



## **The Parameters of the Hydra Probe**

Revised December 2006

### **V1, V2, and V3.**

The first three voltages are the raw signal responses. The Hydra Probe is a Frequency Domain Reflectometer in that it is measuring the behavior of a standing wave generated from the reflection of an electromagnetic wave at a radio frequency of 50 MHz. The 50 MHz electromagnetic wave propagates along the wave guide. The soil absorbs most of the wave. The portion of the wave that reflects back down the wave guide encounters the emission propagation creating a standing wave. The first three voltages represent the behavior of the standing wave and thus the complex dielectric permittivity. The direct measurement of the complex dielectric permittivity from the raw signal responses is the basis behind the other parameters and makes the Hydra Probe unique among other FDR type methods (Campbell, 1990, Seyfried and Murdock, 2003). In almost all applications, V1, V2, V3, V4 and V5 by themselves are of no interest to the average user.

### **V4**

V4 is the raw signal response of the diode thermistor. The diode thermistor is located within the probe housing. V4 is used to make temperature corrections to the electronics. See Diode temperature below for more information. In almost all applications, V1, V2, V3, V4 and V5 by themselves are of no interest to most users.

### **V5**

V5 is the raw signal response of the soil thermistor. The soil thermistor is located in the stainless steel base plate between the tines. It is in close proximity to the soil providing accurate soil temperature readings. Complex dielectric permittivity is influenced by temperature. Not only can the Hydra Probe measure soil temperature, it can make temperature corrections to the calibration curves based on the temperature corrections of the complex dielectric permittivity. See temperature corrected real and imaginary dielectric constant for more information. In almost all applications, V1, V2, V3, V4 and V5 by themselves are of no interest to most users.

### **Soil Temperature in Celsius**

With the Hydra Probe, the user can select Fahrenheit or Celsius. Typically, the soil temperature will be less influenced by the ambient air temperature with depth. In other words the deeper you go the more constant the soil temperature. Diurnal (daily) temperature fluctuations between daytime highs and nighttime lows maybe observed with the Hydra Probe's temperature data. These fluctuations will become less pronounced with depth. Vegetation, tree canopy, and soil moisture are factors that will effect the diurnal soil temperature fluctuations. For example, in the American Southwest, A Hydra Probe buried at a five inch depth will have very resolved temperature fluctuations between the nighttime lows and the daytime highs if there is no vegetation insulating the soil. Seasonal trends can also be observed in soil temperature data.

## **Soil Temperature in Fahrenheit**

With the Hydra Probe, the user can select Fahrenheit or Celsius.

## **Soil Moisture**

### *-Soil Moisture Units*

The Hydra Probe provides accurate soil moisture measurements in units of water fraction by volume (wfv or  $m^3m^{-3}$ ). That is, a percentage of water in the soil displayed in decimal form. (Note: the PDA HydraMon Software displays soil moisture readings in percentage form). For example, a water content of 0.20 wfv means that a one liter soil sample contains 200 ml of water. Full saturation (all the soil pore spaces filled with water) occurs typically between 0.3-0.45 wfv and is quite soil-dependent.

There are a number of other units used to measure soil moisture. They include % water by weight, % field capacity, % available (to a crop), inches of water to inches of soil, and tension (or pressure). They are all inter-related in the sense that for a particular soil, knowledge of the soil moisture in any one of these units allows the soil moisture level in any of the other unit systems to be determined. It is important to remember that the conversion between units can be highly soil-dependent.

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

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

### *-Soil Moisture Calibration*

There are four calibration curves depending on the texture of the soil. The calibration curves are polynomials that include the real dielectric constant and several coefficients (Topp 1980, Seyfried and Murdock 2003). The four user selectable soil texture settings are Sand, Silt, Clay, and Loam. The texture is determined by the percentage of sand silt and clay there is in the soil. Figure 1 shows the corresponding percentages to the different textures.

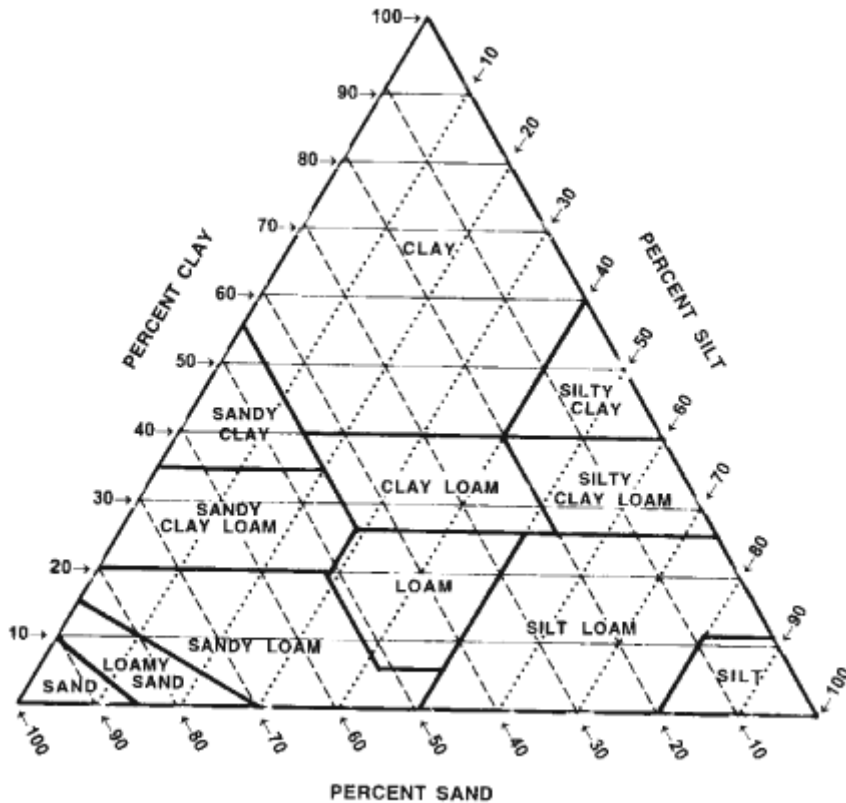


Figure 1. Soil Texture Triangle.

If you are unsure of your soil texture, determining which soil setting that is best for your soil is easy and there are a number of different ways to make the determination (Birkeland 1999).

- a) A detailed soil survey for your area can be downloaded for free from the US Department of Agriculture at <http://soildatamart.nrcs.usda.gov/>
- b) Many times, it will be obvious. Sand looks different from clay.
- c) Grab a baseball size portion of the soil in your hands. Wet the soil with water and work the moist soil with your hands. The stickier it is, the more clay there is. The “soapier” the soil feels the higher the silt content. Grittiness is indicative of sand.
- d) If you have a mixture of sand silt and clay or if you are unsure what the texture of your soil is, then use the Loam setting. The Loam setting is applicable for Loam, Clay Loam, Silty Clay Loam, Silt Loam, Sandy Loam, Sandy Clay Loam, Sandy Clay and Silty Clay textures.

*-Soil Moisture Measurement Considerations*

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

Soil moisture values are particularly important for irrigation and the health of the crop. Equation [1], [2] and [3] will help determine when to irrigate. The following are terms communally used in soil hydrology:

- Soil saturation 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 (FC in equations below) refers to the amount of water left behind in soil after gravity drains saturated soil.
- Permanent wilting point (PWP in equations below) refers to the amount of water in soil that is unavailable to the plant.
- The Allowable Depletion (AD in the equations below) is calculated by equation [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 to get the water.
- Lower soil moisture limit (LL from [3]) is the soil moisture value below which the crop will become stress 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.

The lower soil moisture limit is a very important value because dropping below this value will effect the health of the crops. Equations 1,2, and 3 and the example show how to calculate the lower soil moisture limit.

$$AD = (FC - PWP) \times MAD \quad [1]$$

$$AWC = FC - PWP \quad [2]$$

$$FC - AD = LL \quad [3]$$

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 1** Maxium allowable depletions for different soil textures

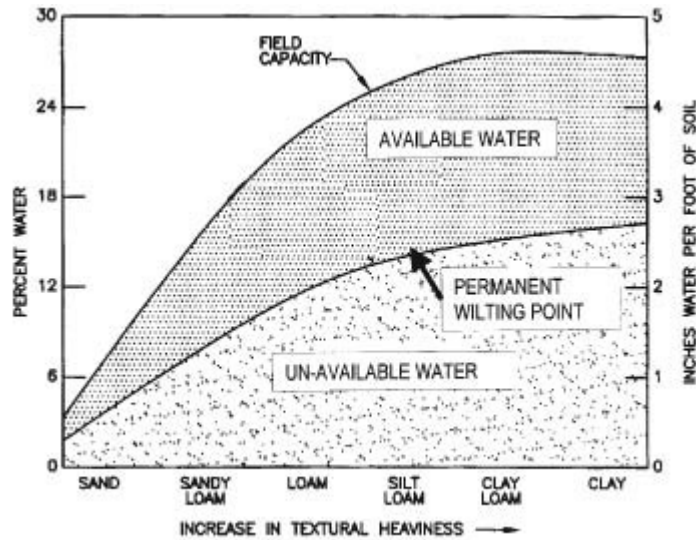


Figure 2. soil textures and the available water.

For example, let us suppose your soil is a sandy loam. From table 1,  $MAD = 0.5$ . From Figure 2 (or a soil survey)  $PWP = 8\%$  and the field capacity is  $15\%$ . Using equation [1] yields;  $AD = (15-8) \times 0.5 = 3.5\%$ . The lower limit would then be calculated by equation [3].  $LL = 15-3.5 = 11.5\%$ . This means for a sandy loam, if the soil moisture drops below  $11.5\%$  (or Hydra Probe reading of  $0.115$ ), the crop may become stressed and it is time to irrigate. Never let the soil moisture drop below the permanent wilting point.

### Soil Salinity (g/L NaCl)

The Soil Salinity (g/L NaCl) parameter is the salinity of a 1:1 soil/water slurry. It is the “total dissolved solids” (TDS) in the form of dissolved salts. The soil salinity parameter is primarily used with the portable versions of Hydra Probe such as the Hydra Reader or the PDA HydraMon Portable Soil Sensing System. The soil salinity is approximated:

$$\text{Soil Salinity (g/L)} \approx \text{EC (S/m)} \times 6.4 \quad [4]$$

Equation [4] is found in the literature (McBride 1994) and works well if the soil is not extremely acidic or extremely alkaline.

To use the Soil Salinity Parameter, mix one part soil with one part water and take a reading with the Hydra Probe’s tines completely submerged. Avoid using metal containers to take the reading and make the slurries because the metal may interfere with the measurements.

In situ soil salinity is usually inferred by the in situ soil electrical conductivity in S/m (see soil electrical conductivity section below).

### Soil Electrical Conductivity (Temperature corrected)

The Hydra Probe measures the in situ electrical conductivity in units of Siemens per meter. Soil electrical conductivity is indicative of dissolved salts, dissolved solids, and

fertilizers (McBride 1994). It may also be indicative of very high pH conditions. The soil electrical conductivity is calculated from the temperature corrected imaginary dielectric constant [ $E_{i(tc)}$ ], by the theoretical expression:

$$EC = 2\pi f \epsilon_0 E_{i(TC)} \quad [5]$$

Where EC is the electrical conductivity, f is the frequency (50 MHz for the Hydra Probe) and  $\epsilon_0$  is the dielectric constant of a vacuum. For more information on soil electrical conductivity considerations, see soil electrical conductivity section below.

As the temperature increases, the molecular vibration increases (Levine, 1993). The molecular vibration has a complex effect on both the orientation polarization and on the imaginary dielectric constant. The temperature corrections are based on the small incremental changes of  $E_i$  and  $E_r$  with temperature (*dE<sub>i</sub>/dT vs E<sub>i</sub> intercept and dE<sub>r</sub>/dT vs E<sub>r</sub> intercept*).

### **Real and Imaginary Dielectric Constants**

The Hydra Probe is a dielectric constant sensor (Seyfried, Grant, and Humes 2005) measuring the complex dielectric permittivity. The complex dielectric permittivity is the raw electrical parameter that has real and imaginary components (the real dielectric constant and the imaginary dielectric constant). These two parameters serve to fully characterize the electrical response of soil and are measured from the response of a reflected standing electromagnetic wave at a radio frequency of 50 MHz. Both the real and imaginary dielectric constants are dimensionless quantities.

**The real dielectric constant** represents the molecular orientation polarizability. The orientation polarization of a water molecule in the presence of an electromagnetic wave is much greater than the polarization of soil, which is mostly due to electronic and atomic polarization. The real dielectric constant of dry soil can be from 1 to 5 where the real dielectric constant for pure water is about 80. That is to say that the real dielectric constant of soil is mostly attributed to the presence of water. Figure [3] illustrates the different kinds of polarization molecules can under go upon receiving electromagnetic energy. The general equation that describes complex dielectric permittivity is:

$$K^* = E_r - jE_i \quad [6]$$

Where ( $E_i$ ) is imaginary dielectric constant,  $j = -1^{1/2}$  and is the imaginary number, and ( $E_r$ ) is the real dielectric constant.

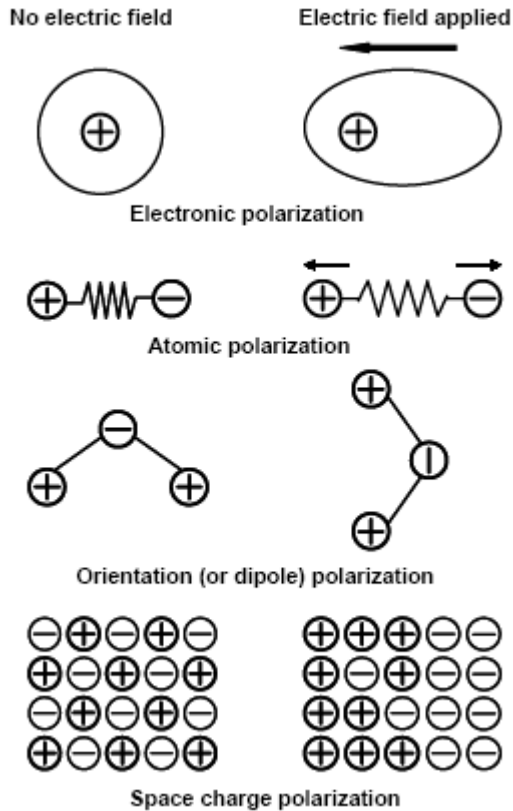


Figure [3]. Illustration of polarization. The real dielectric constant of soil is mostly due to orientation polarization of water (Taken from Lee et al. 2003)

The **imaginary dielectric constant** is directly related to the conductivity of the medium, the higher the imaginary dielectric constant, the higher the conductivity. Assuming the molecular relaxation is negligible, the imaginary dielectric constant is a function of frequency and electrical conductivity by the following relationship:

$$E_i = EC / 2\pi f \epsilon_0 \quad [7]$$

Where EC is the electrical conductivity, f is the frequency (50 MHz for the Hydra Probe) and  $\epsilon_0$  is the dielectric constant in a vacuum. As can be shown by equation [6], as the frequency increases, the  $E_i$  rapidly decreases. Conversely, if the frequency decreases or if cations are introduced, the  $E_i$  will increase thus affecting the real dielectric constant of the matrix.

The Hydra Probes' design features such as the geometry of the wave guide and the frequency at 50 MHz allows the Hydra Probe to simultaneously measure both real and imaginary dielectric constants (Campbell, 1990).

### **Real Dielectric and Imaginary Constants (Temperature corrected)**

For a definition of real and imaginary dielectric constants, see previous section. Since both the real and imaginary dielectric constants will vary somewhat with temperature, the user of the Hydra Probe has the option of selecting the temperature corrected values for the real and imaginary dielectric constants. The uncorrected and the

corrected dielectric values may be of interest for some researchers. The soil moisture calibrations are based on the temperature corrected values because the calibration curves were established at a constant temperature. Similarly, the temperature corrected imaginary dielectric constant was used for the electric conductivity measurement.

As the temperature increases, the molecular vibration increases (Levine, 1993). The molecular vibration has a complex effect on both the orientation polarization and on the imaginary dielectric constant. The temperature corrections are based on the small incremental changes of  $E_i$  and  $E_r$  with temperature ( $dE_i/dT$  vs  $E_i$  intercept and  $dE_r/dT$  vs  $E_r$  intercept).

### **Soil Electrical Conductivity.**

The Hydra Probe measures the in situ electrical conductivity in units of Siemens per meter (S/m). Soil electrical conductivity is indicative of dissolved salts, dissolved solids, and fertilizers (McBride 1994). It may also be indicative of very high pH conditions. The soil electrical conductivity is calculated from the imaginary dielectric constant [ $E_i$ ]. by the theoretical expression:

$$EC = 2\pi f \epsilon_0 E_i \quad [8]$$

Where EC is the electrical conductivity, f is the frequency (50 MHz for the Hydra Probe) and  $\epsilon_0$  is the dielectric constant of a vacuum.

#### *-Electrical Conductivity Pathways in Soil*

The electric conductivity of soil is complex. Figure [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 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, 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 soil water. 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 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. That factor that will be the dominant factor will change with dissolved salt concentration and soil water content.

## Soil Cross Section

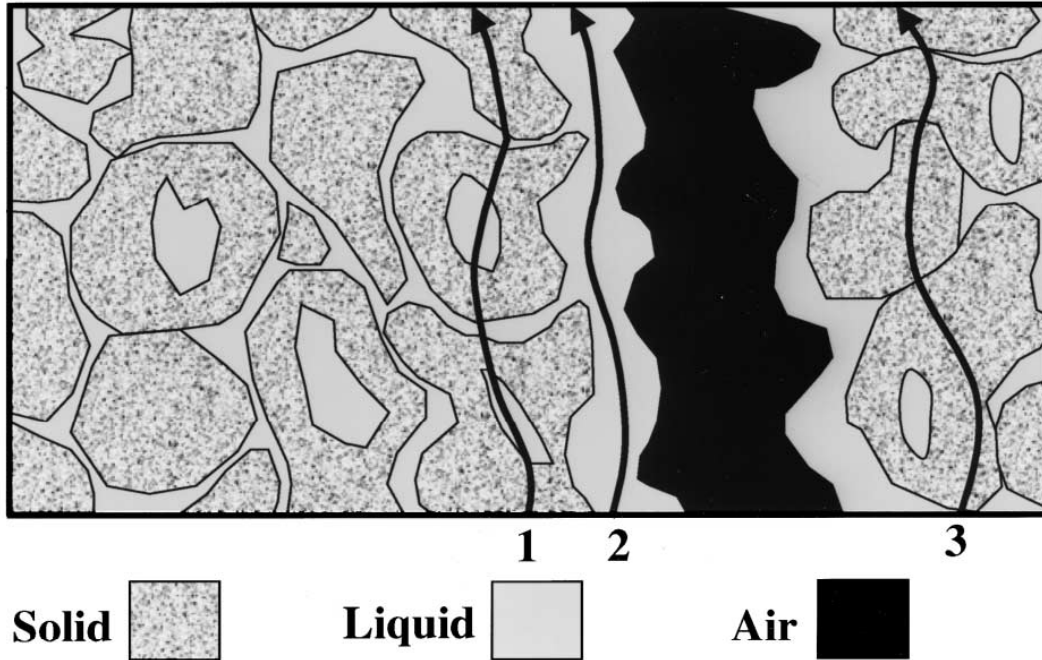


Figure 4. Pathway3 of electric conductivity in soil matrix. 1 water to solid, 2 soil moisture, 3 solid. Taken from Corwin et al. (2003).

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.

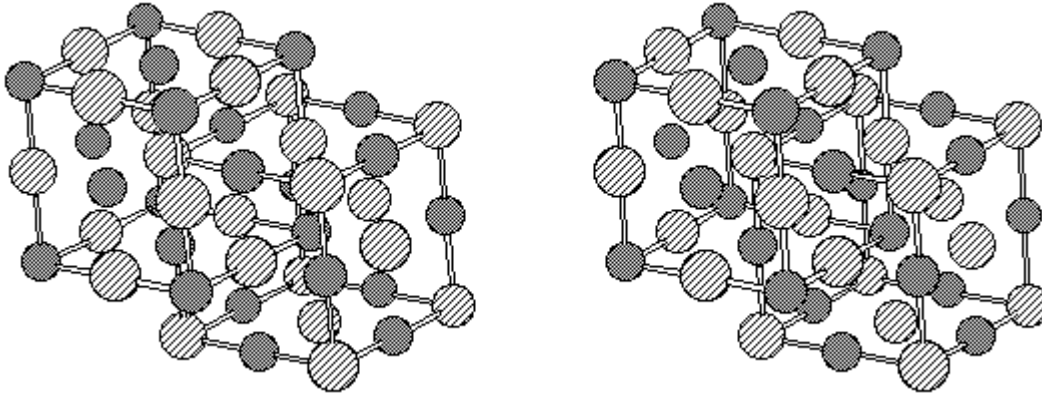
The electric conductivity measurements provided by the Hydra Probe is the electrical conductivity of the dynamic soil matrix as a whole. No in situ soil sensor can distinguish the difference between the different pathways nor can any conventional in situ soil sensor distinguish the difference between sodium chloride and any other number of solutes that all have different electrical conductivities

### *-Solution Chemistry*

Salinity refers to the presence of dissolved inorganic ions such as  $Mg^{+}$ ,  $Ca^{++}$ ,  $K^{+}$ ,  $Na^{+}$ ,  $Cl^{-}$ ,  $SO_4^{2-}$ ,  $HCO_3^{-}$  and  $CO_3^{2-}$  in the aqueous soil matrix (Hamed 2003). The salinity is quantified as the total concentration of soluble salts and is expressed in situ in terms of electrical conductivity. There exist no conventional in situ salinity probe that can distinguish the difference between the different ions that may be present.

When salts such as sodium chloride are in their solid form, they exist as crystals. Within the salt crystal, the sodium and the chlorine atoms are joined together in what is called an ionic chemical bond. An ionic chemical bond holds the atoms tightly together because the sodium atom will give up an electron to the chlorine thus ionizing the atoms. If an atom like sodium gives up an electron, it is said to be a positively charged ion (also called a cation). If an atom such as chlorine receives an electron, it is said to be a negatively

charged ion (also called an anion and is given the suffix ide, like chloride). The sodium and the chloride ions comfortably arrange themselves into a stacked like configuration called a crystal lattice. The sodium chloride crystal lattice has a zero net charge.



**Figure [5]. The crystal lattice model of sodium chloride. The larger spheres are chloride anions.**

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

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

#### *-Cation Exchange and Agriculture*

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

Agricultural soils over time may become sodic or saline and this may dramatically effect the health and yields of the crops. There are techniques that can remove the sodium to improve soil quality and increase crop production. The Stevens Hydra Probe is an invaluable tool for monitoring the progress of a saline soil reclamation, saving time and resources.

The outer portion of a soil particle is typically negatively charged. Positively charged sodium ions will bind or “hook” onto the surface of the soil micro particle. The opposite charges create an electronic attraction between the sodium ion and the soil. The sodium ions compete for negatively charged sites on the soil particle surface and in doing so, disperse the aggregates of soil. The aggregate dispersion of the soil caused by the sodium ions will decrease the porosity of the soil. As porosity decreases, the water holding capacity of the soil decreases. Not only are high levels of sodium ions toxic to the crops, it decreases the water that would be available to the plants.

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

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

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

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

The Stevens Hydra Probe is an important tool in monitoring ion exchange reactions in the soil because it will help manage the amount of irrigation water used and the duration of application save time and money.

### **Diode Temperature**

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

### **ADC Reading 1 through 5**

The ADC Reading 1 through 5 are the analog to digital values at 12 bits. They are the binary numbers that correspond to V1 through V5. They can used by Stevens for developmental or trouble shooting purposes.

### **Communication**

The Hydra Probes' output can be analog or digital. The digital Hydra Probe can be either, RS485 or SDI-12. With both versions of digital Hydra Probes, the raw sensor signal

response is converted to the measurements that are of interest to the user by a microprocessor that is located within the Hydra Probe housing. The logger (such as a Stevens Dot Logger) then receives sensors calculated measurement of interest.

SDI-12(serial data interface at 1200 baud) allows compatibility with SDI-12 compliant data loggers and simplifies the installation. Stevens Water Monitoring Systems Inc. was one of the first members of the SDI-12 Technical Committee. More information about SDI-12 can be found at <http://www.sdi-12.org/>.

The Stevens DOT Logger is the perfect companion for the Hydra Probe. The DOT logger has 100 SDI-12 channels. For example, 33 Hydra Probes each measuring 3 parameters such as EC, temperature and soil moisture, can be connected to a single DOT logger. (100 available SDI-12 channels divided by 3 parameters per sensor = a rounded 33 sensors).

[Table 2]

SDI-12 Index ID	Parameter	Units
A	Voltage 1	Volts
B	Voltage 2	Volts
C	Voltage 3	Volts
D	Voltage 4	Volts
E	Voltage 5	Volts
F	Soil Temperature	Celsius
G	Soil Temperature	Fahrenheit
H	Soil Moisture	Water Fraction byVolume
I	Soil Salinity	Grams NaCl / Liter
J	Soil Conductivity (temp. corrected)	Siemens / Meter
K	Real dielectric constant -	
L	Real dielectric constant (temp.corrected)	
M	Imaginary dielectric constant -	
N	Imaginary dielectric constant (temp.corrected)	
O	Soil Conductivity	Siemens / Meter
P	Diode temperature	Celsius
R	ADC Reading 1 -	Binary
S	ADC Reading 2 -	Binary
T	ADC Reading 3 -	Binary
U	ADC Reading 4 -	Binary

Table 2. SDI-12 Parameters and Index

The SDI-12 Hydra Probe has three wires. A ground wire, a +12 volt power wire and a blue data wire. The digital data can be communicated from the probe to the logger on the single data wire. The data wires from multiple probes can be connected to a terminal assembly or multiplexer. The single data wire from the multiplexer can be connected to a single SDI-12 data port on the logger. An SDI-12 data logger such as the Stevens Dot Logger, can discriminate between multiple probes with multiple parameters from the single SDI-12 data port. This simplifies installation.

Table [2] shows the SDI-12 parameters and the index ID. The SDI-12 index ID is the SDI-12 commands for transparent mode in Hyper Terminal and is used to select the desired parameter set.

The RS 485 Hydra Probe is also digital and uses an RS485 communication format. The RS 485 Hydra Probe has 4 wires, a ground wire, a +12 volt power wire and 2 data wires. The RS 485 Hydra Probe communicates data through two data wires and can be wired into a RS 485 port on a logger. They can be configured on a terminal assembly like the SDI-12 version but with four wires instead of three. The advantage RS 485 would have over the SDI-12 version is that the RS485 version's cable can run over 3000 feet, but in doing so draws more power.

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