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Monitoring soil water content using IoT Time and Frequency Domain Reflectometry Sensors

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Abstract Soil moisture is considered a crucial climatic parameter. Understanding and predicting variations in surface temperature, precipitation, drought, flood and the effects of future climate change need a thorough knowledge of soil moisture fluctuations. Furthermore, quantification of soil water content, one of the two variables that describe soil moisture, is essential to provide an accurate estimate of crop water needs, which is a crucial element in maximizing the effective use of water resources in agriculture. This study presents the development of an integrated monitoring programme of soil water content within the whole range of unsaturated zone using custom-made system that uses time and frequency domain reflectometry (TDR and FDR) probes to monitor complex hydrologic processes taking place in the unsaturated zone, including return flow to the atmosphere via evaporation, plant root uptake, and subsurface flow of groundwater. Signals logged by these sensors are recorded by an extensible and adaptable logging software component and are available both on premise and through a web application, facilitating their remote manipulation. For the purposes of this research a kiwi field was selected in the plain of Arta, which is located in the Epirus region, in the westernmost part of Greece.

Keywords: Time-domain reflectometry (TDR), frequency-domain reflectometry (FDR), IoT, soil moisture, Soil hydrology

1. Introduction

Monitoring water flow and storage in the unsaturated zone is considered a difficult task, when substantial depths must be reached, concerning several scientific fields, such as groundwater engineering and precision agriculture (Kallioras et al., 2016). To date, an abundance of electromagnetic methods, for instance, time- and frequency-domain reflectometry (TDR and FDR), ground penetrating radar (GPR), capacitance, and microwave remote sensing, have proven useful in investigation attempting to characterise the soil moisture profile of the unsaturated zone at substantial depths (Topp, 2003). TDR is a complicated electronic technology that was conventionally used to test high speed communication cables (Topp, 2003), however over the years has been deployed, in conjunction with FDR, as a non-destructive method for determining the apparent dielectric constant, ε_a, the volumetric water content θ, and soil bulk electrical conductivity σ(Moret-Fernández et al., 2022). TDR and FDR hardware designed primarily for telecommunications, along with ground penetrating probes with precise specifications, have typically been deployed for such measurements.

Early TDR device implementations were deemed insufficient for field deployment, due to their necessity of functioning several devices in parallel. Since then, many companies have specialised in producing TDR devices that focus on soil moisture applications, making their use efficient in field conditions. Recently, even smaller data loggers have been developed in order to store the TDR waveforms, as well as interpreting the measured data on web platforms (Villoro et al., 2021).

However, the ever-increasing cost of TDR instruments practically prohibits their use even for academic purposes. According to recent research papers (González-Teruel et al., 2022; Moret-Fernández et al., 2022), NanoVNA, smaller and affordable clones of VNA (Vector Network Analyzers), which are conventionally used for characterizing radiofrequency components, devices, circuits and subassemblies, can be deployed for dielectric measurements in the frequency domain, achieving high precision.

This study aims to implement both TDR and FDR (NanoVNA) instruments to monitor soil water content in the whole range of the unsaturated zone within a kiwi field in the plain of Arta. The waveforms derived from both instruments were stored in a custom-made noncommercial logging system and can be accessed either locally or through a web platform.

2. Methods

2.1. Study Area

The research area is an experimental field in the plain of Arta , located in the Epirus region, in the westernmost part of Greece, and includes the lower part of the drainage basins of Louros and Aracthos rivers. The south boundary of the plain is a complex network of wetlands (Amvrakikos Wetlands National Park) of high environmental significance, protected by the Ramsar Convention (Tsirogiannis et al., 2015). The plain of Arta hosts densely cultivated and intensively irrigated agricultural area, with predominant cultivations citrus trees and kiwi trees.

The area of the kiwi field is approximately 30 acres. Several soil samples have been collected from two depth horizons of the field (0 -30 cm. and 30 – 60 cm.) and are subjected to particle size distribution analysis, concluded that the soils of the field are classified as silty-clay, according to USDA classification system.

2.2 Installation of TDR -FDR sensors

The probes used in the context of this research to monitor the water flow and storage in the unsaturated zone, have been developed in the framework of an earlier research (Kallioras et al., 2016). In accordance with the technique developed in the previous research, three parallel flat copper wires are attached, at a distance of 1 cm. between them, on the outer side of a 63 mm. diameter HDPE tube.

For the purposes of this study, four TDR-FDR probes were installed 1 m. below the soil surface and one 1.70 m. below the soil surface, within an area of 5 m^2. The groundwater depth in a monitoring well within the field fluctuates from 1.1 m. in the wet period to 1.7 m. in the dry period, deducing that the former sensor can monitor the top layer of the saturated zone.

The constructed probes were installed in the soil through a pre-installed bore, drilled with the use of a gasoline powered percussion hammer in combination with percussion gouges. The distinctive advantage of this equipment is portability in conjunction with the storage of the undisturbed extracted soil sample within a PVC sample tube (liner). The airtight storage of the undisturbed soil sample in a PVC liner, sealed with PVC caps, ensure the precise measurement of soil water content in the laboratory, using conventional gravimetric method, to compare it with that measured by the TDR-FDR instruments.

The instruments used for TDR measurements are Campbell TDR 100 and Hyperlabs TDR, while for FDR measurements NanoVNA (50 khZ – 900 MHz) is used.

2.3 IoT logging systems.

In the framework of this research, the star topology was selected to connect the TDR-FDR sensors to a central server running the analysis on the measurements. Although, current TDRs/FDRs have augmented capabilities compared to their past counterparts, they are still lacking basic networking and storage capabilities, which are offered by other hardware and networking devices. To compensate for the minimal computing, networking and storage capabilities of the TDR-FDR systems, each of the sensors was plugged into a Lattepanda DFR0444 (Single Board Computer). Lattepanda offers a complete computing system with an integrated Arduino microcontroller that enables more complex setups allowing the utilisation of the extensive Arduino ecosystem, including the Arduino IDE and libraries. This integration enables seamless communication between the Lattepanda Intel processor and the Arduino microcontroller on the same board. This allows for the integration of the TDR-FDR sensors with the Lattepanda along with other sensors. This setup allows to by-pass the need for 3rd party network servers, common in LoRa projects (Pagano et al., 2023), since the Lattepanda, being an SBC, can offer sufficient capabilities for data pre-processing, network access management and device management. Furthermore, the integrated system of the TDR-FDR sensors along with the Lattepanda can be adjusted to conform with other popular IoT communication protocols and messaging systems to be incorporated into wider monitoring networks (Brewster et al., 2017). On the downside, the current implementation, imposes that devices must be powered by a constant power supply, although, power consumption can be improved in the future as functionalities are subject to optimisations.

Data from the FDR-TDR is transmitted through 4G network to the application servers running on premises, in the Geo-Hydrology NTUA lab where further analysis and more computationally demanding applications are served, along with a web platform that provides access to raw data along with data visualisations to all relevant stakeholders

3. Results and Discussion

Specific TDR measurements from the experimental kiwi field (Figure 1), at the same time, reveal a strong variability of the reflected signal and as a result of the volumetric water content θ, even in a small area of the field. This heterogeneity either on spatial or on depth scale emerges from the strong heterogeneity of soil structure, which is deemed the most prominent factor that determines the water flow and storage within the unsaturated zone (Novick et al., 2022).

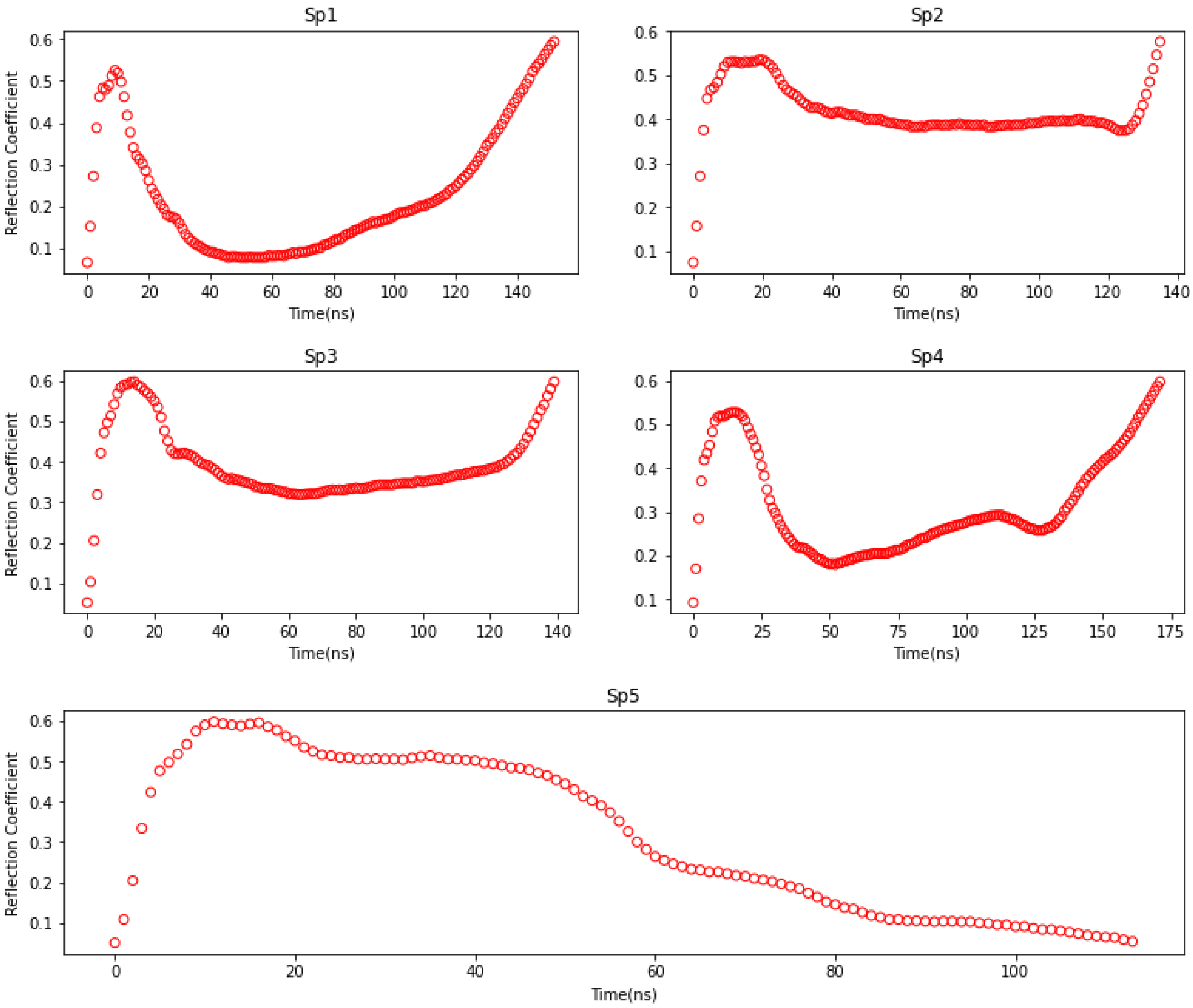

Figure 1. TDR Waveforms measured with TDR 100 connected to four 1 m. probes (Sp1-Sp4) and one 1.70 m. probe (Sp5)

4. Conclusions

Monitoring soil water content on large depths of unsaturated zone remain a challenging task, however, is considered of paramount importance for quantifying several hydrologic processes, such as groundwater recharge and evapotranspiration, as well as providing precise profile soil moisture values for irrigation scheduling based on the real crop needs. To date, several techniques and methods have been proposed for monitoring soil water content. TDR and FDR methods have been evolved throughout the years to compromise with the field functioning necessities, such as low energy consumption and small volume of instruments.

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