An inter-disciplinary approach to airborne electromagnetics (AEM) survey design for groundwater exploration using the Australian Geoscience Data Cube and Morphotectonics

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SUMMARY

Over the past decade, advances in new satellite and airborne sensor technologies provide an opportunity for rapid multi-scale mapping, measurement and monitoring of the physical state of the crust, including resolution of key elements of surface and sub-surface hydrological systems. These advances have been mirrored by the development in advanced computational research infrastructure which is now giving the groundwater research community access to high-resolution (spatial and temporal) biophysical datasets (e.g. climate, ecology, geoscience and geospatial) relevant to broader hydrological systems understanding. This infrastructure facilitates integration of multiple datasets and rapid and improved signal processing, inversion, and sophisticated analysis. These datasets provide a catalyst for collaboration, with inter-disciplinary approaches enabling new discovery science in a 'big data' environment, and enabling the qualitative and quantitative analysis and modelling of landscape and hydrological system processes.

In Australian landscapes, airborne electromagnetics (AEM) is widely used in near-surface (<200m) groundwater investigations due to the ability to acquire consistent, spatially coherent information of high quality using calibrated systems, in very short timeframes. This study reports on an evolving inter-disciplinary approach to AEM survey design for groundwater exploration. Recent investigations have employed time series analysis of surface water availability (using the Australian Geoscience Data Cube (AGDC)) combined with morphotectonic analysis of digital elevation datasets, tectonic analysis, and geomorphic analysis of satellite optical data, to help predict preferential recharge zones and shallow groundwater resources. This novel approach has been used successfully for groundwater exploration in the western Murray Basin and Kimberley Region of northern Australia.

Key words: Airborne Electromagnetics (AEM); Australian Geoscience Data Cube (AGDC); Morphotectonics; Groundwater.

INTRODUCTION

In Australia, groundwater system understanding, resource exploration and assessment, has been hampered by a paucity of data at all scales. Despite significant knowledge and data gaps, there is an increasing demand from policy makers and other stakeholders funding groundwater investigations for studies to be carried out cost-effectively and often within short political timeframes. This is matched by a demand that investigations provide high quality data to parameterise groundwater numerical models, and to provide quantitative assessments of the uncertainties and confidence levels in model predictions (Lawrie et al. 2012).

Fortunately, over the past decade, there have been significant advances in new satellite and airborne sensor technologies which provide an opportunity for rapid multi-scale mapping, measurement and monitoring of the physical state of the crust, including resolution of key elements of surface and sub-surface hydrological systems. These advances have been mirrored by the development in advanced computational research infrastructure which is now giving the groundwater research community access to high-resolution (spatial and temporal) biophysical datasets (e.g. climate, ecology, geoscience and geospatial) relevant to broader hydrological systems understanding. This infrastructure facilitates integration of multiple datasets and rapid and improved signal processing, inversion, and sophisticated analysis. These datasets provide a catalyst for collaboration, with inter-disciplinary approaches enabling new discovery science in a 'big data' environment, and enabling the qualitative and quantitative analysis and modelling of landscape and hydrological system processes.

In Australian landscapes, airborne electromagnetics (AEM) is widely used in near-surface (<200m) groundwater investigations due to the ability to acquire consistent, spatially coherent information of high quality using calibrated systems, in very short timeframes (Lawrie et al., 2012). Other factors in the increased uptake of AEM data lie in improvements in many workflow steps including the development of rapid computational methods for AEM inversion, and trans-disciplinary approaches and data fusion techniques (Lawrie et al. 2012). Optimization of AEM data requires careful consideration of AEM system suitability, calibration, and validation and inversion methods, as well as survey design. Experience over the past 15 years has demonstrated that the use of AEM for near-surface hydrogeological investigations in the Australian landscape context often requires high resolution data to map key functional elements of the hydrogeological system. Over the past decade, a staged approach to AEM survey design combined with forward modelling studies has ensured that appropriate AEM technologies are selected to match the target objectives (Lawrie et al. 2012, 2015).

This paper reports on the use of a novel, inter-disciplinary approach to AEM survey design. An evolving approach to AEM survey is documented in this paper. The most recent projects utilise outputs from the AGDC and combine these with morphotectonic analysis of digital elevation datasets, tectonic analysis of potential field datasets, and geomorphic analysis of satellite optical data, to help predict preferential recharge zones and shallow groundwater resources. Examples are shown from the western Murray Basin, New South Wales.

METHODS AND RESULTS

An evolving approach to AEM survey design is documented in this paper. Most recently, this approach incorporates time series analysis of surface water availability (Water Observations from Space (WOfS) derived using the Australian Geoscience Data Cube (AGDC; http://www.ga.gov.au/about/what-we-do/projects/earth-observation-and-satellite-imagery/australian-geoscience-data-cube). The AGDC is a new approach to storing, organising and analysing gridded geospatial information. The standardised data infrastructure of the Australian Geoscience Data Cube removes the need for difficult and time-consuming pre-processing of the data for individual applications. Effort can be directed more productively toward developing more and better information products with increased value for the public. To manage the large volumes of satellite imagery and other gridded geospatial datasets covering the Australian continent Geoscience Australia, in collaboration with the CSIRO and Australian National University - National Computational Infrastructure, have developed a sophisticated geospatial cataloguing system run on the National Computational Infrastructure supercomputing facility. Running this system on a supercomputing facility makes it possible to generate detailed environmental information at continental scales.

An example of the type of analysis which is enabled by the Australian Geoscience Data Cube is the Water Observations from Space (WOfS) product, which is a key component of the Australian Flood Risk Information Portal. WOfS mapped surface water observations for all of Australia at 25m resolution using data from 1998 to 2012. WOfS is the world's first continent-scale map of the presence of surface water derived from Landsat satellite imagery. This project was continental in scale and mapped observations of surface water for all of Australia as an information source for the National Flood Risk Information Portal. WOfS provides a historical summary of how frequently surface water has been observed over the entire Australian continent between 1987 and present day. It covers the entire Australian continent, showing the presence of water over a 27 year period. By using Landsat data, WOfS is useful at 'paddock scale', providing a quantitative indication of how often surface water has been seen anywhere in Australia.

AEM is a regional-scale mapping tool, and survey design has to incorporate a range of factors including: the area of investigation; scale and nature of the target(s) including depth, geometry, conductivity, layer and inter-layer conductivity contrast; logistics issues; project timeframes and budget (Lawrie et al. 2003, 2012). Recent surveys have built on earlier investigations that identified potential improvements in survey design and potential cost reductions through a number of strategies, including: (a) Greater focus and clarity in the objectives of a survey; (b) Increased focus on maximizing the use of existing data and knowledge of landscapes, landscape evolution, and hydrogeology; (c) Changes to acquisition and processing parameters; (d) Use of wider line-spacing governed by an understanding of the scale of key functional elements of the hydrogeological system and target size; and (e) Swath-mapping strategies to map more linear features (Lawrie et al. 2003).

This paper considers the survey design and results from three groundwater-related investigations in the Darling Valley, western New South Wales, Australia (Figure 1). These studies had contrasting objectives in similar floodplain landscapes, and markedly different client and stakeholder demands and expectations (and budgets). All these factors influenced survey design.

Example 1: Broken Hill Managed Aquifer Recharge (BHMAR) Project

The BHMAR project (Figure 1) was tasked with identifying and assessing managed aquifer recharge (MAR) and/or groundwater extraction options to secure Broken Hill's water supply. In the BHMAR project, the initial scoping study concluded that despite the paucity of data, there were a number of possible MAR and groundwater resource targets in the Darling floodplain near Menindee (Lawrie et al. 2012).

To meet the challenge of rapidly identifying and assessing groundwater targets over a large area (>7,500 km^2) within relatively short timeframes (18 months), it was concluded that the only cost-effective method with the ability to resolve key features of the hydrogeological system in the 0-150 m depth range was AEM. In the BHMAR project, the helicopter-borne SkyTEM transient EM system was selected after a rigorous technology assessment exercise (Lawrie et al. 2012; Christensen and Lawrie, 2012).

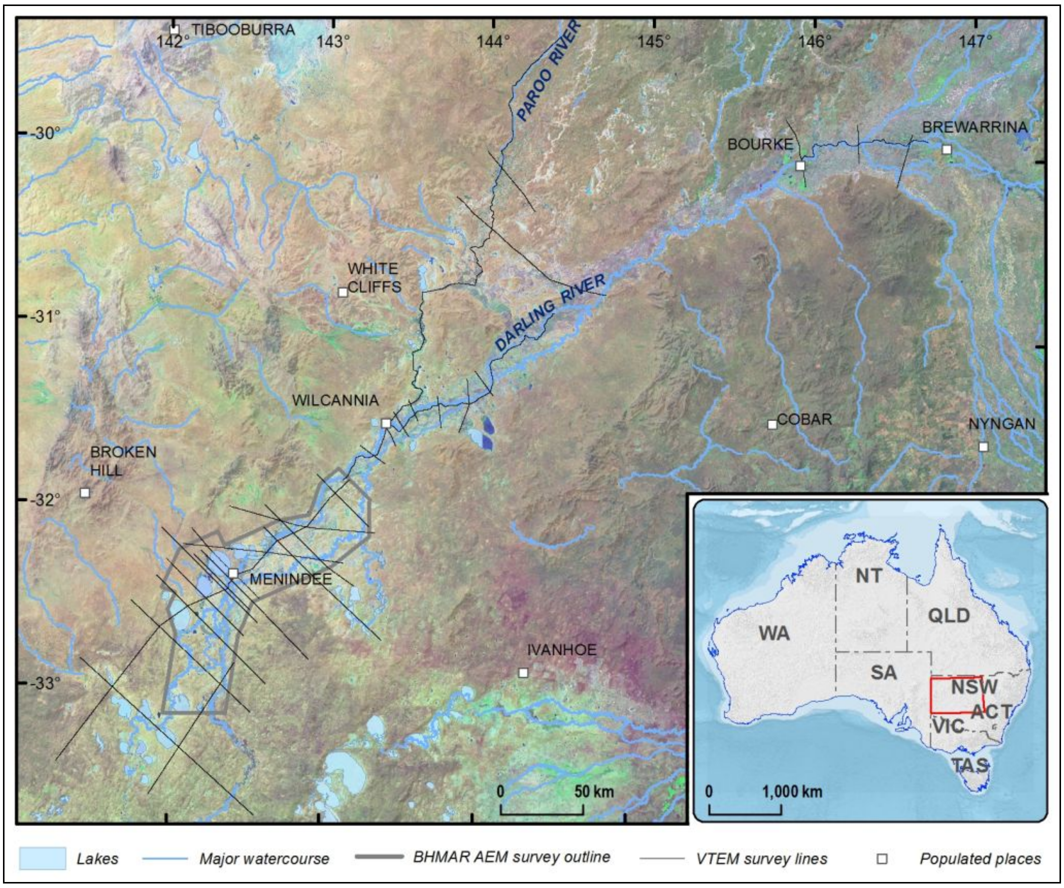

Figure 1 Map showing the location of the BHMAR Project and the VTEMplus transects.

The AEM survey involved the acquisition of 31,834 line km of data in five main blocks, with the data acquired in a 9 week period in 2009 (Lawrie et al. 2012). The flight line orientation and spacing were determined using a conceptual understanding of the geometry of target aquifers, as well as the orientation of surface drainage and landscape elements. The requirement for high-resolution data to be acquired and interpreted in very short timeframes meant that a high-density (200-300m) flight line-spacing was chosen over the majority of the project area.

The survey successfully mapped the key elements of the hydrogeological system including a multi-layered hydrostratigraphy and groundwater salinity distribution. Inversion of the AEM data revealed previously unknown extensive Neogene-to-Recent tectonics, manifested as fault networks that were identified using offsets in marker beds (e.g. the Blanchetown Clay aquitard; Lawrie et al. 2012, 2015). The study identified 14 potential MAR and groundwater targets.

Subsequent to successful project completion, the AEM data were re-inverted to assess optimal line spacing for the different mapping objectives. Data were re-inverted, enabling comparison of line spacing of 200 m, 600 m, 1 km, 2 km, 5 km and 10km. A depth slice example is shown in Figure 2. The spacing between grid points along lines is 40 m in both directions. To investigate the significance of interpolation methods, both Natural Neighbour (NN) and Lateral Parameter Correlation (LPC) methods were compared (Lawrie et al. 2012). For the plots with a high data density (200 m to 1 km line spacing) there is no difference between the NN and the LPC interpolations, but for the more sparse data density, there is a visible difference between the results (Lawrie et al. 2012).

Overall, analysis of these various line-spaced data show that a number of key features of the hydrogeological system required for MAR target mapping and evaluation are only mapped with high resolution (200m) line spacing. In contrast, the larger groundwater resource targets can be identified at coarser line spacing (even at km spacing). The presence of significant Neotectonic faults poses an additional challenge. These faults have strike lengths typically <1km, and varying strike orientations. These faults are critical to the understanding of groundwater processes in the Darling Valley, and high-resolution data is required for borefield-scale investigations. However, regional, wider line-spacing could identify fault systems if data were acquired in swaths, and/or potentially by incorporating ancillary morphotectonic data (Lawrie et al. 2012).

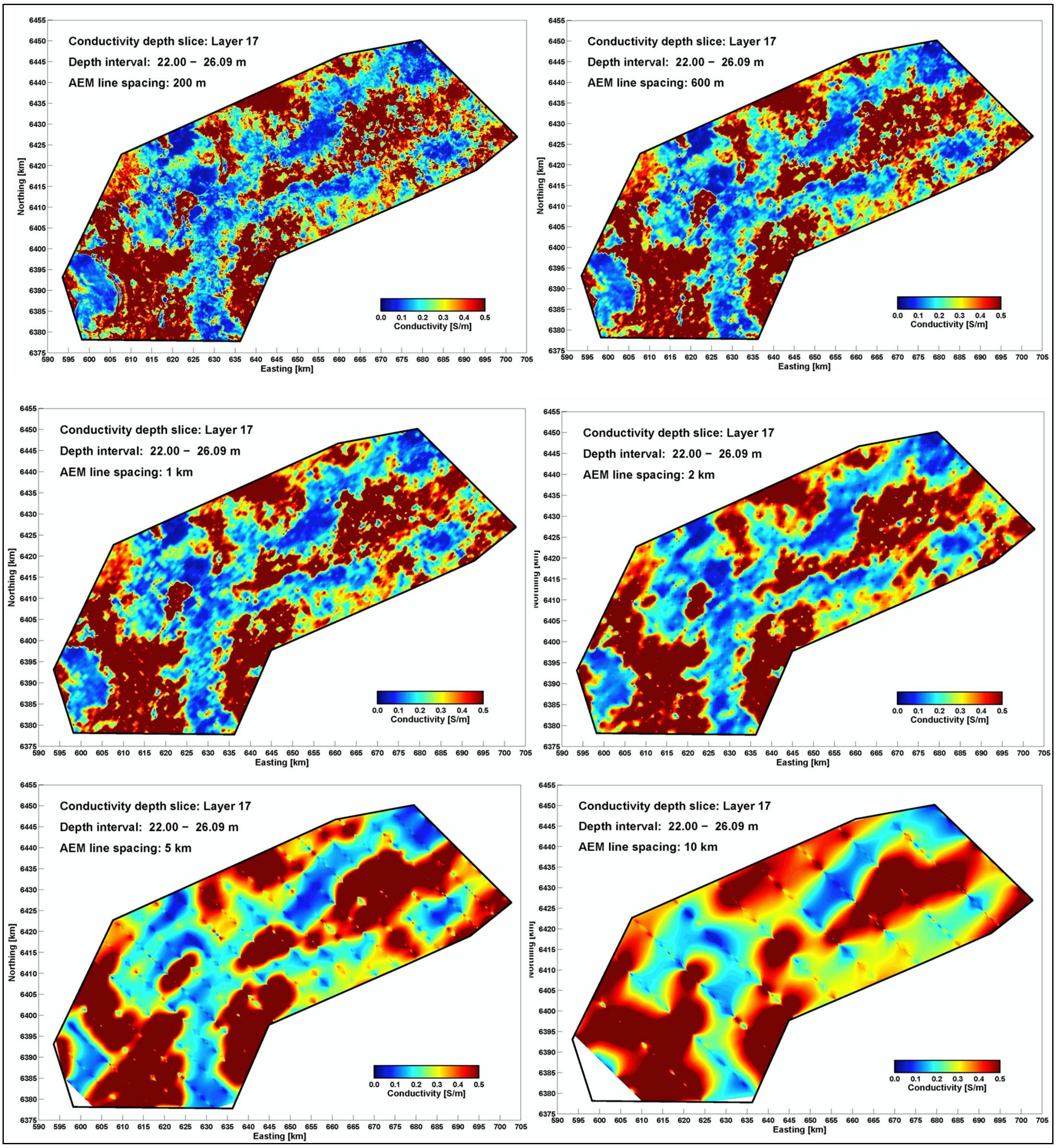

Figure 2. This figure shows re-inversion and NN gridding of AEM data at line-spacing of 200m, 600m, 1km, 2km, 5km and 10km for the 22-26.09m conductivity depth slice.

Example 2: Darling Valley VTEMplus Groundwater Exploration Survey

The more recent of the two investigations was undertaken largely as a strategic test of technologies and methodologies, and incorporated lessons learned in the initial BHMAR Project. In May-June 2014 Geoscience Australia undertook an AEM survey of the Darling and Paroo valleys (Figure 1) using the VTEMplus helicopter-borne system. The survey acquired a total of 2,657 line kilometres of data in a series of 31 transects orientated both longitudinal and transverse to the Darling and Paroo river systems. Transect locations and orientations were selected to address a range of objectives along different reaches of the river systems including the potential for shallow groundwater resources.

Key to survey design was development of a novel systems analysis methodology that built upon the lessons in the BHMAR project and incorporated a range of conceptual hydrogeological and geological models. The methodology also utilised time-series Landsat data (e.g. WOfS; Figure 3), geomorphic, morphotectonic and bedrock structural mapping using a combination of LiDAR, other remote sensing data and potential field geophysics, as well as geological data from drilling, hydrological, hydrogeological and hydrochemical datasets and reports (e.g. Woolley et al. 2004). The methodology also utilised existing river reach mapping (CSIRO, 2008). Trialling this method, the study identified potential groundwater resources close to drought-stricken Wilcannia and further upstream towards Tilpa (Figure 4).

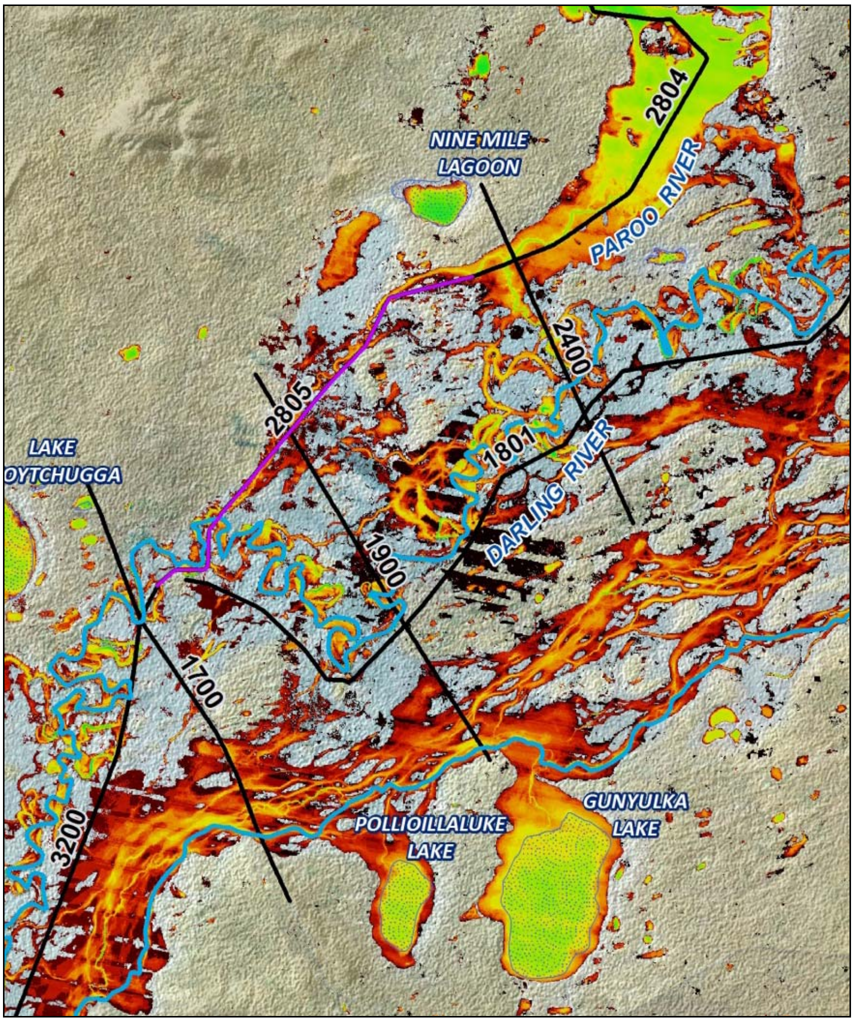

Figure 3. This image shows the WOfS data for one of the Paroo distributaries where it meets the Darling River floodplain. AEM survey lines were selected using a combination of the WOfS data and morphotectonic analysis of digital elevation data, which suggested this most northerly channel would be the most prospective distributary for groundwater exploration.

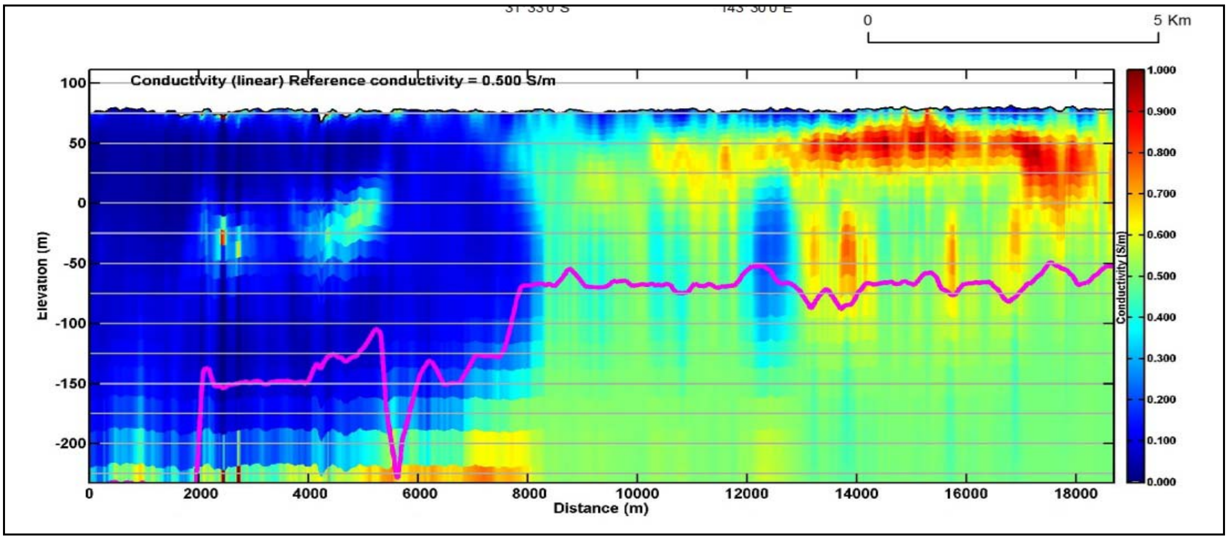

Figure 4. A conductivity depth section (1900- see map above) at the Paroo-Darling River intersection. This shows low conductivities interpreted as fresh groundwater associated with the Paroo River and subjacent groundwater systems, which contrasts with the more conductive (saline groundwater system) in the Darling River floodplain.

Example 3: Yancowinna Creek Groundwater Exploration (SkyTEM 312 survey)

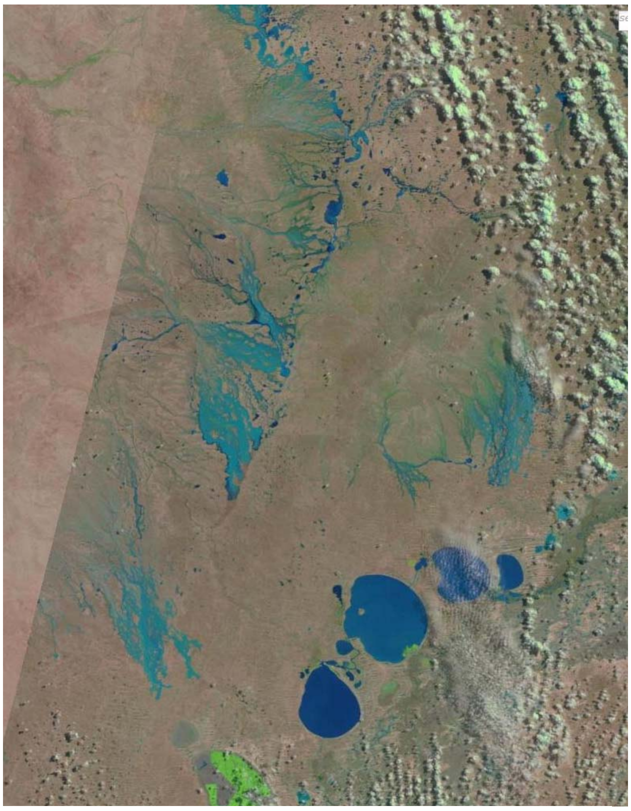

Figure 5. A Landsat image for February 2000 showing fault-controlled streamflow in the Yancowinna Creek.

A small AEM survey (423 line km) was acquired in June 2015 as part of efforts to identify potential groundwater resources to supply an emergency borefield for Broken Hill. Analysis of extreme rainfall events imaged in Landsat data (e.g. February 2000; Figure 4), and temporal Water Observations from Space (WOfS) data in the AGDC highlights the potential for recharge of the groundwater system in high flow events. The imagery also shows active tectonic control on the Yancowinna Creek drainage system, which crosses the route of the existing water pipeline between the Menindee Lakes System and Broken Hill.

Morphotectonic analysis of Google Earth imagery shows contrasting recharge potential along the reach of Yancowinna Creek, and associated lakes. Limited potential for shallow fresh groundwater potential is shown at the northern end of the Yancowinna Creek system (Figure 6a) by the occurrence of deflation lakes (indicating the presence of shallow saline groundwater), combined with lunettes and some surface salt scalds. At the southern end (Figure 6b), the Yancowinna Creek floodout shows no evidence for evaporative deflation, and indicates the potential for a larger fresh groundwater palaeochannel and/or low gradient flow in sub-surface aquifers. The SkyTEM survey was flown to test these different recharge scenarios. A conductivity section through the southern end of Yancowinna Creek (Figure 7) appears to show the presence of a fault-controlled and disrupted palaeochannel. This feature has relatively low electrical conductivity, and has been identified as a target for future drilling.

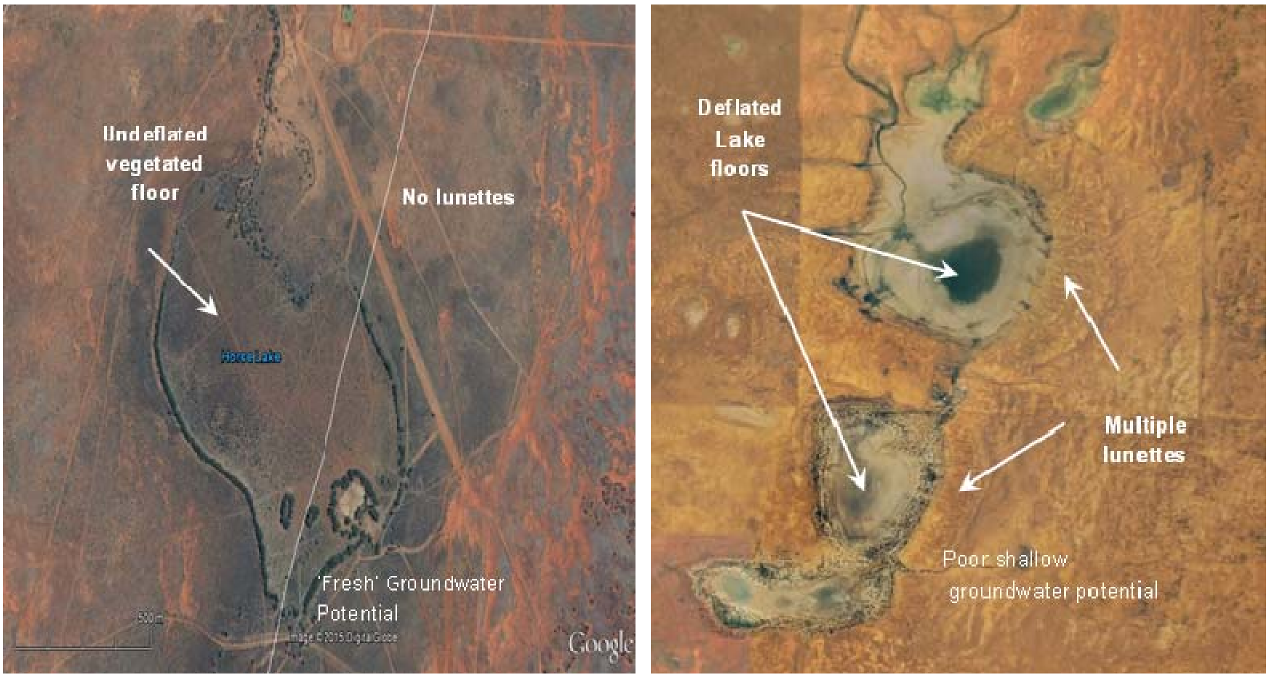

Figure 6. The left hand Google Earth image shows that the Horse Lake has an undeflated, vegetated lake floor, and no lunettes. The right hand image shows lakes further south that have deflated lake floors and multiple lunettes indicating poor shallow groundwater potential.

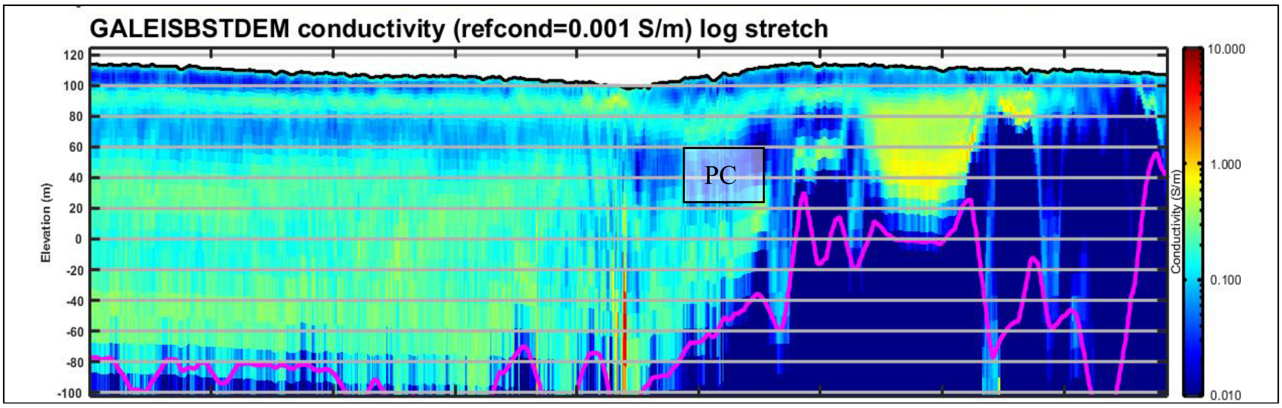

Figure 7. Conductivity depth section through the southern end of Yancowinna Creek. The data suggests active fault control on a palaeochannel (PC) that may contain fresh to brackish groundwater.

CONCLUSIONS

AEM survey design varies enormously depending on the combination of scientific, technical, logistic and other demands. However, from the Darling floodplain projects, the use of complementary knowledge and datasets can aid survey targeting and significantly reduce acquisition costs. The novel use of time-series Landsat data to highlight areas of surface water availability and potential recharge, combined with morphotectonic and geomorphic analysis of digital elevation and visual satellite imagery also helps guide groundwater exploration.

Additional survey flexibility is now possible with the advent rapid turn-around in data inversion. Using a phased, systems analysis (and data) approach, reconnaissance surveys at wide line spacing can be used to identify broad-scale features, with higher resolution data subsequently acquired to address specific questions. This strategy is not always possible in project timelines, and, in the BHMAR project, it was fortunate that a large number of targets were initially mapped at high resolution, due to high failure rates in target assessments (due largely to hydrochemical, aquifer transmissivity and aquitard integrity issues. The BHMAR survey would appear to be the first use of AEM methods in MAR investigation and assessment.

The integration of temporal remote sensing data into holistic landscape analysis approaches, combined with morphotectonic and geomorphic analysis of present day and palaeo-landscapes is also transforming groundwater resource exploration and assessment strategies. This has led to more cost-effective targeting of potential groundwater resources and managed aquifer recharge (MAR) targets in the western Murray Basin and the Kimberley Region of northern Australia. These new approaches and products are also being used in AEM survey design to de-risk investment in irrigated agriculture and associated infrastructure.

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REFERENCES

Christensen, N.B. and Lawrie, K.C., 2012. Resolution analyses for selecting an appropriate airborne electromagnetic (AEM) system. Exploration Geophysics, 2012, 43, 213–227.

CSIRO. 2008. Water availability in the Barwon-Darling. CSIRO Murray-Darling Basin Sustainable Yield Project. CSIRO Australia.

Lawrie, K.C., Gray, M., Fitzpatrick, A., Wilkes P. and Lane, R., 2003. Reducing the acquisition costs of airborne electromagnetics surveys for salinity and groundwater mapping. Preview, October 2003, p. 31-38.

Lawrie, K.C., Brodie R.S., Tan, K.P., Gibson, D., Magee, J., Clarke, J.D.A., Halas, L., Gow, L, Somerville, P., Apps, H.E., Christensen, N.B., Brodie, R.C., Abraham, J., Smith, M, Page, D., Dillon, P., Vanderzalm, J., Miotlinski, K., Hostetler, S., Davis, A., Ley-Cooper, A.Y., Schoning, G., Barry, K. and Levett, K., 2012. BHMAR Project: Data Acquisition, processing, analysis and interpretation methods. Geoscience Australia Record 2012/11. 520p. Geocat 73819.

Lawrie, K.C., Christensen, N.B., Brodie, R.S., Abraham, J., Halas, L., Tan, K.P., Brodie, R.C. and Magee, J., 2015. Optimizing AEM inversions for hydrogeological investigations using a trans-disciplinary approach. In Proceedings of ASEG-PESA 2015. (4p.).

Woolley, D., Williams, R.M. and Varathan, S., 2004. New Water? Groundwater supply for Wilcannia, NSW. Balancing the Basin. 9th MDB Groundwater Workshop. Bendigo, Victoria.