THE RELATIONSHIPS AMONGST MOISTURE CONTENT, PORE WATER SALINITY, TEXTURE AND APPARENT ELECTRICAL CONDUCTIVITY: EVIDENCE FROM THE RIVERLAND AND TINTINARA AIRBORNE EM PROJECTS

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INTRODUCTION

Borehole electrical conductivity and airborne electromagnetic (AEM) data have been widely utilised for natural resource applications. These include numerical modelling of the recharge rates and the establishment of a 3D sedimentary framework (Cook & Kilty 1992, Lawrie *et al.* 2000). The apparent electrical conductivity responses and the spatial distribution of the electrical conductivity signatures depict the chemical and physical attributes of regolith materials and unweathered rock, the latter having a resistive signature.

Rhoades *et al.* (1976) demonstrated that the apparent conductivity of a material is the weighted summation of the electrical conductivity of liquid and solid phases (Equation 1). In the absence of massive sulphides, conductivity is dominantly attributed to the liquid phase, which is in turn driven by the volumetric water content and the electrolyte (mainly sodium and chloride) ion concentration in the pore water.

$$ECa = ECw\theta\tau + ECs \qquad \text{Equation 1}$$

where ECa is the apparent conductivity, ECw is the pore water conductivity, θ is the volumetric water content, τ is the tortuosity and ECs is the solid phase conductivity.

As part of the South Australian Salinity Mapping and Management Support Project (SA-SMMSP), helicopter airborne electromagnetic (HEM) data of the Riverland and Tintinara East have been acquired to map subtle conductivity variations in near surface materials (ca. 1-10 m) at a high spatial resolution as an aid to managing the existing groundwater resource (Cook *et al.* 2004, Leaney *et al.* 2004).

AIM

To establish the effects of moisture content and salinity in the pore fluids of sediments/regolith materials on the apparent electrical conductivity.

THE STUDY AREAS

The Riverland AEM survey was a 15 to 20 km zone extending away from the southern bank of the Murray River, from Lock 3 near Kingston-on-Murray to the Border (Figure 1). The Digital Elevation Model (DEM) produced from the survey data revealed that the surface elevation of most of the area ranges from 20 to 35 m

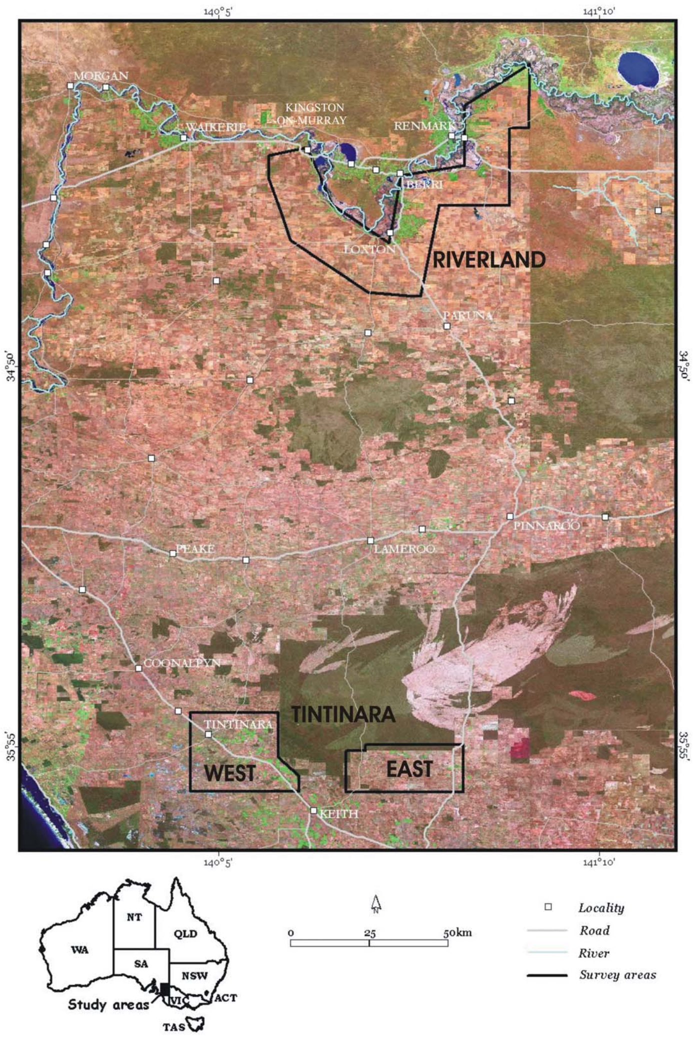

Figure 1: Landsat image with the outlines showing the study areas at Riverland and Tintinara East.

above sea level (AHD) (Tan *et al.* 2004a). However, a prominent ridge, which rises to 90 m AHD occurs in the northeast corner of the survey area. The geomorphology comprises of a dissected terrain that reflects incision by palaeodrainage systems which have been subsequently modified by erosion, deflation and aeolian deposition since the Late Pleistocene (Brown & Stephenson 1991). These geomorphic processes result in the presence of broad depressions, slightly elevated ridges (local relief mostly < 15 m), and east-west trending dunes. The average rainfall at Riverland is 260 mm/yr (Cook *et al.* 2004).

The Tintinara-East AEM survey area is approximately 800 km^2 (Figure 1) and the elevation ranges from 120 m AHD in the east (Mallee Highlands) to 60 m in the west, and the elevation continues to decrease towards the coastal plain (Leaney *et al.* 2004). The landform includes undulating dunes, interdunal sand plains and low rises. The average rainfall at Tintinara is approximately 900 mm/yr. The stratigraphic units (Brown & Stephenson 1991) of the Riverland and Tintinara study areas are shown in Table 1.

Table 1. The stratigraphic units at the Tintinara Study area (Brown & Stephenson 1991).

Stratigraphic Units	Age	Lithology	Environments
Woorinen Formation[1]	Quaternary	Mud, sand and regolith carbonate	Soils, dunes, deflation
Molineaux-Lowan Sands[2]	Quaternary	Mud, sand and regolith carbonate	Soils, dunes, alluvial plains
Bridgewater Formation[2]	Quaternary	Carbonate and quartz sands	Shallow marine
Blanchetown Clay and Bungunnia Limestone[1]	Late Pliocene to Pleistocene	Muddy sand, sandy mud and clay. Calcarenite and calcilutite	Lagoonal, fluvial, flood plain, associated with Lake Bungunnia
Loxton-Parilla Sands[1,2]	Pliocene	Fine to medium sand, well to poorly sorted	Coastal strandlines and shallow marine
Lagoonal Facies of the Loxton-Parilla Sands[2]	Pliocene	Mud and clay interbedded with calcilutite and sand	Lagoonal

[1]Riverland study area; [2]Tintinara study area

METHODS

A total of 19 boreholes were selected to target specific electrical conductivity signatures (at 25,000 Hz) at the Riverland and Tintinara East study areas (Tan *et al.* 2004a, b). Down-hole induction and gamma logs were recorded for 18 of the bores. The cores and drill chips were logged and samples at various depths were analysed for water and chloride contents, grain size distribution (using laser diffraction technique) and mineral composition (using X-ray diffraction method). The results were graphically displayed using LOGVIEW™ software (Figure 2).

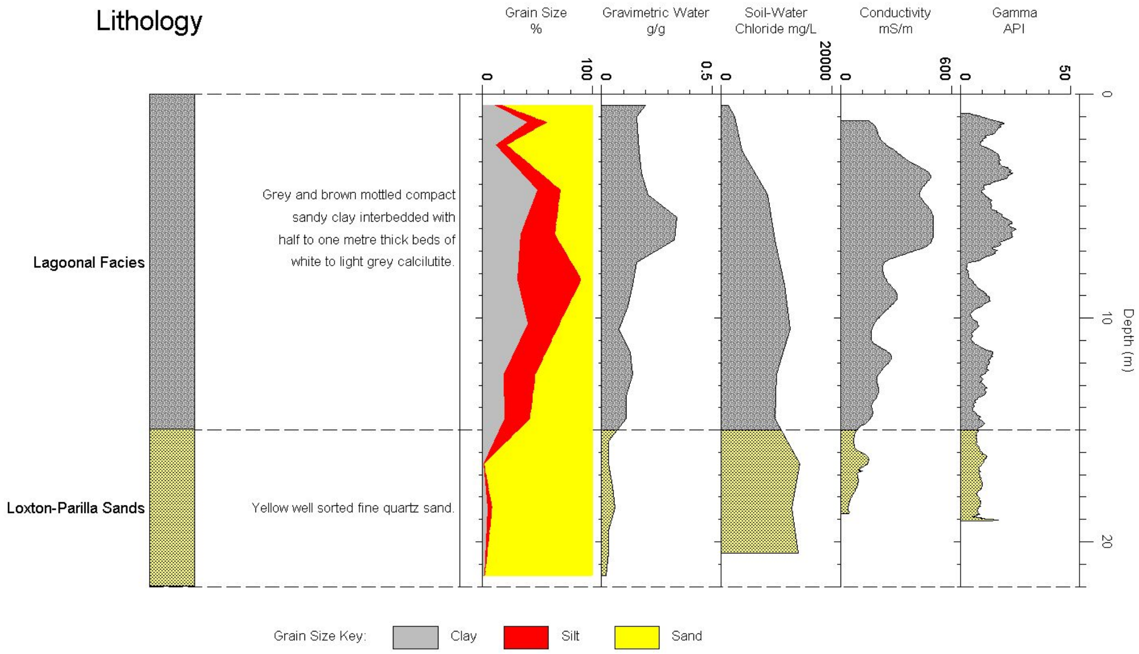

Figure 2: An example of borehole information, including down-hole geophysical logs (conductivity and gamma) and laboratory analytical results, obtained from the 19 bores at the study areas.

RESULTS FROM THE RIVERLAND STUDY AREA

A plot of water content against clay abundance (Figure 3a), with the data points grouped according to electrical conductivity values, reveals that the water content is positively correlated with clay abundance. In other words, the sand was dry and the clay was moist.

The graph of electrical conductivity against chloride concentrations in the pore water shows no clear relationship (Figure 3b). Grouping the data with respect to water content, however, reveals a few significant trends. Except for a few samples with low saline pore water (< 2,000 mg/l), the rest of the pore waters are brackish to saline, with a wide range of chloride concentrations (up to 27,000 mg/l). Samples with moderate amounts of water (5-15 wt. %) and relatively low chloride content (< 2,000 mg/l) exhibit low conductivities (≤ 100 mS/m). In contrast, samples with low water content (up to 5 wt. %), albeit having high chloride concentrations (> 10,000 mg/l Cl), also have low electrical conductivity (mostly < 100 mS/m). This suggests that the principal factor driving the electrical conductivity is not the salinity of the pore water alone. The two samples with highest observed electrical conductivity have a high water content (> 30 wt. %) and high chloride concentrations (approximately 10,000 mg/l). This indicates that it is the combination of the chloride content and the amount of water present that drives the apparent electrical conductivity.

The amount (mass) of saline pore water in a given unit (mass) of sediments is termed salt load. Total salt loads can be calculated by multiplying the sample water content with the sum of major cations and anions concentration. A plot of electrical conductivity against salt load (mg/kg chloride) shows a good correlation between the two ($r^2 = 0.83$) (Figure 3c). Equation 1, would suggest that an increase in salt load would lead to an increase in the electrical conductivity of the liquid phase and a rise in the overall apparent electrical conductivity (ECa). In the unsaturated zone, higher salt loads are associated with samples with high water content and clay abundance. Thus clay abundance is positively associated with the electrical conductivity (Figure 3d).

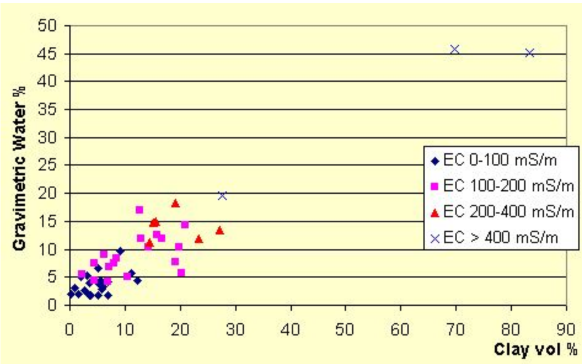

Figure 3a: A plot of gravimetric water content against clay abundance (vol. %).

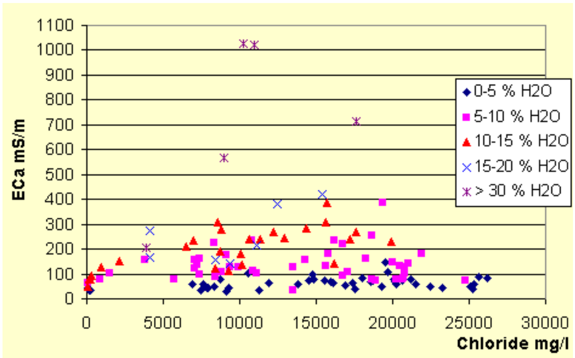

Figure 3b: A plot of electrical conductivity against chloride concentration.

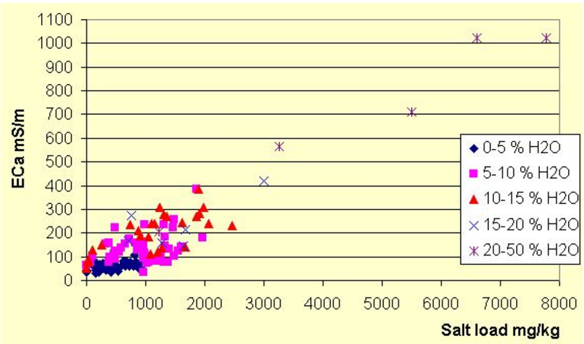

Figure 3c: A plot of electrical conductivity against salt load (i.e., amount of saline pore water in a given mass of sediments).

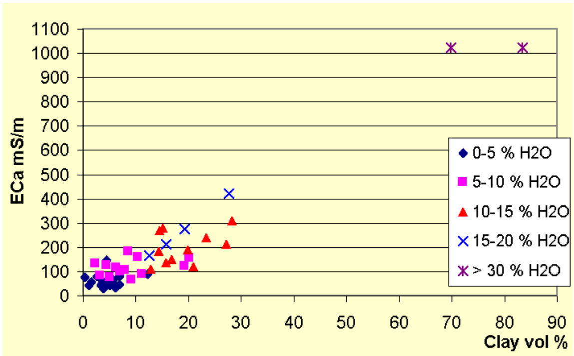

Figure 3d: A plot of electrical conductivity against clay abundance shows positive correlation.

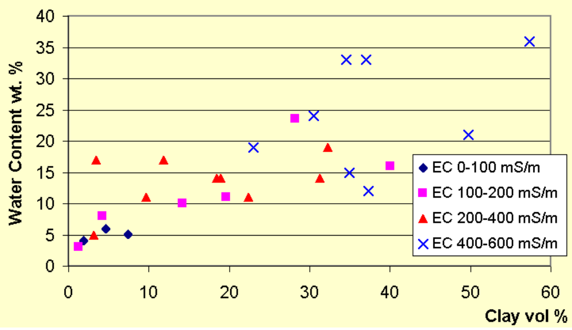

Figure 3e: Scatter plot shows weak, but positive, correlation between water contents and clay abundance (Tintinara study area).

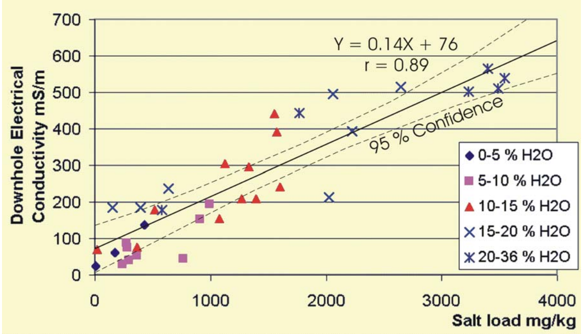

Figure 3f: Positive correlation between electrical conductivity and salt load (mg/kg chloride), suggesting the main factors driving EC are water contents and pore water salinity.

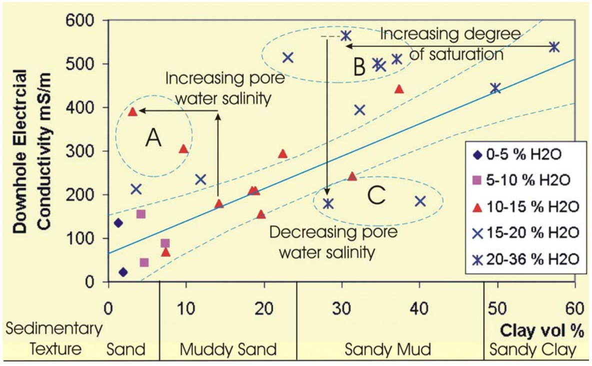

Figure 3g (left): Scatter plot is the same as Figure 3d with outlier groups A, B and C delineated. Improved correlation of r = 0.91 when groups A, B and C are omitted. The regression line (y = 7.4x + 62) denotes constant increase in salt load associated with a proportionate increase in clay abundance.

RESULTS FROM THE TINTINARA EAST STUDY AREA

A graph of water content against clay abundance (Figure 3e) reveals that the water content is positively associated with clay abundance. Nevertheless, materials with similar texture (i.e., clay abundance) may contain varying amounts of water. For example, most sands (i.e., < 7 vol. % clay) contain approximately 5 wt. % water, but up to 17 wt. % water is present for an inter-bedded sand layer of the Lagoonal facies sediments (bore TIN4HC, 10.5 m depth). In addition, up to 20 wt. % difference in water contents (12-33 wt. %) are present for samples containing 30 to 40 vol % clay, which are sandy mud of the Lagoonal facies (Tan *et al.* 2004b).

Positive correlation (r = 0.89) between electrical conductivity and salt load (mg/kg chloride) (Figure 3f) confirms that electrical conductivity depicts salt load, and is a function of water content and pore fluid salinity.

The graph of electrical conductivity against clay abundance shows wide-spread distribution of data that results in a weak, but positive, correlation (r = 0.65) (Figure 3g). To establish the causal factors involved, the data have been grouped according to the water contents. Three outlier groups (groups A, B and C) are observed, with the conductivities of groups A and B higher than those sediments with similar clay abundance, and conductivities of group C are lower. An improved correlation (r = 0.91) is achieved by omitting the outliers. These outliers were resulted from the variation in water contents and pore fluid salinity of materials with similar texture, i.e. difference in salt load and thus electrical conductivity within each textural class.

Since porosity is a function of texture and decreases with decreasing clay abundance (i.e., becoming sand-rich), data with constant salt load (i.e., water content and salinity) but plotted horizontally from the regression line towards lower clay abundance (e.g., from sandy clay to sandy mud) indicate that the sediments contain a higher degree of saturation (e.g., group B, data depicted by stars).

On the other hand, a vertical translation with similar clay abundance and water content (i.e., pore saturation remains constant) but lower conductivity (salt load) is due to a decrease in pore water salinity (e.g., group C, sample contains ca. 3,000 mg/l chloride). In contrast, group A data (10 to 15 wt. % water), compared to triangles plotted on the regression line, suggests both an increase in pore saturation (e.g., from moist muddy sand to wet sand) and salinity (from ca. 5,000 to ca. 13,000 mg/l chloride).

CONCLUSION

The investigation into the relationships amongst water content, pore fluid salinity, textures and electrical conductivity led us to conclude that in the regolith environment, the electrical conductivity is a function of water content and pore fluid salinity, the product of which two variables is termed salt load. When the variation in water content of each textural class is small (i.e., sand, muddy sand, mud and clay), the electrical conductivity shows a good correlation with the clay abundance. This is the case for the Riverland study area. On the other hand, large variation in water content or pore fluid salinity resulted in weak correlation between electrical conductivity and clay abundance, caused by outlying data. Plotting the data according to the water content reveals the factors that caused the data to deviate from the regression line, i.e., increase or decrease in water content of same textural class or pore fluid salinity.

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