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Monitoring and modelling soil water dynamics using electromagnetic conductivity imaging and the ensemble Kalman filter

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ABSTRACT

Understanding the soil water (θ) dynamics is important in irrigated agriculture. Due to the labour-intensive nature of determining θ, non-invasive electromagnetic (EM) induction techniques have been used. However, predicting depth-specific θ is a challenge because EM instruments measure the integral depth of the soil's apparent electrical conductivity (EC_a). Recently, "true" electrical conductivity with depth produced by inverse modelling of EC_a has been employed to establish empirical models of θ. However, the potential to combine empirical models with soil physical models using data assimilation such as ensemble Kalman filter (EnKF) has not been explored. Along a 480-m transect with varying soil texture profiles, repeated EC_a data were collected using a DUALEM-421S on 20 days over a 40-day period. A quasi-2d inversion algorithm was used to convert the temperature corrected EC_a data to σ. An empirical model (artificial neural network) that predicted θ was calibrated using σ values, elevation, and topographic wetness index, as well as the mean and range of σ for each depth and each site over the whole study period. A physical soil-water tipping bucket model was also constructed using θ measured by soil moisture sensors. Afterwards, the EnKF approach was applied to 8 profiles along the transect separately combining both the empirical and the physical models. The results with the EnFK modelling (Lin's concordance = 0.89) were superior to the physical model and superior or equivalent to the empirical model for loam, clay and duplex soil profiles. In order to improve the prediction of θ dynamics, a more robust physical model could be used. In addition, correction of the diurnal effects of EC_a data and redefining the model and measurement errors of the EnFK to account for the temporal dependence should be considered.

1. Introduction

In order to improve water use efficiency, knowledge of the spatio-temporal variation in the volumetric water content (θ) in a soil profile and across a field is essential. In order to measure and monitor θ and for the purpose of precision irrigation (Sadler et al., 2005), various instruments have been developed for in-field installation, including; neutron- (Kodikara et al., 2013) and capacitance-probes (Fares and Alva, 2000), time-domain reflectometry (Wraith et al., 2005) and wireless soil moisture sensor networks (Bogena et al., 2010; Martini et al., 2015). However, most of these instruments only monitor θ in a soil profile and a large number of instruments need to be installed to effectively monitor θ dynamics across larger spatial extents. Alternatively, θ dynamics can be modelled using process-based models. However, these require a large number of hydraulic parameters (e.g., field capacity) which vary spatially in a field (Burns, 1974; Littleboy et al., 1992; Vereecken et al., 2016).

To add value to the limited information that can be collected (i.e., θ), non-invasive electromagnetic (EM) induction instruments are increasingly being used (Doolittle and Brevik, 2014). Among the first to apply EM to measure θ were Kachanoski et al. (1988) who observed a linear relationship between apparent soil electrical conductivity (EC_a) and average θ. Subsequently, Sheets and Hendrickx (1995) found a similar regression between EC_a and θ to a depth of 1.5 m along a transect with homogeneous soil texture. Sherlock and McDonnell (2003) were also able to map θ to a depth of 0.2 m across a hill slope of loamy soil. More recently, Hedley et al. (2013) monitored θ across an irrigated sandy field to a depth of 0.5 m. Instead of using EC_a data alone and as measured using EM38 and EM31 instruments, they incorporated other available information including elevation and rainfall data. Most recently, Stanley et al. (2014) explored the potential to establish linear regression models to predict average (0–0.5 m) θ using EC_a data collected at multiple heights across a 96-ha field with predominantly heavy clays (Vertosols – Isbell, 2002).

Although EC_a data has been successfully used to characterise the spatio-temporal variation in average θ to a certain depth of soil, few researchers have successfully predicted depth-specific θ. This has mainly

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been because EC_a data is the integral of electrical conductivity measured by the instrument to a certain depth of soil (i.e., depth of exploration – DOE), which is not readily comparable to depth-specific θ or other properties, including clay, salinity and bulk density (Corwin et al., 2003). Given the different measuring support between EM and discrete soil samples, EC_a data combined with inverse modelling has recently been used to estimate the true electrical conductivity (σ), and successfully used to map soil properties at different depths; including clay content (Triantafilis and Monteiro Santos, 2009), exchangeable sodium percentage (Huang et al., 2014) and salinity (Zare et al., 2015). Recently, inversion of EC_a data measured by a multi-array DUALEM-421S has shown potential to monitor θ dynamics over 12 days after an irrigation event along a 350-m transect with homogeneous loamy soil (Huang et al., 2016). However, it remains a challenge whether the approach is applicable in a field with varying soil texture. In addition, although the DUALEM instrument has been increasingly used for various purposes, the diurnal temperature effects of the instruments on EC_a measurements have not been explored.

Given the fact that EC_a data is a function of various soil properties, methods to better account for the interrelationships between EC_a and soil properties are required. Advances in data assimilation theory have enabled researchers to better understand such dynamics by merging the information from uncertain environmental covariates and uncertain model predictions (Errico et al., 2000). One approach is to use the Kalman filter and the derived Ensemble Kalman filter (EnKF). The techniques have been used in hydrology and soil science (Wendroth et al., 1999; Reichle et al., 2002; Vrugt et al., 2005; Heuvelink et al., 2006; Li et al., 2012). The objectives of this study were to collect DUALEM-421S EC_a along a transect of differing soil types to: 1) study the diurnal effects of EC_a; 2) apply a correction based on soil and ambient temperatures to EC_a; 3) establish an empirical calibration model between estimates of true electrical conductivity (σ) and θ considering the mean and range of σ as well as elevation and topographic wetness index (TWI); 4) establish a physical model for predicting θ dynamics considering a tipping bucket model; and, 5) combine the empirical calibration model with a physical model using the ensemble Kalman filter.

2. Materials and methods

2.1. Study site

The study field was located north of the Nepean River near Cobbitty, New South Wales, Australia (34° 01′ 22.86″ S, long. 150° 39′ 54.96″ E). It was located on an experimental farm of the Plant Breeding Institute of The University of Sydney (Fig. 1). The field was cropped with lucerne (*Medicago sativa* L.). The climate was temperate with mean annual maximum and minimum temperatures of 23.7 and 10.2 °C, respectively, with mean annual precipitation of 789 mm (BOM, 2016a).

The study transect was approximately 480 m long and located on the western edge of the field (Fig. 1). Irrigation in the field was supplied by sprinklers located approximately on transects spaced 30 m apart (north–south) and the same distance along each transect (east-west). As shown in Fig. 5a, the topography varied along the transect with elevation highest at the northern end (~61.2 m) and lowest close to the centre (~58.0 m), before rising again to an intermediate height at the southern end and near the Nepean River.

2.2. DUALEM-421S configuration

The DUALEM-421S (DUALEM Inc., Milton, ON, Canada) simultaneously measures apparent electrical conductivity (EC_a, mS m^{-1}) to six different depths. It consists of a transmitting coil (Tx) that operates at 9.0 kHz and three pairs of receiver coils (Rx). The Tx and one Rx pair have horizontal windings which form a horizontal coplanar array (HCP). The distance between the Tx to the coplanar Rx are 1, 2, and 4 m. The notation 1mHcon, 2mHcon, and 4mHcon represent EC_a and correspond to depths of exploration (DOE) of 1.5, 3.0, and 6.0 m, respectively. The other coils in each Rx pair have vertical windings and with the Tx forms perpendicular arrays (PRP). The distances between the Tx to the Rx are 1.1, 2.1, and 4.1 m, respectively. The respective EC_a measurements are represented by 1mPcon, 2mPcon, and 4mPcon with DOE corresponding to approximately 0.5, 1.0, and 2.0 m depth, respectively. The DUALEM-421S also has a built-in sensor which measures the internal temperature of the instrument and a temperature compensation system which corrects the drift in EC_a measurements.

2.3. Irrigation and rainfall events

The experiment lasted for approximately 40 days, from 17:00 h on 9 December 2015 to 16:00 h on 26 January 2016. The first and only day of irrigation was carried out from 17:00 h on 9 December 2015 to 11:40 h on 11 December 2015. The irrigation water was alternately applied to the northern and southern halves of the field, which ensured both halves received the same amount of water. In all, approximately 21 h and 40 min of water was applied and amounted to 68 mm of irrigation water. The daily rainfall data from a local weather observation station (BOM, 2016b), which was located 2.8 km away (i.e., Camden Airport), were obtained and used to understand the amount of rainfall and model evapotranspiration.

2.4. EC_a data collection

Soil EC_a data were measured along the transect using a DUALEM-421S. The DUALEM-421S was mounted on a PVC sled, ~2 m behind a 4WD vehicle to avoid interference with the instrument's response. A Trimble GPS was installed at the centre of the sled. The height of the DUALEM-421S sensor above the ground surface was 0.4 m. This was in accord with Triantafilis and Monteiro Santos (2010) and Huang et al. (2015), who both achieved optimal results for predicting soil salinity when the EMI instrument was placed at this height. Travel speed from north to south was ~5 km/h, with each run taking 5 min to complete.

The first EC_a survey was carried out before irrigation at 17:00 h on 9 December 2015. After 1 h and 20 min (18:20 h on 9 December 2015), a second EC_a survey was conducted. The third and fourth EC_a surveys were taken at 10:00 h on 10 December 2015 and 11:40 h on 11 December 2015, in the middle and at the end of the irrigation, respectively. Subsequent EC_a surveys were carried out at 8:00, 10:00, 12:00, 14:00 and 16:00 h on a daily basis from 11 December 2015 to 17 December 2015 and at the same time of the day every 3 or 4 days between 17 December 2015 and 26 January 2016. During each DUALEM-421S survey, the ambient temperature was also recorded using a thermometer. It was noted that repeated EC_a surveys conducted on the same days would be used to study the diurnal effects of the DUALEM-421S while only 20 EC_a surveys (mostly collected at the same time of the day) would be used for modelling θ dynamics over the whole study period.

2.5. Soil moisture sensors installation and soil samples collection

To calibrate the DUALEM-421S readings with θ, 8 sites were selected (see Fig. 1 and Fig. 2) and spaced approximately 60 m apart. For reference, sites 1 and 8 were located at the northern and southern ends, respectively. At each of the sites, a pit was dug with Decagon sensors installed at depths of 0.15, 0.45, 0.75, 1.05 and 1.35 m, respectively. The depths were chosen based on previous work in loam soils (Huang et al., 2016). Except for site 5, Decagon GS3 ruggedized soil moisture, temperature and EC sensors (Decagon Devices, Inc., WA, USA) were installed with measurements made every 5 min. At site 5, Decagon GS1 soil moisture sensors (Decagon Devices, Inc., WA, USA) were installed, which only measured θ. We also note that only 4 GS3 sensors were installed at site 3 and to a maximum depth of 1.05 m.

At the 8 selected sites, soil samples were also collected. The soil samples were sealed in plastic bags and taken to the laboratory for further