Electromagnetic Imaging of Prior Stream Channels using a DUALEM-421 and Inversion

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Abstract
Prior stream channels occupy 15% of the clay alluvial fields used for irrigated cotton production in the lower Gwydir Valley in north-western NSW. They act as significant hydrological features offering pathways for deep draining water to interact with buried palaeochannels. We need to map the connectivity and spatial extent of these formations to improve the scientific understanding of the associated hydrological processes in this region. In this paper we explore this by first measuring the apparent electrical conductivity (σ_a) of the soil with a DUALEM-421. Subsequently, we employ 1-dimensional (1-D) inversion algorithms with 2-dimensional (2-D) smoothness constraints to predict the true electrical conductivity (σ) using DUALEM-2d (partial solution) and DUALEM-2d-Full (full solution). The σ models obtained are compared with soil data (including particle size fractions, soil texture, $EC_{1:5}$ and CEC) collected across the field. All σ models generally reflect the soil properties which characterise the physiographic units of a prior stream channel and the clay alluvial plain. However, the relationship between the measured soil properties and estimated σ is weak and further research is needed to achieve better relationships.

Key Words
Prior stream channels, DUALEM-421, electromagnetic (EM) induction, inversion.

Introduction

Prior stream channels occupy 15 % of the clay alluvial landscapes that are used extensively for irrigated cotton production in the lower Gwydir Valley in north-western New South Wales, Australia (Needham 1991). In order to improve the scientific understanding of the hydrological processes across this landscape, especially where the management of water is crucial and climatic models and trends suggest that rainfall is in decline (Kothavala 1999), there is a need for better representation and ability to map the connectivity and spatial extent of prior stream channels and palaeochannels. Electromagnetic (EM) induction is a cost effective and proximal geophysical method that has successfully been employed in measuring both the areal (Triantafilis *et al*. 2003) and stratigraphic (Vervoort and Annen 2006) distribution of apparent electrical conductivity (σ_a – mS/m) of prior stream channels within the current study site. The aim of this study is to use σ_a data collected by a DUALEM-421 to infer the spatial distribution of soil properties and soil particle size fractions related to σ_a across a prior stream channel in an irrigated cotton field in the lower Gwydir valley. This is achieved by using two inversion programs, DUALEM-2d and DUALEM-2d-Full, that estimates the true electrical conductivity (σ) of the soil at discrete increments. These programs are modified versions of the nonlinear smoothness constrained inversion algorithm described in (Santos 2004) and incorporate a damping factor (the Lagrange parameter) that is used to control the balance between the data fit and its closeness to the initial model.

Materials and Methods

The study site is located within Field 11 of Auscott 'Midkin', a large irrigated cotton farm situated approximately 20 km away from Moree in the lower Gwydir Valley. A large prior stream channel is located in Field 11. It is most prominent in the southern end of the field wherein it dissipates as it extends to the north. The DUALEM-421 is an EM instrument which operates at 9.1 kHz and consists of one transmitting coil and three pairs of receiving coils spaced 1, 2 and 4 m apart from the transmitting coil. Each coil pair consists of a coil with horizontal windings forming a horizontal coplanar (HCP) array and a coil with vertical windings forming a perpendicular (PRP) array. Each coil array measures the apparent electrical conductivity (σ_a) of the soil for six different depths of exploration (DOEs) relating to the geometry of the instrument (i.e. coil spacing and orientation) and the frequency of operation. The HCP arrays measure the σ_a (Hcon – mS/m) of the soil from 0 to 1.5 m (1mHcon), 0 to 3 m (2mHcon) and 0 to 6 m (4mHcon). The PRP arrays measure the σ_a (Pcon – mS/m) of the soil from 0 to 0.6 m (1mPcon), 0 to 1.2 m (2mPcon), and 0 to 2.4 m (4mPcon).

The DUALEM-421 was used for a σ_a survey across twelve transects within Field 11 which are spaced 24 m apart and labeled 16.5 to 22. Of note, transect 21.5 is where soil information is available. The σ_a data was then passed through two inversion programs called DUALEM-2d (Santos *et al*. 2009) and DUALEM-2d-Full (Santos 2009) to obtain an estimate of the true electrical conductivity (σ) of the soil at discrete increments within the soil profile. DUALEM-2d is a partial solution to the inverse problem and DUALEM-2 d-Full is the full solution. In terrains of large σ such as the clay alluvial plains of the lower Gwydir Valley, above a value of approximately 100 mS/m, the relationship between EM instrument response and the σ_a of the soil becomes nonlinear due to operation outside of low induction numbers (McNeill 1980). The full solution takes this limitation into account, whereas the partial solution does not. In order to determine the relationship between the inversion results and soil properties, 17 soil cores were collected to a depth of 1.5 m and bulked into 0.3 m increments. Each soil sample was analysed for soil particle size fractions by the hydrometer method and for other soil properties (i.e. $EC_{1:5}$, CEC and texture) that may influence σ_a across a prior stream channel and clay alluvial plain.

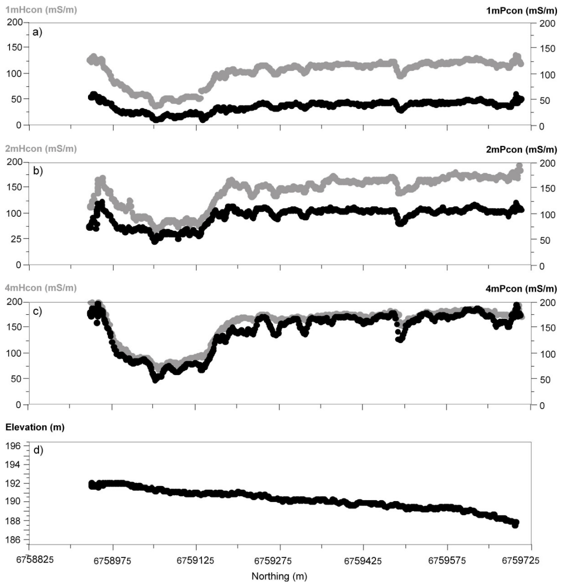

Figure 1. Spatial distribution of apparent soil electrical conductivity (σ_a - mS/m) along transect 21.5 measured using a DUALEM-421 in horizontal coplanar (Hcon) and perpendicular (Pcon) modes of operation, and intercoil spacing of: a) 1m, b) 2m, and, c) 4m, and d) altitude (ASL - m).

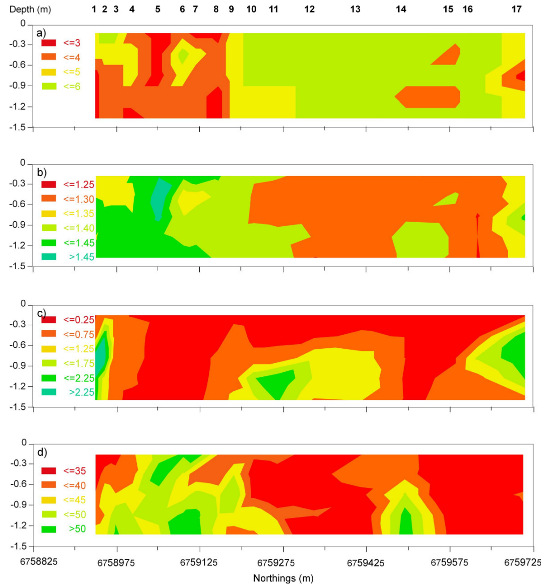

Figure 2. 2-dimensional (2-D) contour plots of a) soil texture (based on soil texture classes, whereby 6 – Clay, 5 – Light Clays, 4 – Clay Loams and 3 – Loams); b) clay content; c) electrical conductivity of 1 part soil and 5 parts water extract ($EC_{1:5}$ – mS/m), and d) cation exchange capacity (CEC – cmol (+)/ kg).

Results and Discussion

Figure 1 shows the 1mHcon and 1mPcon σ_a data (Figure 1a), the 2mHcon and 2mPcon σ_a data (Figure 1b) and the 4mHcon and 4mPcon σ_a data (Figure 1c) from the DUALEM-421, as well as the elevation (Figure 1d) along transect 21.5. In Figure 1a, it is evident that north of 6759125 the larger 1mHcon σ_a and 1mPcon σ_a represent the clay alluvial plain. Conversely, south of 6759125 the smaller σ_a values represent the prior stream channel. Given that the DOE of the 1mHcon σ_a measurement is deeper (0 to 1.5 m) as compared to the shallow DOE of the 1mPcon σ_a (0 to 0.6 m), this suggests that the surficial 0 to 0.6 m of the soil profile may be smaller in σ than the subsurface (0.6 to1.2 m). Figure. 1b shows a similar pattern in terms of the pattern of σ_a distribution however, the 2mHcon and 2mPcon σ_a are approximately 2 times larger than the equivalent data from the 1 m coil spacing. This suggests that the σ is larger within the shallow vadose zone (1.2 to 3 m). Figure 1c shows that both the 4mHcon and 4mPcon σ_a are equivalent. Given that the 4mHcon and 4mPcon σ_a are influenced by layers within the soil profile between 0 to 6 m and 0 to 2.4 m, respectively, this suggests that between depths of 2.4 to 6 m the σ of the soil may be smaller.

Figure 2 shows 2-D contour plots of the particle size fractions of clay (Figure 2a), soil texture (based on soil texture classes, whereby 6 – Clay, 5 – Light Clays, 4 – Clay Loams and 3 – Loams) (Figure 2b), electrical conductivity of 1 part soil and 5 parts water extract ($EC_{1:5}$ – mS/m) (Figure 2c) and cation exchange capacity (CEC – cmol (+)/ kg) (Figure 2d) along transect 21.5. The prior stream channel in the southern end of the transect consists of a uniform loam to clay loam texture reflected by a smaller clay content (15 to 35 %) compared to the finer textured (uniform clay) soil, large in clay content (> 50 %) of the clay alluvial plain

(Figure 2a and b). In addition, the small $EC_{1:5}$ (i.e. < 0.25 mS/m) of the prior stream channel (Figure 2d) is reflected by the coarser texture soil of this soil formation. Owing to the coarser nature of the sediments here, and as shown in Figure 2c, most of the soluble salts within the soil profile that accumulate here due to Aeolian processes or cyclical deposition via rainfall have leached out. Conversely, the larger $EC_{1:5}$ (1.25 to > 2.25 mS/m) in the central and northern end of the transect corresponding to the clay alluvial plain reflects a normal salinity profile due to the accumulation of primary salinity as described previously. Figure 3 shows the 2-D spatial distribution of σ along transect 21.5 that was obtained from DUALEM-2d (Figure 3a) and DUALEM-2d-Full (Figure3b). The σ models were obtained using an automatic initial earth model and a damping factor of 0.1. The global misfits for the σ models are 8.41 % and 9.05 %, respectively.

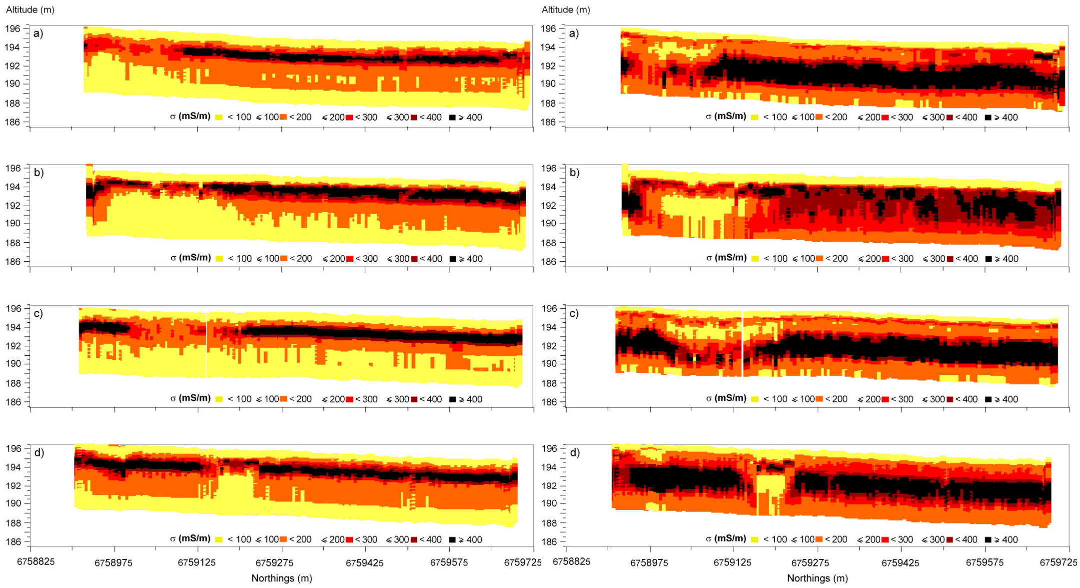

Figure 3. 2-dimensional (2D) spatial distribution of soil electrical conductivity (σ - mS/m) along transects 20.5, 21, 21.5 and 22 obtained from σ_a data and (left) DUALEM-2d data (right) DUALEM -2d-Full.

It is evident that the overall subtle stratigraphic elements of the landscape are well represented by both inversion models, with respect to small σ values (< 100 mS/m) corresponding to the prior stream channel and conversely, the larger σ values (200 to > 400 mS/m) corresponding to the clay alluvial plain. With respect to the clay alluvial plain, the larger σ values are underestimated by the DUALEM-2d partial inversion program due to the large σ_a values that occur within this part of the transect (refer to Figure 1a, b and c). The σ model obtained from DUALEM-2d-Full inversion program represents the larger σ values more realistically. The stratigraphy of the range of σ values in the prior stream channel presented are likely to reflect the range of soil textures that a prior stream channel consists (Stannard and Kelly 1968).

In comparing σ to various soil properties, the Pearson correlation coefficients (*r*) for the σ (DUALEM-2d) versus clay content, $EC_{1:5}$ and CEC are 0.08, 0.27 and 0.19, respectively. The *r* values for the σ (DUALEM-2d-Full) versus clay content, $EC_{1:5}$ and CEC are 0.08, 0.26 and 0.19, respectively. In the case of the σ models obtained from the DUALEM-2d program, the potential for prediction may be limited by the nonlinearity of the cumulative function that the algorithm is based upon. DUALEM-2d-Full takes into account the nonlinearity problem, however this does not produce better correlations between σ and soil properties. This could be attributed to the layer of small σ values that exist in the upper 1 m of soil in all the σ models which may reflect the lack of soil moisture in the topsoil at the time of the σ_a survey.

Conclusion

The spatial distribution of soil properties within a prior stream channel and clay alluvial plain can be inferred from the true electrical conductivity (σ) generated from the inversion of DUALEM-421 σ_a data collected along a single transect located within an irrigated cotton growing field in the lower Gwydir valley. We achieved this by inverting the σ_a data with DUALEM-2d (partial solution) and DUALEM-2d-Full (full solution). The larger σ estimates associated with the clay alluvial plains and obtained the full solution are found to be more realistic. The σ estimates of the prior stream channel are also more realistically represented by the full solution when comparing the pattern σ distribution with the known stratigraphy of the range of soil textures present in prior stream channels and clay alluvial plains as described by Stannard and Kelly

(1968). The calibration information, specifically the CEC, $EC_{1:5}$ and soil textural data (indicating a normal salinity profile in the clay alluvial plain) from the soil cores generally reflects the distribution of σ along transect 21.5. Specifically, small subsurface σ (0 to 200 mS/m) represents the smaller CEC, $EC_{1:5}$ and coarser textures (i.e. sandy loams) of the prior stream channels. Conversely, larger values of σ (> 400 mS/m) characterise the finer textured (i.e. medium to heavy clays) and slightly larger $EC_{1:5}$ of the root zone soil properties of the clay alluvial plain. Whist the σ models are able to generally represent the soil types, the potential to use σ to predict soil properties is limited. The lack of statistical correlation is attributed to a layer of small σ values within the upper 1 m of the soil profile that may be affected by low moisture content in the topsoil at the time of the σ_a survey. Follow up research should be carried out in more favourable conditions (i.e. soon after irrigation or heavy rainfall) to determine the influence of soil moisture.

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