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Performance Evaluation of the Water Advisory for Irrigation Scheduling System (WAISS) Capacitance Soil Moisture Sensor

ABSTRACT

The agriculture sector accounts for 80% of the total freshwater resource use in the Philippines. With increasing competition for the scarce water supply, it is necessary to utilize water resources efficiently. The application of smart irrigation technology can help achieve higher water use efficiency, increase farm water productivity, and maximize crop yield. To minimize excess or insufficient irrigation water application to crops, and provide more effective and efficient water management, an integrated water monitoring system called Water Advisory for Irrigation Scheduling System (WAISS) was developed. The performance of WAISS was initially evaluated by comparing the soil moisture measurements of its capacitance soil moisture sensor with a commercially developed sensor and the standard gravimetric method. Statistical analysis shows that the low-cost WAISS soil moisture sensors are comparable with the commercially developed sensors with a Percent Error of 5.5% compared to METER ECH2O EC-5's 16.1%. This highlights WAISS' potential as a cost-effective yet reliable alternative for soil moisture monitoring.

Keywords: *smart agriculture, precision farming, WAISS, soil moisture, capacitance soil moisture sensor, Project SARAI*

Roger A. Luyun, Jr.[1*]
Ronaldo B. Saludes[2]
Toni-An Mae C. Salcedo[2]
Bryan M. Baltazar[1]
Christian Martin Casedo[1]
Jay Ann Q. Lomod[1]
Ginalyn Robel M. Brazil[1]
Jan Albert M. Atienza[1]

[1] Land and Water Resources Engineering Division, Insitutute of Agricultural and Biosystems Engineering, College of Engineering and Agro-Industrial Technology (CEAT), University of the Philippines Los Baños (UPLB), College, Los Baños, Laguna, Philippines 4031

[2] Agrometeorology, Bio-structures and Environment Engineering Division, IABE-CEAT, UPLB

[*]corresponding author: raluyun1@up.edu.ph

INTRODUCTION

The need for rational agricultural water management has become imperative because of climate change and its subsequent effects on water availability. Philippine agriculture accounts for 80% of the total freshwater withdrawals in the country (*Luyun 2016*). It is important to utilize this effectively and efficiently. In 2016, the Philippines lost PhP 16.5 billion worth of agricultural produce due to El Niño (*FAO 2017*). Some areas, especially located near high-growth centers (Regions II, III, IV, V, VII), may experience water deficits by 2025 (*NWRB-JICA 1998*). Improving water management in agriculture is a key to tackling water security. With the changing global climate resulting in unprecedented extremes in the frequency, intensity, spatial extent, duration, and timing of weather and climate events (*Seneviratne et al. 2012*), as well as the occurrence of other large-scale natural and man-made disaster events that may affect the food value chain and food security, farming in the Philippines must be future-proofed from these uncertainties through smart agriculture.

While traditional inundation irrigation systems still occupy a greater part of the country's fields, many farms have been progressively using drip and sprinkler irrigation systems, especially for high-value crops. Efficient and precise irrigation management has become increasingly important considering the need to conserve water. Irrigation scheduling depends on the level of sophistication of the tools and techniques available.

The use of a more scientific approach to agriculture can contribute to achieving some of the Sustainable Development Goals (SDGs) adopted by the United Nations Development Programme (UNDP) in 2015 (*UNDP 2021*) by achieving food sustainability, economic growth, and by extension, the alleviation of poverty, promotion of good health, and climate change proactiveness. The Philippine Department of Agriculture

(DA), through former Secretary William Dar, aims to push the agriculture and fishery sector to establish “smart farms” which can help attract the interest of the youth to venture into agriculture and apply scientific and technological innovations to farming and fishing (*Gomez 2020*). The DA’s food security development framework for 2020 includes agricultural modernization as one of the strategies, through science-based farming, mechanization, digital agriculture, agricultural entrepreneurship, and food processing and value-adding (*The World Bank 2020*). Additionally, World Bank Country Director Ndiamé Diop stated that “modernizing the country’s agricultural sector is a very important agenda for the Philippines.”

The environmental impact of agriculture is minimized by making it more effective and efficient through precision farming and the use of smart sensors for crop water management, potentially increasing farm productivity and profitability. However, the technical complexity and high acquisition cost of these technologies pose a challenge to small-scale farmers. For the farmers to easily adopt these smart sensor systems, they must not only provide adequate, useful, and timely information but should also be user-friendly, cost-effective, and not time-consuming.

With a wide range of available smart irrigation technologies, it is essential to choose the appropriate technology for a specific situation to help farmers know when to irrigate or how much water is still available on their farm (*Gothcher et al. 2017*). Climate-based smart irrigation technologies rely on evapotranspiration (ET) and climatic data, which can be remotely sensed to determine irrigation schedules. Soil-based technologies utilize soil moisture sensors placed in the root zone of plants to determine the water needed based on the crop growth stage.

Recent technological advances have made soil moisture sensors available for efficient and automatic operation of irrigation systems (*Aashu Bedrae et al. 2018 and Vaishali 2017*). Low-cost soil moisture sensors are recognized as viable alternatives to more expensive foreign brands as long as they undergo proper testing, calibration, and reliability assessments (**Table 1**).

Table 1. Major types of soil moisture sensors.

Soil Water Content	Soil Water Tension
Neutron Probe Time Domain Transmissivity Capacitance Sensors	Tension meters Granular Matrix Sensors

Source: *Peters et al. 2013*

This study presents the development of a low-cost smart irrigation decision support system that is intended to assist users in making irrigation recommendations for crops and to promote more efficient and effective irrigation scheduling. Initial testing of the performance of the WAISS soil moisture monitoring system as compared with commercial soil moisture meters is also presented.

MATERIALS AND METHODS

Water Advisory for Irrigation Scheduling System (WAISS)

The Water Advisory for Irrigation Scheduling System (WAISS) is an irrigation decision support tool developed by Project SARAI (Smarter Approaches to Reinvigorate Agriculture as an Industry in the Philippines) through funding from the Philippine Council for Agriculture, Aquatic and Natural Resources Research and Development of the Department of Science and Technology (PCAARRD, DOST). WAISS is comprised of a field unit and software. The field unit (**Figure 1**) consists of DF Robot capacitance-type soil moisture sensors, a transmitting data logger, and a solar panel. The software (**Figure 2**) processes the data sent from the field unit via short message service (SMS) to generate irrigation advisory that will be sent to the end-users, also via SMS. It is an upgrade of the system developed by *Andales et al.* (*2014*) which uses an Excel-based spreadsheet.

Figure 1. Water Advisory for Irrigation Scheduling System (WAISS) field unit with capacitance-type soil moisture sensors, transmitting data logger, and solar panel.

Computational Methodology

WAISS generates real-time irrigation advisory based on actual soil moisture conditions and the management allowable deficit (MAD). Expressed as a percentage,

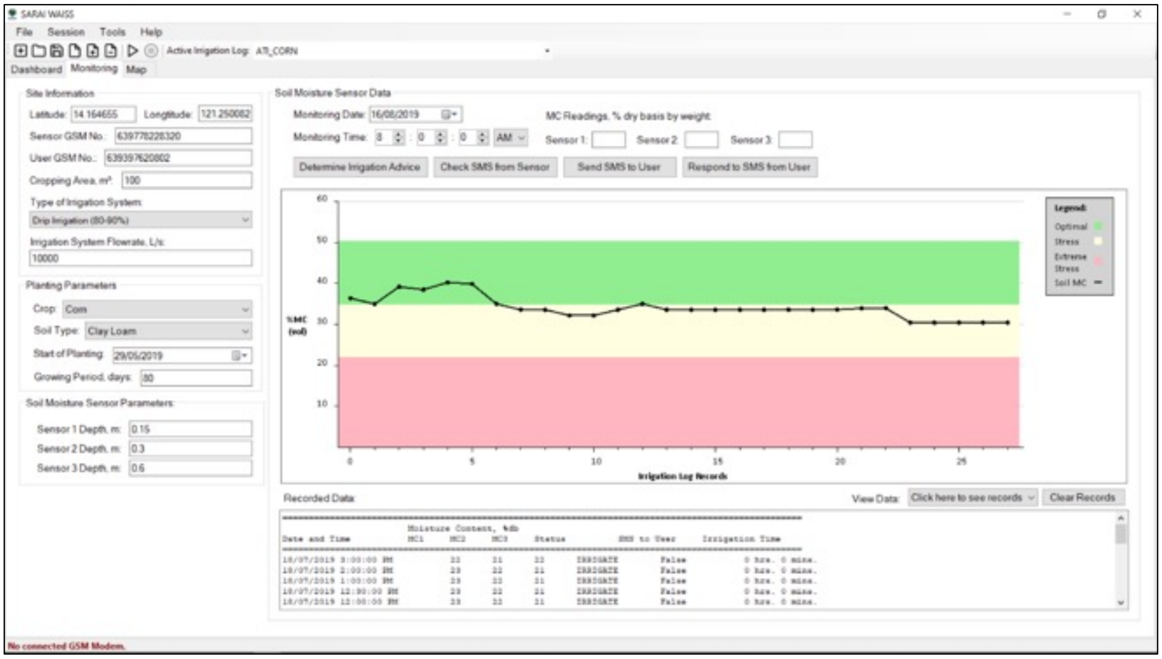

Figure 2. Water Advisory for Irrigation Scheduling System (WAISS) software monitoring interface.

MAD is a prearranged amount of water that is allowed to be depleted before irrigation is applied. Whenever this amount of moisture is removed from the soil, the WAISS generates an irrigation advisory to prevent the plants from experiencing water stress.

Crop data inputs include the crop name, growing period, management allowable deficit, root depth during transplant (zero if crop is direct seeded), and the maximum rooting depth of the plant. If the crop is directly seeded, the growing period is the number of days from seeding until harvesting. If the crop is starting from a mature plant, the growing period means the days from the initial monitoring until harvesting. For root growth estimation, WAISS users have the option to employ the *Borg and Grimes* (*1986*) model, Inverse Kc, or a user-defined equation. *Borg and Grimes'* (*1986*) model describes root depth as a sigmoid development of the roots from the planting date until maturity and only requires the current root depth. The Inverse Kc requires the crop coefficients at different growth stages. The user-defined option applies to researchers and students doing water-saving and/or precision irrigation studies. It allows the use of specific equations for different crops. The current root depth (r_{dt}) will then be used for the computation of the net application depth (Fn), or the depth of water needed to replenish the moisture lost in the soil.

Soil data inputs include the soil type, field capacity (FC) and permanent wilting point (PWP). During early crop stages like transplanting, WAISS primarily relies on the shallowest sensor's readings. As the crop matures, deeper sensor data becomes more critical. Once soil moisture content is determined, WAISS calculates the required water volume to restore the soil's moisture to its field capacity.

The WAISS capacitance-type soil moisture sensors need to be calibrated before installation. This conversion from analog reading to moisture content by volume basis is done for each sensors' readings and the average soil moisture content in the soil will then be computed and also used to compute the net application depth (Fn).

The net application depth (Fn) is used for the computation of irrigation period or the application rate (Ta) depending on the irrigation system type. WAISS also factors in the inefficiencies inherent in the irrigation system. For surface irrigation systems, the field's attributes such as soil infiltration capacity and slope are also considered. By integrating the irrigation system specifications, WAISS generates both the total water volume required and the expected duration to irrigate the field.

Capacitance Sensors

WAISS uses capacitance sensors because they are easy to operate and can provide real-time measurements. Capacitance sensors use dielectric sensors to measure the capacity of the soil to conduct electrical charges between the sensor probes, where a higher soil moisture content means a greater capacity to conduct electricity (*Spann 2015*). Different commercial soil moisture sensors are available from companies like HOBO and METER. However, these can be expensive and therefore not affordable to small farmers.

The ZL6 Data Logger of the METER Group, with the ECH_2O EC-5 soil moisture sensor (**Figure 3**), was used in this study to evaluate the performance of the WAISS sensor. In this system, the soil moisture data can be downloaded near-real time by subscribing to the Zentra Cloud via Bluetooth through Zentra Utility Mobile or via a USB connection while on-site. The data logger can provide soil moisture measurement in analog or percent volumetric moisture content. The system was already pre-calibrated by the manufacturer but in this study, it was recalibrated to the soil sample used in the evaluation.

The accuracy and precision of the WAISS capacitance soil moisture sensor was evaluated and compared to the state-of-the-art METER soil moisture sensor. Both the factory-calibrated and manually-calibrated METER measurements were used. The sensors were calibrated to a sandy loam soil and the soil moisture measurements were compared to the standard gravimetric soil moisture value.

Soil Bulk Density Determination

Core samplers, with known mass, height, and diameter, were used to collect undisturbed soil samples. For each soil sample, the fresh mass, and the oven-dried soil mass, after drying the sample in an oven at 110°C for 48 hours, were determined. The bulk densities of each soil sample were computed using Equation 1.

Figure 3. a) METER ZL6 Data Logger b) ECH_2O EC-5 soil moisture sensor (Source: *METER Group, Inc. 2020*).

$$\rho_B = \frac{m_w - m_d}{V} \qquad (1)$$

Where ρ_B= soil bulk density, g cm^{-3}

m_w= mass of wet (fresh) soil sample and core sampler, g

m_d= mass of oven-dried soil sample and core sampler, g

V= volume of soil core sample with known height and diameter, cm^3

Calibration of Soil Moisture Sensors

Around 10 kg of sandy loam soil was collected from the University of the Philippines Los Banos (UPLB) Central Experiment Station (CES) and air-dried in preparation for calibration of the soil moisture sensors. Large objects were removed from the soil sample and clods were broken up by sifting the soil through a 1.4 mm sieve. The volume of the calibration container was measured using a quantified volume of water multiplied by the bulk density of water to obtain the mass of soil needed to fill the container. The computed amount of soil was transferred and compacted into the calibration container.

The soil moisture sensors were inserted fully into the soil to prevent air gaps between the tines and the soil. For WAISS, the field unit was connected to a computer, and installed with calibration software developed by the project team, to come up with the measurements. On the other hand, the EC-5 sensors' data was read from the Zentra Utility Mobile application downloaded online. Direct readings from METER represent the factory-calibrated measurements.

After the values stabilized and the analog readings from both sensors were recorded, an undisturbed core soil sample was collected from the calibration container, and the fresh mass and oven-dried mass were measured. The soil moisture content by volume (MC_V) was then computed using Equation 2. The same mass of the soil was added back to the calibration container for succeeding measurements, ensuring first that it had the same moisture content as the calibration setup. The steps were repeated while increasing the water content of the calibration soil. Water equivalent to the pre-set percent soil moisture calibration was added into the soil to achieve the desired moisture content as the soil in the calibration container. The calibration procedure was based on *Starr and Platineanu* (*2002*).

The soil moisture values obtained from the gravimetric method were plotted against the readings (independent) from the WAISS and METER sensors. Regression analysis (linear and non-linear) was then conducted to determine the calibration curve for each sensor.

$$MCv = \frac{m_w - m_d}{m_w - m_c} \; x \; 100\ \% \qquad (2)$$

Where MCv= moisture content by volume, %
m_c= mass of core sampler, g

Soil Moisture Sensor Testing and Evaluation

The procedure done during calibration was repeated, this time with both the WAISS and METER sensors simultaneously inserted into the soil. The soil container (**Figure 4**) was divided into three zones around the core sampler to minimize the non-uniform mixing of water into the soil. Each zone should be able to accommodate both the WAISS and the METER sensors while leaving the space for the core sampler undisturbed. Soil moisture measurements were then recorded and analyzed.

Percent error of the soil moisture values from WAISS and the factory-calibrated and manually calibrated sensors were computed relative to soil moisture values obtained from the gravimetric method. The percent differences between the measurements of the different sensors were also calculated. The Root Mean Square Error (RMSE) was used to statistically analyze the variation among gravimetric and sensor-derived moisture content values.

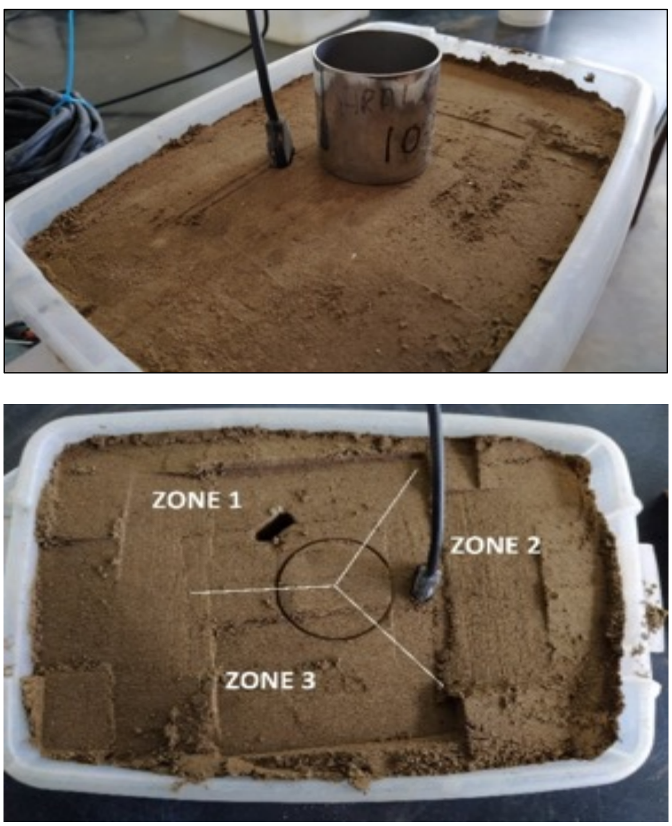

Figure 4. Dividing the sampling area around the core sampler into three zones for Water Advisory for Irrigation Scheduling System (WAISS) and METER sensor calibration.

Field Testing

The WAISS and METER field units were deployed over a 15-day period at the UPLB-CES in Laguna, Philippines operating from August 21, 2019, to September 5, 2019. With each setup, two sensors were placed at depths of 15 cm and 30 cm below the soil surface. The sensors' accuracy was validated through gravimetric soil measurements, compared against the daily average readings obtained from both field units.

RESULTS AND DISCUSSION

The Water Advisory for Irrigation Scheduling System was developed such that end-users can customize it according to their farm's characteristics such as crop planted, soil texture, and available irrigation system using the developed WAISS Web Application. From the crop and site characteristics, and the soil moisture measurements from the field unit/s, the system will generate site-, crop-, and irrigation system-specific irrigation advisories and recommendations to its end-users. The system was also developed for the remote monitoring of soil moisture levels in the field to assist farmers in making smart irrigation choices through the advisories provided. The name "Water Advisory for Irrigation Scheduling System (WAISS)" has a Certificate of Copyright Registration and Deposit with Registration No. N2019-453 dated September 10, 2019. The WAISS WebApp has a Certificate of Copyright Registration and Deposit with Registration No. N2023-82 dated April 14, 2023. A patent application for the WAISS software is being processed.

This SARAI technology is compatible with the five general types of irrigation systems (basin, border, furrow, drip, and sprinkler). The irrigation volume and irrigation time computations are specific to the irrigation system type. WAISS supports farmers, agricultural extension workers, students, and researchers in implementing good irrigation practices by conserving water, reducing the cost of irrigation, and preventing yield loss due to water stress.

The final output of the WAISS WebApp is the irrigation period and the irrigation volume. The irrigation period means that the user should irrigate using its provided irrigation system in that given amount of time. For example, Farmer A should irrigate as soon as possible using its drip irrigation system with unit discharge of 12.16 L day^{-1} for 30 mins. On the other hand, the irrigation volume is the total amount of water needed by the farmer to be able to irrigate at that given rate and period. For example, Farmer A should prepare 1000 L of water to irrigate at 1.0 L sec^{-1} for 17 minutes.

WAISS uses a low-cost DF Robot capacitance soil moisture sensor which can only produce raw, uncalibrated outputs of voltage ratios. The METER data logger, on the other hand, uses a pre-calibrated soil moisture sensor that can measure soil moisture content directly.

The WAISS system significantly undercuts the expense of combining a commercially available datalogger and soil moisture sensor. For instance, the DF Robot capacitance sensor for WAISS is priced at PhP 500 each, while the ECH_2O EC-5 (METER Group) sensor costs PhP 5,500. Moreover, the WAISS transmitting data logger totals under PhP 14,300, whereas the imported ZL6 Data Logger from the METER Group hits PhP 76,900. Factoring in additional materials and bulk-purchased parts applicable to multiple units, WAISS can yield savings up to 68% compared to procuring a commercial set. (exchange rate: US$100 to PhP 5,500)

The bulk density of the sandy loam soil used in this study was determined to be 1.42 g m^{-3}. The gravimetric moisture contents were determined from the collected soil core samples and plotted against the analog readings of the WAISS and METER sensors to determine the calibration curves (**Figures 5** and **6**). It should be noted that these curves are for sandy loam soils only and do not apply to other soil types. This soil type was chosen first because it is loose soil with good drainage, and therefore, suitable for testing rapid changes in moisture contents. While further calibration will be performed to generate the curves for other soil types, it should also be noted that more accurate calibration can be expected for soils with finer particle sizes.

The WAISS sensor fits a symmetrical sigmoidal curve with $R^2 = 0.9996$, while the METER sensor fits a linear equation with $R^2 = 0.996$. The METER sensor is already factory-calibrated, hence the linear relationship. For WAISS, the calibration equations can be directly integrated into the program. The generated equations (**Table 2**) were used to recalculate the soil moisture values from analog readings of WAISS and the manually calibrated METER sensors during calibration and testing.

Comparing the soil moisture (MC_V) values from the WAISS and METER sensors (both manually and factory calibrated) with the standard gravimetric method values (**Table 3**), the WAISS sensor performed well with an average of 0.36% error whereas the METER sensor has a 2.6% error average in the manually calibrated MC_V, and a 15.67% error using the factory-calibrated values.

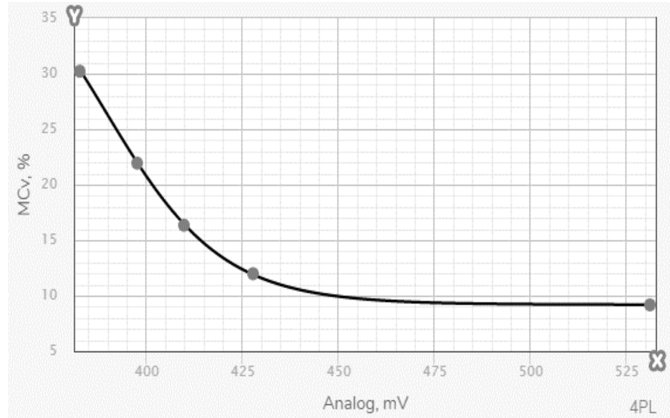

Figure 5. Calibration curve of the Water Advisory for Irrigation Scheduling System (WAISS) Sensor.

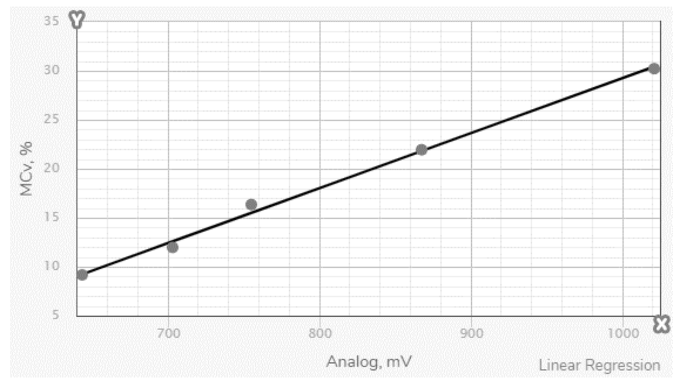

Figure 6. Calibration curve of the METER Sensor.

Table 2. Calibration equations obtained for Water Advisory for Irrigation Scheduling System (WAISS) and METER sensors.

Sensor	Calibration Equation	R^2
WAISS	$y = 9.181 + \frac{33.518}{1 + \frac{x}{390.347}^{26.615}}$	0.9996
METER	y= 0.0562x - 26.877	0.996

The poor performance of the METER EC-5 sensor can be attributed to the generic calibration curve used on it. As stated by *Campbell* (*n.d.*), without density corrections, as is the case with dielectric moisture sensors, the error for mineral and agricultural soils is in the range of ±2.5% MC_V and much greater for organic and compacted soils. The readings from the factory-calibrated METER sensor may have been affected by the relatively high bulk density and biomass of the sandy loam soil used in this study.

Table 3. Soil moisture content by volume (MC_V) during calibration and percent error of Water Advisory for Irrigation Scheduling System (WAISS) and METER compared to the gravimetric method.

Gravimetric	**WAISS**	**METER**		**WAISS**	**METER**	
		Manually Calibrated	**Factory Calibrated**		**Manually Calibrated**	**Factory Calibrated**
9.17	9.19	9.29	9.29	0.26	1.38	28.00
11.97	11.89	12.63	12.63	0.64	5.54	3.08
16.34	16.44	15.56	15.56	0.61	4.79	2.08
21.94	21.88	21.85	21.85	0.27	0.41	15.21
30.22	30.23	30.48	30.48	0.04	0.88	29.95
Average				0.36	2.60	15.67

Note: Values in the table are limited to two (2) decimal places

The percent error for WAISS and the manually calibrated METER generally increased with averages of 7.81% and 7.45%, respectively, while the METER MCv was reduced to 10.45% (**Table 4**). The ECH_2O EC-5 sensor of METER uses a measurement frequency of 70MHz (METER 2020) while the DF Robot SKU: SEN0193 sensor of WAISS outputs at a variable frequency range of 260 Hz (high moisture) to 520 Hz (low moisture) (*Radi et al. 2018*). The wider frequency measurement range of WAISS during testing may have contributed to more accurate readings even at the lowest and highest readings as compared to the constant frequency measurements of METER. Even for cutting-edge sensors, it is better to calibrate them first with the local soil types before installation than to rely on factory-calibrated settings.

The RMSE values were computed to be 1.85%, 1.84%, and 2.36% for WAISS, the manually calibrated, and factory-calibrated METER sensors, respectively. The root mean square error (RMSE) indicates the absolute fit of the data to the calibration curve and how it overestimates or underestimates the measured values. Low RMSE values, as exhibited by the sensors, denote a better fit.

The average percent difference between the MC_V measured using the WAISS and METER sensors is10.15%, while the RMSE is 2.51% (**Table 5**). Low-frequency sensors, which are generally cheaper, are more sensitive to the effects of variabilities in soil properties such as texture, salinity, and temperature (*Nagahage et al. 2019 and Vaz et al. 2013*). Since the study operates under the assumption of constancy of these soil variabilities, the accuracy and precision of the WAISS sensor may be considered comparable to the state-of-the-art and expensive METER sensor.

While the METER ECH_2O EC-5 sensor can give direct soil moisture measurements, the WAISS DF Robot sensor needs the calibration curve. However, the tests showed that the manually calibrated measurements of the METER sensor are more accurate than the pre-calibrated values. The accuracy of these sensors highly depends on the accuracy of the calibration process.

Validation against three gravimetric soil moisture measurements revealed distinct accuracy levels between the two units (**Figure 7**). The WAISS unit demonstrated a notably lower percent error of 5.5%, while the METER unit exhibited a higher discrepancy at 16.1%, (**Table 6**).

Table 4. Soil moisture content by volume (MC_V) during testing and percent error of Water Advisory for Irrigation Scheduling System (WAISS) and METER compared to the gravimetric method.

Moisture Content by Volume Basis (%)				**Percent Error (%)**		
Gravimetric	**WAISS**	**METER**		**WAISS**	**METER**	
		Manually Calibrated	**Factory Calibrated**		**Manually Calibrated**	**Factory Calibrated**
9.25	9.23	10.30	11.00	0.28	11.32	18.87
12.73	11.98	12.58	13.30	5.86	1.18	4.51
15.40	17.75	16.13	16.80	15.30	4.73	9.11
23.91	26.71	21.70	22.90	11.73	9.22	4.21
29.85	31.60	33.09	34.50	5.86	10.82	15.56
Average				7.81	7.45	10.45
Root Mean Square Error (RMSE)				1.85	1.84	2.36

Note: Values in the table are limited to two (2) decimal places

Table 5. Percent difference and root mean square error (RMSE) of the Water Advisory for Irrigation Scheduling System (WAISS) and METER sensors soil moisture content by volume.

Moisture Content by Volume Basis (MC_V) (%)		Percent Difference (%)
WAISS	METER	
9.23	10.3	11.00
11.98	12.6	4.86
17.75	16.1	9.61
26.71	21.7	20.69
31.60	33.1	4.58
Average		10.15
Root Mean Square Error (RMSE)		2.51

Table 6. Percent Error of the field testing of the Water Advisory for Irrigation Scheduling System (WAISS) and METER sensors soil moisture content by volume.

Date	Daily Average MC_V (%)		Gravimetric MC_V (%)		Percent Error (%)	
	WAISS	METER	WAISS	METER	WAISS	METER
27-Aug 2019	47.6	40.8	48.78	50.29	2.4%	8.9%
30-Aug 2919	42	38.7	42.8	44	1.9%	12.0%
4-Sep 2019	40.9	33.4	46.58	40.46	12.2%	17.4%
Average					5.5%	16.1%

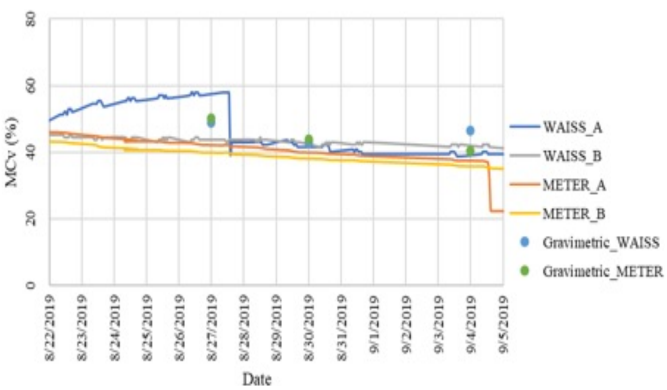

Figure 7. Actual soil moisture readings for Water Advisory for Irrigation Scheduling System (WAISS) and METER sensors.

CONCLUSIONS AND RECOMMENDATIONS

Water Advisory for Irrigation Scheduling System (WAISS) is a decision support system that provides site and crop-specific irrigation advisory and crop water management recommendations. It is comprised of a field unit and computer software. The field unit is comprised of a set of capacitance soil moisture sensors, a data logger and a 5-V solar panel. In its initial development, the WAISS capacitance soil moisture sensor was evaluated and compared to the state-of-the-art METER soil moisture sensor. While the WAISS sensor cannot directly give soil moisture content value without calibration like commercially available METER sensors, its measurements are more accurate with a percent error of 7.81% compared to 10.45% for the METER sensor. However, further calibrating the METER sensor reduced its percent error to 7.45%. Hence, the accuracy of these sensors highly depend on the accuracy of the calibration process. The computed Root Mean Square Error (RMSE) values of the MC_V measurements of WAISS and the manually and factory-calibrated METER sensors, compared to the gravimetric measurements were 1.85%, 1.84%, and 2.35%, respectively. This proves the WAISS sensor can provide comparable soil moisture measurements through an accurate site-calibration process. In the calibration process, higher soil moisture measurement errors can be attributed to the non-uniform mixing of water into the soil and/or non-uniform compaction of the soil within the different measurement zones. Therefore, more replications and on-site calibrations with different soil textures are recommended to increase the accuracy of measurements. Random testing of off-the-shelf soil moisture sensors should also be done to ensure consistency. Despite its lower cost, the WAISS sensor demonstrates comparable accuracy to the state-of-the-art METER sensor in assessing soil moisture. With a percentage error of 5.5% compared to METER's 16.1%, the WAISS readings align closely with gravimetric measurements. This highlights WAISS' potential as a cost-effective yet reliable alternative for soil moisture assessment across diverse applications.

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