# Airborne TEM for the recovery of basin scale solute distribution; Perth Basin, Western Australia.


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## SUMMARY

The distribution of groundwater salinity is a key input for management of water resources. Estimates of the three dimensional distribution of groundwater salinity below areas spanning thousands of square kilometres may be required. Airborne transient electromagnetic methods provide the possibility of recovering first pass large scale solute concentration distributions provided lithological influences on electrical conductivity distribution are not dominant. The Allanooka airborne TEM survey is located in the northern most portion of the Perth Basin in Western Australia. We use data from this Airborne TEM survey combined with data recovered from monitoring wells to highlight the steps used to construct a first pass large scale solute distribution model. We provide a method for converting airborne TEM datasets to estimates of solute concentration distribution for sandstone dominated sediments at a basin scale. For the Allanooka monitoring well network, base line empirical relationships are developed between laboratory derived total dissolved solids and formation conductivity derived from wire line logs. This relationship is then extended to include airborne TEM derived formation conductivities. Appropriate layer discretisation of input seed models for inversion of the airborne TEM data set are based on analysis of resistivities derived from wire-line logs. The interpretation of the inverted airborne TEM was assisted by geological constraints and high resolution seismic reflection transects. Selected inversion statistics were also mapped throughout the 3D volume to provide a quick method for assessing the "importance" of particular layers to the outcome of the inversion.

An approximate volume of low solute concentration sandstone dominated formation below the regional water table was extracted from the airborne TEM data. Our first pass basin-scale Airborne TEM derived 3D solute concentration provides a starting point for more detailed interpretation to commence.


## INTRODUCTION

In Western Australia, the demand for high quality water is increasing because of demands from population growth and a booming resource sector. This increased pressure on groundwater resources requires development of increasingly detailed and complete 3D hydrogeological models. For the Allanooka area in the northern most part of the Perth Basin in Western Australia, an important knowledge gap in the hydrogeological understanding is the distribution of groundwater salinity. We demonstrate how a large airborne TEM data set can be inverted to recover estimates of solute concentration distribution at the basin scale. We have applied the following processes:

1) Develop empirical relationships between laboratory derived solute concentration and formation conductivity at each monitoring well site.
2) Analysis of wire line resistivity logs for a large number of monitoring wells to aid design of the airborne TEM inversion input and control parameters.
3) Display selected inversion statistics across the basin to help understand the level of certainty that can be associated with various conductivity distributions generated by the inversion process
4) Consider the TEM derived conductivities distribution with reference to the major geological interfaces and structural boundaries (e.g. from seismic reflection data).

The Allanooka Airborne TEM survey was completed by the Department of Water and spans an area of approximately 2500km$^2$. The Perth Basin is an elongated sedimentary province in the southern part of Western Australia's continental margin. The Basin is characterized by a series of north striking, fault bound sub-basins and ridges and is separated from the Archaean Yilgarn Craton to the east by the Darling Fault system (Harris, 1994; Iasky and Mory, 1994). To the west the Basin extends under the Indian Ocean. Figure 1 shows the location of survey area.

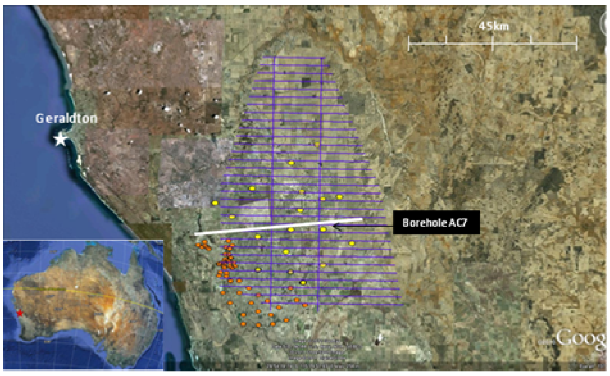


**Figure 1: Location of studied area. Airborne TEM transect are show in purple, yellow dots represent the new water monitoring wells, the red dots represent the location of pre-existing wells and the white line shows a regional high resolution seismic reflection transect completed by Curtin University for Western Australia's Department of Water. Note the location of Borehole AC7.**

## METHODOLGY

The Allanooka airborne TEM survey was completed by Fugro Airborne Surveys with their fixed wing TEMPEST CASA C212-200 system in mid-January 2007. The line spacing was 2000 m at 90 deg and the tie line spacing was approximately 20000 m at 0 deg. The nominal transmitter terrain clearance was 120 m and a total of 1242.7 km of survey lines were completed. The survey was located within the UTM Zone 50S, with the WGS84 Zone 50 coordinate system. The TEMPEST system specifications can be found in literature published by Lane *et. al.*, 2000. Below is a 3D representation of the airborne TEM derived electrical resistivity distribution in the range 10 mS/m to 100 mS/m (i.e. 100 Ohm.m to 10 Ohm.m). The TEM derived conductivity versus elevations data has been converted to SEGY format and imported into Schlumberger's Petrel software. The cube shown in Figure 2 has the east, north and elevations dimensions 50 km by 70 km by 1 km respectively.

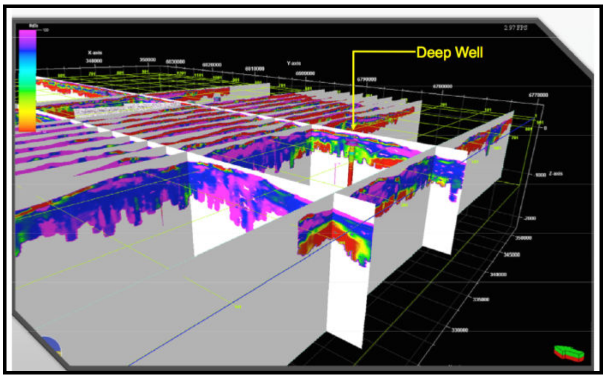


**Figure 2: Three dimensional representation of airborne TEM conductivity distribution in a 50 km (E-W) by 70 km (N-S) by 1 km deep cube. Colours range is from 10 mS/m (purple) to 100 mS/m (red). TEM conductivities are converted to SEGY formation and entered into Schlumberger' Petrel software. An electrical conductivity wire line log for a deep well is displayed against a north-south TEM derived conductivity transect. The same colour stretch is used displaying wire line log conductivity and airborne TEM derived conductivities.**

The first step in recovering basin-scale solute concentrations was to build an empirical relationship between groundwater salinity (measured as mg/L total dissolved solids (TDS)) and the electrical conductivity obtained from wire-line logs. Water samples have been pumped from nested monitoring wells with screens set at various depths. Laboratory analysed groundwater salinity can be related to the formational conductivity at the well screen interval from the resistivity log for each well. The relationship between the wire line logging measurements of electrical conductivity and laboratory derived TDS for all wells in the ground water monitoring well network (i.e. see Figure 1) can be seen in Figure 3. Note that both electrical conductivity and TDS of water samples recovered from each well are measured in the field and verified by laboratory measurement. Given formation resistivity and water resistivity it is possible to derive an approximate Formation Factor which can later be used to convert TEM derived formation resistivity to water resistivity. However, we have chosen to use a direct mapping of the formation resistivity relationship obtained from wire line logs onto laboratory derived total dissolved solids to build our start model for solute concentration distribution.

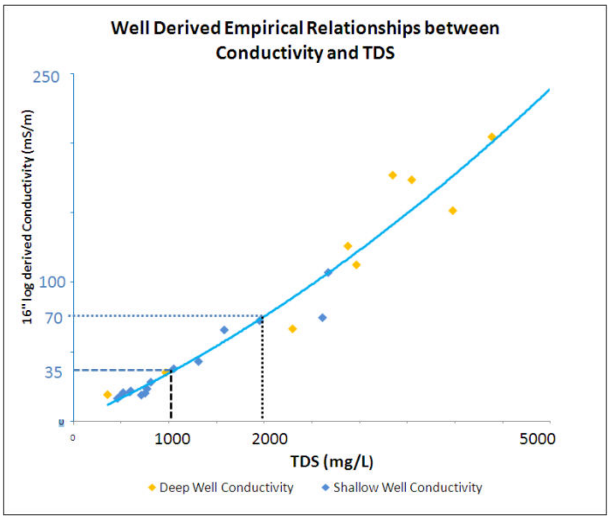


**Figure 3: Cross plot showing the relationship between formation conductivity derived from wire line logs and laboratory derived TDS obtained in the screened interval of shallow and deep groundwater monitoring wells in the Allanooka area. A realistic relationship between formation conductivity and total dissolved salts can be derived (see light blue curve). Such relationships should be used with great care. However, they can at least provide base line mapping of formation conductivity to Total Dissolved Solids.**

Wire line logs from existing deep hydrocarbon exploration wells in the Allanooka area typically show that the formation conductivity increases with depth. If electrical conductivity increases with depth within broadly uniform sandstone dominated sediments, then it can be expected that solute concentration increases with depth. Water salinity measurements from monitoring bores have confirmed this is the case for the inter-bedded sandstone, siltstone and shale of the Yarragadee Formation. The sediments of Yarragadee Formations are dominant within the depth range of investigation of the Allanooka TEMPEST survey. Porosities of the Yarragadee Formation obtained from wire-line logging average 35%. Thus it is considered that useful information can be obtained by developing a simple, direct, first pass relationship between formation conductivity and TDS based on the relationship in Figure 3. This model may need to be refined at a later stage based on improved detailed geological, structural and hydrogeological interpretations.

Electrical conductivity is a tensor quantity. However the electrical current generated by a horizontal inductive loop source (i.e. the TEMPEST transmitter loop) over a layered earth must flow in horizontal planes (Harris, 2001). That is, a horizontal transmitter loop can only recover information about horizontal resistance to current flow. For this reason the layer discretisation for the seed model input for inversion testing at well locations is based on the gradient of the cumulative conductivity curve derived from electrical logs. An example of layer discretisation based on the resistivity log data at monitoring well AC7 is provided in Figure 4a.

The seed model discretisation for all the monitoring wells was determined from the resistivity logs. The inversion input parameter testing was completed with the CSIRO (project P233) developed open source CSEM software layered inversion software AIRBEO. Inversion parameter testing was completed on at least twenty sounding locations nearest to each of the monitoring well locations. The monitoring well locations rarely fell exactly one of the TEMPEST transects. As the TEMPEST survey was flown at 2 km line spacing wells were always less than 1000 m from a line. Note that objective of analysing inversion input parameters (e.g. the seed model) was to establish the general range of electrical structures that exist in the Allanooka study area so that the layered inversion input parameters could be optimized.

An example of the type of analysis that was completed at each monitoring well location is provided in Figure 4b. For each location, we plot conductivity from the wire line log, the wire line log derived seed model and the model from the inversion of the closest airborne TEM sounding. We also plot the "importance factor" obtained from the AIRBEO output file for each layer's parameters (i.e. thickness and resistivity). The importance factor serves as a semi-quantitative indicator of how consequential a layer is within the inversion process. For example, layer 5 from the 8 layer model in figure 4b has a low importance and was removed for final inversion seed models used for inversion of the full data set. As expected, the shallow conductive layers will have the greatest effect on the outcome of the inversion and must be included in the layer discretisation for seed model input to the inversion (Gavin, 2010, Raiche, 1993). Once the analysis of inversion input parameters was complete, a simplified 6 layer model was constructed as the best general seed model for large sub areas and the inversion was completed on the full data set. The outcome of the inversion along with statistics could then be inserted into a 3D volume and compare to the well logs (i.e. resistivity logs) and high resolution seismic data.

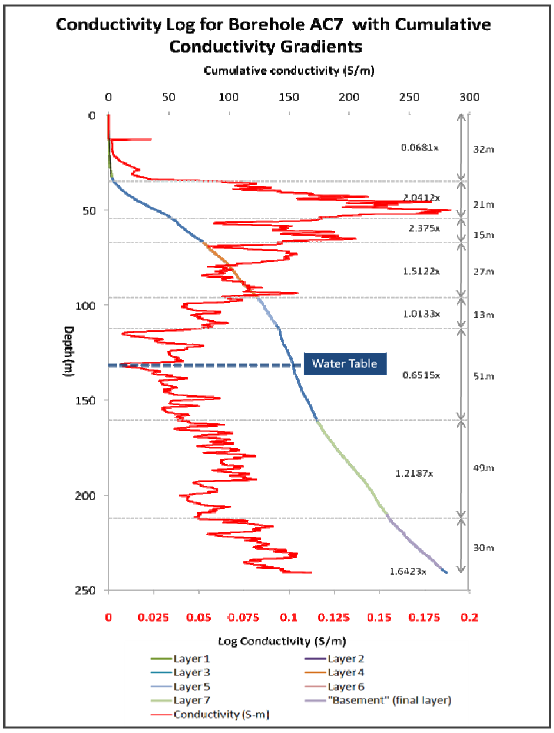


**Figure 4a: Cumulative conductivity plot for well AC7 overlayed on the conductivity log measurements. The gradient of the cumulative conductivity is used to discretise layering for seed models.**

All log data, seismic reflection data and TEM derived conductivity distribution was input to 3D Schlumberger PETREL software. The ability to rapidly view, compare, manipulate and interpret data in 3D was a key component of the processing and interpretation the Allanooka Airborne TEM data set. That is, wire line log data could be directly compared to inversion results to assess accuracy.

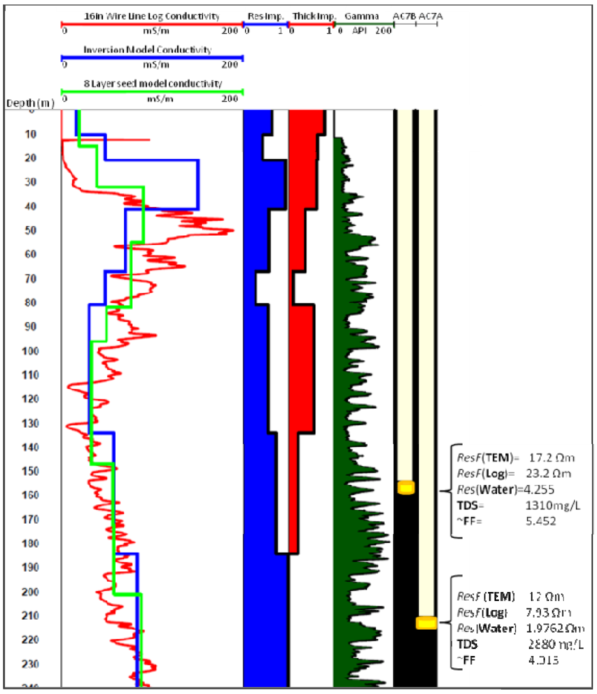


**Figure 4b: Wire line log, seed model and final inversion model conductivity with depth for monitoring well location AC7. Also included are the AIRBEO output importance factors for layer thickness and resistivity along with a gamma log.**

Figure 5 shows the strong correlation between the airborne TEM derived conductivity distribution obtained from 1D inversion along two intersecting lines, overlayed with the conductivity derived from wire line logs at monitoring well AC7.

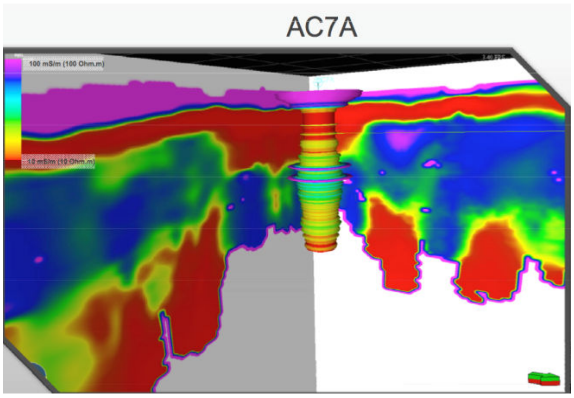


**Figure 5: Comparison of TEM derived and wire-line log derived electrical conductivity proximal to monitoring well AC7A. Notice the good correlation between the conductivity distribution from the log and that obtain from the TEM. Also notice the complex structure (i.e. rapid change in conductivity distribution) at greater distance from the intersection of the two TEM lines (see figure 6)**

For the Allanooka area the high resolution seismic data is important for understanding the conductivity distribution.
The high resolution seismic reflection transect was undertaken in an east-west orientation and spans a total length of 43 km. The seismic reflection data makes it possible to interpret large-scale faulting. It is interesting that faulting in the Allanooka area is not strongly expressed within the Yarragadee Formation, as the sediments are often relatively uniform. However, the faulting is strongly expressed at the interface

with shale dominated sediments below the Yarragadee Formation. As these deeper faults are mapped through the Yarragadee Formation towards the surface they tend to project onto relatively distinct changes in TEM derived electrical conductivity. Note that the penetration of the TEMPEST survey was about 300m below ground level whereas the Seismic survey penetration exceeds one kilometre.

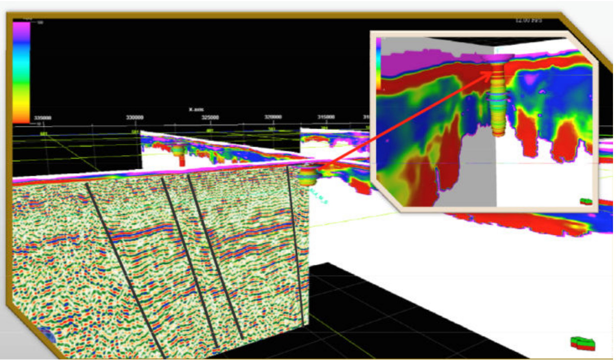

**Figure 6: Major structures along the seismic transect closest the bore AC7. As the fault structures are projected towards the surface they can map to distinct lateral changes TEM derived electrical conductivity distribution.**

One objective of the airborne TEM data analysis was to map out the volume of sandstone dominated sediment containing good to fair quality water in the Yarragadee Formation. For the Yarragadee Formation a conductivity of 70 mS/m maps to a groundwater salinity of approximately 2000 mg/L TDS. At 35 mS/m the estimated salinity is approximately 1000mg/L TDS. The information is captured in the 3D image in Figure 7 where the water saturated sediments painted yellow are expected to have TDS of approximately 2000 mg/L TDS and those marked as purple are expected have a salinity less than 500 mg/L TDS. The top of the volume is cut off by the regional water table such so that it should be possible to calculate the volume of saturated sediment for each broad range of solute concentrations within the Yarragadee. That is, by establishing this empirical relationship at monitoring wells between formation conductivity and salinity we are able to create a start model to resolve solute concentration distribution in sandstone dominated formations at the basin-scale.

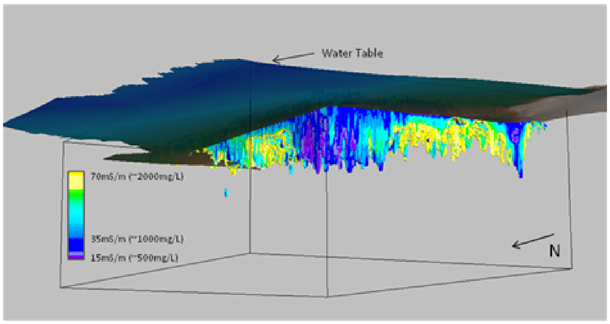


**Figure 7: Estimated solute concentrations below the regional water table in the range of 500 to 2000mg/L from The Allanooka study area. The solute concentration (TDS) values are derived from TEM formation conductivities. This approximation illustrates yellow areas representing high conductivities of 70mS/m with a TDS values ~2000mg/L, where as blue and purple are areas represent low conductivity, below 35mS/m and ~1000mg/L TDS.**

## CONCLUSIONS

We have demonstrated how a large airborne TEM data set can be inverted to estimated solute concentration distribution in large sandstone-dominated formations at the basin-scale. Empirical relationships were established between formation conductivity and laboratory groundwater salinity from small screened intervals in monitoring wells in the Allanooka area, located in the Perth Basin in Western Australia. After establishing the above relationships, the study undertook a detailed analysis and optimization of 1D layered earth inversion parameters at each monitoring well location. The limitations of this approach must be mentioned, as the relationships between TEM derived conductivity and groundwater salinity are not simple. For example, formation conductivity is in fact a result of a complex combination of sediment type and solute concentration (TDS). However, at the basin scale a useful 3D model of solute distribution is believed to have been obtained because, as confirmed by seismic data, the majority of the TEMPEST survey is completed within the sandstone dominated Yarragadee Formation. Refinements of the model may be required at a later stage based on improved detailed geological, structural and hydrogeological interpretations. Finally a 3D volume was calculated of the sediments with TDS expected to be in the range approximately 500 mg/L to 2000 mg/L.

## ACKNOWLEDGMENTS

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