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The application of AEM to mapping sea-water intrusion at La Grange, WA

David Annetts
CSIRO MRF
26 Dick Perry Av. KENSINGTON 6151
david.annetts@csiro.au

Richard George
DAFWA
PO Box1321, BUNBURY 6230
richard.george@agric.wa.gov.au

Tim Munday
CSIRO MRF
26 Dick Perry Av. KENSINGTON 6151
tim.munday@csiro.au

Tania Ibrahimi
CSIRO MRF
26 Dick Perry Av. KENSINGTON 6151
tania.ibrahimi@csiro.au

Kevin Cahill
CSIRO MRF
26 Dick Perry Av. KENSINGTON 6151
kevin.cahill@agric.wa.gov.au

Robert Paul
DAFWA
PO Box 1321, BUNBURY 5230
robert.paul@agric.wa.gov.au

Aaron Davis
CSIRO MRF
26 Dick Perry Av. KENSINGTON 6151
aaron.davis@csiro.au

SUMMARY

We describe interpretation of an AEM survey around the La Grange allocation area, WA. This survey was designed to map aquifer bounds and the sea water intrusion, and then to assess groundwater in the region, and to facilitate planning water use.

The simple, stratified nature of sediments of the western onshore Canning Basin allowed us to use blocky layered earth models and we found that five-layer models were the most parsimonious. After deriving surfaces representing the top of the Jarlemai siltstone and the top of the sea water ingress, we were able to effectively characterise the spatial characteristics of the sea water intrusion.

We found that in places, sea water intruded 40 km inland, and could be found at a depth of over 250 m.

Key words: Airborne electromagnetic, groundwater, inversion

INTRODUCTION

Water allocation plans are used to manage how water is taken from groundwater and surface-water systems. These plans include allocation policies that guide the assessment of water license applications and set upper limits on the amount of water that can be taken for use. The La Grange Groundwater Allocation Plan (Department of Water, 2010) covers the superficial Broome sandstone aquifer.

Currently, use of this aquifer is at a small scale. However, there is interest from pastoralists and horticultural companies to expand irrigated agriculture. If irrigated agriculture is to expand, it must be viable and meet both community and regulatory requirements. Accordingly, there is a need to assess water reserves. Paul et al. (2013) identified major knowledge gaps on aquifer distribution, properties and baseline groundwater level and quality data, and recommended that a regional AEM survey be used to improve knowledge of the Broome sandstone and the sea water intrusion.

AEM Surveys have proven to be an excellent method of mapping groundwater systems. Fitterman (1996) and Fitterman et al (1999) used a frequency-domain electromagnetic (FEM) helicopter system to map the interface between fresh and saltwater in the Florida Everglades. More recently, Kirkegaard et al (2011) mapped the salinity distribution in coastal aquifers using a SkyTEM instrument. With similar aims to the current study, Kok et al (2010) employed a SkyTEM system in conjunction with ground surveys to map salinity distribution in order to calibrate groundwater models for Terschelling Island in the Netherlands. Lawrie et al (2012) recently presented on overview of the role of AEM surveys in mapping sea-water intrusion.

The use of a helicopter-based system is common to all these studies, though this does not preclude the use of fixed-wing systems. Auken et al (2009) describe the use of the Tempest system in the investigation of groundwater resources of the Eyre Peninsula, SA. As the area under study increases, relatively high costs associated with helicopter systems render fixed-wing systems a viable alternative. Often, fixed-wing systems fly faster and higher than helicopter systems.

The Department of Agriculture and Food, Western Australia (DAFWA) commissioned an airborne electromagnetic (AEM) survey in order to improve geological knowledge and assess the aquifer character and water quality in the region. The Tempest AEM system was used to survey 6131 km in two parts.

In order to assess the aquifer character and assess water reserves, this survey was designed to address a number of objectives. For this paper, we focus on two of them. The first of these is to characterise the salt-water intrusion to the Broome Sandstone. Salt-water intrusion has a direct bearing when planning water bores for either agriculture or drinking water. The second survey objective was to map the base of the

Broome Sandstone / top of Jarlemai siltstone. This formation underlies the Broome sandstone and will be used to define the aquitard at the base of the aquifer in upcoming groundwater modelling.

METHOD AND RESULTS

Because of hot, humid flying conditions, the survey area was flown in two parts using two different aircraft between November and December 2013 and May 2013. Data collected using each aircraft were inverted separately for blocky and smooth layered earths. All inversions were on a station-by-station basis and used a code described by Roach (2010). Analysis of inversion results suggested that processing data separately was unnecessary; statistically, no matter the aircraft used to collect data, there was little difference between final models.

Smooth earth models consisted of 30 layers, and were designed to address water quality.. When inverting for smooth earth models, layer thicknesses were constrained while conductivity was allowed to vary. For smooth models, layer thickness, k, may be derived from layer number n using $k = e^{0.58+0.11\,n}$.

Blocky models, consisting of four, five and six layers, were intended to be used for hydro-stratigraphic interpretation. For these models, all model parameters were allowed to vary during inversion. Four-layer earth models were initially used because of the known stratigraphy. However, such models did not model geology well in all sections of the survey and more model parameters were required. Of the blocky models, five layer earths provided an optimal balance between low error and a low number of parameters.

Figure 1 highlights Line 1004301 within the survey area. The city of Broome, and Roebuck Bay lie in the north, and La Grange Bay falls in middle survey northings. In general, survey lines were spaced 5 km apart extending around 40 km inland and oriented west-east. Longer west-east, and north-east tie lines were designed to map the eastern extent of the Jarlemai siltstone and were sited to fly close to petroleum bores in order to aid calibration of results.

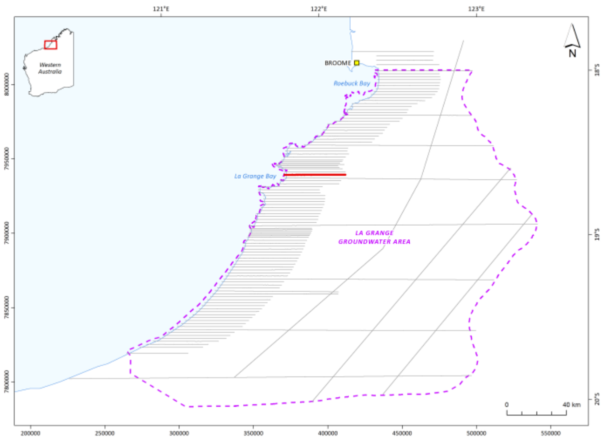

Figure 1 Highlight of Line 1004301 within the survey. This line is 40 km long and was flown from west to east. The La Grange Allocation Area is indicated.

Figure 2 compares inverted models for Line 1004301. Panel A compares error while panels B, C D and E compare four, five, six and 30-layer models respectively. Panels B, C and D are blocky model inversions while Panel E is a smooth model inversion. In general, inverted models show similar features. On this line, the salt-water intrusion is clearly identified as the strong conductor between 370000E and 386000E. The Jarlemai siltstone is also clearly identified as the moderate conductor at depth between 386000E and 412000E. The Broome sandstone is the unit directly overlying the Jarlemai siltstone.

In general, as more layers are used, errors decrease. Because of the known simple geology and the limited information content of AEM data, our preference in this case, invoking *lex parsimonæ* regarding model parameters, is to use blocky models to derive structural information. Parenthetically, sections in Figure 5 are plotted using considerable vertical exaggeration; even the steepest gradients, for example, the top of the conductor between 385000 and 386000 E which rises 80 m over 1 km, are quite flat.

Differences between inverted models lie mainly west of 381000E towards the coast where it appears that a minimum of five layers are required to map the salt-water intrusion. Significant differences are also observed between the blocky and smooth models west of 381000E.

More subtle differences between the models centre on the depth to the top of the Jarlemai siltstone. While there is minor (sub-metre) variation between the blocky model inversions, the smooth model inversion places the top of the most conductive layer some 60 m deeper than blocky models.

DISCUSSION

From Figure 2, it is apparent that blocky inversions could be an excellent foundation from which to derive regional-scale hydro-stratigraphic boundaries corresponding to the tops of the sea-water intrusion, Broome sandstone and the Jarlemai siltstone. Initially, we derived surfaces directly from inverted horizons. Although a good general approximation, this approach was found to be flawed because it is highly susceptible to features such as those shown in Figure 2B.

Blocky model inversion results from each survey line were interpreted for depths to the top of the Jarlemai siltstone and the seawater intrusion. Interpretation of the top of the Broome sandstone was based on clays identified by Vogwill (2003). Generally, interpretation was straightforward, though in some cases, when the Jarlemai was particularly flat, it was difficult to distinguish where the salt-water intrusion ended, and some degree of manual intervention was required. Interpretation of the top of the salt-water intrusion was also difficult near the shore line. In such cases, that the survey line ended at the shoreline provided an end point.

A map of the distance and depth of the interpreted salt-water intrusion is presented as Figure 3. Around Roebuck Bay in the north, and Mandora Marshes in the south, it is difficult to distinguish between seawater intrusion and the estuary. Accordingly, bounds on the confidence of interpretation of sea-water intrusion are indicated by a dotted green line. Outside the region bounded by this line and the coast, the shallow conductivity high is just as likely to be saline clays as it is near-surface sea-water.

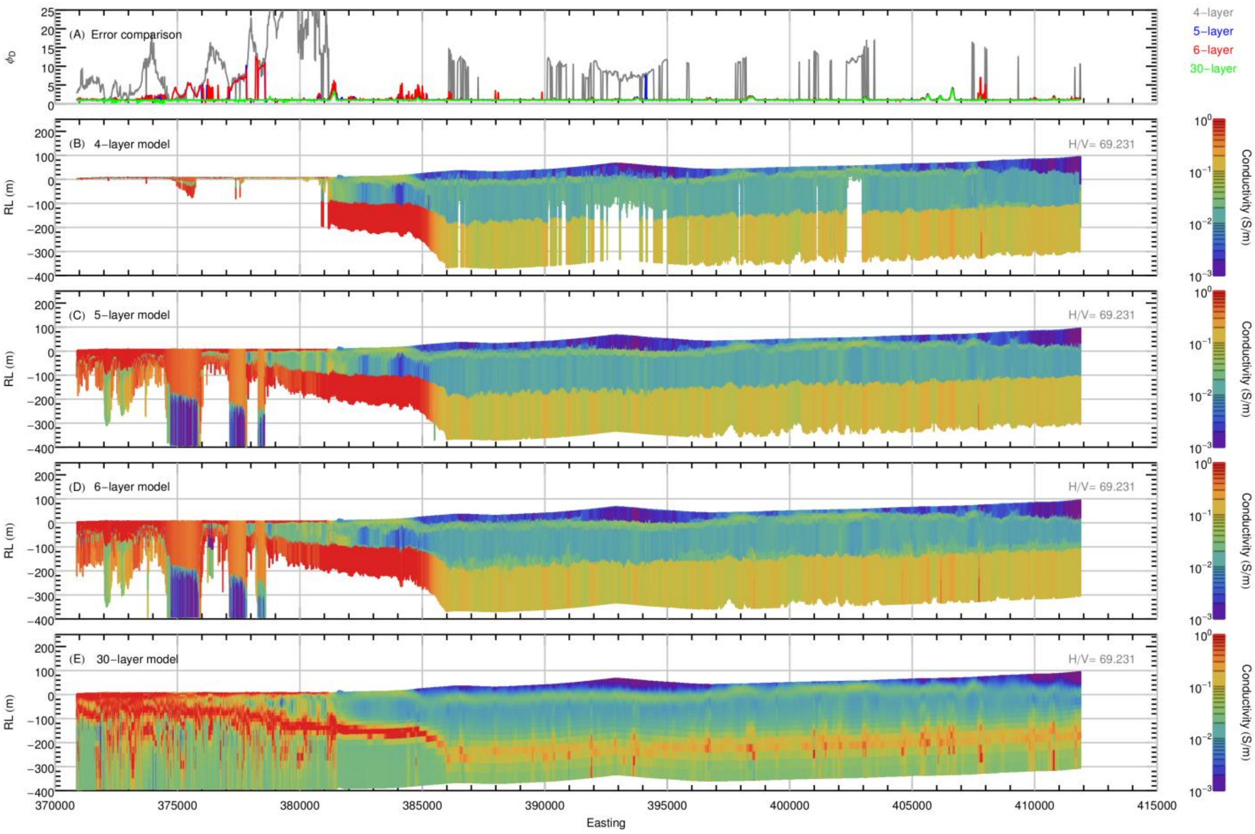

Figure 2 Comparison between blocky and smooth model inversions and their error for Line 1004301. Errors are compared in Panel A. Blocky model inversions are shown in Panels B, C and D (four, five and six layer); smooth model inversion results are shown in Panel E. Five-layered blocky models are generally preferred because of their parsimonious balance between low errors, geological accuracy and model parameterisation.

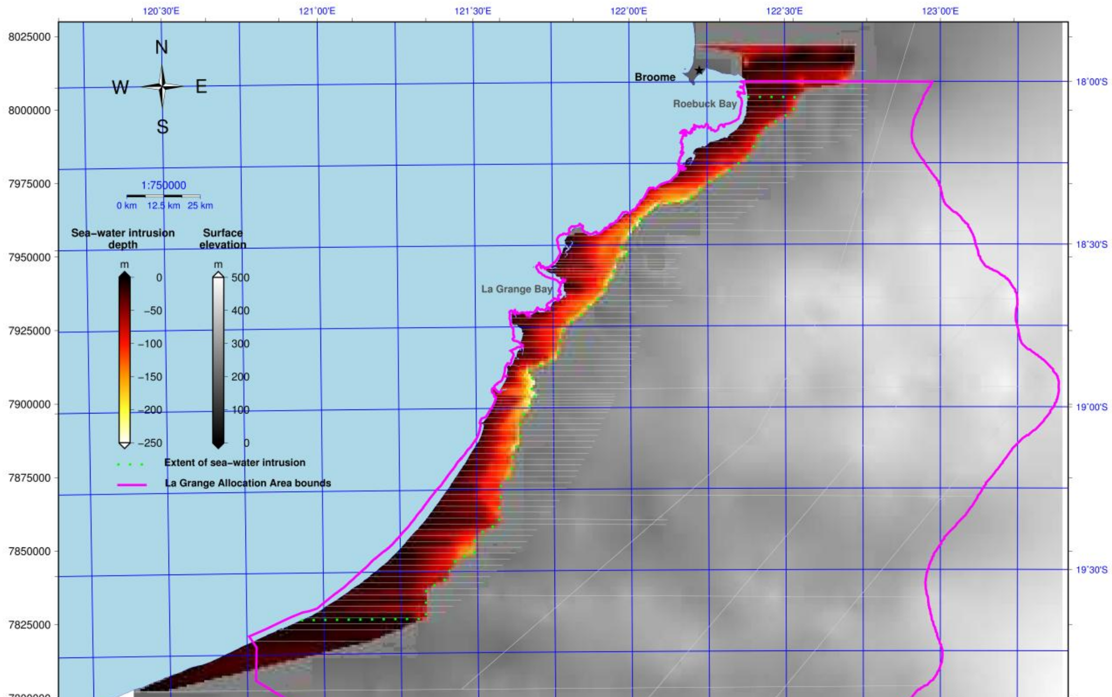

Figure 3 Variation of salt-water intrusion distance and depth. Distance is given by the spatial extent of the colours, and depth is given by colour variation. The dashed green line indicates confidence of interpretation of sea-water intrusion. The magenta line marks the extent of the La Grange Allocation Area. The underlying gray scale image plots surface topography.

Figure 4 compares the distribution of distance of maximum salt-water intrusion within the confidence bounds of Figure 3 with that of a normal distribution with the same mean and standard deviation. Clearly, the derived distribution differs from a normal distribution, and is bimodal. This has implications for simulating such ingress.

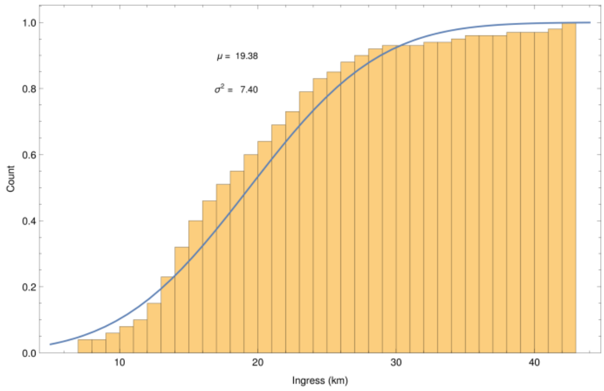

Figure 4 Distribution of distance of maximum salt water ingress. This distribution is compared to that of a normal distribution having the same mean and standard deviation.

Figure 5 compares depth to sea water at its eastermost extent with ingress distance as a function of survey northing. The extents of Roebuck Bay in the north and La Grange Bay in mid survey northings are indicated as a guide, and only data within Figure 3's confidence interval are plotted. The influence of Mandorah Marshes in the south is clearly visible. Roebuck Bay in the north is not as apparent because of the difficulty in picking a clear termination of salt water ingress from data.

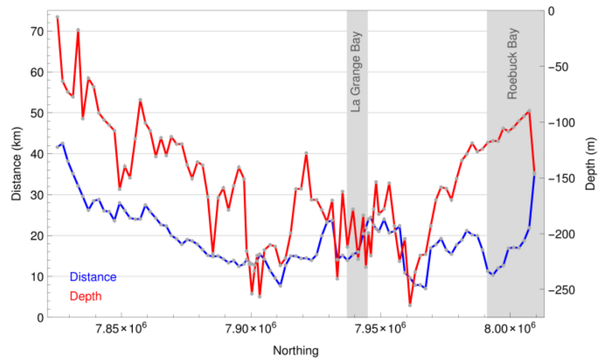

Figure 5 Comparison of depth to sea water at its easternmost extent with intrusion distance. Distance is plotted against the left axis while depth is plotted against the right axis.

CONCLUSIONS

We have given a brief account of the interpretation of a regional-scale fixed-wing survey flown in the La Grange region WA. This survey was designed to provide information to allow mapping of major relevant aquifer and aquitards as well as the extent of the sea water intrusion and its nature. This information is to be used to inform the development of irrigated agriculture in the La Grange region. In all these regards, the survey was successful.

In this paper, we have focussed on the sea water intrusion aspect of the project. We have characterised the sea water intrusion in terms of inland distance and depth variation. Intrusion distance was found to vary from 8 to at least 30 km, and depth was found to vary between 50 and 250 m.

Requiring some degree of interaction, horizons were interpreted from blocky inversions corresponding to the Broome sandstone, Jarlemai siltstone and the seawater intrusion. From these horizons, surfaces will be constructed and used in the next phase of the project which is hydrological modelling.

ACKNOWLEDGMENTS

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