Using regional airborne electromagnetic conductivity data to characterise surface water groundwater interaction in the Cooper Creek floodplain in arid central eastern Australia

Neil Symington*
Geoscience Australia
Symonston
neil.symington@ga.gov.au

Tim Evans
Geoscience Australia
Symonston
tim.evans@ga.gov.au

Nadege Rollet
Geoscience Australia
Symonston
nadege.rollet@ga.gov.au

Larysa Halas
Geoscience Australia
Symonston
larya.halas@ga.gov.au

John Vizy
Geoscience Australia
Symonston
john.vizy@ga.gov.au

Sarah Buckerfield
Geoscience Australia
Symonston
sarah.buckerfield@ga.gov.au

Anandaroop Ray
Geoscience Australia
Symonston
anadaroop.rayr@ga.gov.au

Yusen Ley-Cooper
Geoscience Australia
Symonston
yusen.leycooper@ga.gov.au

Ross C. Brodie
Geoscience Australia
Symonston
Ross.Brodie@ga.gov.au

SUMMARY

Airborne electromagnetic (AEM) data has been acquired at 20 km flight line spacing across much of the Australian continent and electrical conductivity models generated by inverting these data are freely available. Despite the wide line spacing of these data, they are suitable for imaging the shallow subsurface and can greatly assist in understanding groundwater systems.

AEM data acquired using a fixed-wing towed system over the Cooper Creek floodplain, an ephemeral, anabranching river system in arid eastern central Australia, were inverted using deterministic and probabilistic methods. We integrate the AEM conductivity data with a range of surface and subsurface data to characterise the hydrogeology of the region and infer groundwater salinity from the shallow alluvial aquifer across an area of more than 14,000 km^2. The conductivity data reveal several examples of focused recharge through a river channel forming a freshwater lens within the more regional shallow saline groundwater system.

This work demonstrates that regional scale AEM conductivity data can be a valuable tool for understanding groundwater processes at various scales, with implications for water resource management. This work is particularly important in the Australian context, where high quality borehole data is typically sparse, but high quality geophysical and satellite data are often available.

Key words: AusAEM, groundwater, recharge, salinity

INTRODUCTION

Groundwater is a critical resource supporting communities, industry and the environment in many arid landscapes. High evapotranspiration rates and low rainfall in such settings often mean that groundwater recharge rates are very low with implications for water quality and responsible groundwater management. In such environments, focussed recharge through ephemeral streams during periods of high surface water flow is essential for replenishing near-surface aquifers. However, understanding recharge is challenging as borehole data is typically sparse and recharge processes may vary greatly in space and time. In this study we aim to improve understanding of surface water-groundwater interactions within the Cooper Creek floodplain, an ephemeral, anabranching river system located within the Lake Eyre Basin in arid eastern central Australia, by characterising the hydrogeological system using a range of geoscientific data including airborne electromagnetics (AEM).

The use of AEM in assessing shallow groundwater systems is becoming increasingly common, particularly in arid and semi-arid Australian landscapes (e.g., Costar et al., 2019; Mullen and Kellett, 2007). As part of the Exploring for the Future AusAEM program AEM data has been acquired at 20 km flight line spacing across large swathes of the Australian continent, providing valuable information about the conductivity structure of the upper few hundred metres of the subsurface. To characterise surface water-groundwater interactions within the Cooper Creek floodplain, we integrate AEM-derived conductivity data with a range of remotely sensed surface datasets, including satellite-derived flood inundation maps and a digital terrain model, and subsurface datasets including drillhole information water levels and seismic reflection data. By integrating these data, we are able to interpret the AEM conductivity sections to characterise the architecture of the local groundwater system, infer the distribution of groundwater salinity for the near-surface aquifer and improve our conceptual model of surface water-groundwater interaction.

The focus of this investigation is the alluvial groundwater system beneath the Cooper Creek floodplain in south-west Queensland. The floodplain represents the uppermost part of the sediments within the Cooper Creek palaeovalley, which is infilled with a sequence of Cenozoic fluvial sands and minor clay that is up to 150 m thick (Figure 1). The predominantly Pleistocene aquifer sands were deposited in a fluvial environment, at a time when stream power was greater due to a wetter climate and steeper valley gradients (Maroulis, 2000). Quaternary aridity and decreasing valley gradients related to tectonically controlled base-level rise have modified the character of the river system to its present form (Jansen et al., 2013). Consequently, the floodplain is now almost entirely covered with several metres of cracking clay soil, which rapidly seals when saturated and is thought to minimise much of the surface water infiltration deep into the profile (Cendón et al., 2010). The valley fill sediments are underlain by the Cretaceous Winton Formation, which represents the uppermost sedimentary sequence of the Eromanga Basin.

Neotectonic deformation has contributed to uplift of the Innamincka Dome, which has created a shallow subsurface barrier to downstream flow within the Cooper Creek fluvial system. This shallow bedrock high effectively isolates the Cooper Creek groundwater system from alluvial aquifer systems further downstream (Jansen et al., 2013) (Figure 1). Deformation has also produced a series of domes and basins that influence the geometry of the floodplain (Jansen et al., 2013). The floodplain is up to 60 km wide but narrows to 15 km wide where the floodplain is deflected westwards between two north-south trending anticlines (Figure 2).

METHOD AND RESULTS

AusAEM data were acquired using the fixed-wing TEMPEST® system as part of the Exploring for the Future AusAEM Eastern Resources Corridor survey (Ley-Cooper, 2021). Flight lines were oriented east-west and spaced 20 km apart (Figure 1). The AEM bulk conductivity models were derived using the deterministic Geoscience Australia Layered Earth Inversion (GALEISBSTDEM; Brodie, 2023) by inverting for the vector sum (i.e., amplitude of the X- and Z-components) of the AEM data. In areas of potential freshwater recharge, we inverted the AEM data using the probabilistic HiQGA inversion code (Ray et al., 2022) to estimate an ensemble of models from which we calculate the posterior probability density function for conductivity down to 400 metres depth. Although these models were run only in selected areas, they provided a better understanding of AEM model uncertainty and influenced the confidence with which we could interpret the conductivity structures from the deterministic inversion.

AEM bulk conductivity models and other geoscientific data were imported into a 3D environment for interpretation. Using the AEM models, we were able to interpret a number of gentle anticlines and synclines within the top 100 metres of the subsurface below the floodplain (Figure 2). These structures are approximately coincident with structures evident in the underlying Eromanga and Cooper Basins as mapped from seismic and petroleum exploration wells (Vizy and Rollet, 2022). While the floodplain surface is relatively flat, variations in fluvial geomorphology associated with these structures are indicative of river response to deformation (e.g., Ouchi, 1985). This manifests as sediment deposition within structural depressions and incision through uplifted areas. River morphology has implications for groundwater recharge as high river flow velocities are needed to scour the ubiquitous cracking clays to permit more direct connection between surface water and shallow groundwater (Cendón et al., 2010). Moreover, some depressions in the floodplain form terminal wetlands that could provide preferential pathways for surface water infiltration through the unsaturated zone. This process may be significant in groundwater salinisation as infiltrating water can mobilise evaporatively concentrated salts within the unsaturated zone, from where they percolate down to the water table.

AEM-derived conductivity sections and pre-existing drillhole data suggest that the near-surface, Pleistocene sandy aquifer occurs across almost the entire floodplain at an approximate thickness of 20-30 metres (Figure 3). This aquifer comprises mostly fluvial sand (Maroulis, 2000), which is typically a resistive material, and we therefore assume that the high conductivity response (seen as the red response in the AEM in Figure 2) results from the presence of dissolved salts within the aquifer. The general distribution of AEM-derived bulk conductivity in the near-surface is consistent with the limited groundwater salinity measurements from boreholes (Evans, 2020), supporting the assumption of a linear relationship between bulk conductivity and groundwater salinity for this aquifer. These circumstances make AEM the ideal tool for regional scale inference of groundwater salinity.

At the floodplain scale, the distribution of bulk conductivity suggests that groundwater salinity generally increases with distance downstream (Figure 3). Bulk conductivity is generally lower (<0.1 S/m) in the upper reaches of the floodplain where the braided surface channels are indicative of higher surface water flows, as well as along the infrequently inundated eastern margins of the floodplain. Conductivity is highest (>1 S/m) in the narrow, north-south oriented section of the floodplain, and in the far south-west.

At the local scale, resistive lenses within the conductive near-surface in the AEM conductivity sections are coincident with deeply incised channels within the alluvium. These features are observed in at least 15 locations across the floodplain. Probabilistic inference across one such resistive lens (Figure 4; see Figure 1 for location) infers a maximum thickness of at least 10 m and a width of ~400 m within the east-west plane. The presence of this resistive zone in at least 90% of all models from the ensemble provides a very high degree of confidence that the feature exists in the subsurface (Figure 4). The geometry and associated morphology of these features are consistent with hundred-metre scale freshwater lenses identified during a high-resolution drilling and hydrochemical study from the Cooper Creek flood plain (Cendón et al., 2010). The results from the present study suggest that these recharge processes occur more widely than has previously been identified. This has implications for calculating floodplain water budget and identification of potential groundwater-dependent ecosystems along river channels (e.g., Crosbie et al., 2022).

CONCLUSIONS

The results of this work demonstrate that 20 km flight line spaced AEM conductivity data from a fixed-wing system can be used to infer near-surface processes in some alluvial systems. By integrating a range of geoscientific data, we are able to establish an interpretation methodology for characterising the basic architecture of the groundwater system and make inferences regarding groundwater salinity. This allows us to refine our conceptual model of how groundwater interacts with the river. Although groundwater level time-series data and additional hydrochemical data are needed to test the conceptual models, the AEM-derived conductivity has proven valuable at informing a regional understanding by melding local observations. This work reinforces the value of acquiring pre-competitive AEM data for a variety of applications.

ACKNOWLEDGMENTS

The Exploring for the Future (https://www.ga.gov.au/eftf) National Groundwater System project is funded by the Australian Government through Geoscience Australia.

REFERENCES

Brodie, R.C. (2023). *GA-AEM Source Code Repository*. Geoscience Australia. https://github.com/GeoscienceAustralia/ga-aem

Cendón, D.I., Larsen, J.R., Jones, B.G., Nanson, G.C., Rickleman, D., Hankin, S.I., Pueyo, J.J. and Maroulis, J. (2010). Freshwater recharge into a shallow saline groundwater system, Cooper Creek floodplain, Queensland, Australia. *Journal of Hydrology* 392(3-4), 150-163. https://doi.org/10.1016/j.jhydrol.2010.08.003

Costar, A., Love, A., Krapf, C., Keppel, M., Munday, T., Inverarity, K., Wallis, I. and Soerensen, C. (2019). Hidden water in remote areas—Using innovative exploration to uncover the past in the Anangu Pitjantjatjara Yankunytjatjara Lands. *Mesa Journal 90*, 23-35. https://sarigbasis.pir.sa.gov.au/WebtopEw/ws/samref/sarig1/image/DDD/MESAJ090023-035.pdf

Crosbie, R.S., Holland, K.L. and McVicar, T.R. (2023) Regional□scale partitioning of transmission losses and groundwater recharge using satellite estimates of actual evapotranspiration in an arid environment. *Ecohydrology* 16(1) https://doi.org/10.1002/eco.2490

Evans, T. J., Martinez, J., Lai, E., Raiber, M., Radke, B. M., Sundaram, B., Ransley, T., Dehelean, A., Skeers, N., Woods, M., Evenden, C., and Dunn, B. (2020). *Hydrogeology of the Cooper GBA region. Technical appendix for the Geological and Bioregional Assessment Program: Stage 2*. Department of the Environment and Energy, Bureau of Meteorology, CSIRO and Geoscience Australia. https://www.bioregionalassessments.gov.au/sites/default/files/gba-coo-stage2-appendix_hydrogeology_final_0.pdf

Jansen, J.D., Nanson, G.C., Cohen, T.J., Fujioka, T., Fabel, D., Larsen, J.R., Codilean, A.T., Price, D.M., Bowman, H.H., May, J.H. and Gliganic, L.A. (2013). Lowland river responses to intraplate tectonism and climate forcing quantified with luminescence and cosmogenic ^{10}Be. *Earth and Planetary Science Letters 366*, 49-58. https://doi.org/10.1016/j.epsl.2013.02.007

Ley-Cooper, Y. (2021). *Exploring for the Future AusAEM Eastern Resources Corridor: 2021 Airborne Electromagnetic Survey TEMPEST® airborne electromagnetic data and GALEI inversion conductivity estimates*. Geoscience Australia, Canberra. https://dx.doi.org/10.26186/145744

Maroulis, J. (2000). *Stratigraphy and mid-to-late quaternary chronology of the Cooper Creek floodplain, Southwest Queensland, Australia*. PhD Thesis, University of Wollongong. https://ro.uow.edu.au/theses/1982

Mullen, I., and Kellett, J. (2007). Groundwater salinity mapping using airborne electromagnetics and borehole data within the lower Balonne catchment, Queensland, Australia. *International Journal of Applied Earth Observation and Geoinformation 9*(2), 116-123. https://doi.org/10.1016/j.jag.2006.07.004

Ouchi, S. (1985). Response of alluvial rivers to slow active tectonic movement. *Geological Society of America Bulletin 96*(4), 504-515. https://doi.org/10.1130/0016-7606(1985)96%3C504:ROARTS%3E2.0.CO;2

Ray, A., Taylor, R., and Moghaddam, N. (2022). *HiQGA.jl*. https://github.com/GeoscienceAustralia/HiQGA.jl

Vizy, J., Rollet, N. (2022). *Great Artesian Basin geological and hydrogeological surfaces update: report and data package*. Record 2022/019. Geoscience Australia, Canberra. http://dx.doi.org/10.11636/Record.2022.019

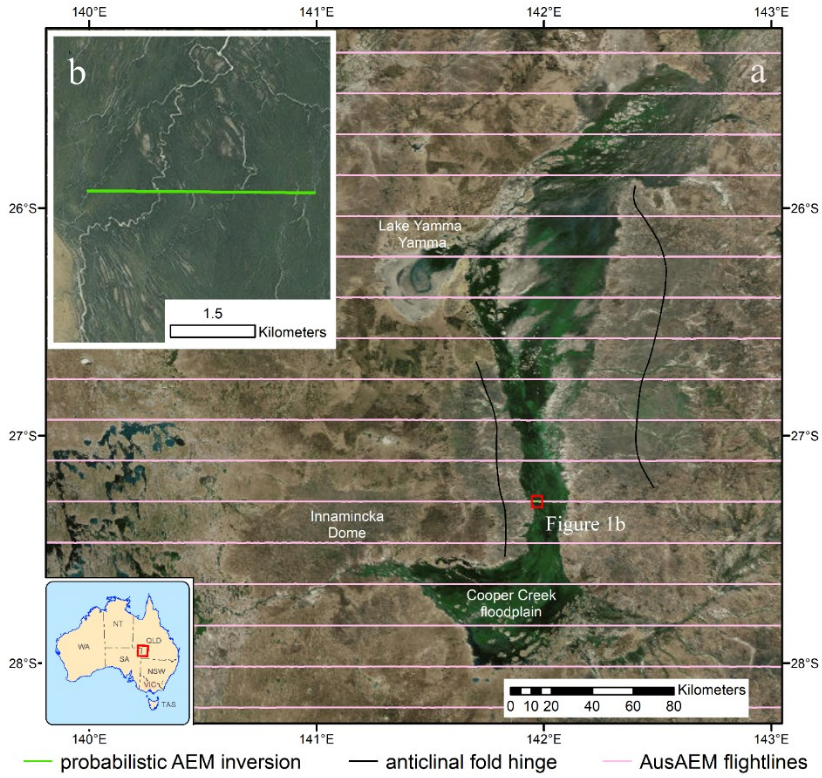

Figure 1. a) True colour visible satellite image of the Cooper Creek floodplain overlain with AusAEM survey flight lines. b) Inset showing segment of AEM flight line 10190001 crossing the Cooper Creek main channel. This line segment was inverted using probabilistic methods – results shown in Figure 4.

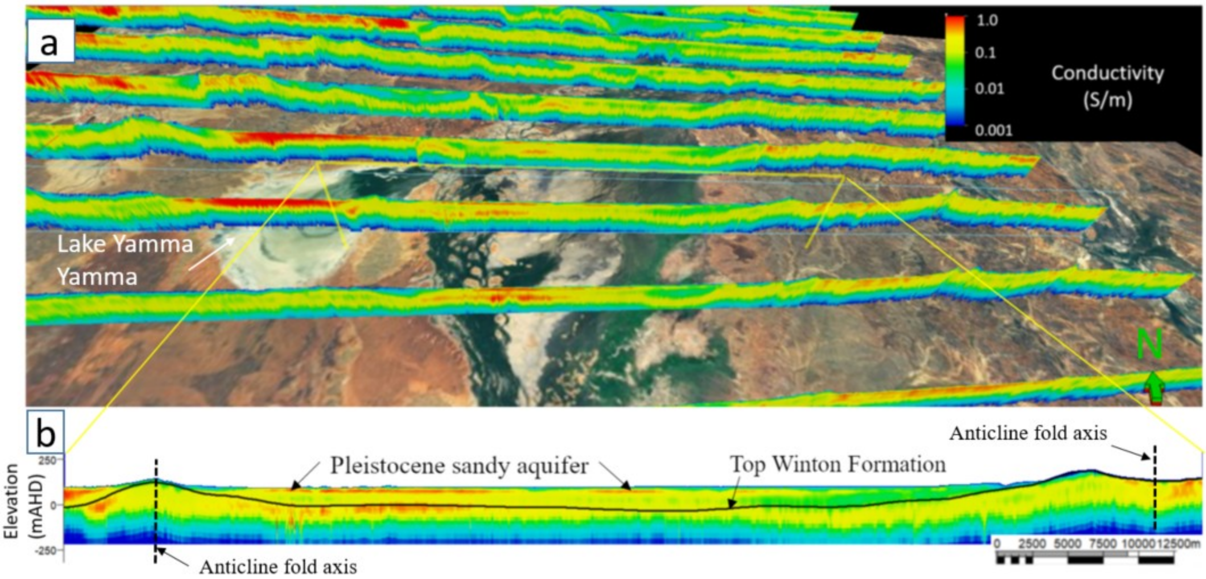

Figure 2. a) Oblique view of of AEM conductivity sections across the central Cooper Creek floodplain east of Lake Yamma Yamma, overlain on true colour visible satellite imagery. b) AEM section 1014001 showing both the flat-lying, conductive Pleistocene sandy aquifer sediments and the gently folded Winton Formation. The floodplain, which contains up to 150 m of Cenozoic sediment, lies within a broad syncline between two anticlinal folds.

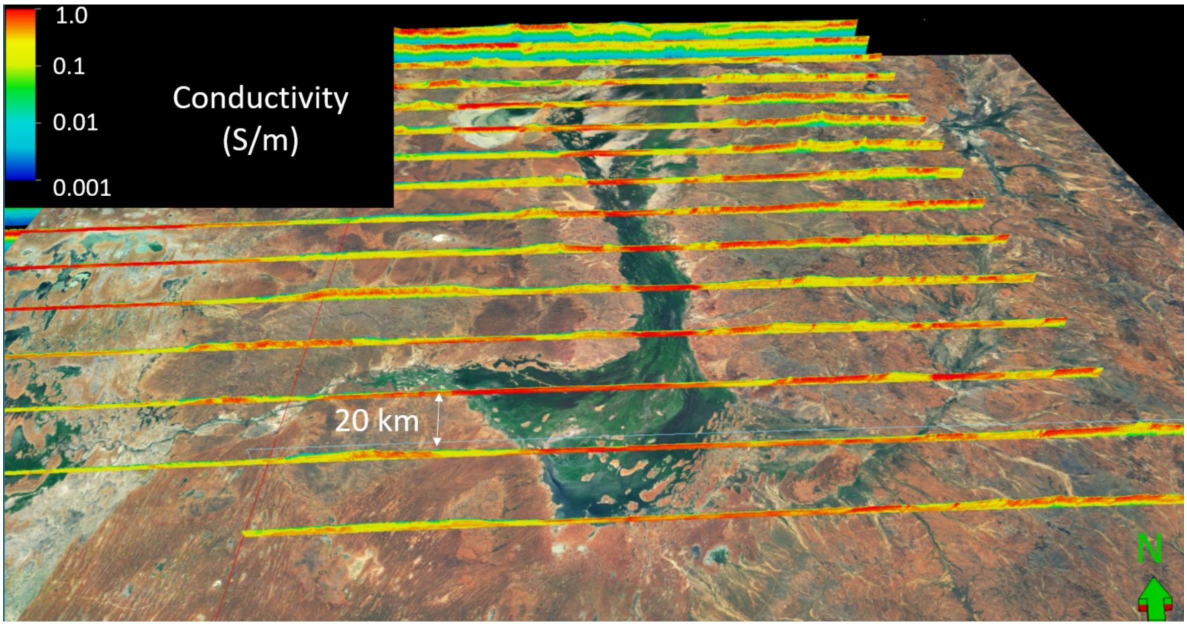

Figure 3. AEM conductivity sections across the Cooper Creek floodplain imaging to depths of ~300 m overlain on true colour visible satellite imagery. The electrical conductivity beneath the floodplain increases where the floodplain narrows in the north, and remains relatively high, peaking again immediately upstream of the Innamincka Dome constriction in the south.

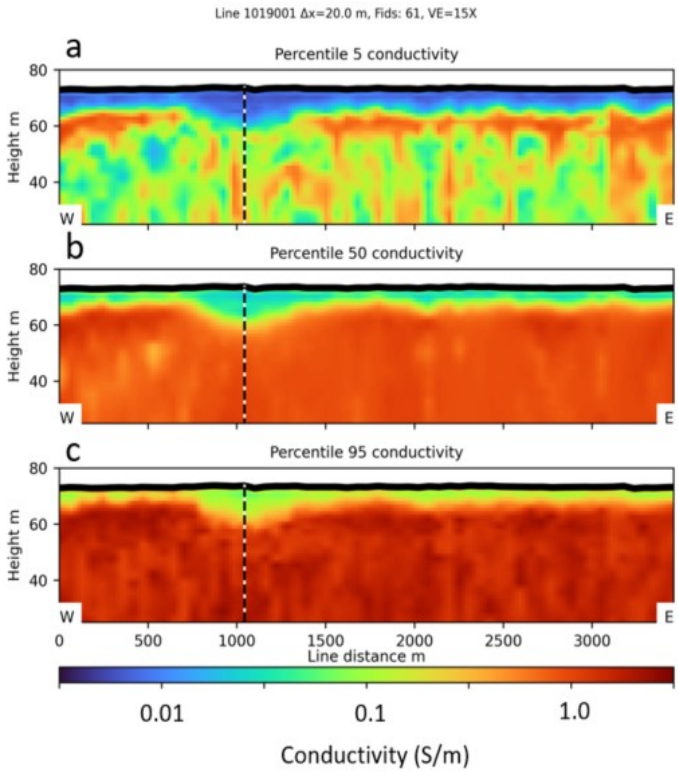

Figure 4. Results from probabilistic modelling of 61 fiducials from AEM flight line 1019001, with conductivity depth sections for a) 5th, b) 50th and c) 95th percentiles. The presence of an approximately 10 metre thick and 400 m wide resistive lens in all sections indicates that this feature persists throughout the model ensemble, giving high confidence in the presence of a real subsurface feature. The persistent resistive feature is interpreted as a freshwater lens perched on the saline groundwater table, indicating focussed recharge of freshwater through the river channel at this location.