Stevens® Water Monitoring System, Inc.

Monitoring Earth's Water Resources Since 1911

The Hydra Probe® Soil Sensor

Comprehensive
Stevens Hydra Probe
Users Manual

92915 January 2015
Rev. IV

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. Read the Stevens Engineering Applications Note, *Surge Protection of Electronic Circuits*, part number 42147. In addition to 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.

Safety and Equipment Protection (Continued)

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 thier 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 Hydra Probe 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 Hydra Probe 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.

Quick Start Guide

A quick start guide is available that includes quick references and installation guidelines.

B. K. Bellingham
Soil Scientist
Stevens Water Monitoring Systems, Inc.
12067 NE Glenn Widing Drive
Suite 106
Portland, Oregon, 97220

1-800-452-5272
1-503-445-8000
www.stevenswater.com

Comprehensive Stevens Hydra Probe II User's Manual

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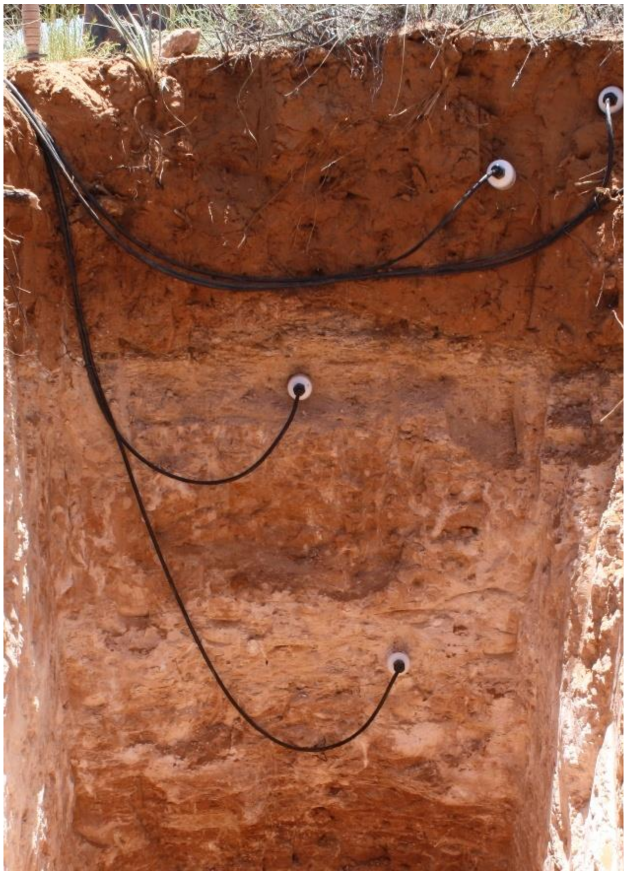


Hydra Probe installation at a typical USDA NRCS SNOTEL Site. Picture complaints of USDA NRCS in Salt Lake City, Utah.

1 Introduction

The Stevens Hydra Probe 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 Hydra Probe 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 Hydra Probes installed more than a decade ago are still in service today.

The Hydra Probe is not only a practical measurement device; it is also a scientific instrument. Trusted by farmers to maximize crop yields, using Hydra Probes 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 Hydra Probe 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 Hydra Probe bases it 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 Hydra Probe can simultaneously measure soil moisture and electrical conductivity. The complex dielectric permittivity is related to the electrical capacitance and electrical conductivity. The Hydra Probe 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 Hydra Probe 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 Hydra Probe 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 Temperature Corrections

The Hydra Probe’s soil moisture and electrical conductivity measurements are temperature corrected providing temperature independent data year round. (See Chapter 4 for more information)

1.3 Calibrations

The Hydra Probe has four factory calibrations that provide excellent performance in most mineral soils regardless of texture or organics. The calibrations are Sand, Silt, Clay and Loam. The Loam soil calibration is the default calibration and is suitable for Silt Loams, Loam, Clay Loam, Silty Clay Loam, Sandy Clay Loam, Sandy Loam, and some medium textured Clays. (See Chapter 5 for more information)

1.4 Dielectric Permittivity

For research studies involving andisol pumas soil, wetland histasol soils or soil with extremely low bulk densities, the uncorrected and the temperature corrected complex dielectric permittivities are provided for custom calibrations. (See Chapter 4 for more information)

1.5 Structural Components

There are three main structural components to the Hydra Probe. 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.

1.6 Accuracy and Precision

The Hydra Probe provides accurate and precise measurements. Table 1.1 below shows the accuracy. For a detailed explanation of accuracy and precision and on the statistical evaluation of the Hydra Probe, see Appendix D.

Parameter	**Accuracy/Precision**
Temperature (C)	+/- 0.6 Degrees Celsius(From -30^o to 36^{o}C)
Soil Moisture wfv † (m^3 m^{-3})	+/- 0.03 wfv (m^3 m^{-3}) Accuracy (Typical)
Soil Moisture wfv † (m^3 m^{-3})	+/- 0.003 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 TUC*	+/- 0.5 or +/- 1%
Real/Imaginary Dielectric Constant TC*	+/- 0.5 or +/- 5%

Table 1.1 Accuracy and Precision of the Hydra Probes' 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.

1.7 Electromagnetic Compatibility

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

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

The Hydra Probe 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.

Configurations of the Hydra Probe

The Hydra Probe is available in three versions, differentiated by the manner that information is transferred.

- SDI-12
- RS-485
- 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 under lying physics behind how the Hydra Probe works and the outer construction are also the same for each configuration. Table 2.1 provides a physical description of the Hydra Probe.

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 is ideal)
Temperature Range	-30 to 65° C
Storage Temperature Range	-40 to 70° C

Table 2.1 Physical description of the Hydra Probe (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.

1.7 Digital Probes

Digital probes offer some advantages over the Analog version. One is that post-processing of the data is not required. Another is that the data is not affected by the length of the cable. Analog probes, since their information is delivered as voltage, should only be used with relatively short cables, on the order of 8 meters (25 feet). Digital cables can be much longer. SDI-12 cables can be up to 310 meters long (1000 feet), and RS-485 cables can be up to 1000 meters (3000 feet). Digital probes can also be used with short cables without any trouble. Some installations use cables that are less than a meter (three feet) long.

1.7.1 Addressing & Programming

The digital versions of the Hydra Probe (the SDI-12 and RS-485 versions) can be connected in parallel so that multiple probes can be connected to a single communications port of a data logger or other device. When multiple probes are connected this way, each probe must be assigned a unique address ***before they are installed***. The methods used for both probes are similar, but unique. In addition, the user can select which processing method for the probe to use and select which data is to be transmitted.

1.7.2 Daisy Chaining Versus Home Run Wiring

If you are contemplating the installation of multiple probes over a large area, consideration should be given to the physical layout of the cables. Digital probes can be connected in a “Daisy Chain” manner, where each probe is spliced onto the cable of the previous probe. This can reduce the amount of cable required along with the corresponding cost. However, this means that splices with have to made, and will likely need to be done in the field. Further if a cable breaks or a splice fails, all probes beyond that point will be out of service until the break is repaired.

“Home Run” wiring means that each probe has a dedicated cable that runs all the way back to the data collection station. The advantages here are just the reverse of “Daisy Chaining”. If there is a break in the cable, only that probe is affected. There are no splices to fail. The disadvantage is that the cable requirements and associated costs will be higher.

1.7.3 SDI-12 Hydra Probe II

The SDI-12 version is digital and can be used with Data Loggers that support this communications method. SDI-12 stands for Serial Data Interface at 1200 baud. SDI-12 was developed in cooperation with the USGS (U.S. Geological Survey) and is a standard communication protocol for environmental sensors and data loggers.

1.7.3.1 SDI-12 Transparent Mode

Transparent Mode allows the user to communicate directly with the Hydra Probe. This is necessary in order to assign an address to the probe or modify the probe's configuration.

To program an SDI-12 Hydra Probe, an SDI-12 compatible device that supports Transparent Mode is required. Most SDI-12 data loggers support Transparent Mode. The SDI-12 protocol is not compatible with common serial data communications, so a device is needed to convert between the two. A typical method is to connect a Personal Computer (PC) to a data logger using a standard nine pin serial data communications cable or USB, and then the probe is connected to the SDI-12 port on the logger, and power is supplied. A terminal program (like Hyper Terminal) is started on the PC. Typically the user must issue a command to the logger to enter Transparent Mode. Most SDI-12 data loggers have terminal emulators in the operational software.

See Appendix A for specific information on SDI-12 commands for the Hydra Probe. Please visit www.SDI-12.org for more information about the SDI-12 Protocol. Table 2.2 describes the physical specifications, wire designations, and other information about the digital SDI-12 Hydra Probe II.

Power Requirements	9 to 20 VDC (12VDC Ideal)
Red Wire	+Volts Power Input
Black Wire	Ground
Blue Wire	SDI-12 Data Signal
Baud Rate	1200
Power Consumption	<1 mA Idle, 10 mA Active

Table 2.2 Digital SDI-12 Hydra Probe II Information.

1.7.4 Digital RS-485 Hydra Probe II

Like the SDI-12 Hydra Probe, the RS-485 probe is also digital. The RS-485 communication format has 2 data wires, consumes more power when idle and has a custom communication protocol. Being digital, the RS-485 version shares many of the benefits the SDI-12 version does. The RS-485 sensors can be “daisy chained” or wired to a terminal assembly to simplify installation. The RS-485 Hydra Probe has a maximum cable length of 1000 meters. The user may have specific applications where this capability is advantageous, however, due to the cost of the cable, it may be more cost effective to run short cables and have additional data loggers or telemetry devices. See appendix B for more information about commands for the RS-485 Hydra Probe.

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 2.3 Digital RS-485 Hydra Probe II Information.

1.7.4.1 Addressing and Programming

RS-485 data communications ports are not commonly found on Personal Computers (PC's). To prepare an RS-485 version of the Hydra Probe it will be necessary to program the address. One method to talk to the probe is to connect the probe to a PC via an “RS-485 to RS-232 converter”. These devices are available from several vendors specializing in data communications products.

Once the probe is connected and power is applied, a terminal emulation program, such as Hyper Terminal is started on the PC. Certain settings will be needed to be set to enable communications with the probe. The following settings are for Hyper Terminal, but most terminal emulation programs should have equivalent settings.

- 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 Hyper Terminal these settings are found under **File / Properties / Settings / ASCII Setup / ACSII Sending**:

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

1.8 Analog Hydra Probe

The Analog Hydra Probe was the first version made available. The Analog version is useful for a number of applications. Current customers of the Analog probe include users that need to replace or add a sensor to an existing system that was specifically tailored for the analog sensors. One advantage the Analog Hydra Probe has over the digital version is the fast measurement rate. For example, on the beach, ocean researchers can use the analog Hydra Probe to measure the hydrology of sands in the surf zone where they would want to take several measurements between waves. This would entail taking measurements several times per second, something the digital probes cannot do.

1.8.1 Analog Hydra Probe Output

The output of the Analog Hydra Probe is 4 voltages. These four voltages are the raw signal response of the measurement and directly represent the behavior of the reflected electromagnetic standing wave. The four voltages need to be processed by a computer program in order to obtain the parameters of interest such as soil temperature, soil moisture, soil electrical conductivity and the dielectric constants.

Table 2.4 below shows the wiring scheme.

Black Wire	Ground
Red Wire	Power 7 to 30 VDC (12 VDC Ideal)
Blue Wire (Output)	V1 (Raw Voltage 1) Range 0-2.5 volts
Brown Wire (Output)	V2 (Raw Voltage 2) Range 0-2.5 volts
Green Wire (Output)	V3 (Raw Voltage 3) Range 0-2.5 volts
White Wire (Output)	V4 (Raw Voltage 4) Range 0-1 volts
Yellow Wire	Reference Ground
Power Draw Active	35 to 40 mA

Table 2.4 wiring scheme for the Analog Hydra Probe.

An easy way to remember the wiring scheme is the colors of the wires are ordered alphabetically. The black and yellow ground wires may be connected and grounded together or grounded separately. The four voltage data wires need to be wired into four separate voltage sensing connection points on the recording instrument. Use the logger data acquisition procedure to obtain the raw voltages values.

2.3.2 Post possessing raw voltages into the measurements of interest.

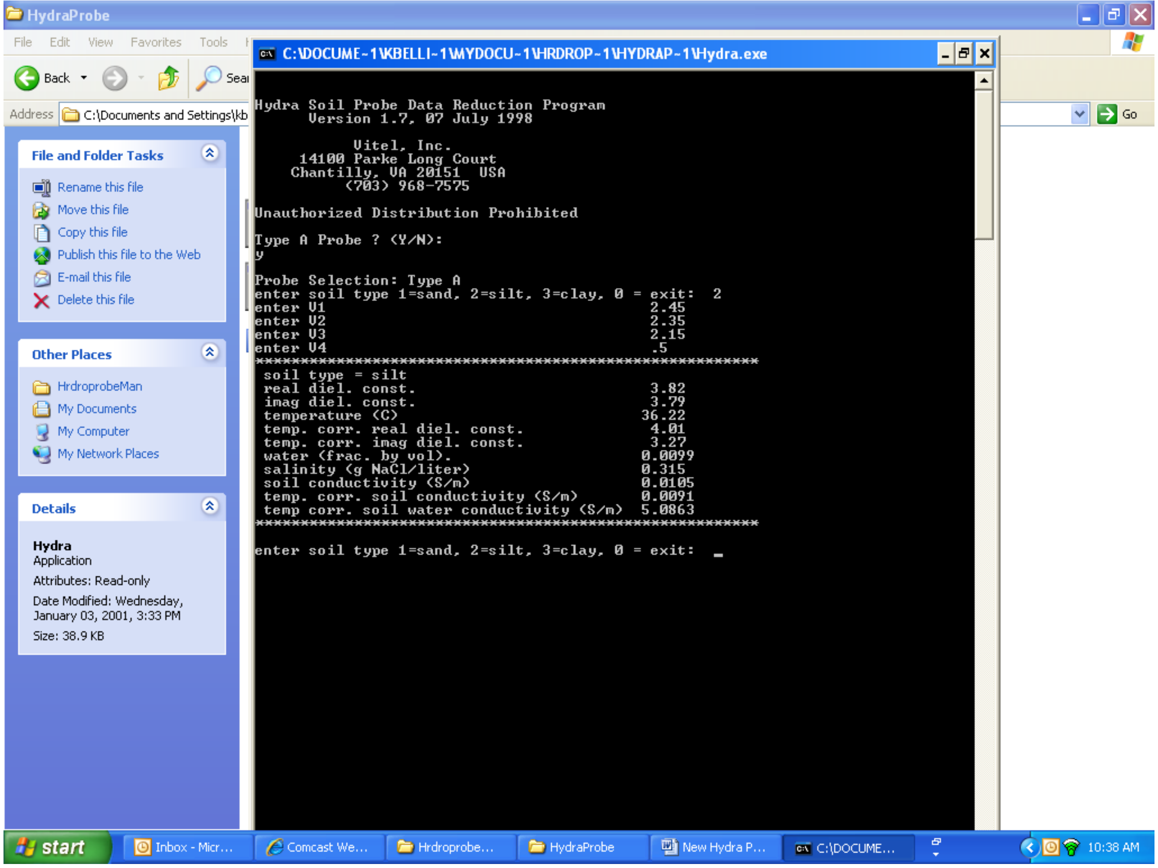
(Section 2.3.2 is not applicable to digital SDI-12 and RS485 probes)

The output of the Analog Hydra Probe is 4 voltages, each on a separate color coded wires. V1 V2 and V3 will be between 0 and 2.5 volts DC. V4 will be between 0.1 to 0.8 volts DC. These 4 voltages need to be processed by a series of algorithms to obtain the parameters of interest. Stevens provides two executable programs to perform these calculations:

- HYDRA.EXE
- HYD_FILE.EXE (see Appendix D)

HYD_FILE.EXE and HYDRA.EXE as well as the instruction procedure for HYD_FILE.EXE can be downloaded from the Stevens website at: http://www.stevenswater.com

HYD_FILE.EXE is the program used for processing tables of raw voltages collected over time. HYDRA.EXE is the program used for a single measurement of the 4 voltages.



```
Hydra Soil Probe Data Reduction Program
      Version 1.7, 07 July 1998

           Vitel, Inc.
     14100 Parke Long Court
    Chantilly, VA 20151  USA
          (703) 968-7575

Unauthorized Distribution Prohibited

Type A Probe ? (Y/N):
y

Probe Selection: Type A
enter soil type 1=sand, 2=silt, 3=clay, 0 = exit:  2
enter V1                                    2.45
enter V2                                    2.35
enter V3                                    2.15
enter V4                                    .5
********************************************************
 soil type = silt
 real diel. const.                          3.82
 imag diel. const.                          3.79
 temperature (C)                           36.22
 temp. corr. real diel. const.              4.01
 temp. corr. imag diel. const.              3.27
 water (frac. by vol).                     0.0099
 salinity (g NaCl/liter)                   0.315
 soil conductivity (S/m)                   0.0105
 temp. corr. soil conductivity (S/m)       0.0091
 temp corr. soil water conductivity (S/m)  5.0863
********************************************************

enter soil type 1=sand, 2=silt, 3=clay, 0 = exit:
```

FIG. 2.1 HYDRA.EXE Input V1, V2, V3, V4 and Output Parameters.

To use HYDRA.EXE simply open the file and follow the prompts. The first prompt will ask "**`Type A Probe ? (Y/N):`**". Type Y. Almost all of the Analog Hydra Probes are type A. Type A probes use a 2.5 volt reference for the temperature sensing element. A non-type A probe uses a 5 volt reference. Next, enter the soil type and then the four voltage values. After the user responds to all of the prompts, the output is displayed. The displayed output consists of the dielectric constants, the temperature, the soil moisture, and the soil electrical conductivity.

1.8.2 Trouble Shooting the Analog Hydra Probe

If the Hydra Probe appears to be malfunctioning, there are three likely causes:

- communication with the logger
- soil hydrology
- a malfunctioning probe.

See the section about soil hydrology.

Programming a data logger is not always a trivial task. The data logger needs to extract 4 raw voltages from four analog ports on the logger with the desired timing interval. If the user is unable to get a response from the Hydra Probe, it is recommended to first physically check wire connections from the probe to the logger. The user may also want to cycle the power to the probe by disconnecting and reconnecting both ground wires. If the connections are sound, the user will next need to check the logger's setup. *Are the data ports enabled? Are the data ports scaled properly in the appropriate units? Are the probes and logger adequately powered? Is the data properly recorded on the logger?* If the logger has GUI based operation software, there may be a help function. If the logger only accepts terminal command scripts in a terminal window, refer to the logger's manual or manufacturer. Also, make sure the computer is properly connected to the logger. *Is the computer on the proper COM port? What about the Baud rate? Does the logger need a NUL modem or optical isolator in order to be connected to a computer?* Most of the technical support questions Stevens receives are not due to malfunctioning probes but rather an incorrect data logger setup.

A good way to verify if the probe is working properly is to submerge the probe in distilled water* in a plastic container and check the real dielectric permittivity. Once the probe is submerged, connect the black and yellow wires to a ground and connect the red wire to a +12 volt DC power source. Use a voltmeter to measure the raw voltage on the 4 data wires. A common hand held unit is adequate. Use HYDRA.EXE to process the voltages. The real dielectric permittivity should be 75 to 85 and the imaginary dielectric permittivity should be less than 5 at ambient tempratures. The user may use this method to verify if the probe is functioning properly, and to verify the logger output. If the probe is buried in the soil, the user can obtain the 4 raw voltage outputs with a multimeter and compare them to the logger's output.

*The user may also use tap water for this procedure, however, it is important to note that tap water may contain dissolved material and trace contaminants that might affect the dielectric constants.

Installation
The Hydra Probe is easy to install and the use of installation tools are seldom required.

1.9 Avoid Damage to the Hydra Probe:

- 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 Hydra Probe 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 Hydra Probe 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 Hydra Probe in the same bucket while powered may create an electrolysis affect that may damage the probe.

1.9.1 Lightning

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

For maximum protection from lightning, attached a duel dissipater 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 dissipater to a buried copper rod 2 cm in diameter. The buried copper rod should be at least 3 meters long buried horizontally 1.5 to 3 meters deep.

1.10 Wire Connections

1.10.1 Analog Probe Wire Connection

Table 2.4 in section 2.4.3 shows the wiring scheme for the Analog Hydra Probe. The four voltage data wires need to be wired into four separate data ports on the logger. The red power wire should be connected to a +12 volt power supply and the black and yellow wires should be connected to a ground. For more information, refer to the data loggers operation manual.

1.10.2 SDI-12 Hydra Probe Wiring Connections

Table 2.2 and section 2.1 provide important information about the SDI-12 Hydra Probe. Connect the red wire to a +12 volt DC power supply, connect the black wire to a ground, and connect the blue wire to the SDI-12 port or the Data Logger. The advantage of SDI-12 communications is that multiple probes can be connected to a single port on data logger. The probes may be "daisy chained" together, or they may all be connected to a central terminal assembly. The single SDI-12 data port on an SDI-12 compliant data logger can accommodate many SDI-12 sensors.

For more than 6 Hydra Probes, the user may find it easier to have the terminal assembly in a separate enclosure from the logger, telemetry and power supply.

1.10.3 RS-485 Hydra Probe wiring Connections

Table 3.1 and section 2.1.4 provide important information about the RS-484 Hydra Probe. Connect the red wire to a +12 volt DC power supply, and connect the black wire to a ground. The green and white wires are the data wires.

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
Power Consumption	<10 mA Idle 30 mA Active
Control system settings	8 DATA BITS
Control system settings	One Stop Bit
Control system settings	NO Parity

Table 3.1 Digital RS-485 Hydra Probe II Information.

Like SDI-12, the RS-485 communication format is also digital, therefore the probes' data wires can be "daisy chained" or connected together at a terminal assembly. See Appendix B for RS-485 command structure.

1.10.4 Soil Classification and Calibrations

For most applications, the default soil moisture calibration will accommodate most all soil types. The default soil moisture calibration is LOAM 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 section 5 and appendix C of the Hydra Probe manual. For firmware calibration programming communication protocols, see appendix C.

1.11 Installation of the Hydra Probe in Soil

1.11.1 Topography and Groundwater Hydrology

The land topography often dictates the soil hydrology. Depending on the users' interest, the placement of the Hydra Probe should represent what would be most useful. For example, a watershed researcher may want to use the Hydra Probe to study a micro climate 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.

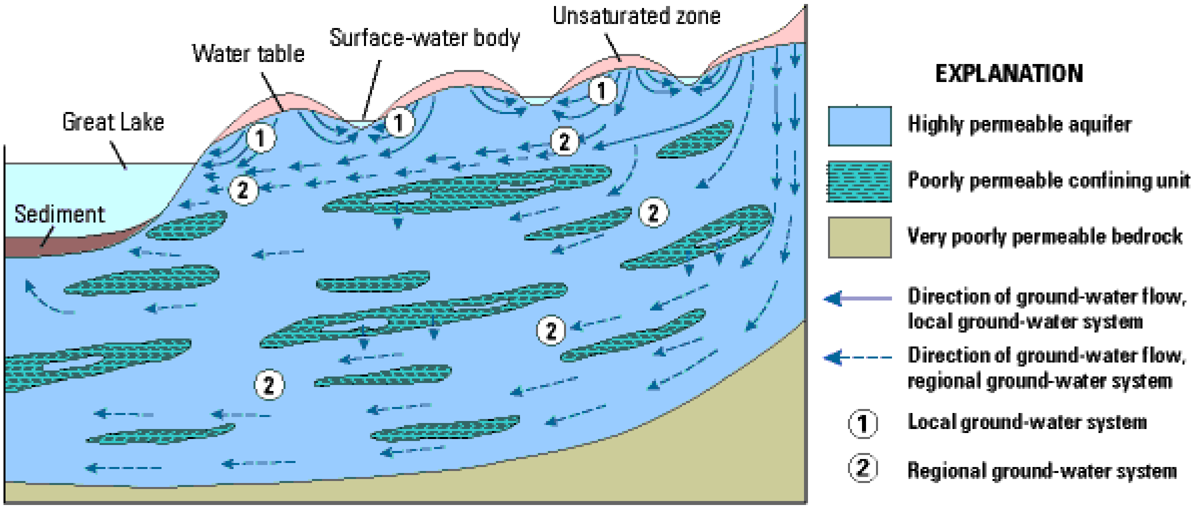


Figure 3.3 Groundwater pathways and Surface water. Taken from USGS Report 00-4008

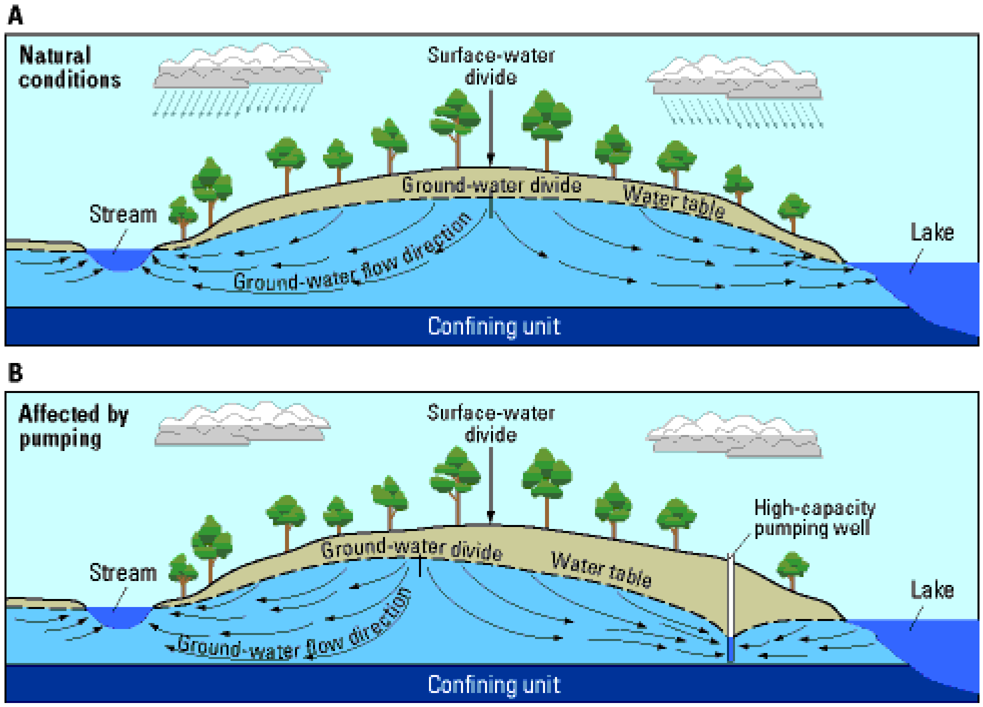


Figure 3.4 Groundwater flow direction and surface water body. Taken from USGS report 00-4008.

Figures 3.3 and 3.4 illustrate subsurface water movement in the water table. The Hydra Probe data is most meaningful in the unsaturated zone where soil moisture values will fluctuate. If the water table rises to the depth of the Hydra Probe, the Hydra Probe soil moisture measurements will be at saturation and will be indicative of the effective porosity. If the user is interested in groundwater level measurements in wells, a water depth sensor might provide the necessary information.

1.11.2 Installation of the Hydra Probe into Soil.

The most critical thing about the installation of the Hydra Probe is the soil needs to 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 3.4.3 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 Hydra Probes 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 Hydra Probe signal will average the gap into the soil measurement and create errors.

Figure 3.5 Hydra Probe Installed in undisturbed soil.

Push the tines of the Hydra Probe into the soil until the base of the tines 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.

The user may also want to run the Hydra Probe cable through a metal conduit like the one shown in figure 3.6 to add extra protection to the cable.

1.11.3 Hydra Probe 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 Hydra Probes may be installed in the root zone and one Hydra Probe 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 5. The probe beneath the root zone is important for measuring excessive irrigation.

Figure 3.6 Six Hydra Probes installed into 6 distinct soil horizons.

The soil horizons often dictate the depths of the Hydra Probes' placement. Soil scientist and groundwater hydrologist are often interested in studying soil horizons. The Steven Hydra Probe 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 3.3). Like other natural processes, the age of the horizon increases with depth. The reason why it is so useful to have a Hydra Probe 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 Hydra Probes 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 mater 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 http://soils.usda.gov/education/resources/k_12/lessons/profile/

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 3.3 Basic description of soil horizons.

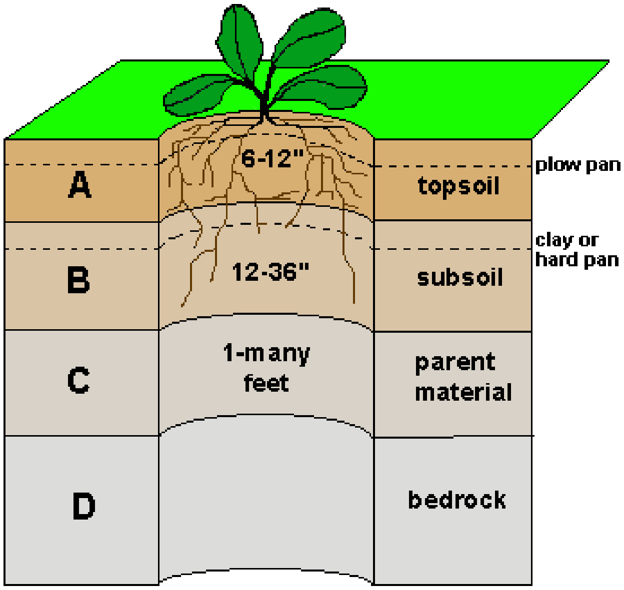


Figure 3.7 Soil Horizons.

Figure 3.8 Illustration of soil horizons. In this frame, the soil horizons are very distinct and show the geological history of the soil.

1.11.4 Back filling the hole after the probes are installed.

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

Hydra Probe 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.

1.12 Introduction

Measuring soil moisture is important for a broad number of applications and can be an important tool for water resources conservation. Described here is the theory behind electromagnetic soil sensors. 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. The Stevens Hydra Probe provides soil moisture values in unit of water fraction by volume.

4.2 Water Potential Measurements

Capillary matric potential sometime 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 10,000,0000 hPa is near dryness. In other words, the drier the soil the more energy it takes to pull water out of it.

Because hectopascals (hPa) is a unit of pressure but can be a clumsy unit to work within the ranges observed in soil, we often express matric potential as the common log of hPa in a unit called pF. For example 10,000,000 hPa is equal to a pF of 7. A pF of 0 is equal to 1 mbar.

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 capillary matric potential including granular matrix sensors such as gypsum electrical resistance blocks, and heat dissipation. Capillary matric potential is important for irrigation scheduling because it can represent the soil water that would be available to a crop. Unsaturated flow equations such as the Richards Equation require both water fraction by volume and water potential to model the movement and distribution of water in the vadose zone (Warrick 2003).

While matric potential does not use electromagnetic waves to make measurements, matric potential and soil moisture are often measured together to fully characterize the soil hydrology. The Stevens pF Sensor (part number 51133) is a highly accurate SDI-12 matric potential sensor that uses heat pulse technology. Note that dielectric based soil sensors output soil moisture in units of water fraction be volume where matric potential sensors output data in units of pressure.

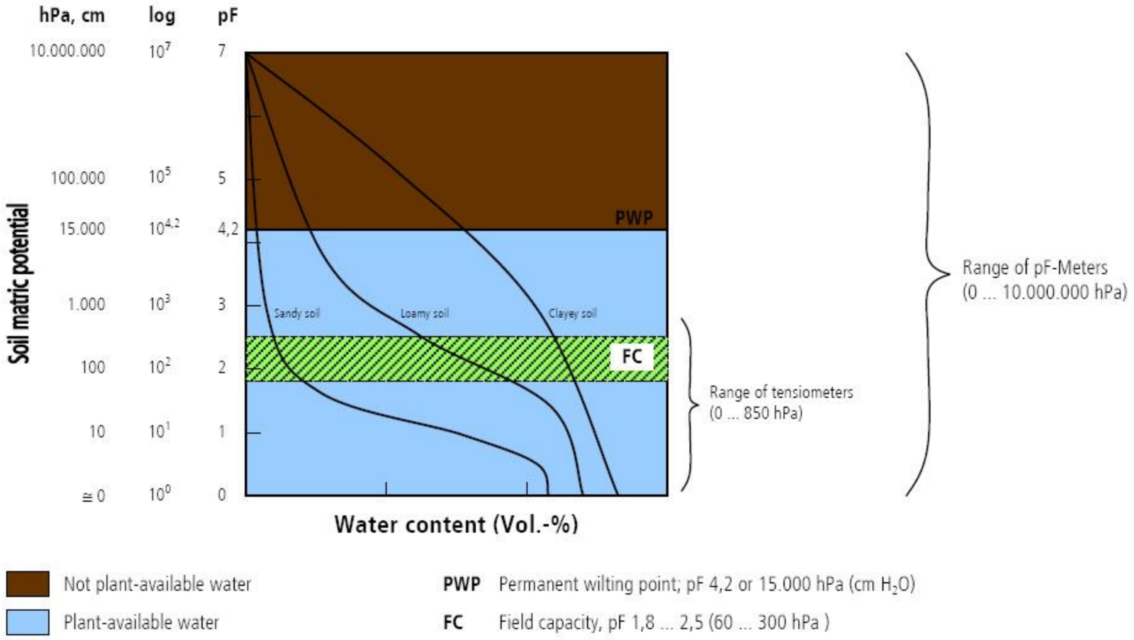


Figure 4.1. Soil matric potential verse soil moisture.

1.13 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. In the twenty first century, there are dozens of different kinds of soil moisture sensors commercially available. Among all of the electronic soil sensors commercially available, measurement or a 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 circuit's capacitance, which is in turn related to the dielectric constant where the in situ soil particle/water/air matrix is the dielectric.

1.14 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 in soil, the properties and water content of the soil will influence the wave. The attributes of the electromagnet radio wave that will be influenced by the soil are the frequency, amplitude, impedance and the time of travel. In general, the real component represents energy storage in the form of rotational or orientational 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} 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 Hydra Probe 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 in 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 an the polarity of a water molecule and how it can reorient itself in response to an electromagnetic oscillations.

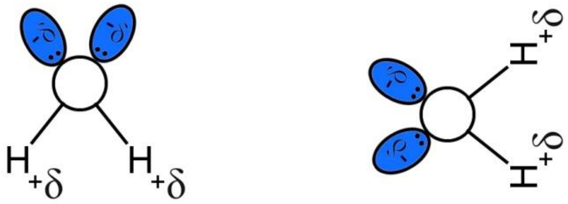


Figure 4.2. A water molecule in the liquid phase reorienting i.e. rotational dipole moment.

[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] illustrates the different kinds of polarizations exhibited by most materials. Soils will have space charge and atomic polarizations while water will reorientate.

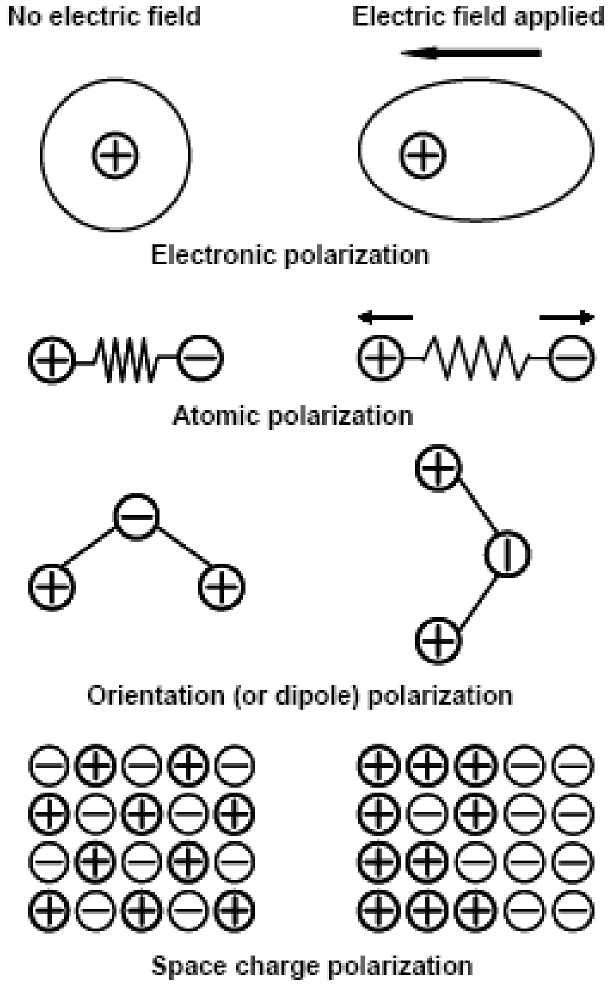


Figure [4.3]. Illustration of polarization. The real dielectric permittivity of soil is mostly due to orientation polarization of water (Taken from Lee et al. 2003)

1.15 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).

1.15.1 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)

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

The Hydra Probe has a temperature corrected real component (parameter L) that is based on equation 4.5. The factory sand, silt and clay calibrations use the temperature corrected real component while other calibrations do not. The reason why this temperature correction is only valid for sand is because the pore water in the sand will behave much in the same way as liquid water will behave. The temperature affects of the real permittivity in soils containing silts or clays will behave very different than water alone due to bound water and cation activity.

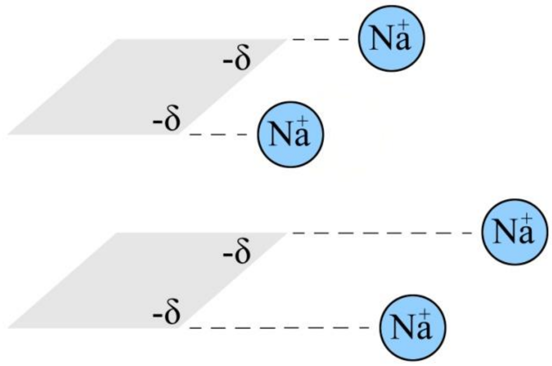


Figure 4.4a

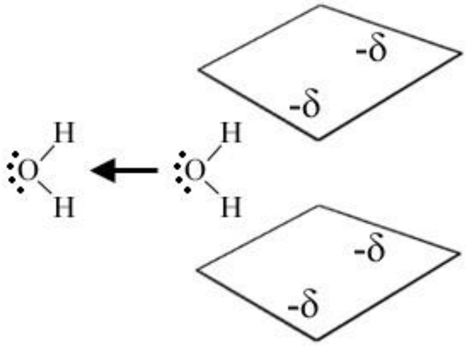


Figure 4.3b

Figure 4.4a shows how cations on a clay lattice will extend their bond length with temperature allowing the cation to have a dipole moment with an oscillating electromagnetic field.

Figure 4.4b shows clay bound water escaping the clay lattice as the temperature is increasing.

1.15.2 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.

1.16 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 4.1 summarizes the types of sensing methods.

Method	**Physical Measurement**	**Basis for Soil Moisture**	**Frequency**
TDR	Time of travel of a reflected wave	Apparent Permittivity	1000 MHz
TDT	Time of travel	Apparent Permittivity	150 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 4.1. Summery 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 of 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).

The Stevens Hydra Probe 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 Hydra Probe and can be calculated from an .exe program for the analog Hydra Probe. These computations are based on the work of J. E. Campbell at Dartmouth College (Campbell 1988, Campbell 1990, Kraft 1988).

The Hydra Probe can be referred to coaxial dielectric impedance reflectometer and works similar to a vector network analyzer at a single frequency.

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

Unlike most other soil sensors, the Hydra Probe measures both the real and the imaginary components of the dielectric permittivity as separate parameters. The Hydra Probe bases the soil moisture calibration on the real dielectric permittivity while most other soil moisture technology 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 Hydra Probe separates the real and imaginary components, the Hydra Probe’s soil moisture calibrations is less affected by soil salinity, temperature, soil variability and inter sensor variability than most other electronic soil sensors.

2 Measurements, Parameters, and Data Interpretation

2.1 *Soil Moisture*

2.1.1 Soil Moisture Units

The Hydra Probe 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 Hydra Probe. 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 0.40-0.55 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, % field capacity, % available (to a crop), inches of water to inches of soil, and tension (or pressure). They are all interrelated in the sense that for a particular soil, knowledge of the soil moisture in any one of these units allows the soil moisture level in any of the other unit systems to be determined. It is important to remember that the conversion between units can be highly soil dependent.

The unit of water fraction by volume (wfv) was chosen for the Hydra Probe for a number of important reasons. First, the physics behind the soil moisture measurement dictates a response that is most closely tied with the wfv content of the soil. Second, without specific knowledge of the soil, one cannot convert from wfv to the other unit systems. Third, the unit wfv allows for direct comparison between readings in different soils. A 0.20 wfv clay contains the same amount of water as a 0.20 wfv sand.

However, the same thing cannot be said about the other measurement units. For example, to use the unit common in tensiometer measurements, a one Bar sand and a one Bar clay will have vastly different water contents. The wfv unit can also be readily used to estimate the effects of precipitation or irrigation. For example, consider a soil that is initially 0.20 wfv, and assume a 5 cm rainfall that is distributed uniformly through the top one meter of soil. What will the resultant soil moisture in the top one meter of soil be? 5 cm is 0.05 of one meter, so the rainfall will increase the soil moisture by 0.05 wfv to result in a 0.25 wfv soil. For other units, this calculation can be much less straightforward, particularly when soil moisture is measured as a tension.

2.1.2 Soil Moisture Measurement Considerations for Irrigation

Soil moisture measurements are important for a number of applications and for a number of different reasons. Some applications include; land slide studies, erosion, water shed studies, climate studies, predicting weather, flood warning, crop quality and yield optimization, irrigation, and soil remediation to name a few.

Soil moisture values are particularly important for irrigation optimization and to the health of a crop. Equations [5.1], [5.2] and [5.3] can help determine when to irrigate. 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 only 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.

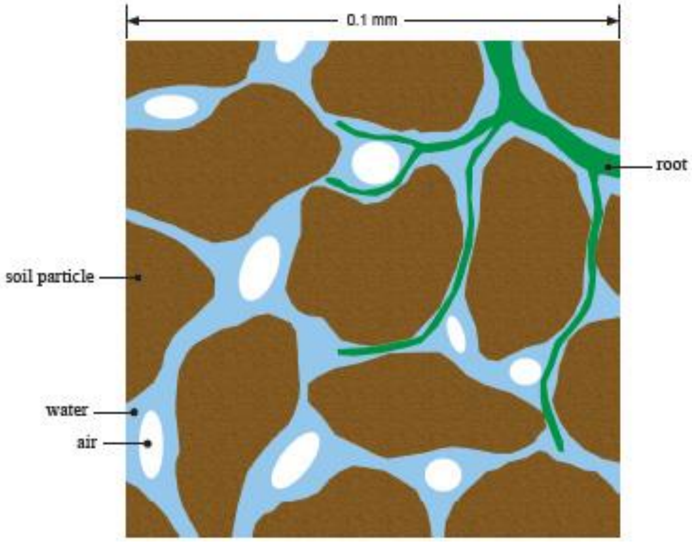


Figure 5.1. Unsaturated soil is composed of solid particles, organic material and pores. The pore space will contain air and water.

The lower soil moisture limit is a very important value because dropping 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.

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

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

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

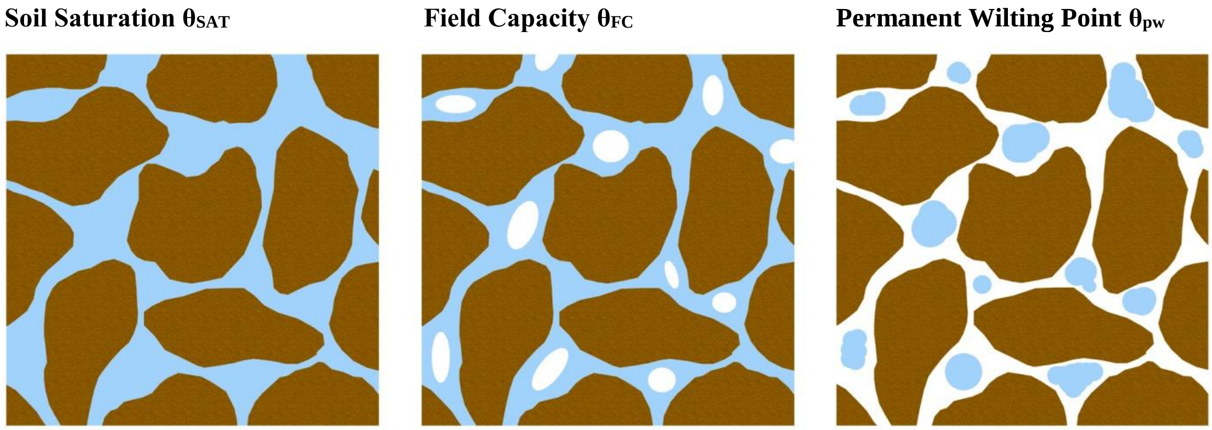

Soil Saturation θ_{SAT}
Field Capacity θ_{FC}
Permanent Wilting Point θ_{pw}

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.

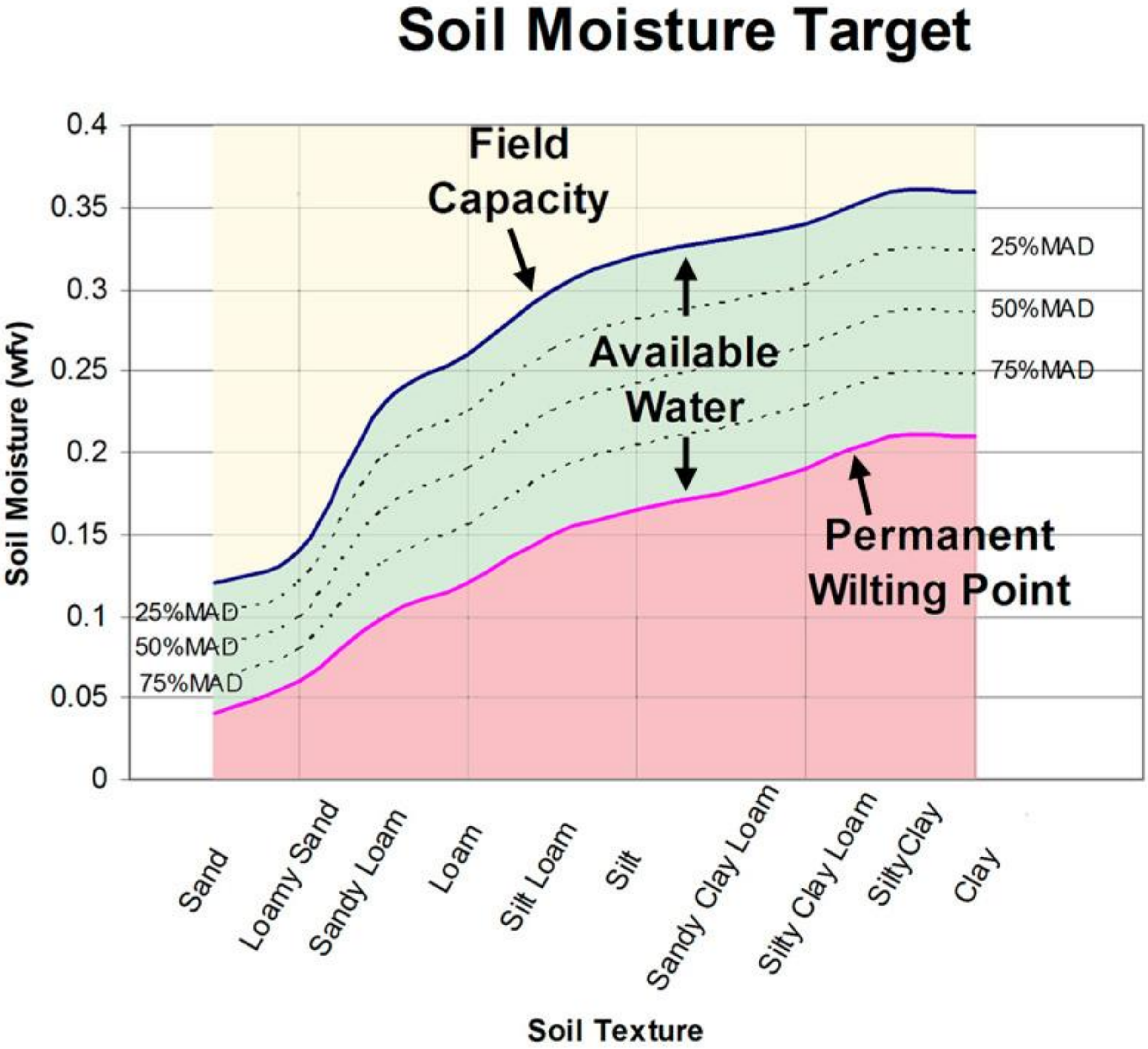


Figure 5.3 soil textures and the available water.

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.

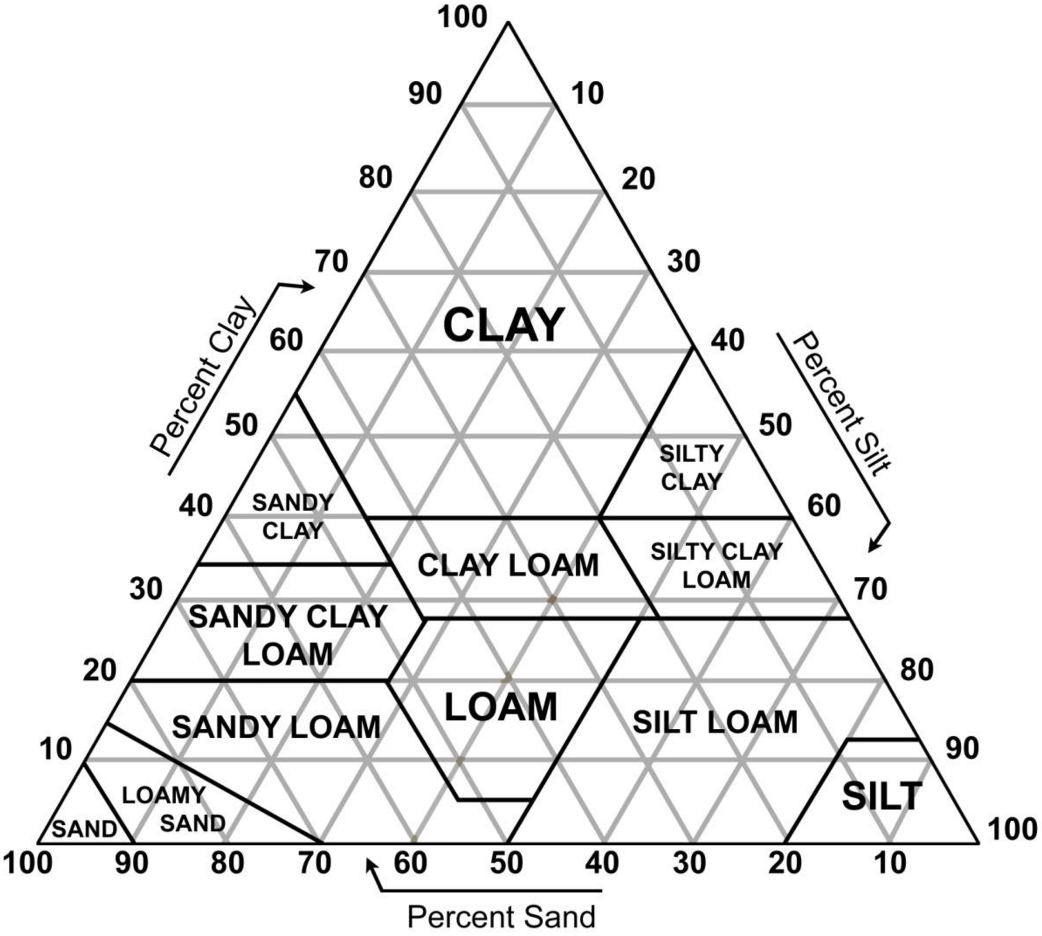


Figure 5.4. Soil textural triangle.

Example of an Irrigation scheduling based on soil moisture values.
For example, let us suppose you are growing a grass species and your soil is a sandy loam. From tables 5.1 and 5.2 the MAD = 0.5, From Figure 5.3 (or a soil surrey) θ_{PWP} = 13% and the field capacity is 25%. Using equation [5.1] yields; θ_{AD} = (25-13) x 0.5 = 6% .The lower limit would then be calculated by equation [5.3], θ_{LL} = 25 - 6 = 19%. This means for a sandy loam, if the soil moisture drops below 19% (or Hydra Probe reading of 0.19), the crop may become stressed and it is time to irrigate. Never let the soil moisture drop below the permanent wilting point. In this example the soil moisture target will be from 19% to 25% (Brouwer 1988 and Blonquist 2006).

2.1.3 Soil Moisture Calibrations (General LOAM Calibration)

The soil moisture calibration is an estimation of the soil moisture from a mathematical equation that contains the real dielectric permittivity (Topp 1980). The Hydra Probe has four factory calibrations to choose from and custom calibration features incase a specific site calibration is necessary. The LOAM calibration is the best general purpose calibration available and is the default calibration on the Hydra Probe's firmware. The LOAM 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. If you are unsure about the most suitable calibration for a specific soil, use the default LOAM calibration. Figure 5.2 shows the textures of soil and the application of the factory provided calibrations.

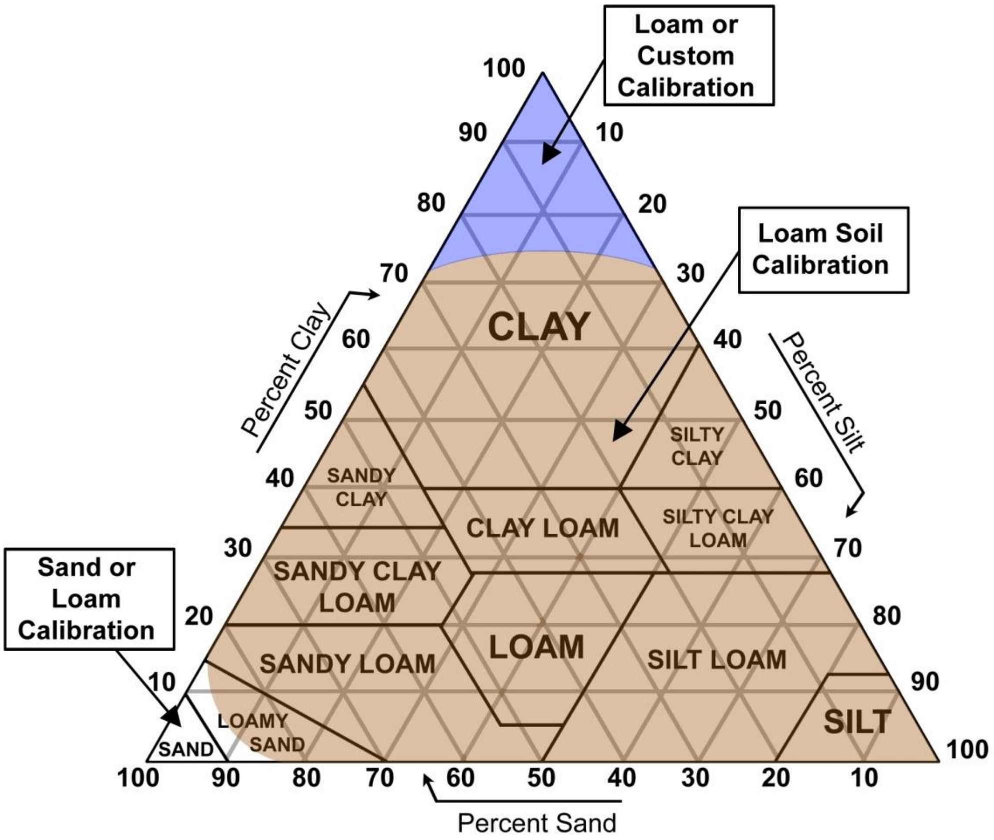


Figure 5.2, Soil textural guidelines for the Hydra Probe's factory calibrations. The LOAM calibration is equation [5.5] where A = 0.109, B = -0.179 and ε_r is the raw real dielectric permittivity.

2.1.4 Other Factory Calibration

As described in section 5.1.3, the Hydra Probe has four factory calibrations LOAM, Sand, Silt, and Clay. LOAM is the general all purpose calibration. The Sand calibration is applicable for typical non-saline sand with low silt content. The Silt and Clay calibration should only be used where a calibration validation has been performed . In the Hydra Probes digital firmware setting, sand is soil type 1, Silt 2, Clay 3 and LOAM is soil type 4.

Between the preset calibrations and the custom calibration option, the Hydra Probe can measure soil moisture in almost any kind of soil. There are thousands of different kinds of soil throughout the world, and almost every nation has some kind of classification system. The most wide spread and most current soil classification system is the Orders of American Soil Taxonomy (USDA Keys to Soil Taxonomy). In this system, all of the worlds' soils are broken into 12 orders based on climate, topography, biology and soil chemistry. Table 3.2 lists the orders.

The Hydra Probe can accommodate all of the soil orders. Andisols, gelisols and histosols are soil that may have soil moistures and properties that depart from the Hydra Probe's built in calibration curves. If the bulk density is extremely low giving the soil an effective porosity greater than 0.5, the user will need a custom calibration If a custom calibration is required see Section 5.1.5. If the Hydra Probe needs to be switched from the default Loam calibration setting, see the RS-485 or SDI-12 command sections in the appendix.

Soil Order	**Climate or Regime**	**Soil Characteristics**	**Hydra Probe Calibration**
Entisol	Sandy Young Soil	Stream Flood Plain	Sand or Loam
Inceptisol	Silty Young Soil	Evidence of red color	Sand or Loam
Vertisol	Shrink/Swell Clay	Homogenized, Cracks	Loam
Histosol	Wetland Soil	Anoxic Reduced State	Loam or Custom
Aridisol	Desert Soil	Higher pH	Sand or Loam
Mollisol	Grass land Soil	Higher pH	Loam
Spodosol	Needle Leaf Forest Soil	Low pH	Loam
Alfisol	Forest Soil	Low pH	Loam
Ultisol	Old Forest Soil	Low pH	Loam
Oxisol	Ancient Forest Soil	Red, Oxidized	Loam
Gelisol	Soil With Permafrost	Organic Rich	Loam or Custom
Andisol	Volcanic Ash Soil	Low Density	Loam or Custom

Table 3.2 The 12 Orders of Soil Taxonomy, Characteristics and Hydra Probe Calibration setting.

The LOAM calibration is equation [5.5] where A = 0.109, B = -0.179 and ε_r is the raw real dielectric permittivity.

2.1.5 Other Applications and Alternative Calibrations

It may be possible to use the Hydra Probe for applications in media other than mineral soil. Some examples include peat, decomposed plant material, compost, ice cream/ food products or other small particle sized material that has a small real dielectric permittivity compared to that of water. The calibration curves used to calculate soil moisture may not be valid for materials different from mineral soil; however, the complex dielectric permittivity is provided allowing the user to calibrate the probe accordingly. The calibration curves will mathematically have the appearance of equation [5.4] or [5.5]

$$\theta = A + B\varepsilon_r + C\varepsilon_r^2 + D\varepsilon_r^3 \quad [5.4]$$

$$\theta = A\varepsilon_r^{1/2} + B \quad [5.5]$$

Where θ is moisture ε_r is the real dielectric permittivity and A,B,C, and D are coefficients. If the user wishes to use the Hydra Probe to measure moisture in a matrix that is not mineral soil, the user must empirically and experimentally solve equation [5.4] or equation [5.5]. Also, The user should review the matrix compatibility requirements of the probe in section 3.1. The user can program the coefficients from equation 5.4 and 5.5 and have the probe output soil moisture values using these custom equations. See appendix C for programming instructions.

2.2 Soil Salinity and the Hydra Probe EC Parameters

Soil electrical conductivity (EC) is parameter O and the temperature corrected electrical conductivity and is parameter J on the digital Hydra Probe II. Electrical conductivity also referred to as specific conductance and is measured in Siemens/meter (S/m). The Hydra Probe will measure EC up to 1.5 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 5.4 below summarizes the unit conversion.

Convert to ⟶	S/m	dS/m	mS/m	µS/m	S/cm	dS/cm	mS/cm	µS/cm
Convert From ↓								
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 5.4. 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

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 Hydra Probe's EC measurements in slurry extracts, water samples, and aqueous solutions will very accurate (<+/- 1%).

2.2.1 Soil Salinity

The soil salinity is salt build up in the soil and is the oldest form of soil pollution dating back to ancient Babylonian times. Salt in the soil is the major component of the soil that conducts electricity. The EC parameter is highly dependent on the level of soil salinity. 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, the proper 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.

2.2.2 Bulk EC versus Pore Water EC

The electric conductivity in soil in 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 Hydra Probe. 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 Hydra Probe can be used to measure the EC_e if properly placed in the watery extract.

2.2.3 Bulk EC and EC Pathways in Soil

As stated earlier, the electric conductivity of soil is less straight forward than in a water sample. 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, he 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.

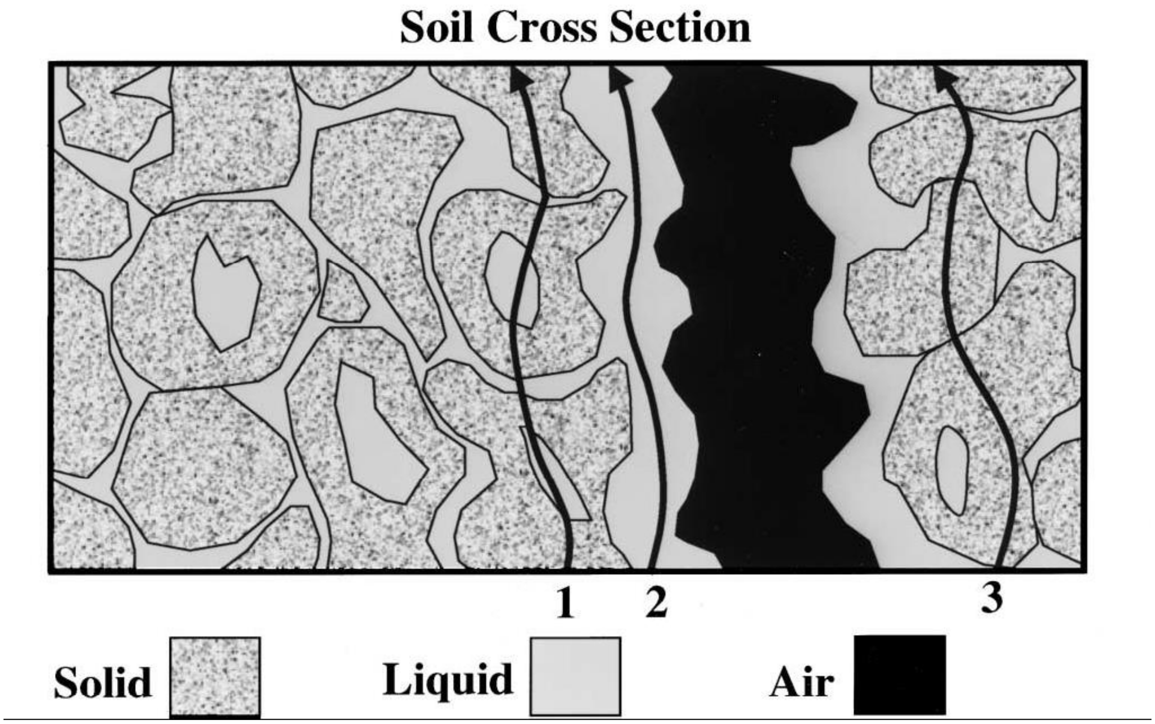


Figure 5.3 3 Pathways of electric conductivity in soil matrix. 1 water to solid, 2 soil moisture, 3 solid. Taken from Corwin et al. (2003).

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 Hydra Probe is in the soil is 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 solutes that all have some influence on electrical conductivity of the soil/water/air matrix.

2.2.4 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 ware 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 is most soils;

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

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 Hydra Probe in soil, ε_{rb} is the real dielectric permittivity of the soil measure with the Hydra Probe, and ε_{rb_dry} is the real dielectric permittivity of the soil when it is completely dry.

2.2.5 Total Dissolved Solids (TDS)

The total dissolved solids (in g/L or ppm) of a water sample can be estimated from the electrical conductivity. TDS is less meaningful for soil because 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 also 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 and phosphates. Another problem facing 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 errors associated with estimating TDS from EC, equation [5.7] can be used to with the Hydra Probe'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 Hydra Probe 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.

2.2.6 Soil Electrical Conductivity (Temperature corrected)

Electrical conductivity and the imaginary dielectric permittivity are highly sensitive to changes in temperature. The raw and the temperature corrected parameter are offered from both EC and the imaginary permittivity.

Parameter Name	Digital Parameter Assignment
Raw Electrical Conductivity	O

Temperature corrected electrical Conductivity	J
Raw Imaginary	M
Temperature corrected imaginary	N

In theory, as temperature increases, the molecular vibrations increase making it more difficult for electricity to propagate through a material, thus electrical conductivity goes down with temperature. The temperature corrections are based on a saline water solution’s EC/temperature relationship to provide an output of what it would be at 20 degrees C. This would allow the user to make reasonable comparisons of different EC values at different temperatures.

2.2.7 Solution Chemistry

Salinity refers to the presence of dissolved inorganic ions such as Mg^+ , Ca^{++}, K^+, Na^+, Cl^-, $SO^2{}_4{}^-$, HCO_3^- and CO_3^{2-} in the aqueous soil matrix (Hamed 2003) . The salinity is quantified as the total concentration of soluble salts and is expressed in terms of electrical conductivity. There exists no in-situ salinity probe that can distinguish between the different ions that may be present.

When salts such as sodium chloride are in their solid form, they exist as crystals. Within the salt crystal, the sodium and the chlorine atoms are joined together in what is called an ionic chemical bond. An ionic chemical bond holds the atoms tightly together because the sodium atom will give up an electron to the chlorine thus ionizing the atoms. If an atom like sodium gives up an electron, it is said to be a positively charged ion (also called a cation). If an atom such as chlorine receives an electron, it is said to be a negatively charged ion (also called an anion and is given the suffix ide, like chloride). The sodium and the chloride ions comfortably arrange themselves into a stacked like configuration called a crystal lattice. The sodium chloride crystal lattice has a zero net charge.

Water will dissolve the sodium chloride crystal lattice and physically separate the two ions. Once in solution, the sodium ion and the chloride ion will float around in the solution separately and randomly.

This is generally true for all inorganic salts. Once in a solution, the ions will float apart and become two separate species dissolved in the water. Typical, charged ions exist separately in a solution. If the water dries up, the cations and the anions will find each other and fuse back into a crystal lattice with a zero net charge.

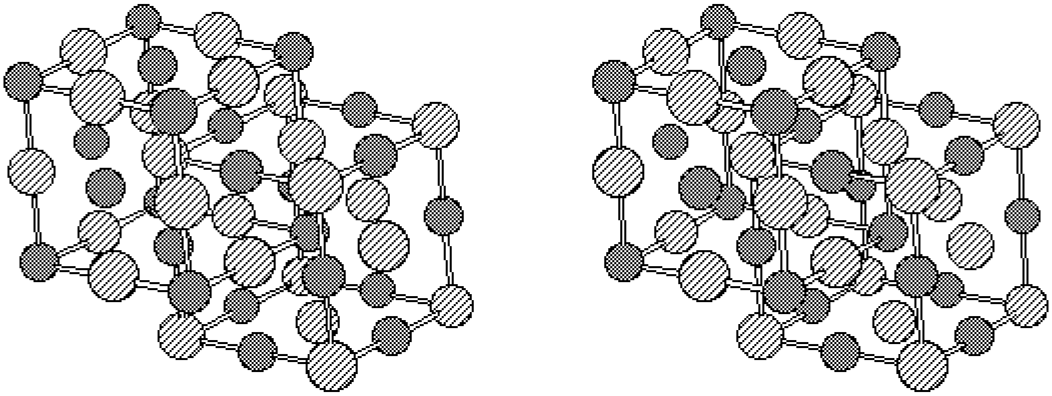


Figure [5.3] The crystal lattice model of sodium chloride. The larger spheres are chloride anions.

2.2.8 Cation Exchange and Agriculture – Reclaiming Salt Affected Land

In situ soil electrical conductivity monitoring is very important in agriculture because the salinity levels in the soil can have dramatic affects on crop health and yields.

Agricultural soils over time may become sodic or saline and this may dramatically affect the health and yields of the crops. There are techniques that can remove the sodium to improve soil quality and increase crop production. The Stevens Hydra Probe can be an invaluable tool for monitoring the progress of saline soil reclamation.
The outer portion of a soil particle at the molecular level is typically negatively charged. Positively charged sodium ions will bind or “hook” onto the surface of the soil micro particle. The opposite charges create an electronic attraction between the sodium ion and the soil. The sodium ions compete for negatively charged sites on the soil particle surface and in doing so, disperse the aggregates of soil. The aggregate dispersion of the soil caused by the sodium ions will decrease the porosity of the soil. As porosity decreases, the water holding capacity of the soil decreases. Not only are high levels of sodium ions toxic to the crops, it decreases the water that would be available to the plants.

Ion exchange reactions are the basis behind the soil reclamation practices. Saline soil reclamation includes the application of calcium rich material (such as lime or gypsum) onto the salt affected land. After application of this material, the saline affected area should be irrigated (with low saline water) to translocate the calcium down into the different horizons (layers) of soil. Once calcium ions are introduced into the horizons of the soil, the ion exchange begins.

The calcium ion has a 2+ charge where the sodium ion has a 1+ charge. Because the calcium ion has a greater electric charge, the soil will have a stronger affinity for the calcium ions than the sodium ions. The sodium is then exchanged with calcium on the soil anionic sites.

Once the calcium becomes the dominant ion present, the porosity of the soil will increase. This will be evident in the Hydra Probe soil moisture data. As the porosity increases the hydraulic conductivity will increase. The user will notice trends in the wetting fronts such as higher soil moisture values after irrigation, quick decreases to field capacity and shorter time intervals from one probe to the next as the water percolates downward.

With calcium as the dominant ion present, irrigation continues, leaching the calcium out of the soil. Calcium is less soluble than sodium, and will fall out of solution at some depth below the root zone. The removal of the calcium will be apparent in the Hydra Probe data by the decrease in electrical conductivity. The decrease in electrical conductivity will start at the Hydra Probe that is the closest to the surface, as the calcium leaches downward. Once the electrical conductivity below the root zone reaches an acceptable level, the soil can then be cultivated.

2.3 Soil Temperature

The user can select Fahrenheit or Celsius. Diurnal (daily) temperature fluctuations between daytime highs and nighttime lows may be observed with the Hydra Probe's temperature data. These fluctuations will become less pronounced with depth. Vegetation, tree canopy, and soil moisture are factors that will affect the diurnal soil temperature fluctuations. For example, in the American Southwest, A Hydra Probe buried at a five inch depth will have very pronounced temperature fluctuations between the nighttime lows and the daytime highs if there is no vegetation insulating the soil. Seasonal trends can also be observed in soil temperature data. The soil temperature range for the Hydra Probe is -30 to 40

2.3.1 Diode Temperature

The Diode Temperature is the temperature of the electronics within the Hydra Probe housing. It corresponds to V4. Because the electronics produces a negligible amount of heat while taking a reading, the diode temperature is usually very close, if not the same value as soil temperature. The diode temperature is used by the Hydra Probe to make algorithmic temperature correction to the electronics.

2.4 Analog Hydra Probe Output

Parameters V1, V2, V3 and V4 returned by the digital probes correspond to the voltages read from the analog probe. In almost all applications, V1, V2, V3, V4 and V5 by themselves are of no interest to most users of the digital Hydra Probe. See section 2.2 for analog processing information.

2.4.1 Raw Voltages V1, V2, and V3.

The first three voltages are the raw signal responses. The Hydra Probe is an impedance based dielectric spectrometer in that it is determining the complex dielectric permittivity by measuring the reflected voltages produced by the characteristic impedance of a coaxial wave guide. A standing wave generated from the reflection of an electromagnetic wave at a radio frequency of 50 MHz. The 50 MHz electromagnetic wave propagates within the wave guide. The soil absorbs most of the wave. The portion of the wave that reflects back down the wave guide encounters the emission propagation creating a standing wave. The first three voltages represent the behavior of the standing wave and thus the complex dielectric permittivity. The direct measurement of the complex dielectric permittivity from the raw signal responses is the basis behind the other parameters and makes the Hydra Probe unique among other electromagnetic based sensors. (Campbell, 1990, Seyfried and Murdock, 2004).

2.4.2 V4

V4 is the raw signal response of the diode thermistor. The diode thermistor is located within the probe housing. V4 is used to make temperature corrections to the electronics. See Diode temperature below for more information.

2.4.3 V5

V5 is the raw signal response of the soil thermistor. The soil thermistor is located in the stainless steel base plate between the tines. It is in close proximity to the soil providing accurate soil temperature readings from -30 to 40 degrees Celsius. Complex dielectric permittivity is influenced by temperature. Not only can the Hydra Probe measure soil temperature, it can make temperature corrections to the calibration curves based on the temperature corrections of the complex dielectric permittivity. See temperature corrected real and imaginary dielectric permittivity for more information. See section 2.2.3 for analog processing information.

2.4.4 ADC Reading 1 through 5

The ADC Reading 1 through 5 are the analog to digital values at 10 bits. They are the binary numbers that correspond to V1 through V5. They are used by Stevens for development or trouble shooting purposes.

3 Maintenance and Trouble Shooting

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) The probe is defective.

3.1 How to tell if the Hydra Probe is Defective

The Hydra Probe goes through several tiers of quality control testing at various stages of production; therefore, it is extremely uncommon for a user to encounter a bad probe. Also, the probes are rugged enough to function for many years buried in soil.

The Hydra Probe is a dielectric constant sensor, therefore if the Hydra Probe is placed in material with a know dielectric constant, the Hydra Probe's dielectric constant measurements should match that of the literature values. Distilled water has a dielectric constant of about 80. The Hydra Probe when placed in distilled water should have a real dielectric permittivity (parameter K at room temperature) from 75 to 85 and the imaginary permittivity constant should be less than 5. Be sure to use a clean plastic container and make sure the probe is completely submerged.

All configurations of the Hydra Probe should have a real dielectric permittivity of about 80 in water. For special instructions for trouble shooting analog probes see Section 2.

If the Hydra Probe produces a real dielectric permittivity of 80 +/-5 in distilled water at room temperature, the Hydra Probe is probably NOT malfunctioning.

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.

3.1.1 SDI-12 Hydra Probe Trouble shooting commands

To verify that the Hydra Probe is functioning properly perform the following commands: Place the Hydra Probe 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 Hydra Probe that is functioning properly should be *1+77.895+78.826+2.462.* From this example, the real dielectric permittivity is 77.895, the temperature corrected dielectric constant is 78.826, 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. After the probe verification, the user may wish to reset the probe back to the default parameter set or any other parameter set.

3.2 Check the Wiring

If the user is unable to get a response from the Hydra Probe it is recommended to first physically check wire connections from the probe to the logger. Check the cable for cuts and abrasions.

3.3 Logger Setup

If the connections are sound, the user will need to check the logger's setup. Programming a data logger is not 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 by disconnecting and reconnecting power. *Are the data ports enabled? Are the data ports scaled properly in the appropriate units? Are the probes and logger adequately powered? Is the data properly reported and archived on the logger's firmware?* If the logger has GUI based operation software, there may be a help function. If the logger only accepts terminal command scripts in a terminal window, refer to the logger's manual or manufacturer. Also, make sure the computer is properly connected to the logger. *Is the computer on the proper COM port? What about the Baud rate? Does the logger need a NUL modem or optical isolator in order to be connected to a computer?* Most of the technical support questions Stevens receives are not due to malfunctioning probes but rather an incorrect data logger setup.

3.4 Soil Hydrology

Sometimes the soil moisture data may look incorrect when in fact the Hydra Probes 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 Hydra Probe 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 6.1 shows the measurement volume where the Hydra Probe 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.

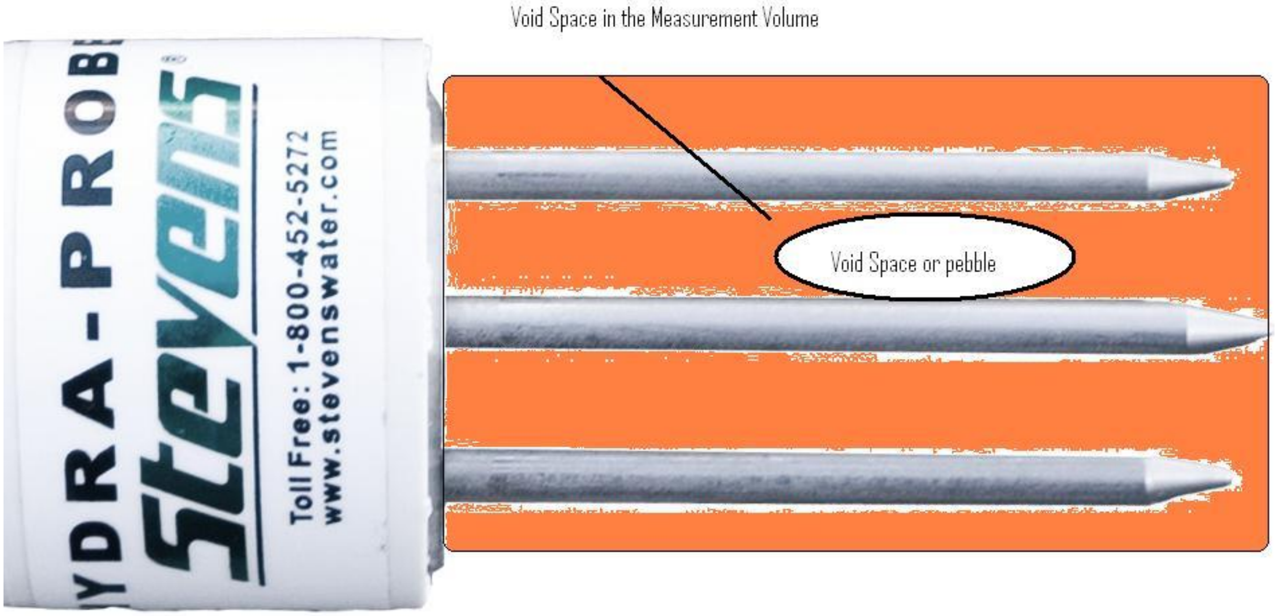


Figure 6.1 Measurement volume with a void space between the tine assembly.

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.

3.4.1 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 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.

3.4.2 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 where as silt particles are spherical. Water basically gets stuck between the planar plate shaped clay particles and thus slows the flow of water.

3.4.3 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 Hydra Probes 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 [6.1]

$$\rho_b = m/V \quad [6.1]$$

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 a individual soil particle such as a grain of sand. The two densities should not be confused with one an other. 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 [6.2]

$$\varphi = 1 - \frac{\rho_b}{\rho_p} \quad [6.2]$$

3.4.4 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 Hydra Probe, the probe will signal average the fissure 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 Hydra Probe measurements are being affected by shrink/swell clays, It recommend to relocate the probe to an adjacent location.

3.4.5 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.

3.4.6 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 Hydra Probes' tine assembly makes an excellent home. If the Hydra Probe'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 3.6 is recommended.

3.4.7 Salt Affected Soil and the Loss Tangent

The Hydra Probe 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 50Mhz. While the Hydra Probe performs relatively well in salt affected soils, salts that are dissolved in the soil water will influence both dielectric permittivities constants and thus the measurements. The salt content will increase the imaginary dielectric constant and thus the soil electrical conductivity. See Chapter 5. The Hydra Probe will not measure electrical conductivity 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 Hydra Probes' performance in salt affected soil, it is useful to use the loss tangent equation [6.2].

$$Tan\ \delta = \frac{\varepsilon_i}{\varepsilon_r} \qquad [6.2]$$

The loss tangent (Tan δ) is simply the imaginary dielectric constant divided by the real dielectric constant. If Tan δ become greater than 1.5 than the Hydra Probes calibration becomes unreliable. It is interesting to note that the Hydra Probe 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 section 5 for custom calibrations.

3.4.8 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 trough 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.

3.4.9 Frozen Soil

The Hydra Probe 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.

Appendix A - SDI-12 Communication

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 Hydra Probe has three wires. A ground wire, a +12 volt power wire and a blue data wire. The data wires from multiple probes can be connected in parallel to a terminal assembly. A single data wire from the terminal assembly can then be connected to the SDI-12 data port on the logger.

Power Requirements	9 to 20 VDC (12VDC Ideal)
Red Wire	+Volts Power Input
Black Wire	Ground
Blue Wire	SDI-12 Data Signal
Baud Rate	1200
Power Consumption	<1 mA Idle 30 mA Active

Table 2.2 Digital SDI-12 Hydra Probe II Information.

Addressing an SDI-12 Sensor

Data is communicated digitally between the probe and the logger on the single data wire. Communications over this single wire is necessarily half duplex. That is, only one device can send data at a time. SDI-12 communications is of the master/slave variety. The logger is the master and all of the probes are slaves. The probes must each have a unique address. This must necessarily be set before the probes are all connected. The probes reply with information only when they have received a valid command that is addressed to them.

It is important to note that each SDI-12 sensor must have its own unique address. If two sensors on a logger have the same address, it will disrupt communication between the loggers and the probes. The default address for the Hydra Probe is “0”. The user must change the address of the probe from 0 to another letter or digit as the probes are added to the terminal assembly. The data logger's “Transparent Mode” can be used to set this address.

Changing SDI-12 Parameter Sets

In Transparent Mode, the parameter set can be changed to an alternate parameter set or set to any parameter set the user wants. For the example below, 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 Hydra Probe 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 “`1M!`” or the user may type

“**1XM=GH!’** to only measure soil moisture and temperature. If the user wishes to display only the 5 raw voltages, type “**1M4!”.**

Stevens Hydra Probe SDI-12 Command Specification

For Firmware Versions 2.7 and Later

The Stevens HP2 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.

A complete description of the SDI-12 Command Grammar is contained in the SDI-12 Protocol Specification. This document is available online from the SDI-12 Support Group website:

http://www.sdi-12.org/

Measurement Commands

The HP2 can return any of 22 values, or parameters, as they are called in SDI-12 terminology. The following table lists the values and letter used to refer to them:

SDI-12 Parameters

Selector	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
Q	-	-
R	ADC Reading 1	-
S	ADC Reading 2	-
T	ADC Reading 3	-
U	ADC Reading 4	-
V	ADC Reading 5	-

Table 1 – Parameter Selectors

The HP2 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 22 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 2 – Measurement Command Sets

SDI-12 Extended Command Summary

The HP2 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**
aXS!	Get soil type
aXS<soil>!	Set soil type
aXP0!	Turn on the probe circuitry
aXP1!	Turn off the probe circuitry
aXM!	Get the default measure set
aXM=0!	Set the default measure set to set 0
aXM=1!	Set the default measure set to set 1
aXM=2!	Set the default measure set to set 2
aXM=3!	Set the default measure set to set 3
aXM=4!	Set the default measure set to set 4
aXM=5!	Set the default measure set to set 5
aXM=<set>!	Set custom default measure set
aXR!	Reset probe to defaults
aXY<constant>!	Get water constant
aXY<constant><float>!	Set water constant
aXW!	Get probe warmup time
aXW<warmup>!	Set probe warmup time

Table 3 – SDI-12 Extended Commands

<soil> Single ASCII character representing the soil type. The default soil type is *4*.

Values:

1	Sand
2	Silt
3	Clay
4	Loam
C	Custom 1
D	Custom 2

<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.*

<constant>	Single ASCII character specifying the water constant accessed by the command. Water constants are used in conjunction with the *Custom* soil types. When a *Custom* soil type is selected, the probe will use the water constants to compute the soil moisture content. Custom 1 uses all 4 constants, Custom 2 uses the first 2 constants only. The default constant values are the same as the *Silt* soil type.

Values:		
	A	Constant A
	B	Constant B
	C	Constant C
	D	Constant D

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

<warmup> 16-bit integer value between 0-65535. This is the number of milliseconds that the probe is enabled before measurements are taken and ready. The default value is *1000*.

<id-string> 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:

```
012STEVENSW0000012.7ST4SN00000000
```

SDI-12 Extended Command Descriptions

aXS! – Get soil type

Returns the current soil type of the HP2.

Response: a<soil><CR><LF>

aXS<soil>! – Set Soil Type

Sets the soil type specified by <soil>. Returns the new soil type of the HP2.

Response: a<soil><CR><LF>

aXP0! – Turn on probe circuitry

Switches on the voltage to the HP2 RF section.

Response: aPROBE:ENABLED<CR><LF>

aXP1! – Turn off probe circuitry

Switches off the voltage to the HP2 RF sections.

Response: aPROBE:DISABLED<CR><LF>

aXM! – Get default measurement set

Returns the <set> specifying the readings returned by the aM! Command.

Response: a<set><CR><LF>

aXM=0! – Set default measurement set to measurement set 0

Sets the default measurement set to *HJFGOKMLN*.

Response: a*HJFGOKMLN* <CR><LF>

aXM=1! – Set default measurement set to measurement set 1

Sets the default measurement set to *FG*.

Response: aFG<CR><LF>

aXM=2! – Set default measurement set to measurement set 2

Sets the default measurement set to *FGHOJ*.

Response: aFGHOJ<CR><LF>

aXM=3! – Set default measurement set to measurement set 3

Sets the default measurement set to *KLMNOPQ*.

Response: aKLMNOPQ<CR><LF>

aXM=4! – Set default measurement set to measurement set 4

Sets the default measurement set to *ABCDE*.

Response: aABCDE<CR><LF>

aXM=5! – Set default measurement set to measurement set 5

Sets the default measurement set to *RSTUV*.

Response: aRSTUV<CR><LF>

aXM=<set>! – Set custom default measurement set

Set the default measurement set to a custom <set>. Returns the new default measurement set.

Response: a<set><CR><LF>

aXR! – Reset probe to defaults

Resets all probe settings to default.

Response: a<id-string><CR><LF>

aXY<constant>! – Get water constant

Returns the water constant specified by <constant>.

Response: a<float><CR><LF>

aXY<constant><float>! – Set water constant

Sets the water constant specified by <constant> with the specified <float> value. Returns the new <float> value of the specified water constant.

Response: a<float><CR><LF>

aXW! – Get probe warmup time

Returns the warmup time used by the HP2 before taking a measurement.

Response: a<warmup><CR><LF>

aXW<warmup>! – Set probe warmup time

Sets the warmup time specified by <warmup>. Returns the new warmup time.

Response: a<warmup><CR><LF>

Appendix B - RS-485 Communication

The RS-485 Hydra Probe is also digital and uses an RS-485 communication format. The RS-485 Hydra Probe has 4 wires: a ground wire, a +12 volt power wire and 2 data wires. The RS-485 Hydra Probe 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.

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 2.3 Digital RS-485 Hydra Probe II Information.

Stevens Hydra Probe RS-485 Command Specification

For Use with Firmware Version 2.7 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>
```

<soil>: `Soil Type, 1 character {‘1’ | ‘2’ | ‘3’ | ‘4’| ‘C’ | ‘D’}`

<quick>: `Quick mode, 1 character {‘1’ – ‘6’, ‘X’}`

<warmup>: `Warmup time, 1-5 digits, 0-65535`

<bool>: `Boolean value, 1 character, {‘0’ | ‘1’}`

<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”`

Hydra Probe 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>`

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>`
Write Response: `<addr><soil><CR><LF>` (No response for wildcard address)

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>`

Custom Water Constants
Description: Gets/sets the custom probe water constants.
Access Level: Read/Write
Read Addresses: Broadcast, Exact
Read Command: `<addr>X<a>=?<CR><LF>`
Read Response: `<addr><float><CR><LF>`
Write Addresses: Exact
Write Command: `<addr>X<a>=<float><CR><LF>`
Write Response: `<addr><float><CR><LF>`

Quick Mode
Description: Gets/sets the probe quick reading response mode.
Access Level: Read/Write
Read Addresses: Broadcast, Exact
Read Command: `<addr>QM=?<CR><LF>`
Read Response: `<addr><quick><CR><LF>`
Write Addresses: Exact
Write Command: `<addr>QM=<quick><CR><LF>`
Write Response: `<addr><quick><CR><LF>`

Debug Commands

Warmup Time

Description: Gets/sets the custom probe warmup time.
Access Level: Read/Write
Read Addresses: Broadcast, Exact
Read Command: `<addr>WT=?<CR><LF>`
Read Response: `<addr><warmup><CR><LF>`
Write Addresses: Exact
Write Command: `<addr>WT=<warmup><CR><LF>`
Write Response: `<addr><warmup><CR><LF>`

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:
      F) Temp C
      G) Temp F
      H) Moisture
      I) Loss Tangent
      J) Soil Electrical Conductivity (tc)
      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
```

Appendix C – Custom Calibration Programming

The Stevens Hydra Probe has four calibrations built into the firmware for four soil textures, sand, silt, clay and loam. While these four calibrations will accommodate most soils, sometimes the user will need to create their own calibration and have the Hydra Probe output the results using the custom calibration.

The calibrations curves are polynomials that calculate the soil moisture from the real dielectric permittivity. There are two polynomials that can be used and will mathematically have the appearance of equation [1] or [2]

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

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

Where θ is moisture E_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 [1] and [2].

A custom calibration or a statistical data validation for an exciting soil moisture calibration is labor intensive. The user will need to experimental 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 values. The volumetric soil moisture value will need to be calculated from the dry bulk density and the gravimetric soil moisture values. The user will then need to mathematically solve 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 Hydra Probe. Below is a procedure for programming a custom calibration into an RS485 and SDI-12 Hydra Probe

Custom Calibration Procedure for the RS485 Hydra Probe

The table below describes the calibration options

Soil Texture	**Key Character**	Polynomial
SAND	1	3rd order polynomial equation [1]
SILT	2	3rd order polynomial equation [1]
CLAY	3	3rd order polynomial equation [1]
Loam	4	Semi linear polynomial equation [2]
Custom 1	C	Sets A, B, C, D for equation [1]
Kustom 2	K	Sets A, B for equation [2]

Table A1

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 Loam soil calibration	<addr>ST=4<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 A2. <CR> means carriage return, <LF> means line feed, <addr> means address of probe. The default address is "000".

The best way to explain this procedure is by example using the commands in table A1 and A2.

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 Hydra Probe

Table A3 and A4 shows the SDI-12 commands for changing or creating different calibrations. In order to communication 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 enter while in an SDI-12 transparent mode.

Soil Texture	**ASCII Character**	**Polynomial**
SAND	1	3rd order polynomial equation [1]
SILT	2	3rd order polynomial equation [1]
CLAY	3	3rd order polynomial equation [1]
Loam	4	Semi linear polynomial equation [2]
Custom 1	C	Sets A, B, C, D for equation [1]
Kustom 2	K	Sets A, B for equation [2]

Table A3

Command Description	**SDI-12 Command**
Get current calibration	aXS!?<CR><LF>
Switches the Probe to Custom 1 calibration	aXSC!<CR><LF>
Switches the Probe to Kustom 2 calibration	aXSK!<CR><LF>
Switches the Probe to Loam soil calibration	aXS4!<CR><LF>
Sets the A coefficient	aXYA<value>!<CR><LF>
Sets the B coefficient	aXYB<value>!<CR><LF>
Sets the C coefficient	aXYC<value>!<CR><LF>
Sets the D coefficient	aXYD<value>!<CR><LF>
Verifies A coefficient	<addr>XA?CR><LF>

Table A4. <CR> means carriage return, <LF> means line feed, <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 Hydra Probe 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 setting 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

A Note About Parameter Storage
The soil type and the coefficients for the custom soil calibrations are stored in EEPROM. The same values are used for both RS-485 probes and SDI-12 probes. This means that if you program a probe for a custom soil type using RS-485 commands, and then switch to SDI-12, the programming will remain. The soil type and coefficients that are set using the RS-485 commands are the same ones that are used by the SDI-12 commands

Appendix D – Hyd_File.Exe For use with Analog Hydra Probes

INTRODUCTION
[Note that Appendix D is not applicable for digital Hydra Probes]

The Stevens Hydra Probe Soil Sensor works with standing wave low impedance based technology rather than with a time-domain-reflectivity (TDR)-based technology like Campbell’s sensor. Therefore its output is a series of four voltages which the CSI data loggers read in volts. HYD_FILE2_5 will allow the user to convert tables of raw voltage data into the parameters of interest.

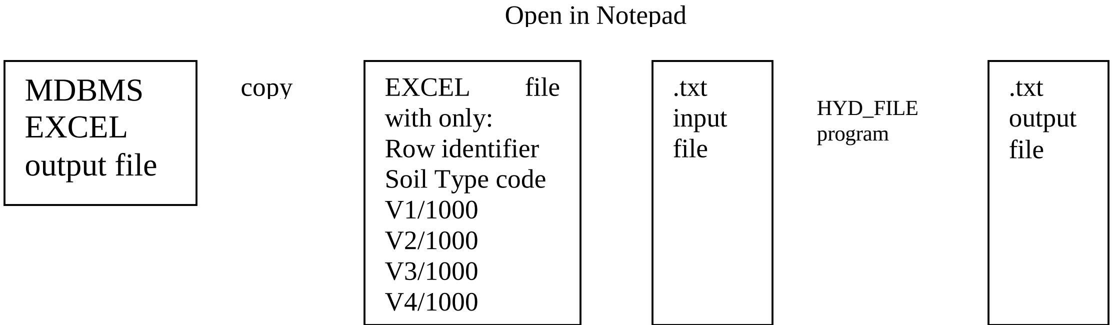
These four voltage outputs must be converted into useful measurement units by the the HYD_FILE2_5 program found at http://www.stevenswater.com/index.aspx at the Hydra Probe page. This documentation covers a procedure to take the four raw voltage values and convert them into the parameters of interest. .

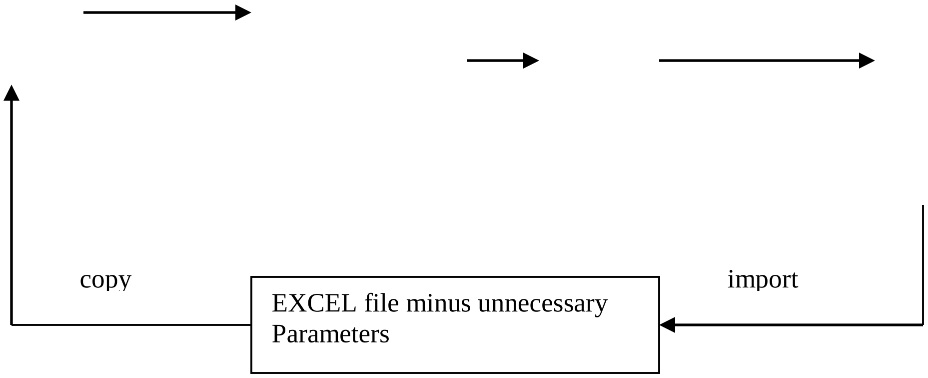
This documentation concludes with an appendix of further documentation of another Stevens program (HYDRA2_5.exe) that converts data one record at a time. HYDRA.exe is useful for quick spot checks of a single set of voltages but not for entire data sets. A second appendix provides contact persons with the company. In most applications, the digital Hydra Probe II should be used instead analog Hydra Probe.

THE PROCESSING PATHWAY

Data are extracted from LoggerNet data that has been put into the AMNET MDBMS database via an EXCEL spreadsheet. The first step: out of all such data you extract the four voltages from each Hydra-Probe onto a new spreadsheet, manipulate and add some more data manually, and then use Notepad to create a .txt file. The second step: you process the .txt file with the Stevens program HYD_FILE2_5 to obtain a second .txt as output. The third step: you import this .txt file into a new EXCEL spreadsheet, delete superfluous data not needed by your customer, and copy into the original EXCEL spreadsheet that you began with.

Here is a flow chart of the process you need to follow in processing Hydra-Probe voltage data into useful units of measurement.



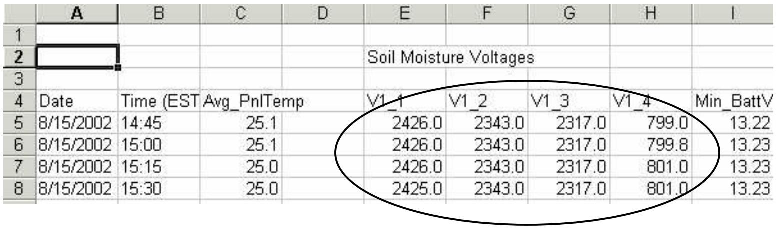


You have to repeat this processing pathway for each probe used on the DCP since the Stevens program <u>can only process one probe at a time</u>.

STEP ONE: PREPARATION OF THE HYD_FILE INPUT FILE

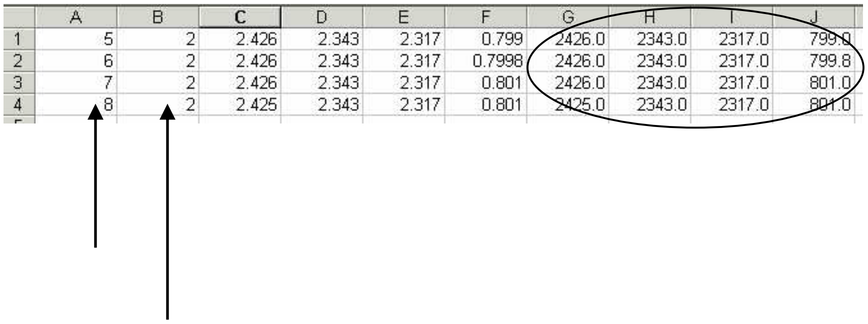
"out of all such data you extract the four voltages from each Hydra-Probe onto a new spreadsheet, manipulate and add some more data manually, and then use Notepad to create a .txt file." The data needs to be in Volts. If the data is in mV, then convert it into volts dividing by 1000.

1. For the date/time period of interest, copy from the MDBMS EXCEL output file of the DCP with the Stevens Hydra-Probe(s), the <u>four columns of voltages</u> for the first probe. Note the row numbers on this original MDBMS output spreadsheet for your date/time period of interest. Copy the four columns to a new spreadsheet and put into columns G, H, I, and J. For example:



	A	B	C	D	E	F	G	H	I
1									
2					Soil Moisture Voltages				
3									
4	Date	Time (EST	Avg_PnlTemp		V1_1	V1_2	V1_3	V1_4	Min_BattV
5	8/15/2002	14:45	25.1		2426.0	2343.0	2317.0	799.0	13.22
6	8/15/2002	15:00	25.1		2426.0	2343.0	2317.0	799.8	13.23
7	8/15/2002	15:15	25.0		2426.0	2343.0	2317.0	801.0	13.23
8	8/15/2002	15:30	25.0		2425.0	2343.0	2317.0	801.0	13.23

2. Create four more columns in this new spreadsheet of the voltages divided by 1000 so that the numbers are in units of volts instead of millivolts which MDBMS gives. Map column G to column C, column H to column D, column I to column E, and column J to column F using the cell formula "C row x = G row x / 1000" for the first mapping, and so on. Put into column A numbers that match the row numbers containing the set of four voltages on the original MDBMS spreadsheet.



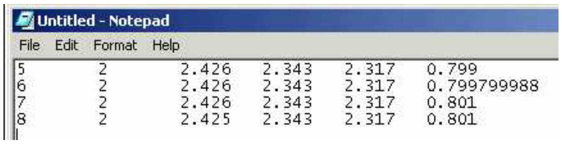
	A	B	C	D	E	F	G	H	I	J
1	5	2	2.426	2.343	2.317	0.799	2426.0	2343.0	2317.0	799.0
2	6	2	2.426	2.343	2.317	0.7998	2426.0	2343.0	2317.0	799.8
3	7	2	2.426	2.343	2.317	0.801	2426.0	2343.0	2317.0	801.0
4	8	2	2.425	2.343	2.317	0.801	2425.0	2343.0	2317.0	801.0

Numbers in Column A correspond to row numbers in original file

Column B is soil type: 1 = sand; 2 = silt; 3 = clay

Columns C through F show numbers from columns G through J
Divided by 1000

3. Step one is finished when you copy the cells you have developed in columns A to F (omit columns G to J) out of this new spreadsheet into MS Notepad. You now have:



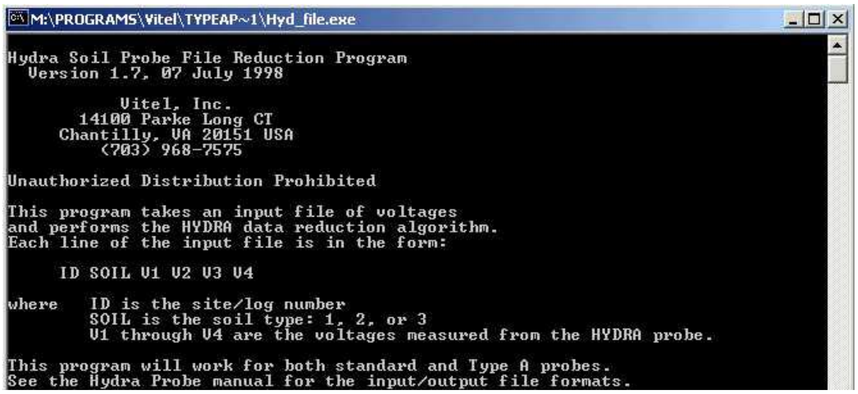
```
5       2       2.426   2.343   2.317   0.799
6       2       2.426   2.343   2.317   0.799799988
7       2       2.426   2.343   2.317   0.801
8       2       2.425   2.343   2.317   0.801
```

So that the HYD_FILE program can access this file, <u>save it</u> to whatever directory and folder where you have HYD_FILE. (Note. You must have the HYD_File and the input notepad sheet in the same file.) You have now created the input file for the Stevens conversion program.

STEP TWO: CONVERTING THE DATA

“you process the .txt file with the Stevens program HYD_FILE to obtain a second .txt as output”

1. Double click on the Stevens program HYD_FILE.exe to get into this DOS-based program. You will see this screen:



```
Hydra Soil Probe File Reduction Program
  Version 1.7, 07 July 1998

         Vitel, Inc.
     14100 Parke Long CT
    Chantilly, VA 20151 USA
        (703) 968-7575

Unauthorized Distribution Prohibited

This program takes an input file of voltages
and performs the HYDRA data reduction algorithm.
Each line of the input file is in the form:

     ID SOIL V1 V2 V3 V4

where   ID is the site/log number
        SOIL is the soil type: 1, 2, or 3
        V1 through V4 are the voltages measured from the HYDRA probe.

This program will work for both standard and Type A probes.
See the Hydra Probe manual for the input/output file formats.
```

2. Scroll down to the <u>first</u> query that asks for the file name of the input file you have just created.

CAUTION: the filename must observe DOS limitations (filename 8 characters or less) and must include the filename extension ".txt".

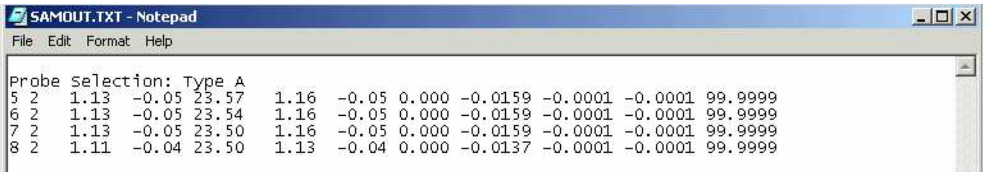
After typing it in and entering, you get a <u>second</u> query for the output file name. SUGGESTION TO AVOID CONFUSION: repeat the filename of the input file and add the 3 letters "OUT" to it (making sure that the total number of characters is 8 or less). That way you can remember which input file goes with which output file.

After responding to the first two queries, you will see the following in the screen the input filename "sam.txt" and the output filename "samOUT.txt":

```
          Vitel, Inc.
      14100 Parke Long CT
     Chantilly, VA 20151 USA
         (703) 968-7575

Unauthorized Distribution Prohibited

This program takes an input file of voltages
and performs the HYDRA data reduction algorithm.
Each line of the input file is in the form:

     ID SOIL V1 V2 V3 V4

where   ID is the site/log number
        SOIL is the soil type: 1, 2, or 3
        V1 through V4 are the voltages measured from the HYDRA probe.

This program will work for both standard and Type A probes.
See the Hydra Probe manual for the input/output file formats.

Enter the file name to be converted:  sam.txt

Enter the output file name:           samOUT.txt

Type A Probe (Y/N):  Y
```

You need to respond to a <u>third</u> query asking whether or not you have data from a Type A Hydra-Probe. The Meteorology Team has both the old "Standard" probes and the new "Type A" probes. Be careful which one the DCP had on it. Generally, we now use all Type A probes because they can be used with the CR10T data logger that only can read voltages up to 2.5 VDC. The old Standard Hydra-Probes output as much as 5 VDC and required a "voltage divider" to be added to the terminal strip of the CR10T data logger.

3. After you hit <Enter> in the third query, HYD_FILE ingests the input text file and outputs a text file with the name you called for in the second query. In the example, HYD_FILE created the output file "samOUT.txt" which, when opened within MS Notepad, looked like this:



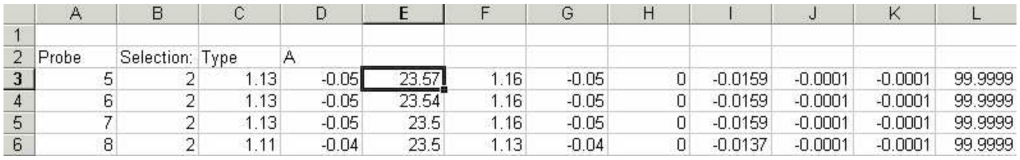
```
Probe selection: Type A
5 2   1.13  -0.05 23.57   1.16  -0.05 0.000 -0.0159 -0.0001 -0.0001 99.9999
6 2   1.13  -0.05 23.54   1.16  -0.05 0.000 -0.0159 -0.0001 -0.0001 99.9999
7 2   1.13  -0.05 23.50   1.16  -0.05 0.000 -0.0159 -0.0001 -0.0001 99.9999
8 2   1.11  -0.04 23.50   1.13  -0.04 0.000 -0.0137 -0.0001 -0.0001 99.9999
```

You now have the actual measurements in proper units and have completed the second step in the Stevens-Vitel data processing.

STEP THREE: MERGING THE DATA INTO YOUR FINAL SPREADSHEET

> “you import this .txt file into a new EXCEL spreadsheet, delete superfluous data not needed by your customer, and copy into the original EXCEL spreadsheet that you began with”

1. Open a new EXCEL worksheet and import the HYD_FILE output text file. In the EXCEL Import Wizard Step 1, click on “Delimited” not “Fixed Width” since the text file records have varying widths. In Step 2, click on “Space delimiter” and click on “Treat consecutive delimiters as one”. Finish with Step 3 as usual and obtain:



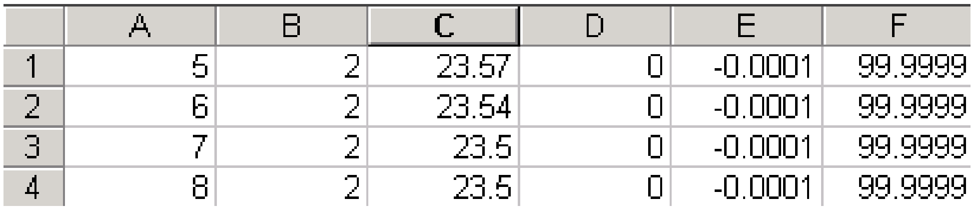
	A	B	C	D	E	F	G	H	I	J	K	L
1												
2	Probe	Selection:	Type	A								
3	5	2	1.13	-0.05	23.57	1.16	-0.05	0	-0.0159	-0.0001	-0.0001	99.9999
4	6	2	1.13	-0.05	23.54	1.16	-0.05	0	-0.0159	-0.0001	-0.0001	99.9999
5	7	2	1.13	-0.05	23.5	1.16	-0.05	0	-0.0159	-0.0001	-0.0001	99.9999
6	8	2	1.11	-0.04	23.5	1.13	-0.04	0	-0.0137	-0.0001	-0.0001	99.9999

2. You must now decide how many of the resulting columns of data you want to delete. It depends upon your customer. Here is the key to the columns (descriptions follow the Stevens-Vitel Instruction Manual in the Tech Library):

Column	Parameter	Units	Description
A	Number of row in original spreadsheet that this row should be merged with	EXCEL Row Integer	Can be deleted after you use this information to “line up” these data with that in the original MDBMS EXCEL spreadsheet
B	Soil Type	Stevens	Should be left in the final data spreadsheet
C	Real part of the dielectric soil constant	Dimensionless	Only needed by research folks and the curious

D	Imaginary part of the dielectric soil constant	Dimensionless	Only needed by research folks and the curious
E	Soil Temperature	Deg Celsius	Probably always kept
F	Column C data corrected to 25'C environment	Dimensionless	Only needed by research folks and the curious
G	Coumn D data corrected to 25'C environment	Dimensionless	Only needed by research folks and the curious
H	Soil Moisture	Fraction of water to soil volume	The whole point of doing this!!
I	Loss Tangent	Unitless	Needs to be <1.5
J	Soil Electrical conductivity	Siemens per meter (Siemen is reciprocal of Ohm = Amps/Volt)	May be of use for detection instrumentation
K	Column J data corrected to 25'C.	Siemens per meter (Siemen is reciprocal of Ohm = Amps/Volt)	May be of use for detection instrumentation
L			

For most customers, you can delete columns C, D, F, G, I, J and may even delete columns K and L for some customers. Be sure to keep column A for now. With columns C,D,F,G,I,J deleted, leaving only A,B,E,H,K,L, you have:



	A	B	C	D	E	F
1	5	2	23.57	0	-0.0001	99.9999
2	6	2	23.54	0	-0.0001	99.9999
3	7	2	23.5	0	-0.0001	99.9999
4	8	2	23.5	0	-0.0001	99.9999

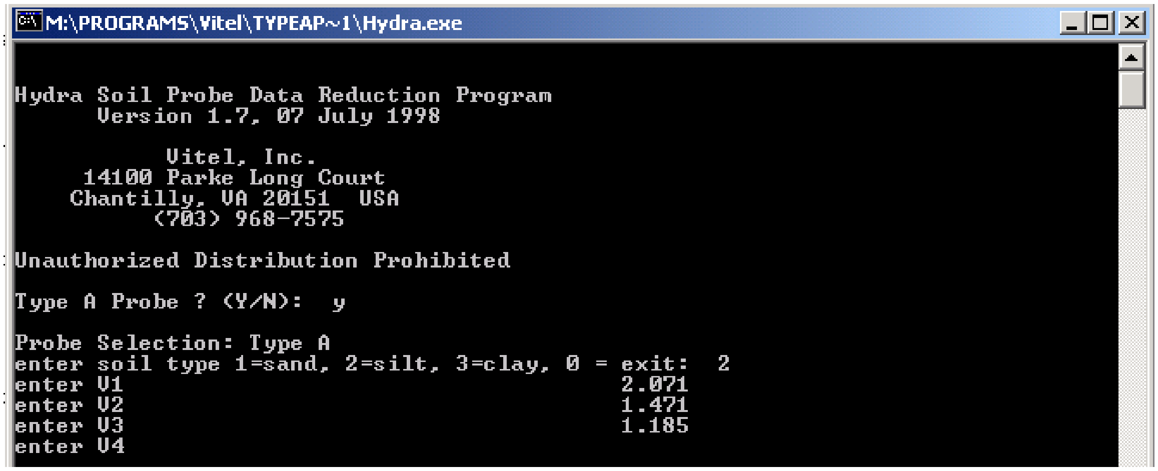
3. Next you merge this new spreadsheet data into the original spreadsheet taken from MDBMS. Here's where the Row A numbers come in handy. These numbers clue you where to copy these new spreadsheet data into the original. Merely line up the numbers with the rows of the original. After copying onto the original, you can then delete the column of these numbers.

You finish the job by correctly labeling the column headers for the customer and by adding any other synchronous data that is required from a nearby Basic DCP.

USING THE MANUAL "CALCULATOR" VERSION (HYDRA.exe)

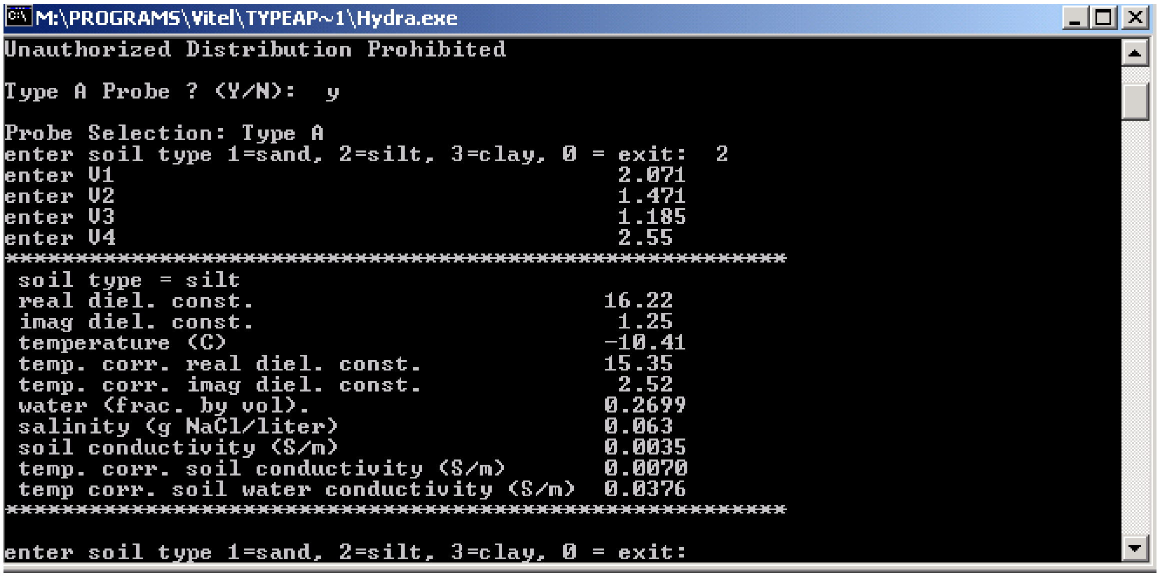
For doing a quick calculation of only a few sets of probe voltages, Stevens-Vitel provides a simple “calculator” version of their program called HYDRA.exe. It may be found at http://www.stevenswater.com/index.aspx under Hydra Probe.

1. Double click on HYDRA.exe and get the input screen:



```
Hydra Soil Probe Data Reduction Program
      Version 1.7, 07 July 1998

           Vitel, Inc.
     14100 Parke Long Court
    Chantilly, VA 20151  USA
          (703) 968-7575

Unauthorized Distribution Prohibited

Type A Probe ? (Y/N):  y

Probe Selection: Type A
enter soil type 1=sand, 2=silt, 3=clay, 0 = exit:  2
enter V1                                        2.071
enter V2                                        1.471
enter V3                                        1.185
enter V4
```

2. Enter the requested data as shown and you get the results instantly:



```
Unauthorized Distribution Prohibited

Type A Probe ? (Y/N):  y

Probe Selection: Type A
enter soil type 1=sand, 2=silt, 3=clay, 0 = exit:  2
enter V1                                        2.071
enter V2                                        1.471
enter V3                                        1.185
enter V4                                        2.55
********************************************************
 soil type = silt
 real diel. const.                            16.22
 imag diel. const.                             1.25
 temperature (C)                              -10.41
 temp. corr. real diel. const.                15.35
 temp. corr. imag diel. const.                 2.52
 water (frac. by vol).                        0.2699
 salinity (g NaCl/liter)                      0.063
 soil conductivity (S/m)                      0.0035
 temp. corr. soil conductivity (S/m)          0.0070
 temp corr. soil water conductivity (S/m)     0.0376
********************************************************

enter soil type 1=sand, 2=silt, 3=clay, 0 = exit:
```

Appendix E – Statistics

All measurements, no matter how careful and scientific, are subject to some uncertainties. Statistics is the branch of mathematics that can quantify uncertainties. The Hydra Probe's design and signal processing reduces error to a magnitude that has little impact on hydrological measurements such as permanent wilting point, field capacity and saturation.

Parameter	**Accuracy/Precision**
Temperature (C)	+/- 0.6 Degrees Celsius(From -10^o to 36^{o}C)
Soil Moisture wfv (m^3 m^{-3})	+/- 0.03 wfv (m^3 m^{-3}) Accuracy
Soil Moisture wfv (m^3 m^{-3})	+/- 0.003 wfv (m^3 m^{-3}) Precision
Electrical Conductivity (S/m) TUC*	+/- 0.0014 S/m or +/- 1%
Electrical Conductivity (S/m) TC**	+/- 0.0014 S/m or +/- 5%
Real/Imaginary Dielectric Constant TUC*	+/- 0.5 or +/- 1%
Real/Imaginary Dielectric Constant TC*	+/- 0.5 or +/- 5%

Table 1.1 Accuracy and Precision of the Hydra Probes' Parameters.
*TUC Temperature uncorrected full scale
**TC Temperature corrected from 0 to 35^o C

The Hydra Probe offers better precision and accuracy than TDR and other FDR type soil probes because:

1) the signal response is ratiometric maximizing reproducibility,
2) the frequency of 50 MHz provides enough energy to achieve the molecular polarization of water while maintaining a quantifiable imaginary dielectric constant,
3) the values are temperature corrected, and
4) the calibration curves are solute independent in most soil environments and have high R^2 values.

The Hydra Probe's precision was calculated from the standard deviation. The accuracy of the soil moisture measurements were calculated from the deviation about the calibration curve. In most cases, the R^2 value for soil moisture is 0.97 to 0.99. The accuracy of the soil electrical conductivity was calculated from the standard deviation of measurements taken in conductivity standards.

Statistical Definitions

R^2 Shows how well a distribution of points fit on a straight line. The closer the R^2 value is to 1 the more correlated the data the better the accuracy.

$$R^2 = \frac{SS_R}{SS_T} = 1 - \frac{SS_E}{SS_T}.$$

In the above definition,

$$SS_T = \sum_i (y_i - \bar{y})^2, SS_R = \sum_i (\hat{y}_i - \bar{y})^2, SS_E = \sum_i (y_i - \hat{y}_i)^2.$$

The average

$$\overline{x} = \frac{1}{N}\sum_{i=1}^{N} x_i = \frac{x_1 + x_2 + \cdots + x_N}{N}$$

The Standard deviation represents precision and reproducibility.

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \overline{x})^2}$$

Precision verses accuracy

Figure A.4.1 Good Precision Bad Accuracy

Figure A.4.2 Good Accuracy Bad Precision

Root Mean

$$\widehat{\operatorname{MSE}}(\hat{\theta}) = \frac{1}{n}\sum_{j=1}^{n}(\theta_j - \theta)^2 \qquad \operatorname{RMSE}(\hat{\theta}) = \sqrt{\operatorname{MSE}(\hat{\theta})}.$$

Appendix F - Ordering Information

Table E.1 lists the part numbers, and some accessories such as the Stevens Dot Logger. The RS-485 Hydra Probe has a cable length limit of 1000 meters. The SDI-12 version has a limit of 50 meters, and the analog versions have a maximum cable length of 33 meters. It is difficult to go beyond the maximum recommended cable length because capacitance effects of the cable absorb the signal. The Analog, RS-485 and the SDI-12 versions are designed to be permanently (or semi permanently) buried in soil and the portable version allows the user to collect the same quality of data with hand held devices.

Part	**Stevens Part number**
Hydra Probe II Digital 25 ft Cable	93460 -025 (SDI-12 or RS485)
Hydra Probe II Digital 50 ft Cable	93460 -050 (SDI-12 or RS485)
Hydra Probe II Digital 100 ft Cable	93460 -100 (SDI-12 or RS485)
Hydra Probe 1 Analog 25 ft Cable	70030-025
Hydra Probe 1 Analog 50 ft Cable	70030-050
Hydra Probe 1 Analog 100 ft Cable	70030-100
HYD JIG Installation Tool	92880
DOT Logger	93273
Hydra Data Reader	93342 (not including the probe)

Table E.1 Stevens Part numbers for available versions of the Hydra Probe and Accessories

Appendix G - 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!
http://soildatamart.nrcs.usda.gov/

Appendix H - References

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Seyfried, M. S. and M. D. Murdock. 2004. Measurement of Soil Water Content with a 50-MHz Soil Dielectric Sensor. Soil Sci. Soc. Am. J. 68:394-403.

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Whalley, W. R. 1993. Considerations on the use of time-domain reflectometry (TDR) for measuring soil water content. J. Soil Sci. 44:1-9.

Appendix I - WARRANTY

Stevens Water Monitoring Systems, Inc. warrants that the product you have purchased will be free from defects in material and workmanship.

This warranty covers all defects which you bring to the attention of Stevens within two years from the date of shipment.

If your Stevens product is defective, Stevens will repair or replace it and will ship it back to you free of charge.

You must return your Stevens product within two years of the ship date, shipping prepaid, to our factory at this address:

Stevens Water Monitoring Systems, Inc.
5465 SW Western Ave, Suite F
Beaverton, OR 97005
(800) 452-5272

In any correspondence with us, or if you send us part of the product but not all, please include both the model and the serial number of the product.

WHAT THIS WARRANTY DOES NOT COVER

Your rights and remedies are limited to those sent out in this warranty. Stevens Water Monitoring Systems, Inc. disclaims all implied warranties, including the warranties of merchantability and fitness for a particular purpose. Stevens shall not be liable for special, incidental or consequential damage. In no event will Stevens liability to you exceed the purchase price of your Stevens product.

For your reference, please enter the date of receipt and serial number of the instrument covered by this warranty in the space below.

____
Date of receipt

____
Serial number

Appendix J – CE Compliance

Declaration of Conformity

The Manufacturer of the Products covered by this Declaration is

Stevens®
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

Hydra Probe 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.

Signed: Steve McCoy

Steve McCoy, VP of Engineering

February 22, 2010

CE