Application of Airborne Geophysical Techniques to Groundwater Resource Issues in the Angas-Bremer Plains, South Australia

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

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EXECUTIVE SUMMARY

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

In the Angas Bremer region of the Murray Basin, the principal goal of the geophysical survey was to map groundwater systems *rather than* salinity. A combination of airborne geophysical techniques and rigorous field and chemical analyses has shed light on the recharge mechanisms and groundwater movement across the Plains and helped define the extents of the groundwater systems and the origins of salt in the region.

The prime objective of the project in the Angas Bremer Plains was to provide information that allowed prevention of, or better management of shallow, saline groundwaters and soil salinity, and protection of sensitive aquatic habitats.

For sustainable management into the future, local irrigators need to know:

- At what rate can they support future expansion of irrigation?
- How robust is the system?
- How do they control the water balance and the salt balance?
- Where are the best sites to re-vegetate for recharge control and for other environmental benefits?

With the amount of information now available for the Angas-Bremer Plains region, we now have the potential to develop truly sustainable conjunctive water management decisions from the paddock through to catchment scale. That is, we can use all water resources, whether surface or groundwater, naturally or artificially recharged, in a sound, responsible, sustainable manner. This could be driven, not by hypothetical ideals and models, but through pro-active response to real data: using data as a sound basis for policy.

This project has specifically helped by defining a number of attributes of the groundwater system.

- Combining the images created from the airborne technologies with drill-hole data, a precise boundary to the deep, confined aquifer can be drawn. In addition, structural features in the sub-surface that control groundwater movement can be delineated. A good distinction can be made between the upper, unconfined aquifer and the lower, confined aquifer, with well- defined leakage zones along the river-beds.

- Major structural constraints can be imaged. Thus, the prominent faults in the east of the area are seen to extend to considerable depth, and the north-west boundary of the alluvial plains is seen to be a lithological facies change, rather than a faulted boundary. Also to the north-west, a fault has given rise to a low scarp near the plains margin. These faults influence groundwater movement in the region.

- Conductivities measured by airborne electromagnetics are similar to the measured salinities of groundwater in the deep aquifer. There is poorer correspondence for the shallow aquifer, as the measured AEM is strongly dependent on the near-surface water content and refined modelling is required to extract the near-surface detail.

- Recharge zones are clearly defined by the AEM. Lower conductivity regions along the courses of the rivers indicate where recent, fresher, flood waters have entered the system.
- Recharge is seen to be dominantly vertical across the plains, though there is some lateral input from the northern hills. The dominant recharge mechanism is direct recharge concentrated along the courses of the major rivers, particularly during high flow or flooding events. This was evidenced by almost complete recovery of depressed water levels following the large flood of 1992 (Cresswell and Herczeg, 2004).
- While there is a strong chemical similarlty between the upper and lower aquifers, indicating similarity in recharge processes, much older ^{14}C groundwater ages in the deeper aquifer suggest that inter-aquifer mixing takes place over thousands of years, except in localised areas close to the rivers (Cresswell and Herczeg, 2004). There is rapid (seasonal) recharge to the upper, unconfined aquifer. Away from the rivers, recharge to the lower aquifer appears to integrate over much longer time periods (thousands of years), but shows a rapid pressure response to major flood events.
- Salt in the region is predominantly derived from rainfall (*i.e.* it is cyclic). Some water-rock interaction takes place in the deep carbonate-rich aquifer, but most salt in the groundwaters is derived from evaporative concentration of rain- and river-waters.

The airborne geophysics has also provided impetus for further work relating to resource management. Specifically, we can combine the digital elevation model with the precise radiometrics to provide a detailed regional soil-mapping tool that exactly defines the extent of land management units.

Unfortunately, a goal of the project to delineate significant sub-surface palaeo-channels was not realised. This suggests that the existing rivers may have followed similar courses for the last 2 million years, or may merely reflect a lack in contrast, in the AEM and magnetic signals, between the channels and other sediments.

Minimal vegetation stress was observed within the Angas-Bremer Plains, largely reflecting the dominant uptake of fresh, surface waters. Water-tables were generally deep at the study sites, thus did not impact on vegetation health. An objective measure of stress is advised (such as chlorophyll fluorescence yield) to monitor vegetation health, rather than the use of subjective observations.

This work provides information that has direct bearing on management directives. In particular we note:

1. The prominent role of river / flood recharge, both in providing surface water to replenish floodplain soils and provision of recharge waters for both the unconfined and confined aquifers, means clever management of flood waters is crucial for the long-term health of the region. Streamflow is the primary source of recharge across the plains so any change to flooding conditions will affect the water system in the floodplain. Salinity is intimately entwined with this and salt may be slowly accumulating in the near surface with implications for future disposal to maintain healthy soils.
2. Water levels need to be controlled both in the unconfined and confined aquifers by judicial use of groundwaters augmented by artificial recharge / aquifer storage and recovery (ASR) and continuing use of Murray water, via Lake Alexandrina. Water

levels have almost returned to pre-irrigation levels, but complete return to pre-irrigation levels may mean loss of productive land along the lakeshore as waterlogging and salinisation is expected along this zone. It needs to be noted that the new groundwater regime is 0.75m higher than the natural one due to the effects of the barrages on artificially raising the height of the lake's surface.

3. Salt levels across the region are gradually increasing due to the application of irrigation waters. This increase in root-zone salinity can be controlled by increased leaching in some areas, but must be managed such that deep drainage to the aquifer is minimised. The rate of increase can be measured by using devices such as FullStops, which are currently installed across the region. The rate of accumulation can be evaluated and, if necessary, this salt might be released to the upper aquifer in a controlled manner, such that there is minimal leakage to the confined aquifer. Drainage of the upper aquifer to the lake would dilute the salt sufficiently for disposal. This should be seen as a very long-term approach.

4. An improved groundwater model should be constructed to enable modelling of these scenarios. There is now sufficient data to facilitate this activity.

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INTRODUCTION

This report is one of a series of final site reports summarising results for the South Australian Salinity Mapping and Management Support Project (SA SMMSP). Conducted under the auspices of the National Action Plan for Salinity and Water Quality (NAP), the project had three underlying goals:

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

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

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

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

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

This report describes the component of the program conducted at the Angas-Bremer Plains site, one of 5 study areas in the SA SMMSP. These sites were chosen on the basis of priority for salinity management as well as representing a range of different landscapes, assets at risk, potential management options and maturity of regional planning. All the sites are shown in Figure 1. Three of the study areas were in the western Murray Basin (Riverland [Lock3 to Border], Angas-Bremer Plain, and the Bremer Hills), one was located in the South East Region (Tintinara) and one in the mid-North (Jamestown).

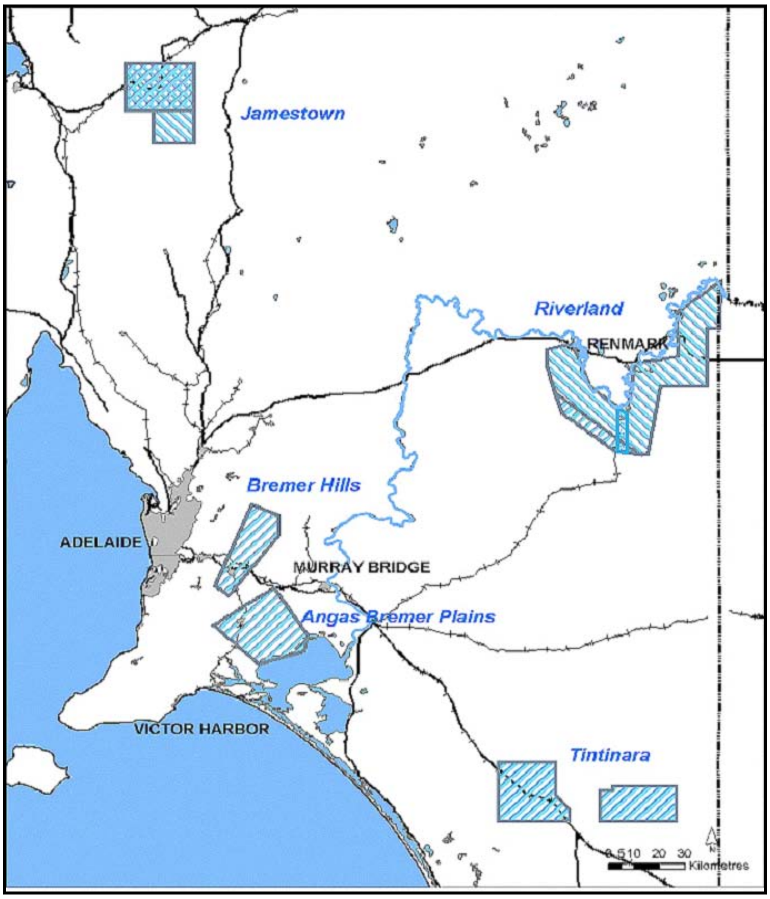

Figure 1. Location of the 5 study areas

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

A. Discussion of the resource management issues

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

C. Developments/ improvements in modelling and decision support tools

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

The prime objective of the project in the Angas Bremer Plains was to provide information that allowed prevention of, or better management of, shallow, saline groundwaters and soil salinity, and protection of sensitive aquatic habitats.

Original contracted outputs included:

1. Three-dimensional maps of the soils and regolith, with emphasis on palæochannels.
2. Maps and associated products, including soil and regolith maps, demonstrating salt stores, solute transport pathways, salt sinks, synthesis of all available data to indicate hazards and management options.
3. Improved groundwater model, with documentation.
4. Report on overall site investigations.

It should be noted that the contracted outputs were changed subsequent to flying the magnetics, as palæochannels were not found to be a prominent feature of the region. Emphasis shifted to answer the resource management issues outlined in the next section. The contracted outputs were modified and a number of detailed reports for the Angas Bremer Plains site were produced. This report aims to summarise those results and synthesise the contribution made by airborne geophysics.

Thus, the revised contractual outputs are accompanied by specific site reports:

1. Three-dimensional maps of the soils and regolith, with emphasis on aquifer boundaries and constraints to recharge.
    - Gibson, D.L. (2004) *An enhanced framework for natural resource studies in the Angas Bremer Plains area, South Australia*. CRC LEME Open File Report 172
2. Maps and associated products, demonstrating salt stores, solute transport pathways, salt sinks, groundwater interaction and aquifer connectivity.
    - Cresswell, R.G. and Herczeg, A.L. (2004). *Groundwater recharge, mixing and salinity across the Angas Bremer Plains, South Australia: Geochemical and isotopic constraints*. CSIRO Land and Water Technical Report No. 29/04 & BRS Technical Report.
    - Henschke, C.J. (2003) *Drilling to verify recharge mechanisms causing dryland salinity*. Rural Solutions SA, report to SA-SMMSP.
3. Assessment of groundwater models, with documentation.
    - *Summarised in this report: Part C*
4. Evaluation of associations between vegetation health and salinity.
    - Camp, A. (2004) *Salinity and Native Vegetation Health – Tintinara and Angas-Bremer Plains 2003*, Department of Water, Land and Biodiversity Conservation
5. Report on overall site investigations, including a synthesis of all available data to indicate hazards and management options.
    - *Summarised in this report*

In addition, the following two reports include details on the airborne geophysics data acquisition and processing for the Angas-Bremer Plains.

- Brodie, R.C. and Cresswell, R.G. (2004). *Acquisition, quality assessment and control, and delivery of airborne geophysical data – South Australian SMMSP*. BRS Technical Report
- Fitzpatrick, A. (2004) *Calculation of conductivity depth images (CDI) S.A. AEM data using EMFLOW 5.30 (AMIRA-P407B): RESOLVE: Riverland and Tintinara (East & West); TEMPEST: Jamestown and Angas Bremer Plains,* CRC LEME Open File Report 176

PART A. RESOURCE MANAGEMENT ISSUES

1 A History of Resource Management

The history of the premium wine-grape region centred around Langhorne Creek, within the Angas-Bremer Prescribed Wells Area, is one of enlightened water resource management as irrigators and government specialists have dealt with expansion and development of the fertile soils across the floodplains of the River Angas and the Bremer River. To oversimplify:

Almost annual flood-waters have been diverted, since shortly after early settlement of the region in the 1830's, and used to irrigate vines, pastures, vegetables and almonds on the Angas-Bremer floodplain. A ten-fold expansion in the lucerne industry in the area through the 1950's to 1970's was achieved through a corresponding expansion in use of deep groundwaters for irrigation. This resulted in unsustainable groundwater extraction from the deeper, generally fresher, semi-confined, limestone aquifer.

Any excess water from irrigation also led to groundwater mounds in the shallow, more saline, sandy aquifer. These rose to levels that threatened crop production by waterlogging and salinisation of the near-surface soils.

Recognition of the severe local depletion of the groundwater resource, and fear of salinity triggered resource analysis by the State agencies resulting in decreased groundwater allocations and an incentive to shift to surface water use via pipelines from Lake Alexandrina. Lake Alexandrina is a 360 km^2 naturally estuarine lagoon at the mouth of the River Murray that has been protected from sea-water incursion by the development of coastal barrages in the 1930's, and is now the largest freshwater lake in the Murray system. Its coastal margin is also part of the Coorong National Park.

While pipelines were initially seen as uneconomic, except for those irrigators very close to the lake, the rise in grape prices (combined with policy incentives to shift from ground to surface water allocations) gave the impetus to develop extensive pipelines for up to 17km away from the lake. This caused a reduction in groundwater usage to a tenth of that prior to 1980, while surface water use increased by a factor of 20 (Table 1). This was also accompanied by a minor component of artificial recharge to help replenish the depleted aquifer.

Table 1. Comparison of water and land use for the Angas-Bremer Prescribed Wells Area for 1985-86 and 2002-03.

		1985-86	2002-03
Land use	Lucerne	1,800 Ha	375 Ha
	Vines	220 Ha	6,000 Ha
	Other	512 Ha	1,500 Ha
Allocation	g/w	24,000 ML	6,300 ML
	R. Murray	n/a	28,700 ML
Use	g/w	12,000 ML	2,100 ML
	R. Murray	1,000 ML	18,600 ML

The shift from lucerne to grapes has allowed the irrigated area to continue to expand whilst still using less water than before, as grapes generally receive only a quarter of the water per unit area compared to lucerne. As groundwater extraction decreased and more surface water was applied to paddocks, concern then shifted to addressing the potential for shallow aquifer water tables to rise excessively. In some locations, at the end of the winter rains, water tables do rise to within 3m of the ground surface. Low irrigation application rates onto grapes, of 2ML/ha, and evaporation of these near-surface waters, have increased concerns that soils may become saline. There are also concerns about the possible leaching of the more saline groundwaters from the upper unconfined aquifer into the lower, confined aquifer that is still pumped for irrigation.

Further, at the lower end of the Plains area, Lake Alexandrina and associated wetlands are important areas for aquatic habitat, and significant red gum swamps occur in other low-lying areas. Rising water-tables in parts of the area and salinisation of the unconfined aquifer present significant hazards to these environmental assets.

For sustainable management into the future, local irrigators need to know:

- At what rate can they support future expansion of irrigation?
- How robust is the system?
- How do they control the water balance and the salt balance?
- Where are the best sites to re-vegetate for recharge control and for other environmental benefits?

2 The Angas-Bremer survey area (Lower Murray NAP region)

The Angas Bremer Plains region is a gently, southerly-sloping (<1%) plain with a few NW-trending dunes up to 5m high. The region is bounded to the north by the Mt Lofty Ranges, to the south by Lake Alexandrina and to the east and west by higher ground.

The River Angas and Bremer River traverse the region roughly from north to south. Both arise in the Mt Lofty Ranges and drain through the irrigated floodplain to Lake Alexandrina, the terminal lake of the River Murray (Figure 2). While ephemeral, both do flow, and generally flood, in most winters and occasionally in summer in response to rainfall on the Mount Lofty Ranges, which experience in excess of 750mm/year rainfall.

The region enjoys a Mediterranean climate of hot, dry summers and cool, moist winters. The rivers sit in the rain shadow of the hills, however, resulting in a rainfall gradient that ranges from 500mm/year in the north-west at Strathalbyn down to only 380mm/year at the lake. Evaporation is also high throughout the year, with pan evaporation values of 1600mm/year in the north reducing to 1150mm/year at the coast. While total pan evaporation does over-estimate the potential evaporation, there is generally only a slight precipitation surplus during winter months, with the implication that direct rainfall is not sufficient to contribute significant recharge to the groundwater systems. The inference is that streamflow from the north provides substantial recharge to the shallow groundwater system during high flow conditions.

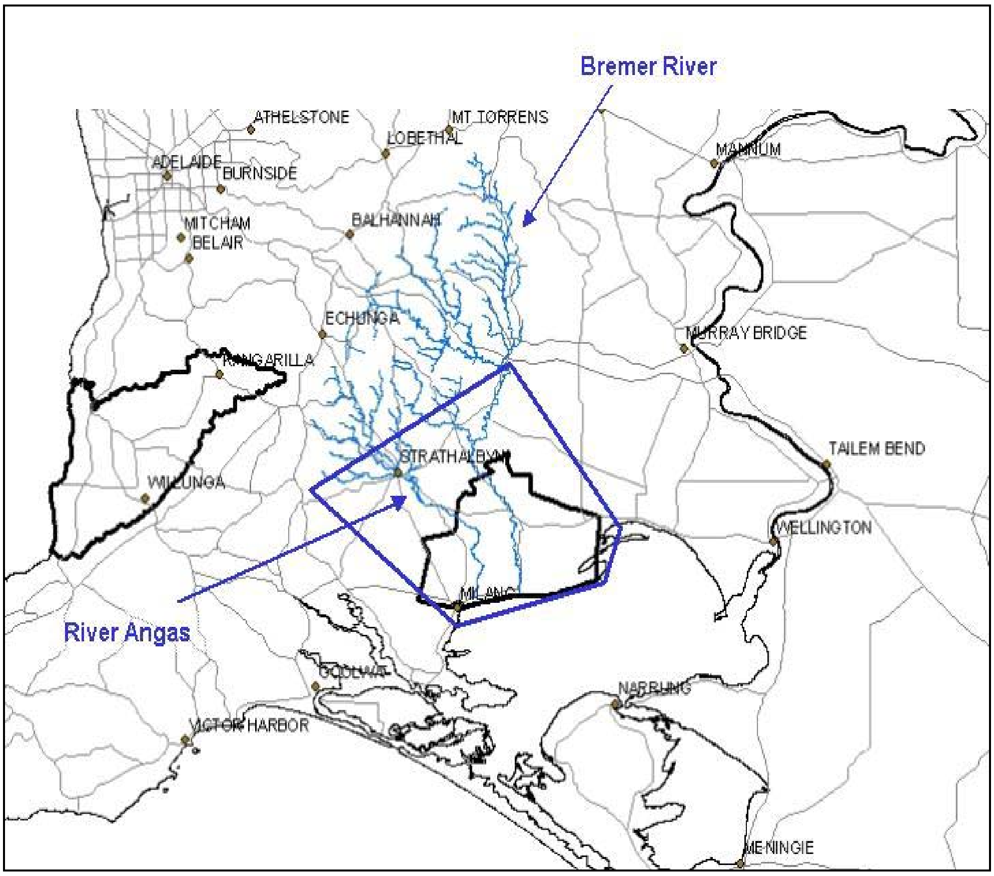

Figure 2. Regional map showing the Angas Bremer Prescribed Wells Area (black polygon) and the extent of the Angas and Bremer Rivers outside the fly zone (shown in the blue polygon)

3 Identification of Problems / Site Project Objectives

The complex nature of the groundwater system requires better data to support proposed management of the land, surface water and groundwater in the Angas-Bremer Plains (ABP). Furthermore, an improved overall understanding of the groundwater systems should also enable a better assessment of the water resources and the likely risks to aquatic habitats. The Angas-Bremer Water Management Committee and the River Murray Catchment Water Management Board have been active in filling these knowledge gaps.

Airborne geophysics is seen as a complement to these efforts, particularly its ability to help define the sub-surface geometry of the aquifers and aid in the understanding of landform processes and soil distributions. Specific components, with reference to the body of knowledge on the Angas-Bremer Plains groundwater system, that have been addressed in this project include:

a) The presence of a tight aquitard between the upper, unconfined, more salty, sandy aquifer and the lower, confined, better quality, limestone aquifer;
b) The presence and effects of faulting in the region;
c) The distribution and interaction between the different aquifers and surface waters; and
d) Encroachment of highly saline groundwaters from the east.

Through better insight into these components, this project has sought to resolve particular local resource management issues (forming the project objectives), namely to:

1. Determine the relative importance of diffuse and direct recharge (via periodic flooding) in replenishing the groundwaters in the Angas Bremer Plains.
2. Determine the source(s) of salt in the groundwater.
3. Determine the effects of faulting in the region on redirecting groundwater flow systems.
4. Evaluate the extent of inter-aquifer mixing in different parts of the Angas Bremer Plains.
5. Estimate groundwater residence times.
6. Assess the state of vegetation health in a salt-stressed environment.

Airborne geophysics may be brought to bear on these issues, but cannot directly provide answers to management directives. Airborne geophysics can help reduce the risks associated with management decisions by providing an increased knowledge base and improved confidence when modelling cause and effect.

As the issues outlined above cannot directly be addressed by airborne geophysics, 6 questions were devised that could provide best input to the information required to address these issues. These are posed in the next section (Part B), together with background information on the airborne geophysical tools used in this study and their limitations.

We also need to evaluate the current management tools and models. A brief summary is presented in Part C, with reference to other research being carried out in the region.

Using the results from the airborne geophysics, and an appreciation of current understanding, we may then re-visit the resource management issues above and assess whether airborne geophysics has improved our understanding of the system and enabled us to refine our management strategies (Part D). We can also assess whether airborne geophysics has been useful and to what extent the results can be transferred to other regions, both in terms of the technologies and the inferences for similar landscapes.

PART B. ROLE AND CAPABILITIES OF AIRBORNE GEOPHYSICS

4 Airborne Geophysics Objectives

To address the 6 resource management issues (project objectives) listed above, airborne geophysics were employed to investigate a series of specific questions as shown in table 2, with the particular technologies employed listed in the right-hand column:

Table 2. Questions addressed by geophysical techniques

	Question addressed by Airborne Geophysics	**Airborne Geophysical techniques employed**
(i)	Can we better define the extent of good (and bad) salinity groundwaters and their host aquifers (ie. define aquifer boundaries)?	Airborne EM Magnetics
(ii)	Can we better define the variability in quality of aquifer waters?	Airborne EM
(iii)	Can we better define recharge to the aquifers?	Airborne EM Magnetics Radiometrics Altimetry
(iv)	Can we map flood-plain extents and the variability in soil types?	Radiometrics Altimetry
(v)	Can we identify sub-surface palaeo-channels that may be targeted for artificial storage and recovery or for pumping?	Airborne EM Magnetics
(vi)	What sub-surface geological structural constraints can we determine?	Airborne EM Magnetics Radiometrics Altimetry

Additional work (eg. drilling, geochemical analysis of ground and surface waters) complemented the geophysics and provided valuable input to help answer some of the resource management questions (eg. residence times, source(s) of salt). Where applicable, these other sub-projects are included in the discussion of the airborne geophysical results; and an integrated review of the project objectives is attempted at the end (see Part D).

5 Airborne geophysics technologies and target definition

One of the prime objectives of the SA-SMMSP was to assess the usefulness of airborne geophysics in addressing salinity and water quality issues such as resource evaluation and problem mitigation. Across the Angas-Bremer Plains, four distinct geophysical technologies were employed (see box on the next page), with each technology used for a different but complementary purpose.

5.1 AIRBORNE TECHNOLOGIES USED ACROSS THE ANGAS-BERMER PLAINS

Further information about the techniques is contained in the information box on the next page.

Airborne electromagnetics (AEM) are used to define the 3-dimensional conductivity structure of the region to describe the salt-water-materials relationships in terms of their defining electrical conductivity signal. This can potentially spatially define high (and low) salinity groundwaters and zones of high (and low) salt load. It may also indicate sub-surface variability in materials, specifically the clay: silt: sand contribution[1].

AEM requires careful calibration to determine the relative contribution of conductive materials, but is the only geophysical technology that has the potential to map salt load directly in the sub-surface with good vertical resolution.

Across the Angas Bremer Plains, the TEMPEST time-domain AEM system was chosen as the system most likely to yield conductivity information with good depth resolution down to 100m, and thus capable of measuring parameters that relate directly to the properties of the deep aquifer. A line spacing of 200m was chosen as adequate to give detailed information across the flood-plain, while a 400m line-spacing extended the survey to the east and west.

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

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

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

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[1] Sub-surface material differentiation was examined in the companion Riverland and Tintinara East surveys, while groundwater quality was the focus for Tintinara West. For the Jamestown survey, the distribution of groundwater conduits defined the role of AEM.

Airborne Geophysical Technologies

AIRBORNE ELECTROMAGNETICS (AEM)

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

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

RADIOMETRICS (GAMMA)

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

MAGNETICS

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

ALTIMETRY

As a necessary by-product of flying the other 3 geophysical techniques, a precise digital elevation model (DEM) is generated from the radar and laser altimetry used to precisely locate the aircraft above the ground. The resolution is a function of the spacing of the flight lines and the signal repeat time, but generally this results in a spot measurement taken every 10m along the flight path, with flight paths 100m apart for the combined radiometrics and magnetics survey and either 200 or 400m for the AEM survey. The resultant data is interpolated to give an exact surface on which to "hang" the other data sets and provide a surface reference for other studies. The DEM also often gives new insights into the evolution of landforms and landscape relationships (Gibson, 2004).

5.2 CAVEATS

It must be remembered, however, that airborne geophysics has 3 significant limitations:

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

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

6 Approach & strategy

All available existing datasets (e.g. groundwater records, mineral exploration surveys, hydrology investigations, previous geophysics, historical anecdotes) were accessed and analysed with regard to the questions posed above. This provided the framework onto which the airborne geophysics could be placed, and provided context when interpreting the airborne geophysical results.

For the resolution thought to be required for this survey, flight line separation was specified as 100m for the MAGSPEC (magnetics, radiometrics and radar altimetry) survey and 200m for the TEMPEST AEM survey across the rivers, and 400m spacing extended the region east and west to the bounding dune-fields (Brodie and Cresswell, 2004). A total of 2,450 line km were flown using TEMPEST and 6,800 line km with MAGSPEC over 690km^2, stretching from Milang on the shores of Lake Alexandrina in the south, north to Strathalbyn and up to Callington in the north-east and back to Tolderol Game Reserve on the shores of Lake Alexandrina east of Milang.

Following flying of the airborne geophysics, field validation was undertaken:

1. Drillholes were sunk at strategic locations;
2. Sub-surface geophysical properties (conductivity, radiometrics and magnetic susceptibility) were logged, and the materials encountered described;
3. Water levels and groundwater salinities were measured in existing and new bores;
4. Groundwater and soil samples were taken for analyses, and

5. Field conditions and landscape features were assessed.

Following the field investigations, the airborne geophysical data was re-interpreted and particularly the AEM, re-modelled. This is an iterative process. As more information becomes available, so a closer match to reality can be achieved through modelling of the remotely sensed data. Interpretation must be viewed as a continually evolving process if we are to benefit from the increased availability, quality and variety of datasets at our disposal.

Engagement of the local community was achieved through public meetings and interaction with management committees. This provided feedback on the efficacy of the approaches and the relevance to local issues.

7 Airborne Geophysics Results

The 6 questions to be investigated using the airborne geophysics, may be addressed using the knowledge gleaned from the existing datasets, combined with the new information derived from the airborne geophysics and the associated field studies:

7.1 DEFINING AQUIFER BOUNDARIES

Combining the images created from the airborne technologies and drill-hole data, a precise boundary to the deep, confined aquifer can be drawn. In addition, structural features in the sub-surface that control groundwater movement can be delineated. A good distinction can be made between the upper, unconfined aquifer and the lower, confined aquifer, with well- defined leakage zones along the river beds.

Prominent linear features picked up by the DEM (Figure 3) relate to faults that may penetrate deep in the sub-surface. DEM's, however, give only the surface expression, while for magnetic images (Figure 4), it is difficult to say more than whether the feature is "shallow" or "deep". AEM, on the other hand gives a better (though still not precise) indication of a feature's depth, particularly where the feature dies out, or is not present. We thus see a strong influence on conductivity by features shown in the DEM, particularly from the Bremer and Sandergrove Faults (Gibson, 2004), that we can also see in the AEM (Figure 5).

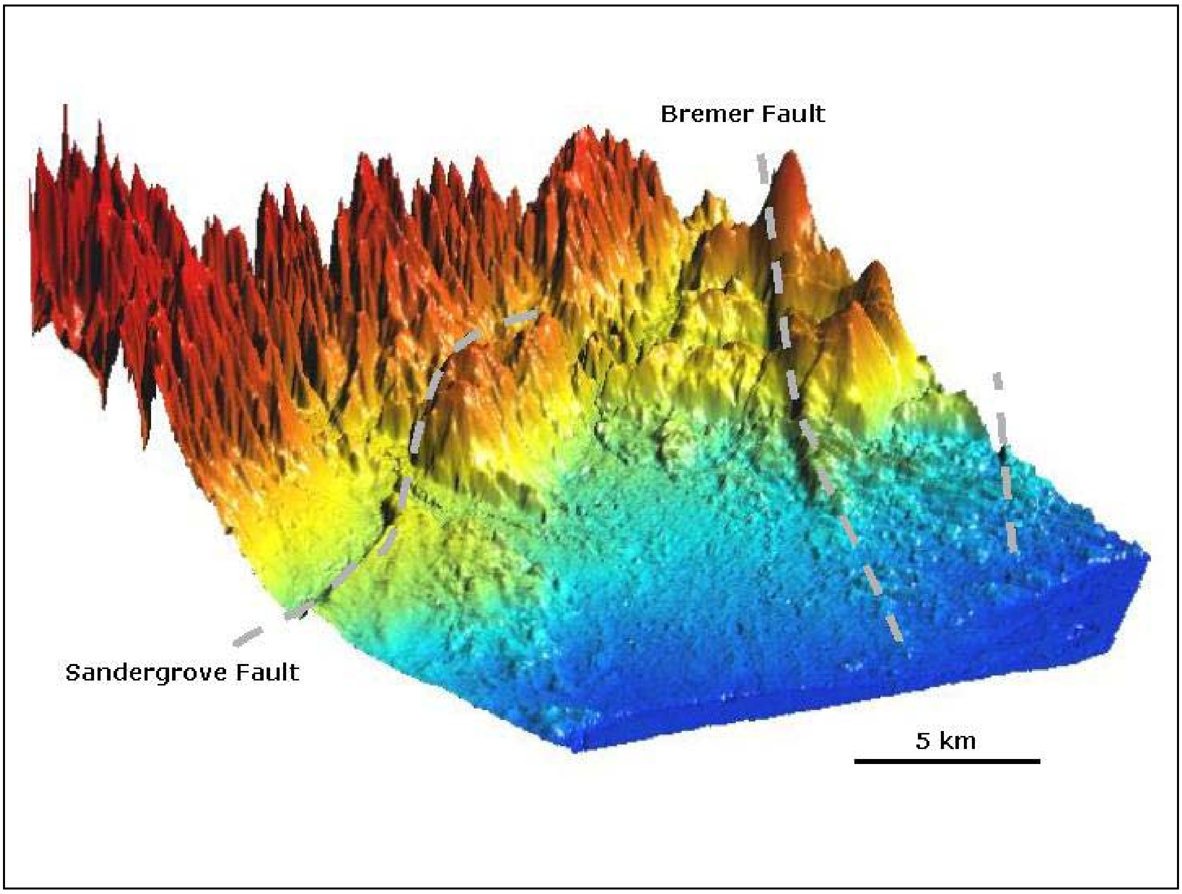

Figure 3. Faults across the region can be picked out from the breaks in slope seen in this exploded DEM (*after* Gibson, 2004). Colour scale grades from 0.5m AHD in dark blue (Lake Alexandrina) to over 300m AHD for dark red at the western corner.

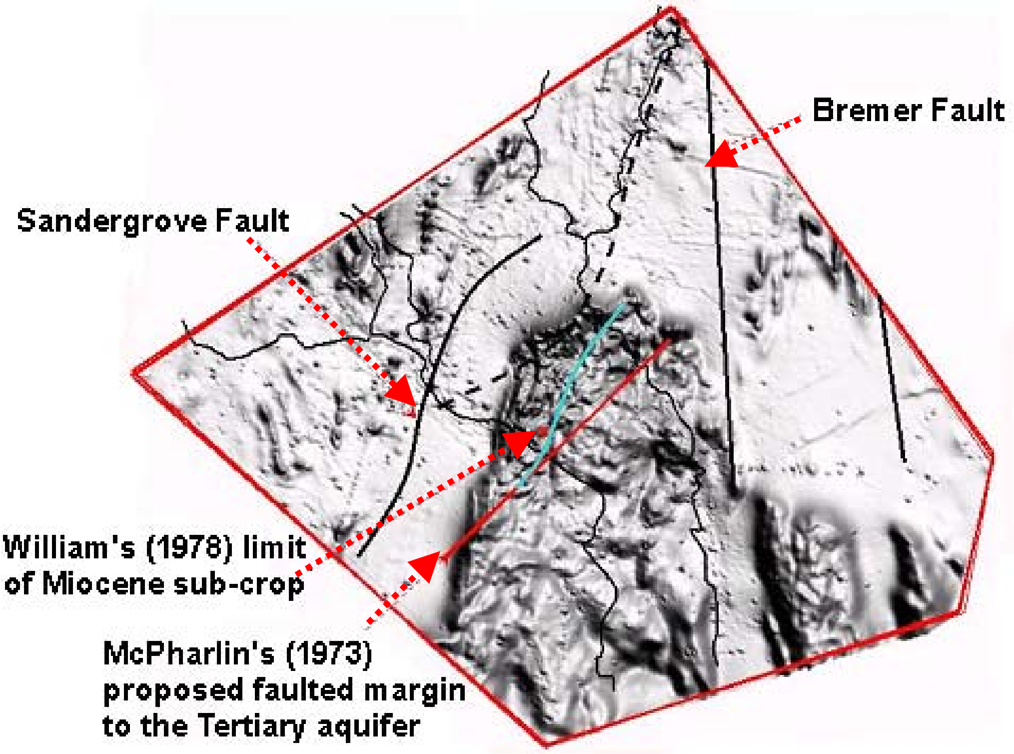

Figure 4. Airborne magnetics are dominated by the response to a deep magnetic high, probably related to a deep (>100m) batholith. Discontinuities in the magnetic response mark possible faulted boundaries and coincide with features seen in the deep AEM but with less surface response. The "faulted" margin picked up by McPharlin (1973) may be a response to the deeper fault in the batholith.

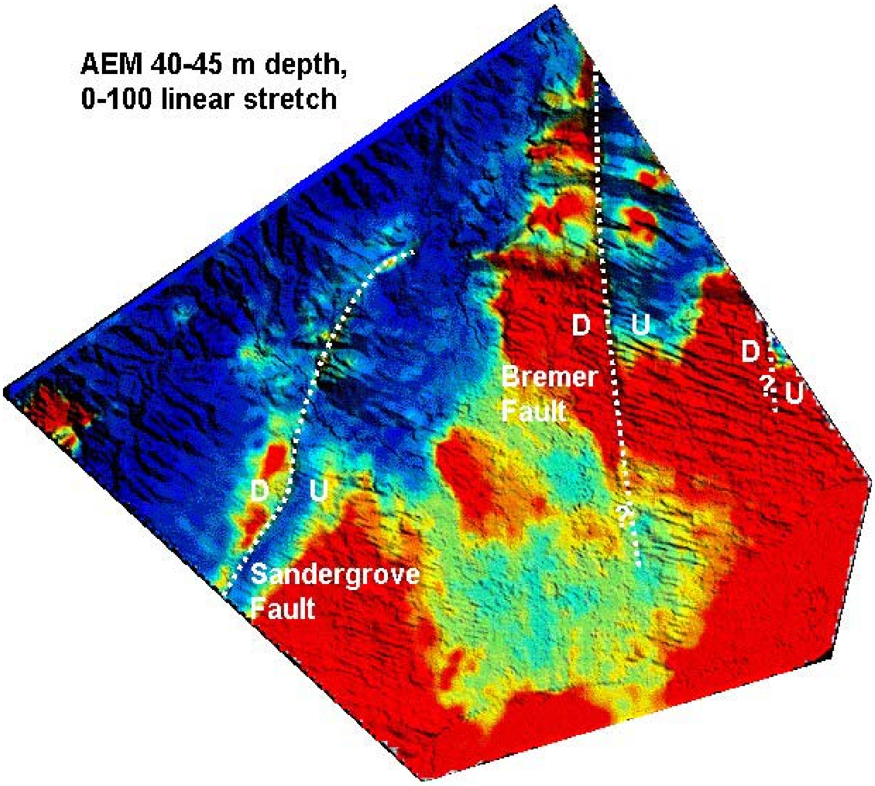

Figure 5. The same structures seen in the DEM can be seen in deeper AEM slices, indicating that deep geological features are controlling the surface topography as well as water movement and lithologies at depth. (D = downthrow side; U = upthrow)

The AEM may be taken further, and depth slices may be stacked to help define the extents of the individual aquifers. Thus, using the AEM 200mS/m cut-off to define a distinctive boundary in the data we see, both in slices (Figure 6) and in perspective (Figure 7) the shape of the 2 main aquifers in the region.

From a generally resistive (shown in green and blue) surface layer (here delimiting fresher soil waters), we see the upper, unconfined aquifer defined down to about 15m, at which depth the conductivity (shown in oranges and reds) constricts the image as the clay-rich, confining layer dominates the conductivity, due to its high water and salt content (but low transmissivity). The 15-20m depth slice is only breached immediately beneath the rivers indicating preferential recharge along these zones. Beneath this, the lower, confined aquifer opens up, but shows clearly demarked boundaries and zones of high conductivity within the broader limits of the aquifer.

The occurrence of faulted margins at depth is evident in the straight edges seen in the 30-50m depth slice. The sharp boundaries also help explain why bores within a few hundred metres of each other near these margins can exhibit quite different salinities.

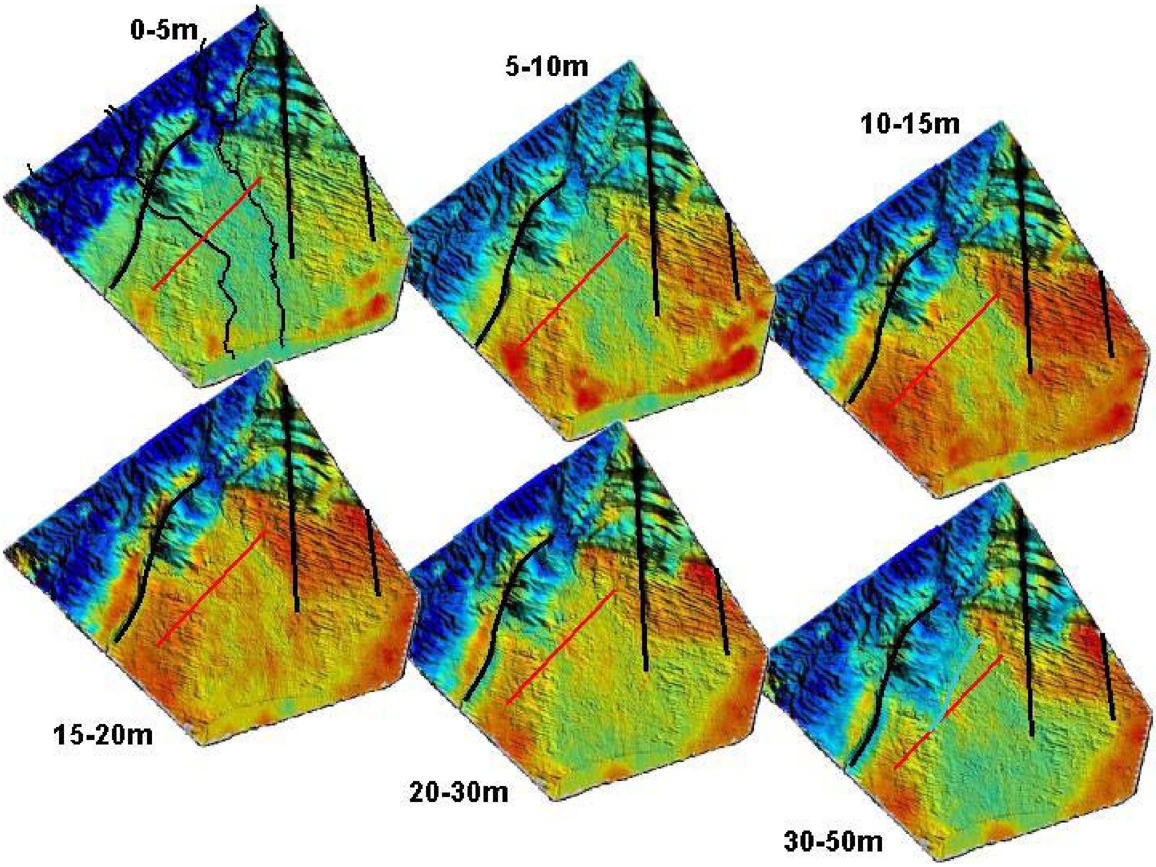

Figure 6. Modelled AEM depth slices superimposed over the surface DEM. Depths are indicative only. Also shown are prominent structural features (see Figure 4). Colours grade from resistive (blue) to conductive (red). Dark blue generally represents low-porosity, basement rocks and outcrop; greens are dominantly high-porosity, water-rich sediments; oranges and reds indicate higher salinity waters. Note that a low-porosity rock with high salinity waters may give the same response as a high-porosity rock with low salinity waters. The 15-20m slice also shows the effect of a higher clay content (giving higher conductivities) in the confining layer between the 2 main aquifers.

Both the Bremer and Sandergrove faults influence groundwater flow, as indicated by the conductivity contrast across the faulted zones (Figure 5). No such contrast is evident at the location of a previously conjectured fault (McPharlin (1973), Waterhouse, et al. (1978)) at the margin of the deep, Tertiary aquifer against the Palaeozoic basement in the north of the region (Figure 4). There is a sloping contact in this area, with an area of high conductivity shifting south as we look deeper in the profile (Figure 6). This gives a slope of 2°, consistent with the maximum slope of 2.5° determined by Gibson (2004) for the Tertiary/basement boundary in this area. This represents the on-lap margin of the Tertiary limestones over the Palaeozoic basement. Further, the continuous signature along the rivers at all depths crossing this zone also favours a non-faulted margin.

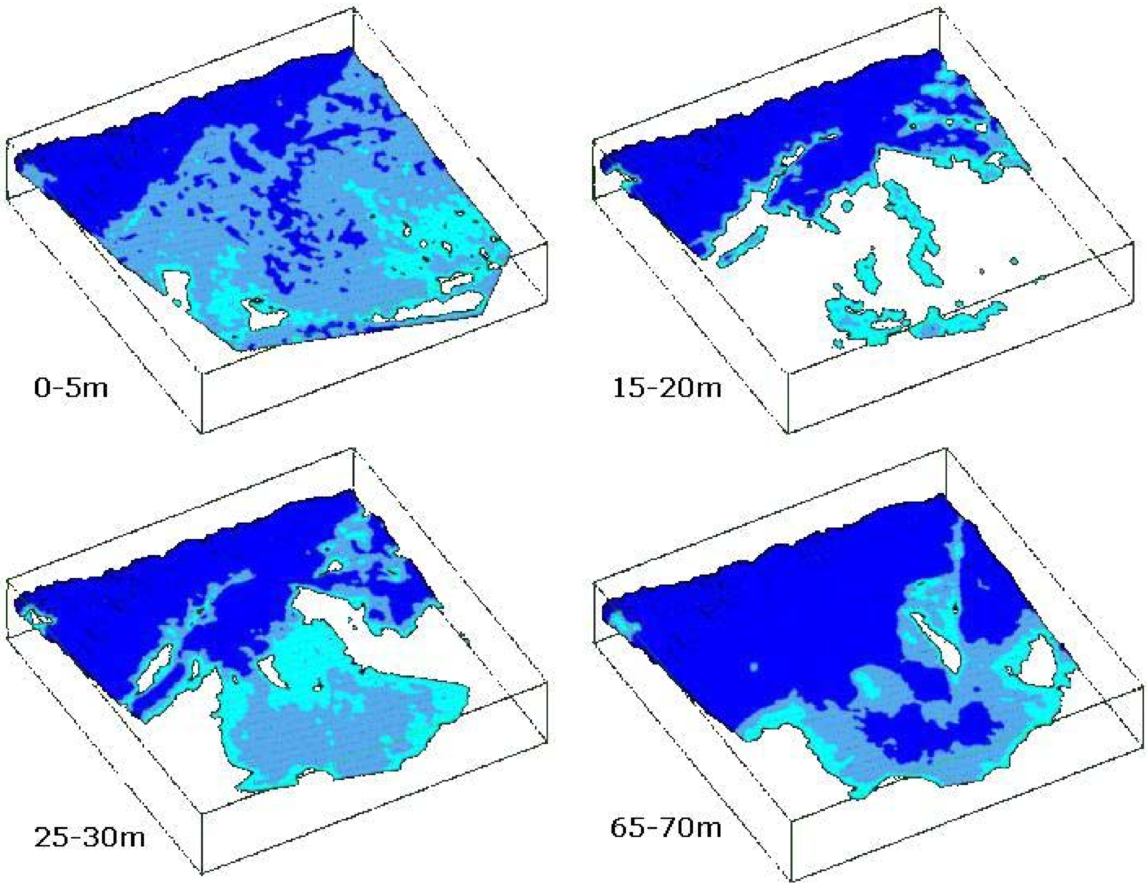

Figure 7. Figure 6 is simplified by extracting only the low conductivity regions (blues and greens in Figure 6) and projecting the depth slices on to elevaton surfaces. Hence we now look at the surfaces representing resistivity from the surface to 5m; 15-20m; 25-30m and 65-70m. This highlights zones of fresher waters, and thus prominent recharge zones, but also includes areas of very low porosity such as bedrock and outcrop.

We now, therefore, have both greater confidence in the aquifer boundaries and a more accurate representation of the boundary than can be determined from the existing bore network (Figure 7).

This geometry may now be included in any future re-modelling of the groundwater system.

7.2 ASSESSING GROUNDWATER SALINITY

> Conductivities measured by airborne electromagnetics approximates the measured salinities of groundwater in the deep aquifer. There is poorer correspondence for the shallow aquifer, as the measured AEM is strongly dependent on the near-surface saturation levels and requires refined modelling to extract the near-surface detail.

Groundwater salinity within the confined aquifer (Figure 8) was assessed, by the South Australian Department of Water, Land and Biodiversity Conservation (DWLBC), as part of their Irrigation Management Zone Annual Report to the Angas Bremer Water Management Committee (Allnutt, pers. comm., 2003, 2004). This can be compared with the AEM conductivity images for the top of the confined aquifer (taken as represented by the 15-20m slice) (Figure 9). This can assess: i) the accuracy of contouring determined from the borehole data (assessing the spatial pattern of salinity), and ii) the accuracy of the AEM in depicting the true salinity of the groundwater (assessing the calibration parameters used for the AEM modelling).

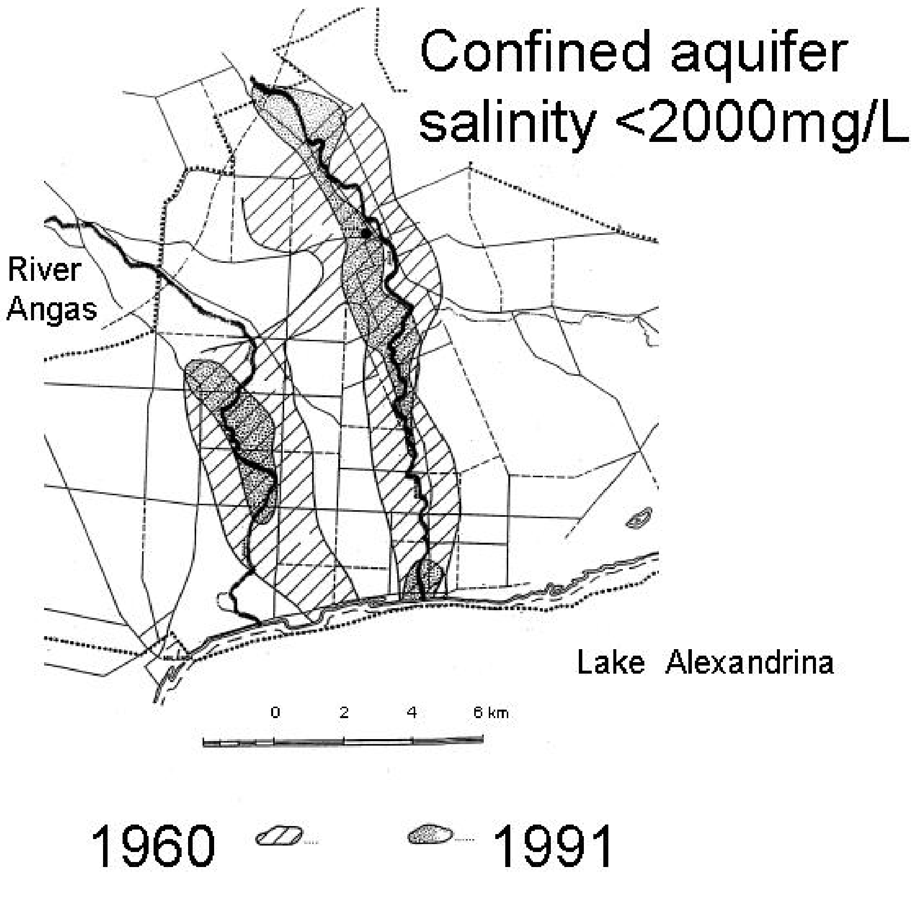

Figure 8. An assessment of bore water quality for the years 1960 and 1991 (Allnutt, pers. comm.), showing the contraction of the zone of good quality water within the confined aquifer over that period.

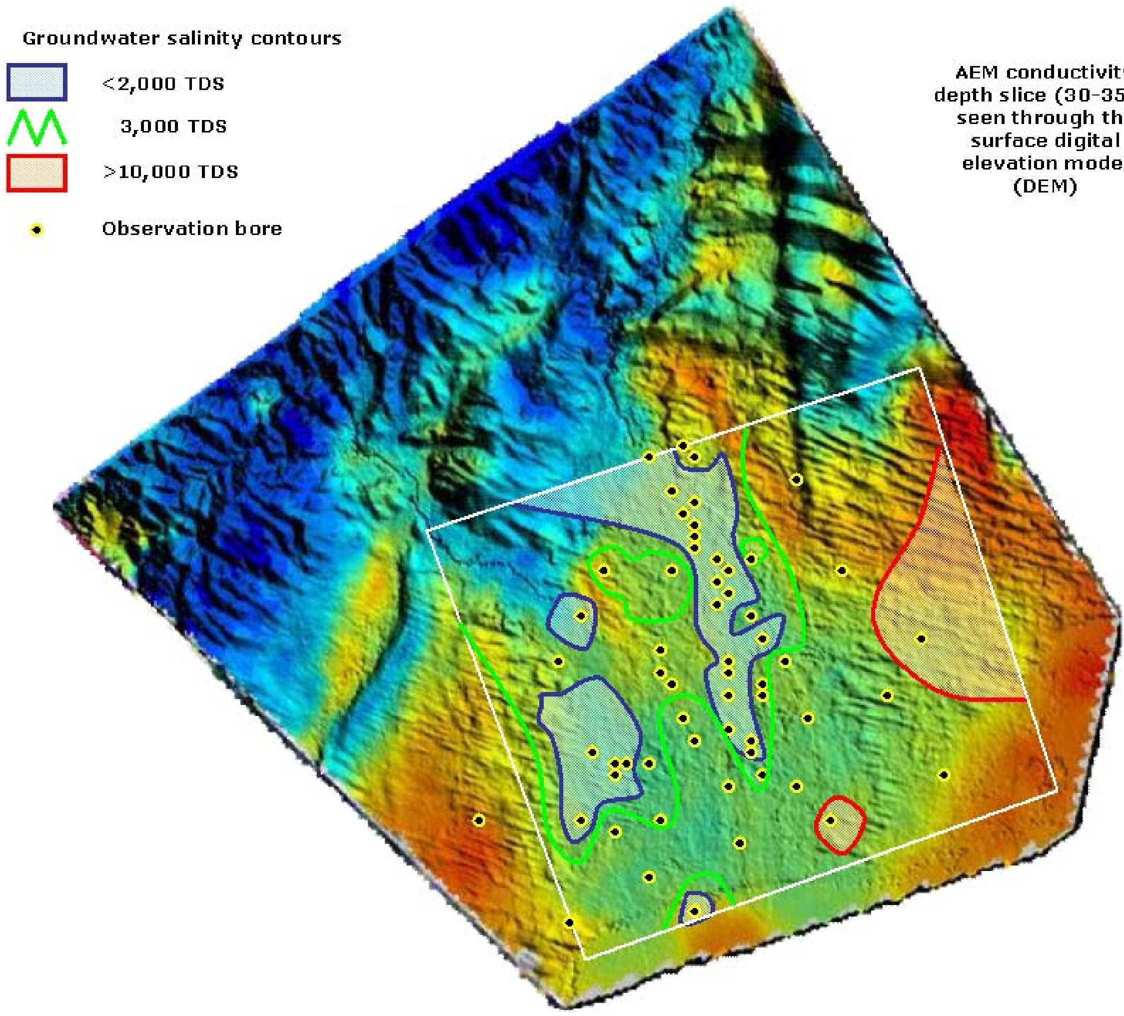

Figure 9. Salinity contours have been generated for the confined aquifer (B. Alnutt, pers. comm.) using data from monitoring and growers bores. Good coverage along the rivers gives good definition to the contours, but away from the rivers, bullseyes develop where single bores constrain the mathematical contouring. The deep AEM conductivity slice infers the true distribution of fresher waters (pale greens).

We see that, while there is broad agreement between the shapes of the 2 datasets, there is more detail, and variability, apparent in the AEM data and we can dispense with the bulls-eyes generated around single data points.

Determining absolute salinities with the AEM is harder to accomplish. Again, broad agreement can be suggested, but a greater sampling of salinities from bores is required to facilitate confidence in the AEM values. We note, however, that it has been observed that it is very difficult to obtain samples from the confined aquifer not contaminated from the unconfined aquifer (Waterhouse, et al., 1978).

7.3 DEFINING RECHARGE ZONES

Recharge zones are clearly defined by the AEM. Lower conductivity regions along the courses of the rivers indicate where recent, fresher, flood waters have entered the system. Recharge is seen to be dominantly vertical across the plains, though there is some lateral input from the hills to the north.

The AEM clearly defines preferential groundwater movement along the trace of the river courses (Figure 6). This appears to be the dominant recharge zone for the region, coinciding strongly with the floodplain, which is clearly delimited by the radiometrics (*see below*).

The Sandergrove and Bremer faults constrict recharge in the north to a zone along the foot of the Mt Lofty's between Strathalbyn in the west and Bletchley in the east, and up along the Bremer River. There is little evidence for any flux of water from the south, beneath the lake. Rather, the AEM patterns suggest the rivers disgorge into the deep aquifer beneath the lake, below 20m (Figure 6).

Near-surface conductivity (5-10m) suggests relatively uniform, direct recharge to the unconfined aquifer within the alluvial plain extents (unit 9 on Figure 10).

Regions of high conductivity to the south-west, south-east and east define discharge areas in the near-surface (down to the base of the unconfined aquifer), while higher conductivities in the deeper sections east of the rivers relate to the influx of higher salinity groundwaters from the Murray basin to the east.

We may, thus, divide the region of the Angas Bremer Plains into the zone beneath the alluvial plain, including the river courses themselves, and the regions away from the rivers, associated with the dune country. We may broadly consider east-west variability crossing from dune to alluvial plain to dune, and north-south variability along the courses of the rivers.

A series of analyses down the Bremer River in 1973 (Williams, 1978) during relatively low flow conditions (Len Potts, pers. comm.) revealed little variation in chemistry from Hartley in the north to near the mouth of the Bremer in the south. Only alkalinity (and field pH - rising) and sulphate (falling) showed variation in concentration. This probably reflects the rapid flow of floodwaters rising in the hills to the north.

Chemistry of the aquifers also shows no obvious trends from north to south pointing towards either local (diffuse) vertical recharge or a dominance of lateral flow away from the rivers.

Lateral flow is indicated from the analyses of waters from the shallow bores at Brinkley (Henschke, 2003). These bore-waters exhibit water chemistry similar to seawater, suggesting a large input from sea spray, and diffuse recharge into the shallow system, but contain less potassium. The chemistry of these bores is viewed as an end-member seen on the mixing curves for all solutes in the Tertiary aquifer waters.

Lateral flow is controlled by infiltration from the rivers, with river waters providing another dominant end-member on the mixing curves. The extent of the rivers' influence is indicated on the AEM images, which help define the region of potable water within the Tertiary aquifer (Figure 7).

7.4 MAPPING LANDSCAPE MANAGEMENT UNITS

Combining the digital elevation model (DEM) with the precise radiometrics provides a detailed regional soil mapping tool and exactly defines the extents of land management units.

The radiometrics compares precisely with existing soil maps of the area (DWLBC, 2002) and is seen as an exciting aid to future soil mapping activities (David Maschmedt, pers. comm.). Some details have been discussed in Gibson (2004).

Gibson (2004) has taken this further to combine the radiometrics with the DEM to describe 10 land management units (LMUs) across the survey area (Figure 10), which are broadly analogous to the landsystems of DWLBC (2002), but which involve the interpretation of deeper earth materials, landforms and their origins, whereas landsystems also take into account soil and vegetation variations (Gibson, 2004).

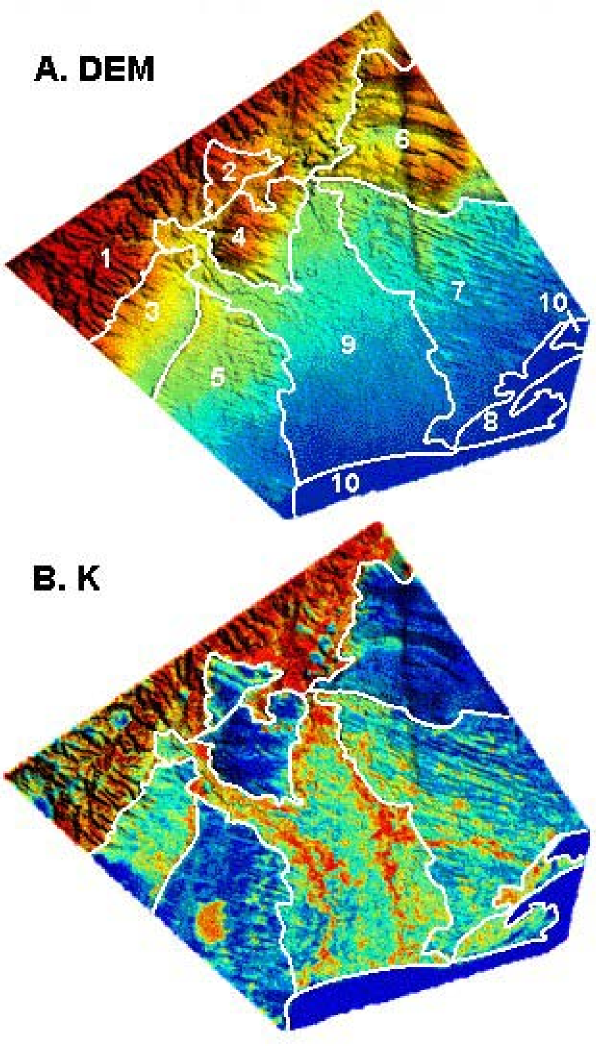

Figure 10. Division of the region into 10 land Management Units based on geophysical response, landscape, regolith and geology. Note that each unit may consist of a number of sub-units (*from* Gibson, 2004). A) shows the units over elevation data (blue=low, red=high). B) shows the Potassium (K) channel of radiometrics (blue=low, red=high).

7.5 UNCOVERING PALAEO-CHANNELS

Significant sub-surface palaeo-channels were not discovered during the survey. The existing rivers may have followed similar courses for the last 2 million years, or may not exhibit adequate geophysical contrast to the adjacent sediments.

One of the prime objectives of the SA-SMMSP in the Angas-Bremer Plains was to identify and constrain sub-surface palaeo-channels that may host supplies of potable water and/or may be targets for pumping to lower regional water-tables in times of excessive recharge, or for artificial storage and recovery (ASR) for periods of low recharge.

Unfortunately, apart from a few small channels closely associated with the current river systems (Gibson, 2004), no significant palaeo-channels were discovered. The existing rivers appear to have followed their current valleys for a considerable time, although palaeo-reconstructions for the base of the Quaternary and Tertiary indicate a proto-Bremer River probably ran parallel to the present day course south of Bletchley, but about 0.5 km to the east.

The very low magnetic response for anomalies in this area (less than half those seen elsewhere in SA (Wilford, 2004), or to the east in Victoria (Christensen, 2002) and NSW (Lawrie, et al, 2000) and the prominence of a strong deeper signal (Figure 4) does not preclude the presence of palaeo-channels, but suggests that either the signal is being masked or the development of maghemite has not taken place to the extent seen elsewhere.

7.6 STRUCTURAL CONSTRAINTS FOR THE ANGAS-BREMER PLAINS

Just as the main aquifers can be defined by the airborne geophysics, so major structural constraints are also imaged. Thus, the prominent faults in the east of the area are seen to extend to considerable depth, and the northern boundary of the deep aquifer is seen to be a gently inclined lithological contact, rather than a faulted boundary. To the north-west, a fault has given rise to a low scarp near the plain’s margin.

As mentioned earlier, combining the AEM with the magnetic image outlines potential structural controls on groundwater movement and aquifer development. These may be tied to the surface DEM to help constrain the shape and extents of the aquifer systems at depth (Figure 11).

We also note that the trace of McPharlin’s (1973) proposed margin fault corresponds with a discontinuity within the deeper batholith (Figure 4), possibly a fault which may have had some control on deposition of the overlying sediments.

Conductivity contrasts also match the faulted boundaries at depth.

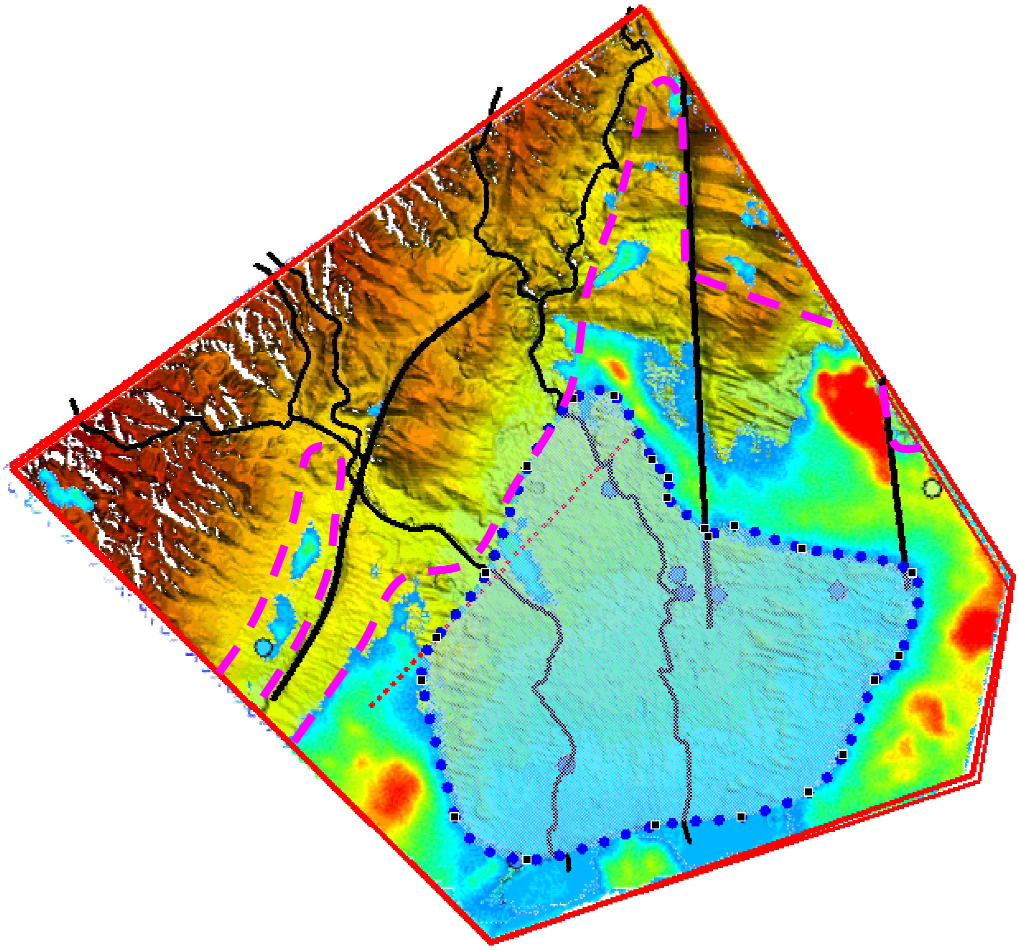

Figure 11. Combining magnetic, AEM and geophysical images for sub-surface elements and tying these to the surface DEM outlines the main structural controls on the groundwater system. This image defines the boundaries of changes in flow regime and water quality for the Tertiary aquifer (within the dashed pink line). The outlined, shaded blue area represents the fresher-water region within the aquifer. Vertical constraints are depicted in the various AEM depth slices (see Figure 6).

PART C. IMPROVEMENTS TO MODELLING / DECISION SUPPORT TOOLS

Local irrigators on the Angas-Bremer Plains need to know:

- At what rate can they support future expansion of irrigation?
- How robust is the system?
- How do they control the water and salt balance?
- Where are the best sites to re-vegetate, both for recharge control and environmental benefits?

8 Groundwater Models

Two groundwater flow models for the Angas-Bremer Plains have been developed, (Sheard, 1979 and Howles, 1999) to help predict the effects of future groundwater use.

The Sheard (1979) model was a preliminary model developed to investigate the hydrologic processes, and to determine the level of understanding of the groundwater system at that time. Howles (1999) developed this model further, with the intent of assessing risk from over-development of irrigation in the region.

Neither model was quantitatively calibrated (i.e. not calibrated against observed heads or flows) and should therefore be viewed as hypothetical (Kwadwo, pers. comm., 2004).

Both models were to be used as predictive tools for future groundwater management. As the accuracy of any groundwater model predictions depends on the degree of successful calibration (and verification of the model), and since the output from the models was not compared with hydrographs from observation wells, the degree of accuracy of the models to predict future groundwater conditions in the basin should be questioned.

A conceptual and numerical model of the basin could be improved by incorporating the latest developments in understanding of the basin's hydrogeology and flow processes.

With our improved understanding of the 3-dimensional variability in aquifer materials and appreciation of water transport in the region, it is possible to develop and calibrate the Howles (1999) hydrogeological model to better evaluate the relationships between natural recharge, irrigation extraction and irrigation supply (via both ground and surface waters).

Hydrogeologically, the piezometric surface indicates that the lower aquifer is confined over most of the plains, becoming artesian south of Langhorne Creek (Alnutt, pers. comm., 2004). Water-table depression in this aquifer, initiated by over-extraction through to the 1970s reflects a pressure head effect and the aquifer readily recovers during non-irrigation periods. Everywhere on the plains, the piezometric head is above the top surface of the confined aquifer, even during maximum drawdown, implying that vertical leakage can only occur through leaking bores or where there is very high head pressure, such as along the rivers during flood conditions. For much of the time, vertical leakage is more likely to be up from the confined to unconfined aquifer, particularly in the south of the area where the confined aquifer becomes sub- to fully artesian.

The south of the area is a strong discharge zone linking to the major discharge complexes to the east and south-west (Barnett, 1994).

Thus we can build a picture of 2 generally hydraulically distinct aquifers that undergo similar hydrogeological process, but at different rates and with peculiarities determined by the host aquifer rock-type. Along the courses of the major rivers, however, we see vertical connection and some mixing occurring during flooding. Lateral flow in the deep aquifer will continue to be towards the lake, though at reduced rate as the pressure gradient relaxes following local extraction.

This revised picture is shown in Figure 12 (with the presumed systems from before and immediately after the main irrigation extraction period of the 1950s to 1980s, shown in Figure 13). We may use these figures to help refine water and salt balance figures across the basin.

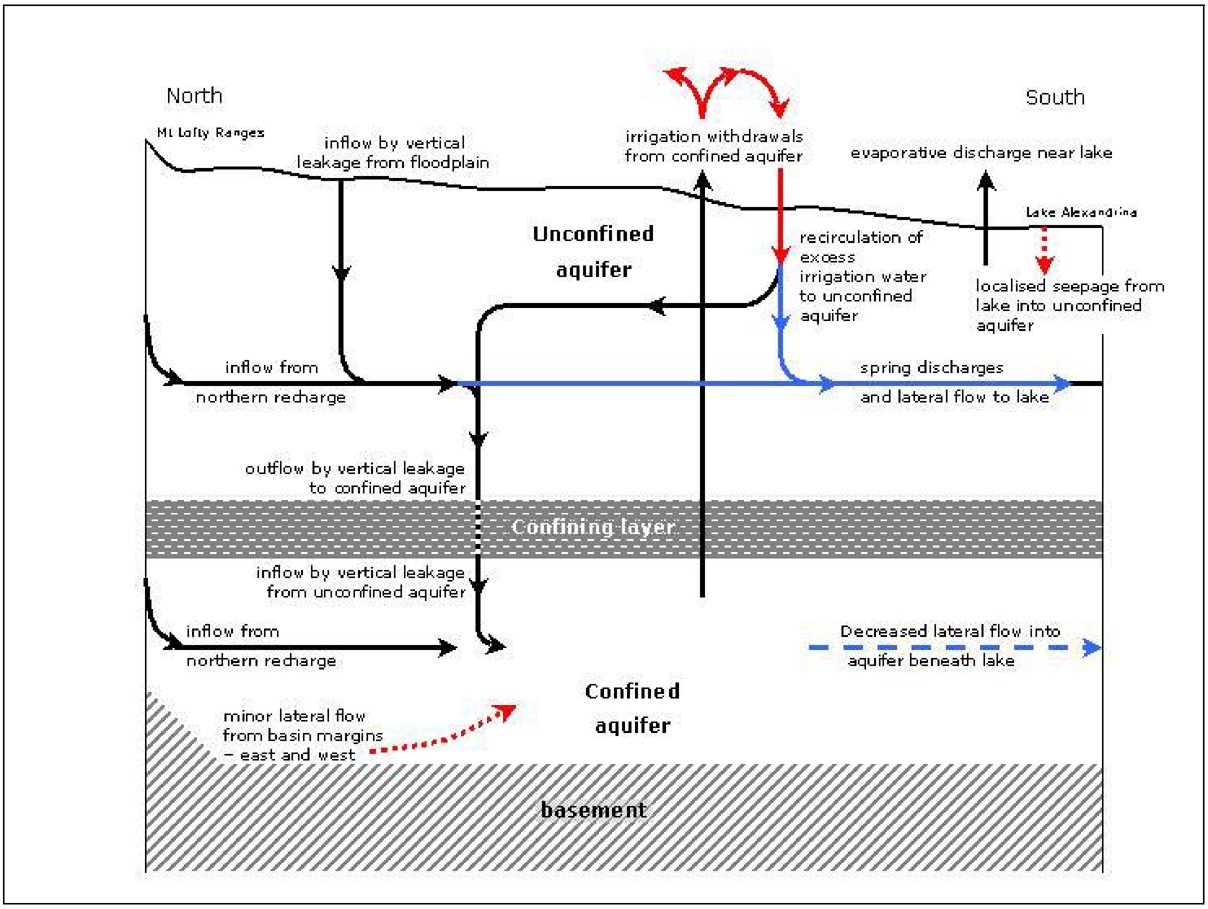

Figure 12. Revised present-day groundwater model for the Angas Bremer Plains, deduced in light of the SA-SMMSP and related work. Red arrows indicate continued modification of the pristine system; blue arrows represent a return to pre-irrigation dynamics. Compare with Figure 13.

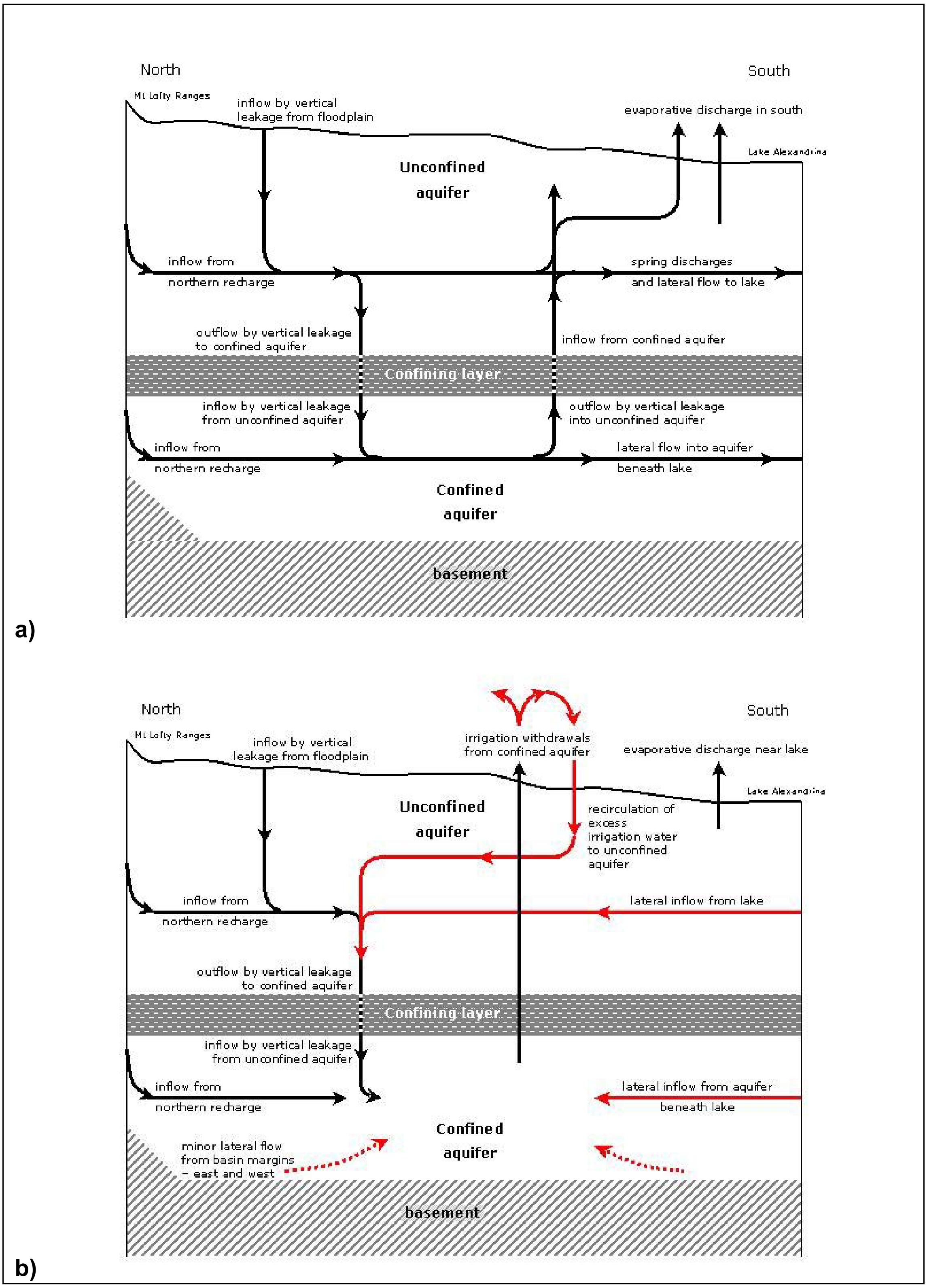

Figure 13. Pre- (a) and post- (b) expansion groundwater models for the Angas-Bremer Plains. (*Summarised and modified after:* Waterhouse, et al., 1978 and Howles, 1999). Red arrows indicate modifications to the pristine system.

9 Additional Data

Four additional initiatives also have direct bearing on this project (Tony Thomson, pers. comm.). All have produced copious amounts of data that needs to be distilled and integrated if we are to address water resource management across all scales, both physical and political:

1. Floodplain study
2. Groundwater monitoring wells
3. CSIRO FullStop implementation
4. Detailed soiland soil-moisture information.

9.1 FLOODPLAIN STUDY

The Angas Bremer Water Management Committee (ABWMC) has equipped each of 8 sites with sensors and data-loggers that are recording (at 15 minute intervals) each of:

1. Soil moisture at every 0.5m depth interval down to the water-table (at up to 6m deep)
2. Water levels in the unconfined, shallow, water-table aquifer
3. Water levels in the deeper, confined aquifer that is used to supply irrigation water.

9.2 GROUNDWATER MONITORING WELLS

Each Angas Bremer irrigator has installed a monitoring well in order to measure and to record the water-level and to measure and to record the salinity of the water-table in Sep, Dec, Mar, and Jun of each year. The water-level data and the water salinity data for each property are collated into the Irrigation Annual Report. The data is distilled to produce, for each season, maps of the district showing the depth to ground-water and maps showing the salinity of the ground-water.

9.3 CSIRO FULLSTOP IMPLEMENTATION

To improve irrigation practices, each Angas Bremer irrigator has installed two CSIRO FullStop devices with one FullStop located within the active grapevine root zone, at 0.5m, and one located below the active root zone, at 1.0m deep. Whenever the FullStop at 1.0m deep collects water, the irrigator measures and records both the volume collected and the salinity of that sample and compares this figure with the salinity applied in the irrigation water. 160 sites each with 2 FullStops have been installed across the region.

A description of the soil profile was recorded when each FullStop was installed. (Rex Jaensch, pers. comm., 2002).

9.4 DETAILED SOILS AND SOIL MOISTURE INFORMATION

Detailed soil information has been collected on many properties in order to develop Irrigation and Drainage Management Plans (IDMP) (Bruce Weir, pers. comm., 2002). Many Angas Bremer properties also routinely log soil moisture.

> The amount of information available for the Angas-Bremer catchments means that we have the potential to develop truly sustainable conjunctive water management decisions from the paddock through to catchment scale. This could be driven, not by hypothetical ideals and models, but through pro-active response to real data: using data as a sound basis for policy.

PART D. INFORMATION FOR MANAGEMENT

10 Addressing the Project Objectives

We may combine the results from the airborne geophysical surveys with the findings from the other sub-projects to address the project objectives:

10.1 DETERMINE THE RELATIVE IMPORTANCE OF DIFFUSE AND DIRECT RECHARGE (VIA PERIODIC FLOODING) IN REPLENISHING THE GROUNDWATERS IN THE ANGAS BREMER PLAINS

> Recharge to all groundwaters beneath the Angas-Bremer Plains appears to be predominantly via stream-bed infiltration, particularly following periodic winter floods. The head potential of the deep aquifer recovers rapidly following these events. Lateral recharge is limited to minor infiltration from the north.

There are three main mechanisms of recharge that are thought to be important across the Angas Bremer Plains. These are:

1. Major direct recharge through infiltration from the beds of the major surface tributaries (*i.e.*, the Angas and Bremer Rivers);
2. Minor indirect (diffuse) recharge through rainfall infiltration to the soil and subsequent movement of soil water past the root zone into the unconfined aquifer;
3. Minor recharge at the basin margins followed by lateral flow to the unconfined and/or confined Tertiary aquifer.

Differences in stable isotopic composition of water can often distinguish diffuse and direct recharge mechanisms due to the latter's propensity to display relative enrichment in the heavy isotopes of hydrogen (^{2}H) and oxygen (^{18}O) due to evaporation prior to recharge.

Diffuse recharge shows less evaporative signature because once water infiltrates below a metre into the soil it is not affected as much by direct evaporation. The isotopic composition of the groundwaters sampled from the observation bores show a slight tendency to be more enriched in ^{2}H and ^{18}O closer to the rivers, and these also display the lowest salinity. The mean values for $\delta^{2}H$ and $\delta^{18}O$ of the two major aquifers are identical indicating that recharge mechanisms are the same for the two aquifers.

The main evidence for recharge rates and mechanisms can be inferred from the ^{14}C data. One sample collected from the fractured rock aquifer up-gradient of the plains gave a ^{14}C activity of 51.6 % modern carbon (mc) which corresponds to an 'uncorrected' age of about 5,000 years. If this represents the starting point for a lateral flowing system, then all groundwaters down-gradient of this location should have lower ^{14}C activities due to radioactive decay of ^{14}C. Shallow groundwaters almost all have modern or near modern ^{14}C values, and some near the rivers have measurable CFC's (which have only been present in groundwater systems since the 1950s), indicating that the shallow, unconfined groundwater system is actively recharged from local sources rather than receiving laterally flowing groundwater from the margins. In other words, input of water less than 50 years old dominates the shallow groundwater recharge.

The deeper, Tertiary groundwater system tends to have ^{14}C activities between 67%mc and 33%mc. This corresponds to uncorrected ages of about 4,000 – 8,000 years. These ages are on the same order as that from the fractured rock aquifer sample to the north. There is no pattern of decreasing ^{14}C with distance along the hydraulic gradient suggesting that a recharge sources from the hills/plain break-in-slope and diversion of water through faults to the Tertiary system are not significant contributors to recharge beneath the plains. More likely, the similar water chemistry and stable isotope composition of the Quaternary and Tertiary aquifers, but the older age of the latter, suggests that recharge is predominantly vertical, with a combination of both direct and indirect local sources. Recharge to the upper aquifer leaks slowly downwards, across the aquitard, into the Tertiary aquifer on a time scale of several thousand years. The flow systems of the two aquifers, though connected, are therefore replenished at time scales that differ by up to three orders of magnitude, with the deeper Tertiary system essentially being a non-renewable resource on the time scale of decades to centuries.

The recharge zone may be usefully defined using the images generated by the airborne radiometrics surveys. The extents of the 1992 floods (Figure 14), which was a major flood event, confirm the use of radiometrics to define the flood-plain extents. It is clear, also, that more significant floods have occurred in the past, as the 1992 flood covered only a third (3,000ha) of the area defined by the radiometrics (>10,000ha). Increased incision of the upper reaches of the rivers (enhanced since settlement of the region) may be responsible for decreased flooding in the upper parts of the alluvial plain.

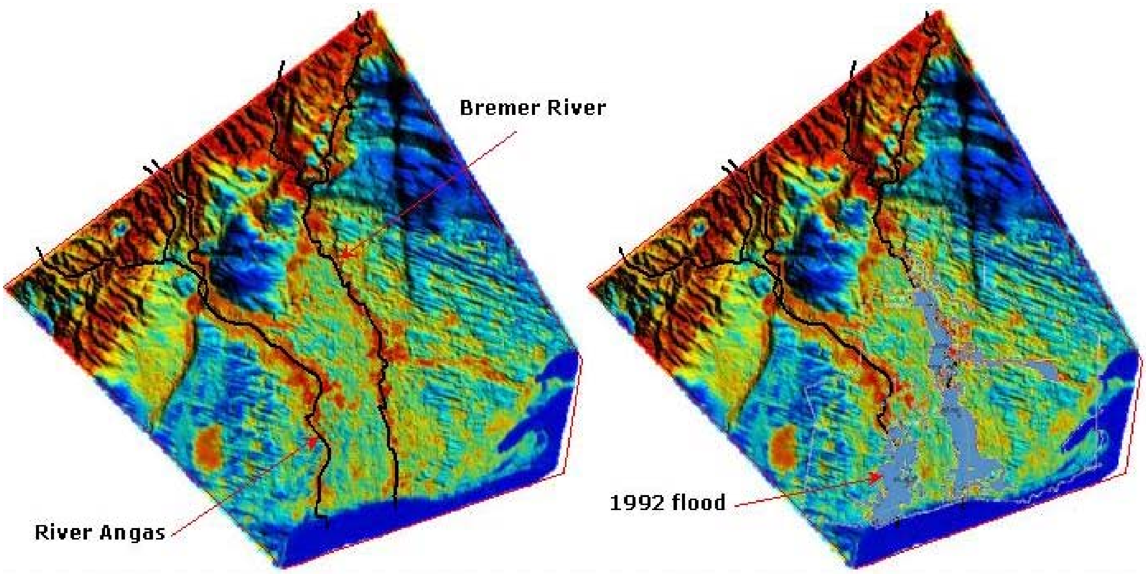

Figure 14. Radiometric response from the area (left) and the extent of the 1992 flood (right). Note the correlation between the river outwash deposits shown in red and orange on the radiometrics image, and the extents of the flood. While the second largest flood in recorded history, the floodplain deposits clearly extend a considerable distance up-stream and may reflect larger flood events.

The December 1992 floods are an example of a major flood event, being the second largest on record (after those of January, 1941) and flow down the Bremer River exceeded the flood markers at the Langhorne Creek Bridge (>3.6m) continuously for 66 hours from midnight December 17th to 6pm December 20th. Five major floods rose and fell over this period. In addition, in a period of 6 weeks from mid-August to early October, 6 further flood events were recorded (Len Potts, *pers. comm.*). If we estimate an average of 1m depth across the flood plain, this implies a volume of water of nearly 30,000 ML (30 gigalitres, GL) ponding across the plain.

The annual flow for the Bremer River in 1992 was 71 GL. Continuous flow was recorded at Langhorne Creek from June 1992 to March 1993. Whilst 3,800 mm of rain fell at Mt. Barker, at the headwaters of the creek, only 500 mm rain fell over this period at the Langhorne Creek post office. Direct precipitation to the floodplain, therefore, could have contributed approximately an additional 15 GL. Evaporation during the major flooding events in December would have reduced the amount of water available for infiltration significantly. Pan evaporation was down from the monthly average of about 200 mm to 150 mm, and if we use a pan evaporation factor of 0.7 (Chiew, et al., 1995), we may estimate potential evaporation to reduce the available water by a little over 100 mm, or 3 GL.

By contrast, the 2001 flood covered an area of 1,200ha with the river level only reaching 3.6m briefly on September 8th. An average flood depth of 0.3m is estimated from river height data, giving a total of only 3.6 GL on the plain. From long term flow data at Hartley, this is a more typical event, with 15 similar magnitude years in the last 25 years, plus 2 elevated years (1992 (71 GL) and 1981 (50 GL)). The 2001 floods occurred during winter, though evaporation still had the potential to remove some of the available water at the surface. Pan evaporation during the period of most intense flooding (8-10th September) was recorded as only 10 mm. In addition, rapid infiltration of surface waters to the shallow aquifer is indicated by the rapid fall in creek levels from 3.6 m to 0.6 m over 3 days, so only minimal evaporation would have taken place during this time (<<120 ML).

Using the historical record (Len Potts, pers. comm., 2002) we see 15 events of this magnitude over the past 25 years, giving an average of just over 2GL available recharge from flood events. We argue that this is the main recharge mechanism, and now balances with the measured extraction of 2GL across the Prescribed Wells Irrigation Area.

Like most groundwater systems, the Angas Bremer system is reasonably robust, and has a certain ‘momentum’, or hysteresis: a delayed response. The reduction in pumping in the early 1980’s saw an immediate stabilisation of water levels between 1 and 2 m AHD around Langhorne Creek (Figure 15), but did not lead to a full recovery to pre-irrigation levels. The very wet season of 1992/3 kick-started that recovery, and, when combined with the further extraction reduction from 10 to 2 GL over the next 5 years, means water levels have continued to rise back to pre-irrigation levels, even though extractions have been relatively unchanged since 1997.

This shows the aquifer has the ability to correct previous imbalances, but requires concerted management intervention if this is to take place. The beneficial effect of high recharge events alone would have lasted only about 5 years if the very high pumping rates of the 1980’s were practiced (Steve Barnett, pers.comm., 2004).

From chemistry indications there does appear to be a small component of flow from the north, beyond the hinge zone at the margin of the Tertiary sediments. The similarity in chemistry of the waters from the north of the river floodplains, and the deeper aquifer waters across the whole area, suggests that there is no direct impediment to recharge to the deep aquifer from the north (Cresswell & Herczeg, 2004).

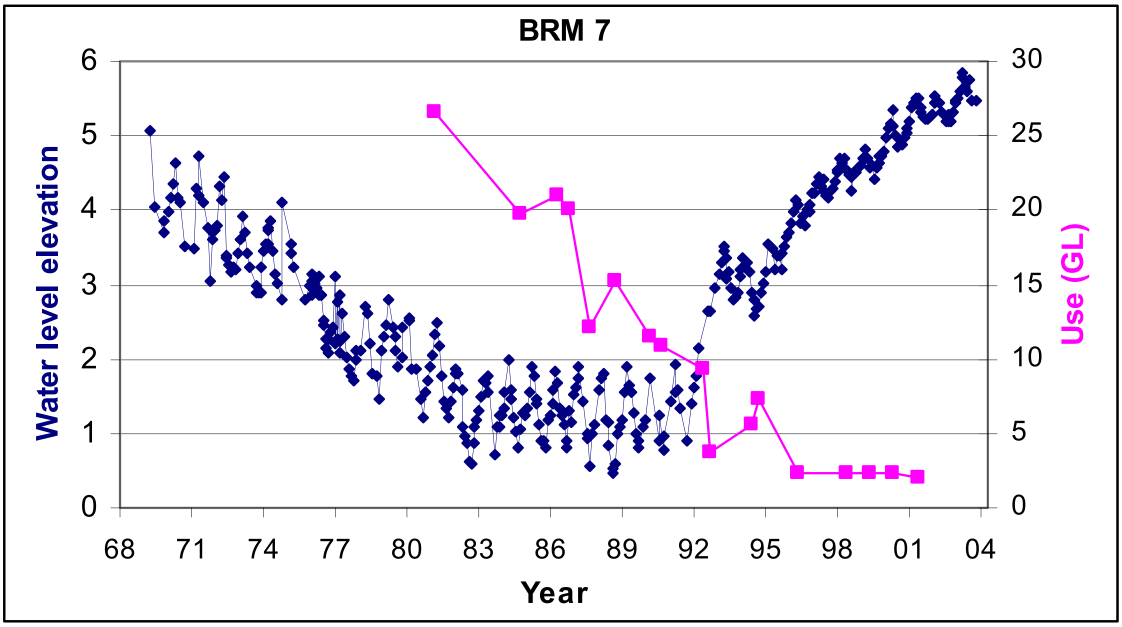

Figure 15. Measured groundwater level (mAHD) and extraction rates (GL/a) in the vicinity of Langhorne Creek

Waterhouse, et al. (1978) have demonstrated, however, from hydro-dynamic principles, that lateral flow takes place at <60m/year. Hence we may expect a minimum of 300 years for waters entering on the dunes to the east and west to permeate to the bores adjacent to the river, and we might expect trends in the environmental tracers towards the lake. As these are not apparent, we deduce that lateral flow is negligible.

We note that there is negligible, if any, input from the lake into either aquifer, though Ramamurthy & Holmes (1983) suggested that locally it may occur along the lake margin, but only into the upper aquifer. In the south of the region, discharge processes dominate, with water movement upwards and towards the lake. We note however, that inflow from the lake might only be expected when a cone of depression was developed in the lower aquifer due to over-pumping.

10.2 DETERMINE THE SOURCE(S) OF SALT IN THE GROUNDWATER

Salt in the region is predominantly derived from rainfall (*i.e.* it is cyclic). Some water-rock interaction takes place in the deep carbonate-rich aquifer, but most salt in the groundwaters is derived from evaporative concentration of rain- and river-waters.

The origin of dissolved salts in the groundwaters can be divided into four possible sources:

1. Dissolution of salt deposits within the sedimentary formations;
2. Entrainment of seawater from the marine sediments;
3. Weathering of aquifer mineral, or
4. Concentration of marine derived atmospheric aerosols.

The relationship between bromide and chloride can be used to evaluate whether salt (halite) or rock minerals contribute significant amounts of dissolved solutes to the salt load. Cresswell & Herczeg (2004) show that sodium and chloride are the dominant ions in solution, and as chloride is the most hydrophilic of all the dissolved halides, the source of chloride (and by association sodium) determine the predominant salt load.

Bromide and chloride relationships for the Angas-Bremer Plain groundwaters are consistent with a marine origin, either through seawater dilution, conservative concentration of salts derived from marine aerosols, or from residual seawater, and are similar to other groundwaters in the Murray Basin (Herczeg, et al., 2001). The data are neither consistent with salt dissolution nor mineral weathering, as halite (NaCl) and most rock-forming minerals are deficient in bromide and would yield Br/Cl ratios in water much less than those observed. The observed values are similar to the seawater value of 2.45 x 10^{-3}. Evaporation does affect the composition of the shallower waters (as indicated above), but to a relatively small degree.

The chemical and isotopic data for the Angas-Bremer Plain groundwaters are typical of much of the Murray Basin sand and carbonate mineral aquifers. The chemical composition of the waters is dominated by Na^+ and Cl^- and the overall composition of the waters are similar to seawater. This observation has led to the hypothesis that the salts in the groundwaters are the product of mixing between the new rainfall recharge, and the remains of connate marine brines left over from the last seawater incursion. Alternatively, the salts may be the left-over precipitated salts from that earlier seawater incursion that are now being dissolved and re-mobilised into the groundwaters due to water table rise. The geochemical and isotopic evidence, however, does not support either of these models (Cresswell & Herczeg, 2004).

The main line of evidence against the seawater dilution proposal is that the isotopic and chemical data all indicate the predominant influence of either recent rainfall (δ^2H, $\delta^{18}O$, ^{14}C, CFCs) or water-rock interaction ($\delta^{13}C$, $^{87}Sr/^{86}Sr$, radon) and not the presence of residual seawater. That the groundwater chemistry trend towards seawater values indicates the evolved nature of some of the waters and the influence of evaporation on rainfall-derived recharge waters. Looking in detail at the chemical relationships, we may summarise the processes dominating for each solute and identify four end members that may reasonably provide source elements, or define processes driving the geochemistry of the waters:

1. River recharge (predominated by flood waters)
2. Seawater input
3. Mt Lofty recharge waters
4. Dissolution of Tertiary carbonates

While there is a suggestion of evaporation as a driver for solute concentration from the isotopic data, this is a minor process in the area, but probably accounts for the initial concentration seen in the river waters from evaporation of rains.

10.3 DETERMINE THE EFFECTS OF FAULTING IN THE REGION ON REDIRECTING GROUNDWATER FLOW SYSTEMS

> Faults define the eastern and north-eastern boundaries of the groundwater system. There is no evidence for a major fault contact to the north, as has been proposed previously. A very deep structure may have influenced the margin of the older sediments, against which the younger limestones were deposited in the Tertiary Period. The north-eastern faults act to direct water movement towards the south and constrain the extent to which fresh waters from the rivers recharge the underlying beds.

Faults have played a major role in defining the groundwater systems. Their main role has been to define the structural extents of the low salinity aquifer systems and the location of main river courses along faulted scarps. The major structural elements are shown in (Figure 12) which shows the control exerted on the deeper aquifer as defined by the AEM. This outlines the major constraint currently imposed by the faults, namely to restrict recent recharge to a region bounded by faults to the east and north-west, while the northern boundary is defined by the on-lapping relationship of the deep aquifer over the Palaeozoic basement. To the south the system appears to open into and below Lake Alexandrina.

There is no evidence that the northern boundary is controlled by a fault, though there may still be preferential recharge along this boundary at the interface between the aquifer sediments and underlying basement.

10.4 EVALUATE THE EXTENT OF INTER-AQUIFER MIXING IN DIFFERENT PARTS OF THE ANGAS BREMER PLAINS

> While there is a strong similarlty between the upper and lower aquifers, indicating similarity in recharge processes, there appears to be little direct inter-aquifer mixing across the plains.

The general hydro-chemistry of the waters in each aquifer is similar (Cresswell & Herczeg, 2004). Isotope and minor element species concentrations, however, suggest that the two main aquifers are distinct. The upper Quaternary aquifer generally shows a wider spread in concentrations and minor element to chloride ratios when compared to the deeper aquifers. The upper aquifer particularly shows considerable variability in sulphate and bromide to chloride ratios indicating incomplete mixing of surface waters and spatially variable interactions in the near-surface. This is typical of shallow, unconfined aquifers where recharge mechanisms vary from place to place.

Environmental isotopes give the strongest evidence for a predominantly split system, with an overlying unconfined sandy aquifer and a lower, confined, calcareous aquifer. While the chemistry and stable isotopes suggest that the processes acting on the two aquifers are similar, the radioisotopes of carbon and radon define distinct properties for each aquifer.

The deeper aquifer exhibits distinct isotopic signatures that strongly suggest a longer period of equilibration and restricted interaction with either the atmosphere or other water bodies. There is some evidence of vertical recharge from the upper aquifer, though this is restricted to zones along the floodplain. The host, carbonate-dominated aquifer, also exerts a strong influence on the chemistry through dissolution and re-precipitation of carbonates.

10.5 ESTIMATE GROUNDWATER RESIDENCE TIMES

> There is rapid (seasonal) recharge to the upper, unconfined aquifer. Recharge to the lower aquifer appears to integrate over longer time periods (thousands of years), but shows a rapid pressure response to seasonal major flood events.

As was discussed above under recharge, we see that shallow groundwaters almost all have modern or near modern ^{14}C values, and some near the rivers have measurable CFC's (which have only been present in groundwater systems since the 1950s). This indicates that the Quaternary groundwater system is actively recharged from local sources of water less than 50 years old, and probably reflects rapid recharge from periodic flood events.

The deeper, Tertiary groundwater system has ^{14}C activities between 67 percent modern carbon (%mc) and 33%mc. This corresponds to uncorrected ages of about 4,000 – 8,000 years. The lack of any spatial pattern in the ^{14}C data suggests a dominant vertical flux. The Quaternary and Tertiary aquifers exhibit similar water chemistry and stable isotope compositions, but the Tertiary aquifer water have older ages also suggesting that recharge is predominantly vertical, with a combination of both direct and indirect local sources. The recharge leaks slowly across the aquitard into the Tertiary aquifer on a time scale of several thousand years. Thus, while the two aquifers are connected, they are replenished at time scales that differ by three orders of magnitude. This implies that the Tertiary system requires decades to centuries to replenish.

10.6 ASSESS THE STATE OF VEGETATION HEALTH IN A SALT-STRESSED ENVIRONMENT

> Minimal vegetation stress was observed on the Angas-Bremer Plains, largely reflecting the dominant uptake of surface waters for plant growth. Water-tables are generally deep enough not to restrict vegetation health. An objective measure of stress is advised (such as chlorophyll fluorescence yield) rather than subjective observations.

At 4 sites across the Angas Bremer Plains, minimal salinity stress was observed. These sites are located within 10km of the shore of Lake Alexandrina and within areas shown to have high conductivities on the shallow AEM images. Water-tables, however are generally below 5m from ground surface and, at least at one site, the AEM response is partly due to clays in the sub-surface. There was some stress observed just outside the AEM-covered zone, in an area with shallow water tables in the dune country.

Thus, water-table depth is the main criteria determining plant health: deeper water-tables allow healthier plants.

This study also found that visual inspection was not a reliable indicator of plant health, but recommended the use of chlorophyll fluorescence yield to detect mature plant stress (Camp, 2004).

11 Conclusions

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

In the Angas Bremer Plains region of the Murray Basin, the principal goal of the geophysical survey was to map groundwater systems *rather than* salinity. A combination of airborne geophysical techniques and rigorous field and chemical analyses has shed light on the recharge mechanics and groundwater movement across the Plains and helped define the extents of the groundwater systems and the origins of salt in the region.

Conclusions from the Project were:

- Airborne electromagnetics usefully defined the extents of the freshwater zones within the unconfined and confined aquifers;
- Airborne electromagnetics defined the deeper controls on groundwater movement;
- Radiometrics helps define the extent of the flood-plain and clearly distinguishes differing soil types;
- Combining the radiometrics with the digital elevation model (DEM) provides an accurate assessment of land management units (LMU's);
- The flood-plain plays a pivotal role in recharge to both the unconfined and confined aquifers;
- Recharge is dominated by vertical (direct) infiltration across the region, driven mainly by periodic floods and high leakage rates beneath the river courses;
- Faults are associated with only minor recharge;
- The confined aquifer is poorly confined, with the confinement determined by the nature and saturation of the confining medium;
- The salinity of the aquifers is controlled by recharge – the confined aquifer is recharged with fresher waters from the rivers;
- Recharge is relatively rapid, with a seasonal response to recharge and rapid re-equilibration of the aquifers following irrigation draw-downs;
- A primary objective of observing palaeo-channels with the airborne magnetics was not achieved, but information on deep structures was obtained;

- AEM and magnetics are good adjuncts to borehole information, even in a well-drilled environment. We can join the dots with confidence.
- Visual assessment of eucalypt health is ambiguous at best. Parameters such as chlorophyll fluorescence yield, however, shows promise as an indicator of salinity stress;
- As long as water tables are below the root zone, salinity stress is not prevalent.

12 Lessons Learnt

Lessons to emerge from this study can be summarised as follows:

1. Airborne geophysical data is a useful adjunct to traditional data collections and can effectively link surfaces, features and attributes that are disjointed in space.
2. We need to ask airborne geophysics specific questions that it can reasonably answer and tightly constrain the variables through careful ground truthing.
3. Local experience and expertise is vital if we are to accurately interpret the geophysical data.
4. Local experts in resource management need to be involved with the project design and throughout the project to provide reality checks and guidance. The community needs to be engaged at an early stage and regularly updated throughout the project.
5. It is important to evaluate all available data and ensure that interpretations are commensurate with that data as well as the airborne geophysics.
6. Prior to flying airborne geophysics, ground surveys should be conducted to ensure airborne geophysics is an appropriate tool and can detect whatever we are investigating.
7. The airborne geophysical modelling should be updated continually through the project as more on-ground results become available.
8. We must maintain a flexible approach both in expectations and the targets we are investigating.
9. Don’t underestimate the power of good images as education tools.
10. A combination of technologies give a better picture than isolated techniques.

13 Transferability

The technologies described here are directly transferable to:

- Regions with multiple aquifer systems, where vertical recharge along river courses is dominant.
- Floodplain regions, where definition of the flood-plain extents, and soil-type distributions, is a goal.

In addition, the information obtained from these studies is also applicable to:

- Upper catchment managers who wish to monitor the downstream responses to their activities.
- Natural resource managers planning future expansion in the region.
- Sites being considered for native vegetation planting.

14 Recommendations for Management

1. The prominent role of streamflow recharge, both in providing surface water to replenish floodplain soils and provision of recharge waters for both the unconfined and confined aquifers means clever management of flood waters is crucial for the long-term health of the region. Streamflow is the primary source of recharge across the plains so any change to flooding conditions will affect the water system in the floodplain. Salinity is intimately entwined with this and salt may be slowly accumulating in the near surface with implications for future disposal to maintain healthy soils.
2. Water levels need to be controlled both in the unconfined and confined aquifers by judicial use of groundwaters augmented by ASR and continuing use of Murray water, via Lake Alexandrina. Water levels have almost returned to pre-irrigation levels, but this may mean loss of productive land along the lakeshore as water levels rise leading to waterlogging and salinisation along this zone. It needs to be noted that the new groundwater regime is 0.75m higher than the natural one due to the effects of the barrages on artificially raising the height of the lake's surface.
3. Salt levels across the region are gradually increasing due to the application of irrigation waters. This increase in root-zone salinity can be controlled by increased leaching in some areas, but must be managed such that deep drainage to the aquifer is minimised. The rate of increase can be measured by using monitoring devices such as 'FullStops', which are currently installed across the region. The rate of accumulation can be evaluated and if necessary, this salt might be released to the upper aquifer in a controlled manner, such that there is minimal leakage to the confined aquifer. Drainage of the upper aquifer to the lake would dilute the salt sufficiently for disposal. This should be seen as a very long-term approach.
4. An improved groundwater model should be constructed to enable modelling of these scenarios. There is now sufficient data to facilitate this activity.

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

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

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