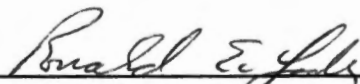


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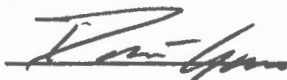
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SOIL MOISTURE SENSOR EVALUATION

A Thesis

Presented for the

Master Of Science

Degree

The University of Tennessee, Knoxville

David L. Johnson

May 1995

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DEDICATION

The author wishes to dedicate this thesis to his sister-in-law Lisa L. Johnson, who lost her life on August 8, 1993 in a hot air balloon accident.

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Company and trade names are given for the benefit of the reader and do not imply endorsement of the product by the author or The University of Tennessee.

ABSTRACT

An experimental apparatus was designed to conduct a comparative laboratory test of 23 soil moisture sensors representing seven different general types. Sensors evaluated were: a Troxler neutron probe, a Troxler Sentry 200-AP capacitance probe, an Aqua-Tel Capacitance sensor, time domain reflectometry (TDR) with two different waveguide configurations, gypsum blocks, Watermark PVC moisture blocks, and Agwatronics heat dissipation blocks. Research efforts were directed toward determining the prediction error of the volumetric water content of the soil for each sensor, over moisture contents ranging from saturation to below two percent by volume.

The apparatus was designed to monitor the weight of water in two columns filled with soil. Soil moisture sensors were placed in the center of the column and the soil subjected to four drying cycles of saturation and subsequent drying. The first drying cycle was used for sensor calibration, and the three following cycles were used to determine the prediction error of each sensor. Soil types used were a loam and a sandy loam. Two soil types allowed differences in performance due to soil type to be observed.

Capacitance sensors proved to be the most accurate sensors included in the study. The neutron probe was not the most accurate sensor, but it was one of two sensors studied that predicted valid values for all data points during the study. Resistance sensors also performed well over their limited range of water content.

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CHAPTER I

INTRODUCTION

Statement of Problem

Determining soil water content is an important factor in irrigation management, construction, transportation, and determining subsurface chemical transport. Underirrigation results in reduced yields due to increased crop stress, while overirrigation wastes water and energy, increases soil erosion, leaches nutrients or agricultural chemicals into groundwater supplies, and degrades surface water supplies with sediment laden runoff (Ley, 1994).

These factors have led to a number of different methods for determining moisture content. Early methods include estimating the water content of a soil by feel and texture, or by gravimetric sampling. However, an experienced estimate is generally only accurate within $\pm 10\text{-}15\%$ of the actual water content (Ley, 1994) and gravimetric sampling, although very accurate, is labor and time intensive and requires destructive sampling at each measurement interval.

Soil moisture determination goals then evolved into the design and production of sensors that determine soil water content quickly with little or no labor and without destructive sampling. These sensors, including tensiometers, neutron probes, resistance methods (moisture blocks), capacitance methods, heat dissipation methods, and time domain reflectometry (TDR), rely on soil matric potential, or the dielectric properties or electrical resistivity of the soil to

electronically determine the water content. Many soil moisture sensors being manufactured today can be used in conjunction with a control device. When a sensor is used as an input to a controller, an irrigation system can be automated and can be operated at its maximum efficiency if the controlling sensor gives accurate results.

Accurately determining the water content of the soil involves many factors, including texture, bulk density, minerals in the soil, salinity, and air pockets. Most of these factors are compensated for by site-specific calibration with a minimal error remaining. However, a laboratory test directly comparing numerous soil moisture sensors would allow these variables to affect each sensor equally. The accuracy of each sensor could then be directly compared to every other sensor.

The absolute accuracy of most soil moisture sensors capable of control is relatively unknown. Very few comparative tests have been conducted to determine the accuracy of these methods (Tollner and Moss, 1985). Ley (1994) conducted a field study with many of these sensors, but no known unbiased test between sensors has been previously conducted in a controlled and comparative environment.

This study consists of a laboratory test comparing 23 different soil moisture sensors, consisting of seven classes, in two soil types. To conduct the test, a lysimeter-like apparatus was designed to suspend a soil column containing the sensors. The dry weight of the column and soil was counterbalanced to allow for a direct reading of the water content in each column with a load cell. With the exception of the down-the-hole moisture meters, all sensors and load cells were

connected to a datalogger and all readings were taken simultaneously to allow for a comparison of sensor output and the actual water content of each column as determined by the load cells.

Sensors were placed in the center of each column as dry soil was packed to a bulk density of 1.4 g/cm^3 (0.0506 lb/in^3). The columns were placed in the frame and suspended by counterbalancing the system. The lysimeter was calibrated using known weights. The columns were then saturated, data were collected for one drying cycle, and calibration equations were fitted to each sensor for each soil type. Soil columns were saturated and dried, going through the cycle three consecutive times following calibration. Data were collected during these three cycles, and predicted moisture content from each sensor was compared to the actual water content of the column.

Objectives

The goal of this study was to determine if a soil moisture sensor could perform adequately for use as an input to a control device. To achieve this goal, three questions that would reflect the accuracy of the sensor were raised: 1) how does each sensor perform over a wide range of soil moisture contents? 2) how does each sensor perform over time? and 3) what is the overall total performance of the sensor?

To answer the first question, the range of moisture contents for the study was varied from saturation to beyond the permanent wilting point for most plants.

This range was broken down into three smaller ranges, with the moisture content of each range dependent on soil type.

The second question was answered by repeating the experiment for a total of four wet to dry cycles. The first cycle was the calibration cycle and the following three cycles allowed sensor output to be compared over time.

The third question was answered by using soils with different textures. The soils represented typical agricultural soils with different textures. The possible variation of sensor response due to soil type, a wide range of moisture contents, and over a period of three drying cycles was then analyzed and the overall sensor performance evaluated.

Sensors included in the study were all available sensors that were widely accepted as reasonably accurate and that could be installed and used for remote nondestructive soil moisture determination. Seven commercial sensors and one fabricated four-waveguide time domain reflectometry (TDR) soil moisture sensor designed by Zegelin and White (1989) were included. The sensors were:

1. Delmhorst Gypsum Blocks
2. Watermark PVC Resistance Blocks
3. Agwatronics Heat Dissipation Blocks
4. Campbell Scientific Time Domain Reflectometry
5. Four-waveguide Time Domain Reflectometry
6. Aqua-Tel Capacitance Probe
7. Troxler Sentry 200-AP Capacitance Probe
8. Troxler Neutron Probe

CHAPTER II

REVIEW OF LITERATURE

Gravimetric sampling has long been the standard method for measuring soil moisture. Gravimetric soil moisture determination requires weighing a soil sample taken from the area of interest. The sample is either placed into a drying oven at 100° to 110° Celsius and dried for 10 hours in a forced draft oven (Gardner, 1986) or, for at least 24 hours in a convection oven (Gardner, 1986), or placed in a microwave oven and dried for 20 minutes (Gee and Dodson, 1981). The sample is taken from the oven, weighed, and the water content of the soil sample is determined by Equation 1.

$$\theta_{dw} = \frac{(\text{weight of wet soil} + \text{tare}) - (\text{weight of dry soil} + \text{tare})}{(\text{weight of dry soil} + \text{tare}) - (\text{tare})} \quad (1)$$

Where the tare is the weight of the container, θ_{dw} is the percentage of water in the sample on a dry mass basis, and all units of mass remain consistent throughout.

Gravimetric sampling is one of the most accurate methods available, but the amount of time and labor involved, the fact that destructive sampling is required, plus the reality that this method cannot be used to automate an irrigation system cause difficulties when using this method for irrigation purposes. These factors give farmers justification to estimate the soil moisture content and irrigate when deemed necessary, even though an experienced estimate is generally only within

$\pm 10\text{-}15\%$ of the actual soil water content (Ley, 1994). Therefore, a number of methods have been developed to determine soil moisture content.

Many nondestructive methods have been developed to determine soil moisture content more quickly with less labor. These methods include lysimeters, tensiometers, neutron probes, resistance methods (moisture blocks), capacitance methods, heat dissipation methods, and time domain reflectometry (TDR).

These methods have been laboratory tested and most are commercially available today. Little test information is readily available on a number of sensors and very few comparative tests have been conducted to determine the accuracy of these methods (Tollner and Moss, 1985). Comparative tests on soil moisture sensors include: field studies conducted by Tollner and Moss (1985), who compared a neutron probe, a tensiometer, and moisture blocks, Ley (1994) who compared a neutron probe, two capacitance sensors, moisture blocks, tensiometry, and time domain reflectometry, and Mead et al. (1994) who compared a capacitance probe, a neutron probe, and gravimetric sampling. These studies aided in the search for determining sensor quality. However, sensors can not be directly compared in a field situation as accurately as in a laboratory.

Tensiometers

Tensiometers were introduced by L. A. Richards in 1929 (Richards, 1949) and have been consistently improved and extensively used for measuring soil matric potential. Tensiometers consist of a porous cup connected to a pressure measuring

device such as a vacuum gauge for measuring the tension of water in an unsaturated soil. The tube connecting the cup and vacuum gauge is filled with water and the water tension equilibrates with the water in the soil.

Tensiometers have been automated to be read by computers and dataloggers (Lowery et al., 1986) but still require much maintenance and only determine moisture content for a limited range. If the soil is near saturation, there is a pressure equilibrium, and at low moisture contents of approximately 85 kPa (12.33 psi) the high amount of soil tension on the tensiometer causes the vacuum to be broken.

Resistance Sensors

Resistive type soil moisture sensors are point measurement sensors that determine the moisture content of the soil by measuring the resistance between two electrodes that are placed in a reference matrix inside a permeable material. The resistance between the electrodes is a function of the amount of water in the soil. Resistance decreases as the moisture level increases. The electrodes are generally placed in a cylindrical block of porous material and are manufactured with different pore sizes to allow for a matric potential close to that of the surrounding soil so the movement of water in the block will be similar to that in the soil.

Gypsum Blocks

One common type of resistive soil moisture sensor, the gypsum block, was first introduced in 1940 (Fowler and Lopushinsky, 1989). The blocks are made of gypsum cast around two concentric electrodes (Delmhorst). The reading indicates the amount of current flowing through the circuit formed when the buried electrodes are connected to a portable electronic meter via the lead wires (Richardson, 1988). As the moisture content of the soil increases, the resistance of the block decreases and the reading from the meter increases. This value is compared to a chart supplied by the manufacturer to determine the soil moisture status (Delmhorst).

Gypsum blocks are popular soil moisture sensors because of low cost, ease of use, low time requirements, ease of automation, and low calibration requirements.

The cost of gypsum blocks is minimal when compared to most other soil moisture sensors, ranging from \$3.50 to \$9.50 for the blocks. This low cost allows numerous blocks to be placed in each field to monitor different areas, giving an overall average moisture content reading that most closely represents the average moisture content of the field. The electronic meter costs approximately \$100, but one meter can be used for all gypsum blocks one wishes to monitor.

Gypsum blocks are placed into the soil at selected sites and are left for the entire season (Delmhorst). The blocks may be read manually with a meter, connected to a datalogger, or to a controller for an automated irrigation system.

Gypsum blocks are easily read by a datalogger for an automated system or for recording data. The blocks are wired to a datalogger and the resistance between the electrodes is measured in a half bridge. The block readings are produced by a short-duration DC pulse generated by the datalogger and the reading is then recorded. The only difficulty is the increase of polarization buildup over a long period of time, which can be prevented by the use of an external discharge path through a changeover relay (Strangeways, 1983).

Time requirements for the blocks include the initial installation and required time for reading. The maintenance requirement for the blocks is minimal; if the reading seems inaccurate, the block must be replaced (Richardson, 1988).

Calibration requirements for the blocks include soaking them in water for a period of 2 hours (Delmhorst), placing the sensor in soil of known moisture, recording the readings, and generating a calibration curve (Fowler and Lopushinsky, 1989).

There are also problems associated with gypsum blocks. These include a limited range of moisture read, durability, accuracy, response time to changes in moisture content, and response to chemicals in the soil such as salinity.

The sensitivity of a gypsum block is limited to read a range from "field capacity" to the "permanent wilting point" (Richardson, 1988). This range can also be expressed as 10 to 1500 kPa (1.45 to 217.55 psi) tension (Brady, 1990), which does not cover conditions at saturation or very low moisture levels.

The accuracy of gypsum blocks has been verified by the manufacturer's curve within 10 percent (Tollner and Moss, 1985). However Gardner (1986) reported the error produced by gypsum blocks depends on the nature of the soil and their wetting and drying history, and can easily be 20 percent or more. The blocks are sensitive to saline water and decompose rapidly when salt or high moisture content is present in the soil, raising the question of reliability over a period of time. Very little information about gypsum block reliability over time has been available since the blocks were introduced in the 1940's (Richardson, 1988).

The response time for a gypsum block can lag from several hours to a day or two (Richardson, 1988). The time lag is due to a number of factors. The water must percolate through the soil until it reaches the depth of the block. After the moisture reaches the block, the reading will not be affected until the water is absorbed by the gypsum surrounding the electrodes. The rate of absorption depends on the pore size of the gypsum. The pore size used should be similar to the pore size of the soil to keep the error to a minimum.

PVC Blocks

The Watermark 200 soil moisture block is a resistance type moisture sensor that operates on the same principle as the gypsum block. As the soil moisture decreases, the resistance between the electrodes increases, yielding a higher reading on the meter, which is in centibars of soil water tension.

The main difference between the Watermark 200 and the gypsum block is the material. The Watermark sensor is a PVC block that contains a gypsum reservoir inside to provide a buffering capacity against salinity. The Watermark block does not deteriorate in high moisture or saline soils like a gypsum block (Hollis, 1992). A second advantage of the sensor is that it covers moisture content of the soil over a range from 0 to 2000 kPa (0 to 290 psi) (Irrometer Company), a larger range than that of a gypsum block. The blocks are also designed for a piece of 1/2-inch (1.27 cm) PVC pipe to be connected to the end of the sensor for removal from the soil prior to harvest (Irrometer Company). This protects the wires against rodents and accidental damage during sensor removal (Hollis, 1992). The Watermark 200 can also be used with dataloggers to automatically record readings and to automate an irrigation system (Irrometer Company).

Research has been conducted on the calibration requirements of the Watermark sensors (Armstrong et al., 1985). Their study revealed the effects of soil temperature on the readings. The temperature correction factor was found to be somewhat greater than 1.8 percent. Linear and non-linear equations were fitted to the data and it was discovered that a quadratic equation gave a better fit than a linear equation. The equation chosen, when solved for soil moisture tension (S) in cm, is Equation 2.

$$S = \frac{R - (3.0204 - 2.962)(38.054 - T + 0.008908 T^2)}{0.0002012[3.0204(38.054 - T + 0.008908 T^2) - R]} \quad (2)$$

R is resistance in kilo-ohms and T is temperature in degrees Celsius (Armstrong et al., 1985). Armstrong stated this equation was adequate for the sensors chosen for the study, but that Irrometer continually changes the sensors and the equation may not be adequate for all Watermark 200 sensors. The Irrometer Company has now developed a meter with an adjustment knob they claim allows for compensation for this error over a range of temperatures. Calibration of the meter consists of attaching a resistor supplied with each meter between the leads and adjusting the meter to get a reading of approximately 100 centibars (100 kPa) (Irrometer Company).

The PVC soil moisture block has been in production since 1978 (Irrometer Company). The life expectancy, however, has not been determined (Hollis, 1992), because there has never been a published extensive study to determine the accuracy of the blocks as time of use increases.

The only fact favoring a gypsum block over the Watermark sensors is the cost. The PVC blocks cost \$18 per block (Hollis, 1992) compared to approximately \$5 per block for a gypsum block. The cost increase may prove to be insignificant if the life span of the blocks is as great as the manufacturer claims. If one installs many sensors to monitor a large area, the cost of using the Watermark 200 would be important to the average farmer who considers price one of the most important factors.

Heat Dissipation Blocks

Heat dissipation in a porous medium depends on thermal conductivity.

Phene et al. (1971) modeled the relationship between this conductivity and moisture content. From this mathematical model, they developed a sensor that supplies a heat source within a porous block made of gypsum, and the temperature rise at this point is measured by a Germanium P-N Junction Diode (RCA,1N2326).

The sensor is now being commercially produced by Agwatronics, Inc.

Phene et al. (1989) reported the sensor as being linear over the range of interest, independent of temperature and soil texture, not affected by salinity, and designed to be connected to a datalogger and used for irrigation control. However, the cost of these sensors, \$125 each, is notably more than that of a gypsum or Watermark moisture block.

Neutron Probe

The basic concept used in the present-day nuclear meter was described in a paper as early as 1941 (Smith et al., 1968). This sensor was developed for petroleum exploration to indicate possible fluid-bearing zones in rock structures.

The neutron source was lowered into a bore hole and the thermalized neutrons were counted. The first known application of a nuclear meter for determining soil moisture was presented in a thesis at Cornell University in 1949. The meter contained a nuclear source and indium foil as a thermalized neutron counter (Smith et al., 1968). The American Society for Testing and Materials (ASTM) committee

D-18 held a symposium on the use of radioisotopes in soil mechanics applications in 1952 (Smith et al., 1968) which led to the development of standard D 3017, which set the guidelines for using a nuclear meter for moisture determination. Research on the nuclear meter steadily progressed during the early 1950's and the first commercial purchase was made in Australia in 1956 (Smith et al., 1968). Since that time, many improvements on the nuclear meter have been made (Reginato and Nakayama, 1988) and the neutron probe is one of the most accurate methods available today for determining soil moisture content (Tollner and Moss, 1985).

The basic structure of the neutron probe consists of a fast neutron source and a helium-3 tube to count the thermalized neutrons (Troxler Electronics Laboratories, 1983). For the Troxler 3220 series meter, the source emits fast neutrons from a 10 mCi Americium-Beryllium source at a rate of 25,000 neutrons per second (Troxler Electronics Laboratories, 1983). These neutrons undergo scattering and are thermalized, or slowed, when they collide with hydrogen atoms found in the soil. The average energy lost by a neutron in a collision with a hydrogen nucleus is 63 percent, requiring only 20 collisions to become thermalized (Klenke and Flint, 1991). The closest collision count required to thermalize a neutron is with boron, which requires 109.2 collisions to thermalize a fast neutron (Troxler Electronics Laboratories, 1983). The helium-3 tube detects the slow neutrons in counts that are directly proportional to the hydrogen content of the soil (Troxler Electronic Laboratories, 1983).

The probe is inserted into the soil via an access tube. Aluminum access tubes are the most popular because they are nearly transparent to the source (Hauser, 1984). Other materials used include, steel, which is strong and reduces the neutron count rate only slightly, and plastic tubes, which may reduce the counting rate by a greater amount. The depth of the probe should also be taken into account. There is a significant loss of neutrons to the air if measurements are taken near the surface (20-40 cm, 7.87-15.75 in) (Hauser, 1984) or at void spaces at the access tube-soil interface, which will affect the calibration of the probe (Carneiro and De Jong, 1985).

Calibration of a neutron probe is one of the most important factors for accurately determining soil moisture. ASTM (1988) Standard D 3017 states that calibration curves shall be established or verified once each year by determining by test the nuclear count rate of at least two samples of different known water content to allow for radioactive decay of the neutron source. Two methods of calibration are commonly used for the neutron probe: (1) in situ gravimetric calibration, by comparing the neutron probe counts with measured soil water contents at a number of sites; and (2) filling drums with soil at different water contents, installing a neutron probe access tube, and measuring the neutron probe counts (Carneiro and De Jong, 1985). Calibration data fit the linear equation illustrated in Equation 3.

$$P = mR + a \quad (3)$$

P is percent soil water on a volume basis, R is the ratio of neutron meter count divided by the shield count, m is the slope, and a is the y intercept (Hauser, 1984; Carneiro and De Jong, 1985; Nakayama and Reginato, 1982). Troxler Electronics Laboratories (1983) recommends fitting the count ratio to a third order polynomial (Equation 4).

$$M = O_f + S(A_0 + A_1X + A_2X^2 + A_3X^3) \quad (4)$$

M is moisture content of desired units, X is the count ratio, A_0 , A_1 , A_2 , and A_3 are derived coefficients, O_f is the offset, and S is the slope. Each probe calibration must also be unique for every soil. The factor most likely to change the reading of the probe is the bulk density, which affects the value of the intercept (Carneiro and De Jong, 1985). It has also been established that the presence of elements such as B, Cl, Co, Mn, and Fe within the 280 mm (11 in) measured radius (Troxler Electronics Laboratories, 1983) will cause a significant offset to a given calibration curve if the effects are not compensated for in calibration (Rahi and Shih, 1981; Hauser, 1984). The other factor known to generate a significant error with the neutron probe is the influence of temperature. Hauser (1984) addressed the affects and concluded the following practices would reduce the error due to temperature:

1. Make all shield counts in the morning when the unit is in equilibrium with relatively constant air temperature.

2. Keep the probe inside an access tube and below the ground surface all day to reduce changes in probe temperature.
3. Shade the surface unit to prevent high temperatures caused by sun shining on the case.
4. Make readings in polyethylene standards only when all units are in equilibrium with constant air temperature.
5. Shade the instrument case during transport to reduce heat buildup due to sun shining on the case.

The calibration of a neutron probe requires time for an accurate reading, but with appropriate training, conscientious farm personnel effectively use the neutron probe for soil moisture measurement (Tollner and Moss, 1985).

The major negative factor influencing the use of the neutron probe is the radioactive source. The user of the probe is subject to government licensing requirements and regulations, which may vary by area (Troxler Electronic Laboratories, 1983). Safety precautions must also be taken when using a neutron probe. The operator should wear a radiation badge (ASTM, 1988) and follow all safety recommendations required by the manufacturer. Another difficulty associated with the neutron probe is that it cannot be left unattended. This makes it impossible to use it for long term data collection or with an automated irrigation system.

Capacitance Methods

Capacitance type soil moisture meters rely on the relationship between the dielectric constant of the soil and the water content to obtain a moisture level reading. The dielectric constant of most minerals found in the soil does not exceed 10 or 12 (Cernyak, 1968), whereas the dielectric constant of water is 78 (Troxler Electronics Laboratories, 1992). Therefore, as the moisture content of the soil increases, the dielectric constant of the soil increases by a significant amount. The mineralogical effect on the dielectric constant for a given soil type remains constant, and the shift caused by this effect in the moisture curve can be compensated for by an offset.

The major source of error with all capacitance meters is that due to void spaces around the probe (Mead et al., 1994), which is caused by careless installation and/or use. The meter will not give an accurate reading of the dielectric constant in these voids because it reads the dielectric constant of the air which is approximately one, compared to the dielectric constant of 78 for water.

Sentry 200-AP

The Sentry 200-AP measures moisture content of a material by responding to changes in the dielectric constant of the material (Troxler, 1992). It is the only non-nuclear soil moisture probe that does not come into direct contact with the soil. An access tube must be used, which is similar to the method used with a neutron probe. The Sentry 200-AP consists of a control unit and a probe which is placed in

the access tube. The probe can be used in numerous access tubes or can be permanently installed in a tube. The probe consists of two electrodes separated by an insulating spacer. The field of the electrodes penetrates the soil at a certain frequency and as the moisture level of the soil increases or decreases, the sensor's output frequency shifts. The upper electrode measures the shift and a correlation is made to determine the moisture content of the soil. The output of the probe is stored in the control unit and can easily be downloaded to a computer (Troxler Electronics Laboratories, 1992).

According to the manufacturer, the access tube must consist of 2-inch (5.08 cm) nominal diameter schedule 40 PVC pipe. Precautions must be taken when installing the access tube to allow for no overcompaction of, or void spaces in the surrounding soil. The probe can then be inserted into the access tube and moisture readings can be taken at the desired depth.

Calibration of the Sentry 200-AP consists of a calibration code supplied by Troxler Electronics Laboratory. Information available on the factory calibration of the probe states that readings are taken at 0, 35, and 100 percent moisture by volume and fit into Equation 5.

$$D = F_0 \exp(F_1 M) + F_2 \quad (5)$$

F_0 , F_1 , and F_2 are factory derived coefficients, M is the moisture content of the soil in the desired units, and D is the measured frequency difference (Troxler Electronics Laboratories, 1992). The factory calibration is conducted in, and is

accurate for, sandy or loamy soils. An offset is required if the probe is inserted in high moisture content soils such as clay or soils with a high organic content (Troxler Electronics Laboratories, 1992). Mead et al. (1994) reported a linear calibration equation yields much better results than the factory and derived exponential calibration equations.

Measuring the dielectric content of a soil as an accurate indication of soil moisture has been known for many years (Cernyak, 1968). However, the Troxler Sentry 200-AP moisture meter has only been in production since 1990. There is little published information available on this specific sensor except for the information supplied by the manufacturer and two field studies. Therefore, the actual accuracy and reliability of the meter compared to other methods has yet to be determined even though the theory behind the meter has been known and studied for a period of time.

Aqua-Tel

The Aqua-Tel soil moisture sensor also relies on changes in the dielectric constant of the soil to remotely determine the soil moisture content (Automata, 1992). This sensor consists of a small encapsulated electronic module for environmental protection with two electrodes attached. Standard electrode length is 81.28 cm (32 in), with various lengths available. Sensors are equipped with a four-wire cable to power the sensor with 12 volts DC. Output from this sensor is 0-1 milliamps, which is converted to a voltage by a shunting resistor (Automata, 1992).

These factors make the sensor very easy to connect to a datalogger and to use with an automated control device. This sensor also obtains an integrated reading along the length of the electrodes and is designed for permanent installation.

No published literature was found for this sensor, therefore, no unbiased study of this sensor is known to exist even though the sensor design meets a number of important criteria for accurately determining soil moisture content.

Aquaterr

The Aquaterr soil moisture meter consists of a capacitance probe that measures the dielectric constant of the soil (Aquaterr Instruments, 1990). As the soil moisture content changes, the Aquaterr moisture meter reads the dielectric constant with the electrodes placed in the end of the probe. The value is then interpreted with the aid of a chart with values for different soil types.

Measurements of soil moisture with the probe require calibrating it one time per day. To calibrate the meter, the end of the probe is submerged in a bucket of water and the reading set to read 100. The meter then yields accurate results according to the manufacturer. The manufacturer recommends re-calibration at any time there is doubt in the reading. The probe can then be inserted into the soil to determine the moisture content in only a few seconds (Aquaterr Instruments, 1990). It is recommended to take several readings in the area with a large enough spacing to clear the 10.16-12.70 cm (4-5 in) radius the probe reads, and to average the results for the representative moisture content. The major criticism of the Aquaterr

moisture meter at this point is the fact that it is difficult to use below the top few inches of soil, it requires a degree of destructive sampling, and that it cannot be connected to a datalogging system, making it impossible to use the meter with an automated system.

Little published information on the Aquaterr meter has been found, leaving the accuracy of this moisture measuring device relatively unknown. However, the determination of soil moisture content by capacitance methods has been studied for a number of years and found to be accurate. Ley (1994) included this sensor in his field study and reported satisfactory results, but the accuracy of this sensor as well as the life expectancy of the meter requires further investigation. This sensor was removed from this study because destructive sampling was required to obtain soil moisture measurements with the probe.

Time Domain Reflectometry

Time domain reflectometry (TDR) has become an established method to measure soil moisture content (Nadler and Lapid, 1991). As early as 1939, scientists recognized the relationship between dielectric properties of the soil and moisture content. However, technology was lacking to utilize this relationship (Trase). From the early 1980's, much research has been conducted on TDR, and moisture measurement units are now available commercially.

TDR is based on the measurement of the propagation time of a wave form to travel over a fixed length of waveguide, usually constructed of stainless steel

(Ledieu et al., 1986), embedded into the soil. The measurement technique and empirical relationship (Equation 6) was published by Topp et al. (1980).

$$\theta_v = -0.053 + 0.029 K_a - 5.5 \cdot 10^{-4} K_a^2 + 4.3 \cdot 10^{-6} K_a^3 \quad (6)$$

θ_v is the percent volumetric water content and K_a is the real part of the dielectric constant. K_a can be calculated by the relationship in Equation 7.

$$K_a = \left(\frac{ct}{2L} \right)^2 \quad (7)$$

Where c is the velocity of light ($3 \cdot 10^8$ m/s), t is the travel time in seconds, and L is the length of the waveguide in meters (Topp et al., 1980).

The waveguides can, in principle, be constructed of any material with a conductivity much greater than the medium in which they are placed (Dalton and Poss, 1990). The choice of placement of the waveguides or transmission guides is also flexible (Topp et al., 1983). Studies by Topp and Davis (1985a) revealed the choice of waveguide configuration depends on the specific requirements of the implementation. Vertical waveguides are easily installed and removed and give a good measurement of total water within the depth spanned by the guides. Horizontal guides, however, give a better integration of the spatial variability in the horizontal directions. The major disadvantage found for horizontal guides was the need to dig an installation pit (Topp and Davis, 1985a). It should also be noted that Topp and Davis (1985b) concluded that as the length and spacing of the transmission guides increased, the resolution of the system decreased. The line

spacing found to be practical for the two-probe waveguide was 50 mm (1.97 in).

This gave a sample cross sectional area of 3800 mm^2 (5.89 in^2), or 1.4 times the spacing between transmission guides (Topp and Davis, 1985b). During the field study, Topp and Davis (1985a) used rods with a diameter of 12.7 cm (1/2 in).

They concluded, however, that it is unnecessary to use a rod this large.

Accordingly, they now use 3 mm (0.118 in) or 6 mm (0.236 in) rods for their studies. Rods of this diameter do not require a bore hole for installation. The soil is primarily undisturbed if they are driven into it. The 3 mm (0.118 in) rods are used for lengths up to 0.5 m (19.69 in) and 6 mm (0.236 in) rods are used for lengths greater than 0.5 m (19.69 in) (Topp and Davis, 1985a). Their study also determined that, with current technology, guides with discontinuities are not recommended for field measurements.

The transmission guides of a TDR unit are connected to a coax cable tester by a coaxial cable with a constant impedance (Ledieu et al., 1986) and the best frequency currently known to measure the pulse is 50 Mhz. This frequency allows one to obtain similar results that agree with previous studies (Campbell, 1990).

TDR when compared to the gravimetric method seems to yield very favorable results. Topp and Davis (1985a) reported that a paired t-test on comparative data from a field test generally showed no significant difference at the 5% level and Dasberg and Dalton (1985) also reported a good relationship between the two methods. In general, variance attributed to line type is not significant (Topp and Davis, 1985a). The accuracy of TDR could be due to the independent

relationship with soil texture, density, temperature, and salt content of the soil (Topp et al., 1980).

Advances in TDR technology include an improved three-waveguide and four-waveguide design that requires no impedance matching balun (Zegelin and White, 1989) and remote diode shorting techniques (Hook et al., 1992). Multiwire probes emulate coaxial transmission guides, reducing noise reflections and eliminating the necessity for a balancing transformer due to the reduction of impedance mismatching (Zegelin and White, 1989). Multiwire designs use a center waveguide connected to the center wire of a coaxial transmission line. Outer waveguides are equally spaced around the circular perimeter of the sensor and are connected to the coaxial cable shield. As the number of waveguides around the perimeter increases, the more closely the probe represents a coaxial transmission line. But greater soil disturbance during installation of four (or more) waveguides per sensor outweighs any advantage gained from the additional waveguides (Zegelin and White, 1989). Remote diode shorting techniques take a reading with the diode shorting the waveguides, take another reading that includes the length of the waveguides, and subtract the readings to cancel any noise in the system (Hook et al., 1992).

Results from these designs appear to be accurate, but the high cost of a TDR system is still a limiting factor. Readings are generally measured with a coax cable tester, that costs approximately \$8500. However, complete commercial TDR

systems that do not require a separate cable tester can now be purchased for approximately \$4000.

CHAPTER III

MATERIALS AND METHODS

The experimental design was developed around non-destructive determination of the actual water content of two soil types, a loam and a sandy loam. To achieve this goal, two identical devices were constructed that monitored the water content of each soil type independently by measuring the weight of water with load cells and recording the reading with a datalogger.

The experimental design was nearly the same as that of a weighing lysimeter. Soil was placed in columns and suspended so the weight of each column could be continually monitored and the actual water content of each column be computed. This allowed sensor output to be fitted to a calibration equation and compared to the water content of each column.

Preliminary Sensor Studies

Preliminary sensor studies included independently connecting each automated sensor to a datalogger to insure proper operation. These studies were conducted with the sensor placed in a bucket of soil. Some sensors worked satisfactorily while others required modifications to make them compatible with a datalogger.

The Aqua-Tel sensor required 12 volts DC as a power source. The output signal from this sensor was a 0-1 milliamp current (Automata) that was converted

to a voltage with a 2.4-K shunting resistor to utilize the full scale 2500-millivolt range of the Campbell Scientific CR10 datalogger. The sensor requires a current of 30 milliamps, therefore the switching device illustrated in Figure 1 was designed and constructed to control the sensor and prevent excessive power drain from the battery. The control board consisted of a normally-open relay switch connected to the 12-volt terminal on the CR10. The relay was operated by exciting an output control port on the datalogger. When the control port was high, the output voltage saturated a NPN transistor and allowed current to flow through the coil of the relay. The contact on the relay closed and a 12-volt power connection to the sensor was made. The voltage drop across the shunting resistor was then read as a single-ended voltage input by the datalogger and recorded.

The Agwatronics heat dissipation blocks were powered by +10 volts DC. When the blocks were purchased, a device to drop the excitation voltage from 12 volts to 10 volts was also purchased. The modification required for this sensor was similar to the switching device used for the Aqua-Tel sensor. A relay switch was used to break the ground of the voltage diversion box connected to these sensors, which allowed the heating element to be powered in one-minute intervals with a control port on the datalogger. Moisture content values were determined with a type-T thermocouple connected differentially to a datalogger. Readings were taken before and after heating the block and the difference between the two temperatures was used to determine the moisture content of the soil.

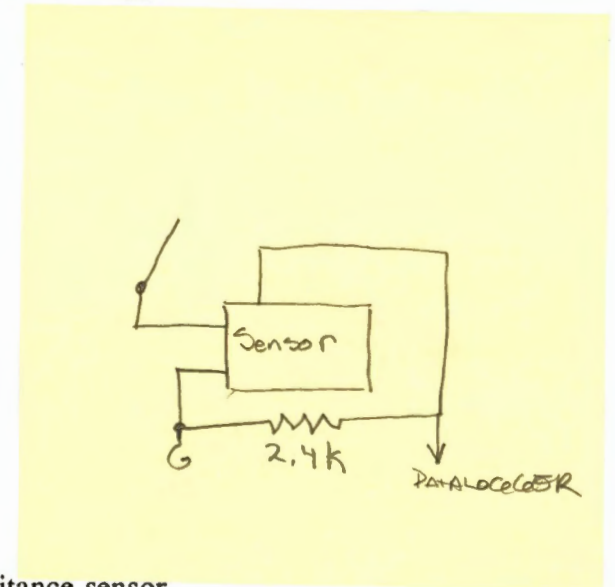
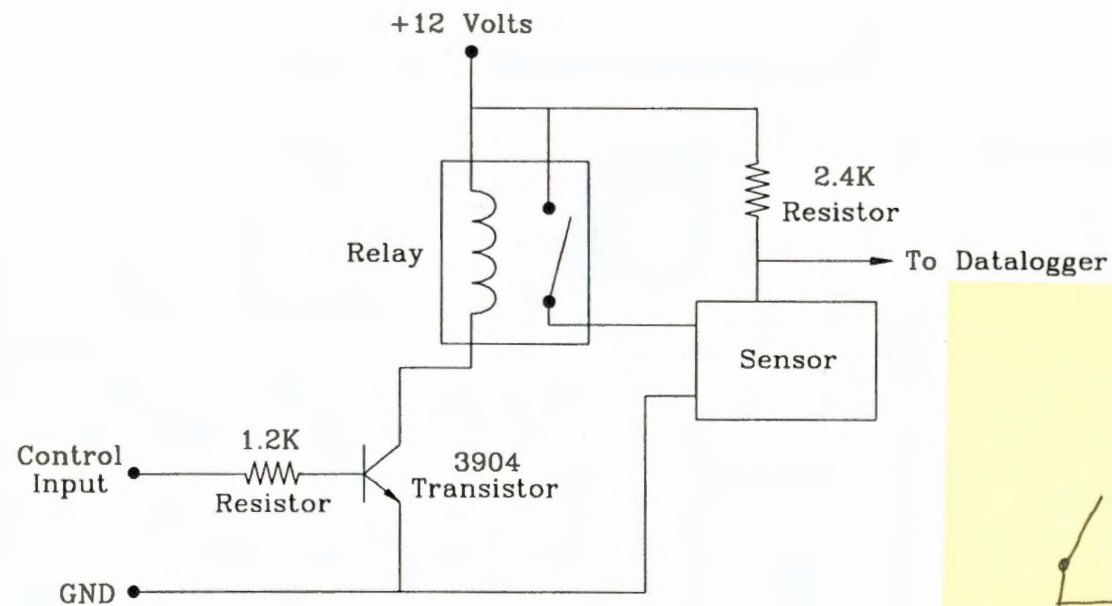


Figure 1. Schematic of the switching mechanism for the Aqua-Tel capacitance sensor.

TDR readings were logged using a Campbell Scientific CR10 datalogger, a Tektronics model 1502 cable tester, and a Campbell Scientific SDMX50 multiplexer. The procedure used for these sensors is as illustrated in the Campbell Scientific TDR manual, with the four-waveguide sensor connected to the multiplexer channel following the channels used for the Campbell Scientific waveguides, allowing all waveguides to be read in the same manner. Figure 2 illustrates the wiring diagram of the TDR system. The 12-volt battery is connected to the CR10, cable tester, and multiplexer. The control ports C1, C2, and C3 on the datalogger are used to control the cable tester and multiplexer. Port C1 is the data port, transferring data from one component of the system to the other. Ports C2, labeled clock, and C3, labeled enable, control the cable tester and the multiplexer. They control when the channel on the multiplexer changes, and set the range and scale on the Tektronics 1502 cable tester (Campbell Scientific, 1990). The program downloaded to the datalogger (Appendix C) determined the operating parameters of the system. The control port C4 is used to control a Campbell Scientific 1502B adapter that allows the cable tester to be powered with 12 volts and controlled by a datalogger.

Soil moisture blocks were connected to a Campbell Scientific AM416 multiplexer that was connected to a CR10 datalogger (Figure 3). Reset, which controls activation of the multiplexer, was connected to control port C1 on the datalogger. The clock line was connected to port C2. This line controls the switching between sequential sets of relays. When the multiplexer receives a pulse

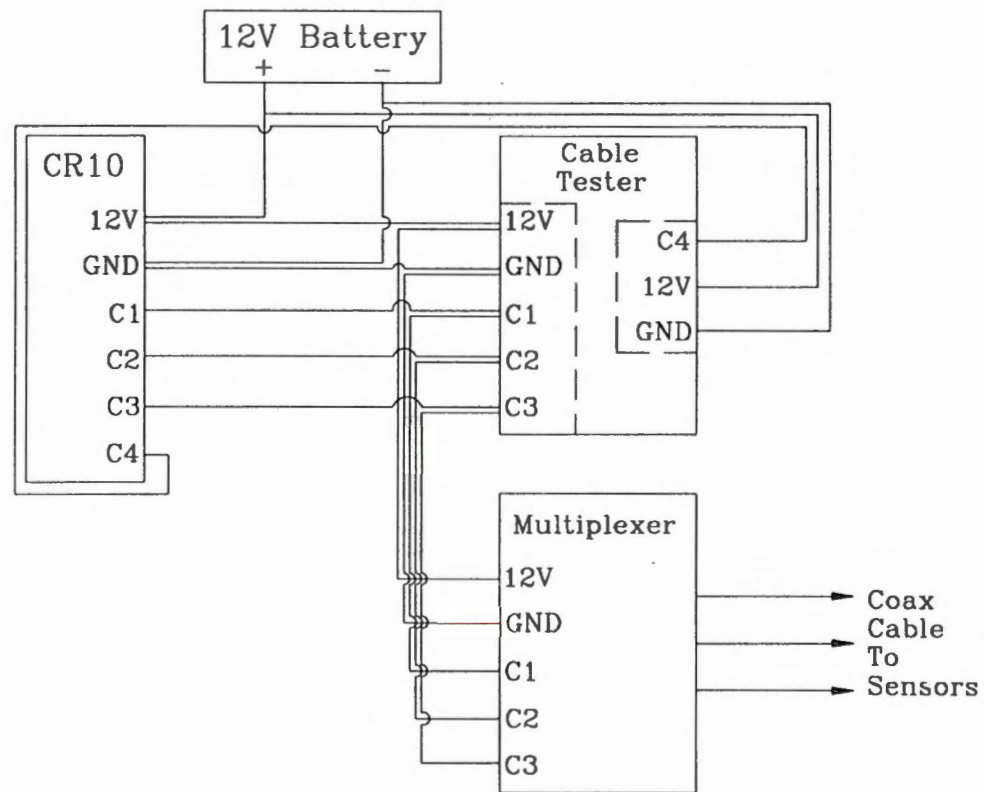


Figure 2. Wiring diagram for TDR system components.

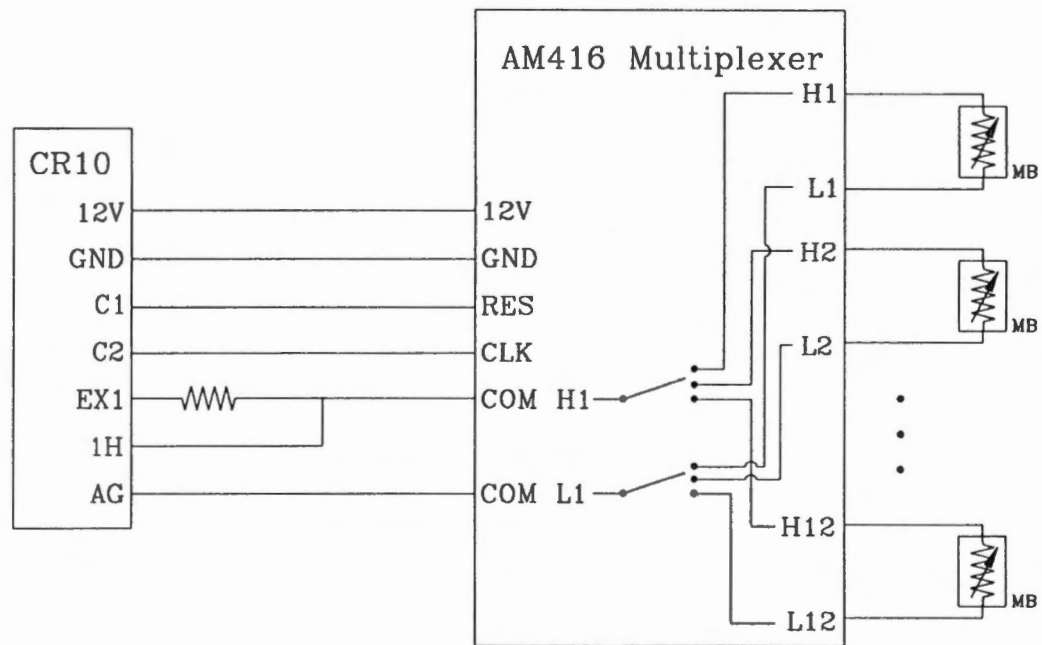


Figure 3. Wiring diagram for AM416 multiplexer and soil moisture blocks.

from the clock, the common lines are switched to the next channel on the multiplexer (Campbell Scientific, 1990). The common lines are connected to the CR10 with a 1-K resistor in-line to complete the half bridge circuit. The resistor is connected to excitation channel 2 and one wire is connected to channel 2H while the other is connected to the common high channel of the multiplexer. The common low channel is then connected to an analog ground port on the datalogger. This allows a differential voltage reading between the 1-K resistor and the variable resistance inside the moisture block. Twelve of the sixteen input terminals were used on the multiplexer. The first six were connected to gypsum blocks and terminals 7-12 were connected to the Watermark PVC blocks.

Following independent sensor testing, logged devices used during the study were connected to two Campbell Scientific CR10 dataloggers. One CR10 was connected to the TDR system, the Aqua-Tel sensors, and the Agwatronics heat dissipation blocks. Sensors connected to this datalogger were read independent of the TDR sensors due to an interference between sensors. It was not determined if the interference was a result of the sensors being confined to a small area or an electrical noise problem within the datalogger. Due to the amount of time required to read these sensors sequentially, and a shortage of datalogger ports and excitation channels, a second CR10 was required. The second datalogger was connected to the load cells on the counterweight boxes and to the AM416 multiplexer that was connected to the soil moisture blocks. Programs downloaded to each datalogger are given in Appendix C.

Lysimeter Apparatus

The hanging apparatus was designed to suspend the columns to allow the weight of water to be continually monitored. This was achieved by using an overhead frame constructed of I-beam, steel pipe, and channel steel as illustrated in Figure 4. A lever arm with a two-to-one ratio was attached to the frame via two flange bearings to minimize friction. An angle steel frame large enough to suspend one soil column was connected to the lever arm. A counterweight box weighing one-half the weight of the soil column was attached to the other end of the lever arm to counterbalance the weight of the column, sensors, and dry soil. The weight change of water from saturation to dry soil for an assumed soil porosity of 40 percent was calculated to be 25.61 kg (56.46 lb). The two-to-one lever arm allowed a 11.3 kg (25 lb) capacity load cell to be mounted on the bottom of the box to monitor the change in weight of water in the column over any desired range of moisture content. The load cell was connected to a lead weight placed on the floor that protected it from being overloaded (Figure 5). If the weight on the load cell exceeded that of the lead weight, the weight would be lifted off the floor and the load cell would not be overloaded. The weight of water in the column was measured directly and the weight of the column, soil, and frame was known, allowing the volumetric water content, θ_v , to be determined with Equation 8.



Figure 4. Lysimeter apparatus suspending the soil columns.

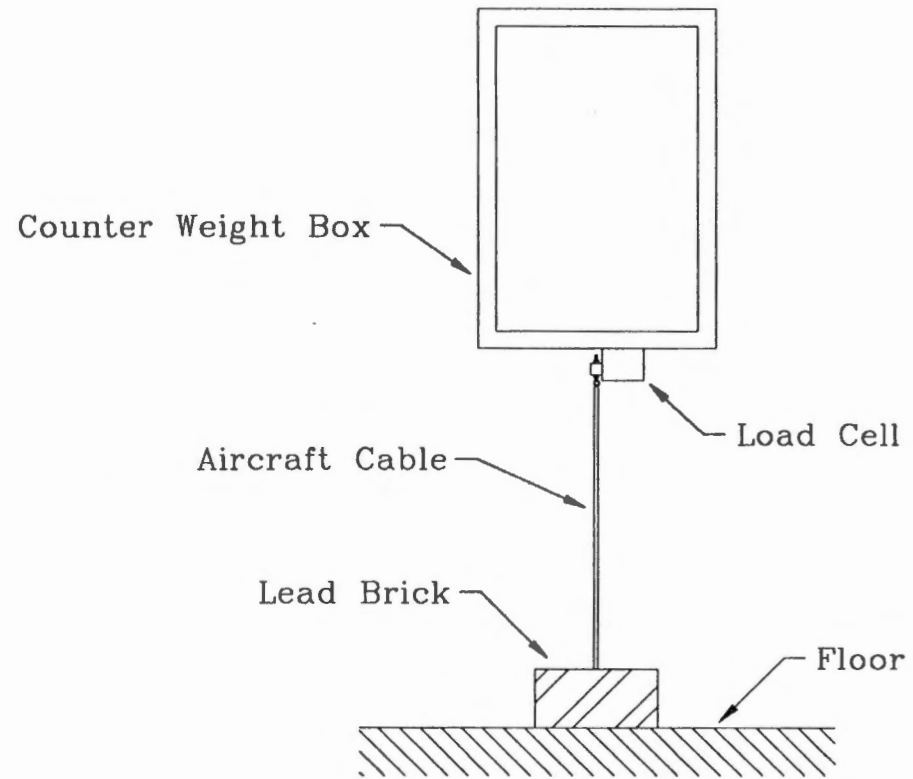


Figure 5. Lead brick connected to a load cell for overload protection.

$$\theta_v = \frac{\text{weight of water}}{\text{weight of dry soil + column}} * 140 \quad (8)$$

To obtain the percent of water in the column by volume, all units of mass must remain constant and the water content on a mass basis is multiplied by the bulk density (1.4 gm/cm³) and by 100.

Soil Physical Characteristics

The soil types chosen for this experiment were agricultural soils typical of the area. Both soils were obtained from The University of Tennessee Plant Science Farm located near Knoxville, Tennessee. The soils chosen were not extremely coarse nor fine, and were chosen to vary the soil type used to compare sensor readings. The soil was collected from the field, taken to the lab, and air dried. When the soil was dry, it was sieved with a #10 sieve to remove gravel, organic matter, and clods.

The finer textured soil was collected from an upper flood plain of the Tennessee River. This soil had previously been removed from a field planted in grass and contained a relatively high amount of organic matter. Particle size analysis revealed that this soil contained 46 percent sand, 34.9 percent silt, and 19.1 percent clay, classifying this soil as a loam.

The coarser soil was collected on the lower flood plain near the Tennessee River. The soil was removed from the edge of a plot that had been planted in corn the previous year. The cover crop was relatively nonexistent in the plot, therefore

the organic matter content of this soil was relatively low. This soil contained 76 percent sand, 16.9 percent silt, and 7.1 percent clay, classifying it as a sandy loam.

Soil Columns

The soil columns were constructed with a length of 15-in (38.1 cm) nominal diameter PVC sewer pipe. A flat piece of 1/2-inch (1.27 cm) PVC was welded on the bottom of the pipe, with a 1/4-inch (0.635 cm) compression fitting located in the center connected to a drainage tube to allow water to escape from the column. Sand was placed in the bottom 1.27 cm (1/2 in) of the columns to allow water flow to converge to the center of the plate. A 12-inch (30.48 cm) nominal diameter by 1/2-inch (1.27 cm) thick 5-bar ceramic plate was placed on a PVC ring that was welded to the sides of the pipe above the sand layer to hold tension on the soil water above the sand.

All sensors to be logged were installed in the columns at a depth of 30.48 cm (12 in) from the bottom around a 2-inch (5.08 cm) PVC access tube (Figure 6). Wires from the sensors ran through the sides of the columns 1.27 cm (1/2 in) from the top and were sealed with compression fittings. The compression fittings (Figure 7) consisted of a brass pipe fitting with a washer placed in the nut. The brass midsection of each fitting was removed and replaced with a rubber grommet with the appropriate diameter hole for the wire drilled in the center. The wires were then connected together and attached to the overhead frame assembly to minimize interference with the load cell values.

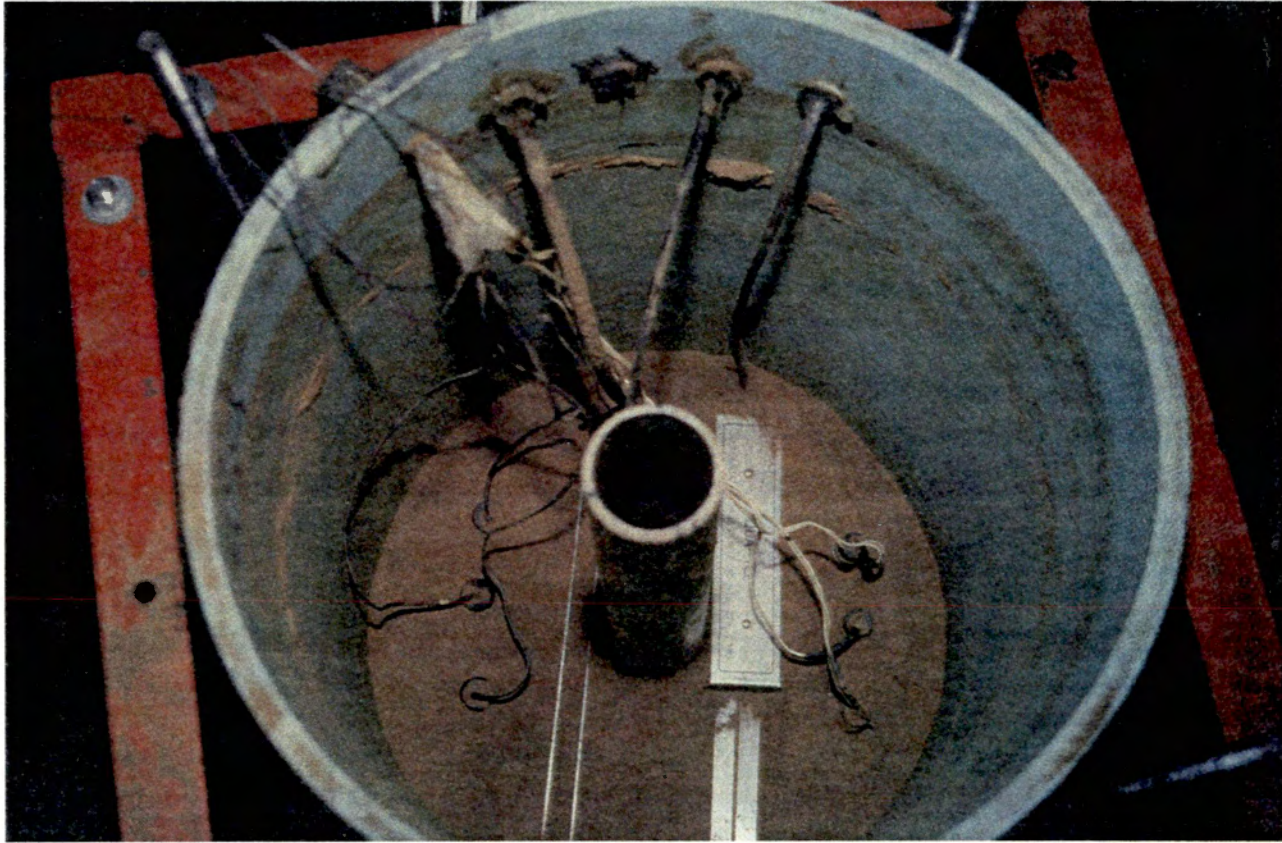


Figure 6. Sensor placement around access tube in soil columns.



Figure 7. Compression fittings in soil columns.

To seal the top of each column, an activated rubber sheet was glued to a 1/2-inch (1.27 cm) flat PVC plate. The plate was placed on the soil column and a reinforced piece of flat steel was placed on the PVC plate. The steel plate was bolted at six points, four to the plate at the bottom of the column and two to the frame (Figure 8).

The PVC plate was drilled and tapped for a 1/2-inch (1.27 cm) NPT fitting. A quick-connect union for an air line was installed in the plate to introduce air to the columns from the top.

Column Packing

The columns were packed by adding soil in layers and packing each layer to a bulk density of 1.4 gm/cm^3 (0.0506 lb/in^3) until a total depth of 60.96 cm (24 in) of soil in the column. The soil was added to a column in 7.62-cm (3-in) layers. To determine the amount of soil to add to each layer, the volume of each section, 7978.62 cm^3 (486.88 in^3), was multiplied by the bulk density, which yielded a total soil weight of 11.170 kg (24.63 lb) to be added and packed for a 7.63-cm (3-in) layer.

The soil for each layer was weighed, approximately half of it was placed in the column and was packed. The remaining soil was then added and packed to marks on the inside of each column which indicated the desired thickness of the layer. This process was repeated four times, all sensors were installed, and 30.48 cm (12 in) of soil was packed above the sensors in 7.62-cm (3-in) layers.

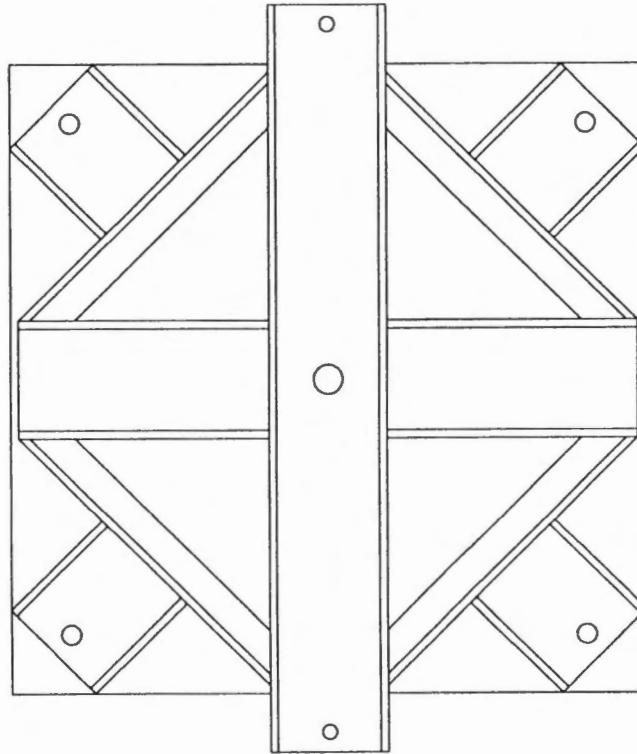


Figure 8. Steel plate that bolted onto top of soil columns.

Sensor Placement

Permanently installed sensors were placed as close to the vertical center of the soil column as practical. Sensors were placed around the access tube with sufficient spacing to prevent interference between sensor types within the column.

Figure 9 illustrates the placement of sensors within the column. Located in the center of the column is the 2-inch (5.08-cm) PVC access tube for the Troxler gauges. Placed next to the access tube are the Campbell Scientific time domain reflectometry (TDR) wave guides and the Aqua-Tel capacitance probe. Three gypsum blocks are installed between the Campbell Scientific TDR and the column wall. Three Watermark PVC Blocks are on the opposite side of the column beside the Aqua-Tel sensors. One Agwatronics sensor is placed between the Campbell Scientific TDR and Aqua-Tel sensors one-half the distance from the access tube to the wall. The four-waveguide TDR sensor was placed 7.62 cm (3 in) above the other sensors with the same orientation as the Campbell Scientific TDR sensor.

Load Cell Calibration

Each load cell was calibrated independently by placing a bucket with known weights of water on the columns. Water was added to the bucket in 3-kg (6.61-lb) increments over a range of 0 to 24 kg (52.91 lb) and load cell output was recorded with the datalogger. The procedure was repeated three times to minimize any error obtained from the procedure. The data collected for each load cell were then fitted

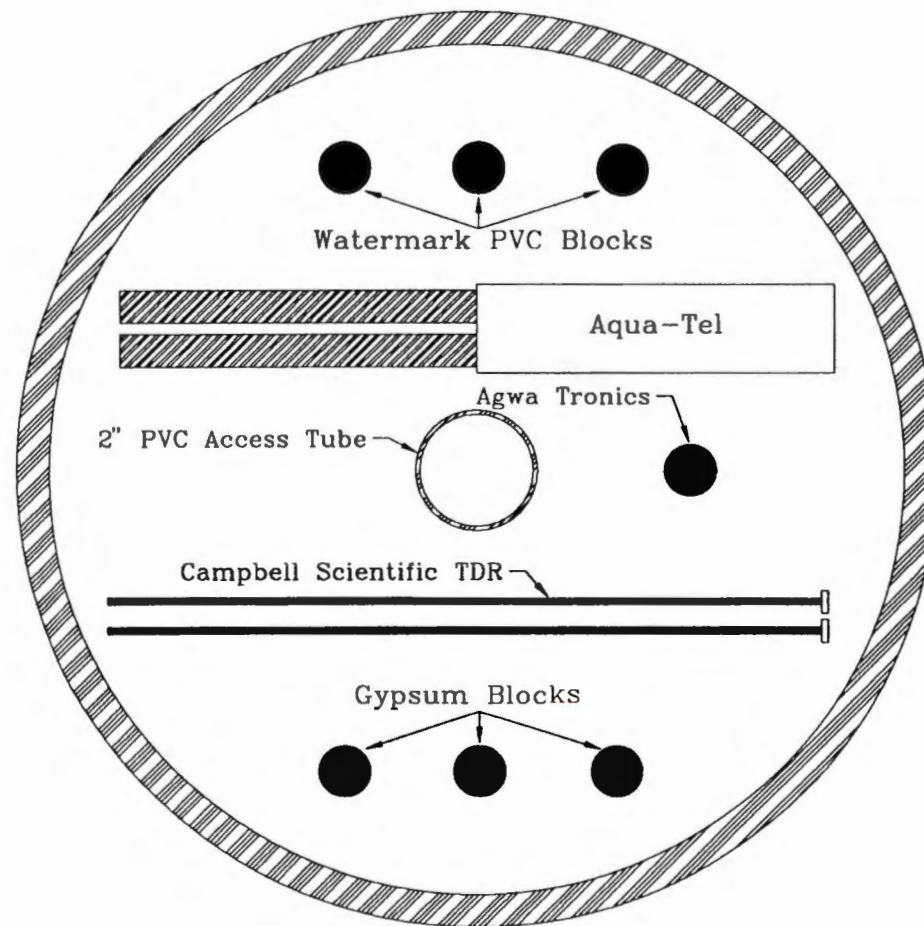


Figure 9. Sensor placement in soil columns.

to a linear calibration equation, allowing the volumetric water content, θ_v , to be determined directly.

Measurement Techniques

Measurement procedures can be broken down into two methods, automated and manual. Each sensor was read five times at each measurement point and the readings averaged. The protocol was designed to minimize variation of each sensor and obtain the best possible results. Measurement points for all automated sensors were taken every 30 minutes continuously throughout the drying cycle. Manual sensor measurement points were taken approximately every 5 percent by volume moisture change as determined by the load cell readings.

Automated Sensors

Automated sensors include all sensors that were connected to a Campbell Scientific CR10 datalogger for continuous monitoring of the soil moisture during a drying cycle. Automated sensors included in the study were: 1) Aqua-Tel capacitance probe, 2) Campbell Scientific TDR, 3) the four-waveguide TDR probe, 4) Agwatronics heat dissipation blocks, 5) gypsum blocks, and 6) Watermark PVC moisture blocks.

Manual Sensors

Both Troxler moisture gauges used in the study are manually operated soil moisture sensors. Troxler manufactures probes for the Sentry that can be permanently installed. However, these probes were not used because the access tube was required for the neutron probe, making one Sentry probe adequate for this study. These sensors require the use of a 2-inch (5.08 cm) nominal diameter access tube that was installed in each column, allowing one sensor to be used for both columns. Readings from these sensors required removing the sealed top of each column, inserting the probe into the access tube, and obtaining the moisture content value.

The neutron probe count was recorded and divided by the standard count to yield a count ratio. The count ratio was then used as the moisture content indicator and fitted into a calibration equation.

The Sentry 200-AP moisture gauge obtained a moisture content value by determining the capacitance between the electrodes. These values were fitted to a calibration equation over a number of different moisture contents.

Soil Wetting and Drying

To determine the amount of water to add to each soil column, field samples of each soil type were collected at field capacity. The samples were dried twenty minutes in a microwave oven as specified by Gee and Dodson (1981), and moisture content values were determined and averaged.

To obtain the amount of water to add to each column, the field capacity moisture content of each soil was fitted into Equation 9.

$$\frac{\text{Field Capacity Water Content}}{100} = \frac{\text{Weight of Water}}{\text{Weight of Dry Soil}} \quad (9)$$

The weight of water added to each column was 20.24 kg (44.62 lb) for the loam and 19.38 kg (42.72 lb) for the sandy textured soil.

Water was slowly added to the top of each column and allowed to infiltrate into the soil profile. After all water was added to each column, two days were allowed for the water to equilibrate throughout the column and any drainage to cease. Following the equilibration period, sensor readings were recorded and stored for the corresponding moisture content and time. The columns were then sealed and pressurized from the top to 51 kPa (7.4 psi) soil tension. Moisture readings for the Troxler gauges were taken when the water content dropped approximately 5 percent by volume and were recorded with logged sensor readings for a given time and soil moisture content.

The procedure remained the same for the duration of a drying cycle with the exception of increased air pressure in steps as the soil water content decreased. At lower moisture contents, increased air pressure forced the soil to release water that was held more tightly by the soil pores, allowing the moisture content in the soil to decrease at a faster rate.

Sensor Calibration

The first drying cycle was considered the calibration cycle. Data points recorded during this cycle were used to calibrate each sensor with the moisture content determined from the load cell readings. Calibration equations with an r^2 value generally greater than 0.99 were fitted for each individual sensor (Table B-1). These equations were generally quadratic or higher order in form with exponential terms for resistance sensors. Software used for this procedure included SAS® statistical analysis program and Table Curve®, a program designed to determine the best-fit curve for a given set of data.

Three subsequent drying cycles were used to compare sensor readings to actual moisture contents. Readings inserted into the calibration equations and the moisture content values determined by each sensor were statistically compared to the actual moisture content of each soil column.

Data Collection

Data collection procedure for the project varied with sensor types. Automated sensor data collection consisted of downloading each datalogger daily into comma-delineated ASCII files. The files were then imported into a single spreadsheet where readings for a given time would be together. Manual sensor data were recorded on paper for each column and entered into a spreadsheet. The count from the neutron probe was then divided by the standard count to be inserted into the calibration equations.

All sensor data were then imported into a single spreadsheet. Rows consisted of all sensor readings for a given day and time, while columns consisted of all data to be analyzed for a given sensor over one drying cycle. The five sensor readings recorded for each sensor at a given time were then averaged and stored in a separate block of the spreadsheet. These data were then imported into a spreadsheet notebook that contained the calibration equations. The actual and predicted soil moisture content values were exported to ASCII files to allow them to be imported into SAS® for statistical analysis.

Statistical Analysis

Statistical analysis of the data consisted of running a number of tests on the data listed in Appendix B to determine which sensors most closely predicted the actual moisture content of the soil. To achieve this goal, several numerical manipulations were implemented. These included breaking the moisture content of the soil into three ranges, with the boundaries of each range determined independently for each soil type. A second variable generated in SAS® was the difference between the predicted and actual water content of the soil. The absolute value of this difference was then used in the analysis. This difference value was used because it allowed the amount of prediction error to be included in the mean without overpredicted values cancelling out underpredicted values of θ_v .

Statistical tests run on the data used PROC MEANS to determine the mean values of the differences and absolute differences. The mean values determined

included testing each sensor independently with various factors including ranges, cycles, and soil types. Secondly, paired t-tests were conducted using PROC GLM to determine what factors contributed significantly to the model. Results of this model were then used to determine which variables to include in the model to determine T groupings and least significant differences for the sensors.

CHAPTER IV

RESULTS AND DISCUSSION

Preliminary testing of the system and system components revealed much about the performance of the apparatus. Pressure testing the columns revealed needed modifications, while the sensor calibration cycle set the operating parameters of the system.

Prior to calibrating the load cells, each column was pressure tested to determine if it would seal and endure the required pressure. The maximum pressure to be applied to the column was limited to 513.35 kPa (74.46 psi) because of the 5-bar ceramic plate. ASTM Standard #D2241 rated the pipe for 813.58 kPa (118 psi), and it was assumed that the 1/2-inch thick (1.27-cm) PVC top and bottom of the column should withstand the pressure with reinforcements. At first, problems occurred around the seal at the top of the columns. When the column was pressurized, the top would bow and leak air at pressures above approximately 138 kPa (20 psi). A steel plate was then welded to the channel steel brace on top to reinforce the PVC top of the column. The first column tested withstood the pressure and did not leak. The second column was then reinforced the same as the first. When this column was tested, a PVC weld failed along the bottom of the column and the bottom plate cracked. The bottom of the column was then glued and welded along the crack. A piece of flat 1/2-inch (1.27-cm) PVC was also welded to the bottom plate on both columns and placed on a piece of flat steel to

further reinforce the columns. These modifications allowed both columns to perform adequately at all pressures. The load cells were then calibrated, the soil saturated, and the sensors calibrated.

The calibration cycle served a multifunctional purpose. It produced data to fit equations to raw sensor output and also revealed the answers to unknown operating parameters of the system.

One important question raised during this cycle was the performance of the ceramic plates. Air and liquid water flowed from the columns at higher moisture contents, and air and water vapor flowed from the columns at lower moisture contents. When the air pressure was held constant the water content of the columns continued to decrease, with only the rate of water removal changing. At this point, it was hypothesized that the ceramic plates had cracked in both soil columns. It was concluded that this was not a critical parameter of the study. Water should be forced from the larger pores in the soil first, which would cause uniform drying, since the soil was packed uniformly throughout the column. However, if the columns did not dry uniformly, individual sensor calibration and the fact that the soil would be undisturbed made it possible to hypothesize that the sensors would be calibrated according to the amount of total water in the column. The columns should repeatedly dry in the same manner for the following three cycles. Therefore, any error in the determined actual moisture content would be accounted for and would only be a calibration offset for a sensor.

A second factor determined was the amount of water that could be removed from a soil column. The addition of a moisture trap placed in the air line allowed the total operating range of the system to be from saturation to less than two percent water by volume. A desiccant was added in the air line to allow for more moisture removal. This practice was discontinued due to the large amounts of water vapor in the air lines requiring the desiccant to be changed often and the fact that extremely low moisture contents seldom occur in field applications.

The time required for a cycle and rates of water removal were also determined during the sensor calibration cycle. The rate of water removal was controlled by applying low pressures to the columns at high water contents and increasing the pressure by approximately 34.5 kPa (5 psi) as the water content decreased between manual sensor measurement points. This allowed the water content to remain consistent throughout the column and allowed the porous soil moisture blocks time to equilibrate with the surrounding soil. The variable air pressures applied to the columns required approximately two weeks to complete one cycle from the initial addition of water to dry soil. An exact drying time could not be determined because the common air line in the building was used and the time for each cycle was dependent on the humidity of the air.

Data Analysis

The data was analyzed to evaluate: 1) sensor performance over the range of soil moisture contents, 2) sensor performance over time, and 3) total overall

performance of the sensors. To evaluate these points, the data was analyzed graphically (Appendix A), and by drying cycles, by moisture content ranges, and as a group that included all drying cycles and ranges. Ranges were created by including all values of θ_v below 10 percent in the lower moisture range, all values between 10 and 30 percent in the loam and all values between 10 and 20 percent in the sandy loam in the middle range, and all higher values in the high moisture range.

Table B-2 lists the mean and absolute mean differences of predicted and actual moisture contents for each range of soil water content in the soil column. These values were chosen to represent the prediction error for each sensor. The mean difference values allow one to observe the average prediction error of a sensor for a given range of θ_v . However, these means can erroneously result in a low value indicating good performance of a sensor when the sensor actually overpredicted and underpredicted θ_v consistently with the values cancelling the others. Therefore, the absolute mean difference allows one to determine, on the average, what percent by volume the sensor prediction error of θ_v is for a given range of moisture contents. Values included in the mean were for all three drying cycles for the percentage of water content defining each range. Information in Table B-2 also allows one to determine the number of valid observations included in each range and how well an individual sensor predicts the moisture content for a certain range of moisture contents and/or soil type. Table B-3 lists the mean values for each range and each cycle. The table also includes the number of observations

included in each block of data. The observations included in Table B-3 consist of all predicted values of θ_v between 0 and 50 percent. These limits were set because predicted values outside this range were obviously erroneous. Therefore, a sensor may have many observations for a given range of a cycle and only one or two for others, so the number of valid observations is important for determining the overall performance of a sensor because a low number of valid observations may not accurately represent the sensor's performance. The results may show a desirable performance from a sensor, when the sensor recorded only a few valid readings from many data points. Table B-3 allows the changes in prediction error for each sensor to be observed from cycle to cycle. The mean and absolute mean differences for each sensor and cycle over all ranges of water content are also included and allow one to determine how the mean difference changed from cycle to cycle over the entire range of moisture contents. Table B-4 includes the mean absolute and mean differences between predicted and actual moisture content over all ranges and cycles. These values allow one to determine the prediction error for a given sensor for the duration of the study over all ranges and cycles of θ_v .

Statistical Analysis

Statistical analysis of the data consisted of performing a paired difference t-test on all sensors with all possible independent variables and interactions included. The results of this t-test allowed all valid readings for each sensor to be analyzed

and overall values of the mean absolute difference to be computed along with T groupings for all sensors included in the study.

Statistical analysis began by testing the data for normality and standard deviations. The data appeared normal with the exceptions of two sensors that performed poorly during the study. Standard deviation values revealed the same results. Therefore it was concluded that the data could be assumed normal and statistical procedures would be valid.

Significant variables were determined with SAS® by running PROC GLM on the data to model the mean absolute difference of values against sensor type, cycle, range, soil type, and all possible combinations of these independent variables. This procedure revealed that, at a 95 percent confidence level, significant variables were sensor, range, sensor*range, and sensor*soil. Therefore, the question of sensor performance over time was answered by comparing results between cycles. Readings from cycle to cycle were not statistically different for all sensors as a group (Table B-5). However, some differences between actual and predicted moisture content changed over time are illustrated in Table B-2. The test also revealed a significant difference for predicted values within each range. Mean differences (Table B-2) allow one to determine the sensors that appear to cause this difference. Sensors such as the gypsum and the Watermark PVC soil moisture blocks may have small mean difference values for one range and large mean values for other ranges. This is an indication that the sensor performs well in one range or soil type but not in others.

The model used to determine the sensor T groupings contained all possible interactions of independent variables and the absolute mean difference of predicted minus actual moisture contents as the dependent variable. Table 4-1 lists each sensor type, the number of valid predicted volumetric water content values, the overall mean absolute difference, and the T groupings. T groupings of the same letter are not significantly different at a 95 percent confidence level. The number of observations is an important factor to consider. Table 4-1 lists the number of valid observations ($0 < \theta_v < 50$) for each sensor. All sensors except the two TDR sensors would have 64 observations, and the TDR sensors would have 32 if all data points were valid since these sensors were only tested on one soil column. Therefore, one erroneous reading would have a greater effect on these sensors since fewer values were included in determining the means.

Sensor Performance

The apparatus was designed to evaluate each sensor under the best laboratory test conditions possible to obtain the highest possible performance from each sensor. The temperature of the soil was held constant to remove any sensor variability, the bulk density of each soil column was held constant throughout the soil profile, and two middle range soil textures were used to observe the difference in sensor output for different soil textures. Since these factors are known to affect the output of many of these sensors, performance may change if these variables are added to the variables determining soil moisture sensor performance.

Table 1. Results from t-test for each sensor for entire study.

Sensor	N	Mean Absolute Difference	T Grouping ⁺
Campbell Scientific TDR	25 [*]	11.82	A
Agwatronics	18	6.73	B
Four-Waveguide TDR	30 [*]	4.49	C
Gypsum Block #3	45	4.32	C,D
Gypsum Block #2	56	3.82	C,D,E
Gypsum Block #1	54	3.81	C,D,E
Neutron Probe	64	3.19	C,D,E,F
Watermark #3	62	3.04	D,E,F,G
Watermark #2	57	2.60	E,F,G
Aqua-Tel	64	2.45	E,F,G
Watermark #1	52	2.09	F,G
Troxler Sentry	62	1.72	G

^{*} The total number of possible observations for these sensors was 32, other sensors had 64 possible observations.

⁺T groupings with the same letter are not significantly different at the 95% confidence level.

Test results revealed that the capacitance sensors studied were the best sensors over all ranges, drying cycles, and soil types. The Troxler Sentry had the lowest average mean absolute difference value of any sensor studied. The other capacitance sensor, the Aqua-Tel, predicted the moisture content with a mean absolute difference that was not significantly different from the Sentry. However, the Aqua-Tel and neutron probe were the only sensors that predicted the water content of the soil for every possible data point, which enhanced the performance of these sensors and allowed their performance to be considered as good as that of the Sentry.

Resistance sensors studied were sensitive to soil type and moisture range. They performed better in a particular soil type and generally in certain ranges, depending on the type of sensor. However the Watermark PVC soil moisture block did, on the average, predict the water content of the soil more accurately than the neutron probe for the limited number of readings included in the analysis. Gypsum blocks predicted average mean absolute difference values that were approximately 1 percent water by volume higher than the Watermark sensors.

Campbell Scientific TDR sensors and the Agwatronics heat dissipation soil moisture blocks predicted values with higher mean absolute differences than other sensors. The four-waveguide TDR sensor closely followed the gypsum blocks with a mean absolute difference value of 4.49, which was not significantly different from the prediction error of the neutron probe.

The Agwatronics and Campbell Scientific TDR sensors had the second highest and highest prediction errors. Many predicted water content values appeared random for both sensors, causing the prediction error to increase and place these sensors below other soil moisture sensors for accuracy.

Dielectric Sensors

Results from dielectric sensors revealed that the sensors are capable of accurately predicting soil water content. As a general rule, all dielectric sensors predicted the moisture content over the entire range from saturation to below two percent by volume.

Capacitance sensors were among the most accurate sensors included in the study. The Sentry had the lowest mean absolute difference value for predicting soil water content, and the Aqua-Tel was not significantly different from the Sentry and was one of two sensors that obtained valid soil water content readings for all data points.

Troxler Sentry

The Troxler Sentry 200-AP proved to be the most accurate sensor included in the study. The sensor predicted θ_v , on the average, within 1.72 percent for all three drying cycles in both soil types, and was affected minimally by the large range of moisture content values or the number of drying cycles included in the experiment.

The Sentry predicted valid moisture content values for 62 of 64 possible data points. The two readings that were omitted from the statistical analysis predicted the moisture content to be more than fifty percent water by volume. The first erroneous point occurred during the first drying cycle. The average of five readings predicted the volumetric soil water content to be 1479 percent, when the water content of the soil was 4.68 percent as determined by the load cell. The second occurrence of an erroneous reading occurred at the beginning of the second drying cycle. The Sentry predicted θ_v to be 68.98 percent, when it was actually 36.00 percent.

The range of moisture did not appear to strongly affect this sensor in the loam soil. Mean absolute difference values of θ_v varied from 1.64 percent water by volume to 1.83 percent over all moisture content ranges during the study. However, the range of soil water content did affect the sensors predicted values in the sandy loam soil. The high moisture range, greater than 20 percent water by volume, had an absolute mean difference value of 4.88 percent water by volume for the duration of the study. Mean absolute difference values of θ_v for the middle and lower moisture content ranges yielded more accurate results. Predicted values in these ranges in the sandy loam soil averaged 1.63 and 1.19 percent for all three drying cycles.

Mean absolute difference values of θ_v did not seem to follow a trend from cycle to cycle for this sensor in the loam soil. The average prediction error for all moisture content ranges varied from 1.39 to 2.07 percent water by volume over

three drying cycles. The largest error occurred during the first cycle, and the lower value occurred in the second cycle. The mean absolute difference then increased to 1.87 percent for the third cycle. Mean absolute values for the sandy loam soil did appear to follow an upward trend from cycle to cycle. The trend indicated a change in the sensor's calibration with time, or changes in the soil. Absolute prediction error of θ_v was 1.26 percent for the first cycle. This error increased to 1.78 percent during the second cycle, and was 1.95 percent by the end of the third drying cycle.

Aqua-Tel

The Aqua-Tel capacitance sensor performed well throughout the study. The sensor had the third lowest mean absolute difference value of 2.45 percent water by volume for all cycles, ranges, and soil types. The Aqua-Tel sensor was not significantly different from the Sentry, which ranked the capacitance sensors as the best sensor type studied.

The Aqua-Tel sensor was one of two sensors that predicted valid moisture content values for all 64 possible data points. This information proves the Aqua-Tel to be one to the most reliable sensors studied. The sensor's prediction error, which was not significantly different from the highest ranked sensors studied, allowed this sensor to be considered one of the best overall sensors included in the experiment.

The range of moisture contents did not severely affect this sensor.

However, prediction error was greater for this sensor in the middle and lower ranges than in the high moisture content range in the loam soil. The mean absolute difference values of θ_v were 5.22 percent and 4.20 percent for all three drying cycles in the middle and lower ranges and 1.11 percent in the high range. It was hypothesized that these errors were attributed to soil cracking as the water content decreased due to the clay content of the loam soil since it accurately predicted the water content of the sandy loam soil. This soil also contained a higher amount of organic matter, that could have affected the output of the sensor. The results from the sandy loam soil were the most accurate of any sensor. The mean absolute difference of water content ranged from 0.58 to 1.84 percent over all three ranges and was not significantly different for any range.

The Aqua-Tel's output from cycle to cycle varied with soil type. The values did not appear to follow a trend for either soil type. However, errors were greater in the loam soil than in the sandy loam soil. The absolute prediction error for the loam soil ranged from 3.69 to 4.56 percent water by volume and averaged a total error in θ_v of 4.00 percent for all three drying cycles. The mean absolute difference values in the sandy loam varied from 0.88 to 0.97 percent water by volume, averaging a 0.91 percent absolute prediction error. This low prediction error placed the Aqua-Tel sensor in the sandy loam soil as the most accurate sensor included in the study.

Time Domain Reflectometry

Time domain reflectometry sensors studied did not perform as well as other dielectric sensors. Published literature on this type of sensor indicate it as an accurate method for soil moisture determination. However, the Campbell Scientific production model of this sensor performed very poorly. The fabricated four-waveguide design more closely predicted the water content of the soil, but it still had the third highest mean absolute difference of any sensor studied.

The two types of TDR sensors were both placed in the loam soil with 32 possible data points. The Campbell Scientific sensor predicted 25 valid readings between 0 and 50 percent soil water by volume, and the four-waveguide design predicted 30 valid readings during the experiment. The mean absolute difference values of water content for these sensors was 11.82 percent for the Campbell Scientific TDR sensor, the highest of any sensor, and 4.49 percent for the fabricated four-waveguide sensor. The number of valid readings of the four-waveguide sensor and the lower overall prediction error clearly rank this sensor as the highest quality of the two TDR sensors.

The range of moisture content appeared to have a minimal affect on sensor performance. The four-waveguide sensor predicted the moisture content of the soil more accurately in the high water content range. The total mean absolute difference value for this range was 3.15 percent. This value increased to approximately 5 percent in the middle and lower ranges of soil water content, much like the Aqua-Tel capacitance sensor. Mean absolute difference values for the

Campbell Scientific sensor proved that this sensor did not accurately predict the soil water content in any range. Values appeared to be random with large errors for nearly every data point.

Variation of predicted values from cycle to cycle support a hypothesis that the calibration of the four-waveguide sensor, or properties of the soil changed between the first and second drying cycles. This change could have been due to soil cracking in the column as the water content decreased. However, it could also be attributed to noise in the Campbell Scientific multiplexer used to read the sensor's output since many difficulties with the multiplexer occurred during preliminary studies. The sensor probably should have been read directly from the cable tester to eliminate the problem and possibly obtain better results from the sensor.

Variation from the Campbell Scientific sensor from cycle to cycle appeared to be random, much like the predicted moisture content values for this sensor. This sensor performed very poorly throughout the study and is clearly the sensor with the greatest prediction error of any studied.

Neutron Probe

The neutron probe's performance during the study placed it as one of the higher ranked sensors. Paired difference t-test results ranked this sensor in the second highest group for overall accuracy for all ranges, cycles, and soil types. The mean absolute difference value of actual minus predicted volumetric water

content values was 3.19 percent. The Troxler Sentry, the Aqua-Tel, and the Watermark soil moisture blocks were the sensors that ranked higher. However, the neutron probe predicted valid θ_v values for all 64 possible data points. The three Watermark sensor groups averaged 57 valid readings of a possible 64. This factor allows the neutron probe to be considered an overall better sensor due to reliability than the Watermark sensors because the mean absolute differences of soil water content were not significantly different, leaving the capacitance sensors as the only sensors performing better than the neutron probe.

Prediction error for the neutron probe did not vary more than 1.5 percent water by volume for the three moisture ranges for either column and three drying cycles. Readings seemed to follow the same trend for both columns. The predicted error was the greatest at higher moisture contents near soil saturation, and the error decreased as the soil water content decreased. The main difference of prediction error for a given range occurred in the loam soil. Predicted values in the high moisture content range of this soil were consistently lower than the actual moisture content. On the average, this underprediction error of soil water content was 4.10 percent by volume.

Prediction error from the neutron probe from cycle to cycle varied with soil type. Measurements recorded in the loam soil appeared to follow no apparent trend from cycle to cycle. The mean absolute difference value for the first cycle over all moisture content ranges was 3.25 percent. This value increased to a prediction error of soil water content of 4.11 percent water by volume during the second cycle

and decreased to 3.81 percent for the third cycle. However, the prediction error increased in the sandy loam soil throughout the study. The mean absolute difference for the first drying cycle was 1.69 percent. This error increased to 2.58 percent during the second cycle, and increased to a value of 3.50 percent for the third drying cycle. This error appears to be due to a calibration shift of the sensor since most other sensors experienced no such change in this soil column. However, the short time span required for the study should not have been sufficient for the radioactive source of the sensor to decay, and any shift should have been offset by taking a standard count before each set of measurements. Temperature effects could not have attributed to the error, because the test was conducted in the laboratory, and the temperature remained constant. Therefore, the shift in readings in the sandy loam soil are unexplained.

Soil Moisture Tension Sensors

Sensors included in this group rely directly or indirectly on soil matric potential to determine the water content of the soil. All sensor measurements used in the analysis were recorded after the air pressure on the columns had been removed for a period of two hours, which should have given each sensor time to equilibrate with the surrounding soil.

All soil moisture tension sensors studied generally predicted the water content more accurately in the middle range of moisture contents. Readings at either end of the soil moisture range typically had larger prediction errors. Many of

these errors were large enough to cause the reading to be removed from the data analysis, resulting in the best possible results for each sensor.

Prediction error due to soil type was more common for these sensors than for other sensors. The error due to soil type was dependent on the sensor type. It was hypothesized that this error was correlated to how closely the pore size of the sensor matched the pore size of the soil.

Gypsum Blocks

Performance of gypsum blocks was clearly better in the loam soil than in the sandy loam soil. Most predicted soil water content values in this soil column were valid. The soil moisture blocks placed in the sandy loam soil did not perform well at any time during the study. However, many readings were removed from the analysis, resulting in overall mean absolute differences of θ_v for these sensors ranging from 3.81 to 4.32. The sensors were ranked in the third lowest T grouping by the paired difference t-test; predicting the soil water content, on the average, 52 of a possible 64 times.

Sensor performance for each range of water content in the loam soil varied with the sensor. Of the three gypsum blocks placed in the loam soil, prediction error varied from 0.96 percent to 5.35 percent for a given range, and no apparent trend could be determined between the sensors over different ranges of moisture content. The prediction error decreased as the moisture content decreased for the first and second sensor in the loam soil, and increased for the third sensor as the

water content of the soil decreased. Results from the sensors in the sandy loam soil indicated a poor performance. The sensors predicted no valid readings in the high moisture content range, predicted values with a mean absolute difference ranging from 6.13 percent to 16.46 percent in the middle range, and predicted values with an error of approximately 4.5 percent water by volume in the lower soil moisture range.

Prediction error for gypsum blocks from cycle to cycle followed no trend in either soil type. The error would increase or decrease for all sensors in both soil types randomly. Therefore, it was determined that the time span of the study was too brief to determine the life span of the soil moisture blocks.

Watermark PVC Blocks

The Watermark PVC soil moisture blocks predicted the soil moisture content more accurately than other soil moisture tension sensors. The T groupings of these sensors placed them in the second highest group of sensors studied. However, none of the sensors predicted valid moisture content values for all 64 possible data points.

Sensor performance over the range of moisture contents varied with the soil type. Performance in the loam soil was poor throughout the study. The PVC soil moisture blocks consistently underpredicted the soil water content in the high range, and prediction values varied from cycle to cycle in the middle range. Sensor calibration deviated in the loam soil between the first and second drying cycle. In

the first drying cycle, middle range values overpredicted or slightly underpredicted the water content of the soil. Results from the second and third drying cycle underpredicted the actual water content of the soil in this range. Results of the Watermark sensors in the lower moisture content range in the loam soil were very poor for all three sensors. Most readings in this range were underpredicted and many were removed from the statistical analysis because they were negative. Predicted soil water content values in the sandy loam soil were more accurate for the Watermark sensors. The first two sensors predicted the water content of the soil nearly the same. In the high and middle ranges the sensors were accurate, predicting the actual water content within 2 percent by volume for all three cycles. The sensors in the sandy loam soil produced consistent results in the lower moisture range. Both sensors closely predicted the water content of the soil at θ_v values above 5 percent. When θ_v dropped below 5 percent, both sensors consistently overpredicted the water content of the soil until it reached approximately 2 percent, where readings underpredicted θ_v and were generally removed from the analysis because they were negative. The third Watermark sensor placed in the sandy loam soil did not perform as well as the first two in the middle and upper moisture content ranges. Readings for all three cycles were consistently high until θ_v decreased to approximately 5 percent. All predicted values except one in the third cycle closely represented the actual water content of the soil below this point.

Heat Dissipation Blocks

The Agwatronics heat dissipation blocks performed poorly throughout the experiment. Calibration equations fitted to these sensors had r^2 values similar to other sensors studied, but predicted moisture content values were erroneous in both soil types. The T grouping of these sensors placed the sensors second from the bottom. However, the magnitude of the prediction error, the removal of these sensors during the study, and the high number of observations in the lower water content range for the sandy loam soil allowed the sensors to place above Campbell Scientific's TDR sensor. When all factors are considered, the sensor's performance was the lowest ranked of all sensors studied.

The sensor placed in the loam soil was removed from the study after completion of the first drying cycle because it shorted out. This sensor predicted values during the cycle that were all removed due to the magnitude of error for all soil moisture ranges.

The sensor placed in the sandy loam soil shorted out at the beginning of the third cycle. During the first two drying cycles, the sensor predicted the water content to be between 2 percent and 5 percent by volume or overpredicted the water content with values that were generally removed because they were greater than 50 percent.

The failure and poor performance of these sensors could possibly be due to the intense wetting and drying of the soil, and the frequent readings of the sensors as the water content of the soil decreased. In a practical field application, the

sensor would probably be read once or twice per day, not five times every 30 minutes.

Soil and Sensor Removal

Following the data collection phase of the study, soil and sensors were removed from each column. Soil physical characteristics were observed as the soil was removed from each column and each sensor was inspected following removal from the soil.

Column 1 -- Loam

Soil in the loam column had cracked on the surface due to expansion and contraction of the soil at different moisture contents. The soil was removed from the loam column in small increments so the cracks could be observed. Removal was achieved by breaking chunks loose from the soil with a screwdriver. The chunks were removed and any loose soil was scooped out with a small, cylindrical container.

Dimensions of cracks could not be determined during the destruction of the column due to loose soil falling into them and crumbling of the soil. However, the depth of the cracks could be determined fairly accurately by brushing all loose soil from the packed soil in the column. All cracking except for one distinct crack along one side of the column had disappeared at a depth of 15.24 cm (6 in) from the top of the column. The large crack continued to a depth of 21.59 cm (8.5 in)

from the top. Other cracking found in the column consisted of a small crack found under the electrodes of the Aqua-Tel sensor. Dimensions of the crack could not be measured due to loose soil particles falling into it, but the density of the soil along this area of the column seemed to be lower than that of the rest of the column from this point to the bottom of the column. This indicated that the crack may have originated from the bottom of the column.

No other sensors appeared to have been affected by cracking or voids. However, the intense wetting and drying had begun to affect a number of sensors. The lower half of the gypsum buffer around the base of the heat dissipation block fell off upon removal. The gypsum blocks also revealed a moderate amount of deterioration. All three were still intact, but the gypsum had partially dissolved, leaving the blocks approximately three-fourths of their actual size. The waveguide connections on the Campbell Scientific TDR sensor had begun to corrode at the connectors between the waveguides and the cable. The four-waveguide TDR, Aqua-Tel, and PVC moisture blocks revealed no physical degradation from being placed in the soil for a period of three months and four drying cycles.

When all soil had been removed, the ceramic plate in this column was found to be cracked with a number of hairline fractures. This explained the fact that air flowed through the column at all air pressures.

Column 2 -- Sandy Loam

Soil removal from the sandy loam column was achieved with the same procedure as used for the loam column. As soil was removed, the soil broke up easily and the bulk density seemed very constant throughout the column. The soil broke up easily due to the amount of sand.

Sensor removal from this column revealed that there was consistent soil placement around all sensors with no voids or cracking. Sensors that seemed to be unaffected in this column included Campbell Scientific TDR, Aqua-Tel, and the Watermark PVC Blocks. The gypsum blocks and Agwatronics heat dissipation blocks had a moderate amount of gypsum degradation, but were otherwise physically unaffected.

The ceramic plate in this column was severely cracked, which was expected because the PVC bottom of the column had cracked when it was pressure tested. The plate was still intact, but many ceramic flakes from around the cracks were loose in the soil.

CHAPTER V

SUMMARY AND CONCLUSIONS

Summary

A laboratory test apparatus was constructed to evaluate the performance of 23 soil moisture sensors consisting of seven sensor types. Sensors evaluated included a neutron probe, a Troxler Sentry 200-AP capacitance probe, an Aqua-Tel capacitance sensor, time domain reflectometry with two different waveguide configurations, gypsum blocks, Watermark PVC soil moisture blocks, and heat dissipation blocks. Research efforts were directed toward determining the prediction error of the volumetric water content of the soil, θ_v , for each sensor over moisture contents ranging from saturation to below the wilting point of most plants.

Two soil columns were incorporated into the test apparatus. Each column contained a different agricultural field soil texture found in East Tennessee. One soil type was classified as a loam and the other as a sandy loam. These soils were not at either extreme of textures, however they represented variations in the range of soils commonly used for agricultural purposes in the area. Each column contained soil moisture sensors and allowed differences in performance due to soil type to be observed.

Water was added to the soil columns and allowed to equilibrate throughout the soil profile. Air pressure was then applied to the top of the columns and water was forced from the soil from the bottom. Sensor readings were recorded as the

volumetric water content, θ_v , decreased to less than two percent. The procedure was repeated four times, once for sensor calibration and three times to determine the performance of the sensors over repeated drying cycles.

Data was grouped according to the drying cycle and the range of θ_v . Three ranges allowed performance of the sensors to be evaluated at high, middle, or lower values of moisture contents. Data from cycle to cycle determined repeatability and sensor performance over time, while a combination of all ranges, cycles, and soil types allowed the total sensor performance to be observed.

Conclusions

Extensive studies conducted to evaluate the performance of seven types of soil moisture sensors resulted in the following conclusions:

- The Troxler Sentry 200-AP proved to be the most accurate sensor over all cycles, ranges, and soil types.
- Capacitance type sensors were not significantly different from each other and were in the highest ranked group from LSD tests.
- Moisture blocks performed well within the range of valid readings. However, the range of soil moisture included in data analysis was limited by a reduced number of valid readings.
- The neutron probe and Aqua-Tel sensors were the only sensors that predicted valid θ_v values at every measurement point throughout the entire study.

- Failure of the Agwatronics sensors could be due to the intense cycling of the sensors. These sensor's life spans could have been decreased by use of the heating element five times every 30 minutes.
- Soil type affected the performance of many sensors. This could be due to pore size of any sensors that rely on soil matric potential. For the dielectric sensors, the cracking of the loam soil could have affected the values.
- The range of moisture contents affected the sensors that rely on soil matric potential and did not appear to affect dielectric sensors or the neutron probe.
- Predicted values varied from cycle to cycle for the neutron probe, TDR, the heat dissipation sensors, and the moisture blocks while capacitance sensors were consistent throughout the study.

CHAPTER VI

RECOMMENDATIONS FOR FUTURE RESEARCH

Prior to this study, little comparative information was available on soil moisture sensors. Studies have typically involved one particular sensor, or sensors have been compared in field studies, where direct comparisons were impossible.

Further studies should be conducted with undisturbed soil and include variations of soil moisture throughout the soil profile. Much has been learned from this study, but a sensor may react differently if placed in an undisturbed soil. Variation of moisture content through the soil profile would allow the volume of soil sampled as an additional variable. It is known that a number of sensors integrate readings along the length of waveguides or electrodes, and some are point measurement devices. In a field situation, the volume of soil sampled represents the entire field, which may or may not be an accurate representation. However, an integrating sensor that averages the moisture content over a larger sample size can more accurately represent an entire field.

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APPENDICES

APPENDIX A

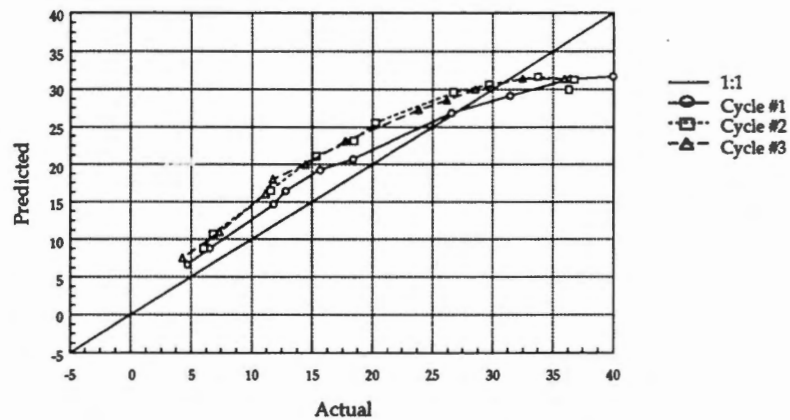


Figure A-1. Actual vs. predicted values of soil water content for the neutron probe in the loam soil.

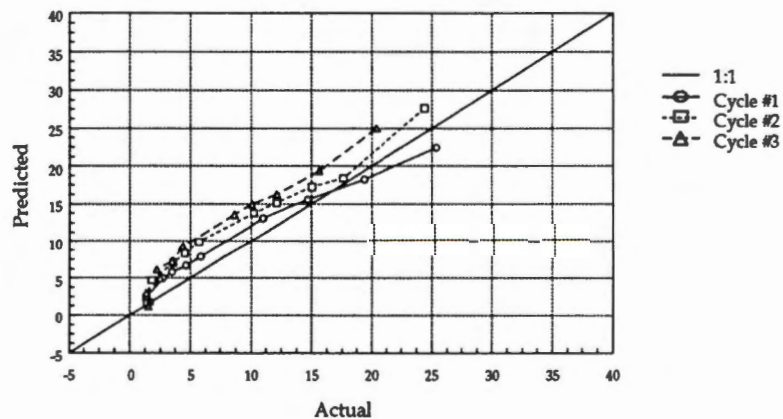


Figure A-2. Actual vs. predicted values of soil water content for the neutron probe in the sandy loam soil.

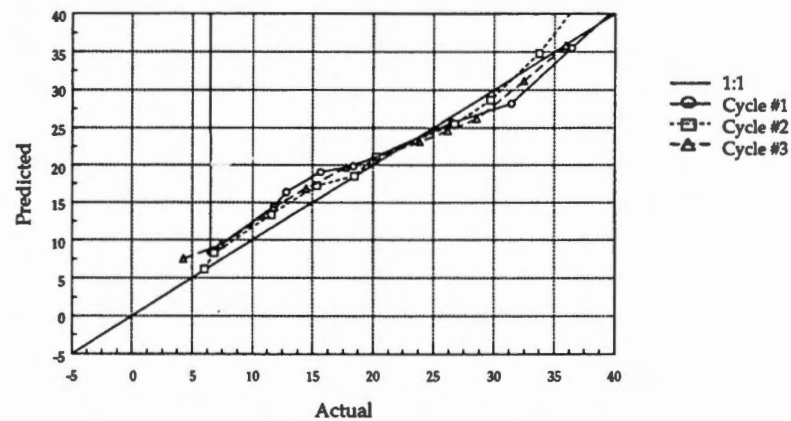


Figure A-3. Actual vs. predicted values of soil water content for the Troxler Sentry in the loam soil.

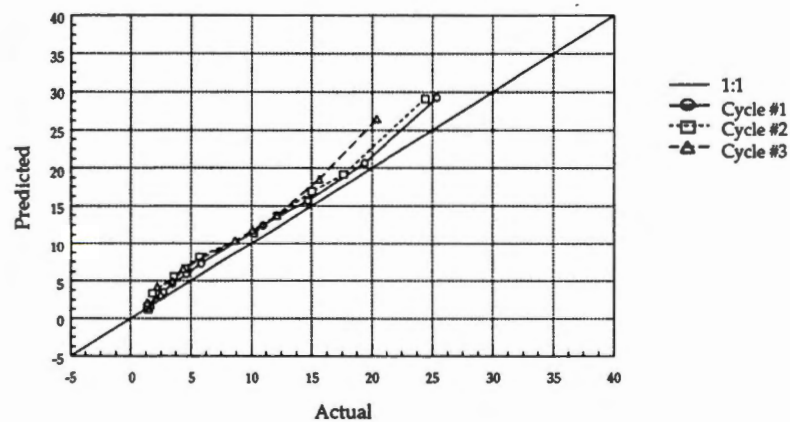


Figure A-4. Actual vs. predicted values of soil water content for the Troxler Sentry in the sandy loam soil.

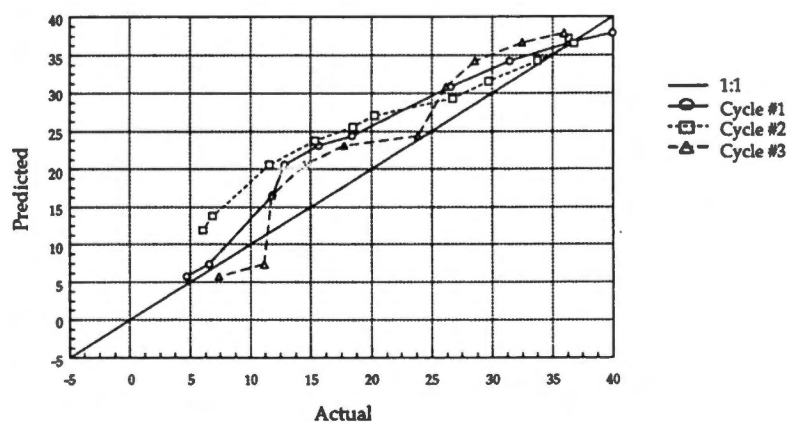


Figure A-5. Actual vs. predicted values of soil water content for the Aqua-Tel sensor in the loam soil.

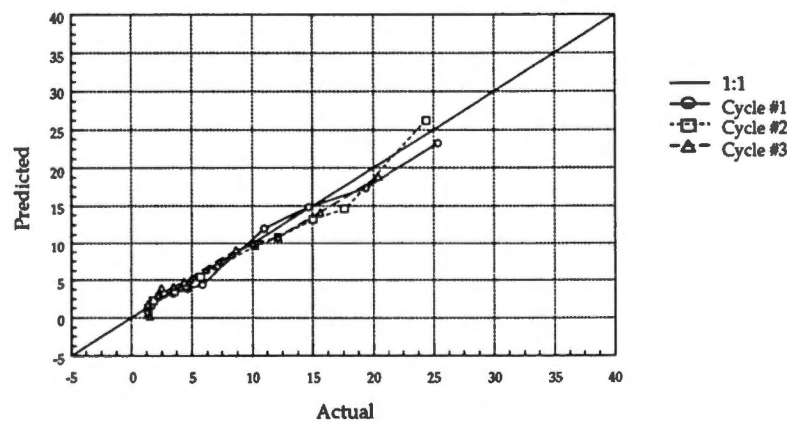


Figure A-6. Actual vs. predicted values of soil water content for the Aqua-Tel sensor in the sandy loam soil.

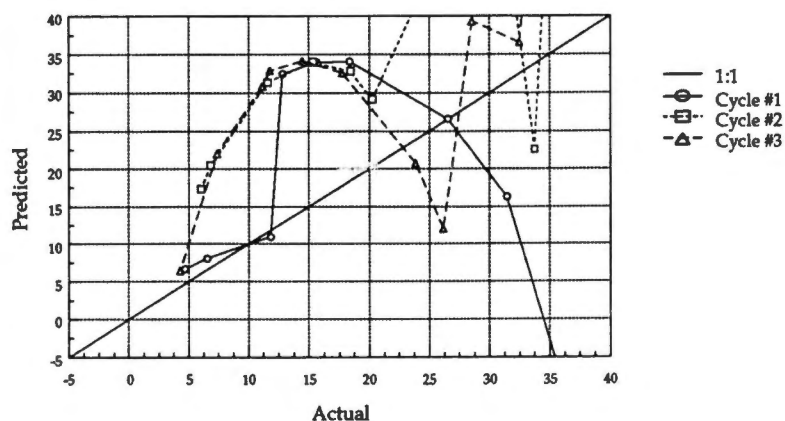


Figure A-7. Actual vs. predicted values of soil water content for the Campbell Scientific TDR sensor in the loam soil.

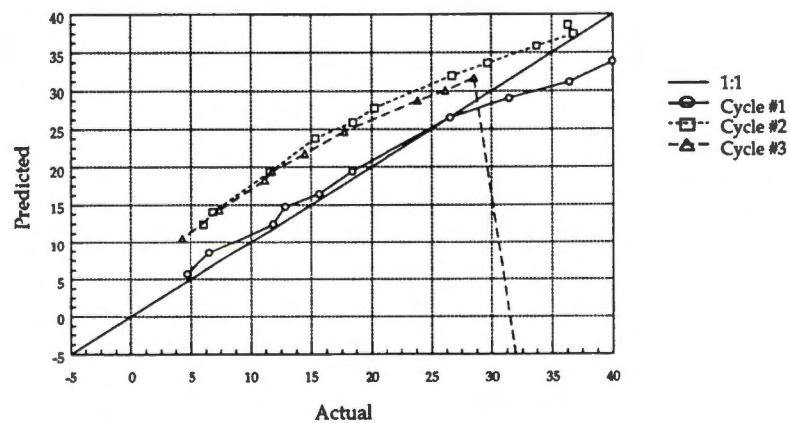


Figure A-8. Actual vs. predicted values of soil water content for the four waveguide TDR sensor in the loam soil.

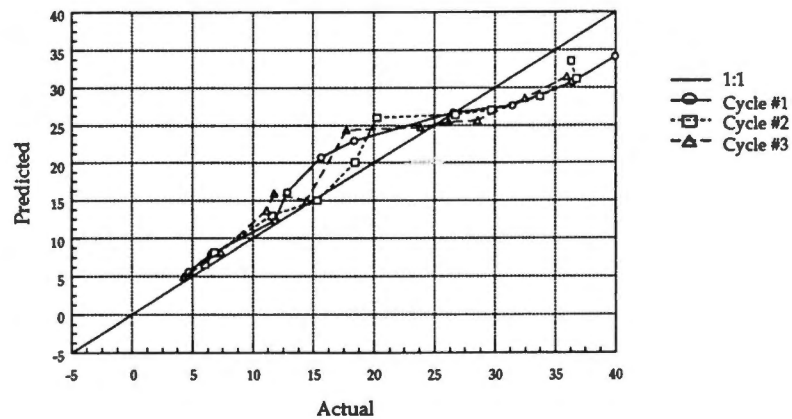


Figure A-9. Actual vs. predicted values of soil water content for gypsum block number one in the loam soil.

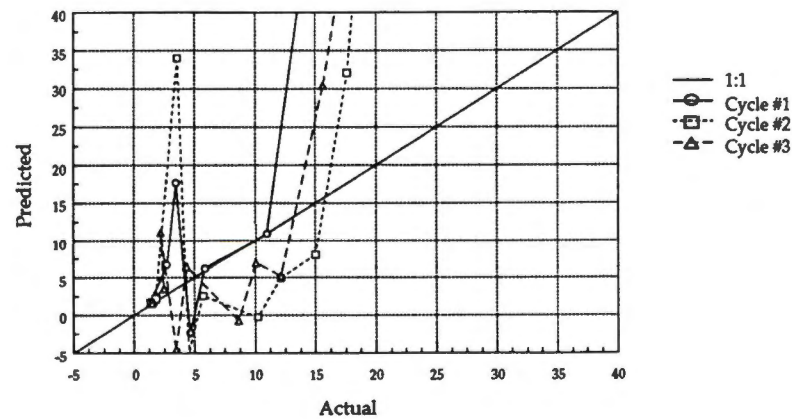


Figure A-10. Actual vs. predicted values of soil water content for gypsum block number one in the sandy loam soil.

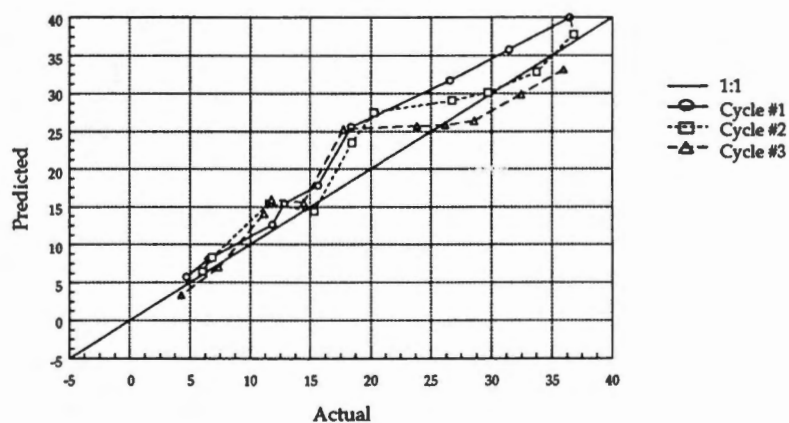


Figure A-11. Actual vs. predicted values of soil water content for gypsum block number two in the loam soil.

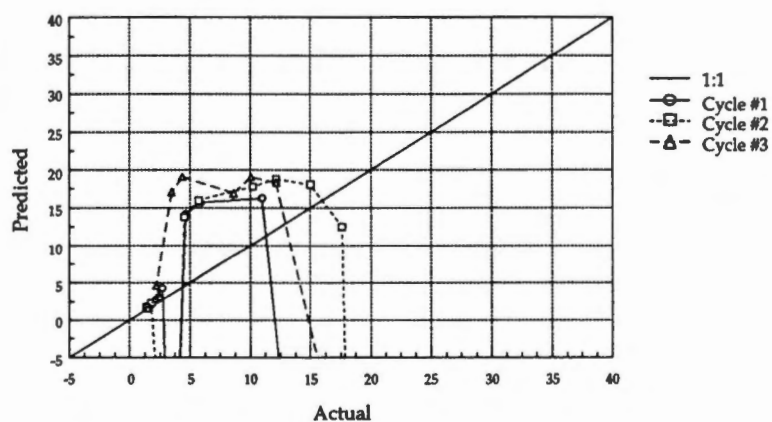


Figure A-12. Actual vs. predicted values of soil water content for gypsum block number two in the sandy loam soil.

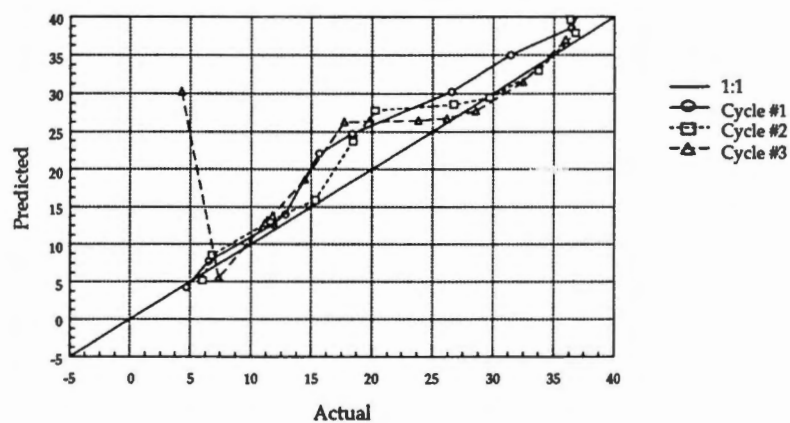


Figure A-13. Actual vs. predicted values of soil water content for gypsum block number three in the loam soil.

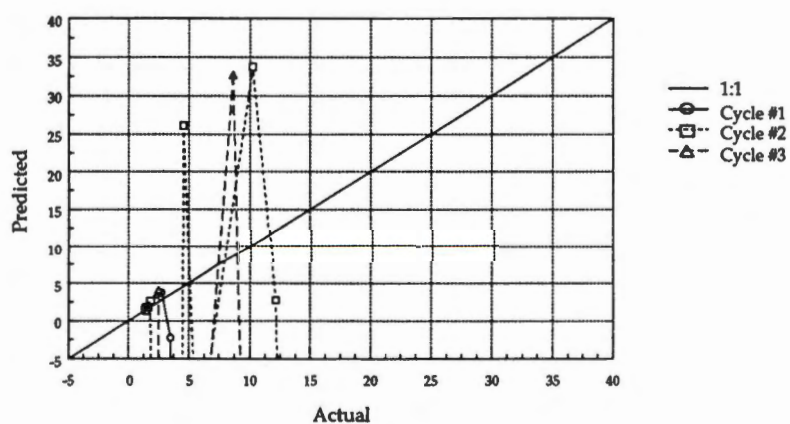


Figure A-14. Actual vs. predicted values of soil water content for gypsum block number three in the sandy loam soil.

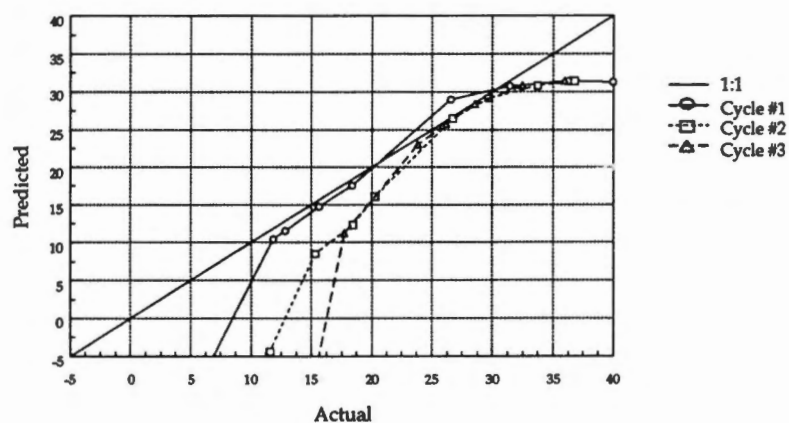


Figure A-15. Actual vs. predicted values of soil water content for Watermark number one in the loam soil.

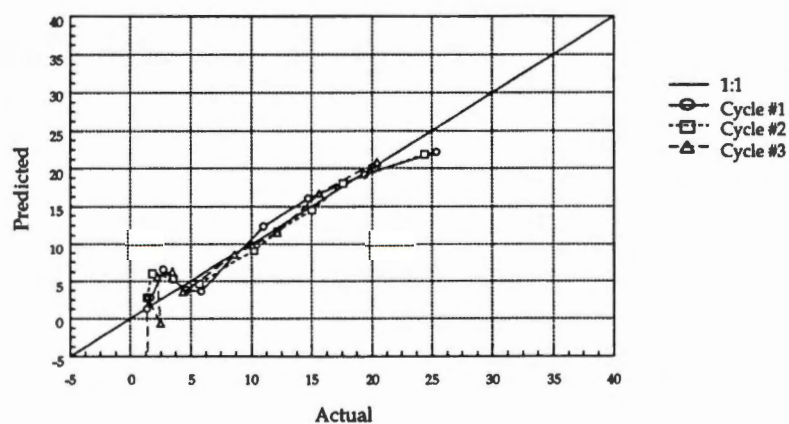


Figure A-16. Actual vs. predicted values of soil water content for Watermark number one in the sandy loam soil.

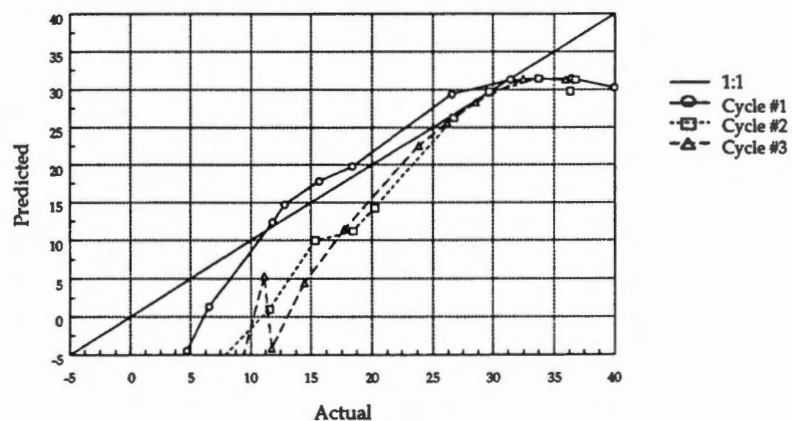


Figure A-17. Actual vs. predicted values of soil water content for Watermark number two in the loam soil.

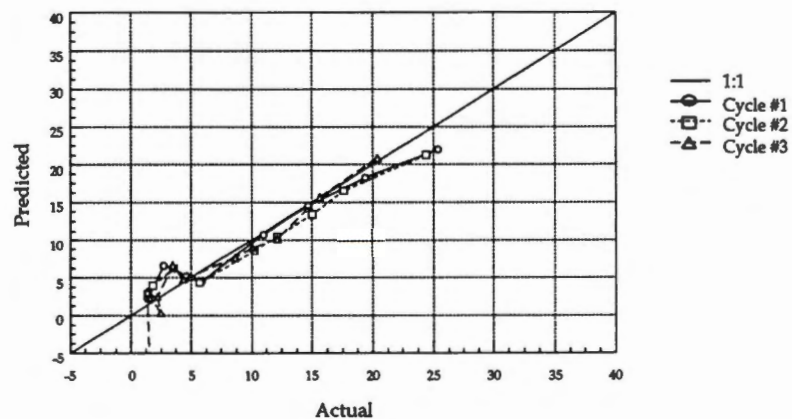


Figure A-18. Actual vs. predicted values of soil water content for Watermark number two in the sandy loam soil.

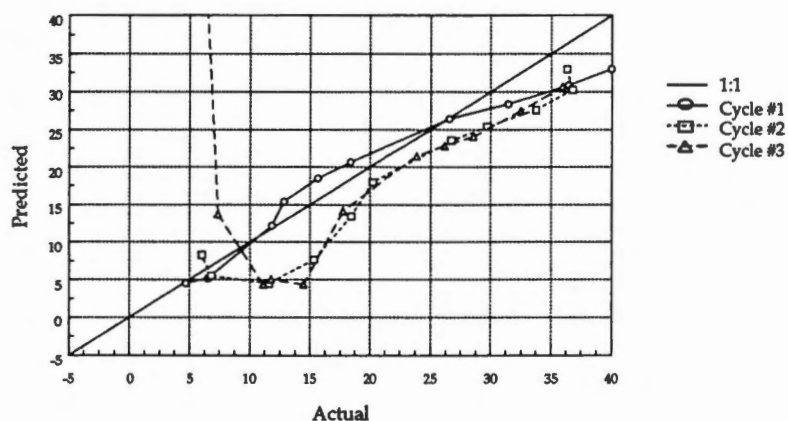


Figure A-19. Actual vs. predicted values of soil water content for Watermark number three in the loam soil.

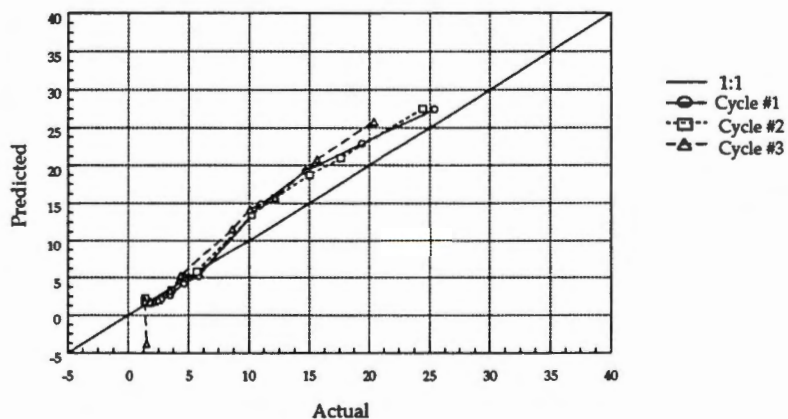


Figure A-20. Actual vs. predicted values of soil water content for Watermark number three in the sandy loam soil.

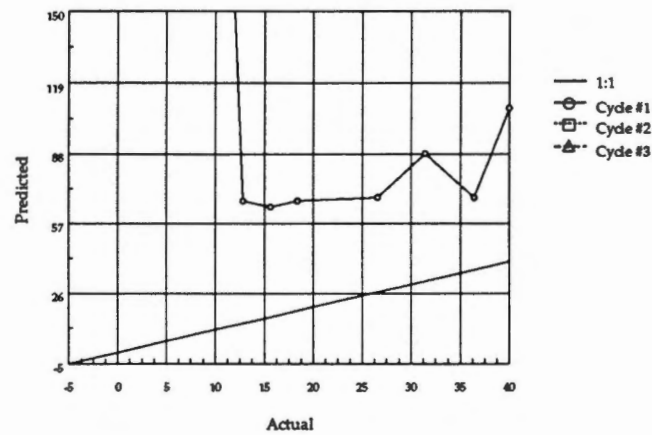


Figure A-21. Actual vs. predicted values of soil water content for the Agwatronics heat dissipation sensor in the loam soil.

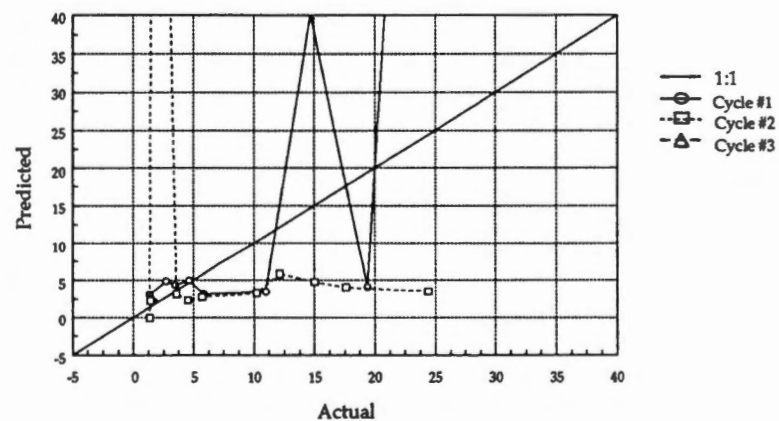


Figure A-22. Actual vs. predicted values of soil water content for the Agwatronics heat dissipation sensor in the sandy loam soil.

APPENDIX B

Table B-1. Sensor calibration equations.

Sensor	Soil	Calibration Equation	r^2
Neutron Probe	1	$Y = -4.616 + 23.104X + 426.71X^2 - 663.791X^3$	0.9921
Neutron Probe	2	$Y = -5.301 + 97.86X - 33.685X^2$	0.9953
Sentry	1	$Y = 277.639 - 0.170X + 2.59E-5X^2$	0.9651
Sentry	2	$Y = 292.489 - 0.172X + 2.54E-5X^2$	0.9976
Aqua-Tel	1	$Y = -16.143 + 0.057X - 1.517E-5X^2$	0.9913
Aqua-Tel	2	$Y = -8.528 + 0.372X - 7.74E-6X^2$	0.9949
Agwatronics	1	$Y = -16.143 + 0.372X - 7.747E-6X^2$	0.9675
Agwatronics	2	$Y = 1106.542 - 460.227X + 63.637X^2 - 2.919X^3$	0.7096
C.S. TDR	1	$Y = 219.510 - 286.674X + 121.858X^2 - 15.761X^3$	0.9690
C.S. TDR	2	N/A	----
Four-Waveguide TDR	1	$Y = -18.500 + 34.266X - 4.376X^2$	0.9932
Gypsum Block #1	1	$Y = 18.606 - 2.258\ln X + 2.546/X - 16.536e^{-X}$	0.9903
Gypsum Block #1	2	$Y = 1.53 + 10.48/X + 13.73/X^2 - 7.55/X^3 + 1.09/X^4 - 0.04/X^5$	0.9985
Gypsum Block #2	1	$Y = 18.558 - 2.318\ln X + 3.394/X - 23.571e^{-X}$	0.9918
Gypsum Block #2	2	$Y = 1.54 + 7.33/X + 16.10/X^2 - 15.54/X^3 + 3.59/X^4 + 0.25/X^5$	0.9981
Gypsum Block #3	1	$Y = 13.919 - 0.144X + 0.0005X^2 + 0.477/X - 0.245/X^2$	0.9892
Gypsum Block #3	2	$Y = 1.19 + 26.79/X - 23.12/X^2 - 57.03/X^3 + 18.78/X^4 - 1.62/X^5$	0.9998
Watermark #1	1	$Y = 30.078 + 3.300X - 2.183X^2 + 0.273X^3 - 0.011X^4$	0.9808
Watermark #1	2	$Y = 39.128 - 31.47x + 9.89X^2 - 1.34X^3 + 0.082X^4 - 0.002X^5$	0.9736
Watermark #2	1	$Y = 26.783 + 8.032X - 3.926X^2 + 0.491X^3 - 0.194X^4$	0.9953
Watermark #2	2	$Y = 42.005 - 37.03X + 13.13X^2 - 2.06X^3 + 0.14X^4 - 0.004X^5$	0.9904
Watermark #3	1	$Y = 35.498 - 5.71X + 0.71X^2 - 0.05X^3 + 0.001X^4$	0.9996
Watermark #3	2	$Y = 40.058 - 29.61X + 10.05X^2 - 1.64X^3 + 0.13X^4 - 0.004X^5$	0.9964

Note: Soil #1 is the loam and soil #2 is the sandy loam.

Table B-2. Mean and mean absolute difference values for each range of moisture contents.

Sensor	Soil	Mean Absolute Difference			Mean Difference		
		High (N)	Mid (N)	Low (N)	High (N)	Mid (N)	Low (N)
Neutron Probe	1	4.39(8)	3.69(18)	2.98(6)	-4.39(8)	3.70(18)	2.98(6)
Neutron Probe	2	3.59(3)	2.66(10)	2.49(19)	1.62(3)	2.43(10)	2.46(19)
Sentry	1	1.64(7)	1.83(18)	1.76(6)	0.05(7)	0.95(18)	1.76(5)
Sentry	2	4.88(3)	1.63(10)	1.19(19)	4.88(3)	1.63(10)	1.13(19)
Aqua-Tel	1	1.11(8)	5.22(18)	4.20(6)	0.13(8)	5.21(18)	4.20(6)
Aqua-Tel	2	1.84(3)	1.28(10)	0.58(19)	-0.62(3)	-1.04(10)	-0.06(19)
C.S. TDR	1	10.13(3)	13.74(16)	7.55(6)	7.39(3)	11.48(16)	7.55(6)
C.S. TDR	2	-----	-----	-----	-----	-----	-----
4 Waveguide TDR	1	3.15(6)	4.76(18)	5.00(6)	-1.43(6)	4.76(18)	5.00(6)
Agwa Tronics	1	-----	-----	-----	-----	-----	-----
Agwa Tronics	2	20.91(3)	12.21(7)	1.48(10)	-20.91(1)	-4.89(7)	10.17(10)
GB #1	1	4.64(8)	2.44(18)	0.96(6)	-4.64(1)	1.66(18)	0.96(6)
GB #1	2	-----	7.73(7)	4.38(15)	-----	0.71(7)	3.97(15)
GB #2	1	3.17(8)	3.22(18)	0.97(6)	1.60(8)	2.84(18)	0.54(6)
GB #2	2	-----	6.13(7)	4.82(17)	-----	4.68(7)	4.82(17)
GB #3	1	2.87(8)	3.12(18)	5.35(6)	2.44(8)	3.00(18)	4.34(6)
GB #3	2	-----	16.46(2)	4.58(11)	-----	7.06(2)	4.52(11)
WM #1	1	4.22(8)	2.32(14)	-----	-4.21(8)	-1.99(14)	-----
WM #1	2	2.07(3)	0.72(10)	1.71(17)	-1.76(3)	0.12(10)	1.02(17)
WM #2	1	4.35(8)	3.67(17)	5.20(1)	-4.34(8)	-2.63(17)	-5.20(1)
WM #2	2	2.34(3)	1.06(10)	1.58(18)	-2.02(3)	-1.06(10)	0.42(18)
WM #3	1	5.25(8)	4.16(18)	2.30(5)	-5.25(8)	-3.27(18)	1.16(5)
WM #3	2	3.53(3)	3.87(10)	0.61(18)	3.53(3)	3.87(10)	0.17(18)

Note: Soil #1 is the loam and soil #2 is the sandy loam.

Table B-3. Mean and absolute mean difference values for each cycle and range.

Sensor	Soil	Cycle	Mean Absolute Difference			Mean Actual Difference			All Range Pred.	
			High	Mid	Low	High	Mid	Low	Absolute	Mean
Neutron Probe	1	1	5.21(3)	2.53(5)	2.11(2)	-5.21(3)	2.53(5)	2.11(2)	3.25(10)	0.12(10)
Neutron Probe	1	2	4.64(3)	4.10(6)	3.36(2)	-4.64(3)	4.10(6)	3.36(2)	4.11(11)	1.58(11)
Neutron Probe	1	3	2.80(2)	4.19(7)	3.47(2)	-2.80(2)	4.19(7)	3.47(2)	3.81(11)	2.79(11)
Neutron Probe	2	1	2.96(1)	1.38(3)	1.64(6)	-2.96(1)	0.63(3)	1.64(6)	1.69(10)	0.88(10)
Neutron Probe	2	2	3.24(1)	2.41(4)	2.59(6)	3.24(1)	2.41(4)	2.59(6)	2.58(11)	2.58(11)
Neutron Probe	2	3	4.57(1)	4.25(3)	3.14(7)	4.57(1)	4.25(3)	3.04(7)	3.57(11)	3.51(11)
Sentry	1	1	1.59(3)	2.41(5)	1.87(2)	-1.18(3)	2.95(5)	1.87(2)	2.07(10)	0.95(10)
Sentry	1	2	2.66(2)	1.16(6)	0.80(2)	2.66(2)	0.41(6)	0.80(2)	1.39(10)	0.94(10)
Sentry	1	3	0.71(2)	1.98(7)	2.66(2)	-0.71(2)	0.63(7)	2.66(2)	1.87(11)	0.76(11)
Sentry	2	1	3.87(1)	1.24(3)	0.83(6)	3.87(1)	1.24(3)	0.78(6)	1.26(10)	1.23(10)
Sentry	2	2	4.70(1)	1.57(4)	1.43(6)	4.70(1)	1.57(4)	1.38(6)	1.78(11)	1.75(11)
Sentry	2	3	6.06(1)	2.10(3)	1.30(7)	6.06(1)	2.10(3)	1.22(2)	1.95(11)	1.90(11)
Aqua-Tel	1	1	1.70(3)	6.04(5)	0.97(2)	0.32(3)	6.04(5)	0.97(2)	3.72(10)	3.31(10)
Aqua-Tel	1	2	0.54(3)	5.95(6)	6.44(2)	0.41(3)	5.95(6)	6.44(2)	4.56(11)	4.53(11)
Aqua-Tel	1	3	1.08(2)	4.01(7)	5.19(2)	-0.57(2)	3.99(7)	5.19(2)	3.69(11)	3.38(11)
Aqua-Tel	2	1	2.18(1)	1.08(3)	0.58(6)	-2.18(1)	-0.28(3)	-0.44(6)	0.89(10)	-0.57(10)
Aqua-Tel	2	2	1.82(1)	1.68(4)	0.36(6)	1.82(1)	-1.68(4)	-0.20(6)	0.97(11)	-0.56(11)
Aqua-Tel	2	3	1.51(1)	0.95(3)	0.76(7)	-1.51(1)	-0.95(3)	0.38(7)	0.88(11)	-0.15(11)
C.S. TDR	1	1	15.14(3)	10.92(5)	1.75(2)	-15.14(3)	10.58(5)	1.75(2)	9.16(8)	5.16(8)

Table B-3. Continued.

Sensor	Soil	Cycle	Mean Absolute Difference			Mean Actual Difference			All Range Pred.	
			High	Mid	Low	High	Mid	Low	Absolute	Mean
C.S. TDR	1	2	11.15(2)	15.46(4)	12.48(2)	-11.15(2)	15.46(4)	12.48(2)	13.99(7)	10.80(7)
C.S. TDR	1	3	4.11(2)	14.77(7)	8.41(2)	4.11(2)	9.85(7)	8.42(2)	12.43(10)	8.99(10)
C.S. TDR	2	1	----	----	----	----	----	----	----	----
C.S. TDR	2	2	----	----	----	----	----	----	----	----
C.S. TDR	2	3	----	----	----	----	----	----	----	----
4 Waveguide TDR	1	1	4.59(3)	0.89(5)	1.53(2)	-4.59(3)	0.88(5)	1.53(2)	2.13(10)	-0.63(10)
4 Waveguide TDR	1	2	1.71(3)	6.74(6)	6.82(2)	1.71(3)	6.74(6)	6.82(2)	5.39(11)	5.38(11)
4 Waveguide TDR	1	3	----	5.84(7)	6.65(2)	----	5.84(7)	6.65(2)	6.02(9)	6.02(9)
Agwa Tronics	1	1	----	----	----	----	----	----	----	----
Agwa Tronics	1	2	----	----	----	----	----	----	----	----
Agwa Tronics	1	3	----	----	----	----	----	----	----	----
Agwa Tronics	2	1	----	16.13(3)	1.41(6)	----	0.93(3)	0.50(6)	6.32(9)	0.64(9)
Agwa Tronics	2	2	20.91(1)	9.26(4)	1.61(4)	-20.91(1)	-9.26(4)	-1.18(4)	7.15(9)	-6.97(9)
Agwa Tronics	2	3	----	----	----	----	----	----	----	----
GB #1	1	1	5.13(3)	2.69(5)	1.15(2)	-5.13(3)	2.69(5)	1.15(2)	3.12(10)	0.34(10)
GB #1	1	2	4.45(3)	2.03(6)	0.95(2)	-4.45(3)	0.90(6)	0.95(2)	2.49(11)	-0.55(11)
GB #1	1	3	4.18(2)	2.63(7)	0.77(2)	-4.18(2)	1.57(7)	0.77(2)	2.57(11)	0.38(11)
GB #1	2	1	----	0.01(2)	3.78(6)	----	0.01(2)	3.78(6)	3.15(6)	3.15(6)
GB #1	2	2	----	9.53(3)	6.88(5)	----	0.10(3)	5.62(5)	2.87(8)	3.53(8)

Table B-3. Continued.

Sensor	Soil	Cycle	Mean Absolute Difference			Mean Actual Difference			All Range Pred.	
			High	Mid	Low	High	Mid	Low	Absolute	Mean
GB #1	2	3	----	8.28(3)	2.48(5)	----	1.57(3)	2.48(5)	4.65(8)	2.14(8)
GB #2	1	1	4.45(3)	3.60(5)	1.30(2)	4.45(3)	3.60(5)	1.30(2)	3.39(10)	3.39(10)
GB #2	1	2	2.21(3)	3.30(6)	0.96(2)	1.61(3)	2.99(6)	0.96(2)	2.58(11)	2.25(11)
GB #2	1	3	2.69(2)	2.88(7)	0.65(2)	-2.69(2)	2.17(7)	-0.65(2)	2.44(11)	0.77(11)
GB #2	2	1	----	5.29(1)	4.28(5)	----	5.29(1)	4.28(5)	4.46(6)	4.46(6)
GB #2	2	2	----	5.61(3)	4.11(6)	----	3.07(3)	4.11(6)	4.77(9)	3.65(9)
GB #2	2	3	----	7.59(2)	5.72(7)	----	7.59(2)	5.72(7)	6.13(9)	6.13(9)
GB #3	1	1	5.21(3)	3.70(5)	0.84(2)	5.21(3)	3.70(5)	0.41(2)	3.58(10)	3.50(10)
GB #3	1	2	1.76(3)	2.83(6)	1.28(2)	1.24(3)	2.77(6)	0.48(2)	2.26(11)	1.93(11)
GB #3	1	3	1.01(2)	2.93(7)	13.92(2)	0.07(2)	2.70(7)	12.11(2)	4.58(11)	3.93(11)
GB #3	2	1	----	----	0.52(3)	----	----	0.48(3)	0.52(3)	0.49(3)
GB #3	2	2	----	16.47(2)	5.66(4)	----	7.06(2)	5.63(6)	9.26(6)	6.11(6)
GB #3	2	3	----	----	6.55(4)	----	----	6.44(4)	6.55(4)	6.44(4)
WM #1	1	1	4.78(3)	1.35(5)	----	-4.78(3)	-0.40(5)	----	2.64(8)	-2.04(8)
WM #1	1	2	4.42(3)	3.58(5)	----	-4.42(3)	-3.58(5)	----	3.90(8)	-3.90(8)
WM #1	1	3	3.06(2)	1.98(4)	----	-3.06(2)	-1.98(4)	----	2.34(6)	-2.34(6)
WM #1	2	1	3.21(1)	1.02(3)	1.64(6)	-3.21(1)	0.85(3)	0.60(6)	1.61(10)	0.30(10)
WM #1	2	2	2.52(1)	0.61(4)	1.78(6)	-2.52(1)	-0.41(4)	1.15(6)	1.42(11)	0.25(11)
WM #1	2	3	0.47(1)	0.60(3)	1.71(5)	0.47(1)	0.11(3)	1.37(6)	1.20(9)	0.85(9)

Table B-3. Continued.

Sensor	Soil	Cycle	Mean Absolute Difference			Mean Actual Difference			All Range Pred.	
			High	Mid	Low	High	Mid	Low	Absolute	Mean
WM #2	1	1	4.93(3)	1.77(5)	5.21(1)	-4.93(3)	1.77(5)	-5.21(1)	3.20(9)	-1.23(9)
WM #2	1	2	4.75(3)	4.92(6)	----	-4.75(3)	-4.92(6)	----	4.86(9)	-4.86(9)
WM #2	1	3	2.87(2)	4.01(6)	----	-2.87(2)	-4.01(6)	----	3.72(8)	-3.72(8)
WM #2	2	1	3.41(1)	0.50(3)	1.69(6)	-3.41(1)	-0.50(3)	1.22(6)	1.50(10)	0.24(10)
WM #2	2	2	3.13(1)	1.49(4)	1.60(6)	-3.13(1)	-1.49(4)	1.15(6)	1.70(11)	-0.19(11)
WM #2	2	3	0.47(1)	1.04(3)	1.46(6)	0.47(1)	-1.03(3)	0.41(5)	1.23(10)	-0.01(10)
WM #3	1	1	5.23(3)	1.65(5)	0.76(2)	-5.23(3)	1.59(5)	-0.76(2)	2.54(10)	-0.93(10)
WM #3	1	2	5.34(3)	4.91(6)	1.78(2)	5.34(3)	-4.91(6)	0.49(2)	4.46(11)	-4.04(11)
WM #3	1	3	5.16(2)	5.34(6)	6.39(2)	-5.16(2)	-5.34(6)	6.39(2)	5.41(10)	-4.12(10)
WM #3	2	1	2.06(1)	3.98(3)	0.54(6)	2.06(1)	3.98(3)	-0.27(6)	1.73(10)	1.24(10)
WM #3	2	2	3.13(1)	3.48(4)	0.38(6)	3.13(1)	3.48(4)	0.25(6)	1.76(11)	1.69(11)
WM #3	2	3	5.40(1)	4.28(3)	0.93(6)	5.40(1)	4.28(3)	0.54(6)	2.38(10)	2.15(10)

Note: Soil #1 is the loam and soil #2 is the sandy loam.

Table B-4. Mean and absolute mean difference values for all ranges and cycles.

Sensor	Soil	Mean Total Difference	
		Absolute	Actual
Neutron Probe	1	3.74(32)	1.54(32)
Neutron Probe	2	2.65(32)	2.37(32)
Sentry	1	1.77(30)	0.88(30)
Sentry	2	1.68(32)	1.64(32)
Aqua-Tel	1	4.00(32)	3.76(32)
Aqua-Tel	2	0.91(32)	-0.42(32)
C.S. TDR	1	11.82(25)	8.27(25)
C.S. TDR	2	----	----
4 Waveguide TDR	1	4.49(30)	3.57(30)
Agwatronics	1	----	----
Agwatronics	2	6.73(18)	-3.16(18)
GB #1	1	2.72(32)	-0.05(32)
GB #1	2	5.42(22)	2.93(22)
GB #2	1	2.79(32)	2.09(32)
GB #2	2	5.20(24)	4.78(24)
GB #3	1	3.47(32)	3.11(32)
GB #3	2	6.41(13)	4.91(13)
WM #1	1	3.01(22)	-2.79(22)
WM #1	2	1.42(30)	0.45(31)
WM #2	1	3.93(26)	-3.26(26)
WM #2	2	1.48(31)	-0.01(31)
WM #3	1	4.15(30)	-3.06(31)
WM #3	2	1.95(31)	1.69(31)

Note: Soil #1 is the loam and soil #2 is the sandy loam.

Table B-5. Statistical results from LSD test comparing all variables and combinations of variables.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Sensor	11	1620.55	147.32	13.11	0.0001
Cycle	2	45.10	22.55	2.01	0.1357
Sensor*Cycle	21	243.30	11.58	1.03	0.4329
Range	2	279.18	139.59	12.42	0.0001
Sensor*Range	22	917.92	41.72	3.71	0.0001
Cycle*Range	4	104.72	26.18	2.33	0.0554
Sensor*Cycle*Range	40	431.73	10.79	0.96	0.5426
Soil	1	0.82	0.82	0.07	0.7873
Sensor*Soil	8	473.05	59.13	5.26	0.0001
Cycle*Soil	2	7.01	3.5	0.31	0.7323
Sensor*Cycle*Soil	16	182.87	11.43	1.02	0.4372
Range*Soil	2	47.84	23.92	2.13	0.1203
Sensor*Range*Soil	12	116.88	9.74	0.87	0.5814
Cycle*Range*Soil	4	39.40	9.85	0.88	0.4780
Sensor*Cycle*Range*Soil	20	53.67	2.63	0.23	0.9998

APPENDIX C

Appendix C. Datalogger Programs

Program: DATALOGGER #1 PROGRAM

Flag Usage:

Input Channel Usage:

Excitation Channel Usage:

Control Port Usage:

Pulse Input Channel Usage:

Output Array Definitions:

* 1 Table 1 Programs

01: 1800 Sec. Execution Interval

01: P87 Beginning of Loop

01: 0000 Delay

02: 5 Loop Count

02: P86 Do

01: 44 Set high Port 4

03: P22 Excitation with Delay

01: 1 EX Chan

02: 0 Delay w/EX (units=.01sec)

03: 500 Delay after EX (units=.01sec)

04: 0 mV Excitation

04: P100 SDM-1502

01: 00 Address

02: 0 Moisture

03: .3 Probe length (meters)

04: 0 Cable length (meters)

05: 1003 MMMP--Mux channels & Probes

06: 13 Loc [:TDR #1]

07: 1 Mult

08: 0 Offset

05: P86 Do

01: 54 Set low Port 4

06: P86 Do

01: 47 Set high Port 7

07: P86 Do

01: 48 Set high Port 8

08: P11 Temp 107 Probe

01: 1 Rep

02: 7 IN Chan

03: 3 Excite all reps w/EXchan 3

04: 6 Loc [:REF TEMP]

05: 1 Mult

06: 0 Offset

Page 2 Table 1

09: P14 Thermocouple Temp (DIFF)

01: 2 Reps

02: 22 7.5 mV 60 Hz rejection Range

03: 2 IN Chan

04: 1 Type T (Copper-Constantan)

05: 6 Ref Temp Loc REF TEMP

06: 7 Loc [:TCU #1]

07: 1 Mult

08: 0.0000 Offset

10: P86 Do

01: 46 Set high Port 6

11: P4 Excite, Delay, Volt(SE)

01: 00 Reps

02: 00 Range Option

03: 00 IN Chan

04: 00 EX Chan Option

05: 6000 Delay (units .01sec)

06: 0000 mV Excitation

07: 0000 Loc :

08: 0.0000 Mult

09: 0.0000 Offset

12: P86 Do

01: 56 Set low Port 6

13: P14 Thermocouple Temp (DIFF)

01: 2 Reps

02: 22 7.5 mV 60 Hz rejection Range

03: 2 IN Chan

04: 1 Type T (Copper-Constantan)

05: 6 Ref Temp Loc REF TEMP

06: 9 Loc [:TCH #1]

07: 1 Mult

08: 0.0000 Offset

14: P1 Volt (SE)

01: 2 Reps

02: 25 2500 mV 60 Hz rejection Range

03: 1 IN Chan

04: 4 Loc [:AQ-TEL #1]

05: 1 Mult

06: 0.0000 Offset

15: P86 Do

01: 57 Set low Port 7

16: P86 Do

01: 58 Set low Port 8

Page 3 Table 1

17: P35 Z=X-Y
 01: 9 X Loc TCH #1
 02: 7 Y Loc TCU #1
 03: 11 Z Loc [:AGWA #1]

 18: P35 Z=X-Y
 01: 10 X Loc TCH #2
 02: 8 Y Loc TCU #2
 03: 12 Z Loc [:AGWA #2]

 19: P86 Do
 01: 10 Set high Flag 0 (output)

 20: P96 Serial Output
 01: 71 SM192/SM716/CSM1

 21: P70 Sample
 01: 12 Reps
 02: 4 Loc AQ-TEL #1

 22: P77 Real Time
 01: 110 Day,Hour-Minute

 23: P86 Do
 01: 20 Set low Flag 0 (output)

 24: P95 End

 25: P End Table 1

Input Location Labels:

1: _____	6:REF TEMP	11:AGWA #1
2: _____	7:TCU #1	12:AGWA #2
3: _____	8:TCU #2	13:TDR #1
4:AQ-TEL #1	9:TCH #1	14:TDR #2
5:AQ-TEL #2	10:TCH #2	15:TDR #3

Program: DATALOGGER #2 PROGRAM

Flag Usage:

Input Channel Usage:

Excitation Channel Usage:

Control Port Usage:

Pulse Input Channel Usage:

Output Array Definitions:

* 1 Table 1 Programs

01: 1800 Sec. Execution Interval

01: P87 Beginning of Loop

01: 0000 Delay

02: 5 Loop Count

02: P4 Excite, Delay, Volt(SE)

01: 00 Reps

02: 00 Range Option

03: 00 IN Chan

04: 00 EX Chan Option

05: 100 Delay (units .01sec)

06: 0000 mV Excitation

07: 0000 Loc :

08: 0.0000 Mult

09: 0.0000 Offset

03: P6 Full Bridge

01: 1 Rep

02: 22 7.5 mV 60 Hz rejection Range

03: 3 IN Chan

04: 1 Excite all reps w/EXchan 1

05: 2500 mV Excitation

06: 1 Loc [:LCVOLT #1]

07: -1 Mult

08: 0 Offset

04: P6 Full Bridge

01: 1 Rep

02: 22 7.5 mV 60 Hz rejection Range

03: 4 IN Chan

04: 1 Excite all reps w/EXchan 1

05: 2500 mV Excitation

06: 2 Loc [:LCVOLT #2]

07: -1 Mult

08: 0.0000 Offset

05: P11 Temp 107 Probe

01: 1 Rep

02: 1 IN Chan

03: 3 Excite all reps w/EXchan 3

04: 3 Loc [:REF_TEMP]

05: 1 Mult

06: 0.0000 Offset

Page 2 Table 1

06: P86 Do

01: 41 Set high Port 1

07: P87 Beginning of Loop

01: 0 Delay

02: 12 Loop Count

08: P86 Do

01: 72 Pulse Port 2

09: P14 Thermocouple Temp (DIFF)

01: 1 Rep

02: 1 2.5 mV slow Range

03: 2 IN Chan

04: 1 Type T (Copper-Constantan)

05: 3 Ref Temp Loc REF_TEMP

06: 16-- Loc [:S_TC #1]

07: 1 Mult

08: 0.0000 Offset

10: P5 AC Half Bridge

01: 1 Rep

02: 14 250 mV fast Range

03: 2 IN Chan

04: 2 Excite all reps w/EXchan 2

05: 250 mV Excitation

06: 4-- Loc [:MB #1]

07: 1 Mult

08: 0.0000 Offset

11: P95 End

12: P86 Do

01: 51 Set low Port 1

13: P59 BR Transform $Rf[X/(1-X)]$

01: 12 Reps

02: 4 Loc [:MB #1]

03: 1 Multiplier (Rf)

14: P10 Battery Voltage

01: 24 Loc [:BATTERY]

15: P86 Do

01: 10 Set high Flag 0 (output)

16: P96 Serial Output

01: 71 SM192/SM716/CSM1

17: P77 Real Time

01: 0120 Day, Hour-Minute

Page 3 Table 1

18: P70 Sample
 01: 24 Repts
 02: 1 Loc LCVOLT #1

19: P86 Do
 01: 20 Set low Flag 0 (output)

20: P95 End

21: P End Table 1

Input Location Labels:

1:LCVOLT #1	7:MB #4	13:MB #10	19:S_TC #4
2:LCVOLT #2	8:MB #5	14:MB #11	20:S_TC #5
3:REF_TEMP	9:MB #6	15:MB #12	21:S_TC #6
4:MB #1	10:MB #7	16:S_TC #1	22:S_TC #7
5:MB #2	11:MB #8	17:S_TC #2	23:S_TC #8
6:MB #3	12:MB #9	18:S_TC #3	24:BATTERY

APPENDIX D

[illegible]

671	114	WM3	110.31	LOW	X
672	20.784	WM1	0.47	HIG	
673	16.6752	WM1	1.0620	MED	
674	11.5974	WM1	0.5484	MED	
675	8.8888	WM1	0.1835	MED	
676	8.5656	WM1	0.0531	LOW	
677	8.5396	WM1	0.3008	LOW	
678	5.5275	WM1	2.8215	LOW	
679	5.5275	WM1	3.3785	LOW	
680	5.5275	WM1	3.3785	LOW	
681	5.5275	WM1	3.3785	LOW	
682	5.5275	WM1	3.3785	LOW	
683	5.5275	WM1	3.3785	LOW	
684	5.5275	WM1	3.3785	LOW	
685	5.5275	WM1	3.3785	LOW	
686	5.5275	WM1	3.3785	LOW	
687	5.5275	WM1	3.3785	LOW	
688	5.5275	WM1	3.3785	LOW	
689	5.5275	WM1	3.3785	LOW	
690	5.5275	WM1	3.3785	LOW	
691	5.5275	WM1	3.3785	LOW	
692	5.5275	WM1	3.3785	LOW	
693	5.5275	WM1	3.3785	LOW	
694	5.5275	WM1	3.3785	LOW	
695	5.5275	WM1	3.3785	LOW	
696	5.5275	WM1	3.3785	LOW	
697	5.5275	WM1	3.3785	LOW	
698	5.5275	WM1	3.3785	LOW	
699	5.5275	WM1	3.3785	LOW	
700	5.5275	WM1	3.3785	LOW	
701	5.5275	WM1	3.3785	LOW	
702	5.5275	WM1	3.3785	LOW	
703	5.5275	WM1	3.3785	LOW	
704	5.5275	WM1	3.3785	LOW	

APPENDIX E

Appendix E. Programs used to analyze data.

```
options ls=72 ps=60 nodate;
```

```
data soilwat;
  infile 'b:\soilwa3.dat';
  input CYCLE ACT PRED SENSOR$ SOIL;
  if PRED > 50 then PRED=.;
  if PRED < 0 then PRED=.;
  DIFF = PRED - ACT;
  ADIFF = ABS(DIFF);
  IF SOIL = 1 AND ACT LE 10 THEN RANGE = 'LOW';
  IF SOIL = 1 AND 10 < ACT < 30 THEN RANGE = 'MED';
  IF SOIL = 1 AND ACT GE 30 THEN RANGE = 'HIGH';
  IF SOIL = 2 AND ACT LE 10 THEN RANGE = 'LOW';
  IF SOIL = 2 AND 10 < ACT < 20 THEN RANGE = 'MED';
  IF SOIL = 2 AND ACT GE 20 THEN RANGE = 'HIGH';

PROC SORT;
  BY SENSOR CYCLE RANGE SOIL;

PROC GLM;
  CLASS SENSOR CYCLE RANGE SOIL;
  MODEL ADIFF = SENSOR | CYCLE | RANGE | SOIL;
  MEANS SENSOR SENSOR*RANGE SENSOR*SOIL/T LINES;

RUN;
```

```

options ls=72 ps=60 nodate;

data soilwat;
  infile 'b:\soilwa2.dat';
  input CYCLE ACT PRED SENSOR$ SOIL;
  if PRED > 50 then PRED=.;
  if PRED < 0 then PRED=.;
  DIFF = PRED - ACT;
  ADIFF = ABS(DIFF);
  IF SOIL = 1 AND ACT LE 10 THEN RANGE = 'LOW';
  IF SOIL = 1 AND 10 < ACT < 30 THEN RANGE = 'MID';
  IF SOIL = 1 AND ACT GE 30 THEN RANGE = 'HIGH';
  IF SOIL = 2 AND ACT LE 10 THEN RANGE = 'LOW';
  IF SOIL = 2 AND 10 < ACT < 20 THEN RANGE = 'MID';
  IF SOIL = 2 AND ACT GE 20 THEN RANGE = 'HIGH';

PROC SORT DATA = SOILWAT;
  BY SENSOR CYCLE RANGE;

PROC MEANS MEAN SUM MIN MAX;
  BY SENSOR CYCLE RANGE;
  VAR ADIFF;

PROC MEANS MEAN SUM MIN MAX;
  BY SENSOR CYCLE RANGE;
  VAR DIFF;

PROC MEANS MEAN SUM MIN MAX;
  BY SENSOR CYCLE;
  VAR ADIFF;

PROC MEANS MEAN SUM MIN MAX;
  BY SENSOR CYCLE;
  VAR DIFF;

PROC SORT DATA = SOILWAT;
  BY SENSOR RANGE;

PROC MEANS MEAN SUM MIN MAX;
  BY SENSOR RANGE;
  VAR ADIFF;

PROC MEANS MEAN SUM MIN MAX;
  BY SENSOR RANGE;
  VAR DIFF;

PROC SORT DATA = SOILWAT;
  BY SENSOR;

PROC MEANS MEAN SUM MIN MAX;
  BY SENSOR;
  VAR ADIFF;

PROC MEANS MEAN SUM MIN MAX;
  BY SENSOR;
  VAR DIFF;

RUN;

```

VITA

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