Discussion

Prior to these geophysical surveys, Department of Environment and Conservation (DEC) and the community Natural Resource Management group, South Coast NRM, were promoting generic management strategies with no particular location priority, over the whole catchment area (Short et al., 2000). They were promoting strategies such as revegetation to reduce groundwater recharge on landscape ridges. This was based on a conceptual hydrological model (Salama et al., 2000) using general assumptions about basement topography, aquitard topography and salt storage distribution. This study, using the AEM data produced spatial information based on high resolution measurement of these key hydrogeological features. It answered all the questions that the project was designed to answer.

These data were processed and interpreted to reveal potential groundwater flow paths in the main aquifers underlying the wetlands. This information along with salt storage distribution maps derived from the conductivity product (Figure 62) was provided to DEC in the form of the maps shown in this thesis. The modelling work by Short et al. (2000) provided an indication of what was happening hydrologically. This study, using AEM data, showed what was happening and where it was happening. This information enabled DEC to formulate a catchment management strategy that focussed on the eastern sub-catchments of Bandy Creek and Neridup

Creek (Figure 39), as they were identified from the geophysical data, as the main sources of saline groundwater.

4.7 Lake Warden Conclusion and Recommendations

Airborne electromagnetic data filled in the information gaps left by previous studies in the Lake Warden wetlands. The data provided information on the spatial extent and depths of the three main groundwater aquifers. The depth dimension provided by the data enabled modelling of groundwater flow potentials at the base of the Werillup Formation aquifer and the Pallinup Formation aquifer. The data clearly displayed the variation in salt storage across the wetlands study area. Together with the groundwater flow potential information product, this enabled DEC and the community to devise management strategies that target actual geological features and hydrological processes. This information enabled them to reduce the area of management focus by 30% and thus be significantly more effective in their investment of limited land conservation funding.

These outcomes would not have been possible without this interpretation and analysis. The standard geophysical survey data and report delivered by the contractors (irrespective of the elevation errors) could not have been directly used by the community or the government agencies managing these wetlands. The involvement of interpreters with understanding of geophysics and land management is essential to ensure production of appropriate information products.

The HoistEM helicopter borne AEM system was susceptible to electromagnetic interference (“noise”) at Lake Warden. The TEMPEST fixed wing AEM system did not appear to be affected by electromagnetic interference at this site.

I recommend that the information provided by this study be used to design on-going monitoring of groundwater piezometric levels and surface water management activities. This information allows for more targeted drilling and hydrological investigation to test the interpretation presented here. Such monitoring will be necessary to learn the impacts of implementation of the targeted remediation works and enable adjustments to the remediation strategy in response to new information.

5. Chapter 5: Conclusions and Recommendations

When I started this doctoral research project, the science of dryland salinity in Western Australia had reached a critical point where popular theoretical frameworks and management actions had lost credibility. This loss of credibility resulted from the observed failure of certain management strategies, given they had been implemented and in place for up to 30 years. At about the same time, hydrological modelling studies were published that recommended recharge reduction as the new theoretical framework for salinity management.

This recharge reduction would have to be achieved by converting 80% of the agricultural areas to a perennial agronomy based agricultural system. The authors promoting this concept also pointed out that such an agricultural system does not yet exist. This left stakeholders in dryland salinity management with few choices of management actions that could be implemented with a high degree of confidence.

Through my previous professional experience of attempting to devise salinity management strategies on the basis of either limited information or theoretical frameworks, I recognised a significant deficiency in the information base that I was using to guide my decisions. When I was given the opportunity to use information from geophysics to design farm plans to manage dryland salinity, the characteristics of this information gap became clear. The missing information was that information pertaining to the hydrogeological architecture of the earth beneath the farm.

As an analogy of the information problem, we had previously lacked information on the "plumbing system" for groundwater in the landscape. It is very difficult to fix a leak in the plumbing if you can't shut off the water, you don't know where the pipes are and you can't see how the water is getting out of the pipe.

I have set out in this thesis to show that to design effective management actions, it is essential to have information products that reveal the hydrogeological structure of the regolith. I set out to show that this information can be cost effectively sourced from geophysical data. I wanted to demonstrate that it is critical that the information products produced are relevant and appropriate for the suite of actions that could be implemented.

I have used three case studies to illustrate my thesis. Two of these case studies used information products that supported effective management and one did not. In each case study I have demonstrated the critical importance of the design of the information products and the qualities of these information products that led to success or failure.

I demonstrated the key quality of the information products is that they must be formulated in representations of the elements and mechanisms that must be managed. For management of dryland salinity, I demonstrated that they must represent:

- The source of salt and location of its storage in the landscape
- The source of water and the mechanism by which it enters the regolith
- The mechanisms that bring salt and water together in the regolith
- The structures that control groundwater storage and movement in the regolith
- The structures and mechanisms that bring saline groundwater to the surface

In the Broomehill case study I demonstrated this process taken a step further to production of map information products that are representations of planned management actions designed to impact upon those elements and mechanisms that cause dryland salinity in such a way that those mechanisms are opposed and reduced. This was supported by independent cost benefit analysis that showed the cost benefit of implementing the proposed management actions guided by geophysical information was positive. However, implementing the same management actions without the guidance of the geophysical information produced a negative cost benefit in the two other properties that were examined.

O'Brien (1998) expressed the view that:
"A major strategic and technical challenge which appears largely in default is filtering of land elements through layers of different methodology to yield reliable and cost effective land management outcomes."

Now, the analysis of the use of SALTMAP at Broomehill has revealed that the methodology devised and used at Broomehill **has** yielded reliable and cost effective land management outcomes.

In the Lake Warden Wetlands study I showed that the combination of information products depicting salt distribution in 3 dimensions and groundwater flow patterns in the key aquifers underlying the study area facilitated strategic decision-making about the management priorities for the area. This information enabled limited management resources to be directed to the locations where the most impact could be obtained.

In the Tammin groundwater pumping study I showed how the limited spatial extent of the geophysical data restricted the type and quality of information products that could be produced. The geophysical data were limited to 4 transects up to more than 2 km apart. To engineer an efficient production bore that taps into a transmissive aquifer with sufficient depth and spatial extent requires information products that represent the whole of the study area. Four geophysical transects, although they were more cost effective than borehole transects, provided little additional information. The project team did not have information products covering the whole study area and pertaining to the structures that control groundwater storage and movement in the landscape. Consequently they were not able to locate a sufficient depth and spatial extent of aquifer into which to install an efficient production bore. Conversely, due to lack of spatial geophysical information, it cannot be stated with any confidence that such an aquifer does not exist in this study area.

The key point I proved here, is that it is not the use or non-use of geophysics that is the issue around geophysical technologies for dryland salinity management. It is the design of the information products needed to decide on cost effective management actions and the design of the geophysical investigation to meet those requirements that is the critical issue that determines the effectiveness of the use of geophysics for management of dryland salinity.

I have demonstrated that the key elements and mechanisms of dryland salinity can be identified using geophysical surveys and that this information is essential to enable the designing of effective management strategies. I have further demonstrated that for this information to result in management actions on the ground, the information products must be framed in terms of the current management tools available to the land manager clients.

Does the use of geophysics in farm and catchment planning produce cost effective environmental and economic benefits? This thesis demonstrates that it does, provided it is undertaken with a view to the information products needed to inform land management actions.

5.1 Recommendations

In the Lake Warden study area, follow-up research is needed to monitor and evaluate the results of focussed management activities in the sub-catchments.

In general, geophysical data of an appropriate spatial scale and coverage and in conjunction with other hydrogeological information, should be used as a basis for salinity management plans in Western Australia. The survey results should only be used if the geophysical surveys are designed such that they can provide the data necessary to answer the key management questions for the site. Standard mineral search geophysical surveys and interpretation reports alone are not suitable for formulating management of dryland salinity.

Geophysical surveys for dryland salinity management should:

- Be considered fundamental land information, as is aerial photography, elevation data, soil mapping and vegetation mapping, to facilitate environmental management and sustainable development
- Be of an appropriate spatial extent to cover the area in which the hydrological issues occur and the area in which the hydrogeological processes that impact those issues occur
- Be of an appropriate resolution (survey line spacing) and appropriate survey line orientation to identify regolith features of interest
- Be suitable for the formulation of information products that can display the processes that must be managed
- Be interpreted by individuals, or teams, with appropriate skills in geophysics AND land management
- Facilitate the creation of information products (such as farm plans or aquifer maps) that display proposed management strategies in terms of the management tools available to the land managers
- Delivery of these products should be part of geophysical survey contracts and a key guide to the design and specifications of the surveys.

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7. Appendix

Letters of request and consent to use material from my published papers.

17-June-2011

The Editor, Australian Journal of Water Resources

Dear Sir/Madame,

It is my understanding that you hold copyrights in the following material:

Wilkes, P., Abbott, S., Harris, B. and Dogramaci, S., 2004, Ground geophysics for rapid location of buried valleys below high value salt-affected land at Tammin, Western Australia. Australian Journal of Water Resources, Volume 9, pp 149-154

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Application of geophysical techniques for 3D visualization of regolith hydrogeological architecture and use of this information for management of dryland salinity in Western Australia.
I am carrying out this research in my own right and have no association with any commercial organisation or sponsor.

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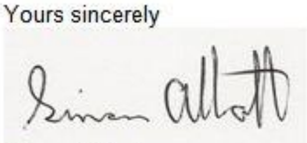

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Signed: L Hardwicke

Name: Leanne Hardwicke

Position: Director, WA Division
Engineers Australia

Date: 23/6/2011

Please return signed form to:

Simon Abbott
gracew@iinet.net.au
32 Hawkesbury Retreat
Atwell WA 6164
Phone 0429 498 537

17-June-2011

Mr. Mark Lackie, Editor, Exploration Geophysics
Dear Mark,

It is my understanding that you hold copyrights in the following
material:

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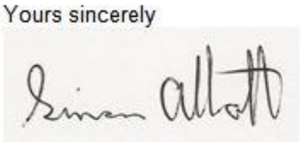

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Position: Publisher, CSIRO Publishing 150 Oxford St Collingwood Vic 3066

Date: 23 June 2011

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32 Hawkesbury Retreat
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17-June-2011

Mr Paul Wilkes

Dear Paul,

It is my understanding that you hold copyrights in the following
material:

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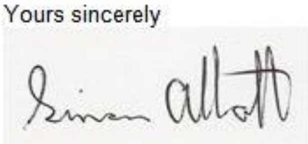

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Signed: P. Wilkes

Name: PAUL. G. WILKES.

Position: Research Geophysicist, Perth. (CSIRO)

Date: 19/6/2011

Please return signed form to:

Simon Abbott
gracew@iinet.net.au
32 Hawkesbury Retreat
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17-June-2011

Mr Brett Harris

Dear Brett,

It is my understanding that you hold copyrights in the following material:

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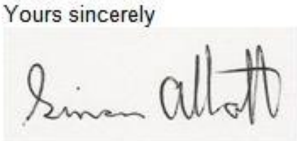
I look forward to hearing from you and thank you in advance for your consideration of my request.

Yours sincerely



Simon Abbott

Simon Abbott

From: Brett Harris [B.Harris@curtin.edu.au]
Sent: Tuesday, 21 June 2011 12:38 PM
To: Simon Abbott
Subject: RE: Permission to use Tammin paper in my PhD thesis

Absolutely from my point view there is no problem with you using the paper in your thesis
regards
Brett D Harris

-----Original Message-----
From: Simon Abbott [mailto:gracew@iinet.net.au]
Sent: Sun 6/19/2011 5:32 PM
To: Brett Harris
Subject: RE: Permission to use Tammin paper in my PhD thesis

Thanks for that, Brett,

However, I'm not doing my thesis by publication, just referring to the work. Accordingly, I need permission from my co-authors to use it. I have also sent the same request to the editor of the Australian Journal of Water Resources in which our paper was published.

Cheers,

Simon

Simon and Ruth Abbott

From: Brett Harris [mailto:B.Harris@curtin.edu.au]
Sent: Sunday, 19 June 2011 3:37 PM
To: Simon Abbott
Subject: RE: Permission to use Tammin paper in my PhD thesis

Hi Simon,

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I strongly suggest you look at the below, which shows what Florian did, as his thesis was dominantly reproduced papers.

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Cheers

Brett

From: Simon Abbott [mailto:gracew@iinet.net.au]
Sent: Sat 6/18/2011 9:24 PM
To: Brett Harris
Subject: Permission to use Tammin paper in my PhD thesis

Hello Brett,

I hope this finds you well.

I am in the final stages of my PhD and am seeking permission from you, as one of my co-authors to use material from our work at Tammin.

Please find attached permission request pro-forma letter.

Please return as soon as possible, as I have to submit this with my thesis before June 30.

Thanks, I really appreciate your help with this.

Cheers,

Simon

17-June-2011

Mr Shawan Dogramaci

Dear Shawan,

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material:

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I look forward to hearing from you and thank you in advance for your consideration of my request.

Yours sincerely

Simon Abbott

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Signed:

Name:
Shawan Dogramaci

Position:
principal Hydrogeologist

Date:
22.6/12

Please return signed form to:

Simon Abbott
gracew@iinet.net.au
32 Hawkesbury Retreat
Atwell WA 6164
Phone 0429 498 537

17-June-2011

Mr Greg Street

Dear Greg,

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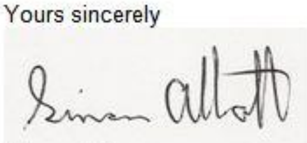

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Signed:

Name: Gregory James Street

Position: Director International Geoscience

Date: 19 June 2011

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17-June-2011

Mr David Chadwick

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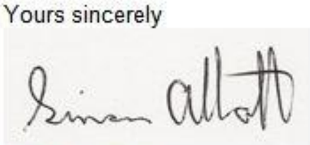

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Permission to use this material is subject to the following conditions: [Delete if not applicable]

Signed: D Chadwick

Name: DAVID CHADWICK

Position:

Date: 5th July 2011

Please return signed form to:

Simon Abbott
HYPERLINK "mailto:gracew@iinet.net.au" gracew@iinet.net.au
32 Hawkesbury Retreat
Atwell WA 6164
Phone 0429 498 537