High-resolution profiling of Soil Moisture Using Flat Thin Mm-sized Soil Moisture Sensors (MSMSs)

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High-resolution profiling of Soil Moisture Using Flat Thin Mm-sized Soil Moisture Sensors (MSMSs)

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High-resolution profiling of Soil Moisture Using Flat Thin Mm-sized Soil Moisture Sensors (MSMSs)

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Abstract

This MS thesis research has focused on the profiling feasibility of flat thin mm-sized soil moisture sensor (termed as MSMS) through field tests at UConn farm and Ethiopia farms. By etching on gold compact disc (CD), MSMS has the distinct merits of small size (mm-carbon interdigitated with 0.5 mm thickness), high accuracy of soil moisture measurement (10 kΩ-10 MΩ for 10%-50% soil moisture), good correlation of resistance readings with soil moisture, long stability (stable at least for half a year in lab tests) and easy fabrication (<1 hr fabrication for each sensor), and low cost (<$1 each sensor), which make it possible for deploying in high amounts for a given field. The 10-month field tests at UConn Farm well demonstrated the profiling capability of MSMS along soil depth (1 meter). The long-term stability and reading accuracy of MSMS was side-side compared with commercial sensors through summer and winter seasons. Furthermore, MSMS mass production was explored to ensure the consistent quality for future mass application of MSMS. The tests have revealed five main factors including nitric acid concentration, thermal press time, etching time, printing density and stirring strength for MSMS quality. A constant nitric acid concentration, time of thermal press reaches to 110s and 13-14 minutes etching time with stirring at 50 rpm will ensure the quality of MSMS sensors. Finally, over 100 pieces of MSMS have been fabricated under quality control and then installed at four farm sites in Ethiopia. The on-going year-long tests will collect the in situ soil moisture data from these MSMS sensors and provide high-resolution date for soil mapping and achieving water-saving irrigation.
Chapter 1: MSMS profiling long-term field test for water-saving irrigation

This study targets at developing flat thin mm-sized soil moisture sensors (MSMS) to solve the long-stand problems of soil moisture profiling: low spatiotemporal resolution, high cost of sensors and disturbance of soil structure during sensor installation. The 10-month field tests conducted at a farm site compared MSMS with commercial capacitance-type soil moisture sensors (SMS) in terms of profiling capability and accuracy, sensitivity to environmental variations (e.g. water shock, temperatures, dry/wet seasons) and long-term stability. Three pieces of MSMS sensors were mounted on the shallow, middle and deep locations of a hollow plastic rod (length: 1.1 meter) and installed along the soil depth to profile the soil moisture variation. The resistance readings of MSMS sensors along soil depth were recorded in a real-time mode and verified with the water content readings of the commercial sensors. Due to soil settlement over time after installation, the MSMS sensors in the shallow soil suffered from unstable readings, while the MSMS sensors in the middle and deep soil exhibited high stability and had the best correlation with water content values of commercial sensors with $R^2$ value of 0.6264. The contact between MSMS surface and soil particles appeared to be a critical factor determining the stability of MSMS readings. In addition, MSMS sensors showed a prompt response to the sharp change of soil moisture in the water shock tests. The soil moisture profiles collected from MSMS sensors in the middle and deep soil exhibited the spatiotemporal variation of soil moisture, which enabled the simultaneous profiling of soil moisture at multiple locations. This field study clearly demonstrated the great potential of mass deployment of low-cost but accurate MSMS sensors to achieve high resolution profiling of soil moisture in a given field for water-saving irrigation.
1.1 Background Introduction

Soil moisture plays a fundamental role in agricultural and farming decision making, and affects crop production under diverse climate conditions [1,2,3]. Accurate soil moisture sensing is essential for irrigation to ensure water availability and to prevent wasteful over-irrigation. In some places (e.g. Florida and California in the United States), nursery irrigation water usage amount has been limited by 40% in the past two decades due to tight restrictions (e.g., Clean Water Act) [4]. Therefore, monitoring soil moisture is a critical strategy in irrigation water management [5].

Until now, soil moisture data collected from remote sensing technology such as radars and radiometers onboard satellites have suffered from low resolution with a magnitude of square kilometers [6]. In contrast, in-situ soil moisture sensors (SMS) deployed in the field with a measuring radius of several meter square can offer a finer measurement. Normally, these SMSs are placed in soil at different depths (e.g. several centimeters to couple meters) and connected with data loggers through wires or wireless capable of uploading the data to remote central database for processing [7]. The most widely used SMSs are neutron probes, tensiometers, and gypsum blocks. Specifically, neutron probes are accurate but hard to calibrate and interpret, and have a problem of radiation hazard [8]. Tensiometers has a limitation of a soil water potential range from 0 to 70 kPa with a substantial narrow range in coarse-textured soils (e.g. sand) [9]. On the other hand, gypsum resistance soil sensor depends on soil water potential instead of soil water content, as the soil resistivity decreases with the increase in soil moisture content, and thus it measures the resistance as the parameter for soil moisture. Although gypsum sensor is inexpensive, it has fatal problems of slow reaction time, gypsum dissolution, clay deposition, and low stability. In addition, the sensors will lose contact with soil slowly over time and fail in giving a consistent reading of soil moisture [10,11].
Besides precision agricultural irrigation, high-resolution profiling of soil moisture along soil depth is critical for elucidating soil formation, ecosystem biogeochemistry, contaminant degradation, and groundwater quality [12-15]. Until now, the soil water content profiles have been conducted using vertical Time-domain reflectometer (TDR) probes of different lengths and horizontally embedded probes, which suffer from several limitations, such as multiple pieces of bulky sensors on different locations could cause the error associated with soil spatial variability at both vertical and horizontal directions, vertical heterogeneity, and steep wetting front [16].

Flat flexible mm-sized SMS (termed as MSMS) was developed to solve the abovementioned problems of soil moisture profiling [17]. By etching on gold compact disc (CD), MSMS has the merits of small size (mm-carbon interdigitated with 0.5 mm thickness), high accuracy of soil moisture measurement (10 kΩ-10 MΩ for 10%–50% soil moisture), good correlation of resistance readings with soil moisture, long stability (stable at least for half a year in lab tests) and easy fabrication (<1 hr fabrication for each sensor), and low cost (<$1 each sensor), which make it possible for deploying in high amounts for a given field. Although the lab-tests (small soil container with a diameter of 11cm and a depth of 8.8 cm) clearly demonstrated these MSMS advantages in different types of soil (several mixtures of pure sand, silt and clay) [18], MSMS long-term stability, reading accuracy and profiling capacity under different environmental conditions and have not been tested in real-world scenarios, which motivated this field study.

1.2 Research objective of the MSMS field tests

The objective of this study was to examine the profiling capability, stability, accuracy and sensitivity of MSMSs in the field under different scenarios (e.g. dry/wet seasons, temperatures, soil disturbance, soil structure, soil salinity, and water shocks). To achieve soil moisture profiling
along soil depth, multiple pieces of MSMS sensors were mounted on small slots along a long plastic rod and inserted into soil. There were five tasks in this study. First, MSMS and commercial SMS were installed in a farm land of University of Connecticut (UConn) with a typical farm soil structure. The resistance and capacitance readings of MSMS sensors were recorded at three soil depths (shallow, middle and deep) and side-side compared with commercial SMS. Groundwater table measurement was conducted in a well next to the installation field as the reference of soil moisture. Second, the reading stability of MSMS along soil depth was examined over 10-month period (July 2017 to May 2018). The long-term impact of soil settlement on the contact between MSMS sensor surface and soil particles was determined. Third, the sensitivity of MSMS to water shocks was examined by pouring high volume of water onto the sensor installation site and the response time was recorded and compared with commercial SMS. Fourth, the profiling capability of MSMS was examined over 4-month period to elucidate the variation of soil moisture at different soil depths under different seasons. Finally, the water saving using MSMS sensors was estimated and high-resolution spectra-temporal profiling of soil moisture using MSMS was explored.
1.3 Material and methods

1.3.1 Mm-sized soil moisture sensor (MSMS) profiling kit assemble

**Figure 1.** Installation of the sensor kits with multiple pieces of MSMS sensors (a) and multiple pieces of commercial sensors individually (b) along soil depth in the field tests.

MSMS sensors were fabricated using a golden compact disc (CD) and covered with a layer of carbon ink [17]. The disc was first soaked into a strong nitric acid (concentration: 70%) to remove the plastic layer, and then a carbon pattern was transferred onto the CD using a thermal press (Model: Maxx garment heat press). The dimension of each MSMS sensor was 3cm×5cm. The MSMS sensor was then mounted on a 3-D printed flat hard-plastic support (7.5cm × 3.5cm, **Figure**
which was made with a slight slope (27%) in order to facilitate the firm contact between MSMS sensor surface and soil (Figure 1a). The MSMS were nailed onto the support through the metal pad of MSMS, which served as the conductivity with the extension wire (Figure 1a). Afterwards, three pieces of MSMS sensors were individually inserted into the slim slots (width: 3.5 cm) on a flat hollow plastic rod (length: 110 cm, width: 4 cm) 35 cm apart (Figure 1a). The rod was used for easy deployment and alignment of multiple MSMS sensors along soil depth in the field tests. The extension wires from each MSMS were individually pulled through the rod and connected with a data logger (Model: Hantek 365D) for data recording and storage (Figures 1a).

MSMS readings were compared with commercial capacitance-type soil moisture sensors (SMS, model: ECH2O EC-5), which is a flat SMS commonly used for soil moisture measurement (Figure 1b). The size of the commercial sensor was 2 cm × 6 cm. The accuracy was ±3% volume water content for most mineral soils. It should be noted that unlike MSMS with only one single side (the top side of sensor) facing soil and in contact with soil particles (Figure 1a), the commercial SMS fully contacted soil particles with all-around surfaces (Figure 1b).

1.3.2 Field tests of MSMS profiling

The field tests were conducted at University of Connecticut (UConn) Research Farm (59 Agronomy Road, Storrs, CT 06268). The 153-acre farm is partially wooded for active cultivation. The soil of this farm is mostly glacial till, a typical soil type in the New England area. Due to the close correlation between soil moisture and soil structure [18], minimal disturbance to soil structure was recommended for installation of SMSs. However, because the hollow plastic rod was used in this study to hold three MSMS sensors through slim slots (Figures 1a and 1a), it was quite difficult to directly punch the hollow rod into soil without damaging the MSMS sensors. Therefore,
an installation site (size: 1.5m × 1.5m) was first excavated on the field, and then three narrow holes (width: 3.2cm width, depth: 7cm) smaller than MSMS were dug on the side wall (Figure 1a). Afterwards, the rod was vertically installed inside the site against the side wall with three pieces of MSMS sensors being individually and firmly squeezed into each narrow hole for full contact with soil particles along soil depth (Figure 1a, shallow MSMS: 7 cm below the ground, middle MSMS: 40 cm below the ground, and the deep MSMS: 75 cm below the ground). It should be noted that soil structure was somewhat disturbed during installation, which could affect the MSMS readings in the initial test period.

Along with the MSMS sensors, three commercial SMSs were installed in a pre-dug site (size: 2cm × 6 cm) 0.5 meter away from the MSMS installation site. Each commercial SMS was installed at the same soil depth as the MSMS sensors (namely, shallow sensor: 7cm, middle sensor: 40cm, and deep sensor: 75cm below the ground) for side-by-side comparison (Figure 1b). Unlike the MSMS sensors being mounted on a long hallow rod to protect the extension wires and align the MSMS sensors during installation (Figure 1a), the commercial SMS had the waterproof wires and the sensor itself was much more sturdy (Figure 1b), and thus were directly inserted into soil without the need of being mounted on a rod (Figure 1b).

The field tests of MSMS profiling lasted 10 months (July 2017—May 2018), during which the seasonal impacts on soil moisture and MSMS reading accuracy were examined through the daily measurement from July to October 2017, and the long-term stability of MSMS in harsh weathers especially soil freeze and thaw was examined using the monthly measurement from November 2017 to May 2018. The resistance and capacitance readings of each MSMS sensor were collected along soil depth on the daily base and then converted to soil moisture values (% v/v)
based on the calibration curves, while the commercial sensors’ readings collected on the daily base were directly the soil moisture values (% v/v). Along with the steady status in the field tests, the shock test was conducted to examine the sensitivity and the profiling capability of MSMS sensors under sharp changes of soil moisture. The shock test was performed by pouring 10L water on the top of the soil at the installation site individually for two times within 2 hours. The resistance readings of MSMS sensors and the soil moisture readings of commercial SMS along soil depth were recorded simultaneously before and after shock tests.

1.3.3 Lab validation tests of MSMS sensors.

Field tests of soil moisture sensors came across many unexpected scenarios, such as soil disturbance, soil settlement, loose contact with soil particles, variation of soil structure and soil salinity along soil depth over time [18], which would affect the accuracy of MSMS sensors tested. To validate the readings of MSMS sensors in field tests, the lab-tests under well-controlled environment were conducted for MSMS sensors and commercial SMS. To best resemble the field test environment, the lab tests used soil samples taken from the installation site on the UConn farm. A MSMS sensor and A commercial sensor were installed side-by-side in a container (diameter: 11cm, depth 8.8cm) holding 300 g dried soil sample (Figure S1) Because the soil had been firmly compacted in the container, the sensors would have a tight contact with soil particles, which was much better than the possible loose contact and varied soil structures in the field tests. Furthermore, to make water uniformly infiltrate through soil in the container, the soil surface was covered with a filter paper (Fisher Scientific, Grade: P4, porosity: Medium fine, format: circle) before adding water. Afterwards, 30 ml deionized water was gradually added into the container, and water slowly and uniformly penetrated throughout the soil covered by the filter paper. The readings of MSMS
sensor and commercial sensor were recorded within the next 3 hours after adding water, and the data were real-time stored using a data logger (Model: Hantek 365D). The lab test results obtained under this well-controlled environment were compared with the field test results to validate the MSMS readings under various conditions and identify the critical factors affecting MSMS accuracy in field tests.

1.4 Results and discussion

1.4.1 Resistance readings of MSMS sensors during 9-month field tests

The resistance readings of MSMS sensors reflect the soil resistivity, in which the soil acts as a resistor [19] Dry soil is an isolator and resists the flow of the electrons between interdigitated electrodes of SMS [20,21]. With the increase in the soil moisture, water gradually replaces the air contained in the soil pore and increases the conductivity of the soil, and thus transforming the soil from an insulator into a conductor. The correlation of soil moisture and resistance is described in Eq. (1).

\[
\frac{R}{R'} = K' \theta \quad \text{Eq. 1}
\]

Where \( R \) is the resistance of the soil tested, \( R' \) is the resistance of the soil saturated with water, \( K' \) is the parameter related to the soil texture [19,20], and \( \theta \) is water content.

The daily readings of the 4-month field tests (July-October 2017) clearly showed that the resistance readings of MSMS sensors varied along soil depth (shallow: 7cm below the ground, middle: 40cm below the ground, and deep: 75cm below the ground). The linear regression of the resistance readings of MSMS sensors and soil moisture readings of commercial sensors varied along soil
depth. Specifically, the MSMS readings on the shallow depth (7 cm below ground) were poorly related with the soil moisture readings of commercial sensor ($R^2$ value: 0.1392) (Figure 2), which might be caused by the soil settlement over time after MSMS installation. Soil structure was disturbed during installation and became loose (Figure 3a). Although the MSMS kit was inserted firmly into soil on the side wall (as shown in Figure 1a), the contact between MSMS sensor surface and soil would become loose when soil started to settle over time. This impact would be the most significant in the shallow soil, where MSMS sensor was stuck in the slim slot of the rod (as shown in Figure 1a) and could not move downward along with soil. The shallow soil granules are subject to low pressure and are therefore more vulnerable to easily affected by the external force from the ground such as wind blowing or animal walking (Figure 3a). On the contrary, the deep soil handled a higher gravity pressure accumulated from shallow and middle soil layers, which made the structure more condense and the soil granules would not settle easily (Figure 3a). In addition, water content (% v/v) and water salinity had been found to vary with soil depth [22] and water conductivity increased along soil depth due to dissolution of minerals into water [23], which would also affect the soil resistance [24] and be reflected by the variation of sensor readings along soil depth.

For the MSMS sensor in the shallow soil (7 cm below surface), it had low resistance (about 10 k$\Omega$-200k$\Omega$) in the 1-5 days and then the reading sharply jumped to about 1500 k$\Omega$ (Figure 2a). The main reason was the incomplete contact between MSMS sensor and soil. Due to the interference from the external force of the ground, the shallow layer of soil may experience the biggest structure change and cause incomplete contact between the sensor and the soil over time (Figure 3a). During 11-17 days, the resistance reading of the MSMS kept decreasing from 1800
kΩ to 600 kΩ ohm, while the water content reading of the commercial sensor remained relatively stable at 5%, which might be caused by the relocation of soil over time and the enhancement of the contact between MSMS sensors and soil. After 25 days, the soil became wet with the water content of 60 %, and the contact between MSMS sensor surface and soil became stable, leading to a stable reading of MSMS sensors. The resistance readings in 1-5 days were much lower than the ones after 11 days, indicating the adjustment of MSMS sensor immediately after installation. Similar trend of resistance readings was also observed in lab experiments [20]. From day 6 to day 25, the resistance readings of MSMS fluctuated between 200 kΩ and 1800 kΩ, while the water content readings varied 0.4-0.6 in the commercial sensor. Previous studies had found that water contents affected the reactions extent of resistance change response [20]. Furthermore, temperature change in shallow soil [25] could also contribute to the fluctuation of MSMS readings, since the sensor on the shallow layer of soil was easily affected by the atmospheric ambient temperature (22 ºC- 27ºC) throughout the 4-month test period. Correspondingly, the R² value of the correlation between MSMS sensors and commercial sensor was 0.4168 for the data collected in the first 26 days (Figure 2b), while the R² value dropped to 0.1343 for all the data collected throughout the 4-month period (Figure 2c), which was caused by the loose contact on the shallow soil layer. The weather became dry after 26 days, and affected the shallow soil substantially. Soil became detached from the MSMS sensor surface, leading to the unstable resistance readings and the poor correlation with the soil moisture readings of commercial sensors.
Figure 2 The side-side comparison of the resistance readings of MSMS at the shallow depth (7 cm below the ground) and the commercial sensors over time and the linear regression. (a: the variation of MSMS data and commercial sensor data throughout the test period, b: the correlation of MSMS data with commercial sensor data in the first 26 days, c: the correlation of MSMS data with commercial sensor data throughout the test period.)
Figure 3. The contact of MSMS sensor and soil during soil sink along soil depth (a) and the contact of commercial sensor and soil during soil settlement (b).

For the MSMS at the middle depth (40 cm below ground), it had a better linear relationship with commercial sensors with the $R^2$ value of 0.5571 (Figure 4). Soil was relatively dry in the first 18 days, with the soil moisture of 20%-50% in the commercial sensor. Correspondingly, MSMS sensor fluctuated at 10 kΩ -1000 kΩ, which was more stable than the one at the shallow depth (reading range: 10 kΩ -1800 kΩ, Figure 2). The possible reason was that the soil structure became compact along soil depth and less sensor displacement occurred than on shallow layer of soil (Figure 3a), and thus making the reading of the middle MSMS sensor stable. From the 18th day, the resistance readings of MSMS dropped substantially to 400 kΩ, and then stabilized, while the water content reading of the commercial sensors dropped to 30%. Theoretically, high water content
in soil should lead to low resistance [26]. However, the abnormality occurred when dry soil caused the poor contact between the sensor surface and soil particles, leading to a sudden drop of the resistance readings even at low water content. Nevertheless, the correlation of determination (R² value) between MSMS sensors and commercial sensors in the first 18 days was as high as 0.9429 (Figure 4b), indicating that MSMS has a good linear correlation with water content as long as the contact with soil particles remained firm. However, the R² value dropped to 0.5571 for the data collected throughout the 4-month period (Figure 4c), due to the loose contact between MSMS sensors and soil after day 26, but was still better than that of the shallow MSMS sensors (Figure 2c).

**Figure 4** The side-side comparison of the resistance readings of MSMS at the middle depth (40 cm below the ground) and the commercial sensors over time and the linear regression. (a: the variation of MSMS data and commercial sensor data throughout the test period, b: the correlation
For the MSMS at the deep depth (70 cm below ground), the reading exhibited the best linear relationship with the commercial sensors ($R^2$ value: 0.6264, Figure 5), which was attributed to the tight contact between MSMS sensor and soil in the deep soil (Figure 3a). The contact between soil and sensor surface is important for soil moisture sensors, since the air conductivity ($3 \times 10^{-15} \text{ S/m}$) is much lower than that of water ($5 \times 10^{-3} \text{ S/m}$) [27]. Once the contact becomes loose, the soil moisture sensors actually measure the resistance between air and sensor surface instead of the resistance between water and sensor surface, which could lead to a meaningless high resistance readings. Due to the disturbance of the soil structure at the sensor installation (Figure 3a), soil started to settle in the first several days and affected the contact between MSMS sensors and soil, leading to the unstable readings for the MSMS sensors at the shallow and middle depths (Figures 2 and 4). However, soil settlement had the minimal impact for the MSMS sensors at the deep depth due to the heavy weight of soil above the MSMS sensor, and did not affect the contact with the soil, and thus showing the best performance among three soil depths. On the 4th day, there was a sudden drought and caused a sudden rise of resistance readings of MSMS sensors to 760 $\Omega$ and then dropped and stabilized at 10 k$\Omega$, which was well corresponded with the variation of the water content readings (17-47%) of commercial sensors (Figure 5b). During 23rd -31st days, the sudden continuous hot weather dried soil and the MSMS readings increased to 1400 k$\Omega$, which might be caused by the loose contact between sensor surface and dry soil particles. On the 34th day, wet season started and increased water content to 34%, which was well indicated by commercial
sensors. Correspondingly the resistance readings of MSMS sensors dropped to 1200 kΩ. The rest 20 days experience a long but stable weather condition, and thus the water content stays at the same level. MSMS sensor also shows a pretty stable status at this period. It was noticed that the MSMS kit was pretty firm with the soil in the first 26 days, and was well correlated with soil moisture readings of commercial sensors (R² value: 0.986, Figure 5b). But the lingering dry weather afterwards might cause the soil cracks and change the soil structure [28], resulting in the difference in the relationship between the resistance readings of MSMS sensors and the water content, as indicated by the lower R² value (0.6264, Figure 5c).

**Figure 5.** The side-side comparison of the resistance readings of MSMS at the deep depth (75 cm below the ground) and the commercial sensors over time (a: the variation of MSMS data and commercial sensor data throughout the test period, b: the correlation of MSMS data with commercial sensor data in the first 27 days, c: the correlation of MSMS data with commercial sensor data throughout the test period.)
It should be noted that three pieces of MSMS sensors were mounted on the slim slots of the long hollow rod and then inserted along soil depth (Figure 1a), while three commercial sensors directly buried into the soil individually along soil depth (Figure 1b). This installation difference would affect the sensor movement afterwards, during which MSMS sensor stuck on the slots of the rod could not move along with soil (Figure 3a) while the commercial sensor could move along with soil when soil settles after disturbance (Figure 3b). Thereby, the contact between commercial sensor and soil did not vary along soil depth, and commercial sensor exhibited a more smooth reading than MSMS sensors over the 4-month test period (Figures 2a, 4a and 5a). Integrating the commercial sensor’s water content (%) readings and MSMS’ resistance readings (kΩ) demonstrated that MSMS can detect pretty low water content (<35%, Figures 2, 4 and 5), which had been regarded as dry soil and caused unreasonably high readings for previously reported soil moisture sensors [20]. The middle sensor and deep sensor has the similar R^2 values (0.5771 and 0.6264), and a very close regression equation (Eq. 2). The regression was better than the reported commercial sensors (capacitance, R^2<0.6) [29,30]. Overall, the resistance readings of MSMS showed similar accuracy (R^2 around 0.6, in the middle and deep locations) as the reported resistance moisture sensors [19]. It should be noted that compared with the resistance-type soil moisture sensors previously reported (size: 5×30 cm) [31], MSMS has a much smaller size (2.5×5 mm), which minimizes the disturbance of the soil structure during soil settlement after installation. MSMS sensors had the resistance readings of 10 kΩ to 1800 kΩ, somehow higher than the reported sensors (0.005 kΩ -466.7 kΩ) [31], which might be attributed to the sensor shape. MSMS was made from inter-digitated mm-sized carbon power electrodes [17], while the MTG (moisture
temperature and gas) sensors were made in a cylinder shape and covered with stainless mesh. The high value in resistance may be caused by the different material and shape of these sensors.

\[
\text{Water content (\%)} = 0.0002 \times \text{MSMS (resistance, kiloohm)} + 0.61 \quad \text{(Eq. 2)}
\]

Along with the MSMS readings on the sensor installation site, the groundwater level obtained from the well 1.2 meter next to the installation site indicated that that MSMS readings could provide the profiling of the water level. A big change in the MSMS resistance was observed when the sensors were below and above the water level (Table S1). The resistance values of MSMS sensors were around 10 kΩ when the MSMS sensors were below the water level, while the resistance values were above 100 kΩ when the MSMS sensors were above the groundwater level, indicating that MSMS kits could be used for groundwater level monitoring. When the groundwater level approaches to a warning value, it can be detected in advance using the multiple pieces of MSMS sensors installed along soil depth to prevent the potential flood.
Figure 6. The side-side comparison of the capacitance readings of MSMS at the shallow depth (7 cm below ground) and commercial sensors over time (a), and the correlation between capacitance readings of MSMS and commercial sensors in the first 6 days (b).

Besides the resistance readings, capacitance has been used for the soil moisture measurement [32]. The interdigital-shaped MSMS could measure the capacitance of soil moisture [17]. Due to the big difference in dielectric constant between air (1.0005) and water (80.4), the capacitance readings were expected to increase with soil moisture [33]. Capacitance readings of MSMS were collected along soil depth (shallow depth shown in Figure 6a and middle and deep depth shown in Figure S2). In the first 6 days, the MSMS and the commercial sensor were correlated well with the R² value of 0.7282 (Figure 6b), which might be attributed to the good contact with soil. But the capacitance could be affected by environmental factors (e.g. soil structure soil salinity) to a higher
extent than resistance readings, which resulted in the unstable readings. After the 6th day, the capacitance reading of MSMS became unstable (Figure 6a). For example, it became zero on Days 7, 9, 11, 12 and 14, and were incredibly high (over 10000 nF) during other days. The capacitance readings of the MSMS sensors at the middle depth and the deep soil were even worse (Figure. S2). The reason for this poor capacitance reading was that the data logger used in this study (Hantek 365) did not have high resolution under 1 nF [33, 34], so that low capacitance (<1 nF) at the soil moisture (around 50%) could not be differentiated using the data logger and only “zero” capacitance readings were obtained.

1.4.2 MSMS response to sharp change of water content in the shock tests

Water shock test was conducted to examine the response and profiling capability of MSMS to the sharp change of soil moisture (water content) before and during precipitating events (e.g. thunderstorm). To simulate the water shock occurring in short duration (e.g. less than 1 minute), a bucket of fresh water (20L) was poured on the top of the sensor installation site, and the resistance readings (kΩ) of MSMS and the soil moisture readings of commercial sensors were real-time recorded along soil depth before and after the water shock. The duplicate water-shock tests (in the 1st minute and 69th minute, Table S2) showed that MSMS sensors in the middle soil depth had a better sensitivity to the water content change than the commercial sensors by responding quickly (Figure 7a), which was attributed to the shape of the interdigitated electrode allowing more direct interaction with the surrounding environment [35]. The respond time was defined as the duration period that the soil sensor readings (e.g. resistance value and water content value) started exhibiting the sharp change that was incurred by the water shock and later on reached a steady state. MSMS sensors had the time resolution of 20 seconds and the respond time was under 20
seconds (red data points in Table S2, e.g. the MSMS readings (kΩ) started the sharp change from 329.00 at the 220\textsuperscript{th} second and quickly stabilized at 121.29 at the 240\textsuperscript{th} second in the middle location under the first water shock). In contrast, the commercial sensor only had the time resolution at the minute scale, and took around 3 minutes to reach a steady state (red data points in Table S2, e.g. the commercial sensor (1- \(\theta\)) exhibited the sharp change from 0.7330 at the 5\textsuperscript{th} minute, dropped to 0.7126 at the 6\textsuperscript{th} minute and then stabilized at 0.6803 at the 7\textsuperscript{th} minutes in the middle location under the first water shock). MSMS exhibited a much better sensitivity than previously reported capacitance-type soil moisture sensor (response time over 300s) [36].

The MSMS sensor at the deep soil depth exhibited a similar pattern as the middle one (Figure 7b), represented by a clear and fast response to water shock. Furthermore, the deep MSMS sensor had a more consistent reading variation with the commercial sensor (Figure 7b), and the trend was much smoother than the middle MSMS sensor (Figure 7a), which reinforced the benefit of firm contact with soil particles for stable sensor readings (Figure 3a). Therefore, MSMS sensors had the capability of real-time profiling of water shocks in soil at the temporal resolution of second (s).
1.4.3 MSMS profiling of soil moisture along soil depth

Because MSMS at the middle and deep depths had exhibited stable performance over time (Figures 4a and 5a), the readings at these two depths were profiled and compared with the commercial sensor to examine the profiling capability of soil moisture along soil depth to capture the impacts of weather conditions (e.g. raining and dry reasons and hot weather) on soil moisture. To make the MSMS data (resistance, Ω) the same trend as the commercial sensor data (water content, %), the resistance reading of MSMS was converted to an indicator of $\log_8 R$ (The value 8 was the lowest resistance reading among all the MSMS data during the field test period). By using this indicator ($\log_8 R$), the MSMS calculated values would have the same trend of variation as the commercial sensors at the significant time points (e.g. temperature rise, heavy rain).

Figure 7. MSMS sensors and commercial sensors under the water shock tests in the middle depth (a) and in the deep depth (b).
Both MSMS and commercial sensors clearly showed the differences between middle depth and deep depth in the first 3 days (air temperature: 27 °C), during which water content in the deep depth was lower than in middle depth and changed drastically (Figure 8). On the 4-5\textsuperscript{th} day, signal from both types of sensors picked up the occurrence of drought event, during which the calculated values of MSMS quickly dropped from 0.7 to 0.3, and the water content readings of commercial sensor dropped from 0.5 to 0.25. On the 6\textsuperscript{th} day, water content value of the commercial sensors jumped back to 0.45 due to a heavy rain, and correspondingly the calculated value of MSMS rapidly increased to 0.7. Because of the soil soaking by heavy rain, the profiles at the middle depth and deep depth converged, indicating the soil column is at or close to saturation.

On the 15\textsuperscript{th} day when hot weather occurred (air temperature: 31°C), the water content readings of commercial sensors dropped from 0.45 to 0.35, and the calculated values of MSMS dropped from 0.8 to 0.3 (Figure 8). The profiles of the middle depth and deep depth started to diverge, reflecting the variation of soil moisture along depth. From the 16\textsuperscript{th} to 22\textsuperscript{nd} day, the profiles of both MSMS and commercial sensors at the deep depth kept the same water content of 0.5, while the profiles at the middle depth plunged to 0.4 on the 18\textsuperscript{th} day. The declining extent of the MSMS was noticeably larger than that of commercial sensors, which might be caused by different water flow pathways around these two types of sensors [37]. The soil structure might be different at the MSMS installation site and the commercial sensor installation site, which were about 0.75 meter apart. Water might flow through soil granules easier at the MSMS site than at the commercial sensor site. Specifically, the profiles at the middle depth and deep depth became closer after the heavy rain on the 6\textsuperscript{th} day and both showed high water content. When the hot weather came on the 15\textsuperscript{th} day, soil
water at the MSMS site evaporated quickly and caused the sudden drop at the middle depth, while the deep depth reading was not affected much and only dropped a bit. In contrast, soil water at the commercial sensor site evaporated slowly, and only caused a small drop on water moisture profile in the middle depth. With the hot dry weather continuing to the 25th day, soil moisture dropped substantially to 0.2 (Figure 8). The profiles in the middle depth and deep depth of both types of sensors converged again, indicating that moisture in the soil column is mostly depleted and there was no variation of soil moisture along soil depth. Profiling tests clearly demonstrated that MSMS had a good capability of realistically monitoring soil moisture along depth.

**Figure 8.** Soil moisture profiles obtained by MSMS sensors and commercial sensors in the middle and deep locations under different weather conditions.
High resolution profiling of soil moisture along soil depth using low-cost MSMS sensors has a great potential for precise agriculture and water-saving irrigation. Due to different rooting profile and depth of crops (e.g. potato: ~54 cm, edible bean: ~60 cm, and field corn: ~105 cm), the water uptake capability of crops and its vertical distribution are different [38,39], which causes different water uptake along soil depth. Traditional irrigation only used water based on empirical values and/or based on weather conditions [40]. In contrast, accurately profiling the variation of moisture along soil depth can tailor the irrigation needs for different crops and eventually enhance the crop output with the lowest water consumption [41]. For example, the MSMS profiles showed that the water content between middle depth (40 cm) and deep depth (75 cm) was different during the dry episode (Figure 8). The irrigation extent can be adjusted accordingly based on the rooting depth of crops to prevent over-irrigation or insufficient irrigation. In response to the abrupt changes related to precipitating events or sudden onset of dry hot weather as represented by 4th-7th days and 15th-24th days (Figure 8), the soil moisture along depth changed drastically over short period of time, so high resolution MSMS profiling can enable the precise irrigation for different types of crops under shock events.

After the daily collection of sensor readings from July to October 2017, the long-term stability of the MSMS sensor, especially its durability under harsh conditions (e.g. soil freeze and thaw) was continuously examined through the monthly data collection from November 2017 to May 2018, during which temperature varied drastically (-4 to 24 °C). The results showed the resistance readings of MSMS sensors at the deep depth were 8-10 kΩ after snow and raining at low temperature and the corresponded soil moisture reading of the commercial sensor was 56% (Table S3), which were well correlated with the MSMS readings at the hot raining seasons (9-10 kΩ in
July and August 2018, Table S3). The good durability of MSMS sensors under soil freeze and thaw throughout the winter and spring seasons was attributed to the stable sensor materials (carbon layer and golden CD surface, Figure 1a) not reacting with the surrounding soil compounds over long period.

1.4.4 Lab validation tests of MSMS sensors

The MSMS values obtained in the field tests under various scenarios were validated using the lab tests conducted in a well-controlled environment. Unlike the possible loose contact between MSMS sensor surface and soil particles and many unknown interferences on the ground that could affect the MSMS readings, the lab-tests conducted in the small chamber ensured the tight contact between MSMS sensor surface and soil particles. The lab results showed that the resistance readings of MSMS sensors clearly dropped with the water content (Figure 9), following the same pattern as in field tests (Figures 2a, 4a and 5a). The slope of the linear regression between the MSMS resistance readings and the soil moisture in the lab tests was 0.00004 (Figure 9), which falls well within the slope range of the linear regression of the MSMS sensors in the field tests (shallow depth: 0.000005, Figures 6b and 7b; middle/deep depths: 0.0002, Figure 4b), indicating the consistence of the MSMS sensors under varied conditions. Specifically, there were many external disturbance (e.g. ground stepping, soil settlement, loose contact between MSMS sensor surface and soil particles) and many uncertainties (e.g. seasonal change, salinity variation along soil depth, temperature variation) in the field tests, while the well-controlled environment with the minimal disturbance was assured in the lab tests and the MSMS sensor surface was always in tight contact with soil particles. However, the slopes of the regression between MSMS sensors and soil
moisture under these two vastly different test environments were still quite close, which well validated the accuracy of the MSMS sensors in the field tests.

Figure 9. The correlation between MSMS resistance readings and soil moisture in the lab validation tests.

1.4.5 Potential issues associated with MSMS deployment in field

Although MSMSs have prevailing advantages of small flat configuration, low cost and easy installation, the readings of MSMS could be affected by soil settlement and soil property (e.g. soil particle size, salinity), which requires the on-site calibration before installation and the periodical check of MSMS reading in the initial stage before reading becomes stable. The ideal scenario for MSMS is to minimize soil disturbance during installation while still maintain firm contact with soil particles in the long run. However, it is almost impossible to meet both requirements simultaneously and certain compromise has to be made sometimes. In this field study, three pieces of MSMS sensors were inserted into slim slots on a hollow rod and squeezed firmly into the side wall of the installation site (Figure 1a), which required pre-digging and resulted in soil disturbance and soil settlement over time. Furthermore, MSMS fixed on the narrow slot on the rod could not
move along the settling soil around the sensor (Figure 3a), leading to partial loss of contact over time. The field tests showed that soil settlement clearly affected the contact between MSMS surface and soil along soil depth, with the shallow depth being affected the most (Figure 3a) and the deep depth being affected the least (Figure 3a). Previous study also found that the surface of dielectric sensors were sensitive and any loose contact between the soil and the sensor would result in measurement errors [42]. Furthermore, MSMS fabricated in this study only had one side of CD etched and in contact with soil (Figure 1a), while the commercial SMS had all-around surface in full contact with soil (Figure 1b) and therefore a large contact area and stable readings. Feasible solutions could be the development of MSMS with both sides of CD to enable full contact with soil particles so to enlarge the effective sensor surface area and ensure stable readings. MSMS sensors could also be directly inserted into soil at different depths without being mounted to a rod so that the sensors would settle together with the soil and maintain full contact with soil particles (Figure 3a). Another solution could be to design a MSMS drilling/digging tool with MSMS on the tip of the driller so that MSMS can be directly installed onto the desirable soil depth with minimal disturbance of soil structure and firm contact with soil. These are topics of follow-up research and development.

1.4.6 Significance of MSMS profiling for water-saving irrigation

Precise profiling of soil moisture at high spatiotemporal resolution using low cost MSMS has a great potential for precise irrigation and groundwater monitoring. High cost of existing SMS (over $200-1000 each sensor) prohibits deploying high number of sensors (e.g. 100-2000 sensors) in a given field to achieve high-resolution monitoring and profiling. Previous study had found that a 20-sensor node system with a total cost of $2500 can provide a better spatial characteristics of soil
moisture in a field (23000 m$^2$) [43], and the micro-irrigation based on these high-resolution profiling of soil moisture achieved the highest efficiency of 35% of water saving. This field study has demonstrated that with low cost MSMS sensor (less than $2 each piece), more accurate profiling of soil moisture in large field (e.g. large farm, watershed and valley) at both horizontal and vertical directions can be achieved by deploying thousands of MSMS sensors. Estimated using the reported information of micro-irrigation [44], high-resolution MSMS sensor profiling is expected to save nearly 35% of water consumption and 80% of existing SMS cost by assuming the same arrangement of MSMS sensors as the existing SMS. This estimation is exciting, since it reveals that deploying high amounts of low cost MSMSs can unprecedentedly provide accurate profiles of soil moisture for diverse water-saving activities (e.g. irrigation, hydrology). Furthermore, MSMS can be used in groundwater level monitoring, flood monitoring and remote sensing [45]. Currently groundwater level has been historically observed using groundwater monitoring wells [46]. Mass deployment of MSMS sensors in large watershed and groundwater areas with a wireless monitoring network is expected to achieve a real-time spatiotemporal groundwater level profiling. [47]

1.5 Preliminary conclusion of MSMS field tests

This study for the first time conducted the field tests of flat thin resistance-type MSMS sensors for profiling soil moisture along soil depth and side-by-side comparison with commercial sensors under different environmental conditions through a 4-month test period. Multiple pieces of MSMS sensors mounted on a hollow rod were inserted along soil depth (5cm, 40cm and 70cm below ground surface). The correlation between the resistance readings of MSMS sensors and water content values of commercial sensors revealed that the sensors at the shallow soil depth (5 cm
below ground surface) had the lowest $R^2$ values (0.1343), while the sensors at the deep soil depth (70 cm) had the highest $R^2$ values (0.6264). Loose contact with soil, soil settlement and ground surface interference might be the main reasons for the unstable MSMS sensor readings from the shallow soil. The effects of environmental variations (e.g. dry/wet seasons, temperature) on soil moisture through the 4-month period were clearly reflected by MSMS profiling along soil depth. Furthermore, results from the lab validation tests conducted under well-controlled environment corresponded well with the field test results in terms of the correlation of MSMS resistance readings and commercial sensors readings, indicting high accuracy and sensitivity of MSMS sensors in field tests. This field study demonstrated the MSMS sensor’ distinct capability for profiling soil moisture in high spatiotemporal resolution, and revealed its great potential for water-saving irrigation and high-accuracy hydrological monitoring.
Chapter 2: MSMS sensors mass production quality control

2.1 Introduction

MSMS sensor is a very promising accurate soil moisture sensor for agriculture. Because of its low-expense and long-term stable character, MSMS can be used largely into the field for the soil moisture profiling. With the technology of Thermal press and CD-etching, it is easy to fabricate MSMS in the lab. The mass production is important for MSMS because of the potential vast use in practical. So it is important to have the discovery of the critical factors in the procedure that which one influences the final quality of MSMS.

The stability and consistence is important for MSMS because MSMS is aimed at a long-lasting (over 1 year) sensor and the future field test needs plenty (>100) of MSMS to be installed. In the fabrication procedure, there are at least 6 steps to accomplish the sensor which includes: CD-etching, carbon pattern print, thermal press etc. In some steps, time should be controlled strictly (e.g. nitric CD-etching) or the result may vary a lot (e.g. golden layer easily peels off) which can severely affect the final quality of MSMS. The concentration of etching solution (nitric acid and) is also found a critical factor that will eventually affect the stability of MSMS.

Quality control of mass production is important for both the future lab test about MSMS characteristic and the future factory production. The exploration of critical factors will help to optimize the production and thus save the time and money for the factory production.
2.2 Research objective of MSMS mass production.

MSMS mass production aims at finding the essential factors of influencing the consistence of MSMS and optimize the whole fabrication process.

2.3 Material and methods

The graphic design software Silhouette Studio (Silhouette America, Inc.) was used to design the mask on 1:1 scale and was then printed onto the slippery side of waxed paper (Avery® Shipping label) with a DELL printer. Gold Archive CD-R (MAM-A Inc.) with four layers (a rigid polycarbonate, an organic dye, a gold metallic layer and an outer protective layer) was used as the substrate for MSMS fabrication. The CD-R was immerged into concentrated nitric acid solution (Fisher Scientific Inc.) for 55 seconds to remove the protective poly layer off the golden layer. Cut...
the CD into four even pieces and use air to blow all the droplets off. Put the pattern paper on the thermal press (Stahls USA, Maxx Press) pad with the pattern facing top, then put the CD with golden layer attached to the pattern. With 248 F temperature, press for 110 seconds. Then cool down all the sensors and cut into the particular size. Put the sensors into the chemical solution which contains [48,49] for etching to remove the unprotected golden layer. Dry the sensors and they are done.

2.4 Results and discussion

Among all the procedures (Figure 10), mass production quality control test has been examined in 5 aspects. These five aspects have been tested to be the critical factors in the fabrication procedures to influence the final result.

2.4.1 Influence of printing density

Shown as ① in Figure 10.

Carbon pattern density has an important factor on the stability of MSMS. The density difference is derived from the printer setting and printer type. A laser-jet printer is the right choice for the fabrication work, because the slippery paper will not be printed a carbon pattern with a ink-jet printer. The print setting refers to the “print quality”; Typically there are 600dpi, 1200dpi two choices and the bigger the number, the higher the quality. In the lab test, 600 dpi will give a blur pattern while 1200 dpi has a good accurate pattern.

The higher the dpi value is, the more dense the carbon powder has been printed onto the paper. Thus give a more tense cover to the MSMS sensor surface. Carbon is essential for the sensors because the carbon powder is a stable material under the ground and protect the golden layer from
being defected. Eventually, MSMS life span will be longer due to a higher density of carbon powder.

2.4.2 Influence of nitric acid concentration

Shown as ② in Figure 10.
The nitric acid is used for etching off the polymer layer which cover on the golden layer of the CD. Different concentration is found to influence the etching result: as time decays, nitric acid concentration will decrease and thus etching time will be longer, the experiment shows that after 1 hour, etching time will extend from 55 seconds to 60 seconds. The reason accounts for the phenomenon is that as the concentration decreases, the corrosion ability of nitric acid decreases which leads to a longer etching time. Different concentration of nitric acid will In order to keep the consistence of the MSMS, the nitric concentration should not be decreased enormously. Every 200 ml of nitric acid can only be used for 10 CD.

2.4.3 Influence of thermal press time

Shown as ③ in Figure 10.
The thermal press is used to get the carbon pattern attached onto the CD. With the heating and pressure, the thermal press will transfer the carbon pattern from the paper to the CD. The time of thermal press is usually 110 seconds. The shorter time (<50 s) of press will make the carbon pattern easily to be scratched off. The longer time (>150 s) will cause the carbon pattern become blur which is not good for the consistence of production.

2.4.4 Influence of etching time

Shown as ④ in Figure 10.
The etching time of the chemical solution should be controlled as to get a fine production. All the four chemicals should be weighed precisely and be put into an aluminum foil covered bottle
immediately after weighing. DI Water for dissolving chemicals should be added several minutes before adding the solution into the etching bottle in case the solution deteriorates. The etching dishes should be also covered by the aluminum foil to prevent the photolysis of the solution. The etching time should be controlled in 13 to 14 minutes. The longer (14-20 minutes) etching time will cause the golden layer has loose attachment and finally will bring bad quality after the final procedure---usually after the procedure of thermal press, the carbon pattern is hard to be attached on the CD and all the interdigitate electrodes are easily to be scratched off. An even longer etching time (over 20 minutes) will give a bad quality immediately---the golden pattern is easily to be washed off the CD in the following steps.

2.4.5 Influence of existence of stirring

Shown as (5) in Figure 10.

The stirring of the etching solution is important for the MSMS due to its influence on a evenly-etching performance. The etching plate is a 15cm-diameter and 2cm high petri dishes. The four pieces from one CD will be put into one dish and poured chemical solution. The stirring will be put into the center of the dish and the dish will be put on the stirring plate. The stirring rate is usually at 50 rpm. With the stirring, the after-etching MSMS will be etching accurately; without the stirring, MSMS usually has some certain area that can’t be etched off and eventually be a dead sensor. The reason which accounts for the phenomenon is that the petri-dish is a shallow container and the solution is very hard to diffuse which results in the incomplete etching. The stirring accelerates the diffusion and convection of the active particle which is good for the etching.
Figure 11. Three different status of MSMS sensors. a.) No stirring when etching in etching solution b.) Good product c.) Stay in etching solution too long

2.5 Preliminary Conclusion of MSMS mass production

The lab MSMS mass production has five main factors which affects the quality mostly which including nitric acid concentration, thermal press time, etching time, printing density and stirring strength. In the test, constant nitric acid concentration are found to be important to influence the firmness of golden layer and with the time goes by, nitric acid concentration decreases and thus will make it longer to get the plastic layer off. The longer time of thermal press can strength the attachment firmness of carbon pattern but should not exceed 150s. 13-14 minutes etching time with stirring at 50 rpm can make sure all the unwanted golden layer part is etched off and the interdigitated electrodes are firmly attached to the substrate.
Chapter 3: In-situ soil moisture monitoring with MSMS in Ethiopia for developing hydrological model

3.1 Introduction

As the second most populous country in Africa, there are only 42% of the population has access to a clean water supply. Access to clean water in Ethiopia reduces water collection time and disease burden, creating transformational change in education, gender equality, and household income. Supporting access to clean water in Ethiopia builds a critical foundation for future development and prosperity. In the past twenty years, droughts have affected several areas of the country, leading to ponds, wells, streams and lakes drying up or becoming extremely shallow. Many people living outside of the cities collect water from these shallow water sources, which are often contaminated with human and animal waste, worms, or disease. The water for irrigation is tight in almost half the country (Figure 12). The test places are located in four watersheds near lake Taka.

![Figure 12. Ethiopia inter-annual variability and water supply map.](image)
The PIRE (Partnerships for International Research and Education) CSI was extended to involve local farmers as “citizen scientists”, collecting soil moisture data using low-cost, soil moisture sensors developed in-house at the University of Connecticut, that have been installed in 12 locations and two soil depths (20 cm and 40 cm). The collected data will be used for the initialization and validation of the hydrological models developed in the region. The PIRE CSI promotes the empowerment of local communities and establishes long-lasting partnerships between scientists and stakeholders.

### 3.2 Research objective of MSMS deployment in Ethiopia

The MSMS sensors are deployed in the different areas in Ethiopia, to collect the soil moisture from different farmland in four watersheds. The objectives of the study are three parts: First, MSMS deployed in different places for a robustness test. Second, the data get from MSMS will compared with the TDR data as well as the lab test data to develop a general model between resistance and soil moisture. Third, data collected from the MSMS will last for a year and they will be used for the crop-yielding prediction.

### 3.3 Material and method

The installation of MSMS is listed as follow:

A 50cm×50cm×50cm site is excavated in the farmland; Use knife to cut two slim slots at different depth at 20cm and 40cm on the wall of the site; Put the MSMS sensors into each slot and squeeze the soil into the slots to make it firmly contact. Buried the site with soil and cover it with some leaves branches for disguise. The basic procedures are showed as in Figure 12.
All the 96 sensors are deployed in 48 different sets in all four watersheds (Brante, Quashini, Markudi, Koga) and data will be collected weekly in a whole year. Two sensors are deployed in one set at two different depth which are 20cm and 40cm and there are 12 sets in each watershed. The MSMS data will be compared with TDR data to ensure its accuracy.

![Installation of MSMS in Ethiopian farmland.](image1.jpg)

**Figure 13.** The installation of MSMS in Ethiopian farmland.

### 3.4 Results and discussion

The data get from Branti watershed compared with TDR.
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Table 1. MSMS data from Branti watershed compared with TDR data.

MSMS is a low-cost and stable soil moisture sensor. It is designed for the water-tight area that needs to irrigate the field strategically. MSMS has been tested in the Uconn farm for about a year and got a good result of field test. The field test showed MSMS can be used as the soil moisture profiling sensor which can gives the whole soil moisture along different soil depth. With an in-situ and frequent soil moisture data collecting, MSMS can gives the soil moisture condition daily. With the soil moisture data, water irrigation can be made accordingly to save the water. Even though, MSMS is now only tested in one place and thus the resilience in other kind of soil condition is not tested. The practical use condition should be more severe including many factors like tailing apart by farmers and drought etc. An expansion in the use and to test the performance in a totally different area is significant for MSMS. The Uconn farm is located in the northeastern part of the U.S. and the temperature is pretty low during the winter. While in the test places in Ethiopia, the temperature range in the whole year is from 20 °C to 24°C which is -9 °C to 25 °C. The rainfall in Uconn farm is about 100mm all over the year, while in Ethiopia is from 20 mm to 140 mm in different seasons.
Chapter 4: Future works in Ph.D. study

First, MSMS should derive a model which can help to transfer the resistance value into water content more accurately. Right now, the MSMS can only give the resistance of the soil and the reading is unstable. Besides, MSMS shows a better performance under high water content soil compared with TDR sensors. Thus, the accuracy between the high and low water content of MSMS could be examined in the future. This study can be extended to develop a circuit board and add remote data transfer system and thus can collect data for monitoring the underground water level.

Second, the sensor of detecting the ammonia (Figure 14) will be developed to help to monitoring the soil ammonia concentration. Since ammonia can only be detected in a wet condition, hydrogel will be covered a three-electrode sensor and a layer of ionophore mixed with PVC. Eventually the in-situ ammonia sensor along with MSMS sensors will give the ammonia data to help to calibrate, constrain, and validate the nitrogen cycling in hydrology model.
**Figure 14.** Ammonia hydrogel sensor paired with MSMS.
Figure and Table List

**Figure 1.** Installation of the sensor kits with multiple pieces of MSMS sensors (a) and multiple pieces of commercial sensors individually (b) along soil depth in the field tests.

**Figure 2** The side-side comparison of the resistance readings of MSMS at the shallow depth (7 cm below the ground) and the commercial sensors over time and the linear regression. (a: the variation of MSMS data and commercial sensor data throughout the test period, b: the correlation of MSMS data with commercial sensor data in the first 26 days, c: the correlation of MSMS data with commercial sensor data throughout the test period.)

**Figure 3.** The contact of MSMS sensor and soil during soil sink along soil depth (a) and the contact of commercial sensor and soil during soil settlement (b).

**Figure 4** The side-side comparison of the resistance readings of MSMS at the middle depth (40 cm below the ground) and the commercial sensors over time and the linear regression. (a: the variation of MSMS data and commercial sensor data throughout the test period, b: the correlation of MSMS data with commercial sensor data in the first 27 days, c: the correlation of MSMS data with commercial sensor data throughout the test period.)

**Figure 5** The side-side comparison of the resistance readings of MSMS at the deep depth (75 cm below the ground) and the commercial sensors over time (a: the variation of MSMS data and commercial sensor data throughout the test period, b: the correlation of MSMS data with commercial sensor data throughout the test period, c: the correlation of MSMS data with commercial sensor data throughout the test period.)
commercial sensor data in the first 27 days, c: the correlation of MSMS data with commercial sensor data throughout the test period.)

**Figure 6.** The side-side comparison of the capacitance readings of MSMS at the shallow depth (7 cm below ground) and commercial sensors over time (a), and the correlation between capacitance readings of MSMS and commercial sensors in the first 6 days (b).

**Figure 7.** MSMS sensors and commercial sensors under the water shock tests in the middle depth (a) and in the deep depth (b).

**Figure 8.** Soil moisture profiles obtained by MSMS sensors and commercial sensors in the middle and deep locations under different weather conditions.

**Figure 9.** The correlation between MSMS resistance readings and soil moisture in the lab validation tests.
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