Estimating the Volumetric Soil Water Content of a Vegetable Garden using the Ground Penetrating Radar

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Abstract- Monitoring of soil water content (volumetric water content, VWC) is an important process in agricultural and ecological programs, and a vital process in flood and water resource management. There are several methods in estimating VWC but often these are time consuming, invasive and expensive. This paper investigates the applicability of a surface based geophysical technique, Ground-Penetrating Radar (GPR), for estimating the VWC in shallow soil (top 0.30 m of soil subsurface). The guided wave sounding, GWS, technique (an invasive application of the GPR technique) was used on a vegetable garden located at latitude 6.67 and longitude -1.56, south of the College of Engineering, KNUST, Kumasi, Ghana. The MALÅ ProEx GPR equipment using shielded antennae with a central frequency of 800 MHz was used for the measurements. The result showed that, on the average, the VWC at the top soil (0.065 m) containing humus was high (0.12 m^3m^{-3}) as compared to depth 0.295 m (0.10 m^3m^{-3}). Thus, the topsoil held more water than the soil beneath due to the presence of the organic humus layer. The cabbage planted which had an average root depth of 0.30 m was found to be good for the area. Comparing GWS-derived soil water content data with the gravimetric soil water sampling yielded a root mean square deviation of ±5%. Our research shows that the GWS technique offers a good, reliable, and relatively easy to use geophysical approach for estimation of shallow soil water content

Index Terms- Electromagnetic wave, Geophysical technique, GPR, Guided Wave Sounding (GWS), Volumetric Water content (VWC)

I. INTRODUCTION

Soil moisture content (volumetric water content, VWC) information is needed for studies across a variety of disciplines, such as hydrology, soil science, ecology, meteorology and agronomy. The accuracy and resolution of soil moisture estimates depend on the particular application and associated spatial scale of interest. The information obtained from monitoring is critical for optimizing crop yields, achieving high irrigation efficiencies, planning irrigation scheduling, and minimizing lost yield due to waterlogging and salinization. Such water content 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.

Direct and indirect methods can be used to determine the volumetric water content of soils. The direct methods consist essentially of drying and weighing a known volume of a soil sample (gravimetric soil sampling method). The indirect methods are based on the correlation of certain physical and physicochemical properties of the soil with its water content (Schlaeger et al., 2005). The guided wave sounding (GWS) survey (which is an indirect method) is an invasive application of the GPR technique in a mode similar to that of the conventional time domain reflectometry (TDR). This (GWS) method records the VWC by making use of the two-way reflection time data from the lower end of a metal rod which is lowered into the soil by constant increments through a vertical access tube or pipe (Preko and Wilhelm 2006).

There are several methods such as time domain reflectometry (TDR), frequency domain sensor, neutron probe and gravimetric method for measuring VWC but often these are time consuming, invasive and sometimes expensive. GPR which seems to overcome these challenges also have some shortfalls which introduce some errors in the measurements (Preko et al., 2009). The main reason as to why GPR techniques are not commonly used lies in the difficulties which accompany the determination of the travel time of the unguided wave. Hence, the application of guided wave sounding (GWS) survey (where additional provision is made for the easy reflection of the transmitted wave) overcomes these difficulties making the GWS technique an alternative for estimating the volumetric water content (Preko et al., 2009).

In the GWS method, a signal is sent down steel probes (wave guide), buried in the soil. The transmitted signal is reflected back from the end of the probe to the receiver due to dielectric contrast between the end of the waveguide and the surrounding. The travel time of the signal depends on the type of soil, its electrical properties and the water content. Guided wave sounding has a number of applications. For example, deep seated hydrocarbon accumulations have been successfully detected through guided wave sounding from active electromagnetic sources (Johansen et al 2005). Other applications of guided waves include the detection of fractures and defects (example Olsson et al 1992), location of underground tunnels and interpretation of geologic features.

This paper focuses on the applicability of the GWS technique in estimating the water content in the upper 0.30 m depth of a vegetable farm. The waveguide used here comprised a metal conductor embedded in a dielectric which was principally a sandy loam soil.

II. BACKGROUND OF GPR

GPR is a geophysical technique that uses electromagnetic energy with central frequencies generally between 50 and 1200

MHz to image the subsurface. Electromagnetic energy propagates the soil from a transmitting antenna, and is modified by subsurface contrasts in dielectric permittivity (ε_r) and magnetic permeability (μ). Part of the electromagnetic energy, the airwave, passes directly from a transmitting to receiving antenna through the air. Another part the ground wave travels between the air-ground interfaces beneath ground surface and still another part is reflected back to the receiving antenna primarily due to vertical differences in the dielectric properties of the soil (Davis and Annan 1989).

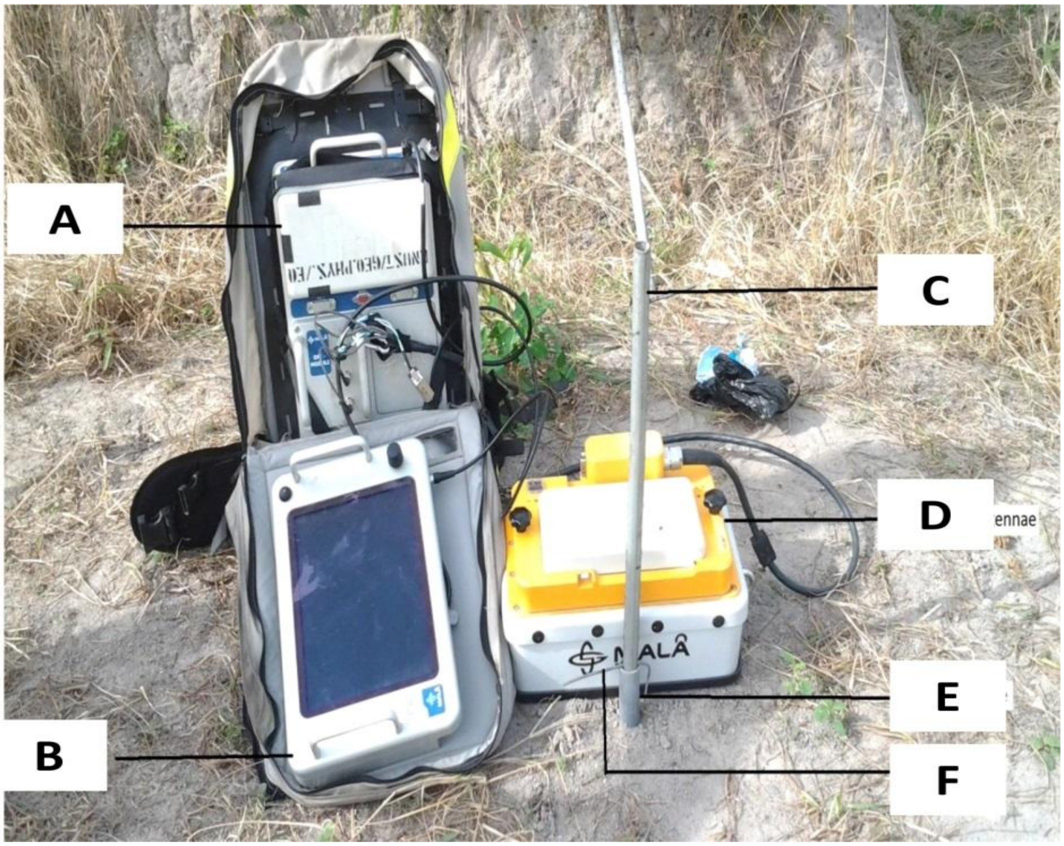

Figure 1. MALÅ ProEx GPR equipment with an 800 MHz Shielded antenna (A – Console B–Monitor C – Metal rod D - 800 MHz Shielded antenna E - PVC access tube F-Stopper)

The electromagnetic wave velocity propagation in subsurface, v is connected to the dielectric constant of the subsurface, ε_r by Maxwell's relation for low media (Scheuermann et al., 2001) by

$$v = \frac{c}{\sqrt{\varepsilon_r}} \qquad (1)$$

where c is the electromagnetic wave velocity in free space

By knowing the travel path length of the radar wave-front, the electromagnetic wave velocity can be estimated from the two way travel time, (TWTT) of the reflected wave. From equation 1, the velocity (v) of the soil can be related to ε_r.

Petrophysical relationships, either developed for specific soils in the laboratory or with appropriate mixing rules can then be used to relate the permittivity to the soil water content. In the present study, the third-degree polynomial equation by Topp et al., (1980) was used to estimate the VWC from the relative dielectric permittivity ε_r (equation 2) i.e.

$$\mathrm{VWC} = -5.3\times10^{-2} + 2.92\times10^{-2}\varepsilon_r - 5.5\times10^{-4}\varepsilon_r^{\,2} + 4.3\times10^{-6}\varepsilon_r^{\,3} \qquad (2)$$

III. METHODOLOGY

Study Area

The experiment was performed on the vegetable garden located at latitude: 6.67 and longitude: -1.56 south of the College Engineering, KNUST, Kumasi, Ghana (figure 2).

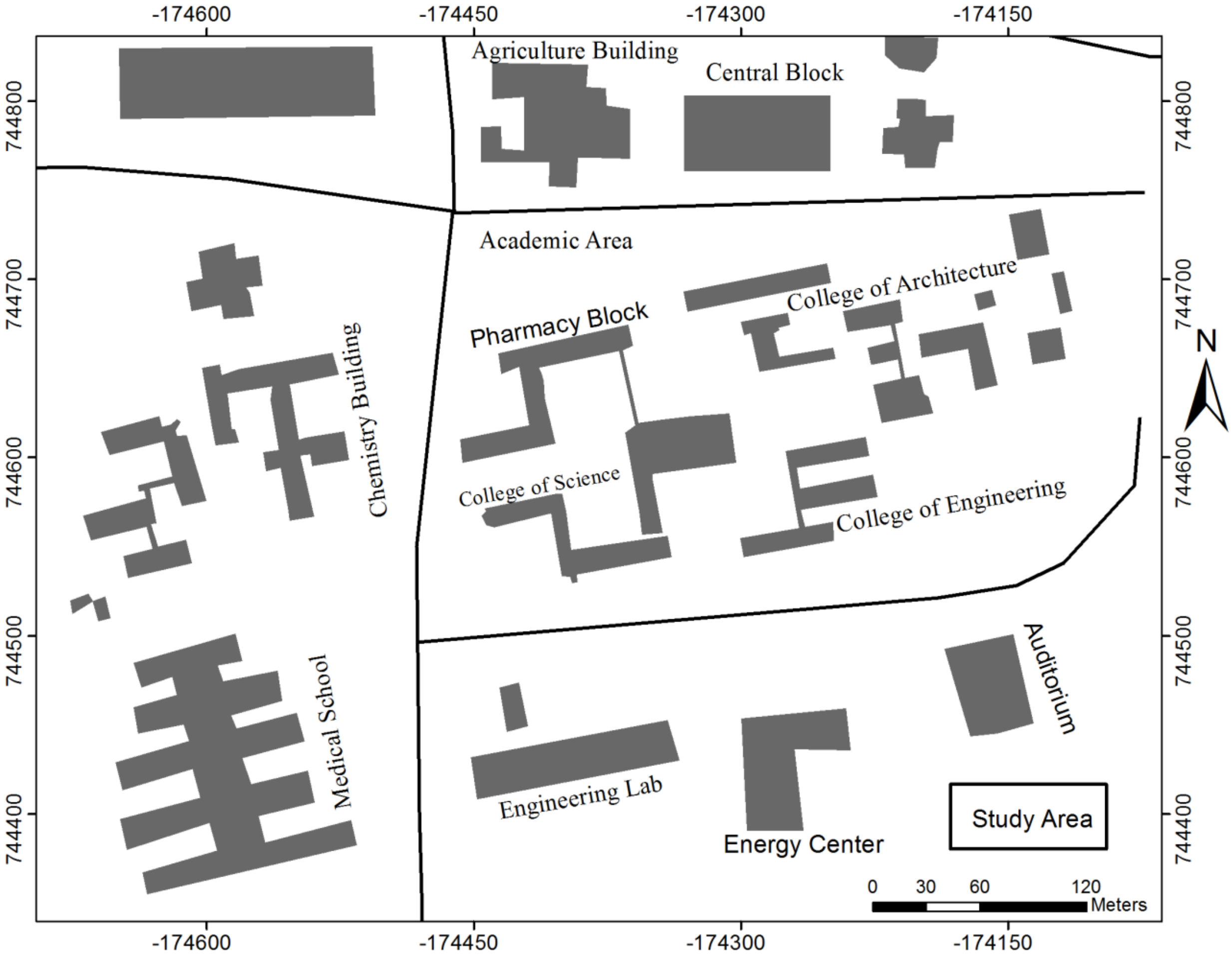

Figure 2 Map of KNUST, Kumasi showing the study area

The study site figure (3a) was mainly used to cultivate lettuce, cabbage and onion which have shallow root zone depth range of 0.05 – 0.4 m. This study site was chosen because of variations in vegetable crop vigour within the areas of identical rootstock might be controlled by natural heterogeneity in soil texture and associated VWC.

IV. DATA ACQUISITION

GWS method

Borehole was augured to a depth of 0.5 m below ground surface and cased with 22 mm external diameter PVC pipe of 0.5 m in length. This was used as an access tube for the metal rod. It was ensured that the contact between the access tube and the soil was very good to avoid errors in the VWC readings (figure 4).

Figure 3: Picture showing (a) the study area and (b) observers in the field

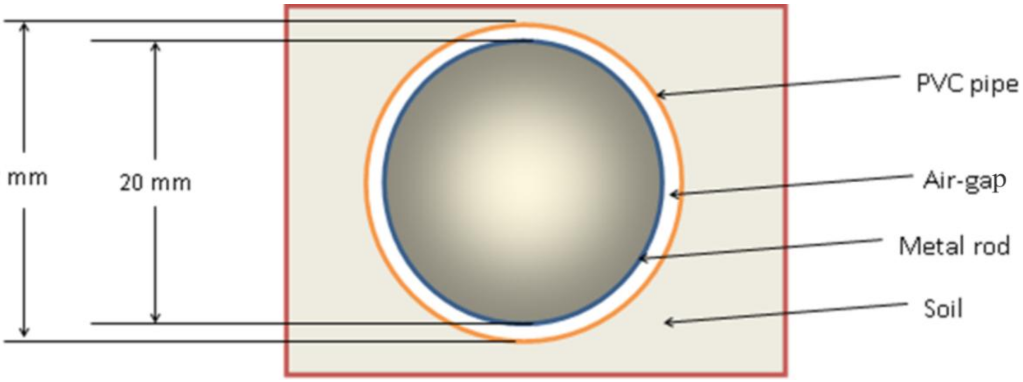

Figure 4 Cylindrical soil model with a metal rod of radius 10 mm at the centre surrounded by a thin air pocket

Precipitation data over the period of measurement was taken from agrometeorological station which is 1.5 km away from the study area. The MALÅ ProEx ground penetrating radar (GPR) equipment with shielded monostatic antenna of central frequency of 800 MHz manufactured by MALÅ Geoscience was used for the measurements (figure 1).

These measurements were taken with the help of a vertical access tube pre-installed into the soil (figure 3b). This served as a passage for a metal rod of about 0.4 m in length and with an external diameter of 20 mm graduated at 1 cm intervals. The air gap between the metal rod and the PVC pipe was very small to minimize measurement errors. The 800 MHz shielded antenna was positioned close (approximately 1 cm) to the access tube with the metal rod midway between the receiver and transmitter. This position was maintained throughout the experiment. Measurements were taken with the metal rod lowered into the access tube at intervals of 1 cm. Guided waves travelling along the metal rod were reflected from the lower end of the rod to the receiving antenna by reason of the impedance contrast between this end and the medium below it (Figure 5).

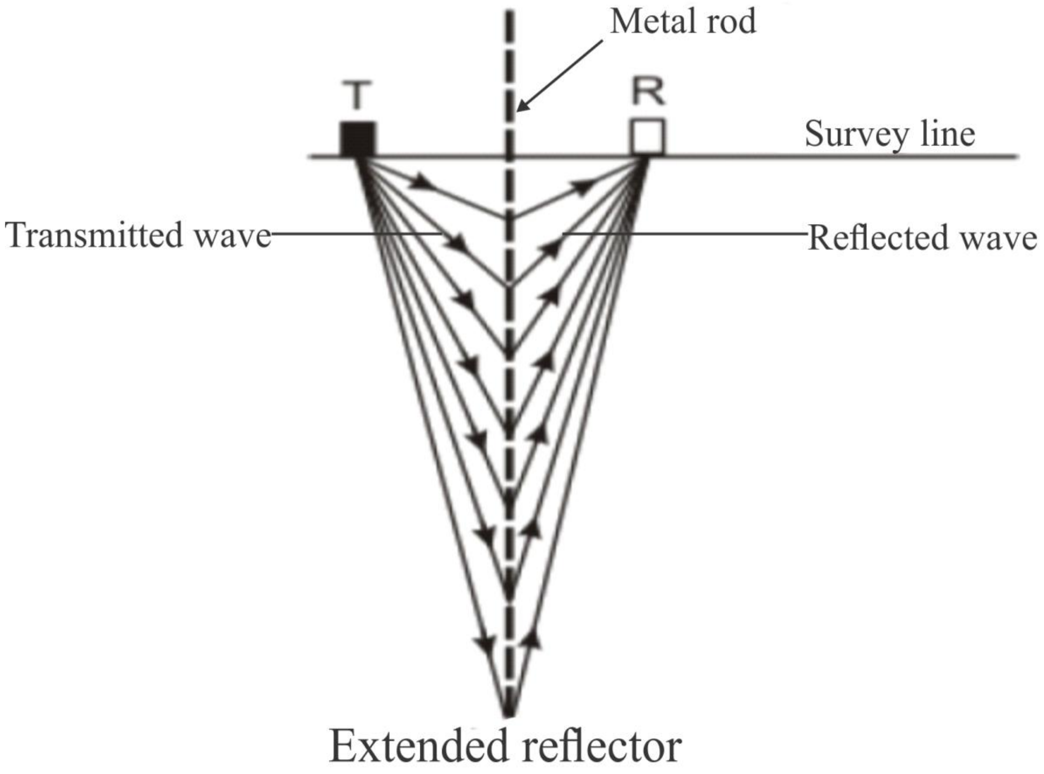

Figure 5 Schematic diagram showing reflected waves from the end of the metal rod (T-Transmitter antenna R- Receiver antenna)

When the rod was lowered down from the depth d_i to the depth d_f, the interval velocity $v_{i,f}$ was calculated from the difference in the guided wave travel times t_i and t_f, and the interval depth $d_f - d_i$ by

$$v_{i,f} = \frac{2(d_f - d_i)}{t_f - t_i} = \frac{2d}{t} \qquad (3)$$

where *i* and *f* are the initial and final respectively

Interval velocities calculated with equation (3) were very sensitive to the position and times of the reflection picks. In order to reduce processing errors in $v_{i,f}$, running harmonic mean values of three interval velocities were calculated by equation 4;

$$H = \overline{v} = \frac{1}{g_i \sum_{k=1}^{n} \frac{s_k}{v_k}} \qquad (4)$$

where $g_i = \left(\sum_{i=1}^{n} s_i \right)^{-1}$, s_i = total distance between arbitrary points, v_i interval velocities, *n* is the number of interval and *H* is the harmonic velocity. The harmonic mean velocity was then related to the permittivity of the soil with equation (1) and subsequently VWC was calculated with the Topp et al (1980) equation. Further similar measurements were taken with this method over a period of 14 days.

V. GRAVIMETRIC SOIL SAMPLING METHOD

Soil samples between depth range of 0.02 m to 0.16 m (0.02 m interval) were taken in crucibles and oven dried at 105°C for 24 hours to measure the gravimetric water content θ_m [g/g]. This water content which is generally used as a standard was converted into volumetric water content by the equation 5 (Black, 1965) and comparison with the GPR-derived VWC yielded a root mean squared deviation (RMSD) of ± 5%.

$$\text{VWC} = \theta_m \frac{\rho_s}{\rho_w} \qquad (5)$$

where θ_m is Gravimetric water content, ρ_w is density of water and ρ_s density of sampled soil.

VI. DATA PROCESSING

GPR data were processed with Reflexw software (Sandmeier, 2011). Each observation from the end of the metal rod at a given depth comprised a minimum of 10 traces. A complete survey from the top to the base of the metal rod comprised 36 observation points. Traces from each observation point were first stacked into a single trace and stored as a file.

Subsequently, all 36 files were merged into a single radargram (figure 6a). Static errors were corrected for and *background removal* and *f–k filtering* (Yilmaz, 1987) were done to remove steeply dipping diffraction hyperbolae tails arising from the 1 cm-interval graduation holes drilled in the metal rod. *Band pass Butterworth* filter with a lower cut-off of 266 MHz and an upper cut-off of 1066 MHz was applied to remove low- and high frequency noise in the data. All these processing steps were aimed at increasing the signal-to-noise ratio.

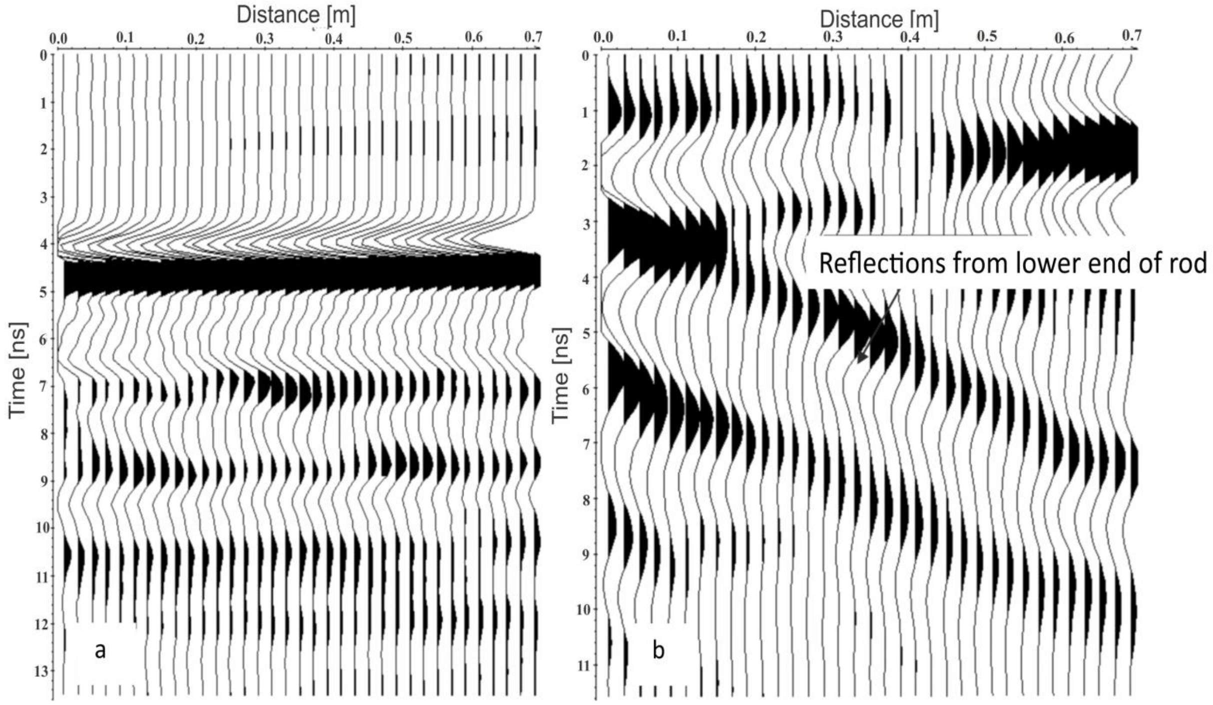

Figure 6 Data processed; (a) after stacking and merging (b) after background removal, bandpass frequency, dynamic correction, static correction and fk filter

Zero-crossing distance–time picks from the radargram (figures 7) were loaded in an ASCII-format and the parameters for estimating the interval velocities extracted.

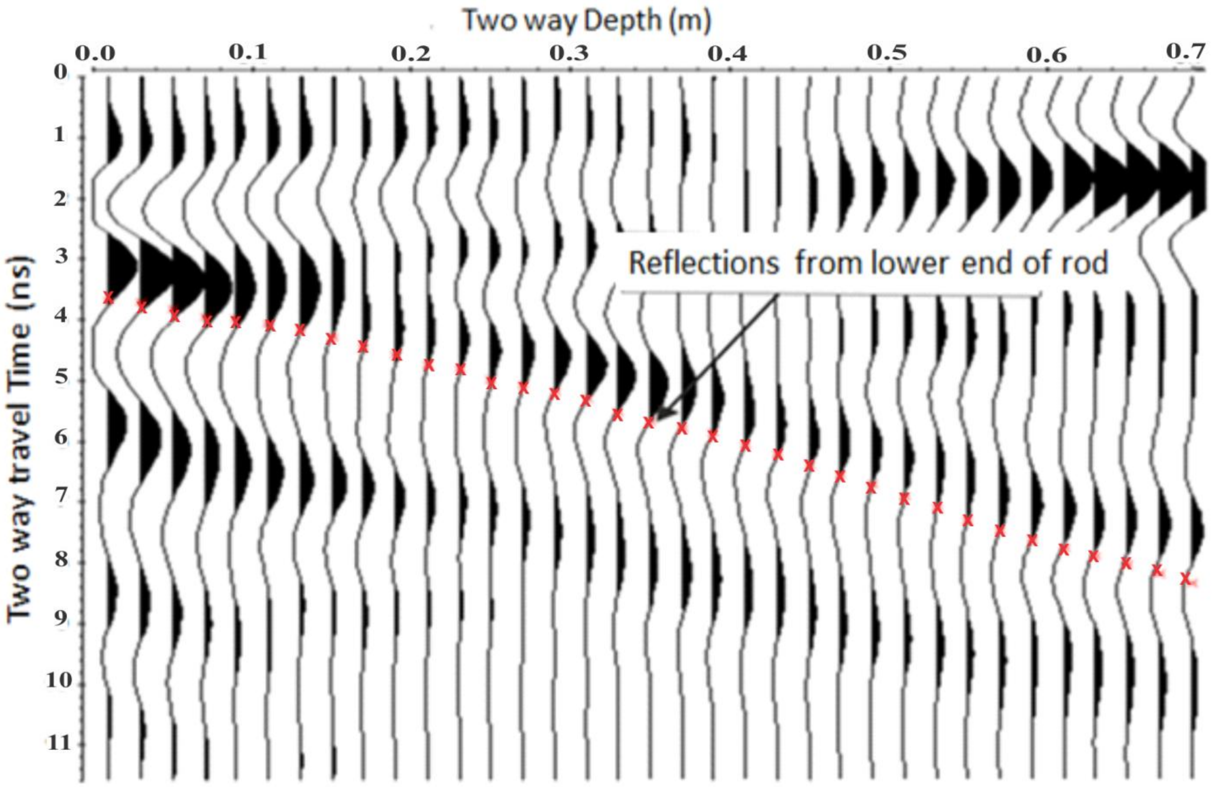

Figure 7 Radargram from GWS survey. Picks are represented by red points

Equation (2) was used to calculate the corresponding relative dielectric permittivity and Topp *et al* (1980) equation (3) was eventually used to determine the VWC. Table 1 shows a table of how a day's VWC was calculated.

Table 1: Steps (from left to right) towards the calculation of VWC

Two way Depth [m]	Two way travel time [ns]	Interval Depth [m]	Interval Velocity [m/ns]	Harmonic Velocity [m/ns]	Dielectric Constant	VWC $[m^3m^{-3}]$ (using Topp's model)
0.050	3.820	0.080	0.149	0.136	4.850	0.076
0.130	4.156	0.020	0.149	0.124	5.822	0.099
0.150	4.290	0.040	0.112	0.116	6.746	0.120
0.190	4.580	0.040	0.128	0.112	7.188	0.130
0.230	4.803	0.080	0.112	0.114	6.965	0.125
0.310	5.295	0.020	0.090	0.112	7.188	0.130
0.330	5.518	0.060	0.128	0.121	6.150	0.107
0.390	5.854	0.020	0.099	0.112	7.188	0.130
0.410	6.055	0.020	0.128	0.122	6.040	0.104
0.430	6.211	0.020	0.112	0.122	6.040	0.104
0.450	6.390	0.020	0.128	0.117	6.601	0.117
0.470	6.546	0.020	0.128	0.107	7.799	0.143
0.490	6.703	0.020	0.099	0.099	9.097	0.170
0.510	6.904	0.020	0.099	0.107	7.799	0.143
0.530	7.105	0.020	0.099	0.117	6.601	0.117
0.550	7.306	0.020	0.128	0.134	4.991	0.080
0.570	7.462	0.020	0.128	0.141	4.505	0.068
0.590	7.619	0.020	0.149	0.149	4.043	0.056
0.610	7.753	0.020	0.149	0.141	4.505	0.068
0.630	7.887	0.020	0.149	0.138	4.745	0.074

VII. RESULTS AND DISCUSSION

The VWC-depth distribution is seen in 2 main peaks (figures 8-9). This scenario is represented by the fitted curve in Fig. 10 which depicts two clear peaks at approximately 0.07 m and 0.28 m depths. The water content was very high at the top 10 cm of the soil. The high VWC here is likely due to the humus layer, which like a spongy matrix has a high water retention capacity. This zone coincided with the root zone (0.05-0.08 m) of the onions. The next peak with the highest VWC reaching 0.25 m^3m^{-3} occurred in the depth range of 0.20-0.30 m. Close examination of this peak shows that it is followed by a sharp VWC decrease. It is most likely that the latter peak represents a porous soil layer underlain by a more compact layer of weaker porosity. Infiltration from other layers into this layer thus results in the accumulation of water here.

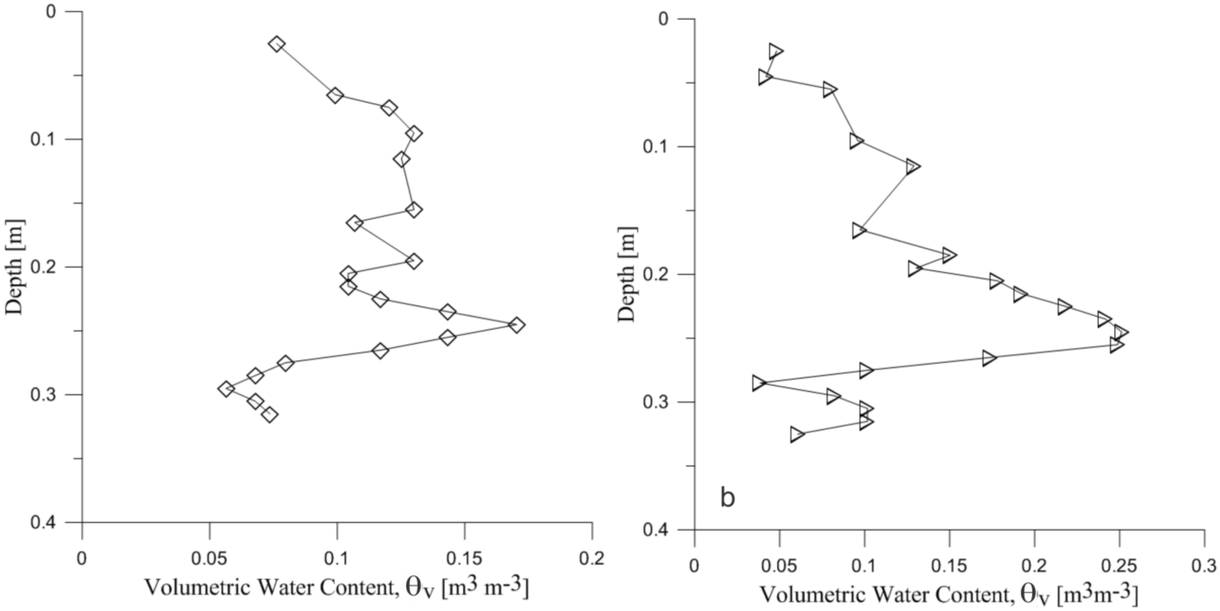

Figure 8 VWC distributions over 2 days; (a) 16th April (b) 18th April

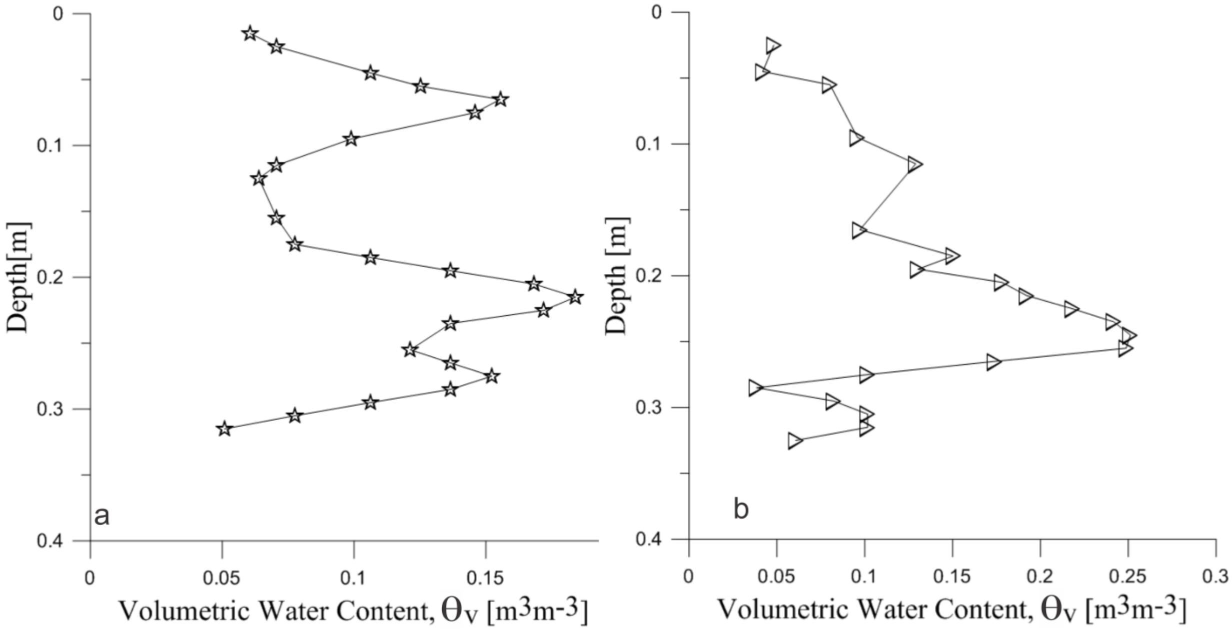

Figure 9 VWC distributions over 2 days; (a) 19st April and (b) 20th April

Figure 10 shows the fourth degree polynomial fit for VWC-depth relation (equation 6). The VWC to depth relation for the study area is generally given by

$$VWC = -660.73x^4 + 420.58x^3 - 87.683x^2 + 6.9491x - 0.0572 \quad (6)$$

where x is the depth of investigation.

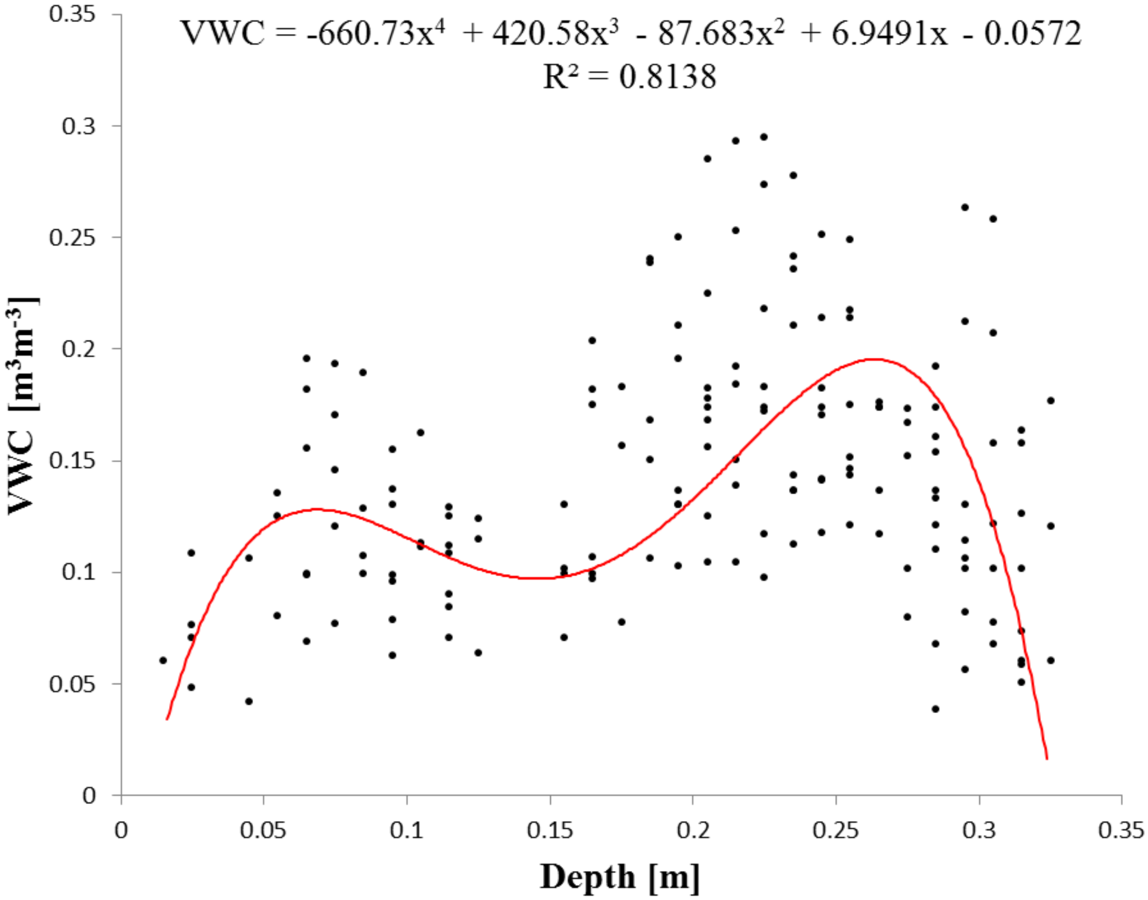

Figure 10 Fourth order polynomial fit for VWC and Depth relation

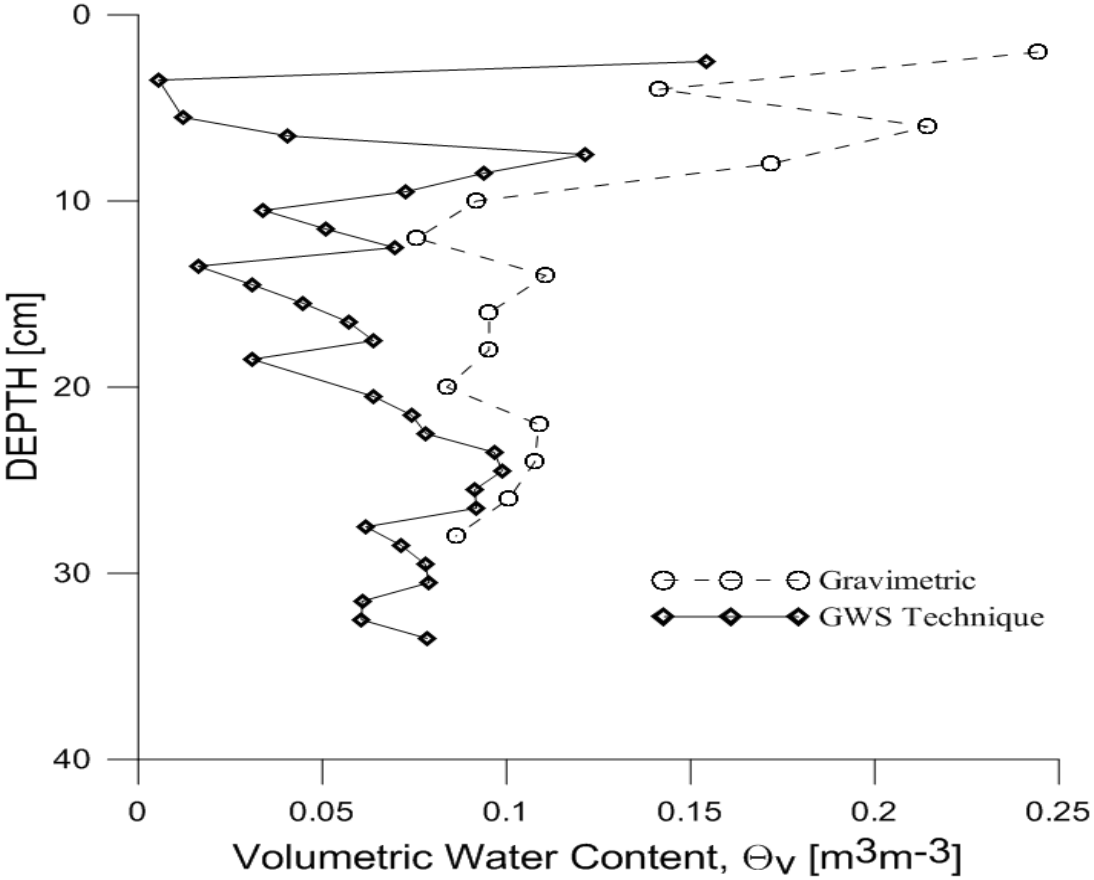

Figure 11 Plot of VWC of gravimetric and GWS technique

Figure 11 shows a comparison between VWC determined in the same day from the gravimetric soil water sampling and GWS methods. From the graph (figure 11) the VWC values estimated using the GWS technique was comparable to that of the gravimetric method. However, VWC from the gravimetric method was relatively higher than that of the GWS technique. This may be due to the fact that the heating (drying) done in the gravimetric method break off all water pockets adsorbed at the surface of the soil particles in addition to those trapped between soil particles, whereas the GWS method only measures the free water between the soil particles, hence rendering the gravimetric water sampling values higher. Error analysis revealed that the error (root mean square deviation) associated with the GWS technique was 5% when compared with the gravimetric method.

Comparison of precipitation with VWC

Rainfall observation for the study period was taken from the Agrometeorological Station on KNUST campus, which is approximately 1.5 km from the field site and experiences similar precipitation and rainfall rates as that of the study area. From the observation it rained heavily on the 19/04/2012 night with an amount of 65.8 mm and also drizzled on the early morning of 20th with an amount of 8 mm. In the early morning of 25th it also drizzled with an amount of 6.7 mm but a day before it was dry (no rains). On the 26th it rained with an amount 0f 21.3 mm. But for the remaining days there were no rains. Attempt was made to ascertain if precipitation influence VWC.

From figure 12, observation form the 20th April's plot, reveals that the VWC at the top 0.1 m of the soil was high. This may be as a result of the infiltration of rainwater, form the previous night, which increased the soil water content at that depth. Also, at depth 0.2 m of the 21st April plot, it was observed that VWC was high and this could be attributed to the infiltration of the rainfall at the top of 0.1 m. (from figure 12). Hence the precipitation in the area generally affects the VWC.

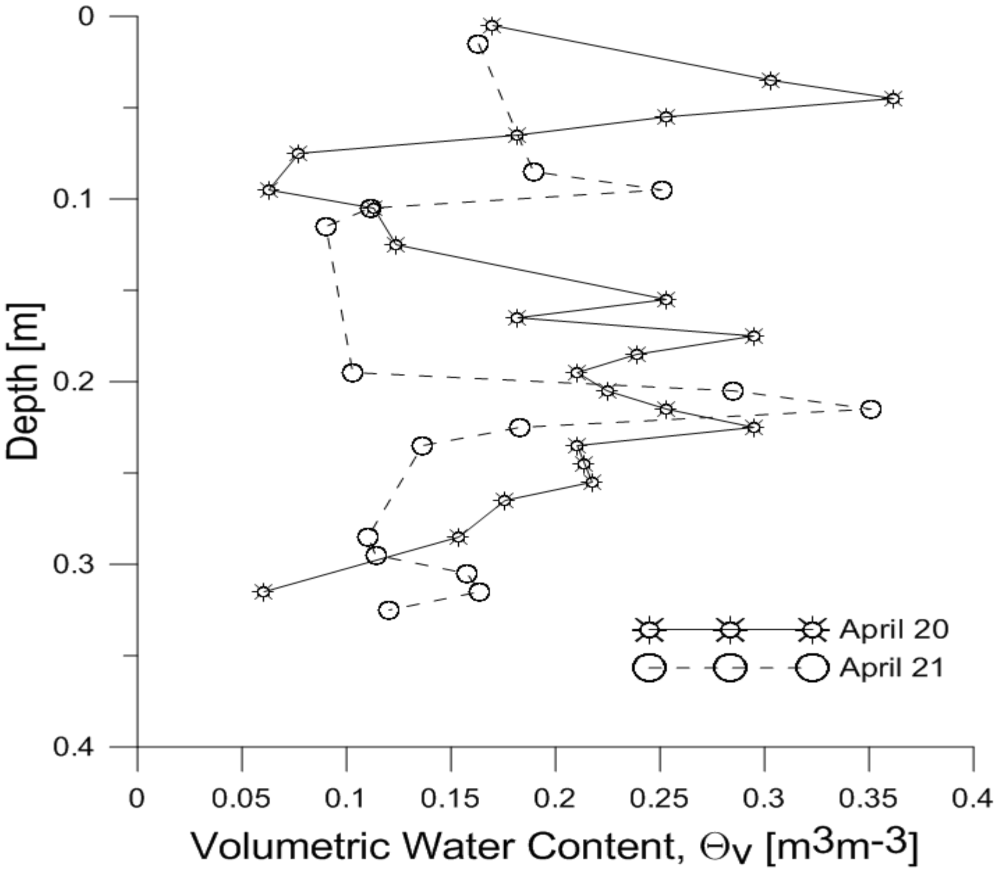

Figure 12 Plot of VWC with depth for 20th and 21st April

Comparing Rainfall event with Average VWC

Average VWC was compared with rainfall amount to establish how rainfall affects the VWC in the soil in general. Generally the rainfall event affects the VWC values obtained (relatively high VWC values).

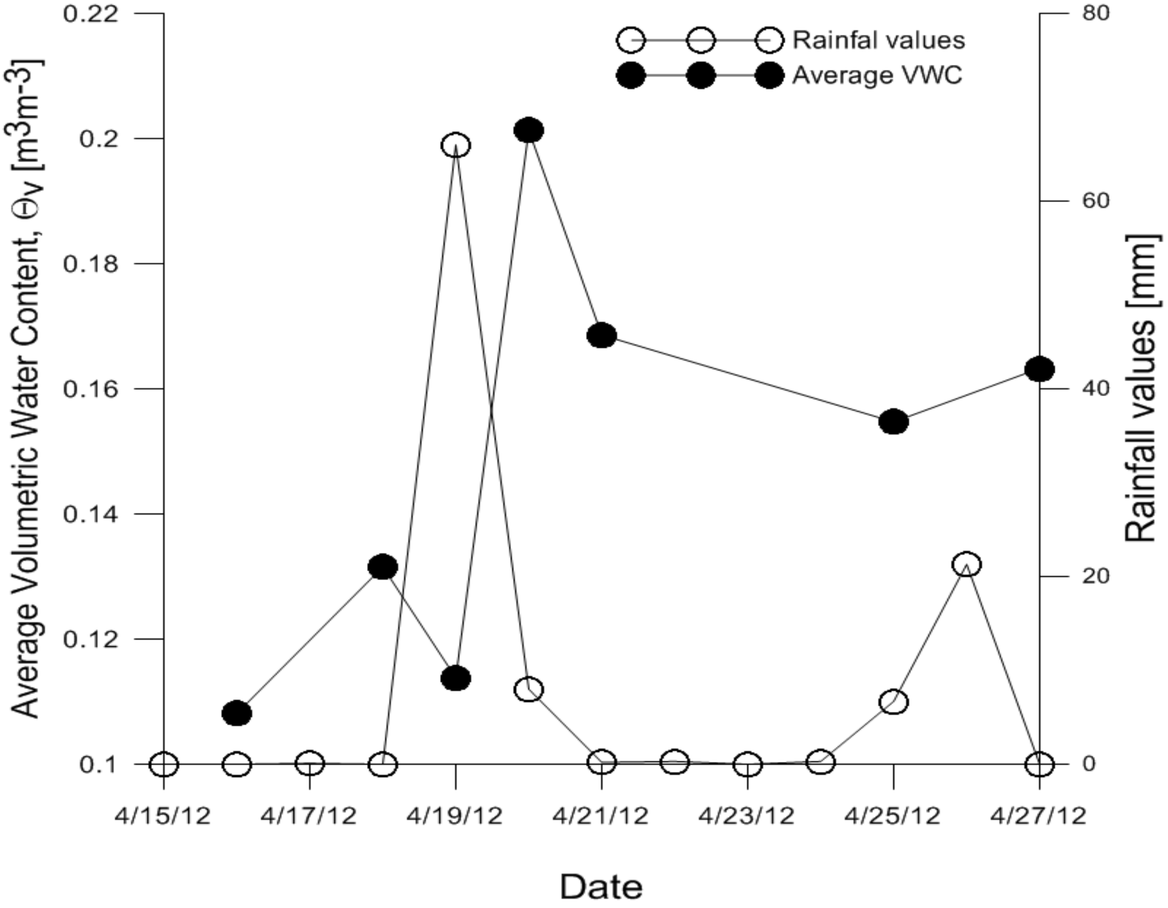

Figure 13 A graph comparing Rainfall event with Average VWC over the period of studies

Considering the average VWC the 20th, it was seen that the value is the highest. This may be due to the fact that it rained heavily on the previous night, with an amount of 65.8 mm and also drizzled in the morning of 20th with an amount of 8 mm. On the average, the average water content decreased with an average amount of 0.03 m^3m^{-3} on the following day (19th). But this amount was very small, indicating that, some of the water was retained in the soil. From 16th to 19th (figure 8a and 9a), there was a small variation in the average VWC of the soil even though it had not rained on any of these days (from figure 13). This indicates that rainfall was not the only factor that affected the VWC in the area.

Temporal VWC for selected depths

The VWC was monitored over 6 days; with 4 days of no rains, a day of rain event and also what happened after the raining event. Temporal volumetric water content for some selected depths (depths of interesting observations) was plotted over the 6 days. This was to observe how the VWC varies with depth during the first 6 days. From figure 13, it was observed that, generally, the VWC at the top depth (0.065 m) was higher than that of the deeper depth (0.295 m). An interesting observation was seen at the depth 0.195 m. It was observed that the volumetric water content at the depth 0.195 m was higher than that or the top layer (0.65 m). This observation likely to be transition two layers a more compact soil layer and a less compact layer (likely to cause accumulation of water).

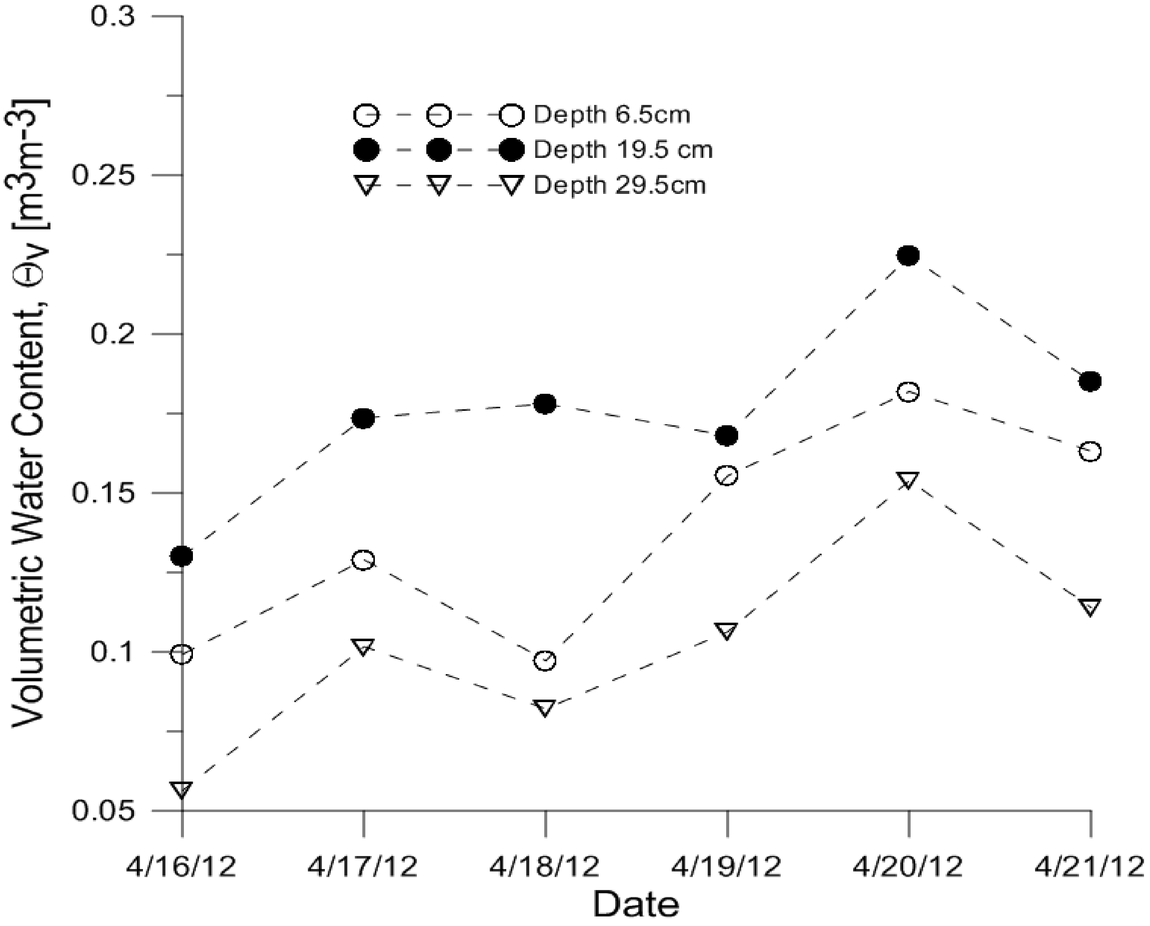

Figure 14 Temporal VWC for selected depths of 0.065 m, 0.195 m and 29.5 m

From the graph (figure 14), it was observed that there was variation in VWC over the days. This variation could be associated to the soil type layers and the weather condition of the day or a day before. Moreover, the variation in VWC with depth can be associated with the heterogeneous nature of the soil with depth.

VIII. CONCLUSION

The research has assessed the utility of guided wave sounding technique for shallow water content estimation (VWC at shallow depth). The result showed that, on the average, the VWC at the top soil (0.065 m) containing humus was high (0.12 m^3m^{-3}) as compared to depth 0.295 m (0.10 m^3m^{-3}). Thus, the uppermost topsoil holds more water than the soil beneath due to the presence of the organic humus layer. Hence planting of short rooted vegetable such as cabbage (which had an average root depth of 0.30 m), onions and lettuce was found to be good for such area. Rainfall event generally affected the VWC values, but it was observed that it was not the only factor. The error (root mean square deviation) associated with the technique was 5% when compared with the gravimetric method. The GWS technique offers a good, reliable, and relatively fast approach for field-scale estimation shallow soil water content. It also offers the possibility of repeated measurement (daily VWC reading) at the same spot and had a minimum disturbance of the soil. A similar project is recommend be done on a bigger scale to know the spatial distribution of the water content in the field.

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