Journal of Hydrology 391 (2010) 24–33

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Estimation of spatio-temporal variability of soil water content in agricultural fields with ground penetrating radar

Y.G.N.S. Wijewardana, L.W. Galagedara *

Department of Agricultural Engineering, University of Peradeniya, Peradeniya, KY 20400, Sri Lanka

ARTICLE INFO

Article history:
Received 18 October 2009
Received in revised form 7 April 2010
Accepted 27 June 2010

This manuscript was handled by Philippe Baveye, Editor-in-Chief, with the assistance of Magnus Persson, Associate Editor

Keywords:
Ground penetrating radar
Volumetric soil water content
Irrigation
Trans ZOP
Trans MOG

SUMMARY

Efficient water management, crop yield variability estimation and prediction of contaminant transport require some measurement of soil water content variation through time and space. This study focused on the estimation of spatio-temporal variability of volumetric soil water content ($\boldsymbol{\theta_v}$) in raised bed agricultural fields using ground penetrating radar (GPR), comparison of GPR method with gravimetric sampling data and development of 2D maps of $\boldsymbol{\theta_v}$. The GPR system (pulse EKKO Pro) with 200 MHz antennas was used to collect data on approximately 1.0 m wide and 13.0 m long raised beds of about 0.1 m height cultivated with vegetables. Transillumination Zero Offset Profile (Trans ZOP) and Transillumination Multiple Offset Gather (Trans MOG) GPR survey modes which are classically used as borehole GPR method were employed as a surface GPR method. In each of these survey modes, the direct ground wave travel time was measured. The $\boldsymbol{\theta_v}$ at each Trans ZOP and Trans MOG location was calculated by first converting the electromagnetic (EM) wave velocity into soil dielectric permittivity and then to $\boldsymbol{\theta_v}$ using a standard empirical relationship. The results revealed that the spatio-temporal variability of $\boldsymbol{\theta_v}$ in raised bed agricultural fields could be estimated using the Trans ZOP and Trans MOG GPR survey modes. The GPR estimated $\boldsymbol{\theta_v}$ and gravimetrically measured soil water content ($\boldsymbol{\theta_g}$) were not significantly different ($P = 0.272$). The correlation coefficient was 0.87, the root mean square error was 0.0184 m^3/m^3 and the average error was 0.20% between the two methods. The Trans MOG survey data allowed us to create plan view maps (2D) of the $\boldsymbol{\theta_v}$ variation which could not be obtained from the Trans ZOP data. No statistical difference ($P = 0.053$) was found between the Trans ZOP and average Trans MOG values.

1. Introduction

As far as agriculture is concerned, soil water content (SWC) variation in the vadose zone is very important in applications such as field water balance, vegetation growth, nutrients absorption and contaminant transport. Agronomists and farmers need information about SWC variation both in spatial and temporal scales in the cultivated areas to manage irrigation practices efficiently. Measurement of SWC variability is complicated due to soil heterogeneity and various environmental variabilities. No single efficient method has been developed to map high or low soil moisture zones at the field scale without disturbing the soil and water flow paths (Galagedara, 2003). Rapid assessment and monitoring of SWC over large areas is therefore necessary in order to achieve efficient water management at field scale. SWC monitoring is also important for addressing issues of water quantity and quality, both relevant for managing the environmental impacts of irrigated agriculture and for protecting functional ecosystems. Rubin (2003) highlighted the importance of SWC in rational water resources management, optimizing crop yields, improving irrigation efficiencies and planning irrigation scheduling.

Gravimetric, Time Domain Reflectometry (TDR), neutron scattering and capacitive sensors are common methods to measure SWC variability. The gravimetric method is considered to be a standard. However, all these methods are inefficient in providing large-scale rapid data collection and most of them are restricted to point scale measurements. Ground Penetrating Radar (GPR) has a couple of advantages over TDR as it measures a larger sample volume, and surface GPR is a completely non-intrusive method (Galagedara et al., 2003a, 2005a,b; Huisman, 2002; Huisman et al., 2003; Takeshita et al., 2004).

GPR is a high-resolution geophysical technique that utilizes the transmission and reflection of high frequency (10–1200 MHz) electromagnetic waves. It has been widely used to map subsurface structure during last 2–3 decades (Davis and Annan, 1989, 2002). Huisman et al. (2003) describes many GPR methodologies that can be used to estimate SWC. The GPR method provides the ability to cover large areas efficiently, which cannot be obtained from other methods. By employing Fixed Offset/Common Offset survey

---

* Corresponding author. Tel.: +94 81 239 5468; fax: +94 81 239 5454.
E-mail address: lgalaged@pdn.ac.lk (L.W. Galagedara).

0022-1694/$ - see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhydrol.2010.06.036

mode and utilizing the travel time of the direct ground wave (DGW), one can estimate the spatial variability of SWC over a large area comparatively rapidly (Du and Rummel, 1994; Grote et al., 2003; Huisman et al., 2001; Schmalholz et al., 2004; van Overmeeren et al., 1997).

Lunt et al. (2005) studied the accuracy of the Common Offset surface GPR reflection method for mapping spatially variable SWC, over space and time and under naturally heterogeneous conditions. In other studies during the last decade, the surface GPR method has been tested for field applications and modeling for estimating spatial and temporal SWC variation elsewhere in the world (Galagedara et al., 2005b; Hubard et al., 2002; Huisman et al., 2001; Lambot et al., 2008, 2009; Schmalz et al., 2002; Steelman and Endres, 2008). The difficulty in field applications of the GPR-DGW method in heavier textural soils have also been documented (Davis and Annan, 1989, 2002; Du and Rummel, 1994; Huisman et al., 2003; Weihermüller et al., 2007). This is mainly due to the strong attenuation of the GPR signal and difficulties in identifying the DGW.

In addition to the surface GPR method, borehole GPR (Galagedara et al., 2003b; Parkin et al., 2000; Rucker et al., 2002) and surface reflectivity method (Chanzy et al., 1996; Redman et al., 2002) were used for volumetric soil water content (θ_v) estimation both spatially and temporally. However, there are only few studies conducted elsewhere in the world to test the applicability of Transillumination Zero Offset Profile (Trans ZOP) and Transillumination Multiple Offset Gather (Trans MOG) survey modes as a surface GPR method especially in crop fields.

The estimation of the spatio-temporal variability of θ_v in raised bed agricultural fields using the Trans ZOP and Trans MOG survey modes (generally these two survey methods are used as borehole survey methods in θ_v estimations) as a surface GPR method is the main task of the experiment described in this paper. Specific objectives of this study are: (i) to estimate the spatio-temporal variability of θ_v in agricultural fields under different crops with Trans ZOP GPR, (ii) to compare the GPR estimated θ_v with gravimetrically measured values and (iii) to develop a two-dimensional θ_v map for the cultivated area using a Trans MOG survey mode.

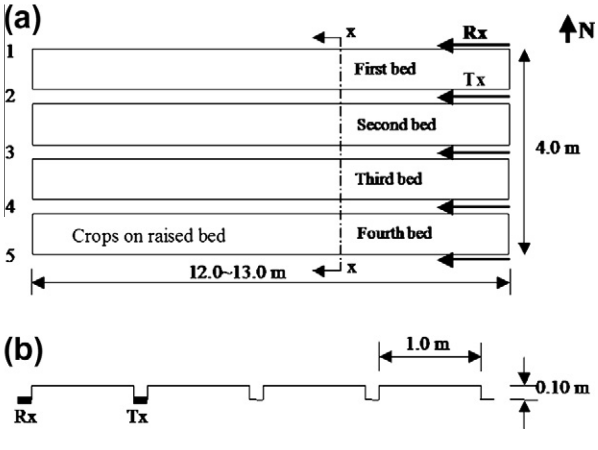

Fig. 1. Schematic diagram of the experimental area with five drains which are also used as survey lines (numbers 1, 2, ..., 5). (a) Plan view; (b) cross sectional view at x–x; Tx – transmitter antenna; Rx – receiver antenna. The transmitter and receiver antennas are shown deployed in drains 1 and 2.

2. Materials and methods

2.1. Study area

This experiment was conducted at the farm of the In-Service Training Institute (ISTI), Department of Agriculture, Gannoruwa, Peradeniya (7° 16N, 80° 36E), Sri Lanka. The area was cultivated with different vegetable crops such as cabbage, beet, intercropped capsicum-radish and chilli. The beds were ~1.0–1.2 m wide, 12–13 m long and were relatively flat with 0.10 m drains alongside each bed (Fig. 1). The crops were planted on the raised bed and the crop rows (length of the bed) were oriented from east to west as shown in Fig. 1.

2.2. Soil properties at the field site

The major soil group in this study site is Red–Yellow Podzolic and basic soil physical properties of the site were measured using standardized laboratory procedures after collecting undisturbed soil samples just outside the cultivated area, from three different depths with two replicates. Basic soil properties measured for the study site are given in Table 1. According to the USDA textural triangle, the soil types are Sandy Clay, Clay and Clay for layers 1–3, respectively (Table 1). Porosity and saturated hydraulic conductivity values are more or less similar in three layers, even though the soil dry bulk density is slightly higher in the top layer. This higher bulk density could be due to the compaction effect in the farm. However, the dry bulk density in raised beds is slightly lower compared to outside the raised beds due to frequent disturbance during cultivation.

2.3. Data acquisition and analysis

A GPR system (pulse EKKO PRO) with 200 MHz antennas (200 MHz was the available one) was used to collect Wide Angle Reflection and Refraction (WARR), Trans ZOP and Trans MOG survey data. In each of these survey modes, the direct DGW travel time of the GPR waves was measured. The velocity of DGW (V_{DGW}) at each measuring location was calculated by dividing the antenna offset (L) by the absolute travel time (t_{ab}) of the DGW (refer to Eq. (5)) as shown in Eq. (1);

$$V_{DGW} = L/t_{ab} \tag{1}$$

V_{DGW} was converted into dielectric permittivity (K_r) using the speed of light c in free space (Eq. (2));

$$K_r = (c/V_{DGW})^2 \tag{2}$$

Table 1
Soil physical properties at the test site.

Soil depth (cm)	Sand (%)	Silt (%)	Clay (%)	OM[a] (%)	Porosity (%)	BD[b] (g/cm^3)	Ks[c] (m/s)
Layer 1: 0–15	47.9	10.8	41.3	1.01	43.0	1.60	3.85E−07
Layer 2: 15–30	42.4	7.5	50.1	1.00	46.0	1.41	3.54E−07
Layer 3: 30–40	40.0	7.9	52.1	1.01	47.0	1.34	2.68E−07

[a] Organic matter.
[b] Dry bulk density.
[c] Saturated hydraulic conductivity.