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Inversion of multi-frequency electromagnetic induction data for 3D characterization of hydraulic conductivity

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ABSTRACT

Electromagnetic induction (EMI) instruments provide rapid, noninvasive, and spatially dense data for characterization of soil and groundwater properties. Data from multi-frequency EMI tools can be inverted to provide quantitative electrical conductivity estimates as a function of depth. In this study, multi-frequency EMI data collected across an abandoned uranium mill site near Naturita, Colorado, USA, are inverted to produce vertical distribution of electrical conductivity (EC) across the site. The relation between measured apparent electrical conductivity (EC_a) and hydraulic conductivity (K) is weak (correlation coefficient of 0.20), whereas the correlation between the depth dependent EC obtained from the inversions, and K is sufficiently strong to be used for hydrologic estimation (correlation coefficient of −0.62). Depth-specific EC values were correlated with co-located K measurements to develop a site-specific ln(EC)–ln(K) relation. This petrophysical relation was applied to produce a spatially detailed map of K across the study area. A synthetic example based on EC_a values at the site was used to assess model resolution and correlation loss given variations in depth and/or measurement error. Results from synthetic modeling indicate that optimum correlation with K occurs at ~0.5 m followed by a gradual correlation loss of 90% at 2.3 m. These results are consistent with an analysis of depth of investigation (DOI) given the range of frequencies, transmitter–receiver separation, and measurement errors for the field data. DOIs were estimated at 2.0 ± 0.5 m depending on the soil conductivities. A 4-layer model, with varying thicknesses, was used to invert the EC_a to maximize available information within the aquifer region for improved correlations with K. Results show improved correlation between K and the corresponding inverted EC at similar depths, underscoring the importance of inversion in using multi-frequency EMI data for hydrologic estimation.

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1. Introduction

Management practices for preservation and remediation of soil quality and groundwater supplies rely heavily on monitoring technologies capable of assessing soil and hydrologic properties such as salinity, soil texture, saturation, and hydraulic conductivity. The electromagnetic (EM) response to soils is primarily a function of water content, salinity, particle size of the soils, soil mineralization, and the distribution of these properties within the soil profile. Electromagnetic induction (EMI) instruments have been used to assess soil salinity (Cameron et al., 1981, 1995a,b; Hendrickx et al., 1992; Lesch et al., 1992, Paine, 2003; Rhoades, 1993; Rhoades et al., 1990; Sheets et al., 1994), soil texture (Abdu et al., 2008; Hedley et al., 2004; Sudduth et al., 2005; Triantafilis and Lesch, 2005), soil water content and saturation (Hezarjaribi and Sourell, 2007, Kachanoski et al., 1988, 1990; Reedy and Scanlon, 2003; Sheets and Hendrickx, 1995; Sherlock and McDonnell, 2003;), and recharge (Cook et al., 1989; Scanlon et al., 1999).

In soils where increased clay content results in decreased hydraulic conductivity, the measured apparent electrical conductivity (EC_a) is inversely proportional to hydraulic conductivity (K) (Curtis and Kelly, 1990; Slater and Lesmes, 2002). The relation between EC_a and particle size distribution was utilized by Callegary et al. (2007a) to estimate potential for ephemeral stream channel infiltration and subsurface horizontal flow. Callegary et al. (2007a) found a generally poor correlation between EC_a and point measurements of particle size, infiltration flux, and saturated hydraulic conductivity but found moderate correlation between EC_a measurements and the borehole-averaged percent of fines.

EMI data most often are interpreted qualitatively by direct observation of EC_a values plotted on plan-view maps. This method of visualizing EC_a allows mapping of the approximate lateral extent of anomalous features (Abdu et al., 2008; Lesch et al., 1995a,b; Sheets et al., 1994) but does not provide quantitative estimates of depth variations in

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EC. Many studies have developed empirical relations from multiple linear regression (Rhoades and Corwin, 1981; Rhoades et al., 1989) or linear response curves (Cook and Walker, 1992; Corwin and Rhoades, 1982) to estimate vertical changes in conductivity. The multiple linear regression approach results in a set of coefficients used to predict *EC* at different depths; these coefficients, however, are site-specific. The linear response curves are derived from the response of homogenous media and can lead to large errors in the predicted values for the linear model when applied to heterogeneous soils (Hendrickx et al., 2002).

Another approach for estimating *EC* with depth is inversion of the EMI data using either linear (Borchers et al., 1997) or nonlinear (Abraham et al., 2006; Hendrickx et al., 2002; Martinelli and Duplaa, 2008) inversion methods. By recording multiple measurements at several heights above the ground surface Hendrickx et al. (2002) obtained a soil depth profile. Nonlinear inversion of these soil conductivity profiles gave slight improvements at higher electrical conductivities compared to linear inversion, but at a greater computational cost.

The objectives of this study are: (1) to demonstrate the usefulness of one-dimensional (1D) inversion of multi-frequency EM data, recorded along densely spaced survey lines across an abandoned uranium mill site, to produce 3-dimensional (3D) maps of soil *EC*, and (2) to show that the obtained *EC* values can be used to produce K estimates across the field site EC_a data that are inverted using the frequency-domain electromagnetic inversion code (FEMIC) originally developed by Schultz (2002) and Schultz and Ruppel (2005). EC_a soundings, co-located with field measured *K* estimates, are inverted and correlated with *K* at the corresponding depth. The relation between measured *K* and inverted *EC* values is used to estimate maps of *K* for the saturated zone across the study site. A synthetic example is used to investigate data recoverability, resolution, loss of correlation between inverted *EC* and *K* with increasing data error and depth, and effective depth of exploration for multi-frequency EMI exploration.

2. Background

Frequency domain EMI theory is described by McNeill (1980) and Ward and Hohmann (1987). Briefly, a primary EM field is generated by a transmitting coil carrying a time-varying electric current at a set frequency. The primary EM field induces small eddy currents in the subsurface, and the eddy currents generate a secondary magnetic field. The primary and secondary fields are recorded by a receiver coil at some set distance from the transmitter coil (Fig. 1a). The ratio of the secondary to primary magnetic fields is recorded as in-phase and quadrature data in parts-per-million (ppm), and the EC_a and magnetic permeability values are derived from a conductive, permeable half-space model estimated from the in-phase and quadrature measurements for each frequency (Huang and Won, 2000). Resulting EC_a values provide a depth-averaged conductivity value of the soil volume in milliSiemens per meter (mS/m).

Some commonly used frequency-domain EMI instruments record data at one frequency with a fixed separation distance between the transmitter and receiver. Multi-frequency EM instruments record data at multiple frequencies within a limited frequency band (Fig. 1b), producing continuous frequency soundings along survey lines. Such frequency soundings provide multi-layer earth information where low frequencies are sensitive to greater depths and higher frequencies are sensitive to materials at shallower depths; the advantages of including more than one frequency in small EM instruments (i.e., with <4-m intercoil spacing) include the ability to resolve fine conductivity structure, however, these instruments continue to challenge practitioners. Huang and Won (2000, 2003) argue that data recorded at multiple frequencies by small EM sensors vary sufficiently to provide useful information for common investigation depths. McNeill (1996) maintains that data from multiple frequencies, at fixed separation, contain mostly redundant information because depth sensitivity is controlled strongly by coil spacing and that megahertz-range data would be required for meaningful depth-dependent information. Nonetheless, a number of practitioners have extracted layer information from multi-frequency EM data (Huang, 2005; Huang and Won, 2003; Martinelli and Duplaa, 2008; Minsley et al., 2010). Abraham et al. (2006) and Minsley et al. (2010) produced images of resistivity versus depth from multi-frequency EM data by calibrating the EM data based on the theoretical response estimated from a direct current (DC) resistivity sounding.

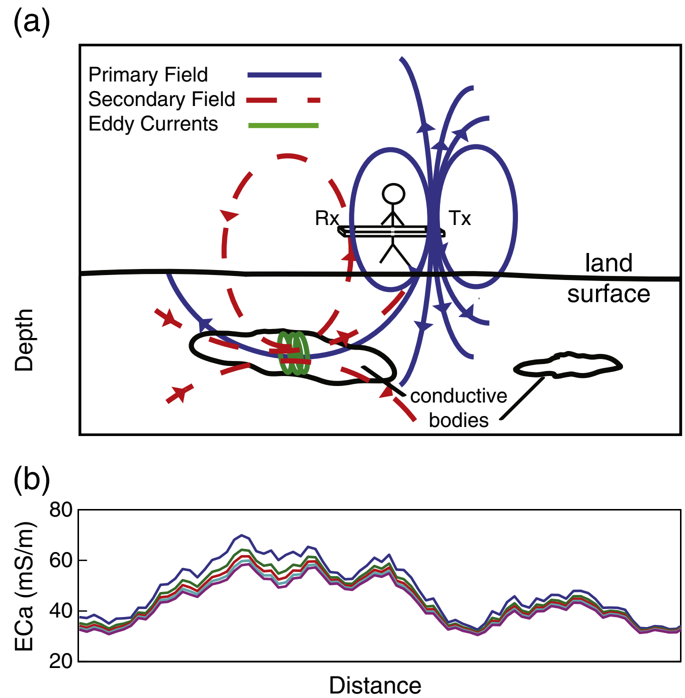

Fig. 1. (a) Electromagnetic (EM) induction data collection. The transmitter (Tx) and receiver (Rx) are separated at some fixed distance. The primary field is generated by the Tx; interactions between primary field, secondary field, and eddy currents are illustrated. (b) Example of apparent electrical conductivity (EC_a) data profile recorded by a multi-frequency EM instrument; each colored line corresponds to a different recording frequency.

Another concern regarding EMI instruments is the effective depth of exploration (d_e). McNeill (1980) defined effective depth of penetration (i.e., effective depth of exploration) based on vertical spatial sensitivity for low induction number (LIN) EM instruments in homogeneous and horizontally layered soils. The induction number (β) is the ratio of the intercoil spacing (s) to the skin depth (δ) (Spies, 1989):

$$\beta = \frac{s}{\delta} = \frac{s}{\sqrt{\frac{2}{EC_a\,\omega\mu}}}, \tag{1}$$

where ω is angular frequency (Hz); and μ is magnetic permeability (H m^{-1}), assumed to be constant and equal to the free space value, $4\pi\times10^{-7}$ H m^{-1} (μ_o). Skin depth is defined as the depth at which the transmitted magnetic field amplitude has been attenuated to e^{-1} of its initial magnitude at a reference point (Sheriff, 1991). The "LIN approximation," as presented by McNeill (1980), is valid for environments where $\beta \ll 1$ (e.g., $EC_a \leq 100$ mS/m, $\omega = 9800$ Hz, and $s = 3.66$ m) and vertical spatial sensitivity and d_e are then independent of EC_a. Assuming a valid β, McNeill (1980) provides a spatial sensitivity analysis using a cumulative response (CR) function to