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Spatial variability of soil water content and soil electrical conductivity across scales derived from Electromagnetic Induction and Time Domain Reflectometry

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ABSTRACT

Quick, reliable and accurate estimates of soil water content (SWC) at intermediate (slope) to larger scale (catchment) are important for understanding hydrological processes and may be provided by electromagnetic induction (EMI). EMI measures the apparent electrical conductivity of the subsurface (EC_{app}) which represents a depth weighted average value of the bulk soil electrical conductivity (EC_b). The relation between EC_b and SWC has generally been investigated in soil cores or using local measurements of SWC and EC_b. Studies that investigated the relation between EC_{app} measured with EMI and SWC in considerably larger and internally more heterogeneous support volumes are far scarcer and cover a limited range of environments with a limited range of factors contributing to EC_{app}. This study developed a new calibration method to obtain quantitative estimates of SWC using EMI measured EC_{app} data in a sub-tropical region in Southern Brazil at sites with different soil properties. SWC and EC_b were measured in soil pits with Time Domain Reflectometry (TDR) probes. Collocated EC_{app} was simultaneously measured with EMI using different coil separations and orientations to measure over increasing sensing volume. EMI measured EC_{app} data were first calibrated against calculated EC_{app}, which were derived from EC_b profiles inserted in an exact EMI forward model. A depth averaged SWC (SWC_{avg}) was calculated and different calibrations that relate EC_{app} to SWC_{avg} were evaluated. EC_{app} measurements of the deeper sensing coil configurations could predict best the variability of SWC_{avg} using a non-linear relation. Spatio-temporal variations of pore water electrical conductivity (EC_w) were found to be an important cofounding factor. Temporal variations of EC_w and the small temporal variability of SWC_{avg} prevented the prediction of temporal variability of SWC_{avg} using EC_{app} measurements. Overall, the combination of both calibration steps resulted in the description of 83% of the spatial variability of SWC_{avg} from EC_{app} measurements.

1. Introduction

Soil moisture is a key variable in many natural soil processes (Dingman, 2002) and it plays a major role in the climate system by controlling plant transpiration and being a storage component for precipitation (Seneviratne et al., 2010). Soil moisture, or soil water content (SWC), is one of the major controls on ecosystem structure, function and diversity (Rodriguez-Iturbe and Porporato, 2005). It also has a strong effect on soil biogeochemistry and is strongly linked with the carbon storage and CO_2 emission from soils (Schjønning et al., 2003). In the future, it is expected that anthropogenic alterations on the climate system (Katul et al., 2012) and land use changes (LUC) (Bosch and Hewlett, 1982; Sahin and Hall, 1996) will have a significant impact on SWC and the water cycle. Therefore, as highlighted by Vereecken et al. (2015), technological and methodological advancements are of primary importance to provide accurate measurements of spatial and temporal SWC variability and to improve our understanding of soil hydrological processes.

In that context, the use of geophysical methods in watershed hydrology is not new (e.g. Shields and Sopper, 1969). However, SWC measurements were mainly obtained at point scale resolution, often using intrusive and time-consuming techniques such as time domain

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reflectometry and/or capacitance sensors (Robinson et al., 2008). Such methods often provided too little information to fully describe SWC at larger scales, which imposed fundamental limits to the understanding of the soil hydrology at larger scales, i.e. hillslope to small-catchment scale (McDonnell et al., 2007; Tromp-van Meerveld and McDonnell, 2009). The recent development of wireless SWC sensor networks has been a promising alternative (Bogena et al., 2010) but they still lack flexibility and may be prohibitively expensive for many users. More flexible, electromagnetic induction (EMI) instruments can also be used to indirectly obtain SWC measurements (Robinson et al., 2008; Vereecken et al., 2008). A transmitter coil (Tx) generates a primary magnetic field which induces eddy currents in the soil that, in turn, generate a secondary magnetic field measured at one or more receiver coils (Rx) (Ward and Hohmann, 1988). The ratio between the secondary and primary magnetic field can be related to a weighted average of the soil bulk electrical conductivity (EC_b) over a certain depth of investigation (DOI), which represents an apparent electrical conductivity (EC_{app}) (Keller and Frischknecht, 1966). The DOI can be varied by increasing the Tx-Rx coil separation and/or changing the coil orientation (McNeill, 1980).

EC_b depends on the SWC as well as on other parameters, e.g. the concentration of dissolved electrolytes, the amount and composition of clays and/or soil porosity (Archie, 1942; McNeill, 1980; Rhoades et al., 1976; Waxman and Smits, 1968). As a result, the relation between EC_b and SWC is an indirect relation that requires a site and soil layer specific calibration (Garré et al., 2013). EC_b-SWC relations have been derived from measurements in soil cores or from local measurements of both EC_b and SWC in soil profiles so that the spatial variability or heterogeneity of factors that influence this relation within the investigated soil volume was small. However, the DOI of EMI measurements encompasses a considerably larger soil volume which exhibits a larger heterogeneity in soil properties including SWC.

The potential of newly developed multi-configurations EMI systems to simultaneously sense the soil over different depth ranges was recently highlighted (e.g. Saey et al., 2013; Von Hebel et al., 2014). These studies used sophisticated inversion algorithms to retrieve depth-specific information from EC_{app} measurements which may lack robustness when influenced by factors that are not accounted for in the inversion model (e.g. rough surface micro topography, presence of trees, measurement noise in soils with low EC, etc.). Whether a simpler combination of the information retrieved with multiple coil configurations can lead to a better prediction of SWC has been seldom assessed (Huth and Poulton, 2007).

In addition, it is important to mention that EMI instruments can be strongly affected by operational set-ups such as instrument instability, cables, the presence of the surveyor himself or the ambient temperature (Abdu et al., 2007; Delefortrie et al., 2014; Huang et al., 2017a; Lavoué et al., 2010; Nüsch et al., 2010; De Smedt et al., 2016; Sudduth et al., 2001), especially at low EC_{app} values (Abdu et al., 2007). Several calibration techniques were developed to allow a quantitative interpretation of the EC_{app} values measured with an EMI instrument. For example, saturated soil paste extracts from soil cores were used to calibrate EC_{app} (Triantafilis et al., 2000; Wollenhaupt et al., 1986), as well as electrical resistivity tomography (ERT) data (Lavoué et al., 2010; Mester et al., 2011; Shanahan et al., 2015; Von Hebel et al., 2014). The calibration based on ERT and linear regressions developed by Lavoué et al. (2010) used soil EC_b depth profiles from inverted ERT data to predict EC_{app} with an EM forward model (van der Kruk et al., 2000; Ward and Hohmann, 1988). This forward model used no low induction approximation such that it is valid for a large range of soil EC values, EMI coil separations, and instrument frequencies.

As highlighted by reviews of Corwin and Lesch (2005) and Doolittle and Brevik (2014), there exists a wide range of applications of the EMI method, motivated in the beginning by the need of quick and reliable data for soil salinity assessment (de Jong et al., 1979; Lesch et al., 1995). EMI instruments were quickly used to map other soil properties such as clay content (Triantafilis and Lesch, 2005), the spatial pattern of the soil textures (Abdu et al., 2008; Sudduth et al., 2005) or the soil depth (Bork et al., 1998). Kachanoski et al. (1988) were among the first to evaluate the potential of EMI measurements to indirectly estimate SWC. They found that EC_{app} measured with EMI could explain between 77% and 96% of the variability of SWC with linear and second order polynomial models. Calamita et al. (2015) conducted an extensive review of the most relevant studies that investigated EMI as a tool to

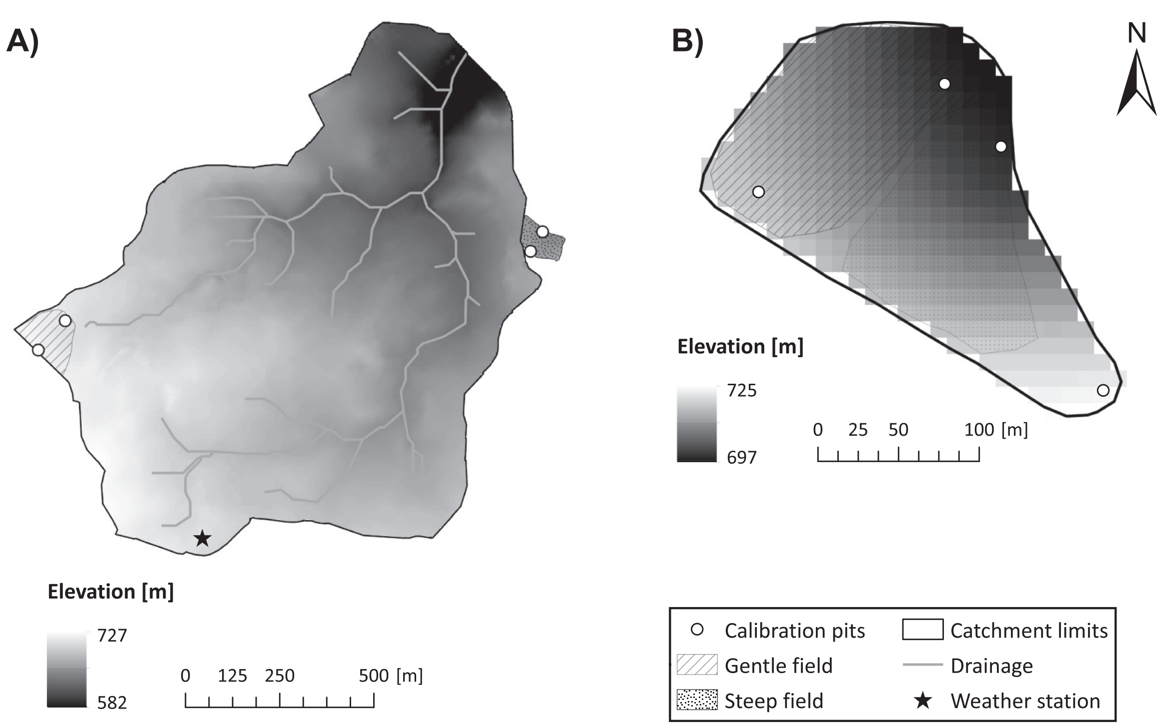

Fig. 1. Detailed overview of A) the Arvorezinha catchment and B) the Ilopolis catchment.

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