AEM bathymetry and conductivity estimation in very shallow hypersaline waters of the Coorong, South Australia

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SUMMARY

The Coorong is a shallow (typically 1 - 2 m) narrow coastal lagoon extending approximately 110 km parallel to the coastline, and forms an extensive wetland area of international significance. It is divided into two lagoons, the North and South lagoons. The northern lagoon section opens into the mouth of the Murray River and the southern lagoon section is closed. During periods of extended drought where there is no flooding to flush the lagoon system, hypersalinisation gradually increases, especially in the southern lagoon section where salinity may be in excess of four times that of seawater. A helicopter time-domain EM (TEM) system was flown along the Coorong, as extensive flood waters from Queensland (2010) were reaching the North Lagoon lowering the salinity. The derived bathymetry from TEM data was shown to be in good agreement with known bathymetry in areas of high salinity. The conductivity of the saline water in the North Lagoon and underlying sediment was estimated from inversion of TEM data using the known water depth as a fixed parameter. The derived conductivity varied from ~1.6 S/m in the north of the North Lagoon to ~8 - 9 S/m at its southern end, underestimating the gradient (~0.6 to ~13 S/m respectively) observed from a sparse distribution of fixed conductivity meters located in the Coorong. These results show that AEM has the potential to remotely map shallow water depths, and water conductivity gradients using known bathymetry to monitor hypersalinisation in these wetlands where changes in the ecology have been linked to high salinity.

Key words: AEM, hypersalinity, bathymetry, Coorong.

INTRODUCTION

The Coorong, combined with Lake Alexandrina, Lake Albert and the Murray (River) Mouth forms one of Australia's largest wetland systems, and is of great habitat significance for migratory birds. The Coorong is a shallow, narrow lagoon that is ~110 km long and runs parallel to the shore, and consists of two lagoon systems that are split by a narrow channel at Parnka Point: the North Lagoon and South Lagoon. Lakes Alexandrina and Albert are connected large freshwater lakes (the Lower Lakes) that flow to the sea by way of several barrages that control flow into the Coorong Channel which connects the North Lagoon to the Murray Mouth. Thus freshwater flushing essentially only occurs between the barrages and the Murray Mouth as the South Lagoon is a closed system. Salt accumulates by way of evaporation and strong salinity gradients occur along the entire length of the Coorong, with significantly higher concentrations found in the South Lagoon, especially during extended drought conditions, when the conductivity of waters in the South Lagoon may exceed ~ 16 S/m, four times the typical seawater conductivity. Tides do not reach very far along the Coorong and strong winds blowing downwards on the narrow lagoon surface elevates water levels against the downwind shore. The system relaxes with drop in wind speed resulting in water currents that flow in the opposite direction. Extreme hypersalinisation, as found to occur in both lagoons has been linked to a decline in the abundance of a number of fish and waterbird species. Further details that examine the response of estuarine species to environmental flows in the Coorong region, including hydrodynamical modelling of the salinity regime can be found in the papers by Brookes et al. (2009) and Webster (2010).

The airborne electromagnetic (AEM) method has been applied to measure the seawater depth and associated conductivity in shallow coastal waters (Vrbancich and Fullagar, 2007). In this study of the Coorong, the AEM technique is applied to very shallow waters including areas where the water conductivity is both significantly less than and significantly greater than typical seawater conductivity, as found during the initial period of flooding of the Murray River following a very extended period of drought. In this context, the Coorong represents a remarkable and challenging AEM test area. Munday et al. (2008) have applied AEM technology to demonstrate the capability for mapping the extent of saltwater intrusion and to define the spatial patterns of salinity in the sediments in a selected target area that crosses the Lower Lakes. Here, I use the AEM technique to determine the accuracy of water depths and the accuracy of water conductivity derived from a layered-earth inversion of AEM data. If water depth and/or conductivity can be determined within acceptable accuracy bounds, the AEM method could be applied as a remote sensing tool to rapidly assess the water depth and water conductivity (salinity) to monitor areas where hypersalinity may impact on the survival of certain ecological communities.

METHOD AND RESULTS

A survey line was flown ~74 km down the centre of the Coorong, from Mundoo Island, along the North Lagoon and half-way down the South Lagoon, to Cattle Island, using the RepTEM (Geosolutions Pty Ltd) time-domain AEM system. A map of the Coorong together with the extent of the survey line is shown in Figure 1. The survey took place on 2

December 2010. Around this time, floodwaters from the north, originating in Queensland following severe flooding, were arriving into the Coorong region through the barrages following an extended period of severe drought.

The RepTEM AEM system consists of central transmitter-receiver loop configuration measuring the vertical field component, using a 25 Hz base frequency, a quasi-trapezoidal waveform with ~5 ms on-time and ~15 ms off-time. The stacked data is binned into 22 approximately logarithmically spaced windows with centre times ranging from 77 µs to 13.9 ms. Layered-earth (1D) inversion using a model of two relatively conductive layers (water/sediment) overlying a relatively resistive basement (underlying consolidated sediment) was carried out using program *Amity* (Fullagar Geophysics Pty Ltd). Altimetry was accurately measured with a laser altimeter (Riegl LD90). Altimetry and water conductivity are usually held as fixed parameters during inversion, although small variations in altimetry are allowed to optimise the data fit in a least squares sense during inversion.

Typically, a conductivity meter is dipped by helicopter into the waters to rapidly sample water conductivity, however our conductivity meters are limited to about 6 – 7 S/m and would therefore be ineffective in hypersaline waters encountered at the end of the North lagoon and throughout the South Lagoon. Fortunately, the South Australian Government (Dept. for Water) maintains a series of sparsely placed permanent water monitoring stations that provide monthly, daily and hourly records of water conductivity and water levels. Water conductivity data from the following stations that extend from the Murray Mouth to Salt Creek were used to assess the water conductivity levels within and around the survey area (locations shown in Figure 1): Barker Knoll, Ewe Island, Pelican Point, Long Point, Parnka Point (Hells Gate), Cattle Island and Snipe Island (near Salt Creek), Table 1. It is expected that variations in water conductivity may occur in the vicinity of these measuring stations because of the very shallow waters and convoluted shoreline.

Locations	December'10	2/12/2010
Ewe (1)	0.54 ± 0.40	0.65
Barker (2)	0.68 ± 0.80	0.23
Pelican (3)	0.33 ± 0.30	0.15
Long (4)	2.6 ± 1.5	5.5
Parnka (5)	9.1 ± 2.1	13.0
Cattle (6)	12.7 ± 0.7	13.9
Snipe (7)	12.4 ± 0.1	12.6

Table 1. Water conductivity (S/m) at stations (1– 7, Figure 1): December 2010 (± standard deviation) and daily (2 December 2010) averages.

Bathymetry in a hypersaline area

A 5 km section of the survey was flown over water (shown in blue in Figure 1) that lies between Parnka Point and approximately the mid-point between Parnka Pt. and Long Pt. (Table 1) and is expected to have a hypersaline water conductivity between ~5.5 to 13 S/m (Table 1). Inversion of AEM data along this section using a tightly constrained water conductivity (10 ± 1 S/m) and an unconstrained sediment conductivity of 1.25 S/m with upper and lower bounds of 10.0 and 0.5 S/m gives good agreement with known water depths (sampled from a 50 m spacing bathymetry grid), typically within 0.5 m or better, as shown in Figure 2. The peak (shoal) at ~346070 mE is considered to be real, based on its geographical location identified by aerial imagery. The AEM data was uncorrected; using corrected data based on rescaling coefficients obtained from deep water measurements (Vrbancich, 2011) made no improvement in the level of agreement between the bathymetry derived from sonar and AEM data. This allows for rapid interpretation of AEM data.

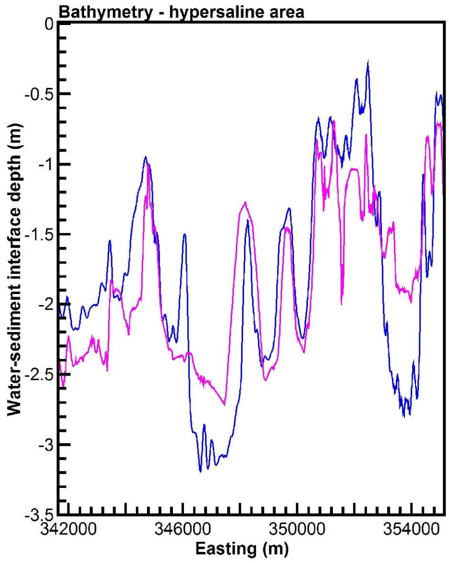

Figure 2. Hypersaline area - (a): bathymetry (m) - known (pink), AEM (blue).

Bathymetry in a moderately saline (seawater) area

A 1.5 km section of the survey was flown over water centred at Long Point (shown in grey in Figure 1) and is expected to have a water conductivity of ~5.0 S/m (Table 1), at the upper end of typical seawater conductivities. Inversion of AEM data using 5.0 S/m (tightly constrained to within ± 0.1 S/m gives good agreement with the known water depths as shown in Figure 3, typically within 0.5 m, west of the shoal at ~334000 mE which is close to Long Point. (The peaks in the AEM-derived bathymetry at 333200, 332500 and 332225 mE, Figure 3, have not been confirmed as real shoal areas, even though the discrepancy with known water depths is less than 1 m at these peaks.) Figure 3 also shows the water depths derived from the AEM data using an artificially high water conductivity of 10 S/m (constrained to within ± 0.1 S/m) that clearly shows a significant discrepancy between known water depths and AEM-derived water depths. East of Long Point (~33400 – 334500 mE) however, the three curves suggest that the water conductivity lies between 5 and 10 S/m, between Long Point and Parnka Point.

Water conductivity variation as a measure of salinisation in the North Lagoon

The AEM data for the section of the survey line flown over the whole of the North Lagoon was inverted for layer conductivities, using the known bathymetry (i.e upper layer thickness) as a fixed parameter in the layered-earth inversion with loose constraints on the water and sediment layer conductivities. (The current inversion software running in this configuration fixes the sediment-basement interface depth which in this case was set to 8 m.) This procedure (i.e. using known water depth as a fixed parameter) was adopted so that the known bathymetry obtained independently from other sources may be used to improve the accuracy of the conductivity parameters estimated from AEM data. The starting water conductivity was set to 9.0 S/m with upper and lower bounds of 15 and 0.1 S/m respectively, whilst the sediment layer staring conductivity was set to 6 S/m with the same upper and lower bounds. The results of the inverted layer conductivities are shown in Figure 4 (the gap was caused by loss of data during flight).

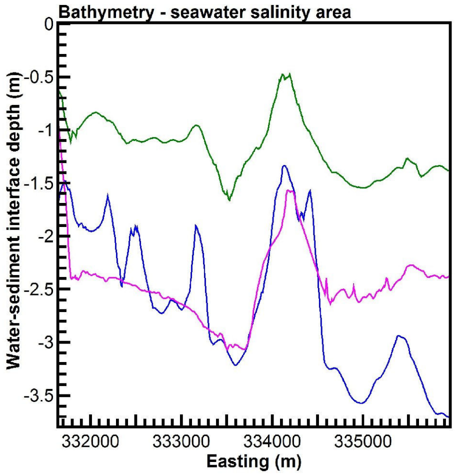

Figure 3. Seawater salinity area: known bathymetry (pink); AEM bathymetry with water conductivity constraints 5.0 ± 0.1 S/m (blue); AEM bathymetry with water conductivity constraints 10.0 ± 0.1 S/m (green). Sediment conductivity: 1.25 S/m with upper and lower bounds of 10.0 and 0.5 S/m.

The water conductivity crossplot in Figure 4 shows a definite trend of increasing conductivity from Barker Knoll in the north to Parnka Point at the southern end of the North Lagoon. There is reasonably good agreement with the daily-averaged conductivities recorded at the measurement stations that are also plotted in Figure 4. Apart from data quality and the applicability of the geo-electrical model assumed for inversion, discrepancies may arise because of the EM footrpint and because waters sampled at the measurement stations were not necessarily the same waters sampled by the AEM survey. The spot measurements at the measurement stations serve to monitor the localised conductivity/salinity levels. However, if additional geological and geophysical information were available to build a more realistic model for inversion, then the AEM remote sensing method, with its relatively large EM footprint, would provide a rapid means of sampling the water conductivity over a significant portion of the Coorong rather than relying on localised sparsely-distributed measurements.

The high sediment conductivity indicates saturation with hypersaline waters, with increasing sediment conductivity following increasing water conductivity as expected. At the northern end of the North Lagoon the sediment conductivity appears to be equal to or greater than the water conductivity. This may be expected because the waters in these areas were significantly more conductive prior to the onset of flooding, e.g. Barker Knoll (~312800 mE, Figure 4) monthly averages in 2010: February, 5.6 S/m; April, 5.2 S/m; June, 5.2 S/m; August, 4.0 S/m; October, 1.6 S/m, November, 0.4 S/m). Consequently, a lag would be expected between the time taken to flush the saline waters with fresh low salinity floodwaters and the time taken for these floodwaters to flush out the highly saline pore water in the unconsolidated sediments.

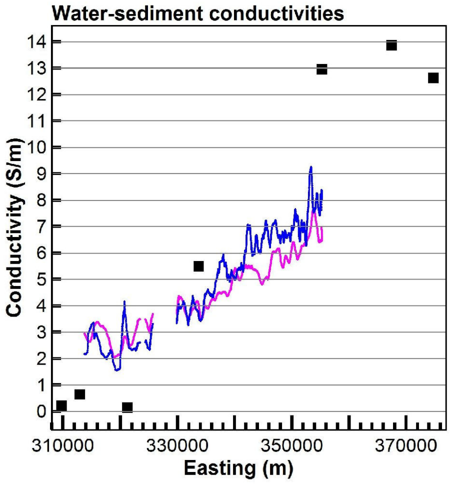

Figure 4. Water (blue) and sediment (pink) conductivities (S/m) for the North Lagoon derived from AEM data. Conductivities at time of AEM survey at the measurement stations (Table 1): black symbols

CONCLUSIONS

A helicopter time-domain airborne electromagnetic (AEM) system (RepTEM, Geosolutions Pty Ltd) was flown over the Coorong, along the full length of the narrow North Lagoon and down the top half of the narrow South Lagoon. The waters in the Coorong region are very shallow (typically 1 – 2 m) and are subject to hypersalinity, especially during extended periods of drought, where waters in the South Lagoon have conductivities that exceed ~ 16 S/m which is about four times that of seawater. At the northern end of the North lagoon, water is less saline and the conductivity may vary between that of seawater and brackish water depending on the discharge of fresh water from several barrages that separate the Coorong region from the Murray River.

AEM systems have been used to estimate water depths in shallow coastal waters using measured seawater conductivities. In these environments, detectable water depths vary from shallow waters approaching the shoreline to depths of approximately 30 to 50 m, and the seawater conductivity is typically 4 to 5 S/m. The AEM survey of the waters in the Coorong have provided a challenging opportunity to evaluate the AEM method for obtaining water depths and conductivity in areas of extended very shallow water depths and in areas where the water conductivity ranges from less than a quarter to about four times the typical seawater conductivity.

Water depths obtained from AEM data agree well with sonar soundings in sections of hypersaline and moderately saline waters, where water conductivity based on measurements from permanent water monitoring stations was used to tightly constrain this parameter in a two-layer-over-basement model used for inversion. Whilst the level of agreement (typically to within 0.5 m) is encouraging, further investigations over the whole range of water conductivities are warranted. Seawater conductivity was also estimated along the entire length of the North Lagoon using the known bathymetry and an assumed fixed sediment-basement interface depth as fixed parameters to “guide” the inversion. The water conductivities revealed a definite trend of increasing conductivity (and hence salinity) that were in reasonable agreement with the sparse data available from the water monitoring stations. These results indicate that AEM methods have the capability to accurately map both water depth and water conductivity in the Coorong, however further studies using geological and geophysical data (e.g. seismic survey data to define sediment thickness and layering, and borehole resistivity data) are required to construct a more realistic geo-electrical model for inversion of AEM data.

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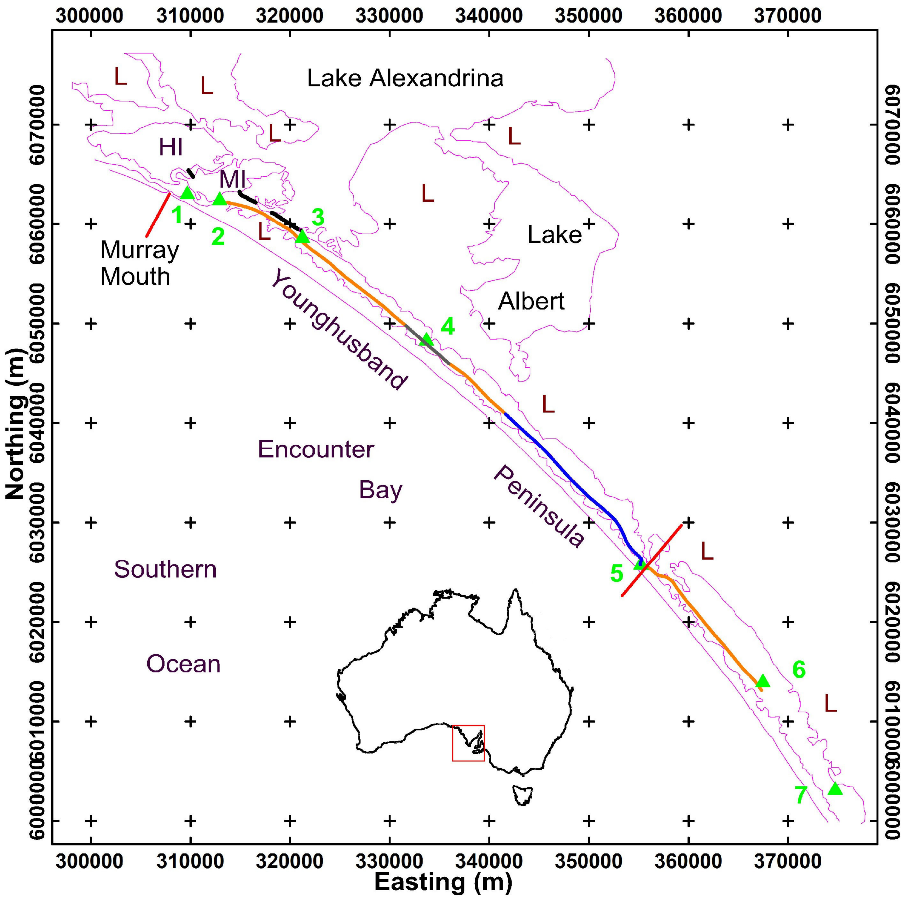

Figure 1. Location map of The Coorong area. MI: Mundoo Island; HI, Hindmarsh Island; L: signifies mainland. The survey line (orange) transects the North Lagoon and the top half of the South Lagoon. The red line at marker “5” separates the two lagoons. Permanent water monitoring stations are marked 1 – 7 (green), see Table 1. The locations of three barrages are shown in black. Average depths and widths:- North Lagoon: 1.2 m, 1.5 km; South Lagoon: 1.4 m, 2.5 km. Grid spacing: 10 km (GDA94/MGA54).