# Resolving Changes to Freshwater Lens Systems in a “Sea of Salinity” using Multi-date Airborne EM

**Tim Munday***
*CSIRO Mineral Resources*
*Kensington, WA*
*tim.munday@csiro.au*

**Camilla Soerensen**
*CSIRO Mineral Resources*
*Kensington, WA*
*camilla.soerensen@csiro.au*

## SUMMARY

Saline aquifers in the Murray River or SE Australia are traversed by freshwater rivers, with adjoining riparian and floodplain regions containing freshwater lenses. Bore data and more recent Airborne electromagnetic (AEM) surveys have determined that these lenses are spatially extensive, but have widely varying geometries. The maintenance of these lens systems is important as they support ecologically significant riparian vegetation communities such as Red Gum and Black Box. A more complete understanding of their hydrogeology is required to ascertain how they develop and degrade. Limited ground investigations including $^{14}C$ geochemistry have determined that the lens systems contain recent water, indicating that they are dynamic systems with their development defined by the relative rates of recharge from the river and mixing with groundwater. Changes in groundwater gradients and depth, floodplain extent, and topography are believed to control their initial location. The same controls also govern their stability.

The potential of AEM systems for defining the geometry of these lens systems in 3D is considered along with an assessment of their value for monitoring variations associated with these ecosystems. The advent of “calibrated” AEM systems and robust inversion tools have given added impetus to their use for environmental monitoring. Spatio-temporal variations are observed in the near surface (top 20m) from a multi-temporal assessment of Clark’s Floodplain, adjacent to the Bookpurnong irrigation area, with co-incident AEM surveys acquired between 2008 and 2015. Spatial changes in ground conductivity, attributed to changing groundwater quality have been observed. The freshwater lens systems appear to have contracted significantly over the last decade. This is attributed, in part, to land use patterns and the development of an irrigation-related groundwater mound on the highlands adjacent to the floodplain, and an increased hydraulic gradient towards the river. The results indicate the geometry of the hyporheic zone may have also changed along the river.

**Key words:** Spatio-temporal Airborne electromagnetics, Floodplain, Freshwater lens

## INTRODUCTION

The application of ground-based geophysical methods for measuring and monitoring shallow subsurface hydrological processes in natural systems has seen wider use in the last two decades (Binley et al., 2015). This is, in part, a result of advances in instrumentation, their relatively low cost, developments in associated automated measurement systems, robust inversion methods, and the ability to capture data at scales appropriate to understanding these processes. Direct current (DC) resistivity methods, in particular, have seen wider use in near-surface applications, being employed increasingly for time-lapse or temporal studies of hydrological processes in natural systems, for these reasons. Recently Singha et al. (2015) presented a detailed review of DC resistivity methods for temporal studies. Although the potential of multi-date AEM techniques for similar purposes has been recognised, the realities associated with a relatively high cost envelope for data acquisition, technology limits linked to system calibration, noise, poor tracking of a system varying geometry during a survey, coupled with the limited availability of robust inversion procedures have limited their take-up for such purposes. Early studies identified the potential but also demonstrated the challenges including those mentioned above.

One of the earliest reported studies of multi-date airborne surveys for environmental monitoring was that described by Smith et al. (1997) when discussing the mapping of subsurface brines associated with oil and gas production in Mississippi in the USA. In the latter part of the 1990’s, Fitterman and Deszcz-Pan (1998) discussed the use of multi-date AEM data for as a means of assessing long term changes in the aquifer system resulting from changes in water management policies aimed at restoring the South Florida ecosystem. Beamish and Mattsson (2003) reported on the application of repeat AEM surveys in relation to the long-term monitoring of large, active, contain and seal landfills. Results from a comparison of two frequency domain helicopter EM data sets acquired a year apart were analysed by Lipinski et al. (2008). They characterised the hydrogeology of an alluvial aquifer along the Powder River Basin in Wyoming, USA, when subject to the infiltration of by-product water from coal bed natural gas (CBNG) production. In a comparable study, Munday et al. (2010) demonstrated an effective procedure for defining spatio-temporal variations in ground conductivity across a salinised floodplain in South Australia, using multi-date frequency domain helicopter electromagnetic (FDHEM) data. Lateral and vertical changes in the conductivity of the floodplain were resolved between surveys acquired. One of the challenges identified in that study was the need to work with “calibrated” or “standardised” data sets if a direct comparison of changes in ground conductivity was to be made between the different dates.

Among the issues identified in these early studies were problems of calibration and the difficulty of being able to examine variability as a function of changing depth, that is, changes associated with vertical conductivity structure. The advent of digital broadband AEM systems, combined with the development of procedures for their calibration (e.g. Deszcz-Pan et al. 1998, Brodie et al. 2004, Lane et al. 2004, Ley-Cooper et al. 2006, Davis and Macnae 2007) and correcting for system geometry (e.g. Fitterman and Yin 2004, Yin and Fraser 2004, Davis et al. 2006), along with more reliable and flexible inversion procedures (e.g. Brodie and Sambridge 2006, 2009, Auken et al. 2015), now provides a more robust basis for realising the potential of AEM in the spatio-temporal monitoring of dynamic landscapes.

The primary advantage of airborne methods lies with their ability to compile spatially contiguous measurements of ecosystems from surface to depth (>10's of metres). Often the lateral variability of lithologic and hydrologic and chemical properties, common and important characteristic of the Critical Zone (CZ) cannot be sufficiently or effectively mapped with direct sampling methods such as drilling or augering (Parsekian et al. 2015), particularly in areas where the ecosystems are sensitive and land access is difficult. Even ground geophysical techniques are limited in terms of studying spatial properties of the subsurface for the same reason.

The objective of this paper is to examine the potential of "standardised" airborne EM system to resolve changes in groundwater conditions in a floodplain setting, specifically to define whether there have been spatio-temporal changes in the geometry and extent of freshwater lens systems that support the riparian vegetation communities along the Murray River, in south east Australia. The study considers data acquired in two surveys separated by almost 10 years, which covers a period when the Murray Basin was subject to severe and prolonged drought and also when the floodplain was flooded. It also considers the issues and challenges of employing AEM systems for such purposes.

## STUDY AREA AND ECOHYDROLOGY

**Study area**

This study was focused on a small floodplain - the Clarkes Floodplain, located adjacent to the Bookpurnong Irrigation District on the Murray River in the Riverland region of South Australia (Figure 1). This floodplain has been a study site for a range of pilot investigations examining options for floodplain management (see, for example, Berens et al. 2009a, b).

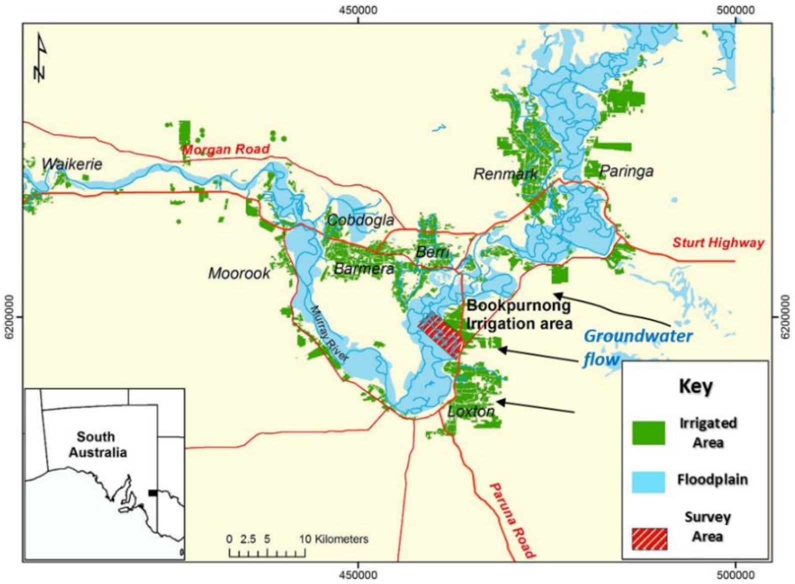


**Figure 1: Location of the Bookpurnong multi-date AEM study site in the Riverland of South Australia. The extent of irrigated area are shown in green.**

**Hydrogeology**

The floodplain has a hydrogeological characteristics of the eastern part of the lower Murray River. Floodplain sediments consist of a clay (the Coonambidgal Clay) ranging from 3 to 7 m thick, overlying a sand (the Monoman Formation) which is approximately 7-10m thick in this area (Figure 2). These sediments occupy the Murray Trench which cuts into a sequence of Pliocene sands (the Loxton-Parilla Sands). These sands outcrop in the adjacent cliffs, and are covered by a layer of Woorinen Sands over Blanchetown Clay, each approximately 2 m thick (Figure 2). The whole area is underlain by the Bookpurnong Beds, which act as an aquitard basement to the shallow aquifer that encompasses the Monoman Formation and Loxton Sands. Regional groundwater salinity in the Loxton Sands and Monoman Formation ranges between 30 and 40 000 mg/L, with the high salinities commonly found on the floodplain resulting from evaporative concentration. Irrigation recharge salinity is typically 1 000-3 000 mg/L.

Excess recharge from the Bookpurnong Irrigation District has led to the formation of a groundwater mound, which displaces saline groundwater towards the floodplain and has led to increased waterlogging and salinisation on the floodplain, coupled with groundwater seepage at the break of slope adjacent to the cliffs. There is considerable variation of evapotranspiration and seepage depending on distribution of soils, vegetation type, floodplain elevation and geometry. Where the freshwater Murray River and its anabranches traverse the floodplain, adjoining riparian and floodplain regions contain freshwater lenses with widely varying geometries (Figure 2).

Woods (2015) noted that freshwater lenses directly affect river salinity providing a buffer between the river and saline groundwater. The maintenance of these lenses, part of the Critical Zone (CZ), is important as they support environmentally significant

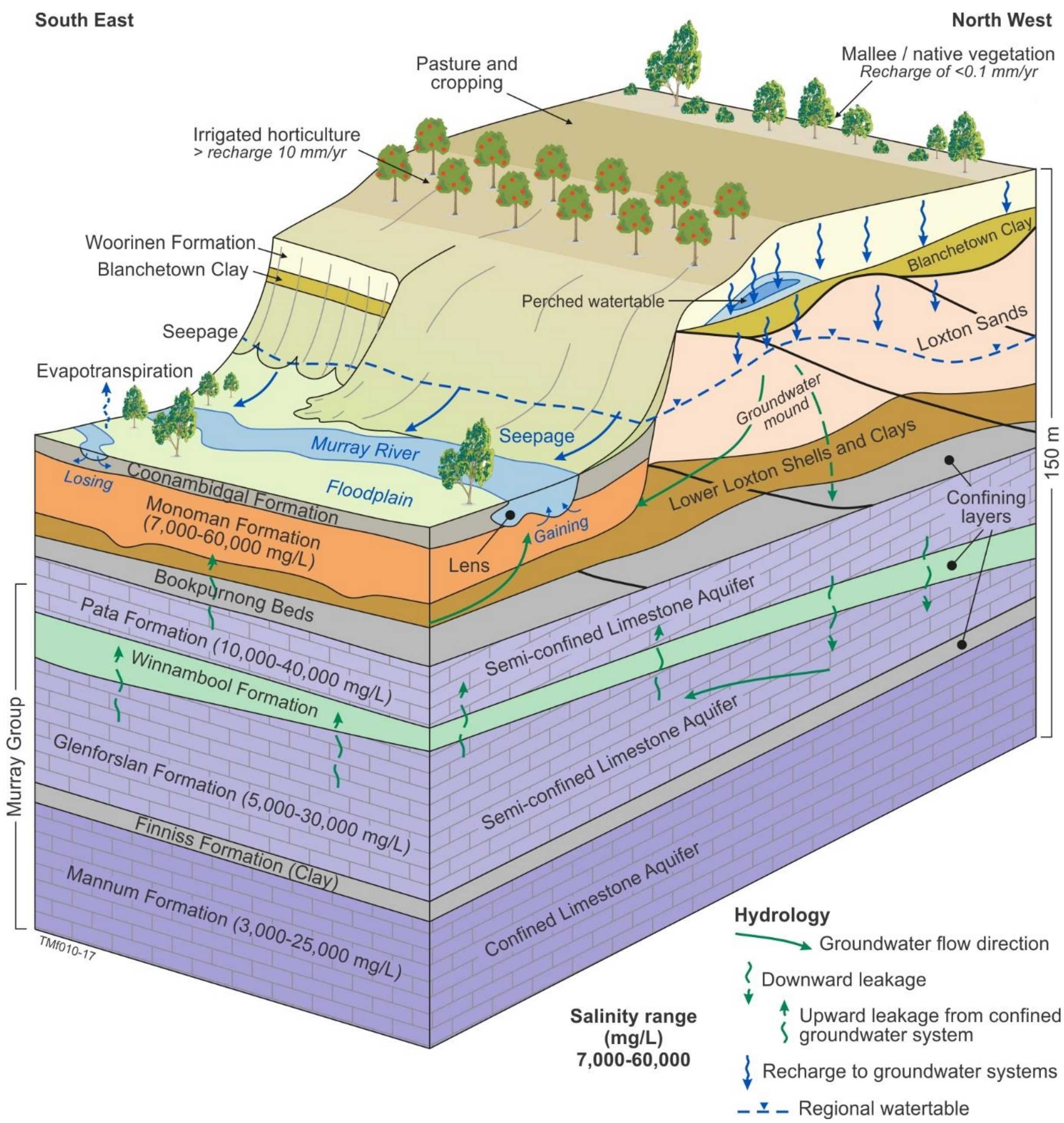


**Figure 2: Schematic representation of the hydrogeology of the Bookpurnong floodplain and adjacent highland areas. High recharge from irrigation on the highlands adjacent to the floodplain results in the development of localised perching and the formation of a groundwater mound in the Loxton-Parilla sands. The mound increases the hydraulic gradient towards the floodplain causing a rise in water levels in the floodplain sediments. High water levels coupled with high rates of evapotranspiration, concentrates salt in the near surface across the floodplain. Elevated water levels also promote the discharge of saline groundwater into the Murray River, along "gaining" stretches of the river system. The ecology of the floodplain is affected by these processes, and the dynamics of freshwater lens systems, along the river and within the floodplain.**

riparian vegetation communities such as Red Gum (*Eucalyptus camaldulensis*) and Black Box (*Eucalyptus largiflorens*) (Holland et al. 2006). Bore data and more recent AEM surveys (e.g. Munday et al. 2016) have determined that these lenses are spatially extensive, and limited ground investigations, including $^{14}C$ geochemistry, have determined that the lens systems contain recent water, indicating that they are dynamic systems, with their development defined by the relative rates of recharge from the river and mixing with the regional groundwater (Cartwright et al. 2010, 2011). However, a more complete understanding of their hydrogeology is required to ascertain how they develop and degrade (Woods 2015).

## METHODS

**Spatio-temporal mapping with “standardised” AEM systems**

This study involved a comparison of AEM data acquired in two periods - August/September 2006, and May 2015, using the SkyTEM time domain helicopter electromagnetic (TDHEM) system (Sørensen and Auken, 2004). The SkyTEM AEM system has been successfully applied to the mapping of alluvial aquifers across Australia (see, for example, Viezzoli et al. 2009, Lawrie et al. 2010, Davis et al. 2015) including the River Murray Floodplains.

Details of the two SkyTEM systems used in this study are summarised in Table 1. The SkyTEM AEM system is carried as a sling load towed beneath the helicopter. The transmitter coil, mounted on a lightweight frame, is multi-turn eight sided loop, transmitting a low moment in one turn and a high moment in all turns. For this study SkyTEM operated in a dual moment mode (Sørensen and Auken, 2004). In the Low Moment mode, a low current, high base frequency and fast switch off provides early time data for shallow imaging. In contrast, the High Moment mode, employing a higher current and a lower base frequency, provides late time data for deeper imaging. The receiver coil is rigidly mounted at the rear and slightly above the transmitter loop in a near-null position relative to the primary field, thereby minimizing distortions from the transmitter loop.

**Table 1: SkyTEM TDHEM system parameters for the 2006 and 2015 surveys**

| | Low Moment | | High Moment | |
|---|---|---|---|---|
| *System and Year of acquisition* / *System Characteristic* | ***SkyTEM$^{314}$ 2006*** | ***SkyTEM$^{304}$ 2015*** | ***SkyTEM$^{314}$ 2006*** | ***SkyTEM$^{304}$ 2015*** |
| *Transmitter area ($m^2$)* | 314 | 340 | 314 | 304 |
| *Transmitter turns* | 1 | 1 | 4 | 4 |
| *Transmitter Current (A)* | 40 | 9 | 85 | 116 |
| *Transmitter Moment ($Am^2$)* | 12600 | 3100 | 107000 | 158000 |
| *Nominal Transmitter Height (m)* | 40 | 40 | 40 | 40 |
| *First Gate ($\mu s$)* | 11.2 | 10.72 | 47 | 81.2 |
| *Last Gate (ms)* | 1.12 | 0.87 | 8.8 | 8.96 |
| *Number of Gates* | 20 | 20 | 24 | 27 |
| *Front Gate ($\mu s$)* | 8 | 0 | 40 | 70 |

Survey altitude of the transmitter loop in the Bookpurnong survey was nominally ~40 m, although this varied close to the river where large river red gums were present. The Clarkes floodplain was first surveyed in August/September 2006 along lines orientated NW-SE, with a line spacing of ~100m, and then again in May 2015. SkyTEM AEM systems are calibrated in the laboratory, and the measured responses of each system, once commissioned, are then standardised with respect to the Danish National Reference Site (Sørensen and Auken, 2004, Auken et al. 2009, Foged et al. 2013). Assuming these airborne systems, when deployed for surveys, remain stable, standardisation of the acquired data against the reference site permits the generation of models of ground conductivity which are, in theory, directly comparable. However, their generation requires a full understanding of system and survey parameters. Given their variability (see Table 1) these need to be incorporated in the processing and inversion of the data.

**Data Inversion**

The two Bookpurnong AEM datasets were inverted using the full nonlinear 1D inversion algorithm, AarhusInv (Auken et al. 2015). A spatially constrained inversion was employed (Viezzoli et al. 2008). This type of inversion uses constraints along and across lines, which means that layer parameters are connected between adjacent soundings. Results from the inversion of data for the two dates are presented in Figure 3. Both datasets were inverted separately using a smooth layer model. This type of model typically consists of 15-30 layers with fixed thicknesses, often increasing with depth. The amount the resistivity of one layer can vary to the next is defined by a vertical constraint. In this study, a 30 layer model was used for the inversion of the two datasets. The first layer thickness was chosen to be 0.3m with logarithmically increasing thicknesses to a depth of 150m, which is the depth of the last layer boundary. The starting model for the inversion was a homogenous halfspace with a resistivity of 40 ohmm (= 25 mS/m). The regularisation constraints were set to a vertical constraint of 3, a value which allows some vertical structure, without introducing artefacts caused by overfitting the data. The horizontal constraint was set to 2 for all layer intervals. The inversion solved for the low and high moment z-component data as well as the transmitter height using the one model, although the transmitter height was not allowed to move excessively during the inversion.

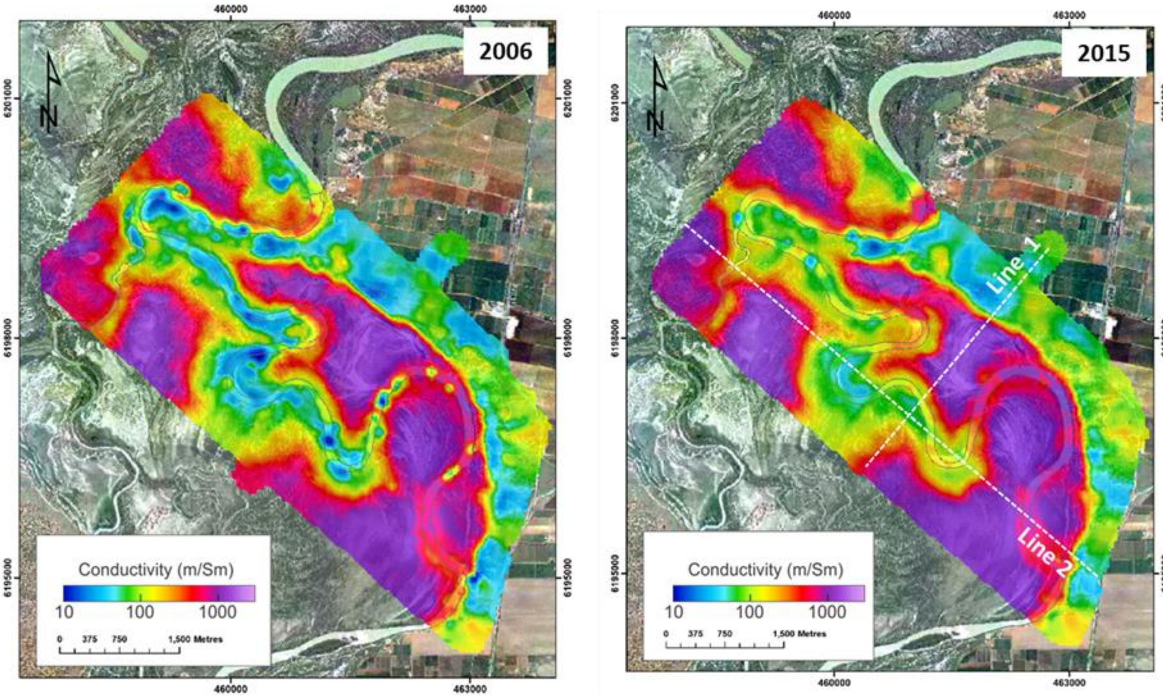


**Figure 3: Interval conductivities calculated from a spatially constrained inversion (SCI) of data for 2006 (left) and 2015 (right), for a depth of 4-10m below the ground surface for two dates.**

## RESULTS

In the Bookpurnong study area, most of the lens systems have developed in the floodplain sediments of the Coonambidgal and the Monoman Formation, and flank the course of the Murray River, in places extending laterally for several hundreds of metres into the adjacent floodplain. Modelled ground conductivities for the depth intervals of 4 to 10m below the ground surface, which sits within the sands of the Monoman Formation on the floodplain, show laterally extensive low conductivity zones, indicative of fresh water, present along the river (Figure 3). However, in places these lens systems are absent. The latter areas are interpreted as regions where the river gains salt (referred to as gaining reaches – see Tan et al. 2007) from discharging saline groundwater from the regional aquifers. Large tracts of the sediments directly beneath the floodplains exhibit high conductivities. These are saturated with saline groundwater which discharges directly into the floodplain. Subtle differences in the modelled conductivity structure are apparent for the same interval conductivities for the two dates shown in Figure 3. In particular there is an observed increase in (groundwater) conductivity in the lens systems adjacent to and beneath the river from 2006 to 2015. This suggests that the lens systems have been contracting and the quality of the water that they contain has decreased over the decade between the survey dates.

Further analysis of these indicated changes was undertaken by examining conductivity depth sections that transect the floodplain and intersect the lens systems adjacent to the river. Figure 4 shows coincident lines (along Line 2 in Figure 3) of inverted data from the two surveys. The geology, interpreted from available bore data, is presented in the Panel A, and the inverted conductivity-depth sections (with stratigraphic boundaries overlain) are presented in Panels B and C. The Murray River, which crosses the transect, is shown by the dark blue shaded areas in the geology section (Panel A) and the depth of the river channels defined from depth soundings is also indicated. A comparison between the two conductivity-depth sections (Panels B and C) for the two dates shows how the overall conductivity of the areas adjacent to and beneath the river has increased from 2006 to 2015, indicating that the lens systems in this part of the floodplain may have contracted significantly over this period. The lens systems are largely confined to the sands of the Monoman Formation. In some places the lens systems have disappeared altogether. For example the small lens system at a distance of about 5000m along the transect, is present in the 2006 data but absent in 2015.

As part of this study the relationship between measured groundwater EC for a limited number of bores and the modelled AEM conductivity response for soundings that were located near to the sampled bores was determined. Bore EC data were acquired within six months of geophysical data acquisition in 2015. To facilitate a more direct comparison between the AEM data and groundwater EC, the weighted ground conductivity response for the modelled AEM data of the screened section of the bore was defined. In determining a relationship between inverted AEM data and the groundwater EC, a simple regression analysis was undertaken (Munday et al. 2016). The available sample is very limited, and although statistically significant, the derived relationship ($R^2$= 0.86) indicates that the AEM data set could be used as an effective predictor of spatial variations in groundwater quality, but the results should be treated as indicative rather than definitive. The relationship defined for 2015 was also assumed to hold for the 2006 data set, and estimates of groundwater quality were plotted for the two dates along transect 1. These results are presented in Panel's D and E in Figure 4. If confirmed, they suggest that the floodplain lens systems have shrunk slightly and become more saline. This could be attributed to only a slow reduction in the potentiometric gradient between the floodplain aquifer and the river (see Figure 2) through the more recent installation of a salt interception scheme along the floodplain-highland boundary aimed at intercepting saline groundwater before it reaches the floodplain or river (Woods 2015). The prolonged effects of drought through 2006 to 2010, may have also contributed to a reduction in the size of lens systems, and in the absence of recharge, either through flooding or bank recharge, the continued mixing of groundwater and freshwater in the lenses would have encouraged their degradation.

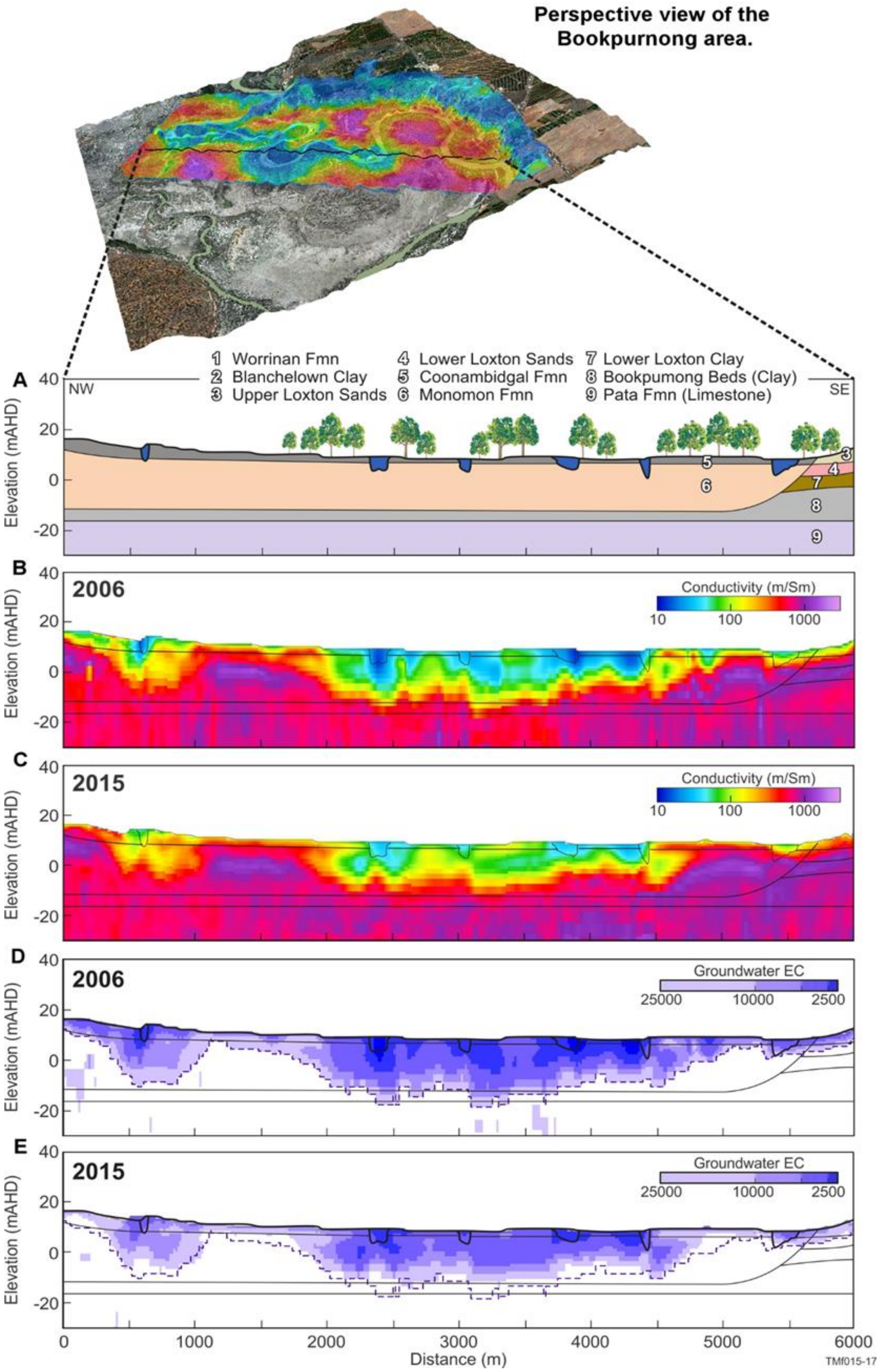


**Figure 4: Conductivity depth sections for Line 2 (Figure 3) for the two dates of the survey (Panels B and C). The lower Panels (D and E) show the modelled groundwater conductivity for the two dates. The dashed line in Panel E is the line representing the extent of groundwater with an EC of 25000EC in 2006.**

## CONCLUSIONS

We have demonstrated an effective procedure for defining spatio-temporal variations in ground conductivity across a salinised floodplain using multi-date heli-borne time domain EM system. Lateral and vertical changes in the conductivity of the floodplain have been resolved between the dates flown. This and related studies indicate that the observed responses are primarily a function of changes in groundwater quality within the floodplain sediments. The AEM system employed in this study defined the geometry and extent of freshwater lens systems in three dimensions, at scales that permit the results to be employed in floodplain management. Arguably, the outputs provide a framework for monitoring hyporheic zones and studying hyporheic exchange in three dimensions. Observable differences in the extent of the freshwater lens systems have been were noted. The results from the two surveys examined suggest that in the decade considered, the floodplain lens systems have shrunk slightly. This could be attributed to the continued encroachment of the salinised groundwater system and only a slow reduction in the hydraulic gradient from the adjacent highlands with the installation of a salt interception scheme along the floodplain- highland boundary. The prolonged drought between 2006 and 2010 could also have contributed to the degradation of the lens systems.

The advent of broad band AEM systems with improved system calibration and standardisation procedures, more robust inversion techniques which account for system and survey characteristics provide for the realistic proposition of using AEM data in the semi-quantitative and quantitative monitoring of landscape change in settings such as those encountered on the floodplains of the Murray River. These changes can be mapped in the subsurface, whether naturally induced or arising as a consequence of a particular management strategy. We emphasize the need for caution when considering the observed spatial variations, stressing the importance of understanding and accounting for system investigation depth and the potential for artefacts that might be introduced from noise, system geometry and/or data interpretation procedures. These issues should always be borne in mind when comparing data and derived conductivity models from different dates. The main benefit from considering AEM data is its non-invasive, spatial nature, which permits the visualisation of freshwater lens dynamics. This is not readily achieved by other investigative methods. However, the biggest impediment to repeat surveys remain the costs involved. Nevertheless, in special cases where the spatial effects of management changes across the floodplain require an independent reference point, the expenditure may be justified.

## ACKNOWLEDGMENTS

We acknowledge the support of the SA Governments' Department of Water, Land and Biodiversity Conservation in helping undertake this study.

### REFERENCES

Auken, E., Christiansen, A. V., Kirkegaard, C., Fiandaca, G., Schamper, C., Behroozmand, A. A., Binley, A., Nielsen, E., Effersø, F., Christensen, N. B., Sørensen, K. I., Foged, N., and Vignoli, G. (2015). An overview of a highly versatile forward and stable inverse algorithm for airborne, ground-based and borehole electromagnetic and electric data. Exploration Geophysics 46, 223-235. https://doi.org/10.1071/EG13097

Auken, E, Christiansen, A.V., Westergaard, J.H., Kirkegaard, C., Foged, N. and Viezzoli, A., (2009). An integrated processing scheme for high-resolution airborne electromagnetic surveys, the SkyTEM system: Exploration Geophysics, 40, 184–192.

Berens, V., White, M., Rammers, N., Souter, N., and Paterson, P., (2009a). Bookpurnong Living Murray Pilot Project: Injection of river water into the floodplain aquifer to improve vegetation condition, DWLBC Report 2009/20, Government of South Australia, through Department of Water, Land and Biodiversity Conservation, Adelaide. 94pp.

Berens, V., White, M., and Souter, N., (2009b), Bookpurnong Living Murray Pilot Project: A trial of three floodplain water management techniques to improve vegetation condition, DWLBC Report 2009/21, Government of South Australia, through Department of Water, Land and Biodiversity Conservation, Adelaide. 111pp.

Binley, A., Hubbard, S. S., Huisman, J. A., Revil, A., Robinson, D.A., Singha, K., and Slater, D.A., (2015), The emergence of hydrogeophysics for improved understanding of subsurface processes over multiple scales, Water Resources Research, 51(6), 3837-3866, DOI:10.1002/2015WR017016.

Brodie, R.C., Green, A.A., and Munday, T.J., (2004), Calibration of RESOLVE airborne electromagnetic data – Riverland and East Tintinara, South Australia: Cooperative Research Centre for Landscapes, Environment and Mineral Exploration, Open file report 173.

Brodie, R.C., and Sambridge, M., (2006), A holistic approach to inversion of frequency-domain airborne EM data, Geophysics, v. 71(6), 301-312

Brodie, R.C. and Sambridge, M., (2009), Holistic inversion of frequency-domain airborne electromagnetic data with minimal prior information. Exploration Geophysics, 2009, 40, 8–16

Beamish, D. and Mattsson, A., (2003), Time- lapse airborne EM Surveys across a municipal landfill. JEEG, 8(3), 157-165.

Cartwright, I., Weaver, T. R., Simmons, C. T., Fifield, L. K., Lawrence, C. R., Chisari, R. and Varley, S., (2010), Physical hydrogeology and environmental isotopes to constrain the age, origins, and stability of a low-salinity groundwater lens formed by periodic river recharge: Murray Basin, Australia. Journal of Hydrology, 380(1-2), 203-221. http://dx.doi.org/10.1016/j.jhydrol.2009.11.001.

Cartwright, I., Hofmann, H., Sirianos, M.A., Weaver, T.R. and Simmons, C.T., (2011) Geochemical and 222Rn constraints on baseflow to the Murray River, Australia, and timescales for the decay of low-salinity groundwater lenses. Journal of Hydrology, 405 3-5: pp. 333-343. doi:10.1016/j.jhydrol.2011.05.030

Davis, A., Munday, T.J. and George, R.J., (2015), Gascoyne River airborne electromagnetic survey II: Inversion Report. CSIRO: Water for a Healthy Country Flagship Technical Report; CSIRO Technical Report EP-13-11-758. 158pp.

Davis, AC, Macnae, J and Robb, T, (2006), Pendulum motion in airborne HEM systems, Exploration Geophysics (2006) 37, 355-362

Davis, A.C., and J. Macnae, (2007), Calibration of time domain AEM systems using aground loop:, ASEG Extended Abstract pp1-4, https://doi.org/10.1071/ASEG2007ab028

Deszcz-Pan, M., Fitterman, D.V., and Labson, V.F., (1998), Reduction of inversion errors in helicopter EM data using auxiliary information, Exploration Geophysics, v. 29, p. 142-146.

Fitterman, D.V. and Deszcz-Pan, M.,(1998), Helicopter EM mapping of saltwater intrusion in Everglades National Park, Florida, Exploration Geophysics, 29, 240-243.

Fitterman, D.V., and Yin, C., (2004), Effect of bird manoeuvre on frequency-domain helicopter EM response: Geophysics, 69, 1203-1215.

Foged, N., Auken, E., Christiansen, A.V. and Sorensen, K.I., (2013). Test-site calibration and validation of airborne and ground-based TEM systems. Geophysics, Vol. 78 (2); P. E95–E106

Holland K. L., Tyerman S. D., Mensforth L. J., Walker G. R. (2006) Tree water sources over shallow, saline groundwater in the lower River Murray, south-eastern Australia: implications for groundwater recharge mechanisms. Australian Journal of Botany 54, 193-205. https://doi.org/10.1071/BT05019

Ley-Cooper, Y., Macnae, J., Robb, T., and Vrbancich, J., (2006), Identification of calibration errors in helicopter electromagnetic (HEM) data through transform to the altitude-corrected phase-amplitude domain: Geophysics, 71, G27-G34.

Lane, R., Brodie, R. and Fitzpatrick, A. (2004), Constrained inversion of AEM data from the Lower Balonne area, Southern Queensland, Australia. CRC LEME Open File Report 163, 140pp.

Lawrie, K.C., Clarke, J.C., Tan, K.P., Munday, T.J., Fitzpatrick, A., Brodie, R.S., Pain, C.F., Apps, H., Cullen, K., Halas, L., Kuske, T.J., Cahill, K. and Davis, A., (2010). Using the SkyTEM time domain airborne electromagnetics (AEM) system to map aquifer systems and salinity hazard in the Ord Valley, Western Australia: Geoscience Australia Professional Opinion 2010/01

Lipinski, B.A., Sams, J.I., Smith, B.D. and Harbert W., (2008). Using HEM surveys to evaluate disposal of by-product water from CBNG development in the Powder River Basin, Wyoming. Geophysics, 73(3), B77-B84. doi: 10.1190/1.2901200

Munday, T.J., Fitzpatrick, A., Berens, V., Viezzoli, A. and Cahill, K., (2010) Spatio-Temporal Monitoring with Airborne EM Data — Still Wishful Thinking, or a Realistic Proposition?. Symposium on the Application of Geophysics to Engineering and Environmental Problems 2010: pp. 277-286. doi: 10.4133/1.3445443

Munday, T.J., Sorensen, C.C., Ibrahimi, T. and Cahill, K., (2016) SARFIIP Salinity Investigations: Katfish SkyTEM AEM Geophysical Survey: Processing and Interpretation Final Report. CSIRO Technical Report Number EP159200, CSIRO, Australia. 68pp

Parsekian, A. D., K. Singha, B. J. Minsley, W. S. Holbrook, and L. Slater (2015), Multiscale geophysical imaging of the critical zone. Rev. Geophys., 53, 1–26. doi: 10.1002/2014RG000465.

Singha K., Day-Lewis F. D., Johnson T., and Slater L. D. (2015), Advances in interpretation of subsurface processes with time-lapse electrical imaging, Hydrol. Process., 29; pages 1549–1576, doi: 10.1002/hyp.10280

Smith, B. D., Bisdorf, R., Slack, L. J.and Mazzella, A. T. (1997) Evaluation of electromagnetic mapping methods to delineate subsurface saline waters in the Brookhaven oil field, Mississippi. in Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems. pp. 685– 693, Environ. and Eng. Geophys. Soc., Wheat Ridge, Colorado.

Sørensen KI and Auken E, 2004. SkyTEM - A new high-resolution helicopter transient electromagnetic system: Exploration Geophysics, 35, 191-199.

Tan, K., Berens, V., Hatch, M. and Lawrie, K, (2007). Determining the suitability of in-stream Nano-TEM for delineating zones of salt accession to the River Murray, A review of survey results from Loxton, South Australia, CRC LEME Open File Report 192.

Viezzoli A, Auken E, and Munday T, 2009. Spatially constrained inversion for quasi 3D modelling of airborne electromagnetic data – an application for environmental assessment in the Lower Murray Region of South Australia: Exploration Geophysics, 40, 173–183.

Viezzoli, A., Christiansen, A.V., Auken, E. and Sørensen, K., (2008). Quasi-3D modelling of airborne TEM data by spatially constrained inversion: Geophysics 73, F105–F113.

Woods, J (ed.) 2015, Modelling salt dynamics on the River Murray floodplain in South Australia: Conceptual model, data review and salinity risk approaches, Goyder Institute for Water Research Technical Report Series No. 15/9, Adelaide, South Australia. 149pp.

Yin, C., and Fraser, D.C., (2004), Attitude corrections of helicopter EM data using a superposed dipole model: Geophysics, 69, 431-439.