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Stevens® Water Monitoring Systems, Inc.

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Soil Data Guide

May 2018

Rev. VI

Firmware version 2.9

Comprehensive Stevens HydraProbe User's Manual

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1.1 Soil Hydrology

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

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

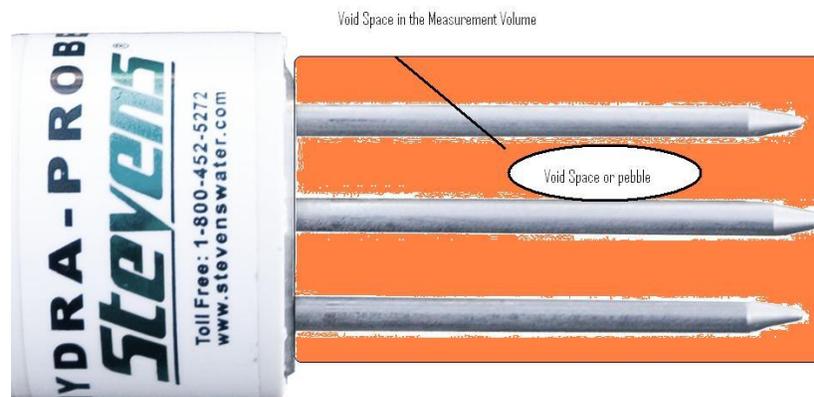


Figure 3.1 Measurement volume with a void space between the tine assembly.

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



1.1.1 Evapotranspiration

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

1.1.2 Hydrology and Soil Texture

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

1.1.3 Soil Bulk Density

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

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

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

Where m is the mass of the dry soil in grams and V is the volume in cubic centimeters.

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

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

1.1.4 Shrink/Swell Clays

Shrink/swell clays belong to the soil taxonomic order vertisol and are composed of smectite clays. These clays have a large ion exchange capacity and will shrink and swell seasonally with water content. The seasonal



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

1.1.5 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.

1.1.6 Bioturbation

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

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

1.1.7 Salt Affected Soil and the Loss Tangent

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

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



$$\text{Tan } \delta = \frac{\epsilon_i}{\epsilon_r} \quad [3.3]$$

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

1.1.8 Ped Wetting

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

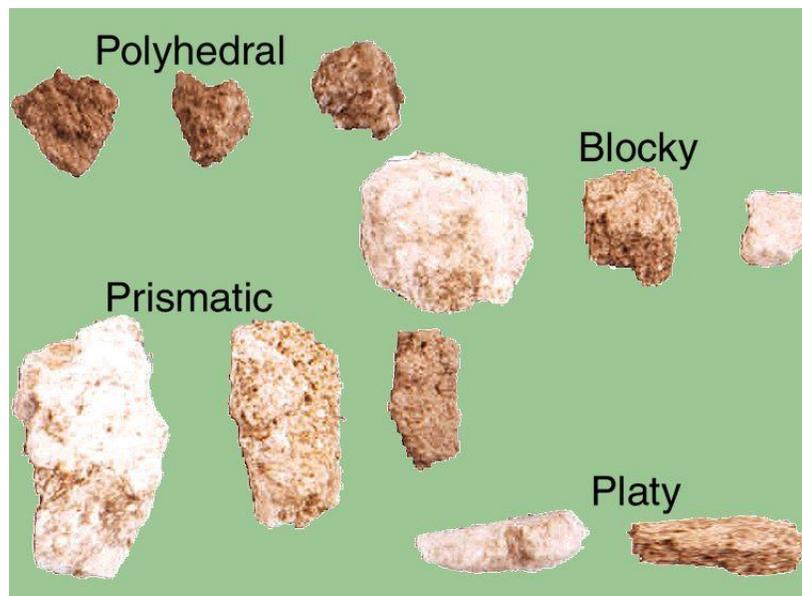


Figure 3.2. Soil Ped Types.



1.1.9 Frozen Soil

The HydraProbe can also be used to determine if soil is frozen. Once ice reaches 0° 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.



2 Theory of Operation, Dielectric Permittivity and Soil Physics.

2.1 Introduction

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

2.2 Soil Matric Potential

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

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

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

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

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





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

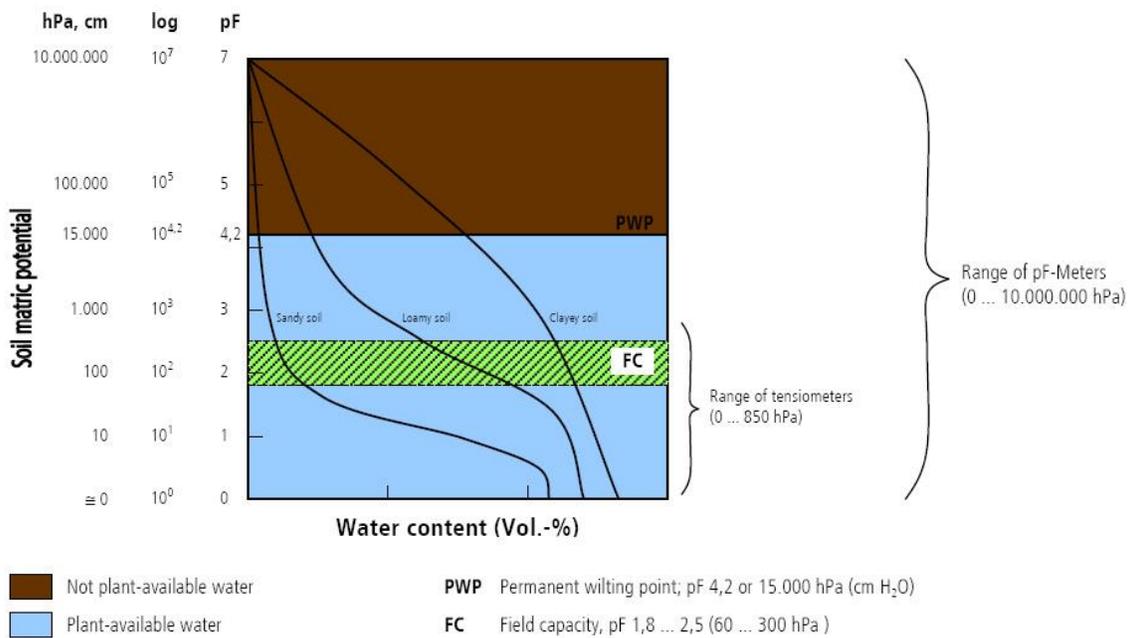


Figure 4.2. Soil Water Retention Curve. Soil matric potential verse soil moisture.

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

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



2.3 Electromagnetic Soil Water Methods and Soil Physics

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

2.3.1 Dielectric Theory

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

$$K^* = \epsilon_r - j\epsilon_i \quad [4.1]$$

where K^* is complex dielectric permittivity, ϵ_r is the real dielectric permittivity, ϵ_i is the imaginary dielectric permittivity and $j = \sqrt{-1}$ (Topp 1980). As the radio wave propagates and reflects through soil, the properties and water content of the soil will influence the wave. The water content, and to a less extent the soil properties will alter and modulate 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 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,

$$\epsilon_i = \epsilon_{rel} + \frac{\sigma_{dc}}{2\pi f \epsilon_v} \quad [4.2]$$



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

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

$$C = g\epsilon \epsilon_v \quad [4.3]$$

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.

$$\epsilon_a = \{1 + [1 + \tan^2(\epsilon_i/\epsilon_r)]^{1/2}\} \epsilon_r / 2 \quad [4.4]$$

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

Water is a polar molecule, meaning that one part of the water molecule carries a negative charge while the other half of the molecule carries 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 constant¹ of about 80. Dry Soil will have a dielectric constant of about from about 4 to 5. Large changes in the dielectric permittivity will be directly correlated to changes in soil moisture. Figure 4.2 shows the polarity of a water molecule and how it can reorient itself in response to electromagnetic oscillations.

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





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

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

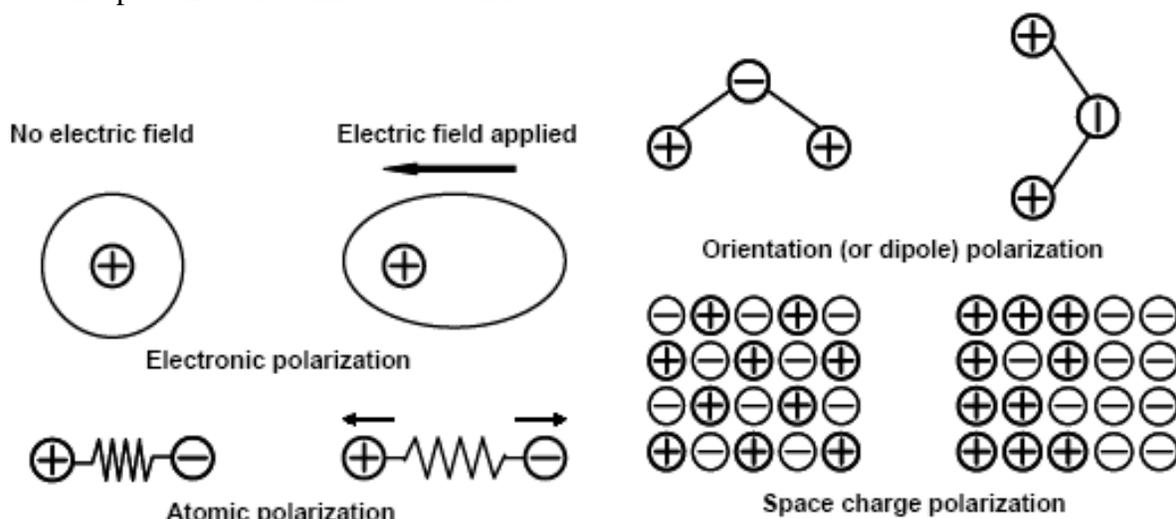


Figure [4.4]. Illustration of polarization. The real dielectric permittivity of soil is mostly due to orientation polarization of water (Taken from Lee et al. 2003)

2.3.2 Temperature

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

2.3.3 Temperature and the Real Permittivity

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

$$\epsilon_{r,w}(T) = 78.54[1 - 4.579 \times 10^{-3} (T - 298) + 1.19 \times 10^{-5} (T - 298)^2 - 2.8 \times 10^{-8} (T - 298)^3] \quad [4.5]$$

While the HydraProbe has a temperature corrections for the electrical components on the circuit board, the factory calibrations do not apply a temperature correction to the measured soil moisture values. Water in liquid form will have its dielectric constant decrease with increasing temperature, but in soil, water's dielectric dependency with



temperature is more complicated due to bound water affects. As temperature changes, the molecular vibrations of the water and cations that are bonded to soil particles at a microscopic level can affect the dipole moments in the presence of a radio frequency. In practical terms, temperature correction to soil moisture calibrations are highly soil dependent. In some soils, the real dielectric can trend downward with increasing temperature as it does in liquid form, or it can trend upward with increasing temperature (Seyfried 2007).

2.3.4 Temperature and the imaginary permittivity

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

2.4 Types of Commercial Electromagnetic Soil Sensors

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

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

Table 4.2. Summary of commercially available soil sensing methods

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

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



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

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

2.4.1 The HydraProbe, a Ratiometric Coaxial Impedance Dielectric Reflectometer

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

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

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

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

2.4.3 The HydraProbe is Easy to Use

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



3 Measurements, Parameters, and Data Interpretation

3.1 Soil Moisture

3.1.1 Soil Moisture Units

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

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

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

3.2 Soil Moisture Measurement Considerations for Irrigation

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

3.2.1 Fill Point Irrigation Scheduling

The fill point method is qualitative in that the irrigator looks at changes in soil moisture. With experience and knowledge of the crop, an irrigation schedule can be developed to fill the soil back up to a fill point. The fill point is an optimal soil moisture value that is related to the soil’s field capacity. The fill point for a particular sensor is determined by looking at soil moisture data containing a number of irrigation events. This can be an effective and simple way to optimize irrigation. Because it is qualitative, accuracy of the soil moisture sensor is less important



because the fill point is determined by looking at changes in soil moisture and not the actual soil moisture itself. This in some ways can be more efficient because lower cost soil moisture sensors can be used without calibration. While the fill point method can be easy to implement and is widely used for many crops, the mass balance method however can better optimize the irrigation, better control salinity build up, and minimize the negative impacts of over irrigation.

3.2.2 Mass Balance Irrigation Scheduling

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

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



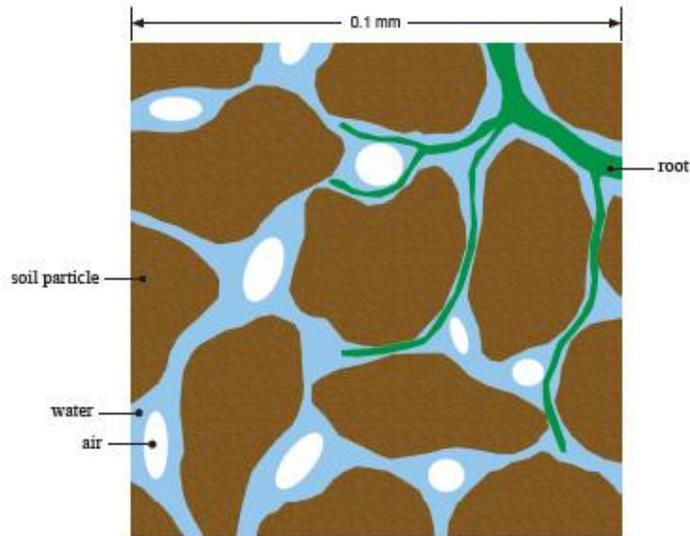


Figure 5.1. Unsaturated soil is composed of solid particles, organic material and pores. The pore space will contain air and water.

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

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

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

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

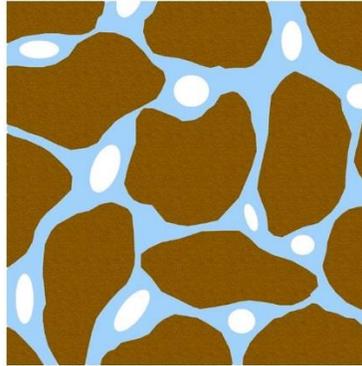
Figure 5.3 can be used to help determine the soil moisture targets based on soil texture. Soil texture is determined by the percentages of sand, silt, and clay using figure 5.4. Note that figures 5.3, and 5.4 and table 5.1 general trends. The actual MAD and field capacity and Permanent wilting point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



Soil Saturation θ_{SAT}



Field Capacity θ_{FC}



Permanent Wilting Point θ_{pw}



Figure 5.2. Hydrological conditions of soil.

<u>Crop</u>	<u>Maximum Allowable Depletion (MAD)</u>	<u>Effective Root Depth (Inches)</u>
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.



Soil Moisture Target

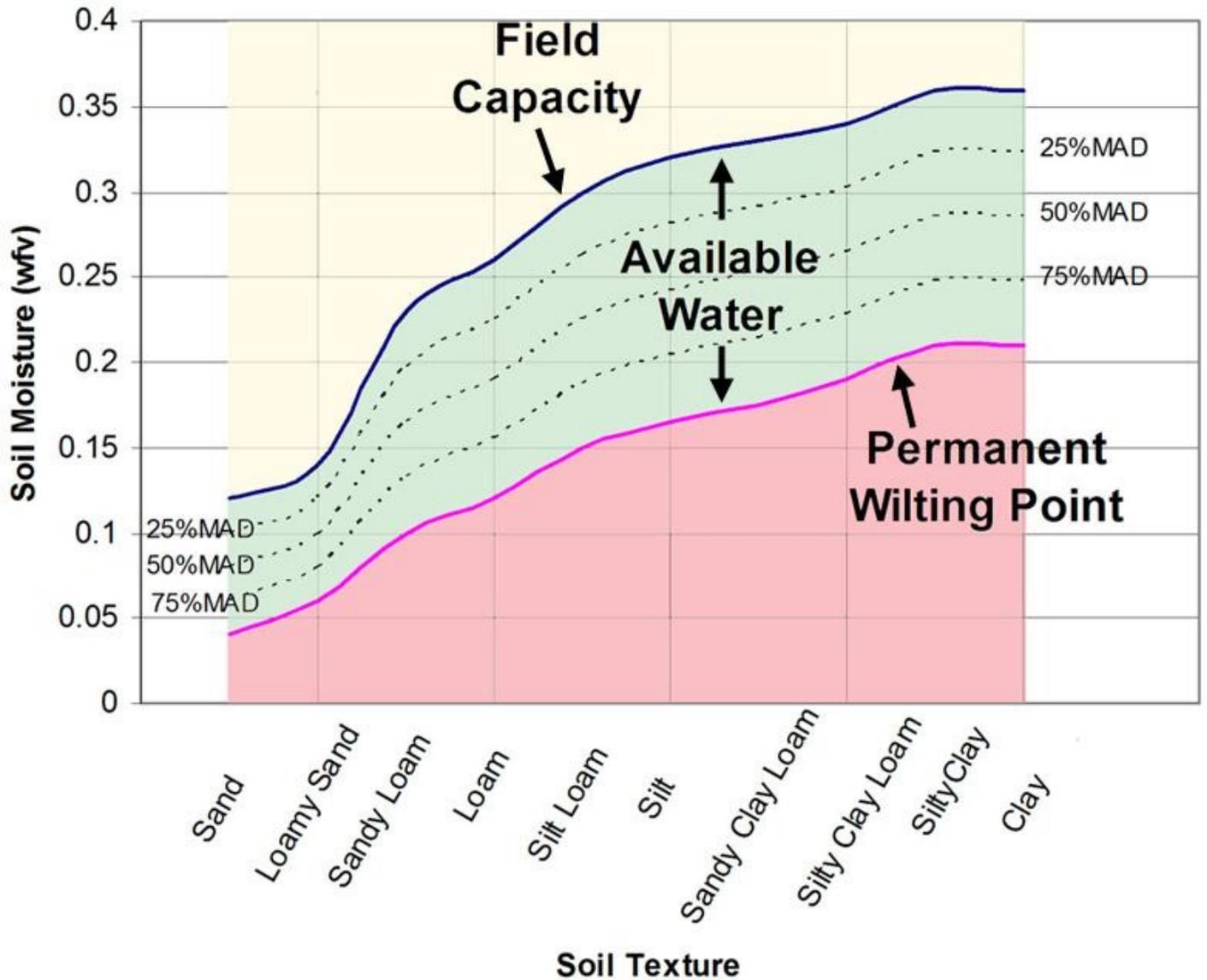


Figure 5.3 soil textures and the available water.

<u>Texture</u>	<u>Clay</u>	<u>Silty Clay</u>	<u>Clay Loam</u>	<u>Loam</u>	<u>Sandy Loam</u>	<u>Loamy Sand</u>	<u>Sand</u>
MAD	0.3	0.4	0.4	0.5	0.5	0.5	0.6

Table 5.2, Maximum allowable depletions for different soil textures.



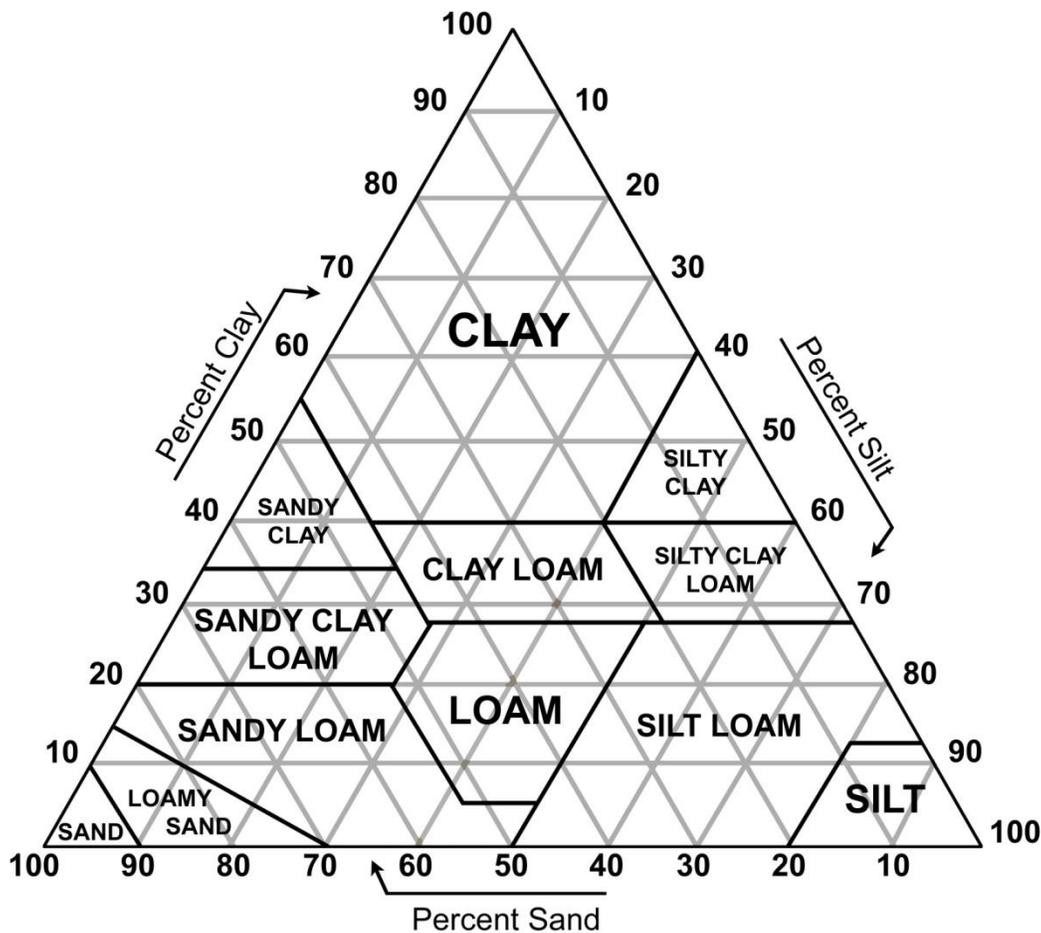


Figure 5.4. Soil textural triangle.

Example of an Irrigation scheduling based on soil moisture values:

How much water should be applied? The soil is a silt, the MAD is 50%, and the soil moisture is 20% throughout the root zone which is down to 24 cm. The sprinkler is 75% efficient.

Answer:

From tables 5.1 and 5.2 the MAD = 0.5, From Figure 5.3 (or a soil survey) $\theta_{PWP} = 16\%$ and the field capacity, θ_{FC} is 32%. Therefore using equations 5.1 to 5.3, the optimal soil moisture is 24 to 32%. $\theta_{FC} - \theta = 32\% - 16\% = 16\%$. Therefore the soil needs to be irrigated to increase the soil moisture by 16% down to 24 cm, $16\% \times 24 \text{ cm} = 3.8 \text{ cm}$ of water need to be added. If the sprinkler is 75% efficient than $3.8 \text{ cm} / 0.75 = 5.12 \text{ cm}$ 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.



3.2.3 Soil Moisture Calibrations

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

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

3.2.3.1 Other Factory Calibration

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

3.3 Soil Salinity and the HydraProbe EC Parameters

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

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



Convert to →	<u>S/m</u>	<u>dS/m</u>	<u>mS/m</u>	<u>μS/m</u>	<u>S/cm</u>	<u>dS/cm</u>	<u>mS/cm</u>	<u>μS/cm</u>
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 5.3. Convert EC units on the left to the EC units on top by multiplying by the factor. For example
2 dS/m X 0.1 = 0.2 S/m**

3.3.1 Soil Salinity

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

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

3.3.2 Bulk EC versus Pore Water EC

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



3.3.3 Bulk EC and EC Pathways in Soil

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

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

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

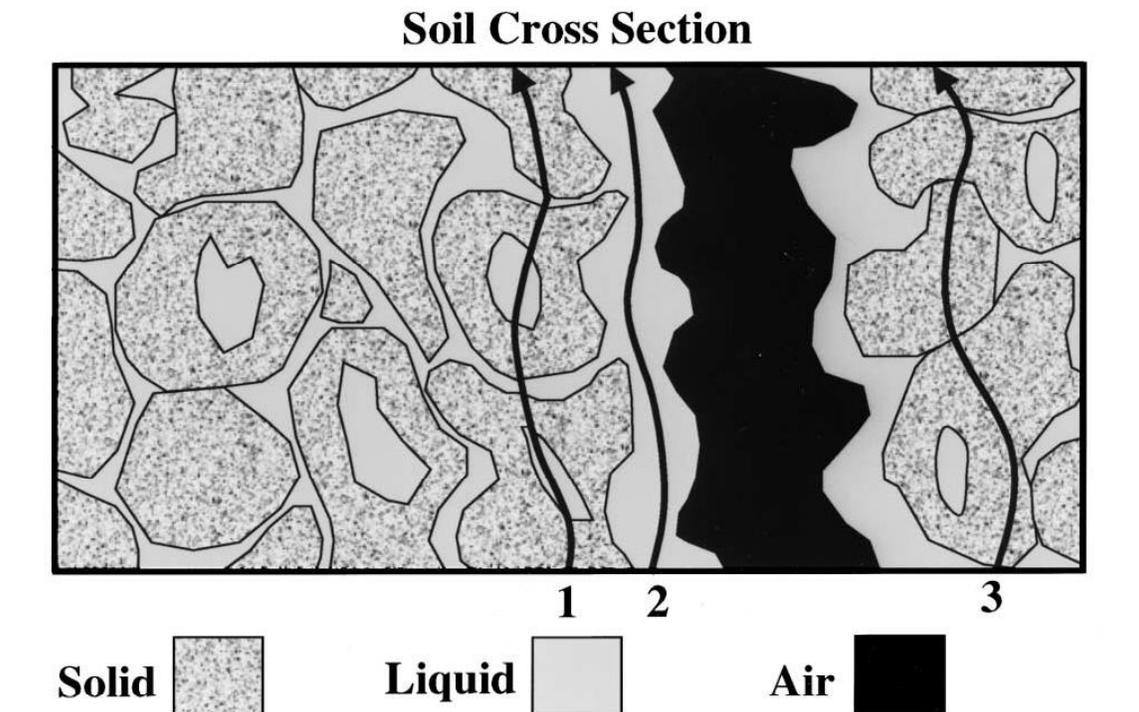


Figure 5.3 Three Pathways of electric conductivity in soil matrix. 1, water to solid, 2 soil moisture, 3 solid. Taken from Corwin et al. (2003).



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

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

3.3.4 Application of Bulk EC Measurements

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

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

$$\sigma_p = \frac{\epsilon_{rp}\sigma_b}{\epsilon_{rb} - \epsilon_{rb_0}} \quad [5.6]$$

Where σ_p is the pore water EC, ϵ_{rp} is the real dielectric content of water (≈ 80), σ_b is the bulk EC measured with the HydraProbe in soil, and ϵ_{rb} is the real dielectric permittivity of the soil measure with the HydraProbe. ϵ_{rb_0} is an offset, and 3.4 can be used as the offset for most inorganic soils.

3.3.5 Total Dissolved Solids (TDS)

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

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





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



4 Custom Calibration Programming

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

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

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

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

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

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

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

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

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

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



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

Table C1. Factory calibration modes.

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

Table C2. Coefficients for factory calibrations.

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

Custom Calibration Settings Procedure for the RS485 HydraProbe

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

Soil Type

Description: Gets/sets the probe soil type.

Access Level: Read/Write

Read Addresses: Broadcast, Exact

Read Command: <addr>ST=?<CR><LF>

Read Response: <addr><CR><LF>

Write Addresses: Broadcast, Exact, Wildcard

Write Command: <addr>ST=<soil><CR><LF> Where <Soil> can be G, O, R, C or K

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



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

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

The procedure below example using the commands in table C3.

Example 1(RS485)

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

000XA=0.3
000XB=-0.6

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

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

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



Custom Calibration Procedure for the SDI-12 HydraProbe

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

SDI-12 Extended Commands For Soil Types		
Command	Description	Response from Sensor
aXS!	Get soil type	aSG=GEN, aSO=ORG, aSR=RW
aXS<soil>!	Set soil type; G, O, R, K, C,	
aXSG!	Puts the probe back in General Calibration Mode	aSG=GEN
aXSO!	Puts Probe in Organic Calibration Mode	aSO=ORG
aXSR!	Puts Probe in Rockwool mode	aSR=RW
aXSC!	Puts the Probe in Custom 1 Mode	aSC=CUS1
aXSK!	Puts the Probe in Kustom 2 Mode	aSK=KUS2
aXY<constant>!	Get water constant	
aXY<constant><float>!	Set water constant	

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

<Soil>	Single ASCII character representing the soil type. The Default is G.
G	General Soil calibration for most soils.
O	Organic Soil Calibration for highly Organic Soils.
R	Rockwool or other inorganic growth media.
C	Custom 1, for a third-order polynomial. Equation [A1].
K	Kustom 2, for a semi-linear square-root formula. Equation [A2].

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

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

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



Example 2. SDI-12 Procedure for custom calibration

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

For example, to program a probe with an address of 0 to use the CUSTOM 1 formula, you would enter this command:

0XSC!

0SC=CUS1

The CUSTOM 1 formula uses four coefficients, so we will need to assign the values to them. To assign a value of -10.0 to the first coefficient, a value of 5.0 to the second, 0.3 to the third and 0.0005 to the fourth we would enter these commands. The probes responses are shown in **boldface**.

0XYA-10.0!

0-10.00000000

0XYB5.0!

0+05.00000000

0XYC0.3!

0+00.30000001

0XYD0.0005!

0+00.00050000

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

0XS!

0SC=CUS1

0XYA!

0-10.00000000

0XYB!

0+05.00000000

0XYC!

0+00.30000001

0XYD!

0+00.00050000

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

You can use the SDI-12 D commands to take current reading. For example the command

0M!

0D0!

Will return the first three reading from the first three parameters. 0D1! Will return the 2nd three readings and so forth.



A Note About Scientific Notation

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

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

and

12345.678 can also be entered as 1.2345678E+4

5 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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