Title: Development of a Standardized Testing Protocol for Soil Moisture Sensors: Current Status and Preliminary Test Results

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Abstract

Soil moisture sensors are an important component of some sensor based irrigation system controllers. The sensor provides information critical to the effective and efficient management of turf and landscape irrigation systems. At the Center for Irrigation Technology (CIT) a testing protocol standard is being established to verify the accuracy of commercially available soil moisture sensors. This protocol will characterize the ability of the sensor to provide reliable results when comparing individual units during multiple wetting cycles for various soil types, soil temperatures, and water salinity levels. In 2003, while initial tests were conducted on a commercially available sensor at CIT, a draft copy of the protocol was posted on the Irrigation Association (IA) website for comments. We propose to present results from the tests to date, such as calibration curve plots of the sensor reading versus the measured mass and volumetric moisture content. In addition we will summarize the comments and suggestions received via the internet to the draft protocol that was posted on the IA website.

Introduction

In January 2003, researchers at the Center for Irrigation Technology began testing a soil moisture sensor in accordance with the draft protocol formulated after joint discussion with industry personnel. Subsequently, the following two draft protocols were posted on the Irrigation Association website for public comment.

PROTOCOL A: **The Center for Irrigation Technology Draft Testing Protocol**

Turf and Landscape Irrigation Equipment – Soil Moisture Sensors

FIRST DRAFT

Reference No.: (CD/3/03) **Date: 03/03**
File: 1000-8 (SEN/03) **CIT/CSUF**

A1.0 Scope

Soil moisture sensors are an important component of some sensor based irrigation system controllers. The sensor provides information critical to the effective and efficient management of turf and landscape irrigation systems. This testing protocol standard is being established to verify the accuracy of commercially available soil moisture sensors. This protocol characterizes the ability of the sensor to provide reliable results when comparing individual units during multiple wetting cycles. This protocol also tests the sensors over the range of conditions encountered in typical field installations. This includes a range of soil types, a range of soil temperatures, and a range of irrigation water salinity levels. The sensor's ability to provide useful performance information when exposed to this range of conditions will be evaluated. Specifically the sensor's calibration curve will be determined and analyzed for stability when subjected to varying on-site conditions. The calibration curve is a plot of the sensor reading versus the mass or volumetric moisture content.

A2.0 Normative References

(Gravimetric Methods for Determining Soil Moisture Content)

A3.0 Terms and Definitions

For the purpose of this draft testing protocol, the following terms and definitions apply.

A3.1 Available Water
The portion of water in a soil that can be readily absorbed by plant roots

A3.2 Bulk Density, Soil
The mass (weight) of dry soil per unit bulk volume

A3.3 De-Ionized Water
Conductivity is 0 dS/m

A3.4 Evapotranspiration (ET)
Water transpired by vegetation plus that evaporated from the soil

A3.5 Field Capacity
The amount of water remaining in the soil after it has been saturated and allowed to drain away

A3.6 Fine Texture
A general term to indicate a soil with large portions of clay and silt

A3.7 Mass Water Content
The water content expressed as the weight of water in the soil divided by the oven-dry weight of soil

A3.8 Mass Water Percentage
The mass water content times 100

A3.9 Oven Dried
Placed in an oven and dried at 105°C for 48 hours

A3.10 Permanent Wilting Point (PWP)
The largest content of water in a soil at which plants will wilt and not recover when placed in a humidity chamber

A3.11 Siemens
The SI unit of electrical conductance

A3.12 Soil Texture
The relative proportions of the various soil size separates

A3.13 Volumetric Water Content
The ratio of the volume of water in a soil to the total bulk volume of the soil, in decimal form

A3.14 Volumetric Water Percentage
Volume water ratio multiplied by 100

A3.15 Water Salinity Level
An electrical conductance measurement characterizing the level of soluble salts that can interfere with the growth of some crops

A4.0 Symbols and Abbreviations

dS - deci-Siemens

A5.0 Sampling

A5.1 Sampling Test

A representative of the testing agency shall select test specimens for each test at random from a sample of at least 20 units supplied by the manufacturer. The number of specimens selected for each test shall be as listed in Table 1.

Table A1

Clause or Sub-Clause	Subject of Test	Number of Test Specimen
A6.2.1a	Calibration in a fine textured soil	2
A6.2.1b	Calibration in a medium textured soil	2
A6.2.1c	Calibration in a coarse textured soil	2
A6.3.1a	Calibration at 20°C	1
A6.3.1b	Calibration at 30°C	1
A6.4.1a	Calibration when wetted with water with a conductivity of 1.5 dS/m	1
A6.4.1b	Calibration when wetted with water with a conductivity of 3.1 dS/m	1

A6.0 Test Method

A6.1 Preparation of the soil containment box [Ref. CIT Drawing No. 4-28 (2/03)] and installation of the sensor.

A6.1.1 Use a standardized box capable of containing a fixed weight and volume of the representative soil type. The box shall wet and drain the soil through a perforated bottom. The box shall allow for the determination of the net weight of water required to bring the soil sample to field capacity. The volume of soil shall be sufficient to permit the sensor to function without being influenced by the box. The soil shall be oven dried and screened for ease of packing around the sensor. The soil shall be placed and tamped so as to result in the representative bulk density (range 1.2 to 1.4). Sensor reading and temperature measuring device output wiring shall be arranged so as not to interfere with the procedure for weighing the box. The weight of all components, except for the soil and water shall be known.

The box is designed to represent a section of turf grass root zone with a depth of 6-7 inches. The sensor will be located at the depth recommended by the manufacturer. It is recognized that the combined effects of surface drying and drainage below the root zone will result in a moisture gradient within the box. This is meant to represent the actual environment in which the sensor is asked to function.

A6.2a Test for the sensor's ability to provide a consistent calibration curve between drying cycles and individual sensors in a fine textured soil.

6.2.1a Assemble two boxes complete with moisture and temperature sensors including provision for electrical hookup to registering and/or recording devices. Predetermine the weight and volume of the soil moisture sensing device. Place the oven dried soil in the box and tamp to achieve the design bulk density. Include in this process the installation of the soil moisture sensor in the location recommended by the manufacturer. Obtain the weight of the box plus soil, and the volume of the soil and calculate the actual bulk density. Place the box in the environmental chamber set at 25°C. By a process of adding known amount of de-ionized (DI) water, fill the box until the soil is completely saturated. Allow the box to drain until all free drainage ceases. Measure the amount of drainage water and calculate the net amount of water stored in the box. Alternatively the box can be weighted before and after being saturated and drained to determine the net amount of water retained. In both methods the box should be covered to be sure the water loss is from drainage only. Read and record the soil temperature and sensor reading and weigh the box. This is the beginning of the test run and represents the water content at field capacity. Let the soil dry in the environmental chamber taking periodic readings of temperature, sensor output, and box weights. Initial test runs with a sandy loam in Fresno suggests that the drying process will take 15-18 days. In this case, two readings per day would be adequate. Plot the results from the two boxes; obtain a regression curve on each box.

Repeat the test by re-wetting the soils and taking readings as previously defined. Plot the results and develop the regression calibration curve.

A6.2b Test for the sensor's ability to provide a consistent calibration curve between drying runs and individual sensors in a medium textured soil.

A**6.2.1b** Repeat Clause 6.2.1a except:

- Use a medium textured soil

A6.2c Test for the sensor's ability to provide a consistent calibration curve between drying runs and individual sensors in a coarse textured soil.

A6.2.1c Repeat Clause 6.2.1a except:

- Use a coarse textured soil

A**6.3** Test for the sensor's ability to provide a constant calibration curve between individual sensors in a medium textured soil at 20°C and 30°C.

Note: Testing to Clause 6.2.1b gives comparable results at 25°C.

A**6.3.1a** Repeat Clause 6.2.1b except:

- Set the environment chamber at 20°C
- Conduct a single wetting run only

A**6.3.1b** Repeat Clause 6.2.1b except:

- Set the environmental chamber at 30°C
- Conduct a single wetting run only

A**6.4** Test for the sensor's ability to provide a consistent calibration curve between individual sensors when water of elevated salinity levels of 1.5 and 3.0 dS/m are used on a medium textured soil at 25°C

Note: Testing to Clause 6.2.1b gives comparable results with a water conductivity of 0 dS/m.

A**6.4.1a** Repeat Clause 6.2.1b except:

- Wet the soil with water with a conductivity of 1.5 dS/m
- Conduct a single wetting run only

A**6.4.1b** Repeat Clause 6.2.1b except:

- Wet the soil with water with a conductivity of 3.0 dS/m
- Conduct a single wetting run only

A7.0 Analysis of Results

A7.1 Summary analysis of the calibration for two sensors subjected to two wetting cycles with a medium textured soil a 25°C and wetted with water with a conductivity of 0.0 dS/m. Develop a regression and confidence limit analysis (95% and 99% levels).

A**7.2** Summary analysis of the calibration for all three soil types at 25°C and water with a conductivity of 0.0 d S/m. Develop a regression and confidence limit analysis. (95% and 99% levels).

A**7.3** Summary analysis of the calibration for the medium textured soil wetted with water with a conductivity of 0.0 dS/m at 20°C, 25°C, and 30°C. Develop a regression and confidence limit analysis. (95% and 99% levels).

A**7.4** Summary analysis of the calibration for the medium textured soil at 25°C when wetted with water with a conductivity of 0.0 dS/m, 1.5 dS/m, and 3.0 dS/m. Develop a regression and confidence limit analysis. (95% and 99% levels).

PROTOCOL B: **The Center for Irrigation Technology Draft Testing Protocol**

Turf and Landscape Irrigation Systems – Climatologically Based Controllers

FIRST DRAFT

B1.0 Scope

This protocol provides a procedure for characterizing the efficacy of irrigation system controllers that utilize climatological data or sensors as a basis for scheduling irrigations. The concept requires the use of accepted formulas for calculating crop evapotranspiration (ETc). Commercial versions of this type of controller include the following:

- Controllers that store historical ETc data characteristic of the site
- Controllers that utilize on-site sensor as a basis for calculating real time ETc
- Controllers that utilize a central weather station as a basis for ETc calculations and transmit the data to individual home owners by a wireless connection

The concept of climatologic control has an extensive history of scientific study and documentation. The objective of this protocol is to evaluate how well current commercial technology has integrated the scientific data into a practical system that meets the agronomic needs of the turf and landscape plants. This will be accomplished by creating a virtual yard subjected to a representative climate and to evaluate the ability of individual controllers to adequately and efficiently irrigate that yard. The individual zones within the yard will represent a range of climatic, soil and agronomic conditions. As a standard from which to judge the controller's performance, a detailed moisture balance calculation will be made for each zone. The total accumulated stress over time will be a measure of the adequacy. The accumulated surplus of applied water over time will be a measure of system efficiency. Further water applied beyond the soil's ability to absorb it will be characterized as run off, further degrading the application efficiency. The study is not meant to include a scientific critique of the many formulas by which crop water needs are calculated from weather data. The study will use CIMIS data from a weather station on the California State University campus in Fresno (#80).

B2.0 Normative References

California Irrigation Management Information System (CIMIS) (ww.cimis.water.ca.gov)

B3.0 Terms and Definitions

B3.1 Crop Coefficient (C)

Coefficients as determined for specific crops that relate ETo to ETc as follows:

ETo (C) = ETc

This provides a convenient method for calculating Etc when field data is not available.

B3.2 Crop Evapotranspiration (ETc)

Specific crop moisture requirements as determined by lysimeter studies or calculated using formulae.

B3.3 Evapotranspiration (ET)

Water transpired by vegetation plus that evaporated from the soil

B3.4 Field Capacity

The amount of water remaining in the soil after the soil has been saturated and allowed to drain away

B3.5 Landscape Coefficient (KL)

A functional equivalent of crop coefficient that integrates the effects of a species factor, microclimate factor, and density factor when calculating landscape water needs

B3.8 Permanent Wilting Point

The largest content of water in a soil at which plants will wilt and not recover when placed in a humidity chamber

B3.9 Reference Evapotranspiration (ETo)

Estimates of crop evapotranspiration as calculated using climatological information and accepted formulas. CIMIS values approximate loss from a large field of 4-7 in. tall, cool season grass that is not water stressed

B3.10 Zones

A portion of the system connected to a common water supply and intended to operate at the same time

B4.0 Functional Tests

B4.1 General

System controllers from individual companies will be installed on-site at (CIT) complete with required weather sensors and/or communication links. The controller will be wired to 5 zones simulated by using an electronic device that will automatically record the run time signal from the controller, to the individual zone "Control Valves".

B4.2 Sampling: A representative of the testing laboratory will select test specimen for each test at random from a sample of at least 10 units.

B4.3 Test for Adequacy and Efficiency: Communicate with the controller manufacturers the starting date of the test run and the source of the real time weather data (CIMIS weather station #80 on CSUF campus). Communicate with the controller manufacturer the definitions of the virtual yard as given in Table B1.
ccess the valve run time monitors to determine the run times per valve as specified by the manufacturers system. Use the run times, the specified application rate, and application efficiency to calculate the net application. Develop a moisture balance calculation assuming the calculation starts with a full root zone. Continue the calculation for a time period long enough to demonstrate the controller's ability to adequately meet a range of climatic conditions. Note: The general lack of summer rainfall in Fresno will be compensated for by manually adding periodic virtual rainfalls.

B4.4 Test Report

The moisture balance by zones for each manufacturer's controller will be developed. Total deficit and surplus for each zone will be calculated. The magnitude of the deficit will suggest an effect on the quality of the vegetation. The magnitude of the surplus will impact the overall operating efficiency.

Table B1: Description of Zones

Item No.	Description	Zone #1	Zone #2	Zone #3	Zone #4	Zone #5
1	Soil type (Texture)	Medium	Fine	Coarse	Medium	Fine
2	Slope, %	0-5	0-2	0-2	4-6	4-6
3	Exposure	Full Sun	50% Shade	Full Sun	50% Shade	Full Sun
4	Root Zone Storage, in. (1)	1.80	0.80	1.40	6.00	3.00
5	Vegetation	Fescue (Tall)	Bermuda	Ground Cover	Woody Shrubs	Trees & Ground Cover
6	Grass (Crop) Coefficient (C)	See Table 2	See Table 2	N/A	N/A	N/A
7	Landscape Coefficient (KL)	N/A	N/A	0.9	0.2	0.8
8	Desired Grass Quality Rating (2)	6.0	7.0 (3)	N/A	N/A	N/A
9	Irrigation System	Pop-Up Spray Heads	Pop-Up Spray Heads	Pop-Up Spray Heads	Pop-Up Spray Heads	Surface Drip Tape
10	Gross Application Rate, in./hr.	1.28	1.28	2.0	2.0	0.16
11	Estimated Application Efficiency, %	50	70	50	60	80
12	Area, FT^2	2,500	2,400	1,200	1,800	4,000

(1) Total moisture storage from field capacity to permanent wilting point for the vegetation noted with assumed typical rooting depths. (2) See Table B3, (3) Assume that the curve for tall fescue also applies to Bermuda.

Table B2: Grass (crop) Coefficients (C)

Month	Fescue	Bermuda
January	0.61	0.52
February	0.69	0.64
March	0.77	0.70
April	0.84	0.73
May	0.90	0.73
	0.93	0.71
July	0.93	0.69
August	0.89	0.67
September	0.83	0.64
October	0.75	0.60
November	0.67	0.57
December	0.59	0.53

Table B 3: Relationship between Grass Quality Rating and % ETc for Tall Fescue

% Etc	Quality Rating
30	2.0
40	3.6
50	5.0
60	6.1
70	7.0
80	7.6
90	7.9
100	8.0

Some Preliminary Results

The following four graphs show results obtained at our CIT laboratory for tests conducted on a moisture sensor operating on Time Domain Reflectometry (TDR) principles. Test conditions are summarized as follows:

Test # 1 - D.I. water (~ EC = 0 dS/m) conducted @ average temp.= 25.1^{0}C (**Figure 1**);

Test # 2- D.I. water (~ EC = 0 dS/m) conducted @ average temp.= 42.1^{0}C (**Figure 2**);

Test # 3- Application of salt solution (~ EC = 1.5 dS/m) conducted @ average temp.= 29.5^{0}C (**Figure 3**);

Test # 4- Application of 2nd dose of salt solution (i.e. an EC = 1.5 dS/m was added to the soil from test no.3) and experiment conducted @ average temp.= 30.1^{0}C (**Figure 4**).

Sensor Measurement vs Calculated Volumetric Water Content with 95% Confidence Limits for Test #1

Sandy Loam; D.I. water (EC ~ 0 dS/m); Avg. temp= 25.1^{o}C.

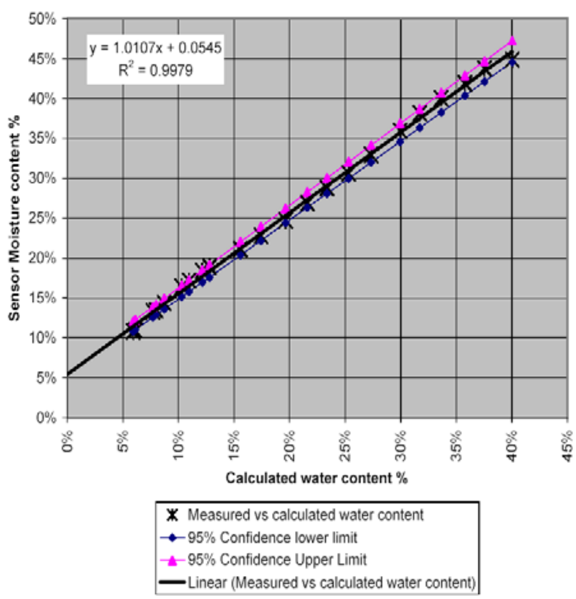


Figure 2: Sensor Measurement vs Calculated Volumetric Water Content for Test #2

Sandy Loam; D.I. water (EC ~ 0 dS/m); Avg. temp= 42.1^{o}C.

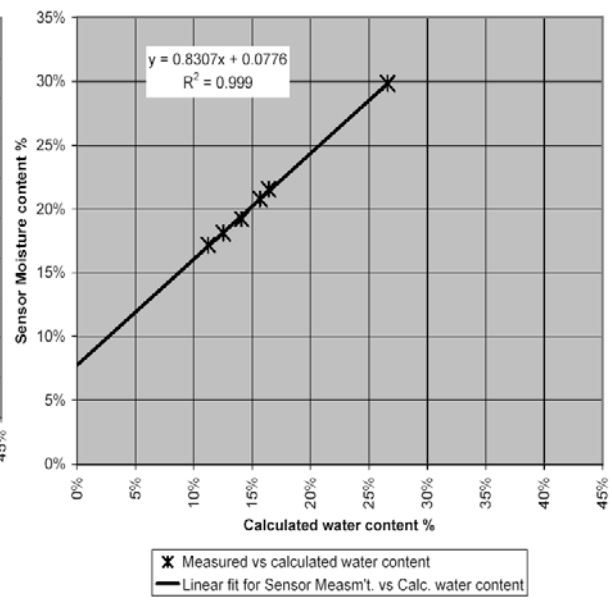
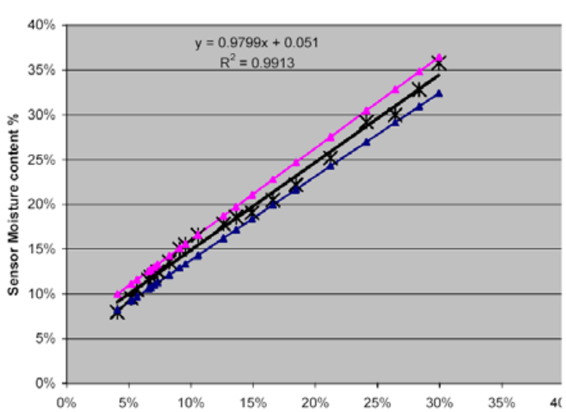


Figure 3: Sensor Measurement vs Calculated Volumetric Water Content for Test #3

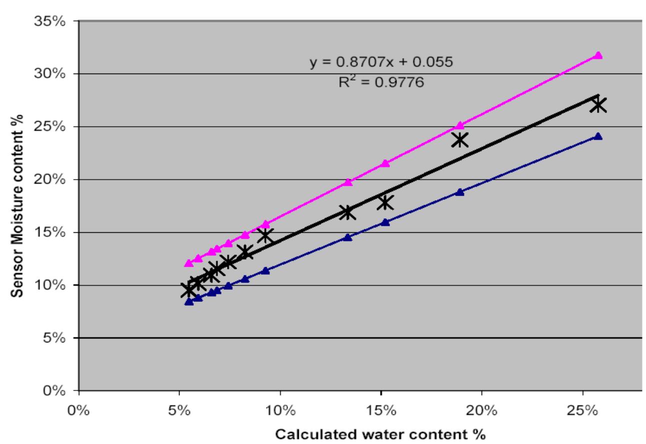
Sandy Loam; D.I. water (EC ~ 1.5 dS/m); Avg. temp= 29.5^{o}C.



Sensor Measurement vs Calculated Volumetric Water Content- Test #4

Two applications of 1.5 dS/m.

Sandy Loam; Water (EC ~ 3.0 dS/m); Avg. temp= 30.1^{o}C.



Some of the Comments Received in Response to the First Draft of the Protocols

Item	Comment/Observations	Accept	Reject	Explanation
(#)				
1	If a sensor provides useable data in the lab tests how can we be sure it will function satisfactorily in the field	✓		Lab tests address the impact of soil moisture content, temperature, and water conductivity on sensor readings. This test is meant to verify the scientific logic of the sensor design. Those sensors with favorable results would be recommended for a second phase of testing where they would be used with a control system to produce satisfactory turf grass.
2	How do we evaluate the sensor based system's ability to deal with soil and microclimate variability?	✓		Both soil and microclimate variability must be dealt with by all currently available control concepts. Some variability will be built into the Phase 2 field study. Also factors not identified in the lab study will be addressed in the field study.
3	Sensors should be tested for tolerance to freezing conditions	✓		Added to standard as paragraph 6.3.1c
4	2.0 No gravimetric soil moisture content referenced	✓		To be added
5	3.0 include a definition of "Soil Water Potential"	✓		To be added
6	Table 1 concerned about two few replications	✓		Made a modest increase in replications (from 2 to 3 & 1 to 2)

Item	Comment/Observations	Accept	Reject	Explanation
(#)				
7	6.0 question fundamental methodology of using containment box. Notes the moisture redistributing effect of roots in a natural environment.		✓	The box is meant to geometrically represent a section of turf root zone. Drying occurs through moisture loss at the surface and through drain holes in the bottom. To that end it represents the root zone in the field except for the presence of roots. The fact that the root zone does not dry out uniformly should not affect the results as long as the sensor is placed in the same relative position for all drying runs.
8	6.0 soil variability could affect results		✓	Soil sample is oven dried and screened and hand placed and tamped. It should be free of stones, roots, and other debris.
9	[illegible]	✓		[illegible]

Item (#)	Comment/Observations	Accept	Reject	Explanation
9	6.0 it would be helpful to have a copy of the soil containment box	✓		Copy of drawing added to appendix
10	6.0 how is sensor depth of placement determined in the absence of roots?		✓	Soil depth in containment box is approximately 6½ in deep. Sensor is placed at a depth of 3 in. or as specified by the manufacturer. See also #28 & # 29. This is meant to simulate a well irrigated root zone
11	Recommend installing a plug of turf grass on the surface of the containment box		✓	This lab test is meant to be a short term screening test. Adding turf would create serious logistical questions involving time and lab space. Questions of performance under actual turf management demands will be addressed in a proposed Phase 2 study involving both sensors and controllers.
12	6.2.1a why use de-ionized water? Why not use a real world water like rainwater?		✓	We need to use water of a fixed and known conductivity as a base. Thus DI is used.
13	How do you deal with the question of a variety of units, (e.g. volumetric moisture content, metric potential, dielectric constant, TDR, etc.)?	✓		Manufacturers are free to put whatever label on the calibration reading that they want. The protocol is only interested in how the calibration readings correlate with soil mass (or volumetric) moisture content. Each sensor will be evaluated on its ability to accurately correlate with soil moisture content when subjected to variations in temperature, conductivity and soil type.
14	What type of least squared regression will be completed? Will it be based on a linear regression?			The program uses a curve fit routine that evaluates the data against a fit to 25 equation forms and 3 polynomials. Best fit results in the highest correlation coefficient (R^2).
15	Could a pressure plate apparatus also be included?		✓	Moisture retention curves will be run on the three soil types involved. Individual sensor's calibration curves will be checked against the moisture retention curves to verify that the range of the sensor's curve covers the stress values involved in managing turf and landscape.
16	TDR probes of significant length integrate moisture content over the length of the probe. This could be an advantage in actual field use.	✓		Other sized containment boxes may be required for sensors sampling large soil volumes. In the field studies planned for Phase 2 of the test program, the importance of sampling larger soil volumes can be evaluated.
17	Could add basic equations involved in the appendix	✓		Included in the definitions

Item (#)	Comment/Observations	Accept	Reject	Explanation
18	Some soil moisture sensors do not have data recording features but operate to interrupt irrigation at predetermined set points.	✓		The protocol needs to be modified to include this type of sensor. In this case the evaluation will be made to determine repeatability of the set points over the range of the test conditions covered in the protocol. A discussion will be held with the manufacturer to determine if set point actuations can be sensed and recorded electronically. It would be desirable to sense all 16 set points with a single wetting run.
19	How will the protocol handle sensors that may have a different response curve for different soil types, water conductivity values, or temperature?	✓		The protocol will determine the repeatability of the sensors calibration for each of the variables involved (soil type, temperature, and water conductivity). The manufacturer will have to explain how this is useful in a water management scheme using a sensor with a matrix of calibration curves. They may also have to deal with transient conditions such as a fertilizer round.
20	Life tests are required to determine the stability of the sensors calibration overtime	✓		This will be suggested for inclusion in the Phase 2 study where sensors with controllers are responsible for the quality of turf in test plots
21	Soil moisture sensor must be easily adjustable to levels of watering that the user decided are adequate.			The protocol will describe the operational characteristics of the sensor with associated controller to allow for familiarization with the concept. The fundamental purpose of the Phase 1 protocol is to determine if the sensor is based on soil physics principals as demonstrated by providing a repeatable calibration curve when subjected to variable field conditions.
22	Reiterate the need for stability over time without the need for re-calibration.	✓		Time related issues to be included in Phase 2 of study with turf plots irrigated for say 3-5 years.

Item (#)	Comment/Observations	Accept	Reject	Explanation
23	Suggest making a distinction between absolute and relative soil moisture sensor.	✓		We understand the distinction between absolute and relative soil moisture sensors to be as follows: **Absolute Soil Moisture Sensor** This sensor is sensitive to soil moisture changes only and not affected by soil type, water conductivity, or temperature. Using moisture retention curves, the sensor can then be used to set limits on root zone tension at values known to provide quality turf with efficient water use. **Relative Soil Moisture Sensor** This sensor is sensitive to soil moisture changes and other factors including for example soil texture, water conductivity and temperature. This sensor must be calibrated "in situ" by an iterative process of adjusting water applications and making observations on turf quality. Related factors such as water conductivity changes during fertilization could change threshold stress and require a change of threshold setting values by the operator. The prime objective of the protocol is to characterize the sensors repeatability under known controlled conditions.
24	6.1.1 "Representative Bulk Densities (range 1.2 to 1.4)". What is the significance of the bulk density range?			Bulk density must be known and controlled to be representative of typical field conditions. Soil water content measurements are expressed on a mass water content basis (wcm) and some are expressed on a volume water content basis (wcv). The relationship between the two measurements involves bulk density (bd) as per the following equation: wvc = wcm (bd)
25	6.1.1 It would be interesting to record the depth of sensor placement.	✓		Documentation added to the protocol