For Firmware Version 2.9 and 3.0

STEVENS

MEASUREMENTS TO MIND

Stevens® Water Monitoring Systems, Inc.

Monitoring Earth's Water Resources Since 1911

HydraProbe

Soil Sensor

Users Manual

January 2018

Firmware version 2.9 and 3.0

Safety and Equipment Protection

WARNING!

ELECTRICAL POWER CAN RESULT IN DEATH, PERSONAL INJURY OR CAN CAUSE DAMAGE TO EQUIPMENT. If the instrument is driven by an external power source, disconnect the instrument from that power source before attempting any repairs.

WARNING!
BATTERIES ARE DANGEROUS. IF HANDLED IMPROPERLY, THEY CAN RESULT IN DEATH, PERSONAL INJURY OR CAN CAUSE DAMAGE TO EQUIPMENT. Batteries can be hazardous when misused, mishandled, or disposed of improperly. Batteries contain potential energy, even when partially discharged.

WARNING!
ELECTRICAL SHOCK CAN RESULT IN DEATH OR PERSONAL INJURY. Use extreme caution when handling cables, connectors, or terminals; they may yield hazardous currents if inadvertently brought into contact with conductive materials, including water and the human body.

CAUTION!
Be aware of protective measures against environmentally caused electric current surges and follow the previous warnings and cautions, the following safety activities should be carefully observed.

Children and Adolescents.
NEVER give batteries to young people who may not be aware of the hazards associated with batteries and their improper use or disposal.

Jewelry, Watches, Metal Tags
To avoid severe burns, NEVER wear rings, necklaces, metal watch bands, bracelets, or metal identification tags near exposed battery terminals.

Heat, Fire
NEVER dispose of batteries in fire or locate them in excessively heated spaces. Observe the temperature limit listed in the instrument specifications.

Charging
NEVER charge "dry" cells or lithium batteries that are not designed to be charged.
NEVER charge rechargeable batteries at currents higher than recommended ratings.
NEVER recharge a frozen battery. Thaw it completely at room temperature before connecting charger.

Unvented Container
NEVER store or charge batteries in a gas-tight container. Doing so may lead to pressure buildup and explosive concentrations of hydrogen.

Short Circuits
NEVER short circuit batteries. High current flow may cause internal battery heating and/or explosion.

Damaged Batteries
Personal injury may result from contact with hazardous materials from a damaged or open battery. NEVER attempt to open a battery enclosure. Wear appropriate protective clothing, and handle damaged batteries carefully.

Disposal
ALWAYS dispose of batteries in a responsible manner. Observe all applicable federal, state, and local regulations for disposal of the specific type of battery involved.

NOTICE
Stevens makes no claims as to the immunity of its equipment against lightning strikes, either direct or nearby.

The following statement is required by the Federal Communications Commission:

WARNING
This equipment generates, uses, and can radiate radio frequency energy and, if not installed in accordance with the instructions manual, may cause interference to radio communications. It has been tested and found to comply with the limits for a Class A computing device pursuant to Subpart J of Part 15 of FCC Rules, which are designed to provide reasonable protection against such interference when operated in a commercial environment. Operation of this equipment in a residential area is likely to cause interference in which case the user at their own expense will be required to take whatever measures may be required to correct the interference.

USER INFORMATION
Stevens makes no warranty as to the information furnished in these instructions and the reader assumes all risk in the use thereof. No liability is assumed for damages resulting from the use of these instructions. We reserve the right to make changes to products and/or publications without prior notice.

Preface

This manual is a comprehensive guide to the Stevens HydraProbe Soil Sensor. Contained within this manual is a theoretical discussion of soil physics that explains the theory behind how electromagnetic soil sensors work as well as a discussion about vadose zone hydrology. References to peer reviewed scientific publications are provided to give the user further background on these topics. Because soil moisture monitoring is becoming increasingly important to researchers across a broad number of fields including hydrology, agronomy, soil physics, and geotechnical engineering, we feel it is necessary to include advanced theoretical discussions with references to help the scientists and engineers understand the measurement technology in a manner that is unbiased and referenced.

Easy to Use

Despite this sophistication, Stevens HydraProbe Soil Sensor is also very easy to use. The user may skip to chapter 3 to learn about the installation and reference Appendix A for SDI-12 probes and Appendix B for RS485 Probes for wiring and communication. Calibration is not necessary for most soils and the default settings will accommodate most users and applications.

Comprehensive Stevens HydraProbe User's Manual

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For Firmware 2.9 and 3.0

HydraProbe installation at a typical USDA NRCS SNOTEL Site.
Picture compliments of USDA NRCS in Salt Lake City, Utah.

1 Introduction

The Stevens HydraProbe Soil Sensor measures soil temperature, soil moisture, soil electrical conductivity and the complex dielectric permittivity. Designed for many years of service buried in soil, the HydraProbe uses quality material in its construction. Marine grade stainless steel, ABS housing and a high grade epoxy potting protects the internal electrical component from the corrosive and the reactive properties of soil. Most of the HydraProbes installed more than a decade ago are still in service today.

The HydraProbe is not only a practical measurement device; it is also a scientific instrument. Trusted by farmers to maximize crop yields, using HydraProbes in an irrigation system can prevent runoff that may be harmful to aquatic habitats, conserve water where it is scarce, and save money on pumping costs. Researchers can rely on the HydraProbe to provide accurate and precise data for many years of service. The inter-sensor variability is very low, allowing direct comparison of data from multiple probes in a soil column or in a watershed.

The HydraProbe bases its measurements on the physics and behavior of a reflected electromagnetic radio wave in soil to determine the dielectric permittivity. From the complex dielectric permittivity, the HydraProbe can simultaneously measure soil moisture and electrical conductivity. The complex dielectric permittivity is related to the electrical capacitance and electrical conductivity. The HydraProbe uses patented algorithms to convert the signal response of the standing radio wave into the dielectric permittivity and thus the soil moisture and soil electrical conductivity.

1.1 Applications

The US Department of Agriculture Soil Climate Analysis Network (SCAN) has depended on the HydraProbe in hundreds of stations around the United States and Antarctica since the early 1990s. The Bureau of Reclamation's Agrimet Network, NOAA, and other mesonets and research watersheds around the world trust the measurements the HydraProbe provides. Some of the applications include:

Agriculture
Viticulture
Research
Water Shed Modeling
Land Reclamation
Shrink/Swell Clays
Satellite Ground Truthing
Predicting Weather
Irrigation
Sports Turf
Soil Phytoremediation
Evapotranspiration Studies
Land Slide Studies
Flood Forecasting
Wetland Delineation
Precision Agriculture

1.2 Calibrations

The HydraProbe has three factory calibrations that provide excellent performance in a variety of soils regardless of texture or organics. The three calibrations are GENERAL good for most all soils composed of sand, silt, and clay, organic (O) and rockwool (R). The factory GENERL soil calibration is the default calibration and is suitable for most all mineral soils. (See Chapter 6.1.3 and Appendix C for more information)

1.3 Dielectric Permittivity

The complex dielectric permittivities are provided for custom calibrations and other applications. (See Chapter 5.2 for more information)

1.4 Structural Components

There are three main structural components to the HydraProbe. The marine grade stainless steel tine assembly is the wave guide. The tine assembly is the four metal rods that extend out of the base plate ground plane. Each tine is 45 mm long by 3 mm wide. The base plate is 25 mm in diameter. Electromagnetic waves at a radio frequency are transmitted and received by the center tine. The head or body of the probe contains the circuit boards, microprocessors, and all the other electrical components. The outer casing is ABS and the internal electronics are permanently potted with a rock-hard epoxy resin giving the probes a rugged construction. The cable has a direct burial casing and contains the power, ground, and data wires that are all soldered to the internal electronics.

1.5 Accuracy and Precision

The HydraProbe provides accurate and precise measurements. Table 1.1 below shows the accuracy.

Parameter	**Accuracy/Precision**
Temperature (C)	+/- 0.3 Degrees Celsius(From -30^{o} to 60^{o}C)
Soil Moisture wfv † (m^3 m^{-3})	+/- 0.01 to 0.03 wfv (m^3 m^{-3}) Accuracy (Typical depends on soil)
Soil Moisture wfv † (m^3 m^{-3})	+/- 0.001 wfv (m^3 m^{-3}) Precision
Electrical Conductivity † (S/m) TUC*	+/- 0.0014 S/m or +/- 1% (Typical)
Electrical Conductivity † (S/m) TC**	+/- 0.0014 S/m or +/- 5% (Typical)
Real/Imaginary Dielectric Constant	+/- 0.1 to 0.2 or +/- 1% FS

Table 1.1 Accuracy and Precision of the HydraProbes' Parameters.
***TUC Temperature uncorrected full scale**
****TC Temperature corrected from 0 to 35^{o} C**
† The Accuracy and precision of the soil moisture, and EC measurements as well as the temperature corrections, are highly soil dependent.

1.6 Electromagnetic Compatibility

The Stevens HydraProbe is a soil sensor that uses low power RF energy. The intended use of the HydraProbe is to be buried in soil underground to depths ranging from 5 cm to 2 meters deep.

The HydraProbe meets and conforms to the conducted emissions criterion specified by EN 61326-1:2006 and FCC 15.107:2010 in accordance with method CISPR 11:2009 and ANSI C63.4:2009

The HydraProbe meets the non-intentional radiator emissions, (group A) specified by EN 61326-1:2006, FCC 15.109(g) and (CISPR 22:1997):2010 in accordance with method CISPR 11:2009 and ANSI C63.4:2009 except at 50 MHz when the probe is NOT buried as specified.

Test results are available upon request.

1.7 Configurations and Physical Specification

The HydraProbe is available in three versions, SDI-12, RS-485 and analog.

The two digital versions (SDI-12 and RS-485) incorporate a microprocessor to process the information from the probe into useful data. This data is then transmitted digitally to a receiving instrument. SDI-12 and RS-485 are two different methods of transmitting digital data. In both versions there are electrical and protocol specifications that must be observed to ensure reliable data collection.

The Analog version requires an attached instrument to measure voltages. This information must then be processed to generate useful information. This can be done either in the attached instrument, such as a data logger, or at a central data processing facility.

All configurations provide the same measurement parameters with the same accuracy. The underlying physics behind how the HydraProbe works and the outer construction are also the same for each configuration. Table 1.2 provides a physical description of the HydraProbe.

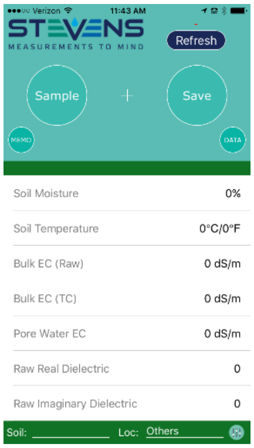
Feature	**Attribute**
Probe Length	12.4 cm (4.9 inches)
Diameter	4.2 cm (1.6 inches)
Sensing Volume* (Cylindrical measurement region)	Length 5.7 cm (2.2 inches) Diameter 3.0 cm (1.2 inches)
Weight	200g (cable 80 g/m)
Power Requirements	7 to 20 VDC (12 VDC typical)
Temperature Range**	-10 to 65° C
Storage Temperature Range	-40 to 75° C

Table 1.2 Physical description of the HydraProbe (All Versions)

***The cylindrical measurement region or sensing volume is the soil that resides between the stainless steel tine assembly. The tine assembly is often referred to as the wave guide, and probe signal averages the soil in the sensing volume.**

**** Standard temperature range is -10 to 60ºC. Extended range models are available.**

1.8 Soil Data Accessories and other Products



Soil Moisture	0%
Soil Temperature	0°C/0°F
Bulk EC (Raw)	0 dS/m
Bulk EC (TC)	0 dS/m
Pore Water EC	0 dS/m
Raw Real Dielectric	0
Raw Imaginary Dielectric	0

Soil: ____ Loc: Others

Figure 1.1. The Portable HydraGO-C and HydraGO -S allows for wireless on the go measurements of soil moisture. Connect via Bluetooth with to smartphone with HydraGO App.

Figure 1.2, The eTracker Cellular Gateway can take sensor inputs directly to the cloud.

Figure 1.3. The SDI-12 Xplorer USB Adapter. For testing any SDI-12 device with a USB.

Figure 1.4. The Tempe Cell for custom calibrations, soil water retention curves

Part Numbers	Description
63646-025	Digital HydraProbe , RS-485, W/25 FT.
63646-050	Digital HydraProbe, RS-485, W/50 FT.
63646-100	Digital HydraProbe, RS-485, W/100 FT.
93640-025	Digital HydraProbe, SDI-12, W/25 FT.
93640-050	Digital HydraProbe, SDI-12, W/50 FT.
93640-100	Digital HydraProbe, SDI-12, W/100 FT.
93640-150	Digital HydraProbe, SDI-12, W/150 FT.
93640-025-30	HydraProbe, SDI-12, 25' cable Extended Temperature Range
93640-050-30	HydraProbe, SDI-12, 50' cable Extended Temperature Range
93640-100-30	HydraProbe, SDI-12, 100' cable Extended Temperature Range
93342-002	Handheld Data Reader, USB
93633-005	Field Portable with GPS, include one HydraProbe and App
93633-006	Field Portable with W/O GPS, include one HydraProbe and App
93669-02	HydraProbe for Field Portable 10 FT. Cable
51139	SDI-12 XPLORER: USB TO SDI-12 Interface
92897	Cable, Analog, 7 conductor (1000' spool)
93539	Cable, RS-485 Probe, 5 conductor (1000' spool)
93924	Cable, SDI-12 probe, 3 conductor (2500' spool)
93723	SDI-12 / RS-485 Multiplexer, 12 Position

Table 1.3 Stevens Part numbers for HydraProbe and Accessories

2 Installation

2.1 Precautions

The HydraProbe is relatively easy to install depending on conditions in the field.
Avoid Damage to the HydraProbe:

- Do not subject the probe to extreme heat over 70 degrees Celsius (160 degrees Fahrenheit).
- Do not subject the probe to fluids with a pH less than 4.
- Do not subject the probe to strong oxidizers like bleach, or strong reducing agents.
- Do not subject the probe to polar solvents such as acetone.
- Do not subject the probe to chlorinated solvents such as dichloromethane.
- Do not subject the probe to strong magnetic fields.
- Do not use excessive force to drive the probe into the soil because the tines could bend. If the probe has difficulty going into the soil due to rocks, simply relocate the probe to an area slightly adjacent.
- Do not remove the HydraProbe from the soil by pulling on the cable.

While the direct burial cable is very durable, it is susceptible to abrasion and cuts by shovels. The user should use extra caution not to damage the cable or probe if the probe needs to be excavated for relocation.

Do not place the probes in a place where they could get run over by tractors or other farm equipment. The HydraProbe may be sturdy enough to survive getting run over by a tractor if it is buried; however, the compaction of the soil column from the weight of the vehicle will affect the hydrology and thus the soil moisture data.

DO NOT place more than one probe in a bucket of wet sand while logging data. More than one HydraProbe in the same bucket while powered may create an electrolysis affect that may damage the probe.

2.2 Topographical Station Placement Considerations

The land topography often dictates the soil hydrology. Depending on the users' interest, the placement of the HydraProbe should represent what would be most useful. For example, a watershed researcher may want to use the HydraProbe to study a microclimate or small hydrological anomaly. On the other hand, a farmer will want to take measurements in an area the best represents the condition of the crops as a whole.

Other factors to consider would be tree canopy, slope, surface water bodies, and geology. Tree canopy may affect the influx of precipitation/irrigation. Upper slopes may be better drained than depressions. There may be a shallow water table near a creek or lake. Hill sides may have seeps or springs.

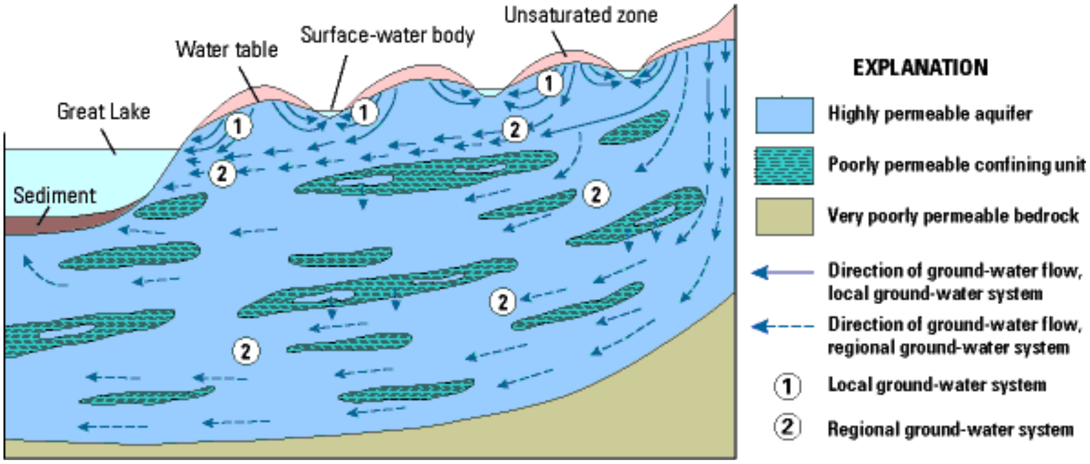


Figure 2.1G**oundwater pathways and Surface water. Taken from USGS Report 00-4008**

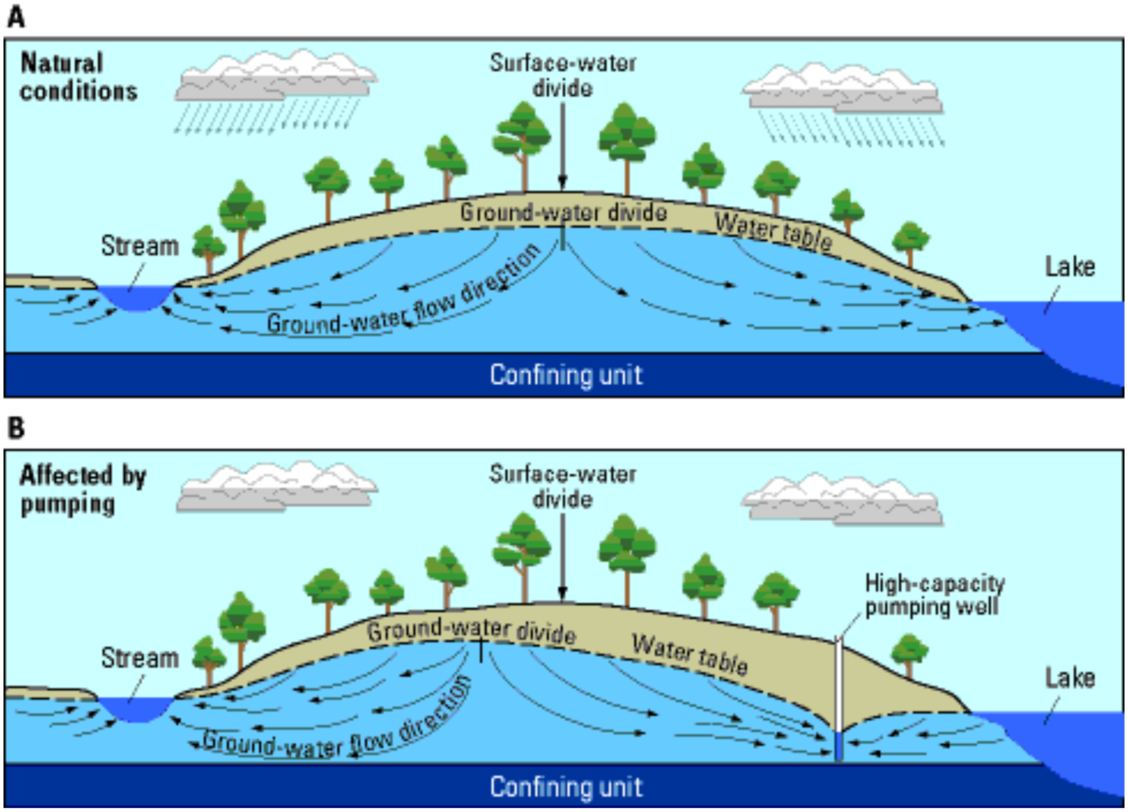


Figure 2.2 Groundwater flow direction and surface water body. Taken from USGS report 00-4008.

Figures 2.1 and 2.2 illustrate subsurface water movement in the water table. The HydraProbe data is most meaningful in the unsaturated zone where soil moisture values will fluctuate. If the water table rises to the depth of the HydraProbe, the HydraProbe soil moisture measurements will be at saturation and will be indicative of the porosity. If the user is interested in groundwater level measurements in wells, a water depth sensor might provide the necessary information.

2.3 Soil Sensor Depth Selection

Like selecting a topographical location, selecting the sensor depth depends on the interest of the user. Farmers will be interested in the root zone depth while soil scientists may be interested in the soil horizons.

Depending on the crop and the root zone depth, in agriculture two or three HydraProbes may be installed in the root zone and one HydraProbe may be installed beneath the root zone. The amount of water that should be maintained in the root zone can be calculated by the method described in section 6. The probe beneath the root zone is important for measuring excessive irrigation and downward water movement.

Figure 2.3 Six HydraProbes installed into 6 distinct soil horizons.

The soil horizons often dictate the depths of the HydraProbes' placement. Soil scientist and groundwater hydrologist are often interested in studying soil horizons. The Stevens HydraProbe is an excellent instrument for this application because of the accuracy and precision of the volumetric water fraction calibrations. Soil horizons are distinct layers of soil that form naturally in undisturbed soil over time. The formation of soil horizons is called soil geomorphology and the types of horizons are indicative of the soil order (see table 2.1) Like other natural processes, the age of the horizon increases with depth. The reason why it is so useful to have a HydraProbe in each horizon is because different horizons have different hydrological properties. Some horizons will have high hydraulic conductivities and thus have greater and more rapid fluctuations in soil moisture. Some horizons will have greater bulk densities with lower effective porosities and thus have lower saturation values. Some horizons will have clay films that will retain water at field capacity longer than other soil horizons. Knowledge of the soil horizons in combination with the HydraProbes accuracy will allow the user to construct a more complete picture of the movement of water in the soil. The horizons that exist near the surface can be 6 to 40 cm in thickness. In general, with increasing depth, the clay content increases, the organic matter decreases and the base saturation increases. Soil horizons can be identified by color, texture, structure, pH and the visible appearance of clay films.

More information about soil horizons is provided by the USDA National Resource Conservation Service at https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/edu/?cid=nrcs142p2_054308

More information about the soil horizons in your area can be found by in a soil survey. A soil survey for your area can be found at http://soildatamart.nrcs.usda.gov/

Soil Horizon	**Property**
O	Decaying plants on or near surface
A	Top Soil, Organic Rich
B	Subsoil, Most Diverse Horizon and the Horizon with the most sub classifications
E	Leached Horizon (light in color)
C	Weathered/aged parent material

Table 2.1 Basic description of soil horizons.

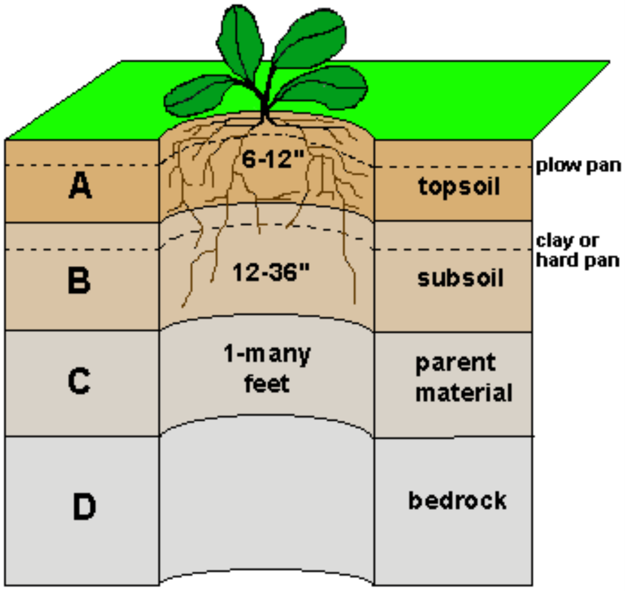


Figure 2.4 Soil Horizons.

Figure 2.5 Illustration of soil horizons. In this frame, the soil horizons are very distinct and show the geological history of the soil.

2.4 Installation of the HydraProbe into the Soil

2.4.1 Checklist before you go into the field

Below are a list of helpful and recommended items to take into the field.

Note pad and pen
Shovel
Knife
Trowel
Tape measure
Zip ties
Screw drivers
Gloves
Water/food
Muncell Color book
Wrench
Toe tags
Wire cutter and wire strippers
Needle nose plyers
SDI-12 Xplorer
Water bottle
Rags and towels
Hand held volt meter
Marker flags

2.4.2 Test the Probes and logger in the Office before going into the Field

It is recommend to setup the logger with the sensors in the office and running the system before installing in the field. This will allow the users to become familiar with the system and identify any problems. The HydraProbes can be placed in water to test functionality. See section 3.1.4

2.4.3 Labeling

It is helpful to label the sensor at the head so they can be quickly identified before going in the hole. The cable at the logger end should also be labeled. The serial number and address should be documented. The serial number is printed on the label or use the SDI-12 “aI!” command to get the serial number.

2.4.4 Installing the HydraProbe in the Soil

The most critical considerations for the installation of the HydraProbe are that the soil should be undisturbed and the base plate of the probe needs to be flush with the soil. To install the probe into the soil, first select the depth (see section 2.3 for depth selection). A post-hole digger or spade works well to dig the hole. If a pit has been prepared for a soil survey, the HydraProbes can be conveniently installed into the wall of the survey pit before it is filled in. Use a paint scraper to smooth the surface of the soil where it is to be installed. It is important to have the soil flush with the base plate because if there is a gap, the HydraProbe signal will average the gap into the soil measurement and create errors.

Figure 2.6 HydraProbe Installed in undisturbed soil.

Push the tines of the HydraProbe into the soil until the base plate is flush with the soil. The tines should be parallel with the surface of the ground, i.e. horizontal. Avoid rocking the probe back and forth because this will disturb the soil and create a void space around the tines. Again, it is imperative that the bulk density of the soil in the probe's measurement volume remain unchanged from the surrounding soil. If the bulk density changes, the volumetric soil moisture measurement and the soil electrical conductivity will change.

2.4.5 Soil Sensor Orientation

Figure 2.7 Horizontal placement sensor and dipping the cable is recommended

It is recommended to keep the tine assembly horizontal with the ground particularly near the surface. A drain loop can be put in the cable to prevent water from running down the cable to the probe's sensing area.

2.5 Wiring to a Logger Station

Connect the red wire to a +12 volt DC power supply, connect the black wire to a ground for all HydraProbe models. The measurement duty cycle is 2 seconds.

Wiring and power for HydraProbes	
Power Requirements	**9 to 20 VDC (12VDC Ideal)**
Red Wire	+Volts Power Input
Black Wire	Ground
Green Wire	Data Signal A -inverting signal (-)
White Wire	Data Signal B non-inverting signal (+)
Blue Wire	SDI-12
Power Consumption RS485	<10 mA Idle 30 mA Active for 2s
Power Consumption SDI-12	<1 mA Idle 10 mA Active for 2s

Table 2.2, Wiring connections and power considerations.

The user may also want to run the HydraProbe cable through a metal conduit like the one shown in figure 2.3 to add extra protection to the cable.

Once the probes are wired to the logger, test the communication between the logger and all of the probes. This can be achieved by current reading features in the logger or in SDI-12 transparent mode. See Appendix A for SDI-12 command or Appendix B for RS485 Commands.

2.5.1 Sensor Setup

It is recommended for most applications to use the default factory settings and the factory soil moisture calibration which will accommodate most all soil types. The default soil moisture calibration is called GENERAL and most users will not need to change it. If you have unique soil that requires a one of the other factory calibrations or a site specific calibration, see appendix C.

2.6 Backfilling the Hole

2.6.1 Test Before you Backfill

Before you begin backfilling the hole, when the probes are securely installed in the undisturbed soil, test the communication between the logger and all of the probes. This can be achieved by current reading features in the logger or in SDI-12 transparent mode. See Appendix A for SDI-12 command or Appendix B for RS485 Commands. The Xplorer SDI-12 to USB adapter PN# 51139 can be used to independently test the SDI-12 bus or individual SDI-12 Sensors in the field.

Figure 2.8. Xplorer SDI-12 to USB Adapter Stevens part number 51139 for testing SDI-12 bus or individual SDI-12 Sensors.

2.6.2 Backfilling Precautions

After soil is removed from the ground and piled up next to the hole, the horizons and soil become physically homogenized. The bulk density decreases considerably because the soil structure has been disturbed. After the probes are securely installed into the wall of the pit, the pit needs to be backfilled with the soil that came out it. It is impossible to put the horizons back the way they have formed naturally, but the original bulk density can be approximated by compacting the soil. For every 24 cm (1 foot) of soil put back into the pit, the soil should be compacted. Compaction can be done by trampling the soil with feet and body weight. Mechanical compactors can also be used, though typically they are not required. Extra care must be taken not to disturb the probes that have exposed heads, cables and conduits when compacting the soil. If the probes were installed in a post hole, a piece of wood, such as a post, can be used to pack the soil.

If the soil is not trampled down while it is being back filled, the compaction and bulk density of the backfill will be considerably less than the native undisturbed soil around it. After a few months, the backfilled soil will begin to compact on its own and return to a steady state bulk density. The HydraProbe will effectively be residing in two soil columns. The tines will be in the undisturbed soil column, and the head, cable and conduit will be in the backfill column that is undergoing movement. The compaction of the backfilled soil may dislodge the probe and thus affect the measurement volume of the probe. After the probes are installed, avoid foot traffic and vehicular traffic in the vicinity of the probes.

2.7 Lightning

Lightning strikes will cause damage or failure to the HydraProbe or any other electrical device, even though it is buried. In areas prone to lightning, surge protection and /or base station grounding is recommended.

While lightning can hit the logger station, the voltage surge propagating underground can cause serious damage to soil sensors. Underground voltage surges are called earth surge transients and the station needs to be protected both above and below ground.

For maximum protection from lightning, attach a dual lightning dissipators to the top of the lightning rod 3 to 6 meters above the ground surface. Using at least a 1 cm thick copper cable, connect the dissipator to a series of buried copper rod 2 cm in diameter. The buried copper rods should be at least 2 meters long buried horizontally 1.5 to 2 meters deep. Figures 2.9 and 2.10 show grounding of the soil monitoring location and the logger station. More information can be found in the Soil Sensor Lightning Protection Guide located at http://www.stevenswater.com/products/sensors/soil/hydraprobe/

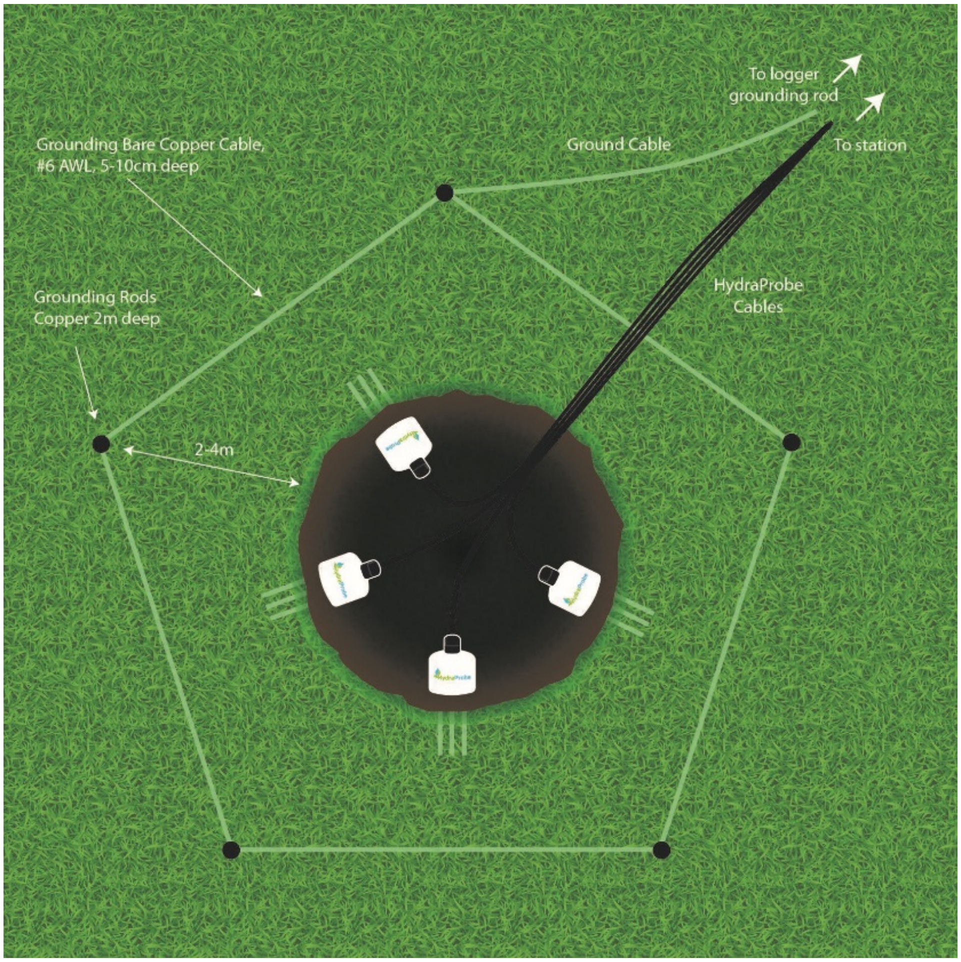


Figure 2.9. Place grounding rods around the perimeter of the soil monitoring area

Place a series of grounding rods 2 to 4 meters away from the soil probes two meters deep and clamp and connect them with a copper cable. Circle the soil sensors with the grounding rods in a way so that electrical surges propagating through the ground will go around the soil sensors.

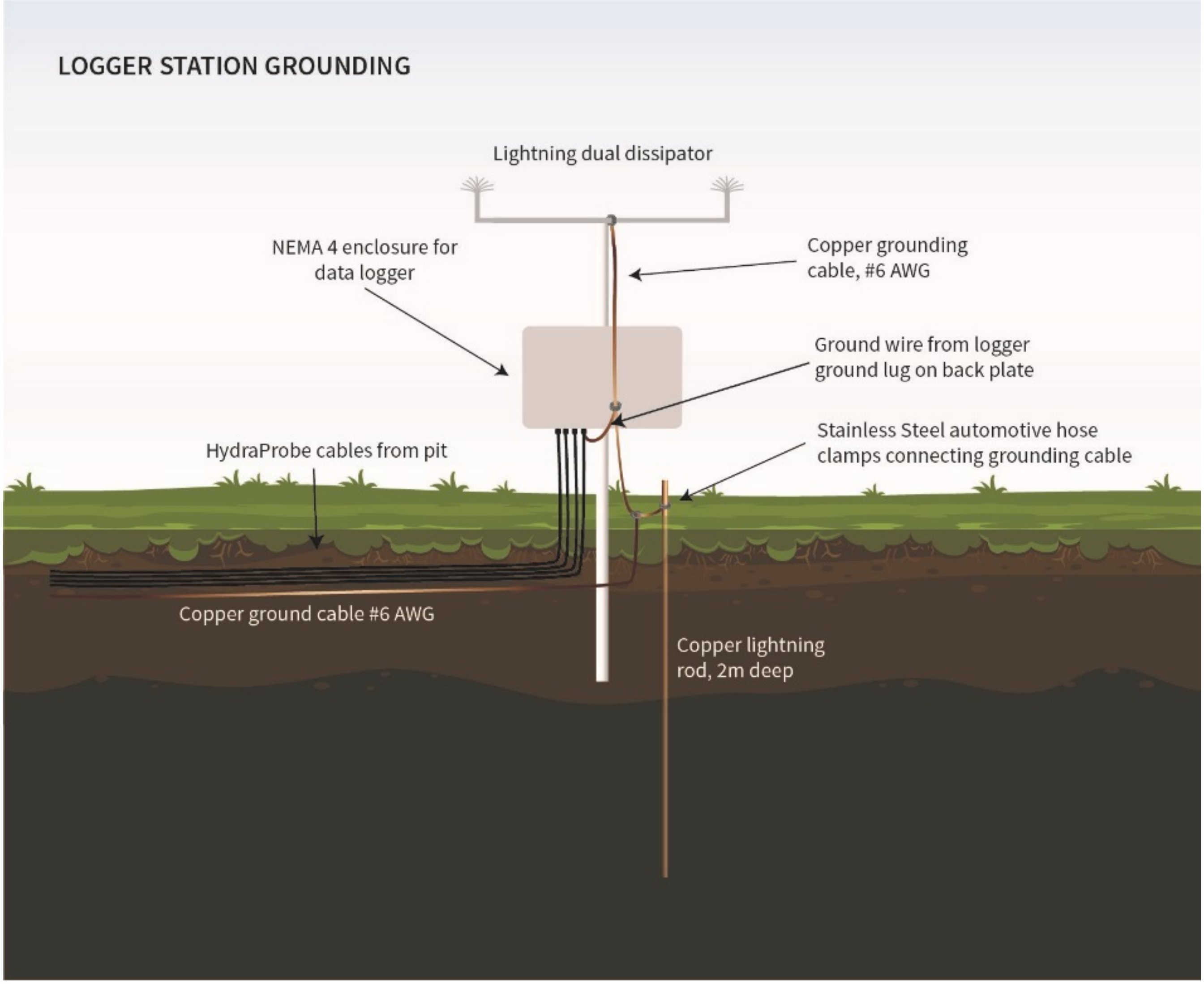


Figure 2.10. Ground the logger station with dual dissipators and ground rod.

3 Trouble Shooting and Soil Considerations

This section discuses trouble shooting and how the nature of soil can affect data. If a probe appears to be malfunctioning, there are generally three main reasons that may explain why a probe may appear to be malfunctioning. The three most common reasons why a probe may seem to be malfunctioning are:

1) Improper logger setup, or improper wiring,
2) Soil hydrology may produce some unexpected results, and
3) Power failure.

HydraProbes have a longevity in soil and a long warranty period, therefore; it is recommend to record the serial numbers on the probes for support purposes.

3.1 Trouble shooting at the Logger end and Out of the ground

Section 3.1 summarizes the steps the user should take if the HydraProbe is unresponsive or outputs data that is suspect. If the probes are in the ground, it is best to try to trouble shoot at the logger end before digging the probes up. Keep in mind that digging the probes out of the ground can be labor intensive and may disturb the other probes in the soil column. If the probe have to be dug out of the ground, they can be tested in water to determine if they are functioning properly.

3.1.1 Check Wiring and Power

If the user is unable to get a response from the HydraProbe it is recommended to first physically check wire connections from the probe to the logger. Check the cable for cuts and abrasions. A handheld voltmeter can be used to check the voltage on the battery and the SDI-12 bus. The voltmeter can also be connected in series with the ground wire to measure the current draw from the sensors. Idle, each HydraProbe draws 1 mA.

3.1.2 Communicate with the Sensor at the Logger End

If the logger has a current reading feature, run this feature from a laptop, app, or display that interfaces with the logger. Try to reproduce what was observed in the logged data.

If the logger has an SDI-12 Transparent mode, issues SDI-12 commands to the sensors on the bus. The “aI!” command can give the serial number. Use the “aM!; aD0!, aD1! aD2!” command to take a reading. Tables 3.1 and 3.2 are a summary of the commands. Isolating the suspect sensor and testing it when it is by itself may also be helpful. An SDI-12 to USB adapter such as the Stevens Xplorer (Figure 2.8) can be used to trouble shoot SDI-12 sensors.

Command Feature	SDI-12 Command
Change Address	aAb!
Get Probe’s serial number and ID	aI!
Take a Reading	aM! Follow by aD0!, aD1!,aD2!

Table 3.1 Common SDI-12 Command

Common Measurement Command sets for aM! And aC!			
Parameter ordering	**Parameter**	**Unit**	**Letter designation (See table)**
Parameter 1	Soil Moisture	Water fraction by volume	H
Parameter 2	Bulk Electrical Conductivity with Temperature Correction	S/m	J
Parameter 3	Temperature	C	F
Parameter 4	Temperature	F	G
Parameter 5	Bulk Electrical Conductivity	S/m	O
Parameter 6	Real Dielectric Permittivity	Unitless	K
Parameter 7	Imaginary Dielectric Permittivity	Unitless	M

Table 3.2 Common M and C command for SDI-12. For RS485 commands, please see appendix B.

3.1.3 Check the Logger Configuration

If the connections are sound, the user will need to check the logger's setup. Programming a data logger is not always a trivial task. The data logger needs to extract the data from data ports on the logger with the desired timing interval. The logger is often times the power source for the probes. The user may also want to cycle the power to the probe and the logger by disconnecting and reconnecting power. Refer to the manufacturer of the logger for tech support with the logger.

3.1.4 Remove the Suspect Probe from the Soil

If the problem cannot be resolved by checking the logger and the wiring, the probes should be dug out of the ground, and cleaned off.

To verify that the HydraProbe is functioning properly perform the following commands: Place the HydraProbe in distilled water in a plastic container. Make sure the entire probe is submerged. In transparent mode and with the third parameter set (aM3!), type "**1M3!**" followed by "**1D0!**" (with a probe address of 1 for this example). The typical response of a HydraProbe that is functioning properly should be *1+77.895+78.826+2.462.* From this example, the real dielectric permittivity is 77.895, and the imaginary dielectric permittivity is 2.462. According to factory specifications, the dielectric constant should be from 75 to 85 and the imaginary dielectric permittivity should be less than 5. If distilled water is not available, the user may use tap water for this procedure. It is important to note, however, that tap water may contain trace levels of material that may affect the dielectric permittivities readings. Isopropyl alcohol with a dielectric constant of 18.6 @20 degree C can also be used.

3.2 Soil Hydrology

Sometimes the soil moisture data may look incorrect when in fact the HydraProbes are accurately measuring the actual soil moisture gradient. Soil Hydrology is complex and can be modeled by Darcy's Law and Richard's Equation. These involved theories are beyond the scope of this manual; however, knowledge of basic soil hydrology is worth discussing.

It's important to note that the soil that resides between the tine assembly is where the measurements are taken. If there is a void space in the soil between the tines, this will affect the hydrology where the HydraProbe is taking measurements. If the void space is saturated with water, it will increase the soil moisture measurement. If the void space is not fully saturated, the soil will appear dryer. Figure 3.1 shows the measurement volume where the HydraProbe takes measurements and a void space between the tine assembly. These void spaces can occur from a poor installation, such as rocking the probe side to side or not fully inserting the probe into the soil.

Figure 3.1 Measurement volume with a void space between the tine assembly.

Void spaces between the tine assembly can also occur from changing soil conditions. Factors such as shrink/swell clays, tree roots or pebbles may introduce a void space. The following sections describe some of these and other factors.

3.2.1 Evapotranspiration

Water in the soil will be pulled downward by gravity, however during dry periods or in arid regions, the net movement of water is up toward the surface. Water will move upward in the soil column by a phenomenon called Evapotranspiration (ET). ET is the direct evaporation out of the soil plus the amount of water being pulled out of the soil by plants. Factors such as wind, temperature, humidity, solar radiation and soil type play a role in the rate of ET. If ET exceeds precipitation, there will likely be a net upward movement of water in the soil. With the net upward movement of soil water, ET forces dissolved salts out of solution and thus creating saline soil conditions.

3.2.2 Hydrology and Soil Texture

Sandy soils drain better than soils that are clay rich. In general, the smaller the soil particle size distribution, the slower it will drain. Sometimes silt may have the same particle size distribution, as clay but clay will retain more water for longer periods of time than silt. This can be explained by the shape of the soil particles. Clay particles are planar whereas silt particles are spherical. Water basically gets stuck between the planar plate shaped clay particles and thus slows the flow of water.

3.2.3 Soil Bulk Density

In general, the greater the soil density, the less water it will hold and the slower water will move through it. There will often times be soil horizons that will be denser than others giving the soil different hydrological properties with depth. Occasionally, water will stop or slow down and rest on a dense, less permeable layer of soil. This phenomenon is called perched water. If two HydraProbes 20 cm apart have very different soil moisture readings, chances are that one of the probes is residing in perched water.

There is also a relationship between soil bulk density and the complex dielectric permittivity. The soil dry bulk density (ρ_b) can be described by equation [3.1]

$$\rho_b = m/V \quad [3.1]$$

Where m is the mass of the dry soil in grams and V is the volume in cubic centimeters.
The bulk density is associated with the density of a soil ped or a soil core sample. The particle density (ρ_p) is the density of an individual soil particle such as a grain of sand. The two densities should not be confused with one another. Because E_r and Ei of dry soil is a function of both the bulk and particle densities (ρ_b, ρ_p), the soil density often creates the need for soil specific calibrations. The relationship between porosity, bulk and particle density can be described by equation [3.2]

$$\varphi = 1 - \frac{\rho_b}{\rho_p} \quad [3.2]$$

3.2.4 Shrink/Swell Clays

Shrink/swell clays belong to the soil taxonomic order vertisol and are composed of smectite clays. These clays have a large ion exchange capacity and will shrink and swell seasonally with water content. The seasonal expansion and contraction homogenizes the top soil and the subsoil. As the clay shrinks during a drying period, the soil will crack open and form large crevasses or fissures. If a fissure forms in the measurement volume of the HydraProbe, the probe will signal average the air gap caused by the fissure into the reading and potentially generate biased results. If the fissure fills with water, the soil moisture measurement will be high, if the fissure is dry, the soil moisture measurement will be lower than expected. If the HydraProbe measurements are being affected by shrink/swell clays, it is recommend to relocate the probe to an adjacent location.

3.2.5 Rock and Pebbles

Often times, it will be obvious if a rock is encountered during an installation. Never use excessive force to insert the probe into the soil. Some soils will have a distribution of pebbles. If a pebble finds its way between the probe's tines, it will create an area in the measurement volume that will not contain water. The probe will signal average the pebble and thus lower the soil moisture measurement. If the pebble is an anomaly, relocating of the probe would provide more representative soil measurements. However, if it is revealed from the soil survey that there exists a random distribution of pebbles, a pebble between the tines may provide realistic measurements because of the way pebbles influence soil hydrology.

3.2.6 Bioturbation

Organisms such as plants and burrowing animals can homogenize soil and dislodge soil probes. A tree root can grow between the tines affecting the measurements and in some cases, tree roots can bring a buried soil probe to the soil surface. Burrowing mammals and invertebrates may decide that the HydraProbes' tine assembly makes an excellent home. If the HydraProbe's tine assembly becomes home to some organism, the soil moisture measurements will be affected. After the animal vacates, the soil will equilibrate and the soil measurements will return to representative values.

The cable leading to the probe may also become a tasty treat for some animals. If communication between the logger and the probe fails, check the cable for damage. A metal conduit like the one shown in figure 2.3 is recommended.

3.2.7 Salt Affected Soil and the Loss Tangent

The HydraProbe is less affected by salts and temperature than TDR or other FDR soil sensors because of the delineation of the dielectric permittivity and operational frequency at 50 Mhz. While the HydraProbe performs relatively well in salt affected soils, salts that are dissolved in the soil water will influence both dielectric permittivities ts and thus the measurements. The salt content will increase the imaginary dielectric constant and thus the soil electrical conductivity. See Chapter 4. The HydraProbe will not measure electrical conductivity or soil moisture beyond 1.5 S/m

In general, if the electrical conductivity reaches 1 S/m, the soil moisture measurements will be significantly affected. The imaginary dielectric constant will have an influence on the real dielectric constant because dissolve cations will inhibit the orientation polarization of water. When addressing the HydraProbes' performance in salt affected soil, it is useful to use the loss tangent equation [3.3].

$$Tan\ \delta = \frac{\varepsilon_i}{\varepsilon_r} \qquad [3.3]$$

The loss tangent (Tan δ) is simply the imaginary dielectric constant divided by the real dielectric constant. If Tan δ becomes greater than 1.5 than the HydraProbes calibration becomes unreliable. It is interesting to note that the HydraProbe will still provide accurate dielectric constant measurements up to 1.5 S/m. If the salt content reaches a point where it is affecting the calibrations, the user can use a custom calibration that will still provide realistic soil moisture measurements in the most salt affected soils. See Appendix C for custom calibrations.

3.2.8 Ped Wetting

A soil ped is single unit of soil structure. Ped shapes include granular, platy, blocky and prismatic and ped sizes can range from 1mm granules to 10 cm prisms. The preferential pathway water travels through soil is between the peds. This is evident by clay film coatings that develops around a ped. The clay film precursors become dissolved in the pore water, as the pore water subsides, the clay film precursors fall out of solution and adhere to and surface of the peds creating the clay film. The clay film will often times delay the infiltration of water into the ped thus as the wetting front move down into the soil, the regions between the peds will be the preferential water pathway. As the wetting font moves through the soil column the soil moisture measurements may be temporarily biased by the peds. For example, if the soil probe's measurement volume is residing entirely in a single ped, the probe would not detect the wetting front until the water infiltrates the ped. Likewise, if the sensing volume is residing between several peds, the soil moisture measurements will reflect the movement of water between the peds. During installation, if a horizon has thick clay films around the peds, the user may want to use daily averages of soil moisture reading to accommodate soil moisture variations in the peds.

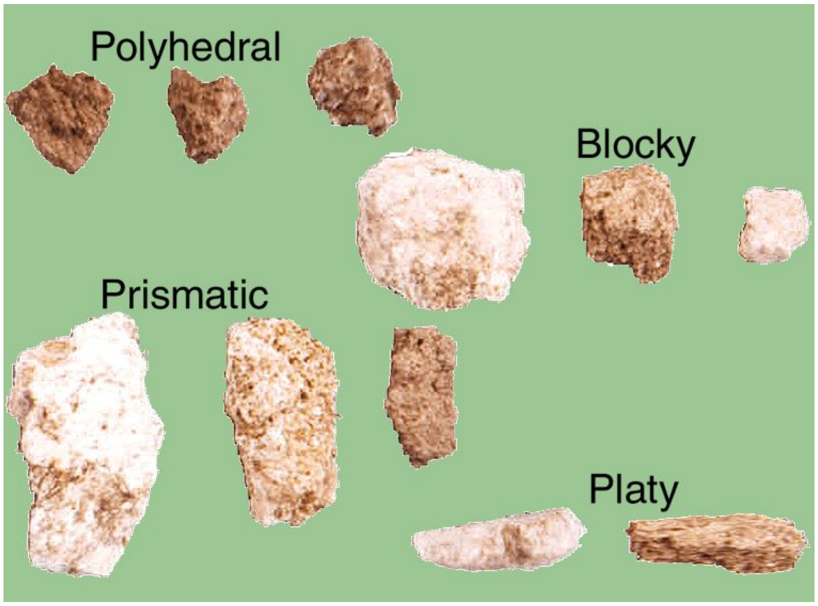


Figure 3.2. Soil Ped Types.

3.2.9 Frozen Soil

The HydraProbe can also be used to determine if soil is frozen. Once ice reaches 0^{o} Celsius, it will begin to thaw and the real dielectric permittivity will increase from 5. The temperature alone may not indicate whether or not the soil is frozen. As the soil begins to thaw, the soil moisture and the real dielectric permittivity should return to values similar to what they were before the soil froze.

4 Theory of Operation, Dielectric Permittivity and Soil Physics.

4.1 Introduction

Analytical measurement of soil moisture and matric potential are represented by a number of different technologies on the market. Described here is the theory behind electromagnetic soil sensors and a brief discussions of matric potential. Soil moisture can be expressed as a gravimetric water fraction, a volumetric water fraction (θ, $m^3\ m^{-3}$) or as a capillary matric potential (ψ, HPa). Soil sensors that employ electromagnetic waves (dielectric permittivity based) to estimate soil moisture typically express the soil water content as volumetric fraction, where sensors measuring soil water potential output units of pressure or the log of the pressure (pF).

4.2 Soil Matric Potential

Capillary matric potential sometimes referred to as tension or pressure head (ψ, hPa) is the cohesive attractive force between a soil particle and water in the pore spaces in the soil particle/water/air matrix. Typical ranges are 0 to 10,000,000 hPa where 0 is near saturation and 10,000,000 hPa is dryness. The drier the soil the more energy it takes to pull water out of it. Capillary forces are the main force moving water in soil and it typically will move water into smaller pores and into drier region of soil. This process is also called wicking.

Because of the wide pressure ranges that can be observed from very wet to very dry conditions, matric potential is often express as the common log of the pressure in hPa. The log of the pressure is called pF. For example 1,000,000 hPa is equal to a pF of 6..

Water potential is highly texture dependent. Clay particles have a larger surface area and thus will have a higher affinity for water than that of silt or sandy soils. The most common methods for measuring or inferring the matric potential including granular matrix sensors such as gypsum electrical resistance blocks, and tensiometers which measure pressure directly.

Heat dissipation type matric potential sensors measure the matric potential indirectly by measuring the heat capacitance of a ceramic that is in equilibrium with the soil. With heat up and cool down cycles of heating elements in the ceramic, the heat capacitance can be calculated which in turn is calibrated to the matric potential. Heat capacitance based matric potential sensors offer advantages in accuracy, range and maintenance over other technologies. The Stevens TensioMark pF Sensor (part number 51133-200) is a highly accurate SDI-12 matric potential sensor that uses heat capacitance technology

Matric potential is important for irrigation scheduling because it can represent the soil water that would be available to a crop. Many unsaturated flow models require a soil water retention curve where water fraction by volume is plotted with the matric potential in a range of moisture conditions (Figure 4.2).A soil water retention curve can help understand the movement and distribution of water such as infiltration rates, evaporation rates and water retentions (Warrick 2003). Table 4.1 shows the general values of matric potential under different hydrological thresholds and soil textures.

Figure 4.1. TensioMark SDI-12 heat capacitance based Matric Potential Sensor. (PN 51133-200)

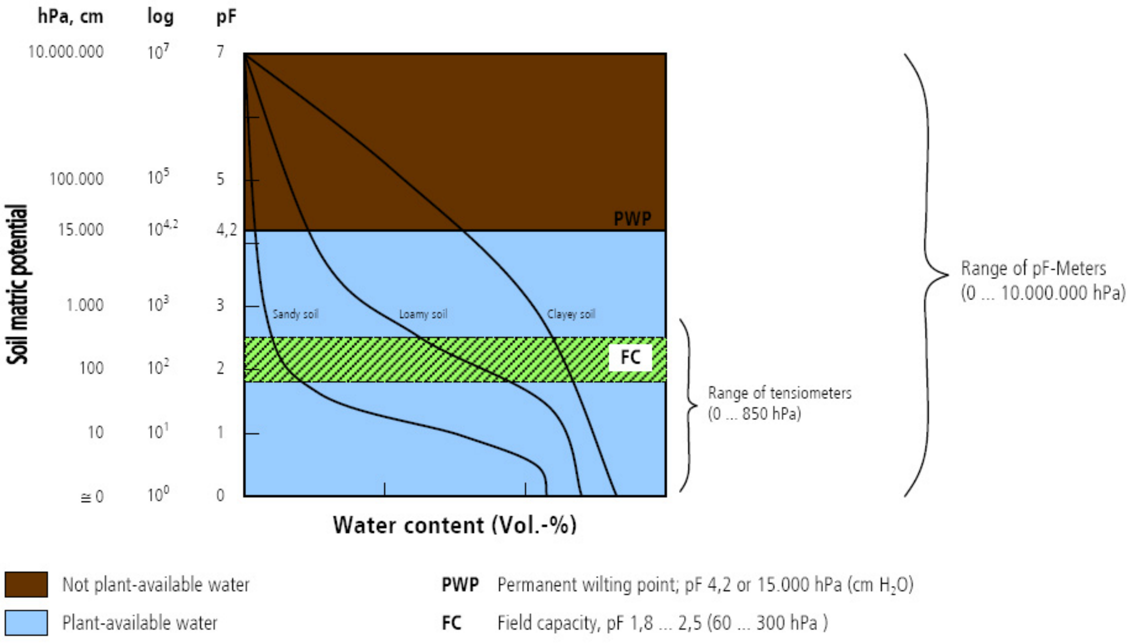


Figure 4.2. Soil Water Retention Curve. Soil matric potential verse soil moisture.

Soil Condition	Matric Potential						Soil Moisture %		
	Bar	kPa	hPa	PSI	ATM	pF	Sand	Silt	Clay
Saturation	0	0	0	0	0		42%	40%	55%
	0.2	20	200	2.9007	0.197	2.30			
Field Capacity	0.33	33	330	4.7862	0.326	2.52	10%	30%	40%
	1	100	1000	14.503	0.987	3			
Permanent Wilting Point	15	1500	15000	217.55	14.80	4.18	4	15%	21%

Table 4.1. General trends of matric potentials under different soil hydrologic conditions and textures

4.3 Electromagnetic Soil Water Methods and Soil Physics

The behavior of electromagnetic waves from 1 to 1000 MHz in soil can be used to measure or characterize the complex dielectric permittivity. Dielectric permittivity was first mathematically quantified by Maxwell's Equations in 1870s. In the early 1900s, research with radio frequencies led to modern communication and the arrival of the television in the 1950s. In 1980, G. C. Topp (Topp 1980) proposed a method and a calibration to predict soil moisture based on the electrical properties of the soil known as the Topp Equation. Today, there are dozens of different kinds of soil moisture sensors commercially available that in one way or another base their soil moisture estimation on the dielectric permittivity. Among all of the electronic soil sensors commercially available, measurement involving the complex dielectric permittivity remains the most practical way to determine soil water content from an in situ sensor or portable device. Electromagnetic soil sensors use an oscillating radio frequency and the resultant signal is related to the dielectric permittivity of the soil where the in situ soil particle/water/air matrix is the dielectric. Subsequent calibrations then take the raw sensor response to a soil moisture estimation.

4.3.1 Dielectric Theory

Complex dielectric permittivity describes a material's ability to permit an electric field. As an electromagnetic wave propagates through matter, the oscillation of the electric field is perpendicular to the oscillation of the magnetic field and these oscillations are perpendicular to the direction of propagation. The dielectric permittivity of a material is a complex number containing both real and imaginary components and is dependent on frequency, temperature, and the properties of the material. This can be expressed by,

$$\kappa^* = \varepsilon_r - j\varepsilon_i \qquad [4.1]$$

where K^* is complex dialectic permittivity, ε_r is the real dielectric permittivity, ε_i is the imaginary dielectric permittivity and $j = \sqrt{-1}$ (Topp 1980). As the radio wave propagates and reflects through soil, the properties and water content of the soil will influence the wave. The water content, and to a less extent the soil properties will alter and modulate electromagnet radio signal as it travels through the soil by changing the frequency, amplitude, impedance and the time of travel. The Dielectric permittivity can be determined by measuring these modulations to the radio frequency as it propagates through the soil. In general, the real component represents energy storage in the form of rotational or orientation polarization which is indicative of soil water content. The real dielectric constant of water is 78.54 at 25 degrees Celsius and the real dielectric permittivity of dry soil is typically about 4. Changes in the real dielectric permittivity are directly related to changes in the water content and all electromagnetic soil sensors base their moisture calibrations on either a measurement or estimation of the real dielectric permittivity of the soil particle/water/air matrix. (Jones 2005, Blonquist 2005). The imaginary component of the dielectric permittivity,

$$\varepsilon_i = \varepsilon_{rel} + \frac{\sigma_{dc}}{2\pi f \varepsilon_v} \qquad [4.2]$$

represents the energy loss where ε_{rel} is the molecular relaxation, f is the frequency, ε_v permittivity of a vacuum, and σ_{dc} is DC electrical conductivity. In most soils, ε_{rel} is relatively small and a measurement of the imaginary component yields a good estimation of the electrical conductivity from 1 to 75 MHz (Hilhorst 2000). In sandy soils, the molecular relaxation can be negligible. The HydraProbe estimates electrical conductivity by measuring the imaginary and rearranging equation [4.2] based on the assumption that the relaxations are near zero.

The storage of electrical charge is capacitance in Farads and is related to the real component (non-frequency dependent) by

$$C = g\varepsilon\, \varepsilon_v \qquad [4.3]$$

Where g is a geometric factor and ε is the dielectric constant. If the electric field of the capacitor is oscillating (i.e. electromagnetic wave), the capacitance also becomes a complex number and can be describe in a similar fashion as the complex dielectric permittivity in equations [4.1] and [4.2] (Kelleners 2004).

The apparent dielectric permittivity ε_a, is a parameter that contains both the real and the imagery dielectric permittivities and is the parameter used by most soil sensors to estimate soil moisture.

$$\varepsilon_a = \{1+[1+\tan^2(\varepsilon_i/\varepsilon_r)]^{1/2}\}\varepsilon_r/2 \qquad [4.4]$$

From equation [4.4], the apparent dielectric permittivity is a function of both real and imaginary components (Logsdon 2005). High values of ε_i will inflate the ε_a which may cause errors in the estimation of soil moisture content. In an attempt to shrink the errors in the moisture calibration from the ε_i, some soil sensors such as time domain reflectometry will operate at high frequencies giving the ε_a more real character. In practice, soils high in salt content will inflate the soil moisture measurement because ε_a will increase due to the DC conductivity component of ε_i. Also, the ε_i is much more sensitive to temperature changes than ε_r creating diurnal temperature drifts in the soil moisture data (Blonquist 2005, Seyfried 2007). The soil moisture sensors that can best isolate the real component and delineate it from the imaginary will be the most accurate and will have a lower inter-sensor variability.

Water is a polar molecule, meaning that one part of the water molecule caries a negative charge while the other half of the molecule caries a positive charge. While water is very polar, soils are rather non-polar. The polarity of water causes a rotational dipole moment in the presence of an electromagnetic wave while soil remains mostly uninfluenced. This means that water will rotate and reorientate with the rise and fall of the oscillating electric field i.e. electromagnetic wave while soil remains mostly stationary. From 1 to 1000 MHz, the water rotational dipole moment of water will occur at the same frequency of the electromagnetic wave. It is this rotational dipole moment of water that is responsible for water's high dielectric constant[1] of about 80. Dry Soil will have a dielectric constant of about from about 4 to 5. Large changes in the dielectric permittivity will are directly correlated to changes in soil moisture. Figure 4.2 shows the polarity of a water molecule and how it can reorient itself in response to electromagnetic oscillations.

[1] Terminology note. The term "real dielectric constant" generally refers to a physical property that is constant at a specified condition. The term "real dielectric permittivity" or "real permittivity" refers to the real dielectric constant of a media that is undergoing change, such as soil.

Figure 4.3. A water molecule in the liquid phase reorienting i.e. rotational dipole moment.

Figure [4.3] illustrates the different kinds of polarizations exhibited by most materials. Soils will have space charge and atomic polarizations while water will re-orientate.

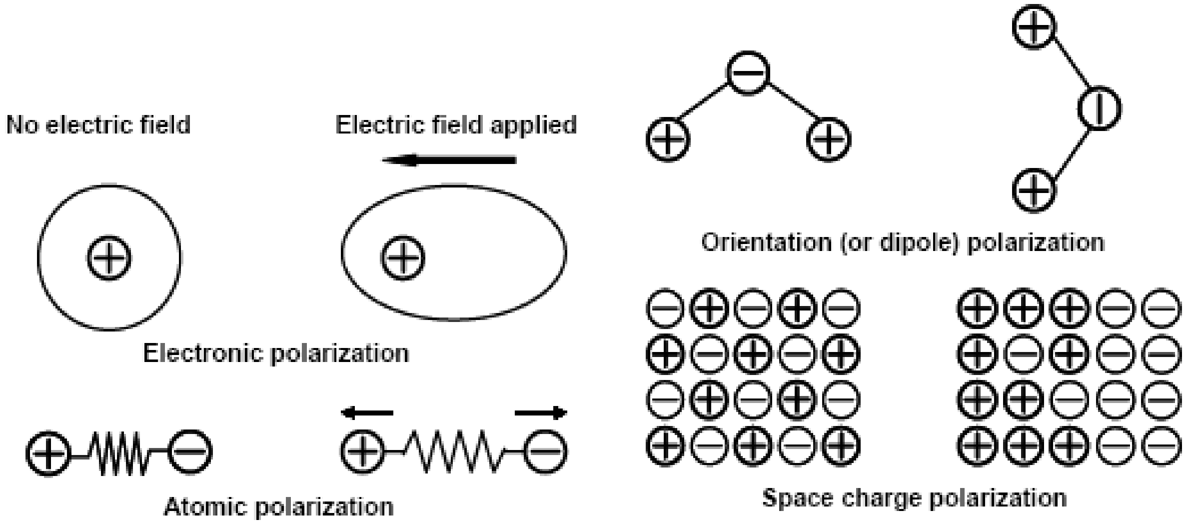


Figure [4.4]. Illustration of polarization. The real dielectric permittivity of soil is mostly due to orientation polarization of water (Taken from Lee et al. 2003)

4.3.2 Temperature

Both the real and imaginary dielectric permittivities will be influenced by temperature. The imaginary component is much more sensitive to changes in temperature than the real component. (Seyfried 2007).

4.3.3 Temperature and the Real Permittivity

The real dielectric permittivity of water will have a slight dependence on temperature. As the temperature increases, molecular vibrations will increase. These molecular vibrations will impede the rotational dipole moment of liquid water in the presents of an osculating electric field; consequently, the real dielectric permittivity of water will decrease as the temperature increases. The empirical relationship with temperature found in the literature is show in equation [4.5] (Jones 2005)

$$\varepsilon_{r,w}(T) = 78.54[1\text{-}4.579X10^{-3}\,(T\text{-}298)+ 1.19\,X10^{-5}\,(T\text{-}298)^{2}\text{-}2.8X10^{-8}(T\text{-}298)^{3}] \quad [4.5]$$

While the HydraProbe has a temperature corrections for the electrical components on the circuit board, the factory calibrations do not apply a temperature correction to the measured soil moisture values. Water in liquid form will have its dielectric constant decrease with increasing temperature, but in soil, water's dielectric dependency with temperature is more complicated due to bound water affects. As temperature changes, the molecular vibrations of the water and cations that are bonded to soil particles at a microscopic level can affect the dipole moments in the presence of a radio frequency. In practical terms, temperature correction to soil moisture calibrations are highly soil dependent. In some soils, the real dielectric can trend downward with increasing temperature as it does in liquid form, or it can trend upward with increasing temperature (Seyfried 2007).

4.3.4 Temperature and the imaginary permittivity

The imaginary permittivity is highly temperature dependent and the temperature dependence is similar to that of the bulk electrical conductivity.

4.4 Types of Commercial Electromagnetic Soil Sensors

There are dozens of different kinds of electronic soil sensors commercially available and it can be confusing to understand the different technologies. Table 4.2 summarizes the types of sensing methods.

Method	Physical Measurement	Basis for Soil Moisture	Typical Frequency
TDR	Time of travel of a reflected wave	Apparent Permittivity	1000 MHz
TDT	Time of travel	Apparent Permittivity	150 to 2000 MHz
Capacitance (Frequency)	Shift in Frequency (Resonance Frequency)	Apparent Permittivity	150 MHz
Capacitance (Charge)	Capacitor Charging time	Capacitance	NA
Differential Amplitude	Difference in reflected amplitudes	Apparent Permittivity	75 MHz
Ratiometric amplitude Impedance	Ratio of reflected amplitudes to measure the impedance.	Real Dielectric Permittivity	50MHz

Table 4.2. Summary of commercially available soil sensing methods

Both time domain reflectometry (TDR and time domain transmission (TDT) use the time of travel of the radio wave to measure the apparent permittivity (Blonquist 2005-A). The primary difference between TDR and TDT is TDR characterizes the reflected wave where as TDT characterizes the travel time on a wave guide of a set path length.

Capacitance can be measured from the change in frequency from a reflected radio wave or resonance frequency (Kelleners 2004). These sensors are often referred to as frequency domain reflectometers (FDR), however the term FDR is often misused because most frequency sensors are using a single frequency and not a domain of frequencies. Other capacitance probes and amplitude impedance-based probes are often mistakenly referred to as “FDRs”.

The capacitance of a parallel plate capacitor can be measured from the time it takes to charge the capacitor. Some commercially available soil sensors can measure the capacitance of the soil from the time of charge and then calibrate for soil moisture.

Another method for determining the apparent permittivity is measuring the difference between the incident amplitude and the reflected amplitude (Gaskin 1996).

4.4.1 The HydraProbe, a Ratiometric Coaxial Impedance Dielectric Reflectometer

The Stevens HydraProbe is different than other soil sensing methods. It characterizes the ratio of the amplitudes of reflected radio waves at 50 MHz with a coaxial wave guide. A numerical solution to Maxwell's equations first calculates the complex impedance of the soil and then delineates the real and imaginary dielectric permittivity (Seyfried 2004, Campbell 1990). The mathematical model that delineates the real and imaginary component from the impedance of the reflected signal resides in the microprocessor inside the digital HydraProbe. These computations are based on the work of J. E. Campbell at Dartmouth College (Campbell 1988, Campbell 1990, Kraft 1988).

The HydraProbe from an electric and mathematical prospective can be referred to ratiometric coaxial impedance dielectric reflectometer and works similar to a vector network analyzer at a single frequency. The term "ratiometric" refers to the process by which the ratio of the reflected signal over incident signal is first calculated which eliminates any variability in the circuit boards from one probe to the next. This step is performed on several reflections. The term "coaxial" refers to the metal wave guild that get inserted into the soil. It has three outer tines with a single tine in the middle that the both receives and emits a radio frequency at 50 MHz. "Impedance" refers to the intensity of the reflected signal, and "dielectric reflectometer" refers to a reflected signal that is used to measure a dielectric.

4.4.2 Advantages of using the real dielectric permittivity over the apparent permittivity

Unlike most other soil sensors, the HydraProbe measures both the real and the imaginary components of the dielectric permittivity as separate parameters. The HydraProbe bases the soil moisture calibration on the real dielectric permittivity while most other soil moisture technologies base their soil moisture estimation on the apparent permittivity which is a combination of the real and imaginary components as defined in equation [4.4] (Logsdon 2010). Basing the soil moisture calibration on the real dielectric permittivity instead of the apparent permittivity has many advantages. Because the HydraProbe separates the real and imaginary components, the HydraProbe's soil moisture calibrations are less affected by soil salinity, temperature, soil variability and inter sensor variability than most other electronic soil sensors.

4.4.3 The HydraProbe is Easy to Use

Despite the complexities of the mathematics the HydraProbe performs, the duty cycle including the warmup time, the processing of the signals, and the mathematical operations being performed by the microprocessor takes under two seconds. The user can connect the sensor to a logger or other reading device with Plug-&-Play ease while maintaining a high level of confidence in the data.

5 Measurements, Parameters, and Data Interpretation

5.1 Soil Moisture

5.1.1 Soil Moisture Units

The HydraProbe provides accurate soil moisture measurements in units of water fraction by volume (wfv or m^3m^{-3}) and is symbolized with the Greek letter theta "θ". Soil moisture is parameter "H" on the digital HydraProbe. Multiplying the water fraction by volume by 100 will equal the volumetric percent of water in soil. For example, a water content of 0.20 wfv means that a 1000 cubic centimeters soil sample contains 200 cubic centimeters water or 20% by volume. Full saturation (all the soil pore spaces filled with water) occurs typically between 0.35-0.55 wfv for mineral soil and is quite soil dependent.

There are a number of other units used to measure soil moisture. They include % water by weight, % available (to a crop), and inches of water to inches of soil, % of saturation, and tension (or pressure). It is important to have an understanding of the different water to express soil moisture and the conversion between units can be highly soil dependent.

Because the bulk density of soil is so highly variable, soil moisture is most meaningful as a water fraction by volume or volumetric percent. If weight percent were used, it would represent a different amount of water from one soil texture to the next and it would be very difficult to make comparisons. .

5.2 Soil Moisture Measurement Considerations for Irrigation

Soil moisture values are particularly important for irrigation optimization and to the health of a crop. There are two different approaches for determining an irrigation schedule from soil moisture data, the fill point method and the mass balance method. Other common irrigation scheduling methods that do not include soil moisture sensors use evapotranspiration (ET). ET is the rate of water leaving the soil by the combination of direct evaporation of water out of the soil and the amount of water being transpired by the crop. ET can be thought of as negative precipitation. ET is determined from calculations based on metrological conditions such as air temperature , solar radiation and wind. The most common ET irrigation scheduling determination is called the Penman-Monteith Method publish in FAO-56 1998 Food and Agriculture Organization of the UN. The FAO 56 method is also a mass balance approach where the amount of water that is leaving the soil can be determined and matched by the irrigation schedule. In practice to ensure the success of the crop, ET methods in combination with soil sensor data can be used by irrigators to best manage irrigation.

5.2.1 Fill Point Irrigation Scheduling

The fill point method is qualitative in that the irrigator looks at changes in soil moisture. With experience and knowledge of the crop, an irrigation schedule can be developed to fill the soil back up to a fill point. The fill point is an optimal soil moisture value that is related to the soil's field capacity. The fill point for a particular sensor is determined by looking at soil moisture data containing a number of irrigation events. This can be an effective and simple way to optimize irrigation. Because it is qualitative, accuracy of the soil moisture sensor is less important because the fill point is determined by looking at changes in soil moisture and not the actual soil moisture itself. This in some ways can be more efficient because lower cost soil moisture sensors can be used without calibration. While the fill point method can be easy to implement and is widely used for many crops, the mass balance method however can better optimize the irrigation, better control salinity build up, and minimize the negative impacts of over irrigation.

5.2.2 Mass Balance Irrigation Scheduling

The mass balance method or sometimes called scientific irrigation scheduling is an irrigation schedule determined by calculating how much the water is needed based on accurate soil moisture readings and from the soil properties. Equations [5.1], [5.2] and [5.3] can help to determine how much water to apply. The following are terms commonly used in soil hydrology:

- Soil Saturation, (θ_{SAT}) refers to the situation where all the soil pores are filled with water. This occurs below the water table and in the unsaturated zone above the water table after a heavy rain or irrigation event. After the rain event, the soil moisture (above the water table) will decrease from saturation to field capacity.
- Field Capacity (θ_{FC} in equations below) refers to the amount of water left behind in soil after gravity drains saturated soil. Field capacity is an important hydrological parameter for soil because it can help determine the flow direction. Soil moisture values above field capacity will drain downward recharging the aquifer/water table. Also, if the soil moisture content is over field capacity, surface run off and erosion can occur. If the soil moisture is below field capacity, the water will stay suspended in between the soil particles from capillary forces. The water will basically only move upward at this point from evaporation or evapotranspiration.
- Permanent Wilting Point (θ_{PWP}) in equations below) refers to the amount of water in soil that is unavailable to the plant.
- The Allowable Depletion (θ_{AD} in the equations below) is calculated by equation [5.1]. The allowable depletion represents the amount of soil moisture that can be removed by the crop from the soil before the crop begins to stress.
- Lower soil moisture Limit (θ_{LL} from [5.3]) is the soil moisture value below which the crop will become stressed because it will have insufficient water. When the lower limit is reached, it is time to irrigate.
- The Maximum Allowable Depletion (MAD) is the fraction of the available water that is 100% available to the crop. MAD can depend on soil or crop type.
- Available Water Capacity (θ_{AWC}) is the amount of water in the soil that is available to the plant.

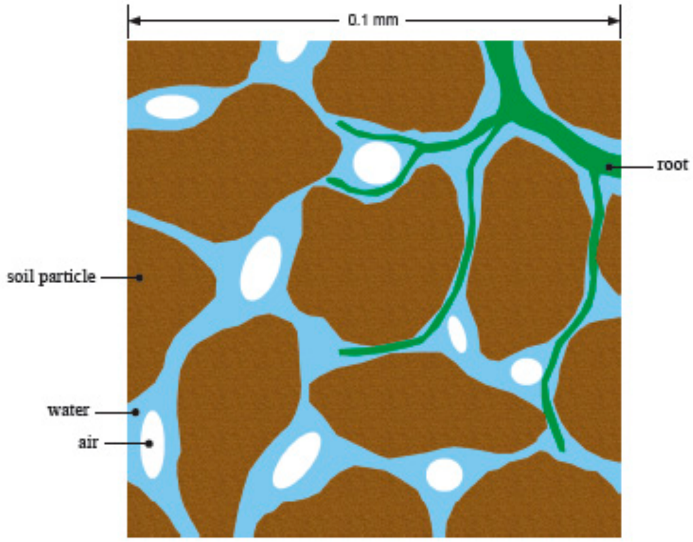


Figure 5.1. Unsaturated soil is composed of solid particles, organic material and pores. The pore space will contain air and water.

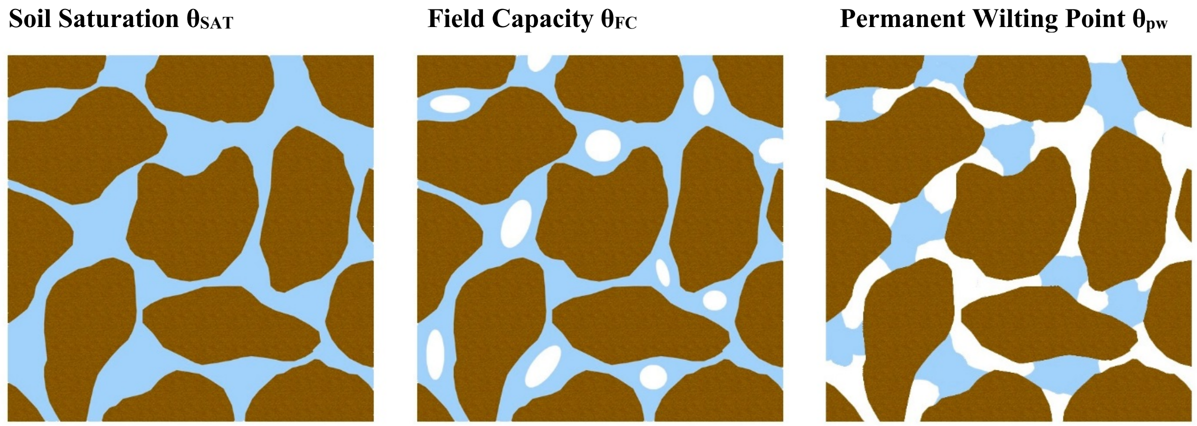
The lower soil moisture limit is a very important value because dropping to or below this value will affect the health of the crops. Equations 5.1, 5.2, and 5.3 and the example below show how to calculate the lower soil moisture limit and the soil moisture target for irrigation optimization.

$$\theta_{AD} = (\theta_{FC} - \theta_{PWP}) \text{ x MAD} \qquad [5.1]$$

$$\theta_{AWC} = \theta_{FC} - \theta_{PWP} \qquad [5.2]$$

$$\theta_{LL} = \theta_{FC} - \theta_{AD} \qquad [5.3]$$

Figure 5.3 can be used to help determine the soil moisture targets based on soil texture. Soil texture is determined by the percentages of sand, silt, and clay using figure 5.4. Note that figures 5.3, and 5.4 and table 5.1 general trends. The actual MAD and field capacity and Permanent wilting point may vary with region, soil morphologies, and the crop.



Soil Saturation θ_{SAT} **Field Capacity θ_{FC}** **Permanent Wilting Point θ_{pw}**

Figure 5.2. Hydrological conditions of soil.

Crop	**Maximum Allowable Depletion (MAD)**	**Effective Root Depth (Inches)**
Grass	50%	7
Table beet	50%	18
Sweet Corn	50%	24
Strawberry	50%	12
Winter Squash	60%	36
Peppermint	35%	24
Potatoes	35%	35
Orchard Apples	75%	36
Leafy Green	40%	18
Cucumber	50%	24
Green Beans	50%	18
Cauliflower	40%	18
Carrot	50%	18
Blue Berries	50%	18

Table 5.1, Typical Maximum Allowable Depletion based on crop. Effective Root Zone Depth. Taken from Smesrud 1998. Note that these values may be region or crop type specific.

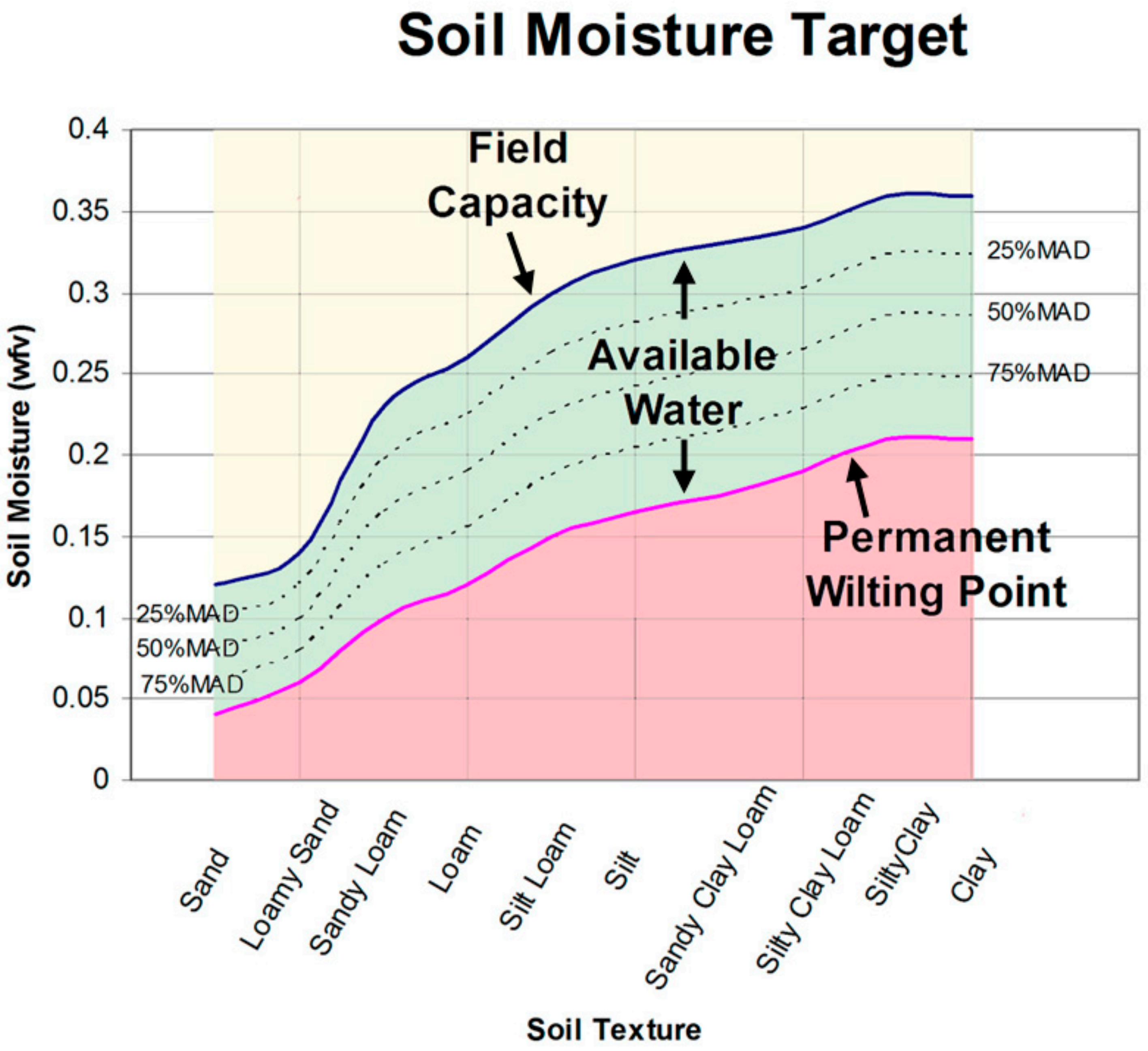


Figure 5.3 soil textures and the available water.

Texture	Clay	Silty Clay	Clay Loam	Loam	Sandy Loam	Loamy Sand	Sand
MAD	0.3	0.4	0.4	0.5	0.5	0.5	0.6

Table 5.2, Maximum allowable depletions for different soil textures.

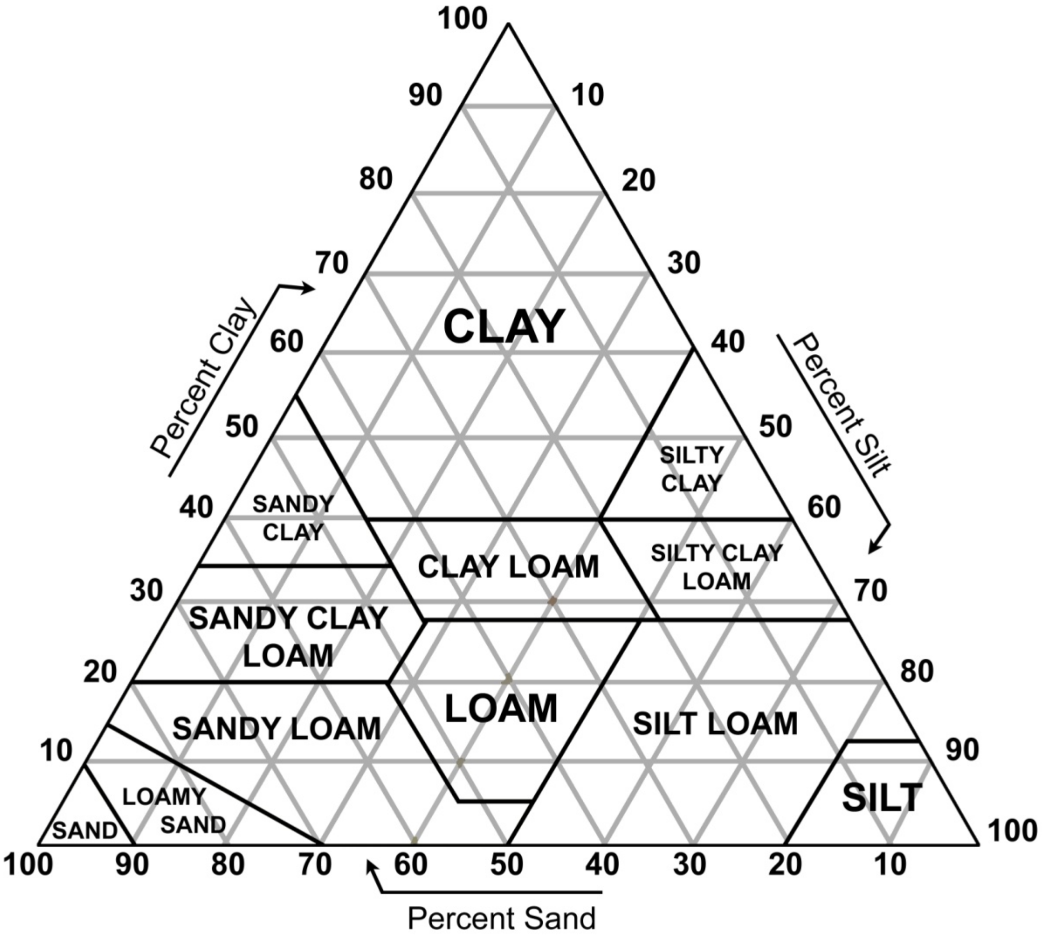


Figure 5.4. Soil textural triangle.

Example of an Irrigation scheduling based on soil moisture values:
How much water should be applied? The soil is a silt, the MAD is 50%, and the soil moisture is 20% throughout the root zone which is down to 24 cm. The sprinkler is 75% efficient.

Answer:
From tables 5.1 and 5.2 the MAD = 0.5, From Figure 5.3 (or a soil surrey) θ_{PWP} = 16% and the field capacity, θ_{FC} is 32%. Therefor using equations 5.1 to 5.3, the optimal soil moisture is 24 to 32%. $\theta_{FC} - \theta$ = 32% - 16% = 16%. Therefor the soil needs to be irrigated to increase the soil moisture by 16% down to 24 cm, 16% X 24 cm = 3.8 cm of water need to be added. If the sprinkler is 75% efficient than 3.8 cm/0.75 = 5.12 cm of water should be applied. Note the rate of water coming out of the sprinkler should not exceed the infiltration rate of the soil and the run time of the sprinklers would depend on the specification of the sprinkler.

5.2.3 Soil Moisture Calibrations

The soil moisture calibration is an estimation of the soil moisture from a mathematical equation that contains the real dielectric permittivity (Topp 1980). The HydraProbe has 3 factory calibrations to choose from and custom calibration features in case a specific site calibration is necessary. The factory GENERAL or GEN calibration is the best general purpose calibration available and is the default calibration on the HydraProbe's firmware. The GEN calibration is based on research conducted by the US Department of Agriculture, Agricultural Research Service (Seyfried 2005) and is the standard calibration for the US Department of Agriculture's SNOTEL, SCAN networks and NOAA's Climate Reference Network. The factory default GEN calibration is equation [A2] in the appendix C where A = 0.109, B = -0.179 and ε_r is the raw real dielectric permittivity.

It is recommended to keep the HydraProbe set to the default calibration. If the soil requires a custom calibration or if further validation of the calibration is needed, the real dielectric permittivity (Parameter 6 on "aM!, aC!) can be logged until a new calibration can be developed. See appendix C for more information about calibration validation and development.

5.2.3.1 Other Factory Calibration

In addition to the factory General Calibration, the HydraProbe has an Organic soil calibration, O, and a rockwool calibration, R. See appendix C for information on the calibration settings. The user may want to validate the factory calibration to make sure it has suitable accuracy for a specific soil. If the factory calibration is off, the user may develop a new soil specific calibration. A new soil specific calibration can be developed through gravimetric analyses. It is recommended to log the real dielectric permittivity (Parameter 6 on "aM!, aC!). If a new calibration is developed, the historical data set can be recalibrated if the data set contains the raw real dielectric permittivity value. Individual sensors do not need their own calibration. Because all HydraProbes measure the same way with extremely low variability from sensor to sensor, the same calibration formula can be applied to any HydraProbe.

5.3 Soil Salinity and the HydraProbe EC Parameters

Soil bulk electrical conductivity (EC) is important for assessing the salinity of the soil and soil pore water. Temperature corrected EC is the second parameter in "aM!,aC!" And the raw un-corrected electrical conductivity and is the 5th parameter in "aM!, aC!" in the SDI-12 parameter sets. Electrical conductivity also referred to as specific conductance and is measured in Siemens/meter (S/m). Siemens is inversely related to resistance in Ohms (Siemens = 1/Ohms) and represents a materials ability to conduct an electric current. There are a number of related units for EC. Table 5.3 below summarizes the unit conversion.

The electrical conductivity parameters are calculated from the imaginary dielectric permittivity by rearranging equation [4.2]. The calculation of EC is based on the assumption that the molecular relaxations are negligible or very small. This assumption provides a good approximation for EC in sandy or silty soils where molecular relaxations are minimal. The approximation of EC from the imaginary permittivity in clay rich soils however will be less accurate due to the possible presents of molecular relaxations. While the accuracy of the EC parameters in soil are highly soil dependent, the HydraProbe's EC measurements in slurry extracts, water samples, and aqueous solutions will be accurate (<+/- 1 to 5%) up to 0.3 S/m. Because EC can be sensitive to changes in temperature, a temperature correction is provided.

Convert to → Convert From ↓	S/m	dS/m	mS/m	µS/m	S/cm	dS/cm	mS/cm	µS/cm
S/m	1	10	1000	1E6	0.01	0.1	10	10000
dS/m	0.1	1	100	1E5	.001	0.01	1	1000
mS/m	0.001	0.01	1	1000	1E-5	0.0001	0.01	10
µS/m	1E-6	1E-5	0.001	1	1E-8	1E-7	0.00001	0.01
S/cm	100	1000	1E5	1E8	1	10	1000	1E6
dS/cm	10	100	10000	1E7	0.1	1	100	1E5
mS/cm	0.1	1	100	100000	0.001	0.01	1	1000
µS/cm	0.0001	0.001	0.1	100	1E-6	1E-5	0.001	1

Table 5.3. Convert EC units on the left to the EC units on top by multiplying by the factor. For example 2 dS/m X 0.1 = 0.2 S/m

5.3.1 Soil Salinity

The soil salinity is salt build up in the soil and can be caused by poor drainage, poor irrigation water quality and salt water intrusion in coastal areas. Salt or specifically the dissolve ions in solution are the primary component of the soil matrix that conducts electricity. While the EC parameter is highly dependent on the level of soil salinity, it will also rise and fall with soil moisture. The buildup of salinity in the soil is typically not beneficial to crops, grasses or the microbial community in the soil. The soil salinity may also affect the soil hydrology. Plant diseases and pathogens, and reduced crop yields or even crop failures may occur from excessive soil salinity therefore, monitoring the soil salinity will help ensure the health of crops.

Soil salinity is dissolved salts such as sodium chloride, calcium chloride and magnesium chloride. The salts may not only be chlorides but carbonates as well. Fertilizers such as nitrates do not have a strong conductivities therefore the EC measured in a soil is primarily going to be attributed to the sodium and soil moisture.

5.3.2 Bulk EC versus Pore Water EC

The EC in soil is more complex than it is in a water sample and can be difficult and confusing to interpret. The bulk soil electrical conductivity σ_b is the EC of the undisturbed soil/water/air matrix and is the parameter measured by the HydraProbe. It is important not to confuse the bulk EC with the soil pore water EC, σ_p. The soil pore water EC is the electrical conductivity of the water in the pore spaces of the soil. Because the pore water EC may be difficult to directly measure, a soil slurry can be prepared by taking one part dry soil and two parts distilled water and measuring the EC of the water extract from the slurry. The EC of the extract (EC_e or σ_e) is the parameter traditionally found in soil science or agriculture literature because is relativity easy to measure and provides an "apples to apples" comparison of soil salinity conditions. The HydraProbe can be used to measure the EC_e if properly placed in the watery extract.

5.3.3 Bulk EC and EC Pathways in Soil

Soil is a matrix that is basically composed of solid material, water in the pore spaces and air. In situ soil sensors (soil sensors in the ground) measure the dc bulk electrical conductivity (σ_b) which is the electrical conductivity of the soil/water/air matrix combined. Figure [5.3] shows the three pathways the electrical conductivity can propagate in soil. The bulk density, the porosity, the tortuosity, the water content, and the dissolved ion concentration working in concert with the different pathways, dramatically influences the bulk electrical conductivity of a soil.

Pathway 1 is the electrical pathway that goes from water to the soil and back through the water again. The electrical conductivity contribution of pathway 1 is a function of the conductivity of the water and soil. As water increases, the electrical conduit of pathway 1 increases which may increase the electrical conductivity of the soil as a whole.

Pathway 2 is the pathway that is attributed to the electrical conductivity of the just the water in the soil pores. Increasing the dissolved salts will increase the conductivity of pathway 2; however, like pathway 1, increases in the soil water content will increase the size of the pathway thus increasing the overall bulk electrical conductivity. That is to say, that there are two factors influencing the electrical conductivity of pathway 2, namely the dissolved salt concentration and the size of the pathway attributed to the amount of water in the soil.

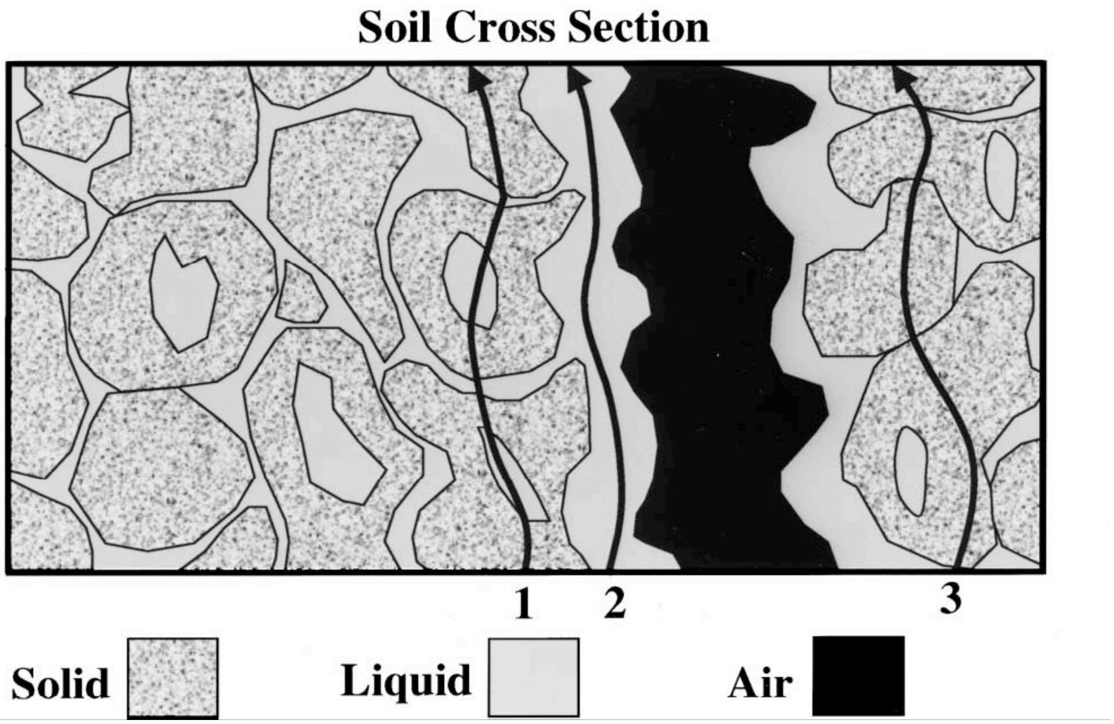


Figure 5.3 Three Pathways of electric conductivity in soil matrix. 1, water to solid, 2 soil moisture, 3 solid. Taken from Corwin et al. (2003).

Pathway 3 is the electrical conductivity of the soil particles. Like the other pathways, the contribution of pathway 3 in influenced by a number of factors that include bulk density, soil type, oxidation/reduction reactions and translocation of ions.

The bulk EC measurements provided by the HydraProbe the electrical conductivity of the dynamic soil matrix as a whole which is the sum of the electrical conductivities from all of the different pathways. No in situ soil sensor can directly distinguish the difference between the different pathways nor can any conventional in situ soil sensor distinguish the difference between sodium chloride and any other number of ions in the solution that all have some influence on electrical conductivity of the soil/water/air matrix.

5.3.4 Application of Bulk EC Measurements

While it is difficult to make apples to apples comparisons with the bulk EC, the user can identify certain benchmarks. For example, if the soil moisture reaches a threshold such as field capacity, the bulk EC can be recorded at that threshold to make comparison. This would be useful in situations where soil salinity is a problem and monitoring is necessary.

In some circumstance, the pore water EC can be estimated from knowledge about the dielectric permittivity of the soil (Hilhorst 1999). Equation [5.6] allows the user to make comparable pore water EC estimates from bulk EC measurement in most soils;

$$\sigma_p = \frac{\varepsilon_{rp}\sigma_b}{\varepsilon_{rb} - \varepsilon_{rb\_O}} \qquad [5.6]$$

Where σ_p is the pore water EC, ε_{rp} is the real dielectric content of water (≈80), σ_b is the bulk EC measured with the HydraProbe in soil, and ε_{rb} is the real dielectric permittivity of the soil measure with the HydraProbe. ε_{rb_O} is an offset, and 3.4 can be used as the offset for most inorganic soils.

5.3.5 Total Dissolved Solids (TDS)

The total dissolved solids (in g/L or ppm) of a water sample can be estimated from the electrical conductivity. To assess the TDS in soil you need to first obtain the pore water EC from either equation 5.6 or from a slurry water extract. TDS calculated from EC may be less meaningful for soil pore water because there could be other constituents dissolved in the water that do not contribute to the EC of the water such and nitrates, phosphates and other factors that exist in soil but do not occur in a water sample. Another source of error with TDS estimation from EC is the fact that different salts have different EC strengths and solubility. Calcium Chloride will be under represented in a TDS calculation because it has a lower EC value and will fall out of solution much quicker than sodium chloride (McBride 1994). Despite the challenges associated with estimating TDS from EC, equation [5.7] can be used to with the HydraProbe's EC measurements to estimate the TDS in a water or slurry extract sample.

$$\text{Water Salinity (g/L)} \approx \text{EC (S/m)} \times 6.4 \qquad [5.7]$$

To verify the TDS estimation from EC or perhaps correct equation [5.7] for a specific water sample, the user can dry down a water sample and obtain the weight of the material left behind for a true gravimetric measurement of TDS. Note that if the HydraProbe EC measurement is used to estimate the TDS, the stainless steel tines need to be completely submerged in the water sample or the water extract of the slurry.

A. Appendix – HydraProbe Basic SDI-12 Communication (2.9 Firmware)[1]

Note: It is recommended to keep the HydraProbe on its defaults and use only the “aM!” or “aC!” to retrieve data.

SDI-12 (serial data interface at 1200 baud) communications protocol allows compatible devices to communicate with each other. More information about SDI-12 can be found at http://www.sdi-12.org/.

SDI-12 Wiring Information

The SDI-12 HydraProbe has three wires. The default address is “0”.

Wiring and Power for SDI-12	
Power Requirements	9 to 20 VDC (12VDC Ideal)
Red Wire	+Volts Power Input
Black Wire	Ground
Blue Wire	SDI-12 Data Signal
Power Consumption	<1 mA Idle, 10 mA for 2s Active

Table A1. Digital SDI-12 HydraProbe Information.

Addressing an SDI-12 Sensor

It is important to note that each SDI-12 sensor must have its own unique address. The default address for the HydraProbe is “0”. Use SDI-12 “Transparent Mode” to issues commands.

Command Feature	**SDI-12 Command**
Change Address	aAb!
Get Probe’s serial number and ID	aI!
Take a Reading	aM! Follow by aD0!, aD1!,aD2!

Table A2. Common SDI-12 Commands

Common Measurement Command sets for aM! And aC!			
Parameter ordering	Parameter	Unit	Letter designation (See table)
Parameter 1	Soil Moisture	Water fraction by volume	H
Parameter 2	Bulk Electrical Conductivity with Temperature Correction	S/m	J
Parameter 3	Temperature	C	F
Parameter 4	Temperature	F	G
Parameter 5	Bulk Electrical Conductivity	S/m	O
Parameter 6	Real Dielectric Permittivity	Unitless	K
Parameter 7	Imaginary Dielectric Permittivity	Unitless	M

Table A3. Common Commands.

---

[1] 2.8 and 2.7 firmware versions have a different array of C commands. Contact Stevens for more information.

A.2 Advanced SDI-12 Communication

Note that it is recommended to keep the HydraProbe on its default setting for everything except changing the address.

Changing SDI-12 Parameter Sets

In Transparent Mode, the "aM!"parameter set can be changed from its defaults to an alternate parameter set or set to any parameter set the user wants; however, it is recommended to keep the "aM!" Parameter set on the defaults because it contains all of the parameters for most applications. The example below, show the alteration of the "aM!" parameter set. The address of the probe is 1.

A) Type "`1M!`". The response should be ***10029***. This means that a sensor with an address of 1 will take 2 seconds to return 9 parameters with one or more D commands.

B) Type "`1XM!`". The response should be ***1HJFGOKMLN***. This means that the sensor with address 1 has been set to the first default Parameter set. The letters correspond to parameters that the HydraProbe is capable of measuring in this set. Most users are only interested in H, J, F, and G. If the probe has another parameter set, you may wish reset the probe to the first parameter set by typing "**`1XM=0!`**" or the user may type "**1XM=GH!'** to only measure soil moisture and temperature.

Stevens HydraProbe SDI-12 Command Specification

For Firmware Versions 2.7 and Later

The Stevens HydraProbe is fully compliant with the SDI-12 Version 1.2 command specification. As such, responses to many of the standard commands are not detailed here.

Measurement Commands

The HydraProbe can return any of 21 values, or parameters, as they are called in SDI-12 terminology. The following table lists the values and letter used to refer to them:

Selector	SDI-12 Parameters Description	Units
A	Voltage 1	Volts
B	Voltage 2	Volts
C	Voltage 3	Volts
D	Voltage 4	Volts
E	Voltage 5	Volts
F	Soil Temperature	Celsius
G	Soil Temperature	Fahrenheit
H	Soil Moisture	Water fraction by Volume (wfv)
I	Dielectric Loss Tangent	-
J	Soil Conductivity (temp. corrected)	Siemens / Meter (S/m)
K	Real Dielectric Permittivity	-
L	Real Dielectric Permittivity (temp. corrected)	-
M	Imaginary Dielectric Permittivity	-
N	Imaginary Dielectric Permittivity (temp. Corrected)	-
O	Soil Conductivity	Siemens / Meter
P	Diode temperature	Celsius
R	ADC Reading 1	-
S	ADC Reading 2	-
T	ADC Reading 3	-
U	ADC Reading 4	-
V	ADC Reading 5	-

Table A4 – Parameter Selectors

The HydraProbe responds to the start measurement command aM!, as well as 5 additional measurement commands, aM1! - aM5!. Each measurement command responds with a different subset of the total parameter set. The start measurement command, aM!, returns a set of readings that is user-configurable through the use of SDI-12 extended commands. This feature allows any of the 21 parameters to be accessed by older SDI-12 loggers, many of which do not support more than one measurement command. Instructions for configuring this reading set can be found in the *Extended Commands* section of this appendix.

The following measurement set descriptions detail the parameters returned by each of the measurement commands. For the aM! command, only the default reading set is listed.

All data transmitted using SDI-12 must be printable ASCII characters. The first character of any command or response is the address. The lowercase 'a' at the beginning of each command represents the address character.

SDI-12 Measurement Sets									
Command	**Response Parameters – Refer to Table 1**								
	P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**
aM!	H	J	F	G	O	K	M	L	N
aM1!	F	G	I						
aM2!	F	G	H	O	J	I			
aM3!	K	L	M	N	O	P			
aM4!	A	B	C	D	E				
aM5!	R	S	T	U	V				

Table A4 – Measurement Command Sets

SDI-12 Extended Command Summary

The HydraProbe implements a number of SDI-12 extended commands. The following table lists all of the supported extended commands and a brief description:

SDI-12 Extended Commands	
Command	**Description**
aI!	Get Probe serial number and information
aAb!	Changes Probe's address from. b is new address
aXS<soil>!	Set soil type
aXM!	Get the current reading measure set
aXM=0!	Set the factory measure set to set 0
aXM=1!	Set the factory measure set to set 1
aXM=2!	Set the factory measure set to set 2
aXM=3!	Set the factory measure set to set 3
aXM=4!	Set the factory measure set to set 4
aXM=5!	Set the factory measure set to set 5
aXM=<set>!	Set custom default measure set
aXR!	Reset probe to defaults
aV!	Factory Verification

Table A4 – SDI-12 Extended Commands

SDI-12 C Command Measurement Sets									
Command	**Response Parameters – Refer to Table 1**								
	P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**
aC!	H	J	F	G	O	K	M	L	N
aC1!	F	G	I						
aC2!	F	G	H	O	J	I			
aC3!	K	L	M	N	O	P			
aC4!	A	B	C	D	E				
aC5!	R	S	T	U	V				

Table A5-SDI-12 C Commands

<set>	String of 1-9 ASCII characters that specify the measurements taken by the standard measurement command (aM!). Valid values are any of the letters A-V. The default measurement set is *HJFGOKMLN*.
<float>	Decimal number, optionally using a form of scientific notation. Ex: "+23.54, 0.001, -123.0E5, 45.E-3"
<id-string>	After sending the I command "aI!" the probes returns an identification string containing the manufacturer, model number, version and manufacturer specific data. In this case the specific data is the soil type and serial number. Example:

```
012STEVENSW0936402.9STGSN00123456
```

B. Appendix - RS-485 Communication

Note: It is recommended to keep the HydraProbe on its defaults and use only the "addrTR" <CR><LF> followed by "addrT0"<CR><LF> to take a reading and retrieve data.

The RS-485 HydraProbe has 4 wires: a ground wire, a +12 volt power wire and 2 data wires. The RS-485 HydraProbe communicates through two data wires and can be wired into a RS-485 port on a logger. They can be connected to a terminal assembly like the SDI-12 version, but with four wires instead of three. The advantage RS-485 has over the SDI-12 version is that the RS-485 version's cable can run over 3000 feet. The disadvantage is that it draws more power.

The COM port setting are as follows

- COM Port should be set to correspond with actual port on the PC where the communications cable is plugged in. For instance COM1, COM2, etc.
- Baud rate should be set to 9600
- Data bits should be set to 8
- Parity should be set to none.
- Stop bits should be set to 1 (one).
- Flow control should be set to none.

In addition, these setting will make the program easier to use. In a terminal emulator these settings are found in the setup options:

- Select "**`Send line ends with line feeds`**". All commands sent to an RS-485 version of the HydraProbe must end with a "Carriage Return" "Line Feed" pair.
- Select "**`Echo typed characters locally`**". The HydraProbe does not echo any commands. Checking this enables you to see what you have typed.

Wiring and power for RS484	
Power Requirements	**9 to 20 VDC (12VDC Ideal)**
Red Wire	+Volts Power Input
Black Wire	Ground
Green Wire	Data Signal A -inverting signal (-)
White Wire	Data Signal B non-inverting signal (+)
Baud Rate	9600 8N1
Power Consumption	<10 mA Idle 30 mA Active

Table B1. Digital RS-485 HydraProbe Information.

Stevens HydraProbe RS-485 Command Specification

For Use with Firmware Version 2.9, 3.0 and Later

Command Format

`AAACC<CR><LF>`	Execute
`AAACC=?<CR><LF>`	Query current setting
`AAACC=XXX…<CR><LF>`	Assign new value

AAA: 3 byte address
ASCII characters, 0-9 A-Z a-z
Wildcard character: "/"
Broadcast address: "///"

CC: 2 byte command

XXX…: Command data. See command info for specific requirements.

<CR>: Carriage return character (ASCII 13)

<LF>: Linefeed character (ASCII 10)

Other Grammar

<d>: Digit, ASCII '0' through ASCII '9'

<a>: ASCII 'A' through ASCII 'D', used for custom water constant

<serial>: Serial number, 8 digits. <d><d><d><d><d><d><d><d>

<firmware>: Firmware, 3 or 4 bytes, formatted like "2.7" or "R2.7" or "2s7"

<text>: Printable ASCII text

<float>: Decimal number, optionally using a form of scientific notation.
Ex: "+23.54, 0.001, -123.0E5, 45.E-3"

<readings>: Comma-delimited string of floats. Ex: "+23.54,-42.532,+2342.12"

HydraProbe Specific RS-485 Commands

Information Commands

Serial Number

Description: Returns the factory serial number.
Access Level: Read only
Read Addresses: Broadcast, Exact
Read Command: `<addr>SN=?<CR><LF>`
Read Response: `<addr><serial><CR><LF>`

Firmware Version

Description: Returns the firmware version number.
Access Level: Read only
Read Addresses: Broadcast, Exact
Read Command: `<addr>FV=?<CR><LF>`
Read Response: `<addr><firmware><CR><LF>`

Standard Configuration Commands

Address

Description: Gets/sets the probe address.
Access Level: Read/Write
Read Addresses: Broadcast, Exact
Read Command: `<addr>AD=?<CR><LF>`
Read Response: `<addr><CR><LF>`
Write Addresses: Exact
Write Command: `<addr>AD=<serial><new_addr><CR><LF>`
Write Response: `<new_addr><CR><LF>`

Advanced Configuration Commands

Location

Description: Gets/sets the probe location.
Access Level: Read/Write
Read Addresses: Broadcast, Exact
Read Command: `<addr>LO=?<CR><LF>`
Read Response: `<addr><text><CR><LF>`
Write Addresses: Exact
Write Command: `<addr>LO=<text><CR><LF>`
Write Response: `<addr><text><CR><LF>`

Description

Description: Gets/sets the probe description.
Access Level: Read/Write
Read Addresses: Broadcast, Exact
Read Command: `<addr>DS=?<CR><LF>`
Read Response: `<addr><text><CR><LF>`
Write Addresses: Exact
Write Command: `<addr>DS=<text><CR><LF>`
Write Response: `<addr><text><CR><LF>`

Debug Commands

Probe Enable

Description:	Gets/sets whether the probe circuitry is enabled.
Access Level:	Read/Write
Read Addresses:	Broadcast, Exact
Read Command:	`<addr>PE=?<CR><LF>`
Read Response:	`<addr><bool><CR><LF>`
Write Addresses:	Exact
Write Command:	`<addr>PE=<bool><CR><LF>`
Write Response:	`<addr><bool><CR><LF>`

Measurement Commands

Take Reading

Description:	Instructs a probe or group of probes to take a reading sample.
Access Level:	Execute
Execute Addresses:	Broadcast, Exact, Wildcard
Execute Command:	`<addr>TR<CR><LF>`
Execute Response:	`(none)`

Transmit Reading Set

Description:	Instructs a probe to transmit a specific reading set.
Access Level:	Execute
Execute Addresses:	Broadcast, Exact
Execute Command:	`<addr>T<set><CR><LF>`
Execute Response:	`<addr><readings><CR><LF>`

RS-485 TRANSMIT SETS

```
(tc) indicates values that have been temperature corrected

T0 - Transmit Set 0:
      H) Moisture
      J) Soil Electrical Conductivity (tc)
      F) Temp C
      G) Temp F
      O) Soil Electrical Conductivity
      K) Real Dielectric Permittivity
      M) Imag Dielectric Permittivity
      L) Real Dielectric Permittivity (tc)
      N) Imag Dielectric Permittivity (tc)
```

```
T1 - Transmit Set 1:
      F) Temp C
      G) Temp F
      I) Loss Tangent

T2 - Transmit Set 2:
      F) Temp C
      G) Temp F
      H) Moisture
      O) Electrical Conductivity
      J) Electrical Conductivity (tc)
      I) Loss Tangent

T3 - Transmit Set 3:
      K) Real Dielectric Permittivity
      L) Real Dielectric Permittivity (tc)
      M) Imag Dielectric Permittivity
      N) Imag Dielectric Permittivity (tc)
      O) Soil Electrical Conductivity
      P) Diode Temperature
      Q) Blank



T4 - Transmit Set 4:
   A) V1 (volts)
   B) V2 (volts)
   C) V3 (volts)
   D) V4 (volts)
   E) V5 (volts)

T5 - Transmit Set 5:
    R) V1 raw adc
    S) V2 raw adc
    T) V3 raw adc
    U) V4 raw adc
    V) V5 raw adc
```

C. Appendix – Custom Calibration Programming

The Stevens HydraProbe has a total of four factory calibrations built into the firmware for various soil conditions. While these four calibrations will accommodate most soils, sometimes the user will need to create their own calibration and have the HydraProbe output the results using the custom calibration.

The default soil moisture calibration is called GENERAL or GEN. The GENERAL soil calibration has been heavily tested, widely used in many soil types, and is suitable for most agricultural and mineral soils consisting of sand, silt and clay. It is recommended to keep the HydraProbe set to the GENERAL soil calibration. Other factory calibrations include O (organic soil), and R (Rock wool). A custom calibration can be entered using either CUS 1 or KUS 2 modes. In CUS1 Mode, the user can enter four coefficients for a 3rd order polynomial and in KUS 2 Mode, the user may select two coefficients for a semi-linear square root formula.

The calibrations curves are polynomials that calculate the soil moisture from the real dielectric permittivity. Soil moisture calibrations will typically take one of two different general formulas. There are two general formulas will mathematically have the appearance of equation [A1] or [A2]

$$\theta = A + B\varepsilon_r + C\varepsilon_r^2 + D\varepsilon_r^3 \qquad [A1]$$

$$\theta = A\sqrt{\varepsilon_r} + B \qquad [A2]$$

Where θ is moisture, ε_r is the real dielectric permittivity, and A, B, C, and D are coefficients. This procedure will allow the user to select their A, B, C, and D values for equations [A1] and [A2].

A custom calibration or a statistical data validation for an existing soil moisture calibration is labor intensive. The user will need to experimentally solve equation [1] or [2] from data obtained from the soil. Gravimetric soil moisture values will need to be obtained for a range of soil moisture conditions. The volumetric soil moisture value will need to be calculated from the gravimetric soil moisture values. Gravimetric soil moistures need to be converted to volumetric values with either the dry bulk density of the soil or the know volume of the soil sample. The user will then need to mathematically curve-fit one of the two polynomials using the real dielectric permittivity and the volumetric soil moisture values for the range. The relationship between volumetric soil moisture and gravimetric soil moisture is described by equation [A3].

$$\theta_v = \theta_g \frac{\rho_b}{\rho_w} \qquad [A3]$$

The coefficients for equations [A1] and [A2] can be programmed into the firmware of the digital HydraProbe. Below is a procedure for programming a custom calibration into an RS485 and SDI-12 HydraProbe

Development of a new calibration involves collecting soil samples and drying them down in a gravimetric analyses. Great care must be taken to obtain data points that are representative of the field conditions. It is recommended to first post process the new calibration and compare it to the General factory calibration for a period of time before programming it onto the sensor. It is also recommended to log the real dielectric permittivity (SDI-12 parameter K or #6 on T0 for RS485) so that new calibrations can be applied to the data set.

Calibration	Application	Formula
G	Most all Soils (probe Default)	A2
O	Highly organic soils, Peat, Fine compost	A1, C = 0 and D = 0
R	Rock Wool	A1, C = 0 and D = 0
C	Custom 1	A1
K	Kustom 2	A2

Table C1. Factory calibration modes.

Calibration	Formula	A	B	C	D
G	A2	0.109	-0.179	NA	NA
O	A1,	-0.02134	0.013148	0	0
R	A1,	-0.02134	0.013148	0	0
C (CUS1)	A1	0	0.0224	-0.00047	0.00000514
K (KUS2)	A2	0.109	-0.179	NA	NA

Table C2. Coefficients for factory calibrations.

Note that the General (G) calibration was published in the Vadose Zone Journal (Seyfried 2005), The default coefficients for Custom 1 are a general soil moisture calibration published in the Soil Science Society of America Journal (Logsdon 2010). The O and R calibration coefficients are based on gravimetric analysis of common samples.

Custom Calibration Settings Procedure for the RS485 HydraProbe

Note: It is recommended to first post process a new calibration for a period of time before programming the coefficients into sensors. It is also recommended to log the real dielectric permittivity (Parameter K on T0) so that a data set can be recalibrated if needed.

Soil Type

Description:	Gets/sets the probe soil type.
Access Level:	Read/Write
Read Addresses:	Broadcast, Exact
Read Command:	`<addr>ST=?<CR><LF>`
Read Response:	`<addr><CR><LF>`
Write Addresses:	Broadcast, Exact, Wildcard
Write Command:	`<addr>ST=<soil><CR><LF>  Where <Soil> can be G, O, R, C or K`
Write Response:	`<addr><soil><CR><LF>` (No response for wildcard address)

Command Description	**RS485 Command**
Get current calibration	<addr>ST=?<CR><LF>
Switches the Probe to Custom 1 calibration	<addr>ST=C<CR><LF>
Switches the Probe to Kustom 2 calibration	<addr>ST=K<CR><LF>
Switches the Probe to the Organic Soil calibration	<addr>ST=O<CR><LF>
Switches the Probe to the Rockwool calibration	<addr>ST=R<CR><LF>
Switches the Probe to General soil calibration	<addr>ST=G<CR><LF>
Sets the A coefficient	<addr>XA=<value><CR><LF>
Sets the B coefficient	<addr>XB=<value><CR><LF>
Sets the C coefficient	<addr>XC=<value><CR><LF>
Sets the D coefficient	<addr>XD=<value><CR><LF>
Verifies A coefficient	<addr>XA?CR><LF>

Table C3. RS485 Commands for setting soil moisture calibration. <CR> means carriage return, <LF> means line feed, <addr> means address of probe. The default address is "000".

The procedure below example using the commands in table C3.

Example 1(RS485)

To program a probe with an address of 000 to use the KUSTOM 2 formula, you would enter this command: 000ST=K. The KUSTOM 2 formula uses two coefficients, so we will need to assign values to them. To assign a value of 0.3 the first coefficient and a value of -0.6 to the second, we would enter these two commands:

```
000XA=0.3
000XB=-0.6
```

To verify that your setting have been programmed into the probe, enter the following query commands. The probe should respond as shown in **boldface**:

```
000ST=?
000K
000XA=?
000+00.30000001
000XB=?
000-00.60000002
```

The values that the probe returns are slightly different than the values you entered. This is an artifact of the conversion from decimal to binary and then back again. The difference, for our purposes, is negligible.

Custom Calibration Procedure for the SDI-12 HydraProbe

Note: It is recommended to first post process a new calibration for a period of time before programming the coefficients into sensors. It is also recommended to log the real dielectric permittivity (Parameter K on “aM!” or “aC!”) so that a data set can be recalibrated if needed.

SDI-12 Extended Commands For Soil Types

Command	**Description**	**Response from Sensor**
aXS!	Get soil type	aSG=GEN, aSO=ORG, aSR=RW
aXS<soil>!	Set soil type; G, O, R, K, C,	
aXSG!	Puts the probe back in General Calibration Mode	aSG=GEN
aXSO!	Puts Probe in Organic Calibration Mode	aSO=ORG
aXSR!	Puts Probe in Rockwool mode	aSR=RW
aXSC!	Puts the Probe in Custom 1 Mode	aSC=CUS1
aXSK!	Puts the Probe in Kustom 2 Mode	aSK=KUS2
aXY<constant>!	Get water constant	
aXY<constant><float>!	Set water constant	

Table C4. SDI-12 commands for setting calibration and custom calibration.

<Soil> Single ASCII character representing the soil type. The Default is G.

G	General Soil calibration for most soils.
O	Organic Soil Calibration for highly Organic Soils.
R	Rockwool or other inorganic growth media.
C	Custom 1, for a third-order polynomial. Equation [A1].
K	Kustom 2, for a semi-linear square-root formula. Equation [A2].

Table C4 and C5 shows the SDI-12 commands for changing or creating different calibrations. In order to communicate in SDI-12, the user will need to have a data logger that has an SDI-12 Transparent Mode. All of these commands must be entered while in an SDI-12 transparent mode.

Command Description	**SDI-12 Command**
Get current calibration	aXS!?
Switches the Probe to Custom 1 calibration	aXSC!
Switches the Probe to Kustom 2 calibration	aXSK!
Sets the A coefficient	aXYA<value>!
Sets the B coefficient	aXYB<value>!
Sets the C coefficient	aXYC<value>!
Sets the D coefficient	aXYD<value>!
Verifies A coefficient	<addr>XA!

Table C5. SDI-12 commands for setting coefficients <a> means address of probe. The default address is “0”.

Example 2. SDI-12 Procedure for custom calibration

Several commands are needed to program the HydraProbe to use a Custom Soil Setting. They are "XS" for setting the soil type and a separate "XY" command for setting each coefficient. All commands are preceded by the probe's address.

For example, to program a probe with an address of 0 to use the CUSTOM 1 formula, you would enter this command:
0XSC!
0SC=CUS1
The CUSTOM 1 formula uses four coefficients, so we will need to assign the values to them. To assign a value of -10.0 to the first coefficient, a value of 5.0 to the second, 0.3 to the third and 0.0005 to the fourth we would enter these commands. The probes responses are shown in **boldface.**
0XYA-10.0!
0-10.00000000
0XYB5.0!
0+05.00000000
0XYC0.3!
0+00.30000001
0XYD0.0005!
0+00.00050000

To verify that your settings have been programmed into the probe, enter the following query commands. The probe should respond as shown in boldface:
0XS!
0SC=CUS1
0XYA!
0-10.00000000
0XYB!
0+05.00000000
0XYC!
0+00.30000001
0XYD!
0+00.00050000

The values that the probe returns are slightly different than the values you entered. This is an artifact of the conversion from decimal to binary and then back again. The difference, for our purposes, is negligible.

You can use the SDI-12 D commands to take current reading. For example the command
0M!
0D0!
Will return the first three reading from the first three parameters. 0D1! Will return the 2nd three readings and so forth.

A Note About Scientific Notation

The probe can accept values for coefficients in a form of scientific notation. The decimal number is followed by the letter "E" and then the power of ten that is to be applied. For example:

-0.0007345 can also be entered as -7.345E-4

and

12345.678 can also be entered as 1.2345678E+4

D. Appendix - Useful links

Stevens Water Monitoring Systems, Inc.
www.stevenswater.com

The Soil Science Society of America
http://www.soils.org/

The US Department of Agriculture NRCS Soil Climate Analyses Network (SCAN)
http://www.wcc.nrcs.usda.gov/scan/

The US Department of Agriculture NRCS Snotel Network
http://www.wcc.nrcs.usda.gov/snow/

The US Bureau of Reclamation Agricultural Weather Network (AgriMet)
http://www.usbr.gov/pn/agrimet/

Free Nationwide Soil Survey Information!
https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm

E. Appendix - References

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Topp, G. C., J. L. Davis, and A. P. Annan. 1980. Electromagnetic Determination of Soil Water Content: Measurement in Coaxial Transmission Line. Water Resources. Res. 16:574-582

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F. Appendix – CE Compliance

Declaration of Conformity

The Manufacturer of the Products covered by this Declaration is

Water Monitoring Systems, Inc.

12067 NE Glenn Widing Dr. #106
Portland, Oregon 97220 USA
503-448-8000 / 1-800-452-5272

The Directive covered by this Declaration

2004/108/EC Electromagnetic Compatibility directive

The Product Covered by this Declaration

HydraProbe soil measurement sensor

The Basis on which Conformity is being Declared

The manufacturer hereby declares that the products identified above comply with the protection requirements of the EMC directive for and following standards to which conformity is declared:

EN61326-1:2006

Electrical requirements for measurement, control and laboratory use EMC requirements

Class A equipment – Conducted Emissions and Radiated Emissions

The technical documentation required to demonstrate that the products meet the requirements of the EMC directive has been compiled and is available for inspection by the relevant enforcement authorities.