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Original Article

IoT-Based Low-Cost Soil Moisture and Soil Temperature Monitoring System

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***Abstract** - Soil Moisture (SM) is a finite amount of water molecules within the pore spaces and is a crucial parameter of hydro-meteorological processes. The behaviour of soil moisture water changes spatially and temporally in response to topography, soil characteristics, and climate [1]. Soil moisture is overseen by various hydro-meteorological factors that vary vertically with depth, laterally across terrestrial shapes, and temporarily in feedback to the climate. Precisely monitoring and quantifying high-resolution surface and subsurface soil moisture observations are essential. This paper highlights the outcomes of the fieldwork carried out at IITM, Pune, wherein we have developed a soil moisture and temperature measurement system using Raspberry Pi and the Internet of Things (IoT). The development is classified into three stages; the first stage includes the sensor assembly with the microprocessor. The deployment of the low-cost system, data generation, and communication through a wireless sensor network is part of the second stage. Finally, the third stage includes real-time data visualization using a mobile application and data server for analyzing soil moisture and temperature. The soil moisture profile obtained through the sensor deployed is highly correlated (r=0.9) with in-situ gravimetric observations, having Root Means Square Error (RMSE) of about 3.1%. Similarly, the temperature observations are well-matched with the in-situ standard temperature observation. Here, we present the preliminary results and compare the accuracy with the state-of-the-art sensors.*

***Keywords** - Soil Moisture, Soil temperature, Raspberry Pi, Internet of Things (IoT), ThingSpeak platform IITM- COSMOS site.*

1. Introduction

Soil Moisture (SM) variability is crucial to agricultural, natural hazards (landslides and debris flow), ecological, hydro-meteorological, and climate studies. The availability of SM data helps deduce important conclusions in these fields. In operational hydrology, SM is one of the essential state variables [2].

Soil water content varies significantly over time and across regional scales. From centimetres to decimetres, many parameters such as soil texture, vegetation distribution, bulk density, precipitation, and irrigation vary [3]. The soil layer is split into four layers based on the standard deviation and Coefficient of Variation (CV) of SM: the quick-change layer, active layer, sub-active layer, and generally stable layer [4]. At 30 cm, the distinction between the active and sub–active layers is made.

The difference between rainfall and evapotranspiration has been found to explain a significant part of the dependability characteristics of SM content in forest ecosystems. Evapotranspiration is a crucial factor affecting the stormwater retention capacity of green roofs and their hydrological performance [5, 6].

Due to the variability of environmental elements such as water, energy input, and soil texture, moisture changes vertically in-depth and laterally. Due to various applications in the different research domains., accurate and precise measurement of SM is required. Various methods have been developed to record and analyze it.

Measurement of SM is done through various techniques, such as remote sensing and in-situ-based platforms. Classical SM measurement methods like a thermo-gravimetric, sensors-based approach are classified into three categories: resistive sensor, conductive sensor, inductive sensor, dielectric methods, electromagnetic induction, tensiometer method, neutron moisture meter, etc [8].

The primary method for measuring SM is the gravimetric method, regarded as the conventional and accurate method adopted for measuring the quality of SM measurements based on other techniques. It is also used for calibration purposes. The size of SM using a capacitive SM sensor is popular due to its low cost and better accuracy. This sensor can be used for the measurement of SM at different depths. These measurements can be standardized with the help of calibration through the gravimetric method [9, 10].

Continuous SM measurements at specific intervals and analysis are required to prepare hydrological models for climate modelling. Modern techniques like IoT and cloud storage can perform this analysis. Many microprocessors and microcontrollers are used in this method for this purpose, like Arduino [11], where a data logger is used. In this approach, the system design cost and complexity cause scalability issues [12]. In this paper, we developed a network of low-cost SM conductive and temperature sensors using Raspberry Pi and IoT.

The optimization of low-cost SM and temperature profile monitoring systems evolved at the COSMOS-IITM site is a part of the CCCR-IITM internship project work. This development comprises low-cost capacitive sensor [13] SM and temperature sensors.

This system measures soil parameters at different depths across one profile. This system can be classified into three stages; the first stage includes designing and assembling a sensor deployment system.

The second stage includes designing and implementing a wireless sensor network to observe SM and temperature profiles, and the third stage comprises real-time data visualization/analysis of SM and temperature of the field scale network for modelling using various software.

Additionally, we have designed a web portal for a better user experience, and CSV data format can be generated through this system to analyze data. This is a fully automatic system. Further, this paper describes the methodology and safety measures taken while assembling and developing the system, along with the calibration and the standardization of the values received.

2. Materials and Methods

The materials and methods section should contain sufficient detail to repeat all procedures. It may be divided into headed subsections if several methods are described. The system sends data using IoT with the help of sensors collecting the data from the soil. The following diagram illustrates the generalized work of the system with a set of blocks used in the system. The block diagram systematically describes the system. The Raspberry Pi is used as a microprocessor to process sensor data. Sensors like SM measurement sensors and temperature sensors are used in the system [14]. The network of 4 pairs of SM and temperature sensors is made to measure the parameters of different soil levels inside the ground. These sensors are connected to the Raspberry Pi's GPIO, and an analog-to-digital converter connects an SM measurement sensor to the Pi.

The system is developed with the help of a low-cost sensor; it sends the data over an open-source cloud using the MQTT protocol; the data collected by these sensors are also displayed on the website. The CSV file is generated of this data to analyze and calibrate the sensor.

As described in the block diagram Figure 1, Raspberry Pi is used as a microprocessor. It is a 40-pin board having different pins for different purposes like power pins, ground, etc., and the 28 pins are used as general-purpose input-output for interfacing various sensors, which means it can be programmed for these pins according to the use of the sensor. it is supported by Raspbian OS, which is similar to Linux; therefore, it is easy to handle and analyze. This processor can be connected with a cable to the internet. It also supports the wireless connection of the Wi-Fi network. These features make raspberry pi an ideal processor for applications like monitoring systems and IoT.

Temperature is measured using the temperature sensor DS18B20 temperature sensor. In the system, a probe sensor with waterproof shielding is used. It communicates with an inner microprocessor using the Dallas one-wire bus protocol, which employs only one data line.

The DS18B20 provides temperature readings in the 9-bit to 12-bit range. The voltage across the diode terminals is the primary working mechanism of temperature sensors. When the voltage rises, the temperature also increases, resulting in a voltage drop between the base and emitter transistor terminals of a diode. It directly converts temperature into a digital value. This sensor does not require an analog-to-digital converter as it has a digital output.

To measure SM, there are various methods. This system uses the dielectric method to measure the soil's moisture as it is a low-cost sensor method. The system uses capacitive SM sensors, and soil acts as the dielectric. This capacitive moisture sensor operates by detecting variations in capacitance produced by soil dielectric changes. The dielectric created by the soil is measured capacitively, and water is the most essential factor that impacts the dielectric. This analog sensor is low-cost and good for applications like soil monitoring. This sensor needs to be calibrated with standard sensors to get appropriate readings.

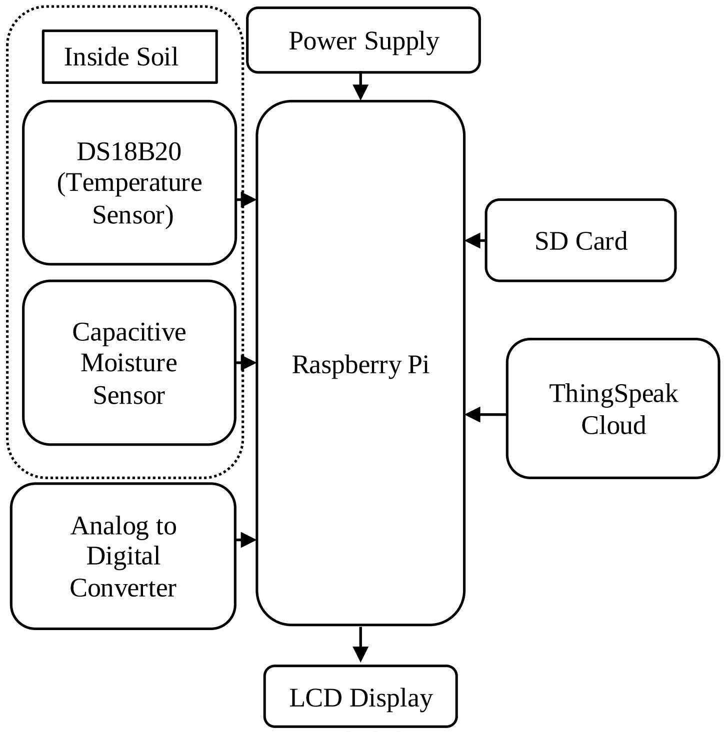

Fig. 1 Block diagram

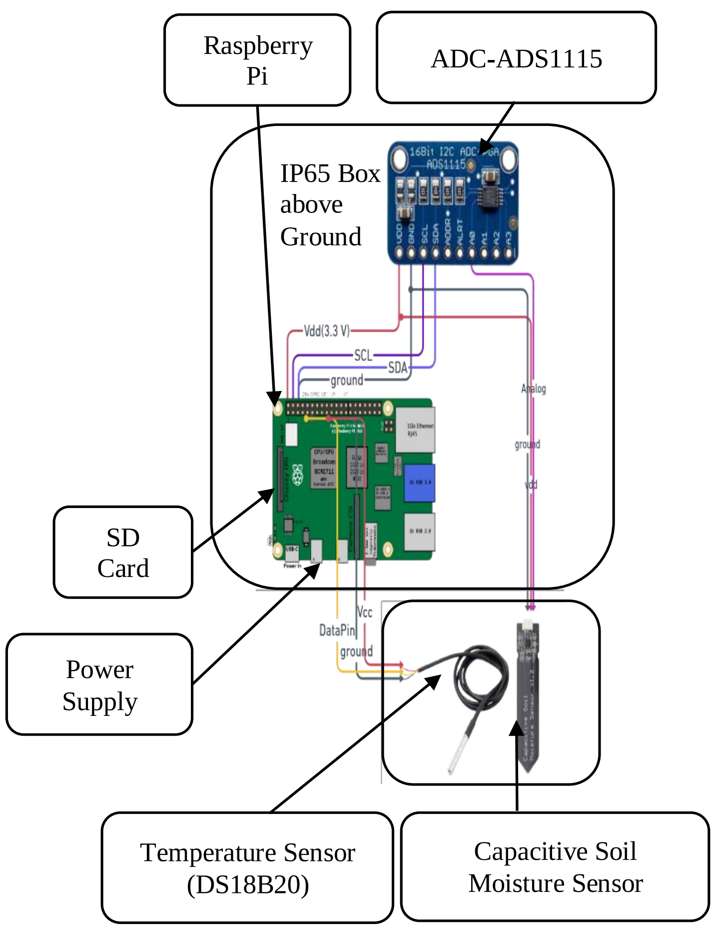

Fig. 2 Circuit diagram

As the capacitive sensor is analog out, it has been converted into digital output using 16-bit Analog to Digital Converter (ADC) -ADS1115, which gives a digital value of the analog sensor up to 4 decimals after a point. Also, to connect various sensors, this ADC is useful. As the sensor is capacitive, its soil and moisture content acts as a dielectric material for the capacitive sensor.

The capacitance is inversely proportional to voltage. This shows that the output voltage decreases when the moisture content increases and vice versa. It has various pins like SCL (Serial Clock), SDA (Serial Data) and four analog out pins. The ADC sends data over two lines using the I2C interface. Raspbian is the operating system that the Raspberry Pi runs on. This is a highly optimized operating system. It's for the Raspberry Pi range of ARM-based small single-board computers.

All programs have been running on this OS along with real-time and other computer processes. The code is put in the start-up of Raspberry Pi, i.e., in the bashrc of the OS. This ensures that the program is automatically started at the start-up of the Raspberry Pi board. This makes the system autonomous and reliable.

IoT is used for data transmission and data storage. Data from Raspberry Pi is directly sent to the thing speak Cloud; thing communicate saves all the data and is used for further work. It is attached to the website. The website is made by PHP, which is used for the backend of the website. The gateway of the sign-in and signup system to the database is done with the help of this tool. HTML, CSS, and JS are languages used for the website's frontend, and website design is done with the help of these languages.

MySQL database is used to store data. The website has features of hashing security for passwords so that unauthorized users can't access or decrypt the password; the complete responsive architecture is supported for mobile, tablet, and laptop screens.

Auto-importing data from ThingSpeak Cloud without refreshing the browser. After Raspberry Pi senses data, data is sent on the ThingSpeak to the Cloud. All the data is saved on the ThingSpeak cloud, which can be used further. That data is imported into the website and then monitored on the website for further evaluation.

This system is programmed mainly in Python programming language as Raspberry Pi supports Python, with the help of different libraries like urllib, i.e., used for making web requests, Date-Time, time, i.e., used to give delays and other time functionalities, etc., the functionalities are provided in the project. These invasive soil sensors need settlement time to obtain stable output signals. The raw data from the DS18B20 sensor is acquired using one wire connection. This sensor works on Dallas's one-wire bus protocol, which enables the connection of multiple sensors to the same pin as this is a bus protocol.

The system uses four temperature sensors. Each sensor has its address, which the processor calls the data collected. This information is saved in Raspberry Pi's directory, accessed through the Integrated Development Environment (IDE), and the raw data is processed using Python programming. The temperature data was then calculated and sent to the ThingSpeak cloud using Message Queuing Transport of Telemetry (MQTT).

To support communication between IoT devices, this protocol employs a publish-subscribe method. MQTT allows client devices to publish messages to a central broker, allowing other client devices to subscribe to the notifications allowing the broker to mediate communication between the publisher and the subscriber. ThingSpeak has added an MQTT broker so devices can send messages to ThingSpeak.

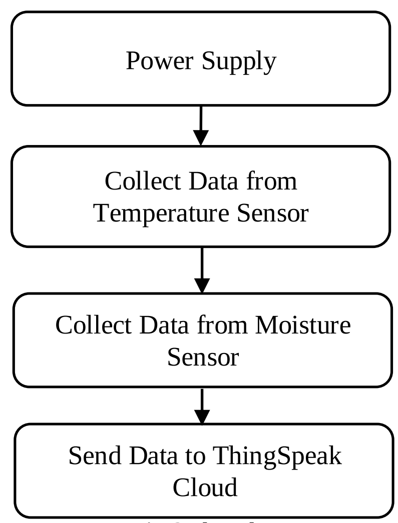

Fig. 3 Flow chart

The ADC collects the analog data from the capacitive moisture sensor. Raspberry Pi collects this digital information. The voltage information is saved in a file. The temperature sensors' data is provided to the ThingSpeak in the same way as the temperature sensors' data. The final code comprising both of these actions simultaneously is done by putting the program in the start-up of the Raspberry Pi.

This ensures that the program is run whenever the Raspberry Pi is powered up and starts continuing the data. The finished software uses both sensors at the same time. The same procedures as before are followed but with a new function. The information gathered by the various parts is saved locally in CSV format. The data from both sensors are shared on platforms such as ThingSpeak cloud. The system is deployed onto the site by taking various safety measures to get a correct reading with minimum loss and accurate measurement of intended parameters.

With the help of hardware and software, this system is made autonomous. The procedure starts and gives the data over the internet whenever powered up for 15 minutes. This study placed four pairs of SM and temperature sensors at 1-meter intervals on four different soil levels. The sensors are connected to a Raspberry Pi that produces output on screens. It has been programmed so that we can watch the output.

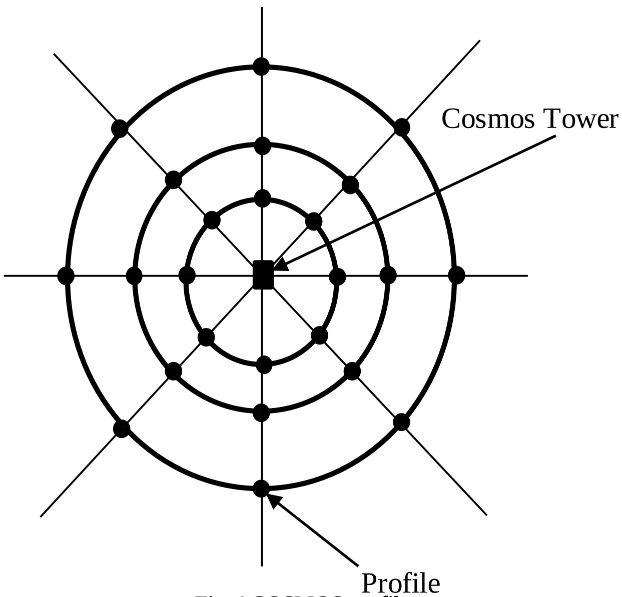

Fig. 4 COSMOS profile

In the above Figure 4, the COSMOS tower is at the centre, denoted by blue-coloured squares, and profiles are represented by the red-coloured circles at specified distances from the COSMOS-tower. Each profile has a one-meter depth, containing four SM sensors and four temperature probes. One profile is shown in the Figure 4: example profile.

As shown in the figure, these eight sensors were installed in each profile in the vast land area at specific distances. The first SM sensor is installed from the top at a 5 cm distance, the second one is at 15 cm, the third one is at 50 cm, and the last fourth SM sensor is at 100 cm. The Raspberry Pi is above the ground in the box. These four SM sensors are connected to the Raspberry Pi, sending data to the server. The server receives the collected data from the sensors in comma-separated values, i.e., CSV file format.

The system communicates data using a CAT 6 cable, which connects sensors to the Raspberry Pi and the power supply. As it has a bandwidth of up to 250 MHz and a speed of up to 10 Gbps, this cable helps reduce data loss for extensive distances. Its outer sheath is made of solid material, so it can't be harmed by insects, soil, or moisture that can't reach the inner copper wires.

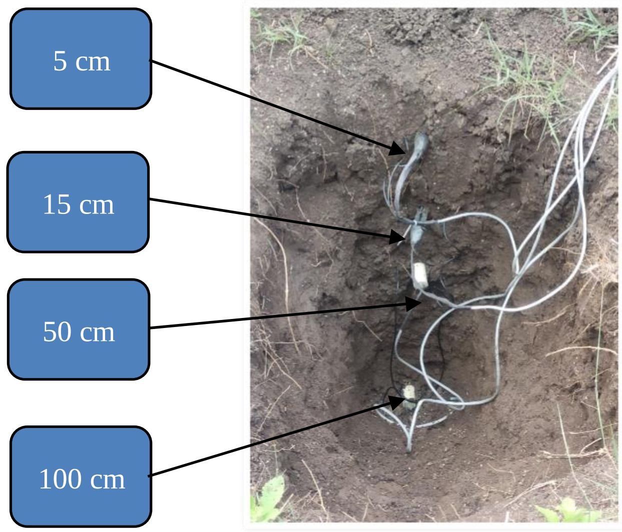

Fig. 5(a) Deployment of the sensor at various levels in the depth

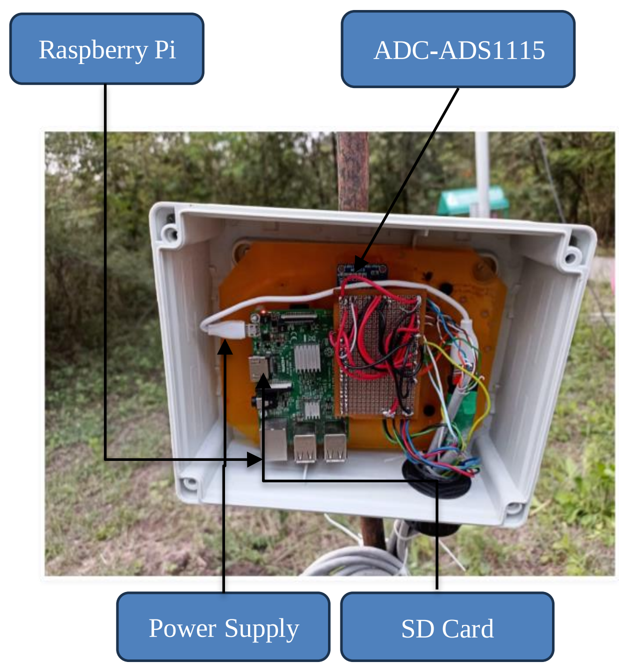

Fig. 5(b) Deployment of hardware system

The kind of care is taken while working with the sensors. Heat shrink/ insulation is used to insulate the sensors for the desired part to prevent them from being damaged by any insect soil or to protect them from SM/water reaching the sensitive part of the sensors.

A heat sink is used in Raspberry Pi to cool it efficiently, as it is used 24/7. The heat sink takes away the increase in heat flow from the device by increasing the amount of low-temperature fluid across the surface. They used an IP66 box of polypropylene, reinforced glass fibre, thermoplastic elastomer sealing, and 10 mm2 terminals/poles.

With quick-release lid and plastic screws that close the box with a quarter turn, it is captive and rust-free. Also, it is weatherproof, ultraviolet-resistant, shatterproof, and impact-resistant.

2.1. Calibration

The capacitive sensors are deployed at the IITM-COSMOS site [11], and the data collected from the sensors are sent to a mobile application through IoT every 15 min. This can be observed on ThingSpeak IoT platforms Figure 6; this data can be accessed in various formats like CSV, XML, and JSON.

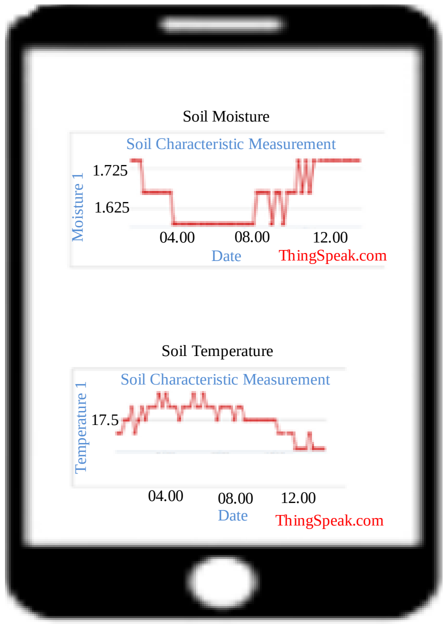

Fig. 6(a) Soil moisture and temperature data representation on the mobile application and website

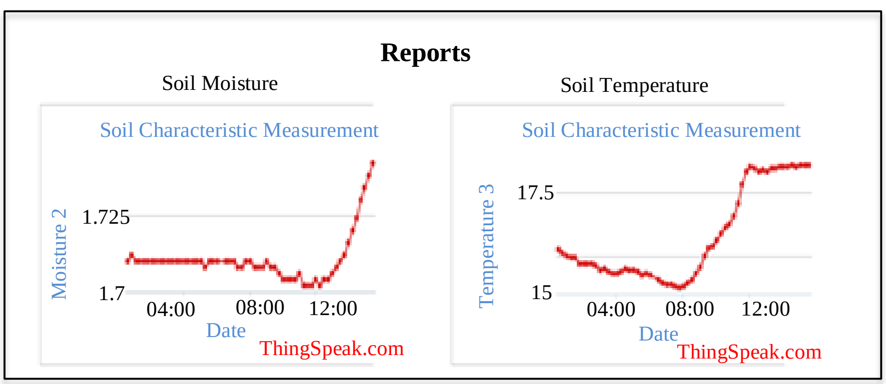

Fig. 6(b) Soil moisture and temperature data representation on the website

Simultaneously, soil samples from various locations and depths were collected and processed using the conventional gravimetric soil analysis method at the IITM-COSMOS site. The pieces were kept in a plastic bag to prevent SM loss during the calibration, and they were then sealed with a lid and stored. The weight of the soil samples was obtained first. Then, the pieces were baked in an oven at 100 degrees Celsius for 24 hours, after which the importance of the soil samples was retaken, and the volumetric water content was estimated. The ratio of the volume of water to the volume of soil is the volumetric water content (θv) of a sample [7]. The technique described above is repeated for different locations, and the soil types procedure is repeated for other areas and soil types.

$$\theta_v = \left(\frac{m_s - m_d}{m_d}\right)\frac{\rho_{d,s}}{\rho_w} \quad (1)$$

Where, m_s - a measured mass of the wet soil
m_d -measured mass of the dry soil
$\rho_{d,\ s}$ - bulk density of soil (mass of dry soil divided by sample volume)
ρ_w - density of water

The measured data from the gravimetric sensor (θV) and observed sensor output data are compared and analyzed per the standard procedure. It is observed that volumetric water content (θVnew) is computed following the best fit [15] carried out through rigorous calibrations and given as:

$$\theta_{Vnew} = (-71.789x^2 + 158.04\,x - 37.711) \quad (2)$$

Here, x is the sensor output voltage. The relation between the inverse of the voltage reading from the capacitive sensor and θv derived by gravimetric methods.

The inverse of the voltage reading was fitted via least-squares regression, which resulted in the relationship between the capacitive sensor and θ_v (Equation 2).

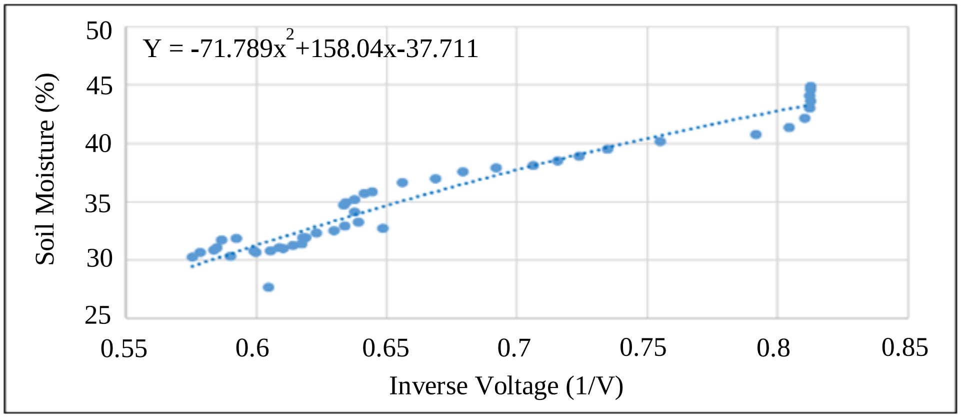

Fig. 7 Calibration results with inverse voltage vs Soil moisture

3. Results and Discussion

These SM and temperature profile data sets obtained using the assembled low-cost observation system at the COSMOS-IITM site for 5 cm, 15 cm, 50 cm, and 100 cm depth are validated and analyzed to explore surface and subsurface variations. The techno-scientific expertise, distinctive infrastructural facilities, and ample in-situ hydro-meteorological data set at the COSMOS-IITM site having natural vegetation cover have extended valuable support for calibration and validation in this study. The correlation coefficient of SM profile observations with those of in-situ Gravimetric data sets is about 0.8; however, the Root Mean Square Error (RMSE) is found to be about 3.1 %. The temperature profile observations match (~95%) well with those obtained from standard sensor-based temperature measurements. Figure 8 (a and b) shows the time series of SM and temperature observations at 5 cm, 15 cm, 50 cm, and 100 cm depth. The variations at surface levels (5 and 15 cm) are relatively higher than those of subsurface groups (50 cm and 100 cm). The distinction between SM and temperature variations at the surface and subsurface is remarkable. However, the soil moisture is higher in the subsurface levels and persists smoothly. At the same time, the soil temperature was lower in subsurface groups. The data observed for two months and plots are shown in the following Figure 8(a) and Figure 8(b) for SM and temperature.

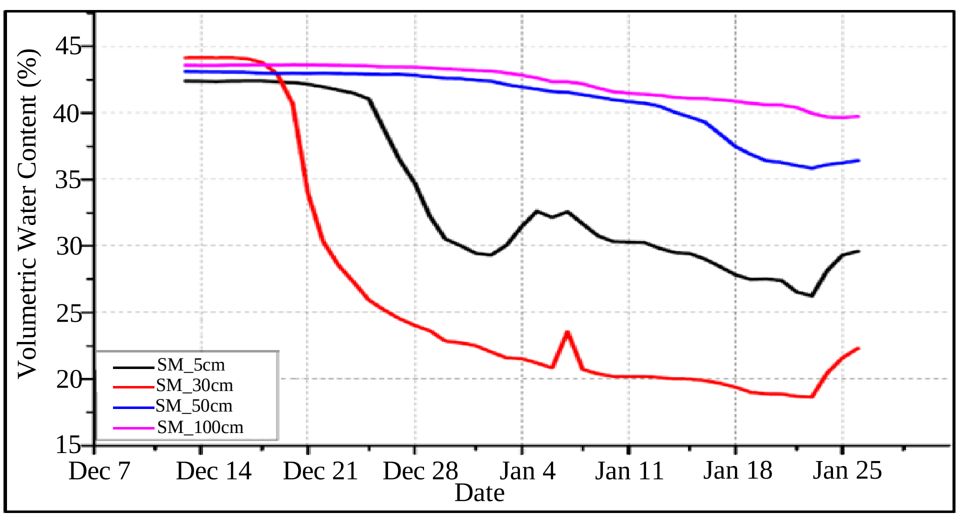

Fig. 8(a) Soil moisture variation

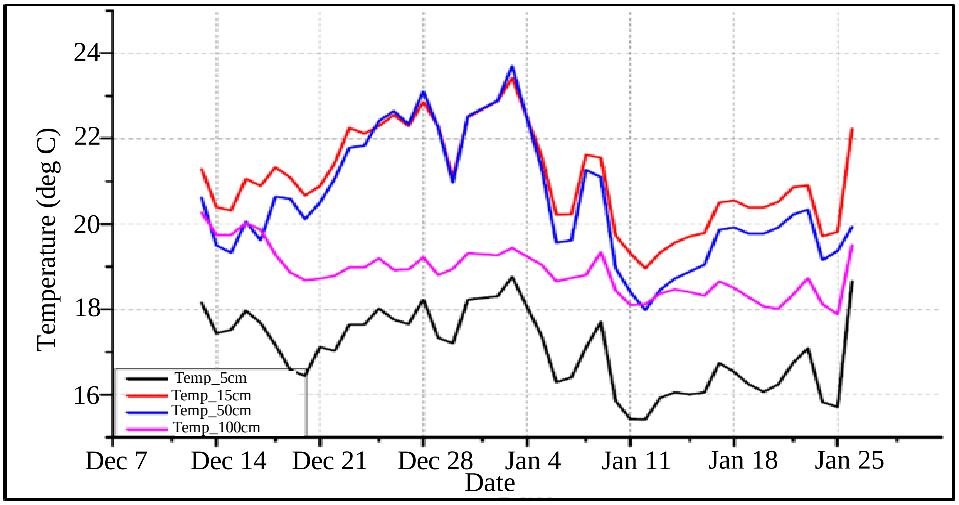

Fig. 8(b) Soil temperature variation

4. Conclusion

The optimization of low-cost SM and temperature profile monitoring systems evolved at the COSMOS-IITM site is a part of the CCCR-IITM internship project work. Capacitive and temperature sensors are used here to monitor SM and temperature at surface (5 and 15 cm) and subsurface (50 and 100 cm) levels. This system has been developed in three steps: assembly design, data management, and real-time visualization with analysis.

The credentials of SM and temperature observations are set through critical calibration and validation using standard in-situ data sets available at the COSMOS-IITM site. Interestingly, real-time data access through mobile using ThingSpeak cloud or a data server is a crucial component of this system.

The time-series analyses depict the higher variability of surface SM with lower magnitudes than those of higher subsurface SM volumes. Also, the distinct, more downward subsurface temperature variations, having lower magnitude, complement the subsurface SM variations. Real-time SM and temperature profile variation knowledge is crucial for hydro-meteorological, agricultural modelling, and various applications.

Researchers can study different crops and moisture variations with this observation system to optimize irrigation practices. Also, SM sensors can be customized to fit a variety of soil types.

Bluetooth, Lora can provide the output data straight to the user wirelessly without internet connectivity, according to the application. A GPS module can be fitted to determine the amount of moisture in a specific area. A camera can also be added to this observation system to periodically record sky and ground conditions to monitor crops and their health.

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