Application of Airborne Geophysical Techniques to Salinity Issues Around Jamestown, South Australia

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

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EXECUTIVE SUMMARY

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

In the Jamestown region of the Northern and Yorke Agricutural District, the principal goal of the geophysical survey was to map groundwater systems *rather than* salinity, with a view to providing improved information to assist in the protection of high value cropping land. The area has a history of localised outbreaks of salinity and waterlogging following periods of higher than average rainfall. While local land managers have implemented practices to deal with the problem, the better understanding of groundwater systems provided through the SA SMMSP will give land managers greater confidence in the effectiveness of their actions. Another factor in choosing the Jamestown site was the relatively high level of existing knowledge, which is valuable for both proving the geophysical techniques and optimising benefits from the newly acquired data.

A combination of airborne geophysical techniques and rigorous field and chemical analyses has shed light on the recharge mechanics and groundwater movement through the valleys and helped define the extents of the groundwater systems and the origins of salt in the region.

Combining the images created from the airborne technologies, precise boundaries to the groundwater systems can be drawn in 3 dimensions. Surface and sub-surface divides are not always coincident, but we can now stipulate where surface waters will end up when they percolate through the soils.

Salinity is expressed at the surface where convergent groundwaters are impeded by bottlenecks in the subsurface geology. This is compounded for the Caltowie Valley in the west, as it has a shallow groundwater system, while in the east, good sub-surface drainage in the Belalie valley suggests salinity will not be a major problem. During wetter than average years the central, Bundaleer, Valley will experience salinity south of Jamestown.

Close attention to rainfall trends and monitoring of groundwater levels is vital to give good prior warning of impending salinity. The use of drains to protect important assets, such as the township of Jamestown, is appropriate. Maintaining vegetation cover on hillslopes will also moderate any water-table rise that will lead to salinity.

Three expressions of salinity are recorded in the region:

1. **Water-table driven salinity**, south of Jamestown and east of Caltowie, has developed where groundwater flow systems are restricted above confluences of surface and sub-surface water flow: the system cannot drain as fast as it fills. This occurs particularly following a run of wetter than average years. Rising water-tables entrain the salts in the landscape, bringing them to the surface.

2. **Break-of-slope salinity** occurs locally where coarser-grained hill-slope sediments meet the finer-grained valley sediments along valley margins. Rainfall recharging on the hills flows through the coarser sediments, but cannot flow as rapidly through the valley floor sediments, so seeps out at the junction. Evaporation concentrates the salts in the near-surface at these sites.
3. **Dry saline land** (ie. transient salinity, 'magnesia patches', sub-soil salinity) is not associated with groundwater / shallow watertables. Magnesia patches are expressed where hillslope vegetation is removed, topsoils erode and naturally saline sub-soils are exposed. Transient salinity, as the name suggests, can produce intermittent low yields or patchy growth in cropping situations and is caused by the seasonal movement of salts up and down the unsaturated soil profile, generally where salts have been trapped above an impermeable sodic clay sub-soil. Unlike the other forms of salinity, dry saline land increases in area during dry years, and reduces during wet years, as the salts are flushed deeper into the soil profile.

The differing geological setting for each valley gives rise to different expressions of salinity. Each expression needs to be viewed in the appropriate context with regard to groundwater flow systems, landscape geomorphology and soil/ regolith[1] profile.

We can ultimately only distinguish different expressions of salinity by on-ground investigation. Remote techniques (including airborne and ground geophysics), however, can define the landscape environments that are prone to particular expressions and indicate where to concentrate further investigation. Once particular associations of remotely-sensed data can be ascribed to a particular expression of salinity, that combination may be used to identify other areas with a similar problem.

Combining the digital elevation model with the precise radiometrics images, for example, provides a detailed regional soil mapping tool and defines the extents of land management units.

The recent geological history controls the present-day expression of salinity across the region. Incised valleys have slowly filled with sediments eroded from the hills and washed down during flood events. As these sediments have filled the valleys, so constrictions in the bedrock structures have enhanced the build-up of salts in soil and regolith profiles. Where coarser sediments, weathering from the hillcrests, abut the alluvial sediments washed down in the floods, a break-in-slope coincides with a change in hydraulic conductivity, again enhancing concentration of salts.

Salt in the region is predominantly derived from rainfall (*i.e.* it is cyclic). Some water-rock interaction takes place as the groundwaters move through the soils, but most salt in the groundwaters is derived from evaporative concentration of rain-waters.

Recent filling of the eastern, Belalie Valley has resulted in overflow of the surface waters into the Jamestown Valley to the west. This compounds the problem of excess water seen during wet years in the Jamestown/ Bundaleer Valley, but further reduces the issue for the Belalie valley.

This work has provided information that is relevant to the management of salinity in the region:

1. Climate variability is the dominant driver for salinity. Monitoring of bore networks and response to rainfall events will give time constraints on water table rise and fall.

[1] Regolith comprises the soils and weathered material that overly fresh (unweathered) bedrock.

2. Sub-soil constraints (eg. boron toxicity, sodicity) are known to occur in the region but are difficult to identify at the paddock scale. Techniques are sought which can help identify their presence or absence, without the expense and effort currently required (eg. deep soil sampling and analysis). However airborne geophysics did not prove useful in this regard.

3. Magnetics and airborne electromagnetics (AEM) can delimit zones of higher moisture content. These may be areas that are more productive during drier periods, but may become water-logged and saline during wetter times. Some of these areas may require planting with salt-tolerant species to help maintain ground cover during periods of high water tables.

4. Geophysics can provide information on areas where drains might be appropriate (eg. where bottlenecks are identified).

5. Prolonged wet periods (>3-5 years) will result in elevated water-tables regardless of intervention strategies. Living with a few years of salinity-affected land should be accepted. Salinity will abate once a drier cycle ensues. The land should be managed to ameliorate the symptoms. Salt tolerant plant species and controlled grazing are options.

6. Dry saline land is minimally expressed in the region, mainly due to the adoption of best management practices: contour-banking to maintain moisture in hillslope profiles, restricted stocking in prone areas and maintenance of cover (e.g. crop stubble) to minimise evaporation.

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INTRODUCTION

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

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

The SA SMMSP 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 Jamestown 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).

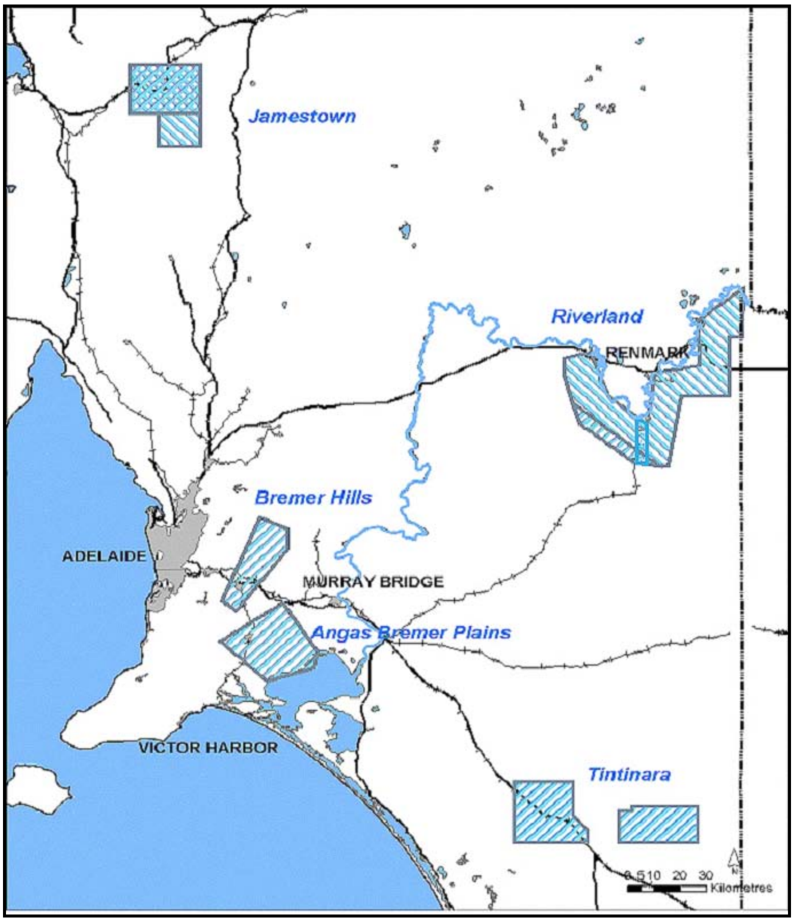

Figure 1. Location of the 5 study areas

The aim of this report is to summarise the study and main findings from the Jamestown site. Issues of extrapolation to other groundwater resources are also discussed. Similar reports have been written for each of the other study areas and a final report exists for the overall program. The report is divided into 4 parts, reflecting the staged approach taken 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 Jamestown region was to provide information to assist in the protection of high value cropping land, based on an improved knowledge of groundwater, soil and salinity distributions.

The contracted outputs included:

- Maps and associated products including enhanced soil and regolith maps demonstrating salt stores, solute transport pathways, salt sinks, synthesis of all available data to indicate hazards and management options.
- Hydrogeological model for the valley-floor groundwater systems
- Report on the application of ground-based techniques for non-water table related salinity.
- Report on overall site investigations

As the project progressed, these general outputs were refined to more accurately reflect the nature of the results emerging from the studies in the area. A number of detailed reports have been compiled to accompany the revised contractual outputs:

1. Maps and associated products to describe the soil and regolith landscape, including reference to salt stores, solute transport pathways and salt sinks.
    - Cresswell, R.G. and Herczeg, A.L. 2004. *Groundwater flow systems and salinity in the Valleys around Jamestown, South Australia: Geochemical and Isotopic Constraints*. CSIRO Land and Water Technical Report **30/04**, CSIRO, 36pp
    - Wilford, J.R. 2004. 3D regolith architecture of the Jamestown area – implications for salinity. Report to SA-SMMSP./ CRC LEME Open File Report 178. Cooperative Research Centre for Landscape Environments and Mineral Exploration.
2. Hydrogeological setting for the valley-floor groundwater systems
    - Henschke, C.J., Jones, G.L. and Cresswell, R.G. 2004. *Groundwater investigations an valley fills: Jamestown, South Australia*. Report to SA-SMMSP/ BRS Technical Report
3. Report on the application of ground-based techniques for non-water table related salinity.
    - Fitzpatrick, R.W., Thomas, M., Davies, P.J. and Williams, B.G. 2003. *Dry saline land: an investigation using ground-based geophysics, soil survey and spatial methods near Jamestown, South Australia.* CSIRO Land and Water, Technical Report **55/03**, CSIRO, 64pp.
4. Report on overall site investigations, with 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 Jamestown site.

- 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): TEMPEST: Jamestown and Angas Bremer Plains; RESOLVE: Riverland and Tintinara*. CRC LEME Report

An associated project, funded by the Grains R&D Corporation was aimed at evaluating the usefulness of airborne geophysics at the farm-scale. This project will be completed in the near future; an interim product has been produced:

- Kingham, R., Baskaran, S. and Cresswell, R.G. 2004 Targeting salinity at the farm scale. Jamestown Interactive Geographic Information System Data CD. Bureau of Rural Sciences, Canberra.

PART A. RESOURCE MANAGEMENT ISSUES

1 A History of Resource Management

Previous State agency reports indicate that dryland salinity started being recognised as a major issue in the Jamestown area in 1982. Farmers reported marked increases in dryland salinity during 1982 and were becoming increasingly concerned with the loss of production particularly in the lower lying areas of the Bundaleer Valley (pers comm. SA Dept of Agriculture internal reports, 1983 and 1985).

Three expressions of salinity are recorded in the region:

1. Dryland salinity associated with shallow seasonally fluctuating groundwater tables within low-lying alluvial plains
2. Break of slope salinity associated with seasonal fluctuations of perched watertables, commonly in the colluvial slopes adjacent to the alluvial plains, and
3. Dry saline land: Salt-induced scalds in upland areas (steep slopes and ridge crests) sometimes referred to as “magnesia patches”, and transient salinity (which can produce intermittent patchy crop growth).

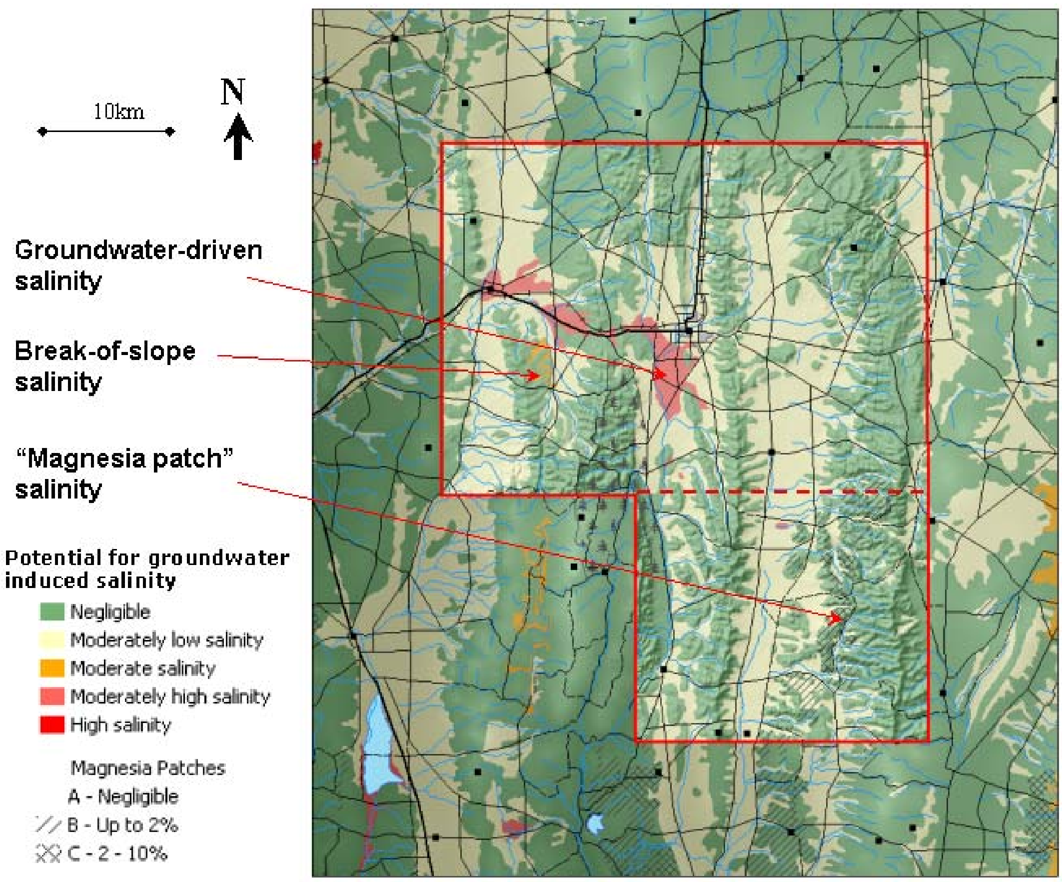

Figure 2. Distribution of salinity potential across the Jamestown region. (Data from DWLBC, 2002). Areas of severe dryland salinity indicated in red. The airborne geophysics fly-zone is marked by the red polygon. Only the top rectangle was flown with electromagnetics. (Figure compilation by Kingham, et al., 2004).

Dryland salinity is expressed as waterlogged and scalded areas in the Caltowie and Bundaleer Valley catchments (Figure 2). These areas have reduced recently as watertables have fallen by several metres over the past 10 years with corresponding decreases in salinised and waterlogged land. This has allowed the re-establishment of lucerne and wheat in some areas of the valley floor that have previously been unfarmable.

Historic, anecdotal evidence has put some crucial dates on the development of salinity problems in the region. These dates have been compared to the climate record (as indicated by the rainfall cumulative deviation from the mean, Figure 3) (Mary-Anne Young, pers. comm.). Periods of observed salinity (or waterlogging as it may have been termed) are shown to correspond with climatic trends. This is confirmed by monitoring of groundwater observation wells (see Figure 4), in more recent times, which shows that shallow watertables respond relatively quickly to rainfall trends.

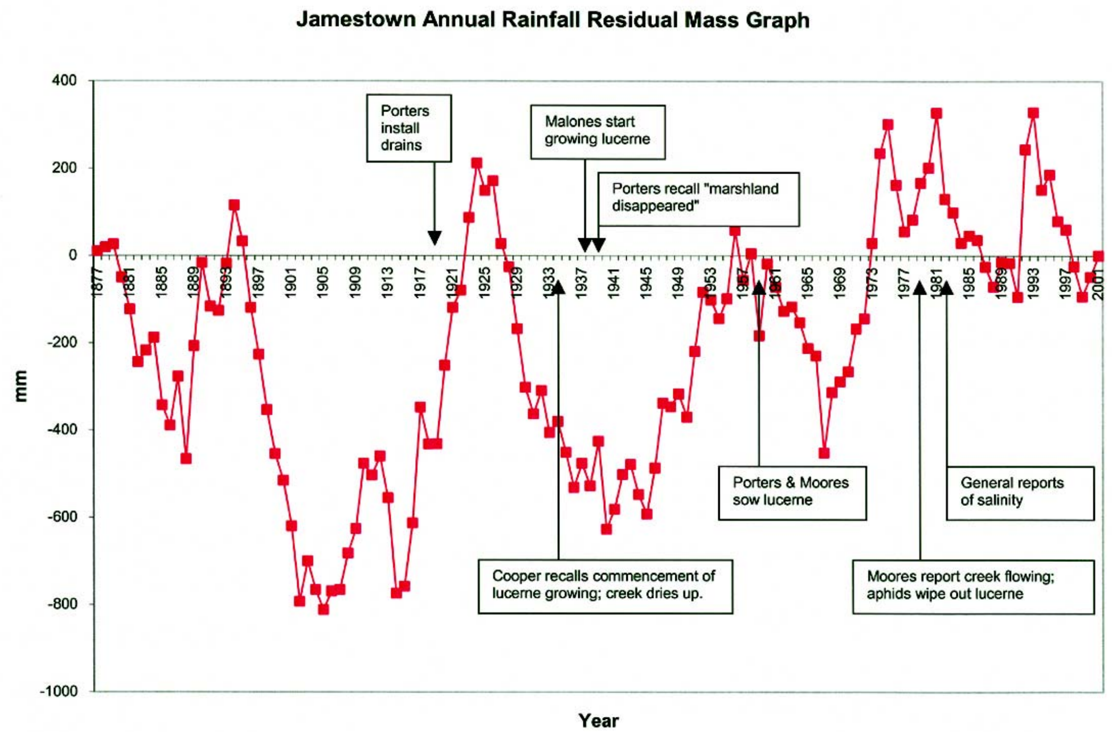

Figure 3. Cumulative deviation from the mean rainfall for the Jamestown Post Office. Significant environmental events are indicated from local knowledge (Mary-Anne Young, pers. comm.).

Recent salinity studies in the area have included Henschke et al. (1994), an intensive study of a small sub-catchment 3km west of Jamestown; and Rust PPK (1994), a dryland salinity investigation undertaken for the Bundaleer Valley Landcare group.

The study by Henschke et al. (1994) was part of a project aimed at establishing salinity management demonstration sites in key areas of the State. This investigation provides detailed information on the particular hydrogeological characteristics and salinity processes operating in this 301ha sub-catchment. Management options, including high water use plants (eg. lucerne) are presented, based on discrete land management units.

Rust PPK (1994) provides recommendations for minimising incidences of dryland salinity along the central floor of the Bundaleer Valley. These include a requirement for the long

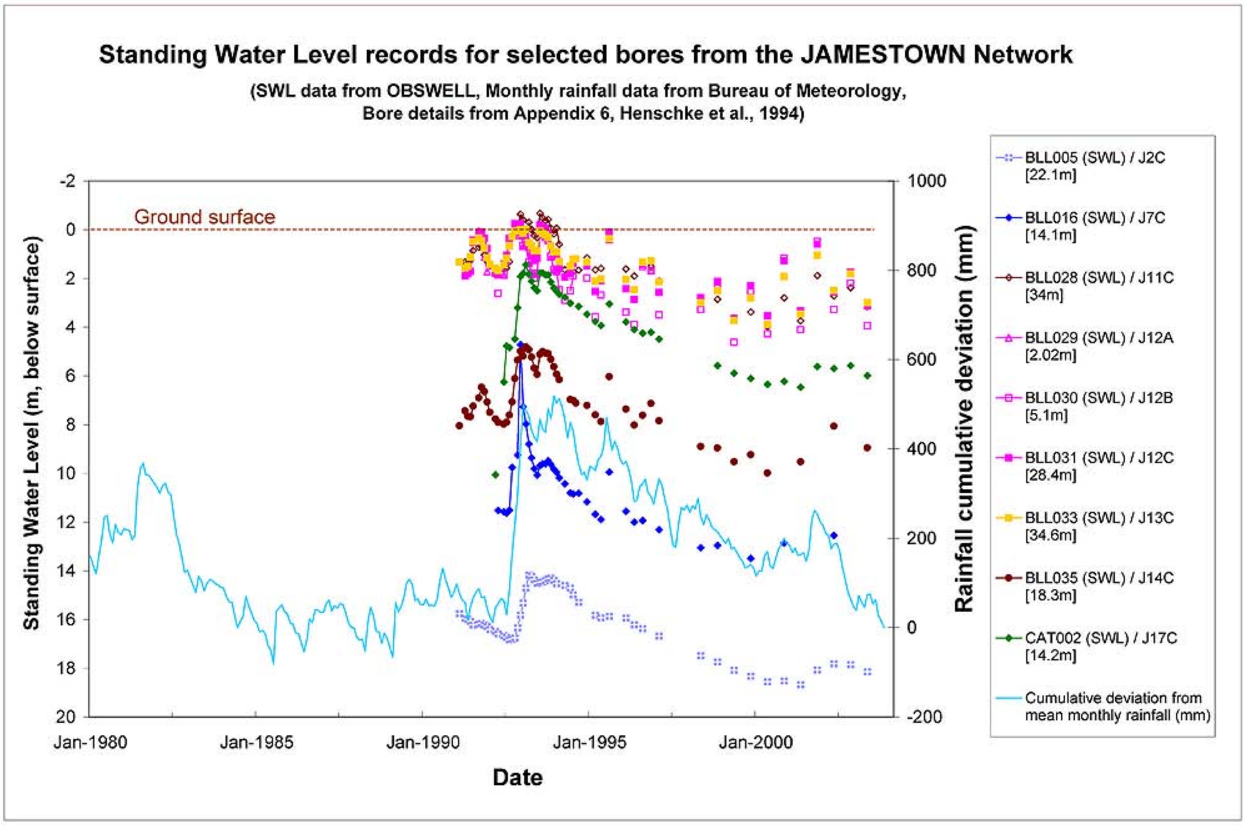

Figure 4. Hydrographs from observation bores in the Jamestown region indicate that watertables respond quickly and correlate well with rainfall trends. The light blue line shows the cumulative deviation from mean monthly rainfall. (from Liddicoat and Dooley, 2004)

term maintenance of at least 415 ha of lucerne in the valley floor, and high plant water use options for the high recharge potential ridges and higher slope skeletal and 'Yangya' series soil units of the eastern range.

Virtually no dryland salinity is observed in the Belalie Creek and Belalie Plains catchments. While the present broad Belalie Creek valley "pinches out" at Belalie gorge, the older, now buried, ancient valley (palaeovalley) continues south, crossing a subdued catchment divide (Wilford, 2004; Cresswell and Herczeg, 2004). This southerly extension of the valley contains the ancient buried watercourse (paleochannel) and the associated alluvial sediments of this tributary of the Broughton River (Rowett, 1997). Dry saline land is an issue in these areas, however, with locally named "magnesia" patches on northerly hill slopes and regions of poor production due to sub-soil, or root-zone, salinity, sodicity and toxicity (Rengasamy, 2002). These areas expand during drier periods in contrast to groundwater-driven salinity that increases during wetter times.

"Magnesia patches" are generally the result of erosion brought on by overgrazing on northern, warmer, drier hill-slopes. The recognition of this problem, and remediation by controlled grazing and contour banks on cropped land to retain moisture has seen almost all occurrences disappear over the last 10 years.

Farmers in the region are still concerned over the possible recurrence of salinity in the Caltowie and Bundaleer Valleys and need confidence that the management strategies they have in place will be adequate to constrain the extent of any future salinity outbreaks. This also applies to areas susceptible to further outbreaks of "magnesia patches".

2 The Jamestown survey area (Northern and Yorke Agricultural District NAP region)

The wide valleys and rolling hills of the Jamestown area belie a potentially complicated geological setting which includes a network of meandering underground ancient streambeds (paleochannels) and layered alluvial[2] and colluvial[3] fan deposits. Using airborne geophysics and supporting ground information the SA SMMSP attempts to delimit the nature, extent and origin of these regolith units and help define their relationship with groundwater quality and potential salinity hazards.

The Jamestown airborne geophysics fly zone straddles three broad north-south valleys (Figure 4), which are part of the Broughton River catchment. For the purpose of this report, the valleys have been named from west to east as follows:

- Caltowie catchment (headwaters of Yackamoorundie Creek)
- Bundaleer valley (headwaters of Baderloo Creek), including the Belalie Creek catchment (which feeds into Bundaleer Valley via Jamestown)
- Belalie Plains catchment (headwaters of Freshwater Creek)

There are three main geological zones that influence groundwater flow systems in the catchments:

- Basement rock (fractured rock aquifers)
- Colluvial outwash fans fringing the ridges
- Valley-fill alluvium (sedimentary aquifers in the broad valleys)

The Jamestown region is characterised by a range of landforms from low relief colluvial and alluvial fans, floodplains and pediments[4] through to rises, low hills and hills. Depositional materials occur in three main valleys: the Belalie, Bundaleer and Caltowie. Coalescing colluvial and alluvial fans of Quaternary age have filled these valleys to depths of up to 40 metres. The thickest sediments consisting of silt, clay, fine sand and minor gravels occur in the Belalie and Bundaleer valleys. The Caltowie valley has a thinner sediment cover which appears to have a lower electrical conductivity when compared with the other two catchments. Low angle pediments characterise the upper parts of the Caltowie catchment (Wilford, 2004).

The study area covers the upper parts of three catchments which occupy about a quarter of the area of the Broughton River catchment (see Figure 5). The central (Bundaleer) valley contributes water to the Bundaleer Reservoir. This is considered an unreliable reservoir in terms of water quality with a mean salinity of 1100 mg/L. Previous diversions from Freshwater Creek (Belalie Valley) have ceased due to high salinity, indicating that dryland salinity has impacted on this storage (Jolly *et al.,* 2000). However, it has also been reported that maximum acceptable salinity levels for inputs to this reservoir were lowered, which may have rendered the higher salinity water from Freshwater Creek unusable (rather than as a result of a recent increase in stream salinity) (Mary-Anne Young, pers. comm.).

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[2] Alluvial sediments are materials deposited due to the action of rivers and streams.

[3] Colluvial sediments are generally coarse, unsorted materials weathered from higher slopes, and transported down-slope due to the action of gravity.

[4] Pediments are gently inclined surfaces with very thin soils.

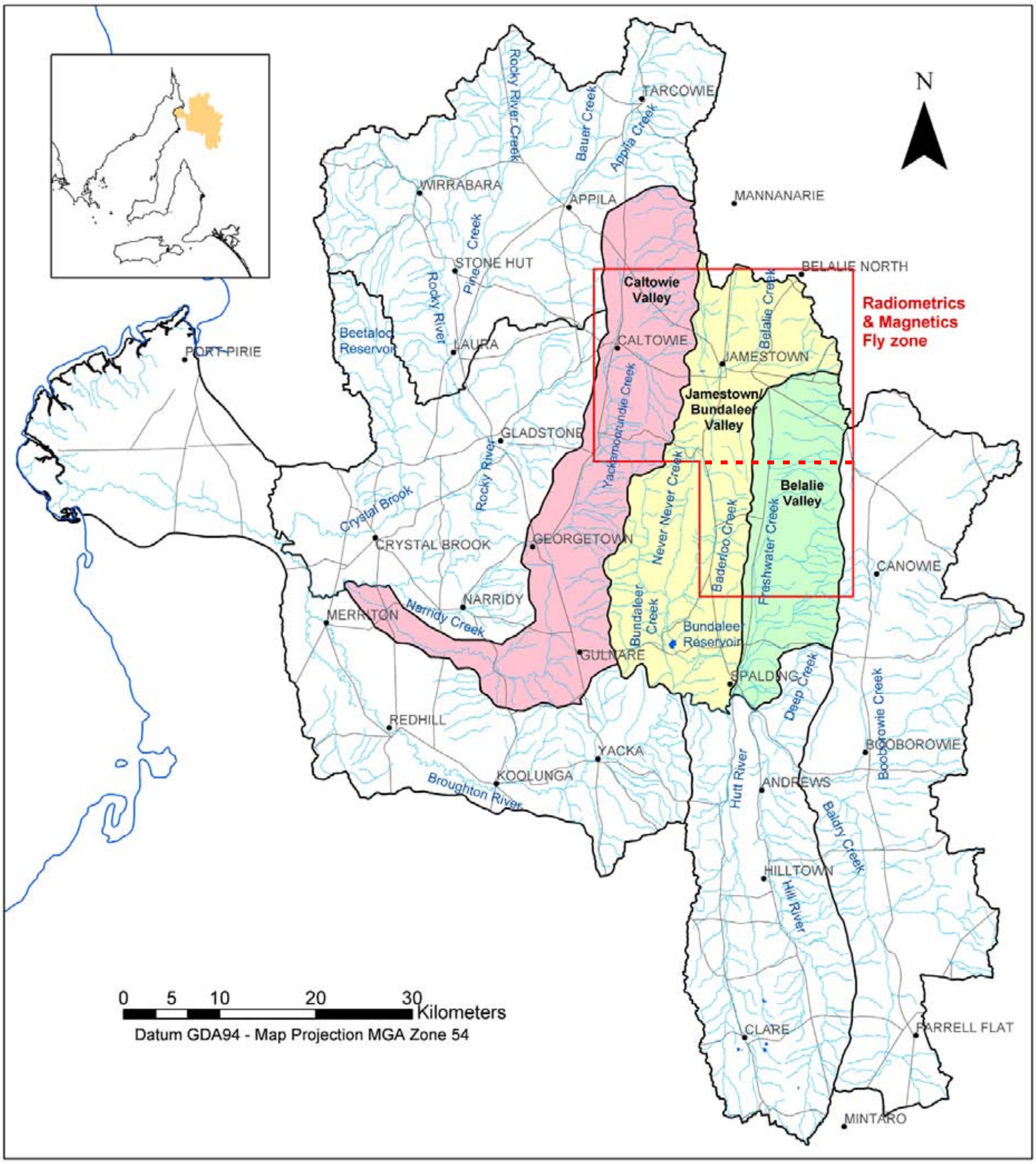

Figure 5. The sub-catchments of the Broughton River catchment, geophysics fly zone (in red) and the three valleys under consideration in this project. The airborne electromagnetics (AEM) survey only covered the rectangular area to the north (ie. did not include the portion extending south along Freshwater and Baderloo Creeks), while the radiometrics and magnetics surveys covered the whole fly zone.

3 Problems Identification / Project Site Objectives

The prime objective of the project in Jamestown was to provide information that improved salinity management to protect high value cropping land, based on an improved knowledge of groundwater, soil and salinity distributions.

To this end, specific components that have been addressed in this project include:

a) Enhanced soil and regolith maps demonstrating salt stores, solute transport pathways, salt sinks, synthesis of all available data to indicate hazards and management options;

b) A hydrogeological model for the valley-floor groundwater systems; and

c) An assessment of ground-based techniques for non-watertable related salinity.

Through these components this project sought to deliver the following site specific objectives:

1. Define the processes leading to salinity
2. Determine why salinity was expressed in some places and not others
3. Determine whether the different expressions of salinity can be distinguished
4. Understand the origins of the salt and its mobility
5. Understand the recent geological history that has a bearing on salinity

Wilford (2004) examines the physical relationships between surface materials, aquifers, and geology in general (with an emphasis on the recent history of the region and the regolith relationships) and outlines the airborne geophysical results. The results from the ground investigation are summarised and assessed for the Jamestown region in Henschke et al. (2004), and Cresswell & Herczeg (2004) presents hydrochemical and environmental tracer data obtained from groundwaters to better constrain models of hydrogeological interaction and resource assessment and the contribution made by airborne geophysics to these studies. Fitzpatrick, et al. (2003) outline and assess the ground-based geophysical tools used to survey sub-soil constraints, while Kingham, et al. (2004) have examined the causes and effects of sub-soil constraints across the region.

PART B. ROLE AND CAPABILITIES OF AIRBORNE GEOPHYSICS

4 Airborne Geophysics Objectives

To address the 5 project objectives listed above, airborne geophysics were employed to investigate a series of specific questions as shown in Table 1, with the particular technologies employed listed in the right-hand column:

Table 1. Questions addressed by the geophysical techniques

	Question addressed by Airborne Geophysics	Airborne Geophysical techniques employed
(i)	Can we map sub-surface groundwater systems?	Airborne EM Magnetics Altimetry
(ii)	How does the groundwater system relate to the surface expression of salinity?	Airborne EM Magnetics Radiometrics Altimetry
(iii)	Can airborne geophysics be used to help define management strategies?	Airborne EM Magnetics Radiometrics Altimetry
(iv)	Can we map the variability in soil types?	Radiometrics Altimetry
(v)	Can airborne geophysics help define sub-soil constraints?	Airborne EM Magnetics Radiometrics

Additional work (eg. drilling, soil sampling, geochemical analysis of ground and surface waters), and existing datasets, complemented the geophysics and provided valuable input to help answer some of the questions (eg. source(s) of salt, mapping soil variability). Where applicable, other sub-projects of the SA SMMSP 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 Jamestown region, four distinct geophysical technologies were employed (see box on next page), with each technology used for a different but complementary purpose.

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 are commonly associated with stream-bed deposits and have been used elsewhere (e.g. to the north around Jamestown (Wilford, 2004) and to the east across Honeysuckle Creek, Victoria (Cresswell, et al., 2004)) to pick-out sub-surface drainage lines – palaeochannels – that may act as conduits for groundwater flow (Cresswell, et al., 2004). Further, these minerals are common in many igneous rocks, both as primary and secondary minerals, and can often be used to depict geological structures 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 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).

5.1 AIRBORNE TECHNOLOGIES USED AROUND JAMESTOWN

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[5].

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 Jamestown region, the TEMPEST time-domain AEM system was chosen as the system most likely to give good depth resolution of conductivity down to 100m, and thus capable of measuring parameters that relate directly to the properties of the groundwater system. A line spacing of 400m was deemed adequate as long as the flight lines were perpendicular to the valley trends (N-S) to give maximum resolution across the valleys (E-W).

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

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

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

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.

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[5] Sub-surface material differentiation was examined in the companion Riverland and Tintinara east surveys, while groundwater quality was the focus for Tintinara west and Angas Bremer.

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 assessed 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 400m for the TEMPEST AEM survey. Flight-lines would trace across the valleys, giving maximum resolution in an east-west direction. The topography of the north-south-trending valleys suggested that continuity along the valleys would not compromise the wide flight-line spacing. 1,400 line km of AEM was flown, covering 540km^2 around Jamestown (Brodie and Cresswell, 2004). This area, plus an additional 154km^2 to the south was flown using MAGSPEC (7,820 total line km) to tie in with the research sites of Fitzpatrick et al. (2003) 15km south of Jamestown.

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-interpretated 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 5 questions outlined as the airborne geophysics objectives above 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 GROUNDWATER SYSTEMS

Combining the images created from the airborne technologies, precise boundaries to the groundwater systems can be drawn in 3 dimensions. Surface and sub-surface divides are not always coincident, but we can now stipulate where surface waters will end up when they percolate through the soils.

Generally, groundwater systems found in high relief fractured rock and infilled valley landscapes are defined in relation to the surface hydrological boundaries. Thus, watersheds define the catchments and these define the extent of the groundwater system under scrutiny. The reality, however, is that groundwater systems often cross beneath surface catchment boundaries and we must look deeper and wider to define the limits of a system. We need to uncover the sub-surface watersheds in order to cover the extents of recharge and discharge for a given system and so unravel the groundwater pathways and linkages.

While the Jamestown region has a relatively low average rainfall (<500mm/a), episodic high rainfall events can result in flooding, intense erosion of river channels, and cause floodwaters to deposit alluvial sediments across the valley floors. The worst case of erosion occurred in 1941, largely as a result of poor land management (Mary-Anne Young, pers. comm.). The town of Jamestown itself is built on a floodplain and has suffered from flooding during some of these high rainfall events. The DEM generated by the airborne geophysics (Figure 6) allows us to simulate the effects of high rainfall, and hence deduce the potential surface drainage system (Figure 7). This then defines the present day catchment boundaries.

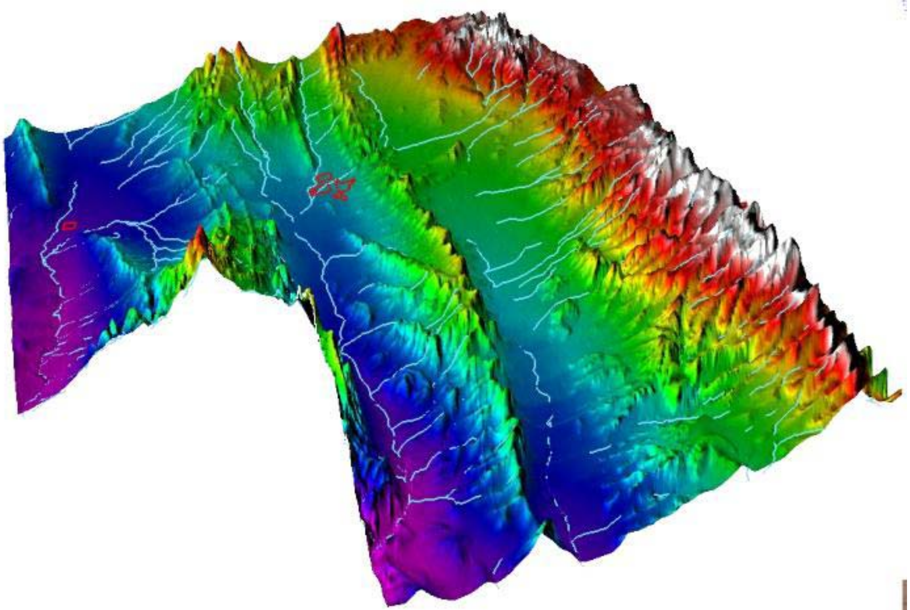

Figure 6. Exploded oblique view of the area around Jamestown (*from* Wilford, 2004). Heights range from 749m for the highest peak to the south-east (white) down to 316m in the far west (purple). The red boxes in the centre of the image mark Jamestown; Caltowie near the western margin. North is to the top of the figure.

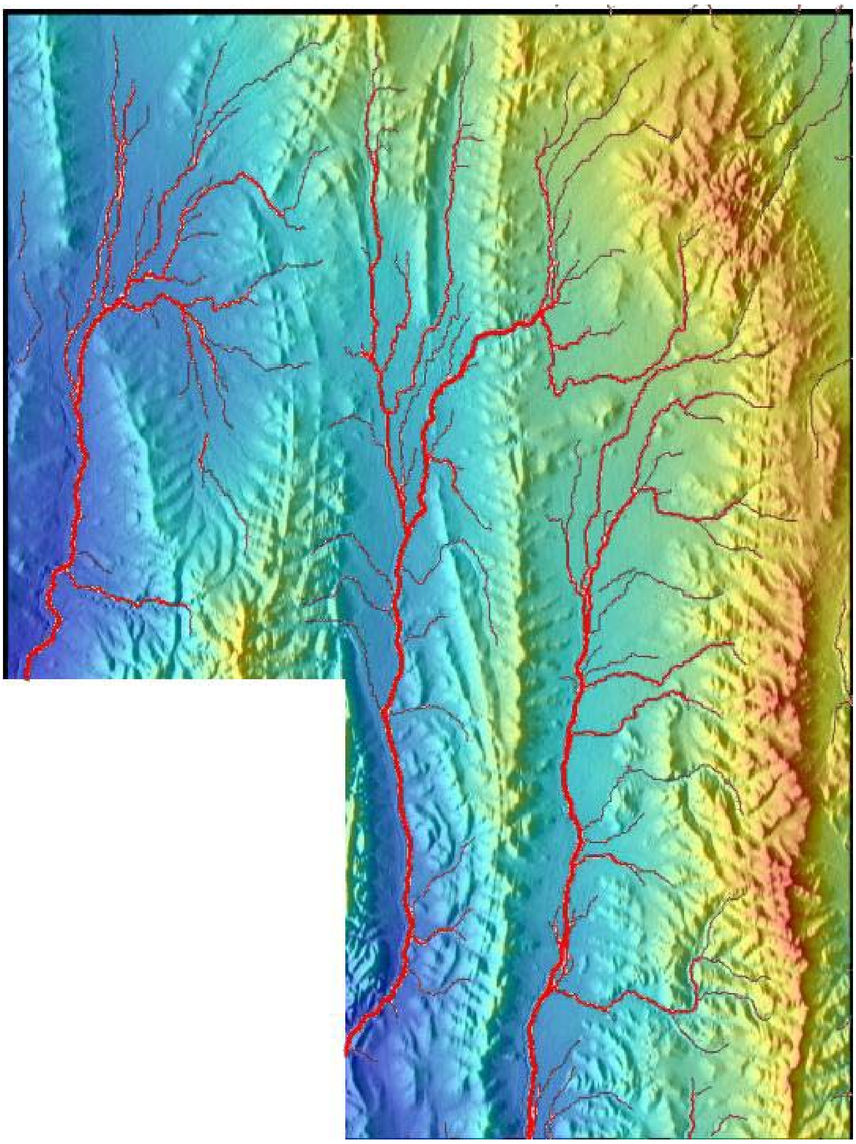

Figure 7. Potential drainage lines for the region deduced by analysis of the DEM. Surface water flow defines the shape of the three catchments shown in Figure 5.

Airborne magnetics images highlighted an extensive network of sub-surface palaeochannels (buried prior stream channels, *see* Figure 8), rivalling any found elsewhere in Australia (e.g. Dent, 2003). The prior pathways of streams through the landscape can be discerned (Figure 9). This now allows us to define potential sub-surface groundwater system boundaries, but, unfortunately, still leaves a few ambiguities in the patterns observed. In particular, we can see that a strong signal (indicating a significant channel) flowed south through the Belalie Valley, crossing beneath the present-day divide. We also see that a channel cuts through the main dividing ridge between the Belalie and Jamestown Valleys, just north of Jamestown, following the present day course of Belalie Springs. The magnetics cannot, however, tell which of these 2 channels transfers most of the groundwater, and at what depth they operate.

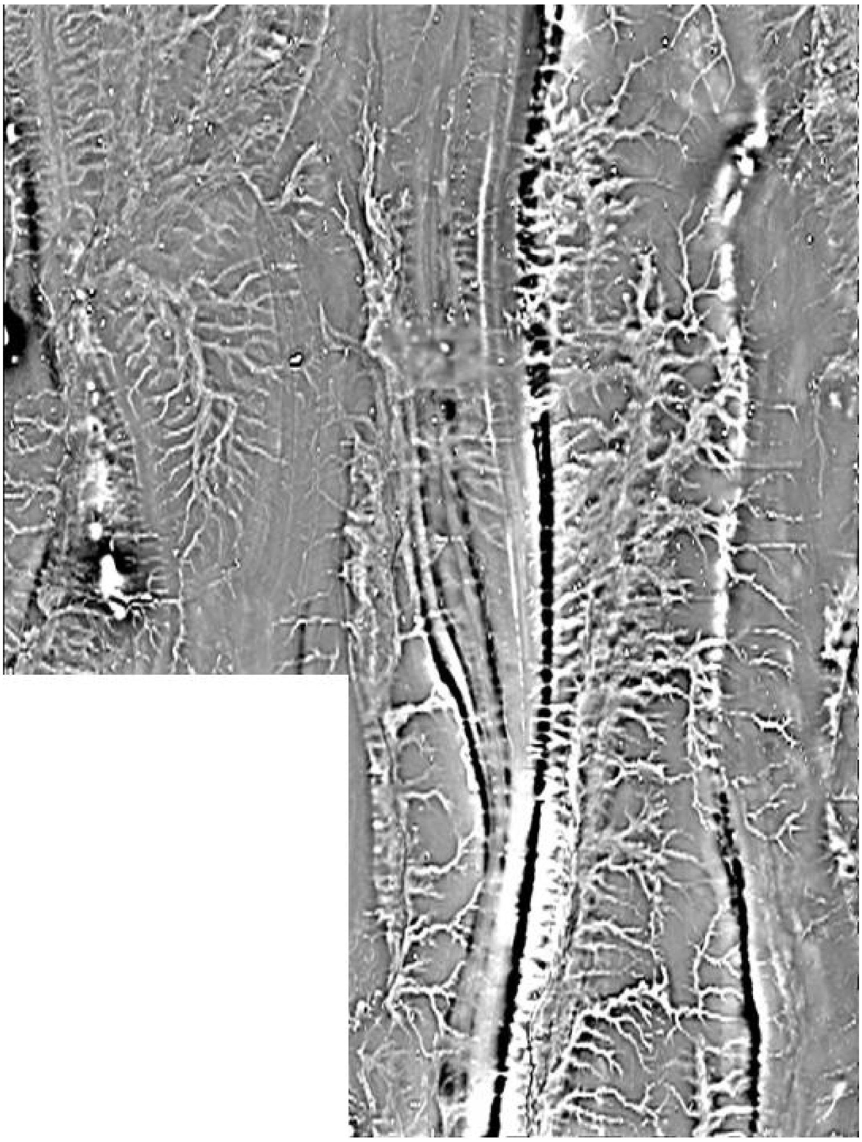

Figure 8. Image of magnetic variability across the region. No depth information is given, but the magnetic response is predominantly from very shallow (<50m) features and materials containing iron-rich minerals.

Superimposing the AEM signal, however, shows that the deeper channel runs to the south down the Belalie Valley, with minimal transfer of waters across the surface divide to the west (Figure 10). We can therefore determine that the stream to cutting the divide across to Jamestown is a recent feature, presumably instigated when valley infill of the Belalie Valley reached a level that permitted breaching of the ridge.

The AEM has also been modelled by Wilford (2004) to create a 3D image of the groundwater systems (Figure 11), which shows that the groundwater effectively runs through the valley infill deposits, across the contact with the underlying basement rocks. The AEM can help define the depth and width of these deposits to aid in modelling groundwater transport and the effects of increasing or decreasing water levels in the valleys.

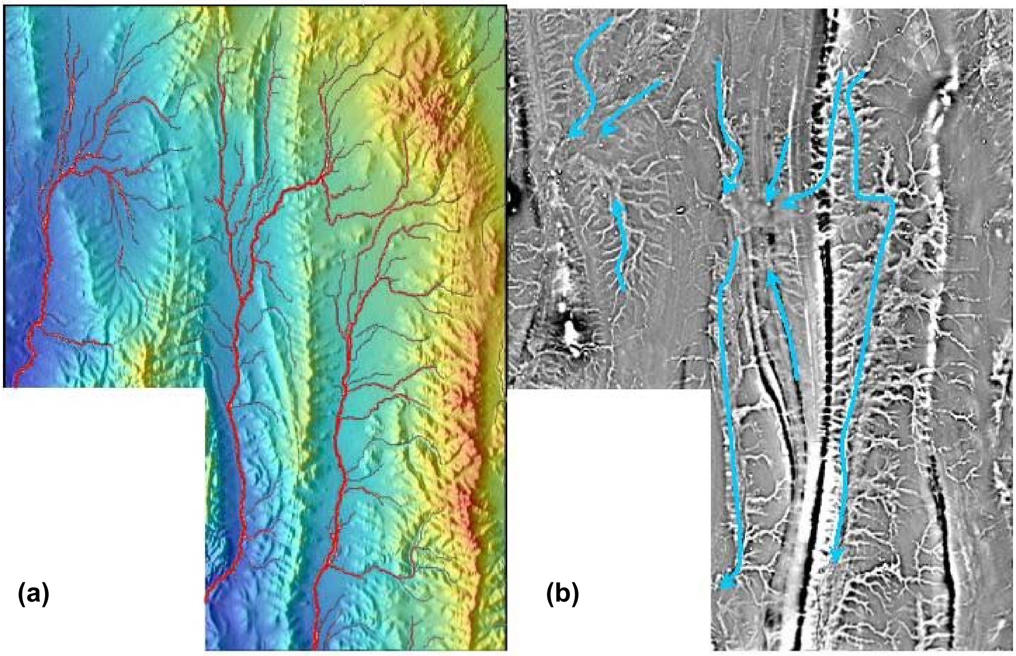

Figure 9. Comparison of flow lines deduced from the surface DEM (a) and from the magnetic image (b). A slightly different drainage pattern is seen when compared to the surface drainage in (a). Note the continual flow in the eastern (Belalie) valley from north to south, crossing the present day Belalie/Jamestown Valley divide.

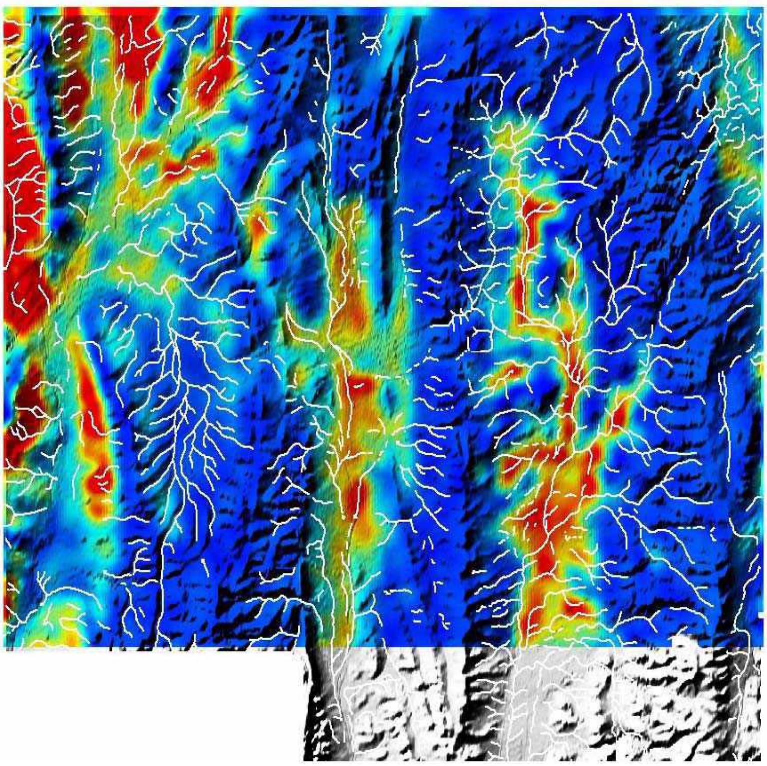

Figure 10. AEM conductivity depth image (CDI) of 10-15m below the ground surface superimposed on the digital elevation model. Preferential groundwater pathways are delimited by the high conductivity signals (red) indicating higher moisture content in these zones (*from* Wilford, 2004). Sub-surface drainage (from the magnetics image) is superimposed in white. We see no transfer of groundwater from the eastern into the central valley at this depth.

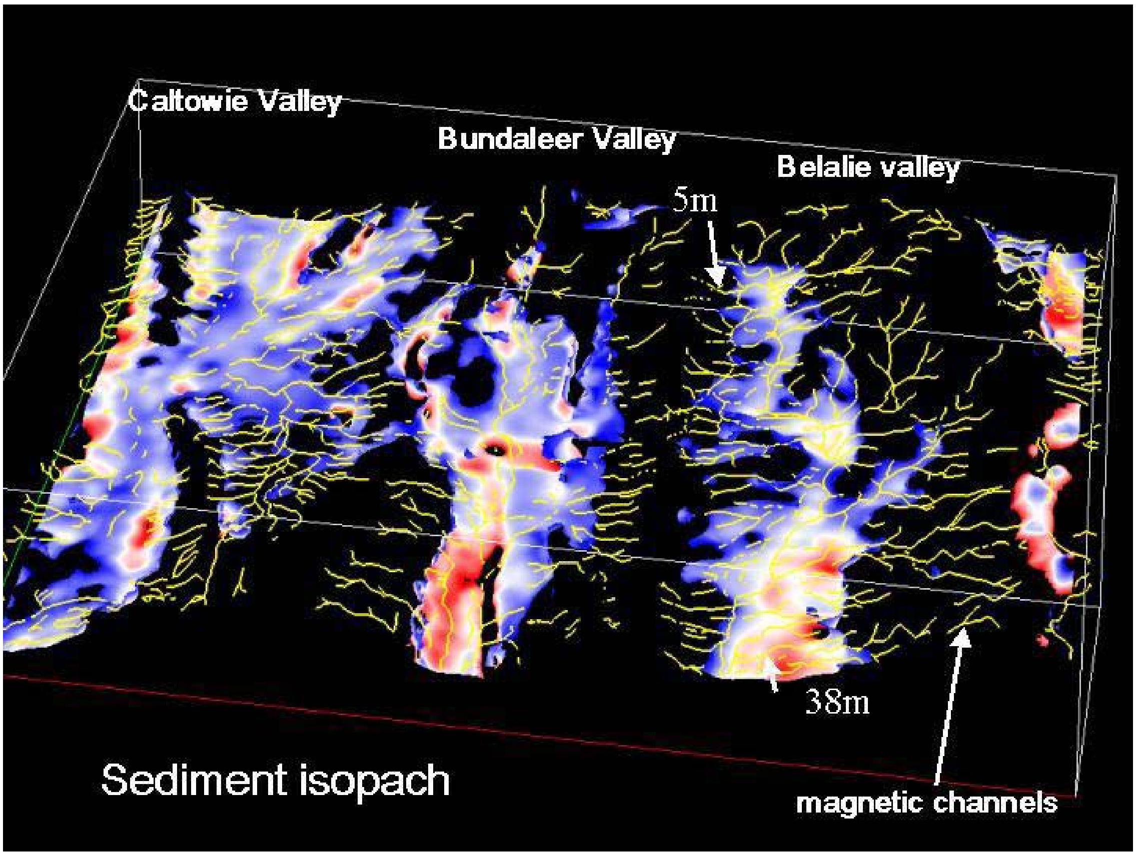

Figure 11. High conductivity zones in the sub-surface usefully delimit the extent of the transmissive sediments in the valleys. Thicknesses of sediment piles can be determined after the AEM images are calibrated against drill-hole data (from Wilford, 2004).

We may thus define two distinct but connected systems: a surface system defined by the present day topography and controlled by the amount and frequency of rainfall, and a deeper groundwater system travelling along the valley-fill / basement boundary, probably preferentially recharged at valley margins, but also in contact with the surface system via an unsaturated zone of varying thickness, depending on how full the groundwater system has become due to the prevailing climatic regime.

7.2 THE IMPACT OF GROUNDWATER SYSTEMS ON SURFACE SALINITY

Surface salinity occurs where convergent groundwaters are impeded by bottlenecks in the subsurface geology. This is compounded for the Caltowie Valley that has a shallow groundwater system, but good sub-surface drainage in the Belalie suggests salinity will not be a major problem. During wetter than average years the Bundaleer Valley will experience salinity south of Jamestown.

Combining the surface-water drainage with the sub-surface drainage, as defined by the airborne magnetics (Figure 12) gives insights into the causes of salinity SW of Jamestown and east of Caltowie during periods when groundwater levels are high. Both areas are at the confluence of a number of sub-catchments, and occur upstream of significant constrictions in the subsurface flow of groundwaters. During periods of enhanced flow (wetter climes) water will back-up behind these obstructions resulting in water table rise in these regions at a faster rate than elsewhere.

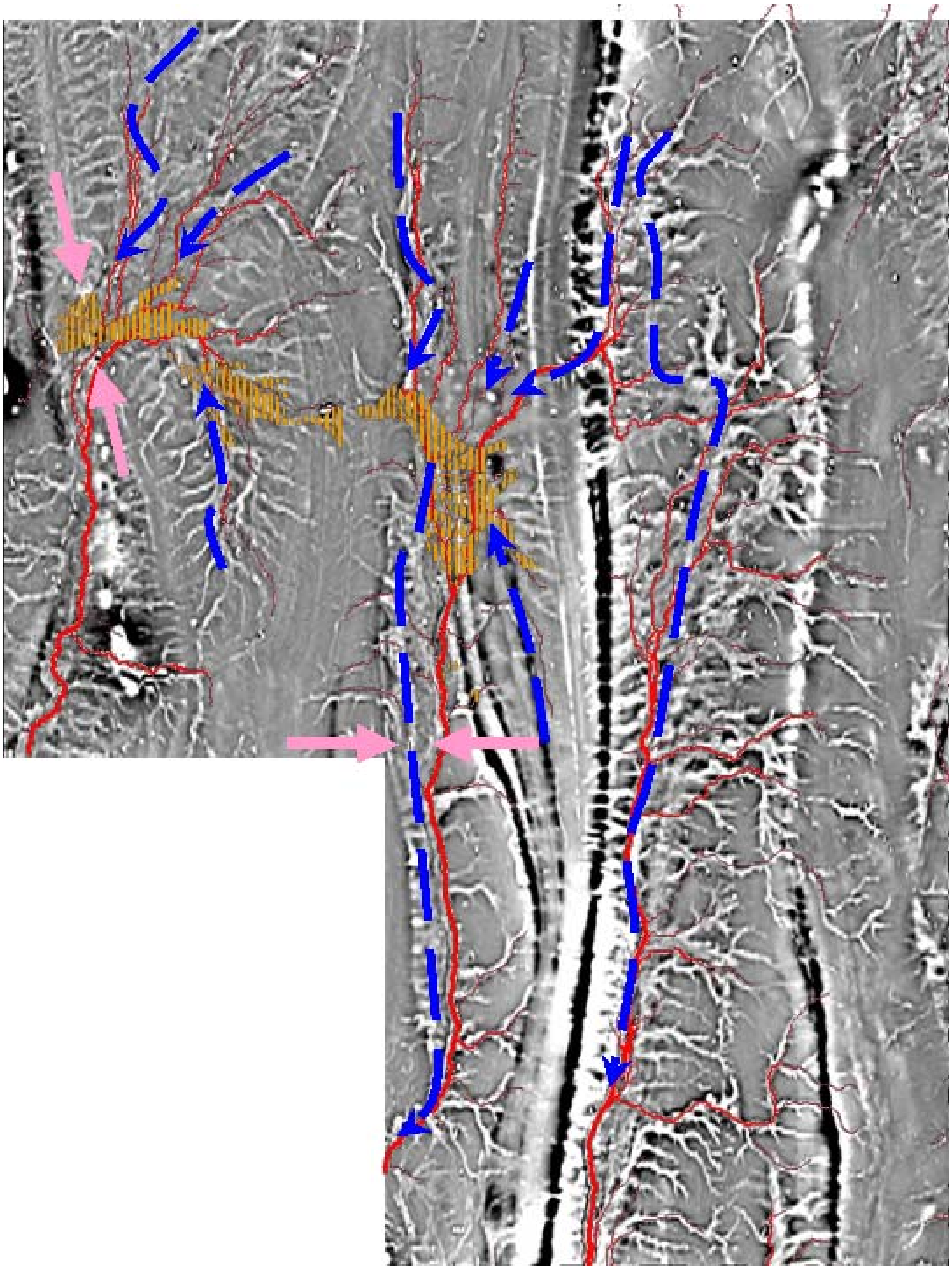

Figure 12. The regions mainly affected by groundwater-induced salinity (orange hatch) are seen to occur at the confluence of a number of sub-catchment, sub-surface streams (blue arrows), but upstream of significant bottlenecks in the underlying geology (pink arrows). Present-day drainage shown as red lines.

7.3 IMPLEMENTING MANAGEMENT STRATEGIES

Close attention to rainfall trends and monitoring groundwater levels will give good prior warning of impending salinity. The use of drains (eg. to manage surface water flows) to protect important assets, such as the township of Jamestown, is appropriate. Maintaining vegetation cover on hillslopes, and throughout the catchment, will moderate any water-table rise that will lead to salinity.

Through trial and error and informed resource management decisions, the farmers of this region are well-armed to combat the problems of salinity and soil sodicity. Implementation of mitigation strategies over the past 50 years has resulted in:

- large increases in the areas sown to lucerne, on areas adjacent to saline land;
- better maintenance of surface cover on hill-slopes;
- controlled grazing; and
- development of drainage systems to control surface water flows, thereby minimising flooding and recharge to groundwater.

The region has also seen drier years since the 1990s and water-tables are now at the lower end of the range of recorded levels. This has seen areas that were previously too saline for cereals now planted to crops. Concerns for a return to wet conditions and a rise in watertables has prompted continual development of drains through the most severely affected areas and most farmers will continue to plant deep-rooted perennials.

7.4 MAPPING LANDSCAPE MANAGEMENT UNITS

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

The radiometrics compares well with existing soil maps of the area (DWLBC, 2002; Stephens et al., 1945) (Figures 13, 14) and is seen as an exciting aid to future soil mapping activities (David Maschmedt, pers. comm.). Some details have been discussed in Wilford (2004).

Pertinent to this study, we may clearly define the alluvial plains and distinguish the colluvial slope sediments and the differences between the valleys, which may be ascribed to differences in source rocks. Also, the palaeo-channel depicted in the AEM is clearly defined using radiometrics (Figure 15), and derived products (Figure 16) confirming the prominent flow-paths determined by DEM analysis.

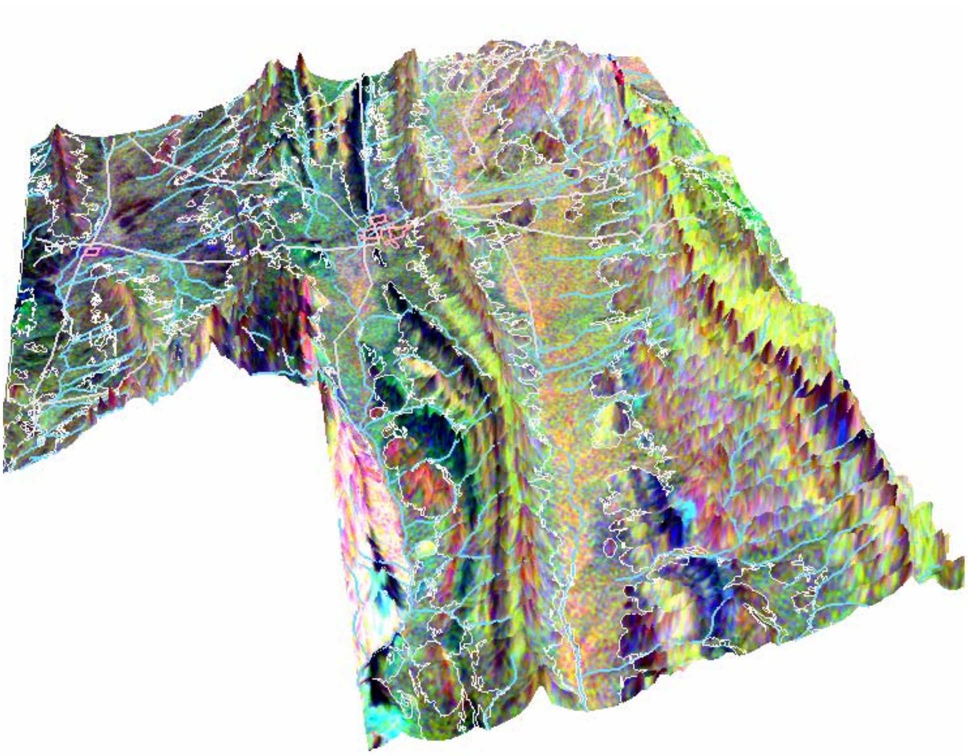

Figure 13. 'Ternary (3 band)' gamma-ray spectrometry (radiometrics) draped over the digital elevation model. The white line delineates slopes above (erosional) and below (depositional) 1.5° (from Wilford, 2004).

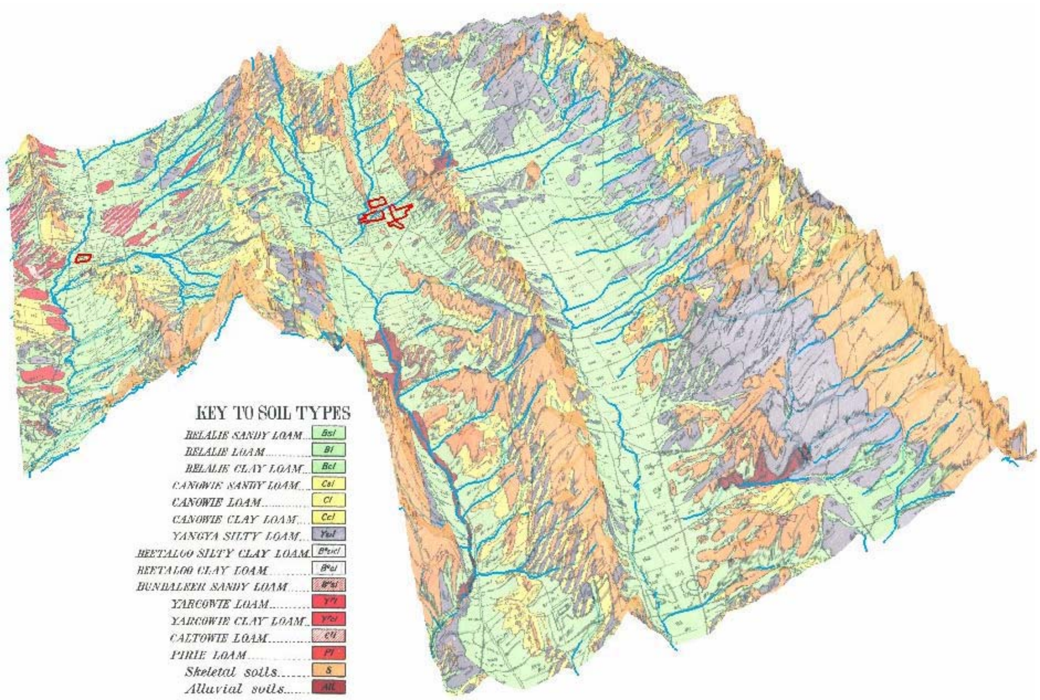

Figure 14. 1945 Soil map in the region (Stephens et al., 1945) draped over the digital elevation model (from Wilford, 2004). Compare with the radiometrics image (Figure 13).

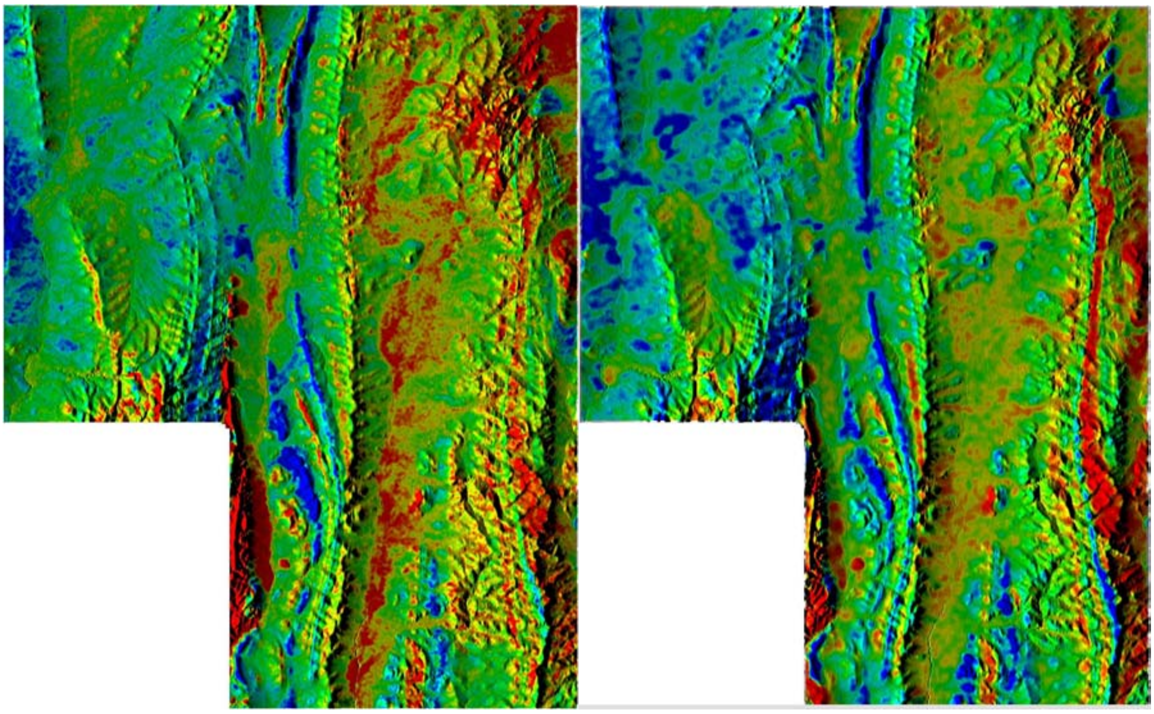

Figure 15. Airborne gamma response for potassium (left) and thorium (right) across the Jamestown region.

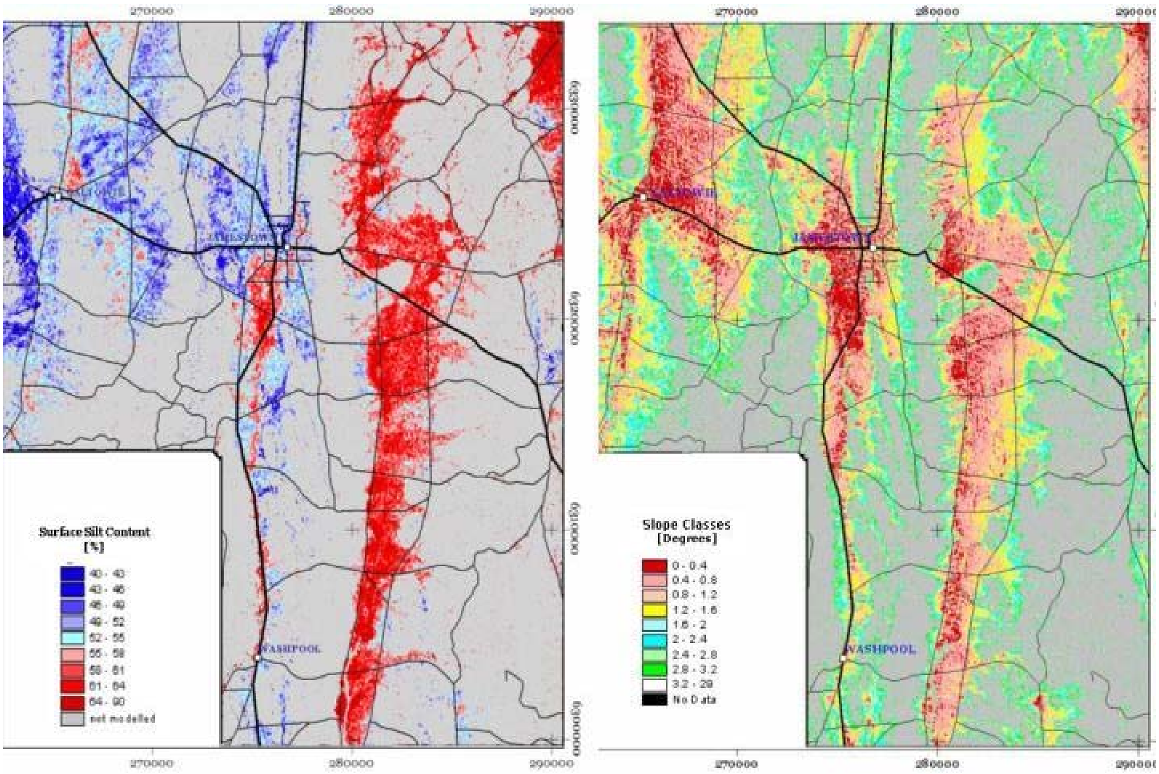

Figure 16. Potassium was found to relate strongly to the silt content of the sediments (Wilford, 2004), and distinguishes the Belalie from the other valleys (left). Slope class is useful in defining the regions that might be prone to waterlogging (low slope – in red in the right figure). The areas with high salinity potential are coincident with low silt and low slope areas.

7.5 DRY SALINE LAND: TRANSIENT SALINITY, MAGNESIA PATCHES AND SUB-SOIL CONSTRAINTS

> Airborne geophysics has not yet demonstrated a capability to map near-surface, yet sub-soil, constraints on agriculture. Ground-based techniques show promise, but are time and labour intensive (though cheaper). Management of transient salinity and magnesia patches requires careful treatment of soils on hill-slopes through maintenance of ground cover by controlled stocking and retention of moisture by contour banking.

Shallow, sub-soil constraints to crop production are a serious issue in this region. In particular, salinity and sodicity in the root-zone severely inhibit crop growth. A project aimed at using on-ground geophysical techniques to detect sub-soil salinity (Fitzpatrick, et al., 2003) found a reasonable correlation between shallow electro-magnetic surveys (EM38) and saline sub-soils (Figure 17), though this still requires further evaluation. Using the correlation between slope and total volume magnetic susceptibility (VMS) also indicates regions of higher sub-soil salinity (Figure 17), but all these techniques are time and labour intensive and require high levels of interpretation and understanding of soil and landscape attributes. Being ground-based also limits the areal extent of these studies.

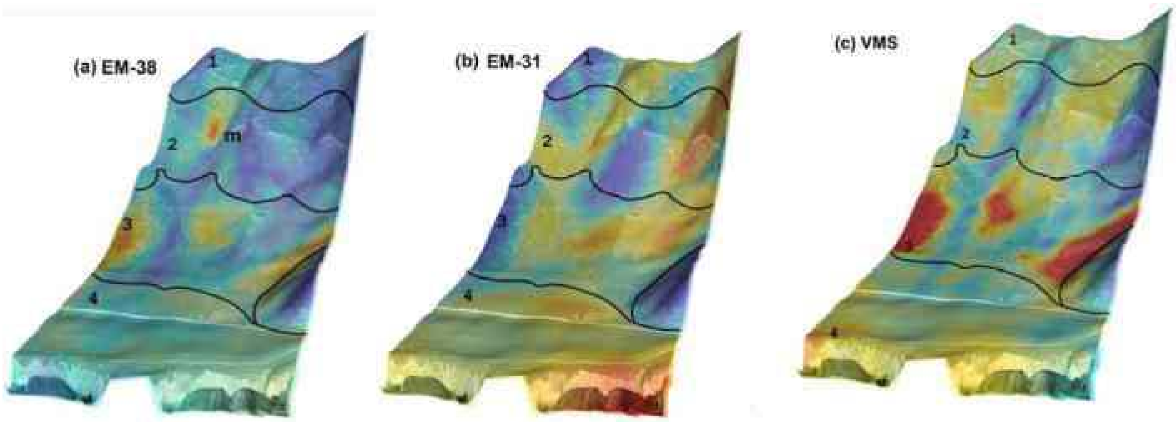

Figure 17. Ground-based surveys on a hill-slope south of Jamestown. EM38 and VMS image a response from the top 1.5m of the soil profile, while EM31 penetrates to >5m. More saline soils were found in the high conductivity (red) areas of the EM38 image, but showed poor correlation with EM31. The VMS (volume magnetic susceptibility) response also delineated the saline areas, but probably represent an association with magnetic particles coincident with salinity-prone soils (from Fitzpatrick et al., 2003).

The resolution of the airborne techniques in the vertical sense limits our ability to observe these features, and near-surface conductivity gives an ambiguous response to salinity (Figure 18).

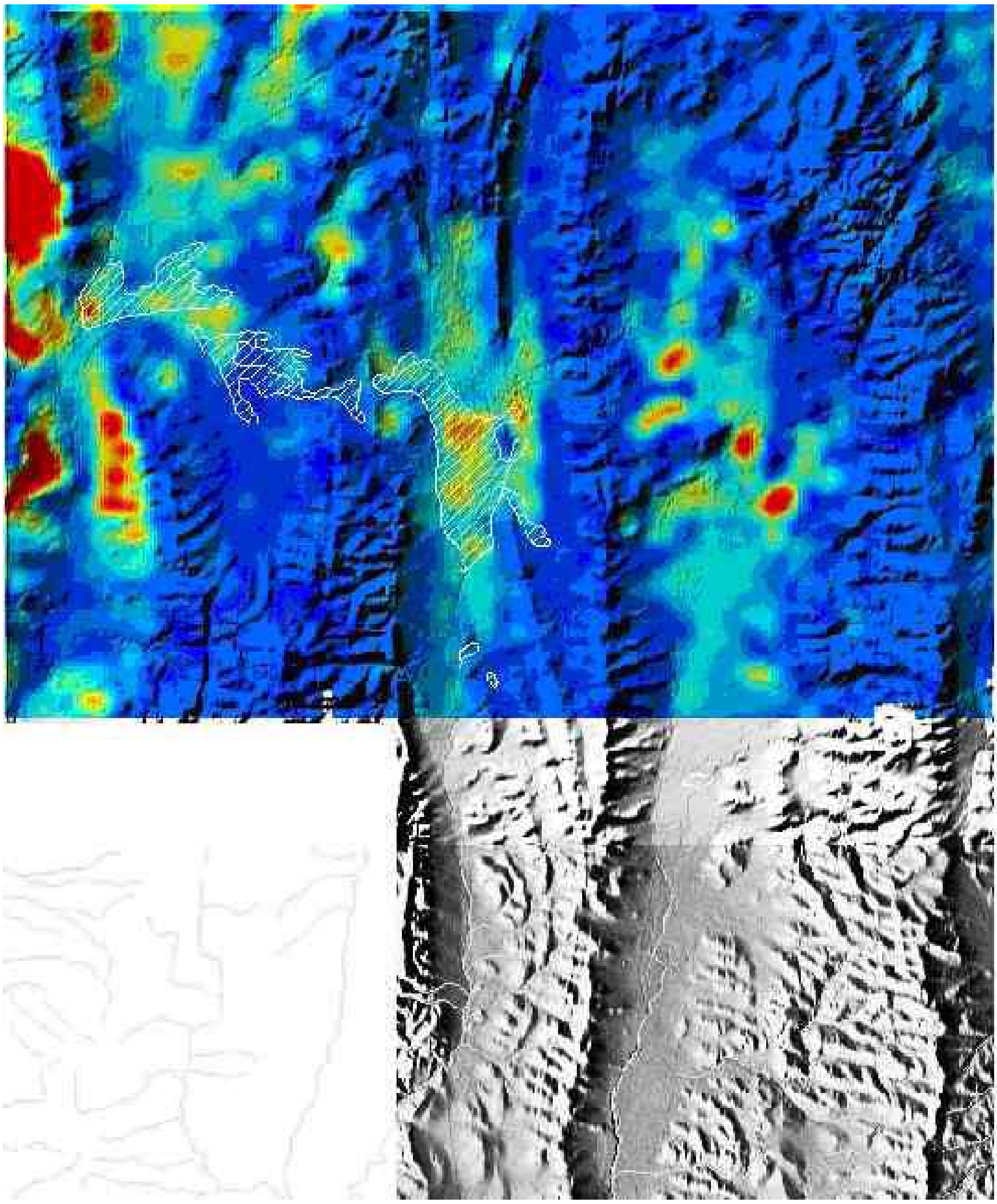

Figure 18. Shallow response signal form the airborne electromagnetics (from Wilford, 2004). While the high conductivity in the centre and to the west are coincident with expressions of salinity (hatched areas), the high levels in the eastern valley are not related to surface salinity, but may represent higher sub-soil levels of salt. Areas of sub-soil expressed salinity are not discernable with the resolution of these images. Further processing of the early time response components of the airborne EM data may help resolve this.

PART C. IMPROVEMENTS TO MODELLING / DECISION SUPPORT TOOLS

Extensive computer modelling of the groundwater flow systems in the study area was not considered necessary to assist with management under the SA SMMSP. The data now assembled, however, would allow such work to proceed if at a future time the value of resources under threat provides justification for this type of work.

The information gathered to date, however, has greatly advanced conceptual models of groundwater behaviour in the region and indicates its strong interaction with climate and landscape.

To understand the hydrogeology of salinity we must understand the processes operating at the catchment scale. This scale can be relatively small, dealing with a sub-catchment (Henschke et al., 1994) but often this must be combined with broader-scale studies to encompass the entire region affected by a groundwater flow system. Around Jamestown, consideration of sub-catchments defined by the surface hydrology can be misleading and we need techniques that can rapidly survey large areas (100km^2) to evaluate whether we are investigating at the appropriate scale. Airborne geophysics provides technologies that are well suited to this type of investigation.

Across the Jamestown region 4 airborne geophysical technologies were used and assessed.

1. *Airborne magnetics* revealed an extensive network of prior stream channels, defining the extent of sub-surface catchments, which, in places, do not coincide with present-day surface watersheds.
2. *Airborne radiometrics* highlight the surface distribution of materials and are used to evaluate soils and present-day surface features.
3. *Airborne electromagnetics (AEM)* expose the sub-surface conductivity structure and relates to salt, water and sediment type. In this region, water is the defining parameter and the course of groundwaters can be delineated at depth. This was confirmed by on-ground drilling, sampling and chemical analyses, and provides a framework on which to develop hydrogeological models.
4. *Altimetry* gave a detailed picture of the landscape, generating a digital elevation model (DEM) that can be modelled to deduce for surface water flow regimes.

The different expressions of salinity can be explained:

1. Caltowie Valley suffers from surface scalding, infrastructure damage and very shallow, saline watertables caused by too much water blocked by a bedrock constriction in a shallow system.
2. Jamestown/ Bundaleer Valley has regions of crop failure across the valley floor, seasonal waterlogging and periodic shallow, saline watertables also caused by ponding of groundwaters behind a bedrock constriction, but enhanced by overflow of waters from the adjacent, Belalie valley.
3. In Belalie Valley isolated soil degradation and scalding occurs only on north-facing slopes, with minimal salinity issues on the valley floor. The hill-slope salinity is due to sub-soil salinity effects exacerbated by over-stocking and poor land management. This has all but been eliminated in this region by contour banking

and refined stocking practices. The valley floor is unlikely to suffer from water-table salinity as the deeper valley fill provides a ready conduit for waters, flushing the saline groundwaters out of the system towards the opening valley to the south.

With our improved understanding of the 3-dimensional variability in aquifer materials (Wilford, 2004; Cresswell and Herczeg, 2004) and appreciation of water transport in the region, we can now develop new hydrogeological models that may better evaluate the relationships between natural recharge, discharge and salinity around the region.

Hydrogeochemistry

Chemistry of groundwaters and environmental isotopes also helps us understand the origins of the groundwaters and salts and can be used as checks on our models of groundwater movement. Samples taken for radiocarbon, stable isotopes, strontium isotopes and ion chemistry, showed some important differences between the three valleys investigated.

Caltowie Valley has higher chloride, sodium and sulphate; Bundaleer Valley generally has the lowest levels of all ions and Belalie Valley has high calcium and chloride. The stable isotopes (^{18}O, ^{2}H, ^{34}S) all show a seawater signature that suggests all waters were derived from rainwaters, or atmospheric fallout, with no input from any connate waters.

Plotting bromide concentration against chloride concentration for the Jamestown groundwaters (Figure 19) shows that all samples plot within the bounds of evaporation of a rainfall source for these halides. This is consistent with conservative concentration of salts derived from marine aerosols, or possibly residual seawater. The data are not consistent with either salt dissolution or mineral weathering because halite (NaCl) and most rock forming minerals are deficient in bromide, which would yield Br/Cl ratios in water much less than the seawater value of 2.45×10^{-3}. Evaporation does slightly affects the composition of the waters, but to a relatively small degree.

Strontium ratios are high ($^{87}Sr/^{86}Sr \sim 0.714$) and reflect dissolution of plagioclase from the source granites to the north-east. Radiocarbon, meanwhile, gives two signals: A modern signature for waters sampled above 25m; and roughly 50 percent modern for deeper waters. This appears to be independent of valley and aquifer type and does not correlate with calcium or alkalinity, indicating that carbonate dissolution is not diluting the signal.

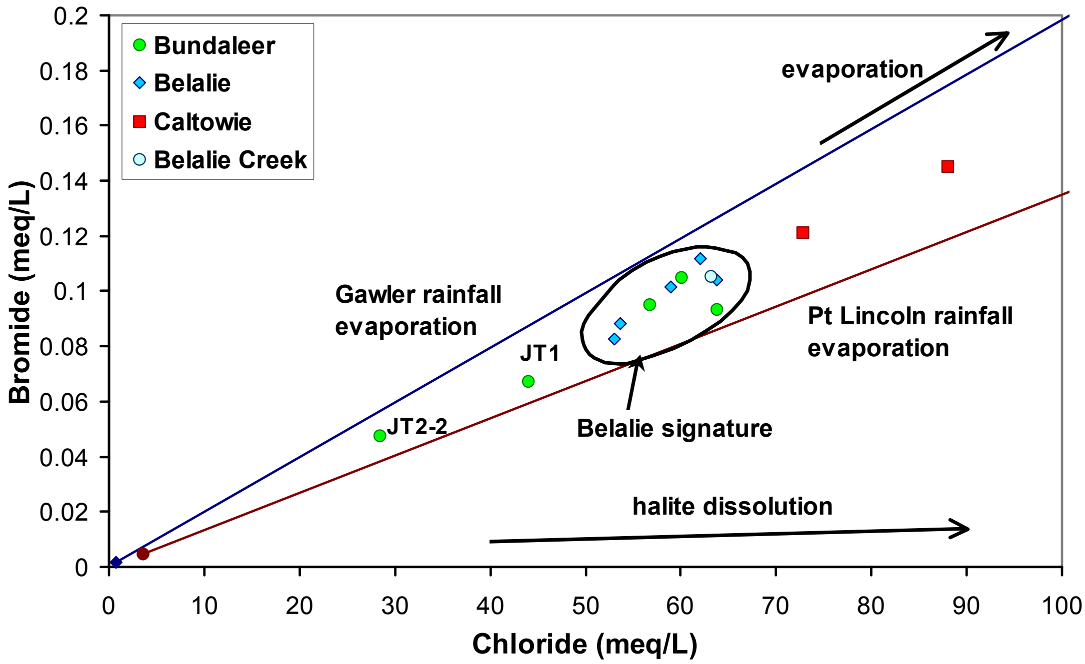

Figure 19. Chloride concentration plotted against bromide concentration for groundwaters around Jamestown. Bounds on the data can be set by evaporation of rainwaters from the south (Pt. Lincoln) and west (Gawlers). We do not see any evidence for dissolution of any salts already present in the soils, as these would plot along the bottom axis.

Conceptual Model of Groundwater Flow

Groundwater flow systems indicated by the airborne geophysics and the hydrogeological model indicate flow that is focused towards the valleys from the highlands and then converges and continues southwards. Chemically, the groundwaters from each valley are self-consistent, with similar stable isotope compositions. This suggests that the groundwater pathways are all hydraulically connected. ^{14}C compositions, though few in number and sampled from variable depths, are broadly consistent with such a conceptual model. Estimated groundwater ^{14}C ages are of the order of a few thousand years and increasing 'age' correlates with greater depth below groundwater, and with distance along inferred flow paths.

The flownet, deduced from water-levels in the existing and newly drilled bores, indicates an intermediate scale groundwater flow system is occurring in each of the three valleys. Groundwater flow paths range from 4 to 7+ km in length.

Groundwater flows in a general northeast to southwest direction in each of the three main valleys. The elevations of the groundwater contours indicate a step-up in elevation from west to east across the three valleys (eg Caltowie: 390-410m, Bundaleer: 430-450m, Belalie Creek: 500-530m). Surface water and groundwater tend to want to flow from east to west, but north-south quartzite barriers force the flows to trend toward a north - south direction.

Recharge

The major recharge areas would appear to be the colluvial outwash fans fringing the ridges on the eastern side of each valley. Recharge also occurs along the rocky ridge-lines.

Recharge to the groundwaters is predominantly diffuse, though possibly at higher rates through the hill-slope colluvial fans. The stable isotope concentrations in the groundwater are similar to mean winter rainfall compositions for Adelaide indicating that there is no preferred flood-out recharge and that evaporation of surface floodwater prior to recharge is minimal. The high Cl^- concentrations throughout the area (1,000 – 2,000 mg L^{-1}) suggest low historical recharge rates in the vicinity of 0.5 – 2 mm yr^{-1}.

Expressions of Dryland Salinity / Groundwater Discharge

Groundwater flow converges towards alluvial “pinch-outs” in both valleys. The alluvial “pinch-outs” occur near Caltowie and south of Jamestown in the Bundaleer valley. These are the areas where dryland salinity would be expected to occur. Dryland salinity is not apparent downstream of the “pinch-outs”.

Some smaller areas of dryland salinity are associated with fractured rock aquifers at the break in slope of the ridges and the broad valleys. Groundwater flow paths are expected to be much shorter in these local flow systems (about 1km).

Although groundwater data is sparse in the Belalie Creek subcatchment, construction of a flownet has been attempted.

The Belalie Creek sedimentary valley “pinches out” at Belalie gorge, while the sedimentary valley continues south, crossing a subdued catchment divide. This southward extension of the valley may indicate the existence of a palaeovalley of the old Broughton palaeochannel, which apparently originated just east of Jamestown (Rowett, 1997).

The “Belalie Springs” are an expression of groundwater discharge at the alluvial “pinch-out”. The spring water has an EC of 7 dS/m and this water discharges down the Belalie Creek through Jamestown and disappears underground in the Bundaleer drain some 3 km south of Jamestown. The flownet suggests that groundwater in the north-western part of the Belalie Creek catchment, converges toward the Belalie infilled gorge and discharges as springs.

The spring-fed creek, which flows through Jamestown, has been gauged on a number of occasions. Discharge rates range from 25-70 L/s. Salt loads range from 2 to 20 tonnes per day.

Groundwater in the south-eastern half of the Belalie Creek catchment flows south across the subdued catchment divide into the Belalie Plains catchment where groundwater continues to flow south. The groundwater drains out of the catchment to the south due to the presence of the palaeochannel, which prevents the aquifers from filling up.

Airborne EM and magnetics data (Wilford, 2004; Cresswell and Herczeg, 2004) confirmed the existence of palaeochannels in the Belalie Creek/Plains catchments. The gravelly transition zone may act as a preferred pathway for groundwater flow. This catchment is not “filling up” like the other two western catchments.

While connectivity between the surface and shallow groundwaters can be surmised through evaluation of rainfall and stream flow records and groundwater levels, which indicate a direct causal impact on alluvial groundwater levels through rainfall infiltration, the lack of either surficial or deep, bedrock water samples does not allow us to comment on the chemical connectivity, or interaction between the surface, shallow and deep groundwater systems.

Sufficient data now exists for the Jamestown region for potential future work to create a numerical hydro-geological model that could be used to predict the impacts of changing management scenarios and varying intensity rainfall events on water levels, and thus salinity, in the main valleys.

The airborne geophysics provides a catchment-scale framework on which to base future management decisions.

PART D. INFORMATION FOR MANAGEMENT

8 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

8.1 DEFINE THE PROCESSES LEADING TO SALINITY

Three expressions of salinity have developed through 3 separate processes:

1. Water-table driven salinity, south of Jamestown and east of Caltowie, has developed where groundwater flow systems are restricted above confluences of surface and sub-surface water flow: the system cannot drain as fast as it fills. This occurs particularly following a run of wetter than average years. Rising water-tables entrain the salts in the landscape, bringing them to the surface.
2. Break-of-slope salinity occurs locally where coarser-grained hill-slope sediments meet the finer-grained valley sediments along valley margins. Rainfall recharging on the hills flows through the coarser sediments, but cannot flow as rapidly through the valley floor sediments, so seeps out at the junction. Evaporation concentrates the salts in the near-surface at these sites.
3. Dry saline land (transient salinity, 'magnesia patches', sub-soil salinity) is expressed where hillslope vegetation is removed and naturally saline sub-soils are exposed, through erosion of the top soil. Unlike the other forms of salinity, this form increases in area during dry years, and reduces during wet, as the soils are flushed deeper into the soil profile.

To understand the processes leading to salinity we must understand the hydrogeological processes operating at the catchment or sub-catchment scale.

The four airborne technologies used complemented each other: *Airborne magnetics* revealed the extensive network of prior stream channels, defining the extent of sub-surface catchments, which, in places, do not coincide with present-day surface watersheds (Figures 7, 8 and 9). *Airborne radiometrics* highlight the surface distribution of materials and can be used to evaluate soils and present-day surface features (Figures 13, 14, 15 and 16). *Airborne electromagnetics (AEM)* expose the sub-surface conductivity structure that relates to salt, water and sediment type (Figures 10 and 11). In this region, water is the defining parameter and the course of groundwaters can be delineated at depth. This was confirmed by on-ground drilling, sampling and chemical analyses, and provides a framework on which to develop hydrogeological models.

With our improved understanding of the 3-dimensional variability in aquifer materials (Wilford, 2004) and appreciation of water transport in the region, we can develop new hydrogeological models that can better evaluate the relationships between natural recharge, discharge and salinity around the region.

We must also appreciate that there is more than one expression of salinity. In this region, three main expressions are seen: water-table induced salinity; break-of-slope salinity and dry saline land (locally known as “magnesia patches”). In addition, highly saline sub-soils in some areas are also a serious impediment to agriculture. Thus, we must assess the processes leading to each form and assess their inter-relationships.

1. Water-table driven salinity

The valleys act as natural funnels for any rain falling on the region. The slope of the valleys determines where water will pool and where it will be transported rapidly through the system. The nature of the sediments of the valleys will determine how fast the water will infiltrate through the soils and the depth to the basement rocks determines how much water each valley can store. In periods of high rainfall we may get ponding in areas of low slope, slow recharge in areas of clay-rich soils and filling of the valley sediments where there is only a thin veneer of sediments. Each of these areas are more prone to elevated water-tables. Where 2 or all occur in the same location the likelihood is increased. These are the areas that develop water-table driven salinity. The soils of this region are naturally saline, due to thousands of years of gradual build-up of salts deposited by rain (cyclic salts). When the water-table rises these salts are brought up into the root zone and plants find it increasingly difficult to extract the water and nutrients they need from the saline solutions. Ultimately, the water-table rises to within a metre of the surface and capillary rise bring saline waters to the surface, which then evaporate leaving salt efflorescences at the surface. Only halophytic plants can survive in these conditions.

2. Break-of-slope salinity

While rain falls across the entire landscape, more rain tends to fall on the windward side of hills. If these zones consist of materials that allow water to readily infiltrate, then recharge rates can be high. As the soils on these slopes tend to be less capable of retaining moisture (being commonly coarser-grained and more permeable) compared to soils in valleys, this water can rapidly flow down-slope towards the valley floors. The break of slope between hill slopes and valley floors commonly marks the junction between coarser, colluvial material and the finer, more clay-rich, alluvial deposits of the valleys. This marks a strong hydraulic conductivity contrast and water flowing down slope is slowed in its progress and can fill the profile at these locations. Where this occurs, springs or seeps may develop and evaporation may lead to concentration of salts, or deeper more saline water may be brought to the surface.

Break-of-slope salinity has been detected in the past on the slopes to the west of Jamestown (Figure 2), but is not present today. We did not detect any inference of this form of salinity in the airborne techniques.

3. Dry saline land

Where naturally saline soils in hill slopes are exposed due to over-grazing, or change from perennial to annual cropping, the exposed soils, which tends to be naturally friable when dry, will be eroded exposing ever more saline soils in the sub-surface. Where the cause is from livestock, these salt-licks become preferred resting sites and the expression is made worse.

Remedial action requires contour-banking to maintain soil moisture and controlled stocking once vegetation returns. Ideally, perennial plants should be maintained on these areas.

At the time of the survey, it was difficult to identified these soils as remedial action by the landholders has all but remedied this form of salinity in this area.

We could not determine the presence or absence of this form of salinity by any of the airborne techniques. Ground-based surveys using shallow probing electromagnetics did detect salinity-prone areas and volume magnetic susceptibility also showed some correlation at one site.

8.2 DETERMINE WHY SALINITY WAS EXPRESSED IN SOME PLACES AND NOT OTHERS

The differing geological setting for each valley gives rise to different expressions of salinity. Each expression needs to be placed in the appropriate context with regard to groundwater flow systems, landscape geomorphology and soil / regolith profile.

The different expressions of salinity can be localised:

1. Caltowie Valley suffers from surface scalding, infrastructure damage and very shallow, saline watertables caused by too much water blocked by a bedrock constriction in a shallow system.
2. Jamestown / Bundaleer Valley has experienced areas of crop failure across the valley floor, seasonal waterlogging and periodic shallow, saline watertables also caused by ponding of groundwaters behind a bedrock constriction, but enhanced by overflow of waters from the adjacent, Belalie valley.
3. In Belalie Valley isolated soil degradation and scalding occurs only on north-facing slopes, with minimal salinity issues on the valley floor as soils are freely draining and the valley opens downstream to the south. The hill-slope salinity is due to sub-soil salinity effects exacerbated by over-stocking and poor land management. This has all but been eliminated in this region by contour banking and refined stocking practices. The valley floor is unlikely to suffer from water-table salinity as the deeper valley fill (and particularly the more permeable sediments of the palaeochannels) provides a ready conduit for waters, flushing the saline groundwaters out of the system towards the opening valley to the south.

We thus see that landscape position and hydrogeological context are critical determinants in the location and expression of salinity around Jamestown.

Reduced rainfall over recent years, increased areas sown to lucerne and improved crop production (and water use) on land adjacent to previous salinity outbreaks have also had a major influence on salinity expression, particularly in the Bundaleer Valley (Mary-Anne Young, pers. comm.).

8.3 DETERMINE WHETHER THE DIFFERENT EXPRESSIONS OF SALINITY CAN BE DISTINGUISHED

We can only distinguish different expressions of salinity by on-ground investigation. Remote techniques (including airborne and ground geophysics), however can define the landscape environments that are prone to particular expressions and indicate where to concentrate further investigation. Once a series of remotely sensed techniques can be ascribed to a particular expression, that combination may be used to identify other areas with a similar problem.

Field investigation is the only valid method of distinguishing the different expressions of salinity. Having said that, once the specific landscape and characteristics of a particular expression is correlated with a more remote, or secondary, method, then similar expressions can be distinguished and investigated. Thus, once we recognise that saline soils in the hills are associated with enhanced near-surface conductivity (EM38) and magnetic susceptibility (VMS), we can use these techniques to survey other areas (e.g. north-facing slopes) that may also be prone to this expression. Similarly, understanding the hydrogeological environment that is prone to water-table driven salinity allows us to distinguish sites where this expression may occur in the future, despite the fact that it is not present today. Airborne EM can detect areas that have experienced water-table driven salinity in the past, but for which the salinity expression is now beneath the surface. This is generally due to lower than average water-tables, due to a recent run of drier than average years. Break-of-slope salinity was not detected using the methods employed here. Slope analysis can define areas where it may occur. Ground-based surveys are required at present to detect its presence.

8.4 UNDERSTAND THE ORIGINS OF THE SALT AND ITS MOBILITY

Salt in the region is predominantly derived from rainfall (*i.e.* it is cyclic). Some water-rock interaction takes place as the groundwaters move through the soils, but most salt in the groundwaters is derived from evaporative concentration of rain-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 (Figure 19) indicates that rainfall-derived salts, rather than rock-salt (halite) or halide-rich rock minerals contributes the dominant amount of dissolved solutes to the salt load. As chloride is the dominant ion in solution, and is the most hydrophilic of all the dissolved halides, the source of chloride (and by association sodium) determines the source of the predominant salt load.

Indeed, the isotopic and chemical data all indicate (*see* Part C) the predominant influence of recent rainfall (δ^2H, $\delta^{18}O$, ^{14}C, Br) with minor water-rock interaction (Ca, SO_4, Na, $\delta^{13}C$, $^{87}Sr/^{86}Sr$) and not the presence of residual connate waters (Cresswell & Herczeg, 2004).

We may thus assess the chemistry of the waters at each of the bores in relation to the dominant processes operating in the area, namely:

1. Direct rainfall recharge on the ridges
2. Diffuse rainfall recharge (following floods and sheet wash)
3. Water:rock interactions of deeper groundwaters
4. Dissolution of basement carbonates and salts

While there is a suggestion of evaporation as a driver for solute concentration from the chemical data, the isotopic data suggest that this is a minor process in the area.

The chemical composition of the groundwaters shows some subtle variations amongst the different valleys, and over the range of observed TDS. But the dominant ions (Na^+ and Cl^-) have ratios identical to seawater, as do the Br^-/Cl^- ratios, indicating a predominant marine aerosol origin for the salts. Mineral weathering plays a subordinate role and there are no residual salts in the formation that contribute Cl^- or SO_4^{2-} to the groundwaters and to the temporary surficial salt efflorescence.

Groundwater flow systems indicated by the airborne geophysics and the hydrogeological model indicate flow systems that are focused towards the valleys from the highlands and then converge and continue southwards. The spatial continuum in chemical composition, and similarity of all groundwaters in stable isotope composition suggest that the groundwater pathways are all hydraulically connected. ^{14}C compositions, though few in number and sampled from variable depths, are broadly consistent with such a conceptual model. Estimated groundwater ^{14}C ages are of the order of a few thousand years and increasing 'age' correlates with greater depth of groundwater, and with distance along inferred flow paths.

8.5 UNDERSTAND THE RECENT GEOLOGICAL HISTORY THAT HAS A BEARING ON SALINITY

The recent geological history controls the present-day expression of salinity across the region. Incised valleys have slowly filled with sediments eroded from the hills and washed down during flood events. As these sediments have filled the valleys, so constrictions in the bedrock have enhanced the build-up of salts in soil and regolith profiles.

Where coarser sediments weathering from the hill crests abut the alluvial sediments washed down in the floods, a break-in-slope coincides with a change in hydraulic conductivity, again enhancing concentration of salts.

Filling of the Belalie valley has resulted in overflow into the Jamestown Valley to the west, compounding the problem of excess water during wet years in the Jamestown/Bundaleer Valley, but reducing the issue for the Belalie valley.

Combining the information gathered from the airborne geophysics and the associated projects of the SA SMMSP, the recent geological history of the region can be explained, as outlined in Figure 20.

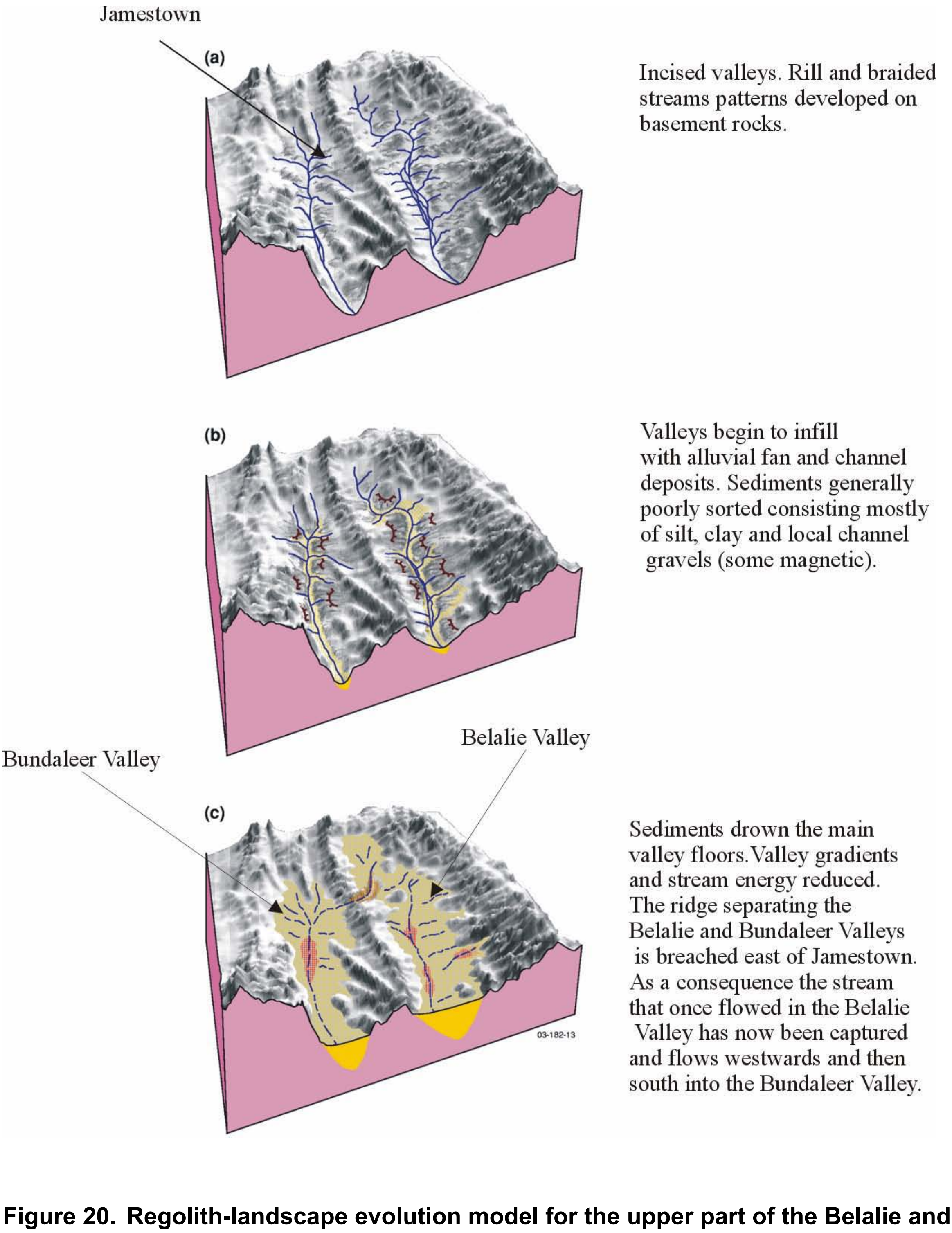

Figure 20. Regolith-landscape evolution model for the upper part of the Belalie and Bundaleer River catchments. Based on drilling, terrain analysis and geophysical interpretation (*from* Wilford, 2004).

Sediments filling deeply incised valleys act as sponges, accumulating the salt that is brought into the area via rainfall. Shallow gradients in the valleys result in pooling of rainwaters and slow infiltration, allowing evaporation to concentrate salts in the near-surface and drying of soil profiles leads to concentration of salts in the groundwaters. Coarser sediments on the valley margins act as preferential flow pathways adding fresher waters to the deeper sediments of the valley floor.

The underlying geology creates natural sub-catchments, which funnel waters into the main valleys (Figure 12). Where there are bottlenecks in the geology, this leads to a rise in local water-tables as water cannot flow out of the valleys fast enough. This situation occurs in the Caltowie and Bundaleer Valleys, while the Belalie Valley opens to the south and can hence cope with any increase in water.

This situation was worsened for the Bundaleer Valley when progressive accumulation of sediments in the Belalie Valley, washed in from the hills to the northeast, raised the valley floor until it reached a low point in the dividing range to the west. As the general topography tilts to the west, towards the ocean, natural stream-flow led to waters from the northern Belalie crossing into the Bundaleer Valley and a new (present-day) divide in the Belalie Valley was created. This increased the supply of water to the valley sediments of the Bundaleer Valley, while decreasing water flow down the Belalie, thus reducing the risk of salinity in the Belalie and increasing it in the Bundaleer.

Addition of salts from rainfall over thousands of years on the hills around Jamestown have resulted in pockets of saline soil, through the action of direct evaporation or transpiration by plants. The salt is kept at depth in the soil, while vegetation keeps the soils intact, but with over-grazing or vegetation removal, the soils rapidly become loose and are readily removed by wind or water erosion. Exposed soils are subjected to greater evaporation which draws water to the surface through capillary action, concentrating salts at the surface and producing salt efflorescences.

9 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 Jamestown region of the Northern and Yorke Agricutural District, 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 through the valleys and helped define the extents of the groundwater systems and the origins of salt in the region.

Conclusions from the Project were:

1. Rainfall is an over-arching constraint and appreciation of climate variability and cyclicity is vital when managing these systems.
2. The land is naturally salty. Any water passing through it will entrain those salts and become saline.
3. Geophysical techniques can provide a 3D understanding of the sub-surface, thereby elucidating situations where the surface hydrology does not fully explain salinity occurrence.
4. Geology plays a strong constraining role for groundwater systems. Bedrock constrictions restrict the flow of groundwaters through the region. The underlying structures also constrain groundwater flow in the valley fill to a dominant north-south direction, despite a regional trend to flow west, towards the ocean.
5. Surface features do not necessarily coincide with sub-surface features.
6. Airborne geophysics are currently unable to detect sub-soil constraints.
7. Salts are predominantly cyclic in nature.
8. Recharge is rapid, but groundwaters include both young and old components, with younger waters derived locally.
9. Recharge is dominantly vertical, occurring diffusely across catchments, but enhanced along valley (colluvial) slopes, which generally comprise coarser-grained materials.

10 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. The present-day hydrological regime may not be representative of the sub-surface (groundwater) regime.
3. In this environment, concentration of magnetic minerals in ancient streambeds means that airborne magnetics surveys can identify prior stream channels (ie. zones of higher porosity / preferential groundwater flow paths).
4. Climate is the dominant driver behind the surface expressions of salinity.
5. Different forms of salinity (groundwater-driven, break-of-slope and dry saline land) are expressed under different climatic regimes.
6. Different forms of salinity require different surveying approaches.
7. Local experts in resource management and the local land managers should 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.
8. It is important to evaluate all available data and ensure that interpretations are commensurate with other data as well as the airborne geophysics.
9. 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.
10. The airborne geophysical modelling should be updated continually through the project as more on-ground results become available.
11. We must maintain a flexible approach both in expectations and the targets we are investigating.
12. A combination of technologies give a better picture than isolated techniques.

11 Transferability

The technologies described here are directly transferable in a local and regional sense. Thus:

1. These valleys are typical of the in-filled valleys of the Broughton catchment and may serve as a model for groundwater movement through the entire system.
2. Similarly geologically constrained systems may be analogous.
3. Export of salt from these valleys to the broader Broughton region may be estimated.
4. Soil attributes may be directly transferable to other regions where radiometrics are flown.

12 Recommendations for Management

1. Monitoring of climate variability is crucial. Also monitoring of bore networks and response to rainfall events to give time constraints on water table rise and fall.
2. Magnetics and AEM delimit zones of higher moisture content. These may be more productive areas during drier periods, but may become water-logged and saline during wet times.
3. Geophysics provides information on areas where drains might be appropriate (*e.g.* to help channel water out of bottleneck areas).
4. Prolonged wet periods (>3-5 years) will result in elevated water-tables regardless of intervention strategies. Living with a few years of salinity-affected land should be accepted. These will reduce once a drier cycle ensues. The land should be managed to ameliorate the symptoms. Salt tolerant plant species and controlled grazing are options.
5. Dry saline land is best managed in line with current practice in the region: through the maintenance of surface cover to reduce evaporation and protect the soil from erosion; and contour banking to retain soil moisture.

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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.

Valuable local input and insight has resulted in a more meaningful study and special thanks should go to the many farmers in the area that allowed access to property and gave freely of their knowledge and time and to all under the umbrella of the Bundaleer / Belalie East branch of the Agricultural Bureau of SA. Also special thanks to Mary-Anne Young of Rural Solutions SA (PIRSA), Jamestown, for her input to the project and comments on the draft report.

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