Soil Sensor

Soil Data Guide

Rev. V
For Firmware Version 6.2

DOC# HP008A

Portland, Oregon, USA | 1 800 452 5272 | 503 445 8000 | www.stevenswater.com

Safety and Equipment Protection

WARNING!

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

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

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

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

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

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

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

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

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

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

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

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

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

The following statement is required by the Federal Communications Commission:

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

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

Regulatory

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
503-445-8000
The Directive covered by this Declaration2004/108/EC Electromagnetic Compatibility directive

The Product Covered by this Declaration

HydraProbe Soil Measurement Sensor

The basis on which Conformity is being Declared

The manufacturer hereby declares that the products identified above comply with the protection requirements of the EMC directive for and following standards to which conformity is declared: EN61326-1:2006

Electrical requirements for measurement, control, and laboratory use EMC requirements Class A equipment – Conducted Emissions and Radiated Emissions

1907/2006/EC REACH
Stevens Water Monitoring Systems, Inc. certifies that the Stevens HydraProbe, including all models and components, are compliant with the European Union Regulation (EC) 1907/2006 governing the Registration, Evaluation, Authorization, and Restriction of Chemicals (REACH) and do not contain substances above 0.1% weight of a Substance of Very High Concern (SVHC) listed in Annex XIV as of June 15th, 2019.

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.

CE

RoHS √

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Preface

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

Easy to Use

Despite this sophistication, the Stevens HydraProbe Soil Sensor is very easy to use. For information about installation, please see the Quick Start Guides, Installation Guide and Manual.

Supporting Documents

Document Number	**Document**
HP003A	HydraProbe Quick Start, SDI-12
HP004A	Soil Data Guide
HP005A	HydraProbe Install and Troubleshooting Guide
HP006A	HydraProbe Quick Start, RS-485
HP007A	Regulatory Information
HP008A	HydraProbe Comprehensive Manual
HP009A	Soil Geomorphology Guide for Soil Sensors
HP010A	Lightning Protection for Meteorological Stations
HP011A	HydraProbe Quick Start, Modbus

Stevens HydraProbe Soil Data Guide

Table of Contents

1 Introduction

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

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

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

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

1.1 **Applications**

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

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

1.2 **Calibrations**

The HydraProbe has three factory calibrations that provide excellent performance in a variety of soils regardless of organic content or texture. The three calibrations are: GENERAL (G) good for most all soils composed of sand, silt, and clay; ORGANIC (O); and ROCKWOOL (R). The factory GENERAL soil calibration is the default calibration and is suitable for most all mineral soils. (See the User Manual for more information)

1.3 ***Dielectric Permittivity***

The complex dielectric permittivities are provided for custom calibrations and other applications. (See the User Manual for more information)

1.4 ***Structural Components***

There are three main structural components to the HydraProbe: the tine assembly, body, and cable. The marine grade stainless steel tine assembly is the four metal rods that extend out of the base plate ground plane and is the wave guide. Each tine is 58 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 other electrical components. The outer casing is PVC and the internal electronics are permanently potted with a rock-hard epoxy resin giving the probes a rugged construction. The cable has a direct burial casing and contains the power, ground, and data wires that are all soldered to the internal electronics.

1.5 *Accuracy and Precision*

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

Parameter	Precision
Real Dielectric Permittivity (isolated)	Range: 1 to 80 where 1 = air, 80 = distilled water Accuracy: < +/- 0.5% Or +/- 0.25 dielectric units
Imaginary Permittivity	Range: 0 to 80 where 1 = air, 80 = distilled water Accuracy: +/- 0.1 up 0.25 S/m and +/-7 at or above 0.5 S/m
Soil Moisture for inorganic mineral soils	Range: From complete dry to full saturation (0% to 100% of saturation) Accuracy[1]: +/-0.01 WFV for most soils (θ m^3,m^{-3}) +/- $\leq$0.03 for fine textured soil
Bulk Electrical Conductivity (EC)	Range: 0 to 1.5 S/m Accuracy[2]: +/- 2.0% or 0.02 S/m whichever is greater
Temperature	Range: -40 to 75^o C Accuracy: +/- 0.3^o C
Inter-Sensor Variability	+/- 0.012 WFV
Pore Water EC	Hilhorst Equation

Table 1.1 Accuracy and Precision of the HydraProbes' Parameters.

[1]Soil Moisture accuracy can vary with soil properties.
[2]Accuracy and range of Bulk EC depends on soil properties and distribution of ions present.

1.6 *Electromagnetic Compatibility* CE

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

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

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

1.7 *Configurations and Physical Specification*

The HydraProbe is available in SDI-12, RS-485, and Modbus, with standard cable lengths of 7.5, 15, and 30 meters.

The three digital formats, SDI-12, RS-485, and Modbus 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, RS-485, and Modbus are three different methods of transmitting digital data. In all versions there are electrical and protocol specifications that must be observed to ensure reliable data collection.

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

Feature	Attribute
Probe Length	12.4 cm (4.9 inches)
Diameter	4.2 cm (1.6 inches)
Sensing Volume[1] (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 16 VDC (12 VDC typical)
Storage Temperature Range	-40 to 75˚C

Table 1.2 HydraProbe Physical Description (All Versions)

[1]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.

1.8 ***Soil Data Accessories and other Products***

1.8.1 Portable soil sensors

Figure 1.1. The portable HydraGO-FLEX and HydraGO-S allow for wireless on the go measurements of soil moisture. Connect via Bluetooth with a smartphone and the HydraGO App.

There are two portable HydraProbe soil sensor systems, the HydraGO-FLEX and the HydraGO-S. Each model of the HydraGO has Bluetooth and can connect to a mobile device. The HydraGO App will work with either Android or Apple iOS devices. The HydraGO-S provides GPS data from the device's GPS which has a typical accuracy of 5 to 10 meters depending on the device. The HydraGO FLEX has an internal survey grade GPS, which has sub-meter accuracy depending on satellite conditions. The HydraGO-S has a HydraProbe mounted to a shaft for quick soil measurements. The HydraGO-FLEX includes a detachable HydraProbe that comes in two models. One model of the HydraGO Probe has a flexible cable good for spot measurements, down holes, or on-the-go surface measurements. The second model has a direct buriable grade cable so that the probe can remain buried underground.

1.8.2 Tempe Cell

The Stevens Tempe Cell System can employ various methods to eliminate the uncertainties from soil moisture measurements to achieve the highest level of accuracy. This system uses an enhanced gravimetric method to measure soil moisture to obtain the actual volumetric water content. The volumetric water content determined gravimetrically can help develop a custom soil moisture calibration equation or to validate the soil moisture value output from a sensor. In addition to the soil-specific calibration and validation, an algorithm can be developed to determine the soil's matric potential using the HydraProbe up to 2 bars of tension. The Stevens Tempe Cell is ideal for mesonets, climate reference networks, and soil monitoring stations.

Figure 1.2A. The Tempe Cell for custom calibrations, soil water retention curve

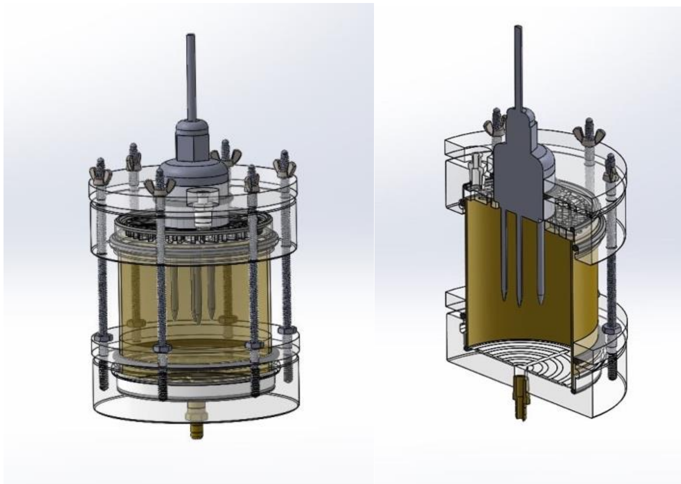

Figure 1.2B. Cross sectional diagram of Tempe Cell.

Water is infiltrated from the bottom which pushes the air out the top ensuring full saturation of the soil core.

1.9 *HydraProbe Versions*

- **Professional** – A scientific instrument designed for long-term climate references, research, and applications requiring high accuracy and quantitative data assessments.
- **Temperature Test Certificate** – Optional additional testing available to guarantee and show the HydraProbe operates down to -40^{o} Celsius.

Parameter	Unit
Soil Moisture	Water fraction by volume
Bulk EC Temperature Corrected	S/m
Temperature	C
Temperature	F
Bulk EC	S/m
Real Dielectric Permittivity	-
Imaginary Dielectric Permittivity	-
Pore Water EC	S/m
Dielectric Loss Tangent	-

Table 1.3. HydraProbe Parameters

HydraProbe SDI-12	
56012-02	SDI-12, Professional, w/25 ft. cable
56012-04	SDI-12, Professional, w/50 ft. cable
56012-06	SDI-12, Professional, w/100 ft. cable

Table 1.4 Stevens part numbers for SDI-12 HydraProbes

HydraProbe RS485	
56485-02	RS485, Professional, w/25 ft. cable
56485-04	RS485, Professional, w/50 ft. cable
56485-06	RS485, Professional, w/100 ft. cable

Table 1.5 Stevens part numbers for RS485 HydraProbes

HydraProbe Modbus	
56585-02	Modbus, Professional, w/25 ft. cable
56585-04	Modbus, Professional, w/50 ft. cable
56585-06	Modbus, Professional, w/100 ft. cable

Table 1.6 Stevens part numbers for Modbus HydraProbes

HydraProbe Accessories	
56000-TST	Temperature Test Certificate
93633-007	HydraGO-S Portable Soil Sensor
93633-500	HydraGO FLEX Portable Soil Sensor with GPS
51169-100	Tempe Cell Basic Kit
93723	SDI-12 / RS-485 Multiplexer, 12 Position
93539	Cable, RS-485/Modbus Probe, 5 conductor (1000' spool)
93924	Cable, SDI-12 Probe, 3 conductor (2500' spool)

Table 1.7 Stevens part numbers for accessories

2 Theory of Operation, Dielectric Permittivity, and Soil Physics

2.1 *Introduction*

Analytical measurements of soil moisture are represented by several different technologies on the market. Since it is difficult to know the differences between soil sensor technologies; what we describe here is the theory behind in situ electromagnetic soil sensors. In situ soil sensors employ electromagnetic waves in the radio frequencies between 20 and 1000 MHz (dielectric permittivity-based sensors) to estimate soil volumetric soil moisture. The physics behind how soil moisture sensors work is similar to that of how electromagnetic signals travel and propagate up and down transition lines where the wave guide is the metal portion of the soil probe and the circuit load is the soil. As the radio signal travels and propagates through the soil, the water content and the soil properties change the radio signal's time of travel, frequency, phase shift, and amplitude. These alternations in the electromagnetic waves and then characterized and measured to estimate soil moisture.

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

2.2.1 Real, Imaginary and Complex Numbers

Because radio signals are waves of electric fields that have energy and because these waves separate to form phase shifts and standing waves; mathematical tools need to be employed to properly understand these phenomena. Electromagnetic fields and waves are mathematically expressed as differential equations such as Maxwell's equations, which are difficult to solve even with computers. A common tool used in the solution to these mathematical constructs is the imaginary number, *j*, where $j = \sqrt{-1}$. A real number is a number that doesn't have *j* in it, and a complex number has a real part and an imaginary part containing *j*. The two components of a complex number don't necessarily mix together. For in situ soil moisture sensors, the real component is energy storage and the imaginary component represents energy leaving the system.

2.2.2 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,

$$\kappa^{*} = \varepsilon_{r} - j\varepsilon_{i} \qquad [2.1]$$

where K^* is complex dialectic permittivity, ε_r is the real dielectric permittivity, and ε_i is the imaginary dielectric permittivity (Topp 1980). As the radio wave propagates and reflects through soil, the properties and water content of the soil will influence the wave. The water content, and to a lesser extent the soil properties, will alter and modulate the electromagnetic radio signal as it travels through the soil by changing the frequency, amplitude, impedance, and the time of travel. The dielectric permittivity can be determined by measuring these modulations to the radio frequency as it propagates through the soil. In general, the real component represents energy storage in the form of rotational or orientation polarization which is indicative of soil water content. The real dielectric constant of water is 78.54 at 25 degrees Celsius and the real dielectric permittivity of dry soil is typically 2.5 to 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,

$$\varepsilon_{i} = \varepsilon_{rel} + \frac{\sigma_{dc}}{2\pi f\varepsilon_{v}} \qquad [2.2]$$

represents the energy loss where ε_{rel} is the molecular relaxation, f is the frequency, ε_v permittivity of a vacuum which is a constant, and σ_{dc} is DC electrical conductivity. In many soils, ε_{rel} is relatively small and a measurement of the imaginary component yields a good estimation of the electrical conductivity from 1 to 75 MHz (Hilhorst 2000). In sandy soils, the molecular relaxation can be negligible. The HydraProbe estimates electrical conductivity by measuring the imaginary and rearranging equation [2.2] 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

$$C = g\varepsilon\,\varepsilon_{v} \qquad [2.3]$$

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 [2.1] and [2.2] (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.

$$\varepsilon_{a} = \{1+[1+\tan^{2}(\varepsilon_{i}/\varepsilon_{r})]^{1/2}\}\varepsilon_{r}/2 \qquad [2.4]$$

From equation [2.4], 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 such as the HydraProbe will be the most accurate and will have a lower inter-sensor variability.

2.2.3 Behavior of Water and Soil in an Electric Field

Water is a polar molecule, meaning that one part of the water molecule caries a negative charge while the other half of the molecule caries a positive charge. While water is very polar, soils are rather non-polar. The polarity of water causes a rotational dipole moment in the presence of an electromagnetic wave while soil remains mostly uninfluenced. This means that water will rotate and reorientate with the rise and fall of the oscillating electric field i.e. electromagnetic wave while soil remains mostly stationary. From 1 to 1000 MHz, the water rotational dipole moment of water will occur at the same frequency of the electromagnetic wave. It is this rotational dipole moment of water that is responsible for water's high dielectric constant[1] of about 80. Dry Soil will have a dielectric constant of about from about 2.5 to 4. Large changes in the dielectric permittivity are directly correlated to changes in soil moisture. Figure 2.1 shows the polarity of a water molecule and how it can reorient itself in response to electromagnetic oscillations of static electric field.

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

Figure 2.1 A water molecule in the liquid phase reorienting i.e. rotational dipole moment.

Figure 2.2 illustrates the different kinds of polarizations exhibited by most materials. Soils will have space charge and atomic polarizations while water will re-orientate.

2.2.4 Molecular Relaxations.

The imaginary permittivity in equation [2.2] contains two parts, the frequency and electrical conductivity component, and the molecular relaxation component, ε_{rel}. Molecular relaxations are lag times. It is the time it takes for the molecule to achieve its dipole moment after encountering the electric field and the time it takes to relax to a free random motion after the electric field subsides. Relaxations can be significant in some soil because some clay mineralogy can adhere to the water molecular causing the lag time. This is particularly true with potassium saturated smectite clays which can cause significant errors in the water content estimation of a clay.
Soils with high salinities and high molecular relaxations have high energy loses and are often called lossy soils.

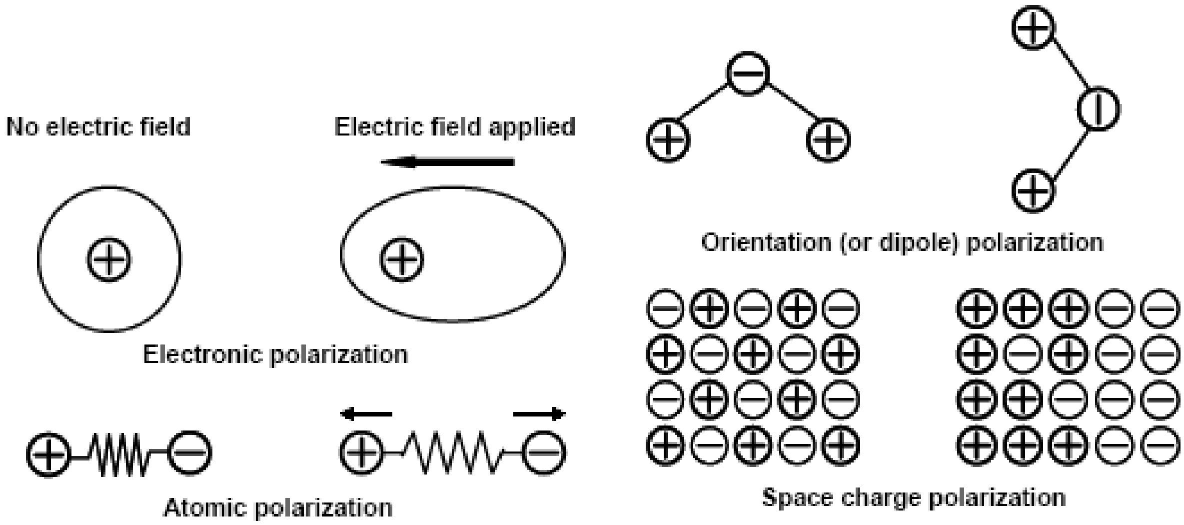

Figure 2.2 Illustration of polarization. The real dielectric permittivity of soil is mostly due to orientation polarization of water (Taken from Lee et al. 2003)

2.2.5 Temperature and the Permittivity

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).

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 presence 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 [2.5] (Jones 2005)

$$\varepsilon_{r,w}(T) = 78.54[1\text{-}4.579X10^{-3}\,(T\text{-}298)\text{+ }1.19\,X10^{-5}\,(T\text{-}298)^2\text{-}2.8X10^{-8}(T\text{-}298)^3] \quad [2.5]$$

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

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

2.3 *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 2.1 summarizes the types of sensing methods.

Method	Physical Measurement	Basis for Soil Moisture	Typical Frequency
TDR	Time of travel of a reflected wave	Apparent Permittivity	1000 MHz Or Pulse
TDT	Time of travel along a path length	Apparent Permittivity	150 to 2000 MHz
Capacitance (Frequency)	Shift in Frequency (Resonance Frequency)	Apparent Permittivity	150 to 200 MHz
Capacitance (Charge)	Capacitor Charging time	Capacitance	NA
Simplified Impedance	Difference in reflected amplitudes	Apparent Permittivity	75 MHz
Ratiometric amplitude Impedance	Ratio of reflected amplitudes to measure the impedance.	Real Dielectric Permittivity	50MHz

Table 2.1 Summary of commercially available soil sensing methods

2.3.1 Time Domain Reflectometry and Transmission (TDR and TDT)

TDR was first used in the mid twentieth century to detect the location of breaks along cables. 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.

There are a variety of TDR soil sensors on the market. Some provide an analysis of a waveform while other capture the time of a return pulse across a transistor.

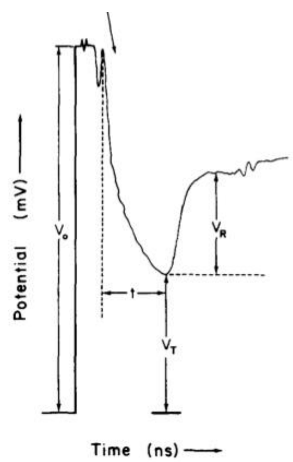

Figure 2.3 TDR Waveform

Figure 2.3 is an example of a TDR Waveform. It is a plot of voltage on the y axis and time on the x axis. If the length of the waveguide is known, the time of travel can be determined by be the time when the return signal V_R increases. The height of V_R is proportional to the soil electrical conductivity. Waveforms in soil can often be hard to interpret because there can be multiple arrival times (overtones) or large amounts of noise. Some TDRs have algorithms that analyze the waveform to determine the best arrival time while TDT simply measures the time of a voltage spike to reduce the cost of the circuitry and signal processing.

As can be shown in figure 2.3, a pulse is sent out, it is reflected back to the source, and the time of travel is measured. The amount of water in the soil will slow the radio signal down. The mathematical relationship between the time of travel, t, and the apparent permittivity, ε_a, is shown in [2.6a] and [2.6b], where [2.6a] is for TDR and

[2.6b] is for TDT. In equations [2.6 a&b] L is the length of the waveguide, c, is the speed of light and they are different by a factor of 2 because TDT is not a reflection.

$$t = \frac{2L\sqrt{\varepsilon_a}}{c} \qquad [4.6a] \qquad\qquad t = \frac{L\sqrt{\varepsilon_a}}{c} \qquad [4.6b]$$

Note that both TDR and TDT base the soil moisture calibration on the apparent dielectric permittivity which is a mixture of both real and imaginary components as can be shown in equation [2.4]. Large imaginary permittivities, such as those found in saline soils or lossy soils, can distort the waveform causing errors.

2.3.2 Topp Equation

In 1980 the Topp equation was published (Topp 1980) which is an empirical relationship between soil moisture and the apparent permittivity. Many reflectometers today use the Topp equation as their soil moisture calibration and is shown in equation [2.7]. The Topp equation is reasonably accurate in a wide variety of soils assuming the TDR has an interpretable waveform or a sound measurement of the permittivity. In equation [2.7], θ is soil moisture and ε_A is the apparent permittivity from equation [4.6] and [4.4 a &b].

$$\theta = -5.3x10^{-2} + 2.92x10^{-2}\varepsilon_A - 5.5x10^{-4}\varepsilon_A^2 - 4.3\ x\ 10^{-6}\varepsilon_A^3 \qquad [2.7]$$

2.3.3 Frequency Domain and Frequency Capacitance Reflectometry

There are a lot of soil sensors on the market that are called "frequency domain reflectometers" (FDR); however, this is somewhat of a misnomer. The term "frequency domain" in physics refers to a spectrum of many frequencies where many different frequencies are transmitted and a broad range of frequencies of the return signals are measured. The change in frequency between the transmitted frequency and the reflected signal is called the resonance frequency. To keep costs down and simplify the circuitry, most soil sensors that are labeled FDRs only transmit a single frequency from 100 to 200 MHz and measure only one resonance frequency.

Capacitive properties of soil can be measured from the change in frequency from a reflected radio wave or resonance frequency (Kelleners 2004). While there are a small number of FDRs on the market the sweep frequencies to gain more insight in the dielectric permittivity of the soil, most simply measure a single resonance frequency using a raw voltage response on a circuit board. From the resonance frequency, the capitative properties of the soil can be determined with the relationship described in equation [2.8] which is in turn related to water content.

$$F = \frac{1}{2\pi\sqrt{LC}} \qquad [2.8]$$

In equation [2.8] F is response frequency, L is a length term, and C is capacitive properties of soil.

2.3.4 Other Reflectometer In Situ Soil Sensors

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 on a transmission line to get an impedance of the load. This methodology is termed "simplified impedance" (Gaskin 1996).

2.3.5 The HydraProbe, a Ratiometric Coaxial Impedance Dielectric Reflectometer

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

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

$$\frac{Z_p}{Z_c} = \frac{1+\Gamma}{1-\Gamma} \qquad [2.9a] \qquad\qquad \Gamma = {}^{V_r}/_{V_i} \qquad [2.9b]$$

$$Z_p = \frac{Z_0}{\sqrt{\kappa^*}} \coth\left(\frac{\omega\sqrt{\kappa^*}L_g j}{c}\right) \qquad [2.10]$$

Equations [2.9a], [2.9b] and [2.10] summarize the HydraProbe's mathematical process for measuring the real and imaginary as separate parameters. In a standing wave at 50 MHz, the ratios of the reflected to the incident signal strengths are measured for several geometric points along the transmission line, Γ. This ratio approach eliminates inner sensor variability. The ratios are then used to compute the complex impedances on the transmissions line, Z_p and Z_c. Equation [2.10] then takes the impedances, and the geometry for transmission line, to get both components of the complex dielectric permittivity, κ^*, which are the real component for the permittivity, ε_r, and the imaginary permittivity, ε_i, as described in equation [2.1].

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

Unlike most other soil sensors, the HydraProbe measures both the real and the imaginary components of the dielectric permittivity as separate parameters. The HydraProbe bases the soil moisture calibration on the real dielectric permittivity while most other soil moisture technologies base their soil moisture estimation on the apparent permittivity which is a combination of the real and imaginary components as defined in equation [2.4] (Logsdon 2010). Basing the soil moisture calibration on the real dielectric permittivity instead of the apparent permittivity has many advantages. Because the HydraProbe separates the real and imaginary components, the HydraProbe's soil moisture calibrations are less affected by soil salinity, temperature, soil variability, and inter sensor variability than most other electronic soil sensors.

2.3.7 The HydraProbe is Easy to Use

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

3 Measurements, Parameters, and Data Interpretation

3.1 *Soil Sensor Types*

There are two families of in situ soil moisture sensors. There are the electronic soil moisture sensors that use electromagnetic waves to estimate the volumetric water content often expressed as a percentage or water fraction such as the HydraProbe, TDRs, FDRs etc. and there are the soil sensors that measure the soil's matric potential such as tensiometers, gypsum blocks, heat capacitance probes, and other porous media methods. While soil moisture can be expressed as a gravimetric water fraction, the volumetric water fraction (θ, $m^3\ m^{-3}$) is used to take into account the soil's bulk density which can vary widely. The soil's matric potential is related to soil moisture. It is the amount of negative pressure or suction it takes to pull water out of soil. The negative sign in the pressure is often left out. Both soil moisture and matric potential are important in the understanding of soil water dynamics. A simple way to think of the difference is that the matric potential tells you when a plant is thirsty and the soil moisture tells you how much water you need.

3.2 *Soil Matric Potential and Soil Moisture Units*

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

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

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

Heat dissipation type matric potential sensors measure the matric potential indirectly by measuring the heat capacitance of a ceramic that is in equilibrium with the soil. With heat up and cool down cycles of heating elements in the ceramic, the heat capacitance can be calculated which in turn is calibrated to the matric potential. Heat capacitance based matric potential sensors offer advantages in accuracy, range, and maintenance over other technologies.

Matric potential is important for irrigation scheduling because it can represent the soil water that would be available to a crop. Many unsaturated flow models require a soil water retention curve where water fraction by volume is plotted with the matric potential in a range of moisture conditions (Figure 5.1). A soil water retention curve can help understand the movement and distribution of water such as infiltration rates, evaporation rates, and water retentions (Warrick 2003). Table 5.1 shows the general values of matric potential under different hydrological thresholds and soil textures.

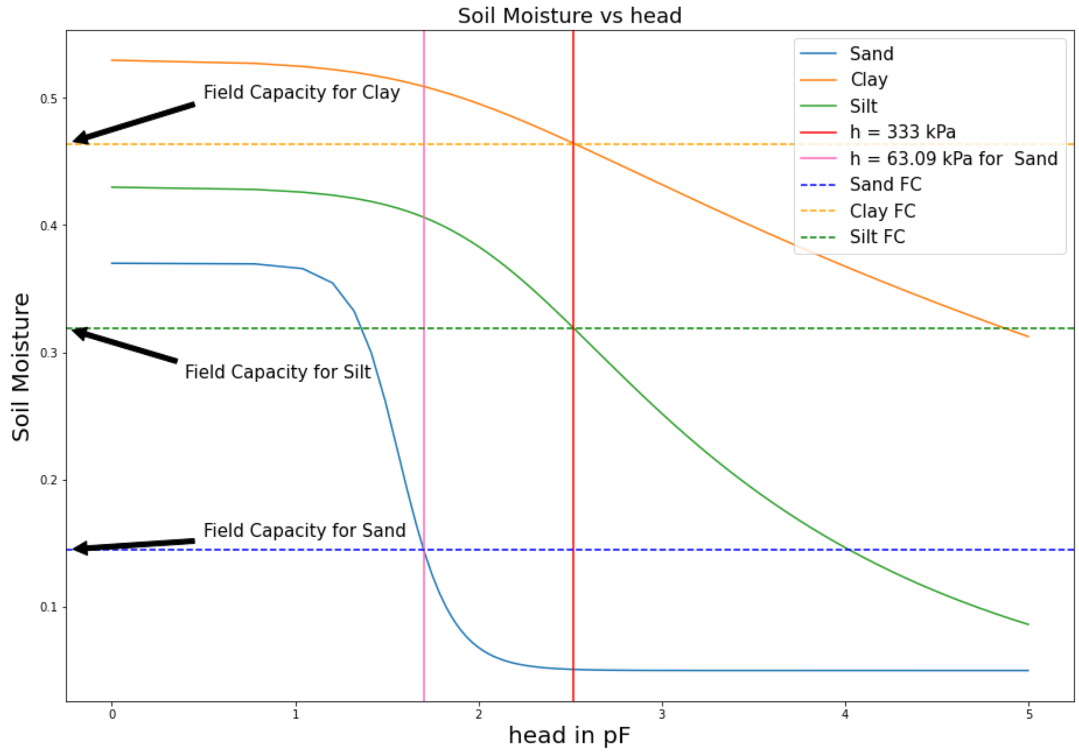

Figure 3.1 Soil Water Retention Curve. Soil moisture wfv vs. Soil matric potential (head).

Soil Condition	Matric Potential						Soil Moisture %		
	Bar	kPa	hPa	PSI	ATM	pF	Sand	Silt	Clay
Saturation	0	0	0	0	0		37%	45%	55%
Field Capacity*	0.33	33	330	4.7862	0.326	2.52	10-15%	32%	44%
Permanent Wilting Point	15	1500	15000	217.55	14.80	4.18	4%	15%	21%

Table 3.1 Soil Water Retention Curve. Soil matric potential verse soil moisture for typical soils.

***Note that the field capacity of sand is typically 5 to 20 bar.**

3.2.1 Soil Moisture Units

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

There are several other units used to measure soil moisture: % water by weight, % available (to a crop), inches of water to inches of soil, % of saturation, and tension (or pressure). It is important to understand different ways to express soil moisture and the conversion between units can be highly soil dependent.

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

3.3 *Soil Moisture Measurement Considerations for Irrigation*

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

3.3.1 Fill Point Irrigation Scheduling

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

3.3.2 Mass Balance Irrigation Scheduling

The mass balance method or sometimes called scientific irrigation scheduling is an irrigation schedule determined by calculating how much the water is needed based on accurate soil moisture readings and from the soil properties. Equations [3.1], [3.2], and [3.3] can help to determine how much water to apply. The following are terms commonly used in soil hydrology:

- Soil Saturation, (θ_{SAT}) refers to the situation where all the soil pores are filled with water. This occurs below the water table and in the unsaturated zone above the water table after a heavy rain or irrigation event. After the rain event, the soil moisture (above the water table) will decrease from saturation to field capacity. Saturation can range from 35% to 55% depending on texture, organic matter, and bulk density.

- 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 have a net upward movement at this point from evaporation or evapotranspiration. θ_{FC} = 0.33 bar in most soils.
- Permanent Wilting Point (θ_{PWP} in equations below) refers to the amount of water in soil that is unavailable to the plant. θ_{PWP} = 15 bar in most soils.
- 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.

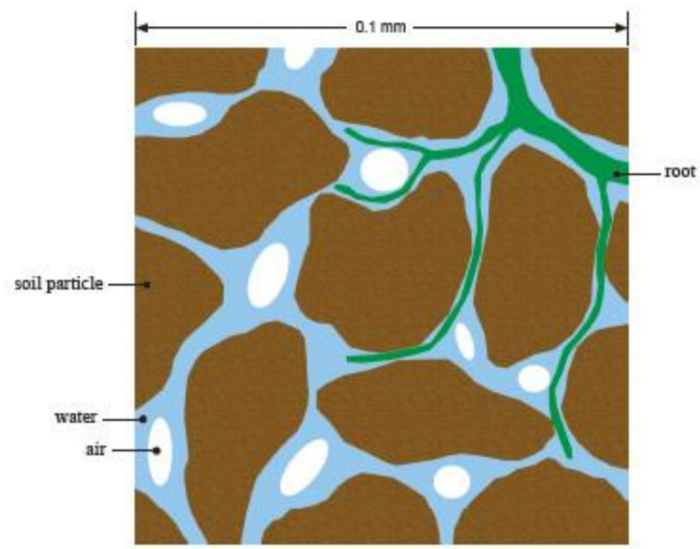

Figure 3.2 Unsaturated soil is composed of solid particles, organic material, and pores. The pore space will contain air and water.

The lower soil moisture limit is a very important value because dropping to or below this value will affect the health of the crops. Equations [3.1], [3.2], and [3.3] and the example below show how to calculate the lower soil moisture limit and the soil moisture target for irrigation optimization.

$$\theta_{AD} = (\theta_{FC} - \theta_{PWP}) \times MAD \qquad [3.1]$$

$$\theta_{AWC} = \theta_{FC} - \theta_{PWP} \quad [3.2]$$
$$\theta_{LL} = \theta_{FC} - \theta_{AD} \quad [3.3]$$

Figure 3.3 can be used to help determine the soil moisture targets based on soil texture. Soil texture is determined by the percentages of sand, silt, and clay using figure 3.4. Note that figures 3.3, and 3.4 and table 3.1 are general trends. The actual MAD and field capacity and permanent wilting point may vary with region, soil morphologies, and the crop.

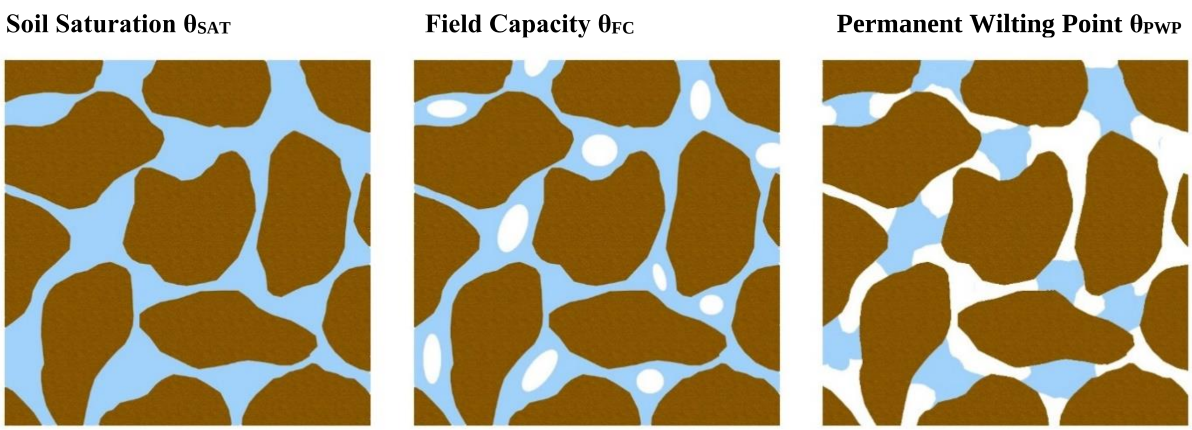

Figure 3.3 Hydrological conditions of soil.

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 3.2 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.

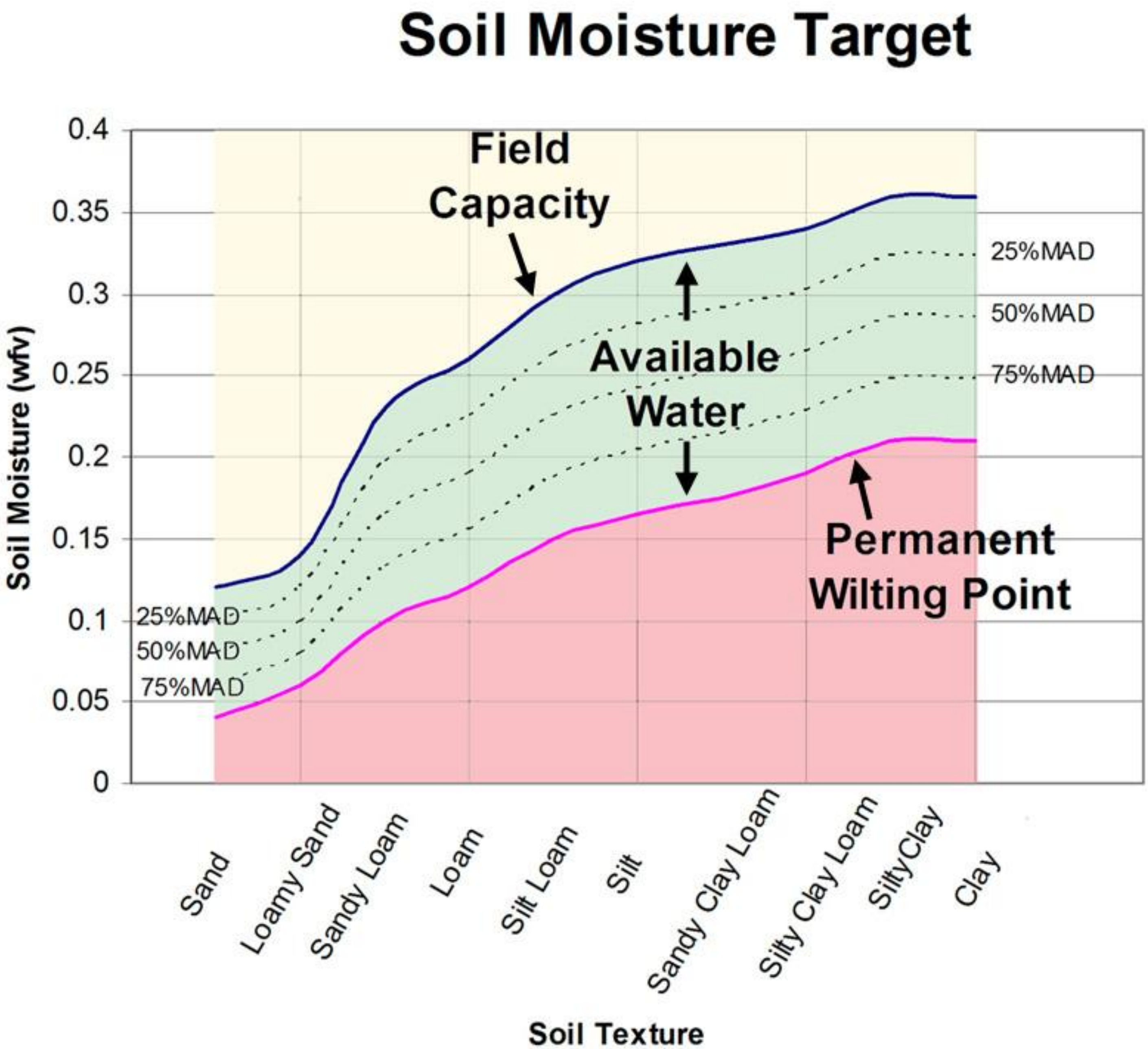

Figure 3.4 Soil textures and the available water.

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 3.3 Maximum allowable depletions for different soil textures.

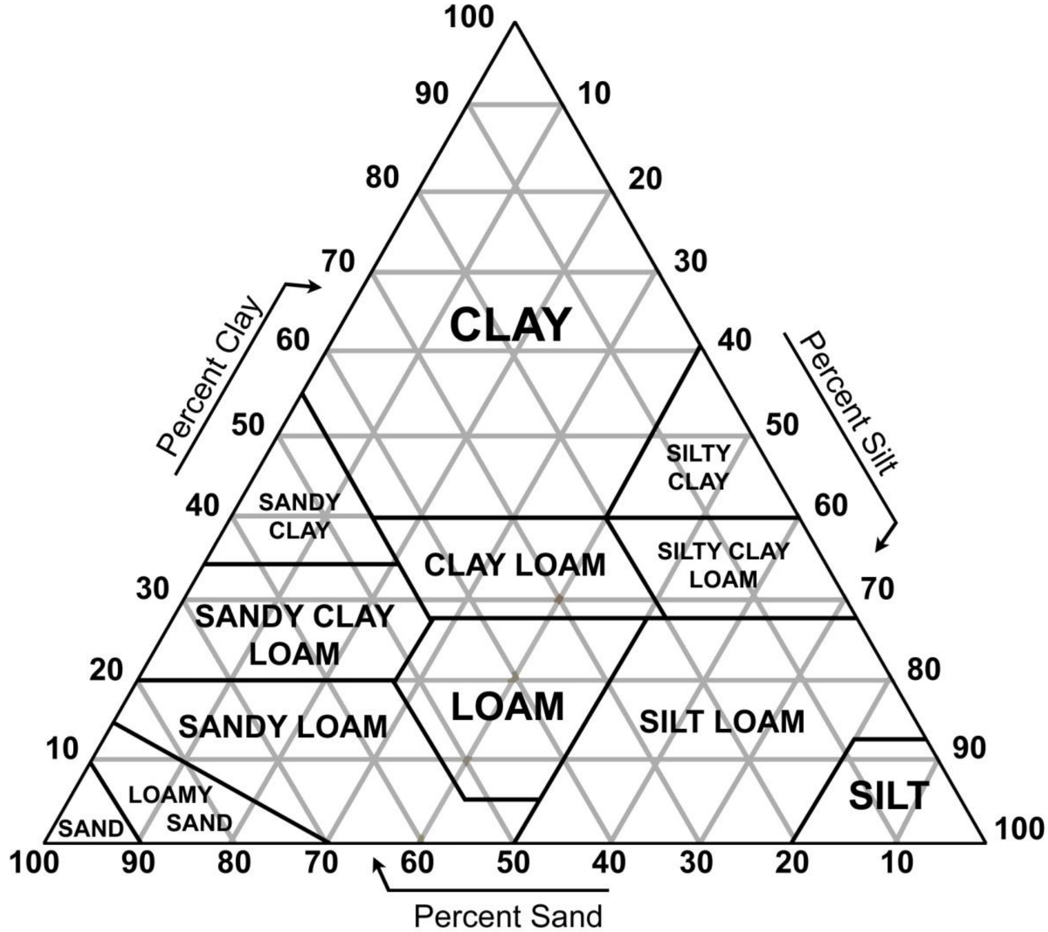

Figure 3.5 Soil textural triangle.

Example of irrigation scheduling based on soil moisture values:

How much water should be applied? The soil is a silt, the MAD is 50%, and the soil moisture is 16% throughout the root zone which is down to 24 cm. The sprinkler is 75% efficient.

Answer:

From tables 5.1 and 5.2 the MAD = 0.5, From Figure 5.3 (or a soil survey) θ_{PWP} = 16% and the field capacity, θ_{FC} is 32%. Therefore, using equations 5.1 to 5.3, the optimal soil moisture is 24 to 32%. $\theta_{FC} - \theta$ = 32% - 16% = 16%. If the MAD is 50%, then 8% would be half of the available water capacity. Subtracting 8% from the field capacity of 32% will give a lower limit of 24%. Because the soil moisture is 16%, it is 8% lower than the optimal 24%. Therefore, the soil needs to be irrigated to increase the soil moisture by 8% down to 24 cm, 8% X 24 cm = 2 cm of water needed to be added. If the sprinkler is 75% efficient than approximately 2 cm/0.75 = 2.66 cm of water should be applied. Note the rate of water coming out of the sprinkler should not exceed the infiltration rate of the soil and the run time of the sprinklers would depend on the specification of the sprinkler.

3.3.3 Soil Moisture Calibrations

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

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

3.3.3.1 Other Factory Calibrations

In addition to the factory general calibration, the HydraProbe has an organic soil calibration, O, and a rockwool calibration, R. See Appendix D for information on the calibration settings in the HydraProbe User Manual. You may want to validate the factory calibration to make sure it has suitable accuracy for a specific soil. If the factory calibration is off, you can develop a new soil specific calibration. A new soil specific calibration can be developed through gravimetric analyses. We recommend logging the real dielectric permittivity (Parameter 6 on "aM!, aC!). If a new calibration is developed, the historical data set can be recalibrated if the data set contains the raw real dielectric permittivity value. Individual sensors do not need their own calibration. Because all HydraProbes measure the same way with extremely low variability from sensor to sensor, the same calibration formula can be applied to any HydraProbe.

3.4 *Soil Salinity and the HydraProbe EC Parameters*

Soil bulk electrical conductivity (EC) is important for assessing the salinity of the soil and soil pore water. Temperature corrected EC is the second parameter in "aM!,aC!" and the raw un-corrected electrical conductivity and is the 5th parameter in "aM!, aC!" in the SDI-12 parameter sets. Electrical conductivity also referred to as specific conductance and is measured in Siemens/meter (S/m). Siemens is inversely related to resistance in Ohms (Siemens = 1/Ohms) and represents a materials ability to conduct an electric current. There are several related units for EC. Table 5.4 summarizes the unit conversion.

The electrical conductivity parameters are calculated from the imaginary dielectric permittivity by rearranging equation [4.2]. The calculation of EC assumes 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 presence of molecular relaxations. While the accuracy of the EC parameters in soil is highly soil dependent, the HydraProbe's EC measurements in slurry extracts, water samples, and aqueous solutions will be accurate (<+/- 1 to 5%) up to 0.3 S/m. Because EC can be sensitive to changes in temperature, a temperature correction is provided.

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

Table 5.4 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

3.4.1 Soil Salinity

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

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

3.4.2 Bulk EC versus Pore Water EC

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

3.4.3 Bulk EC and EC Pathways in Soil

Soil is a matrix that is basically composed of solid material, water in the pore spaces, and air. In situ soil sensors (soil sensors in the ground) measure the dc bulk electrical conductivity (σ_b) which is the electrical conductivity of the soil/water/air matrix combined. Figure [5.6] shows the three pathways the electrical conductivity can propagate in soil. The bulk density, the porosity, the tortuosity, the water content, and the dissolved ion concentration working in concert with the different pathways, dramatically influences the bulk electrical conductivity of a soil.

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

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. 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.

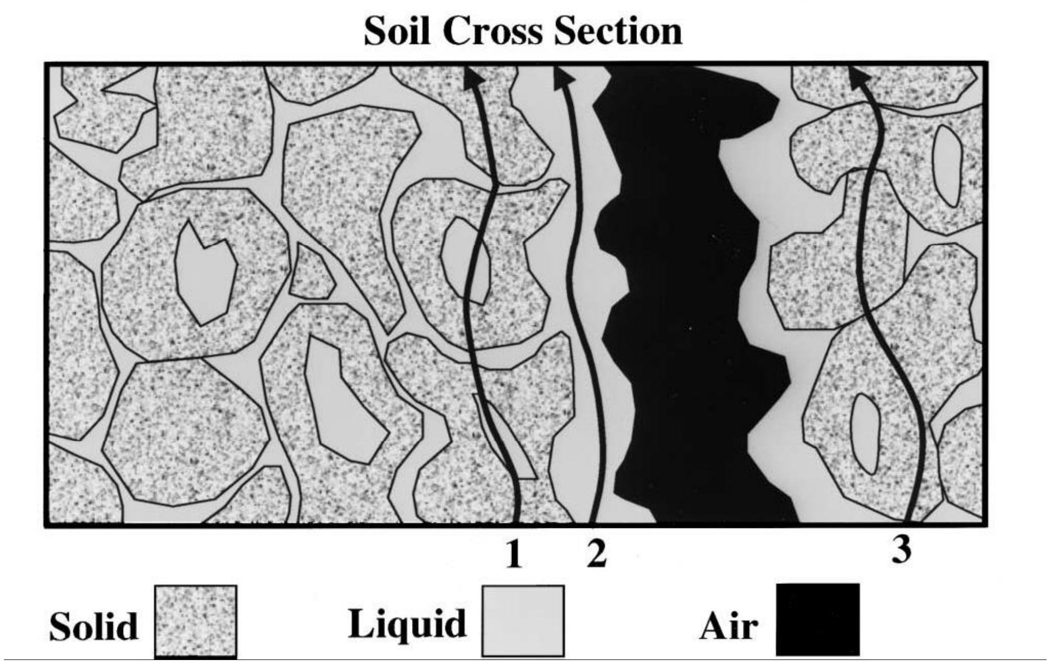

Figure 3.6 Three Pathways of electric conductivity in soil matrix. 1, water to solid, 2 soil moisture, 3 solid. Taken from Corwin et al. (2003).

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

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

3.4.4 Application of Bulk EC Measurements

While it is difficult to make direct comparisons with the bulk EC, you 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 circumstances, the pore water EC can be estimated from knowledge about the dielectric permittivity of the soil (Hilhorst 1999). Equation [3.4] allows the user to make comparable pore water EC estimates from bulk EC measurement in most soils.

$$\sigma_p = \frac{\varepsilon_{rp}\sigma_b}{\varepsilon_{rb} - \varepsilon_{rb\_O}} \qquad [3.4]$$

Where σp is the pore water EC, εrp is the real dielectric content of water (≈80), σb is the bulk EC measured with the HydraProbe in soil, and εrb is the real dielectric permittivity of the soil measure with the HydraProbe. εrb_O is an offset, and 3.4 can be used as the offset for most inorganic soils.

3.4.5 Total Dissolved Solids (TDS)

The total dissolved solids (in g/L or ppm) of a water sample can be estimated from the electrical conductivity. To assess the TDS in soil you need to first obtain the pore water EC from either equation [3.6] or from a slurry water extract. TDS calculated from EC may be less meaningful for soil pore water than a water sample or dry down weight analyses. There could also be other constituents dissolved in the water that do not contribute to the EC of the water such as nitrates, phosphates, and other factors that exist in soil but do not occur in a water sample. Another source of error with TDS estimation from EC is the fact that different salts have different EC strengths and solubility. Calcium chloride will be underrepresented in a TDS calculation because it has a lower EC value and will fall out of solution much quicker than sodium chloride (McBride 1994). Despite the challenges associated with estimating TDS from EC, equation [3.5] can be used to with the HydraProbe's EC measurements to estimate the TDS in a water or slurry extract sample.

$$\text{Water Salinity (g/L)} \approx \text{EC (S/m)} \times 6.4 \qquad [3.5]$$

To verify the TDS estimation from EC or perhaps correct equation [3.5] for a specific water sample, you can dry down a water sample and obtain the weight of the material left behind for a true gravimetric measurement of TDS. Note that if the HydraProbe EC measurement is used to estimate the TDS, the stainless-steel tines need to be completely submerged in the water sample or the water extract of the slurry.

Appendix A - Useful links

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

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

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

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

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

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

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