



# Soil Physics Workshop

## Soil Hydrology with the Stevens HydraProbe Soil Sensor

Keith Bellingham,  
Hydrologist/Soil  
Scientist

# COURSE SUMMARY

- Knowledge of soil moisture and the measurement of soil moisture help society answer some important questions about drought, flood forecasting, greenhouse gas emissions, food security and crop production.
- This course will focus on the science of the analytical measurements of soil water content and water potential.
- From an applications in the field prospective to a more theoretical approach, this course provides tools, information, and insight for users of soil moisture sensors and soil moisture data.

# CONTENTS

1. History and Introduction (5 minutes)
2. Soil Geomorphology (15 minutes)
3. Featured Soil Sensor Technology (3-5 minutes)
4. Soil Sensor Applications (10 minutes)
5. Soil Water Movement (40 minutes)
6. Dielectric Permittivity (15 minutes)
7. Calibration of Soil Sensors (20 minutes)
8. Bulk EC and Salinity (10 minutes)
9. Installation
10. Soil Moisture Data
11. Lightning Protection

## **Instructor:**

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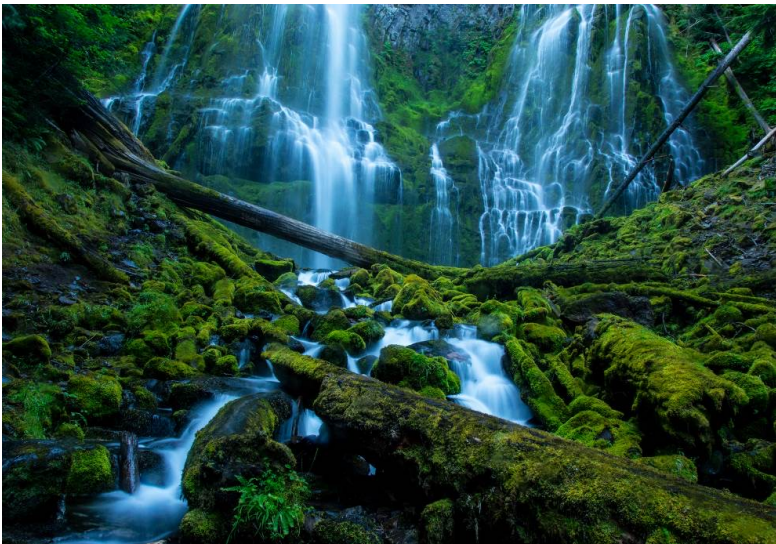


# HISTORY & INTRODUCTION





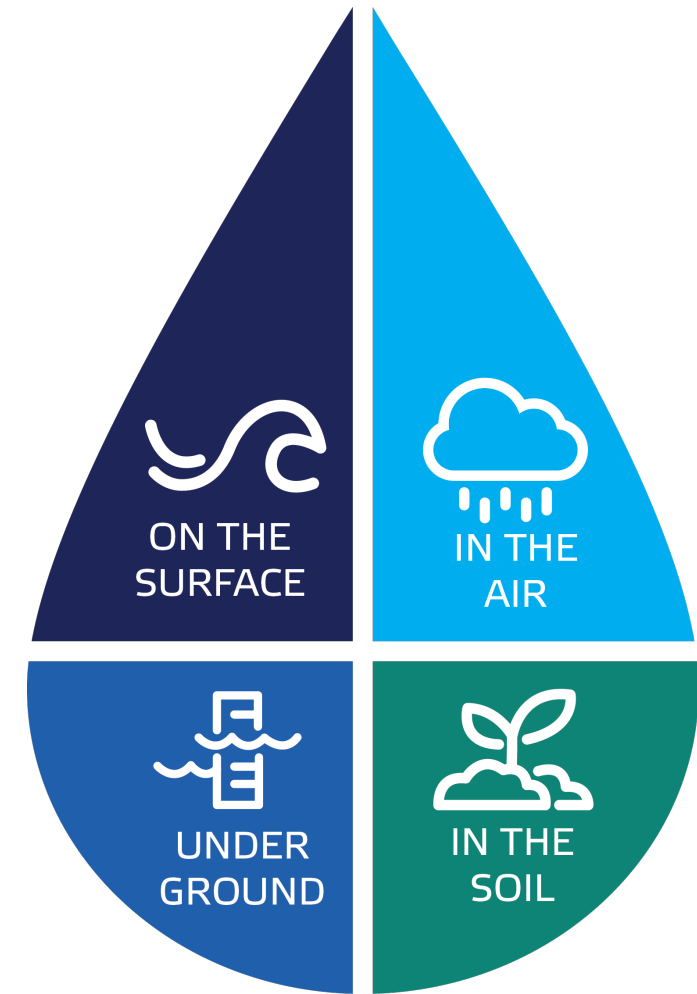
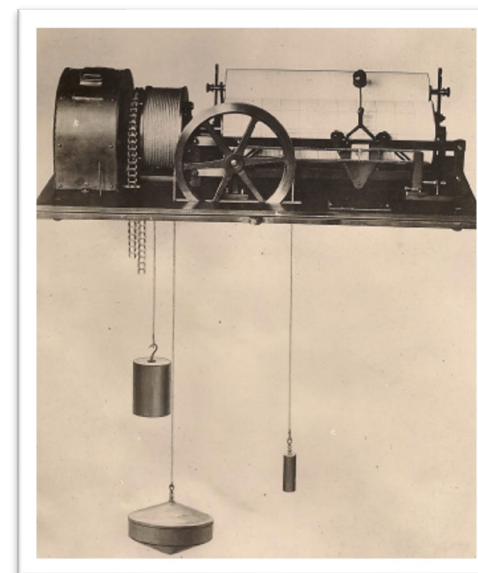
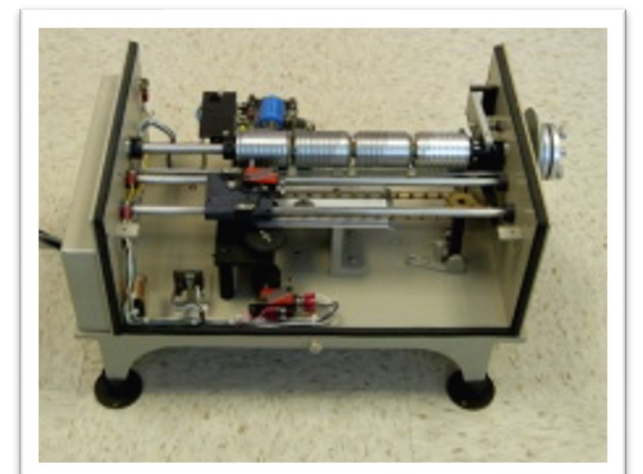
# BASED IN THE STATE OF OREGON





# ABOUT US

- Founded in 1911, Stevens Water Monitoring Systems, Inc. is a manufacturer and marketer of integrated hydrological, meteorological and oceanographic monitoring instrumentation, accessories and information systems that help optimize water resource management and enhance forecasting.
- Our focus is the earth's valuable water resources, in every form it occurs.



STEVENS



# INNOVATION AND ADAPTATION

With a Focus on the Customer



STEVENS



1911

**Stevens**  
Water Monitoring Systems



1985

**STEVENS**

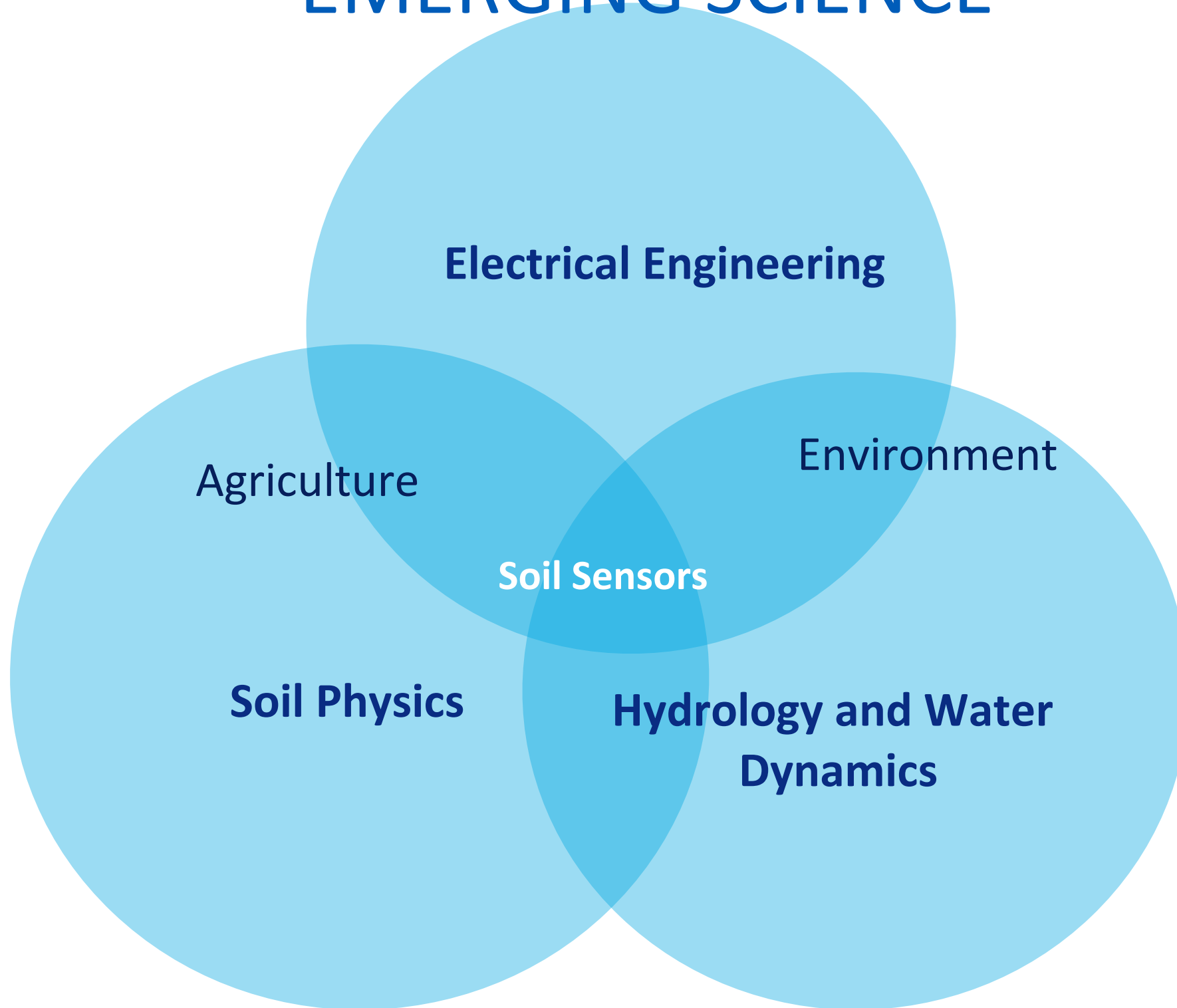
 **HydraProbe**



2019

**STEVENS**

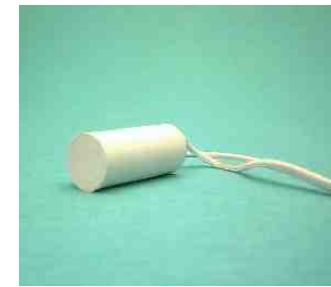
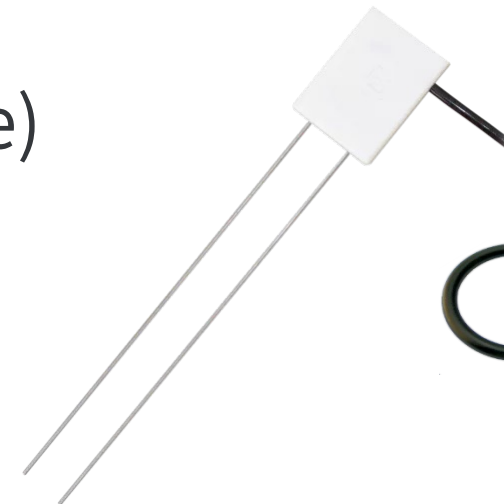
# SOIL MOISTURE MONITORING IS AN EMERGING SCIENCE





# TWO FAMILIES OF SOIL SENSORS

- Water Potential (or Water Matric Potential)
  - Matric potential is the amount of pressure it takes to pull water out of soil.
  - Symbol is  $\psi_m$ .
  - Typically measured by a tensiometer, heat capacitance sensor, or granular matrix sensor like a gypsum block. (Kpa, hPa, Bar, PSI, pF (-log hPa)).
  - Tells you when to water.
- Water Fraction by Volume (Soil Moisture)
  - Voltmeters water fraction  $\theta$ . Typically electric sensors such as a TDR, FDR, Capacitance or impedance.
  - Units fraction  $m^3m^{-3}$ , or multiply 100 to get %.
  - Tells you how much water to put on.



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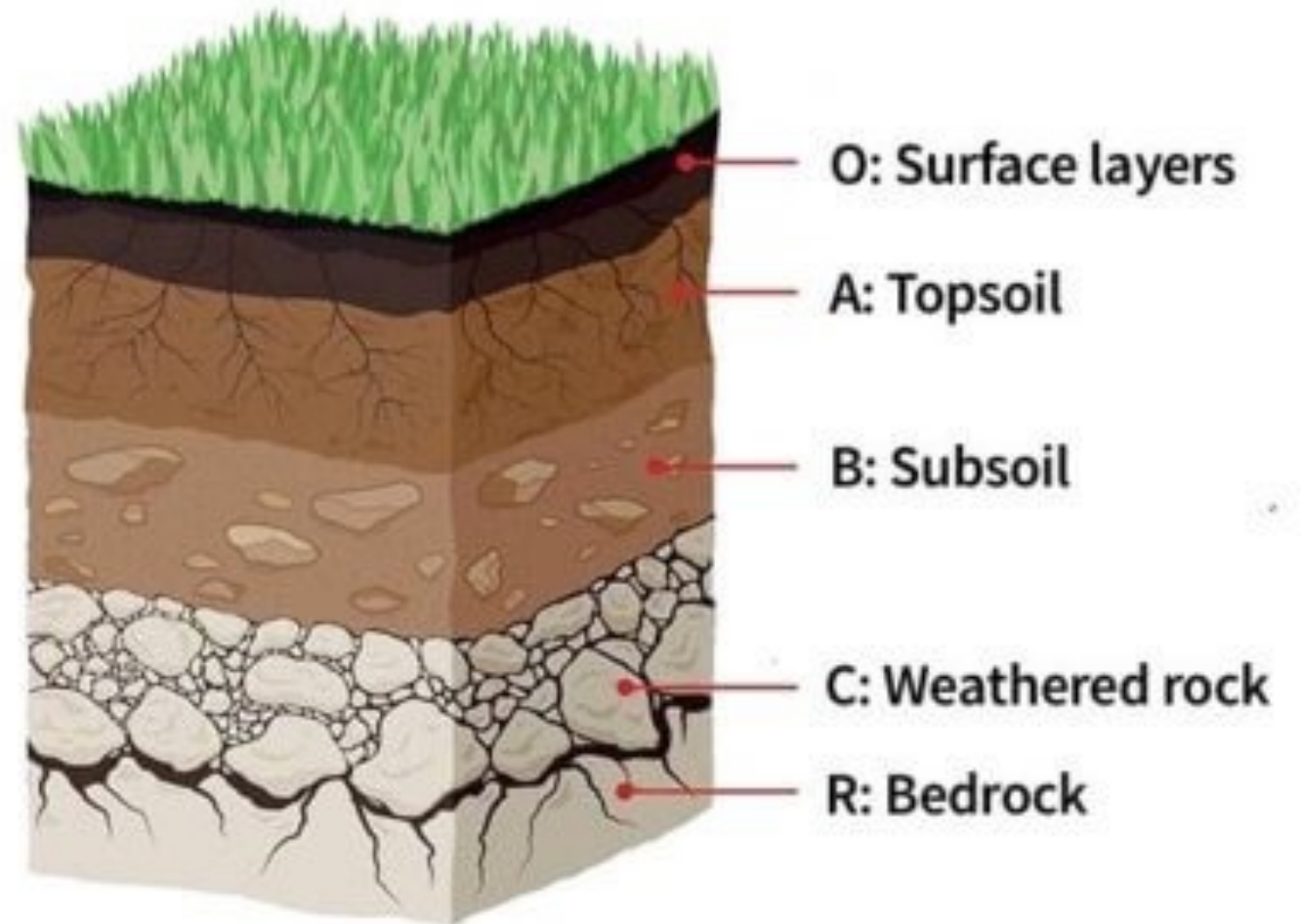


# SOIL GEOMORPHOLOGY



# SOIL GEOMORPHOLOGY

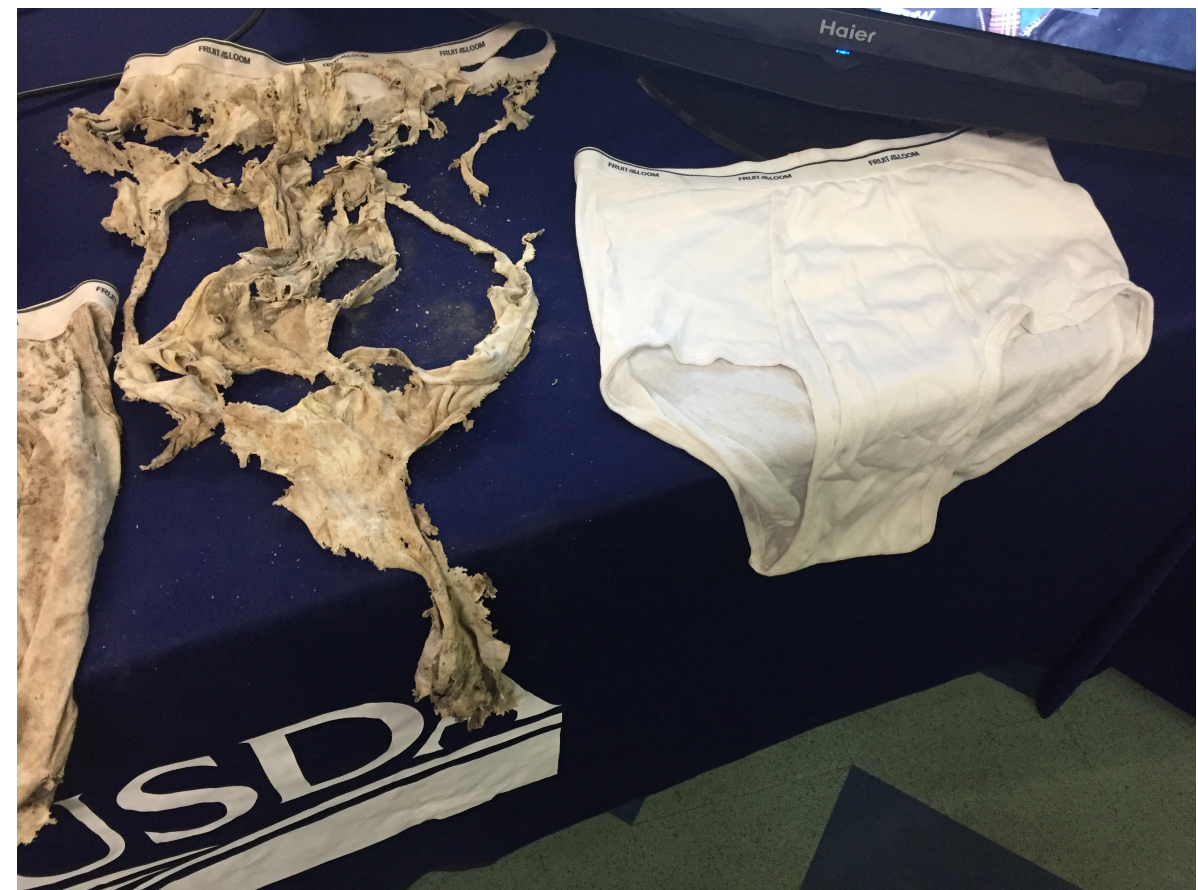
- Soil Geomorphology is the science of soil properties and formation over time.
- AKA Pedology, the study of soil peds (a structural unit of a specific soil).
- The topic is important because it explains how water will behave in a given soil and it can give insight into where and how deep to place soil moisture sensors.





# SOIL HEALTH

- Soil health is a function of the biological activity in the soil which also influences water holding and conducting properties as well as crop/plant health

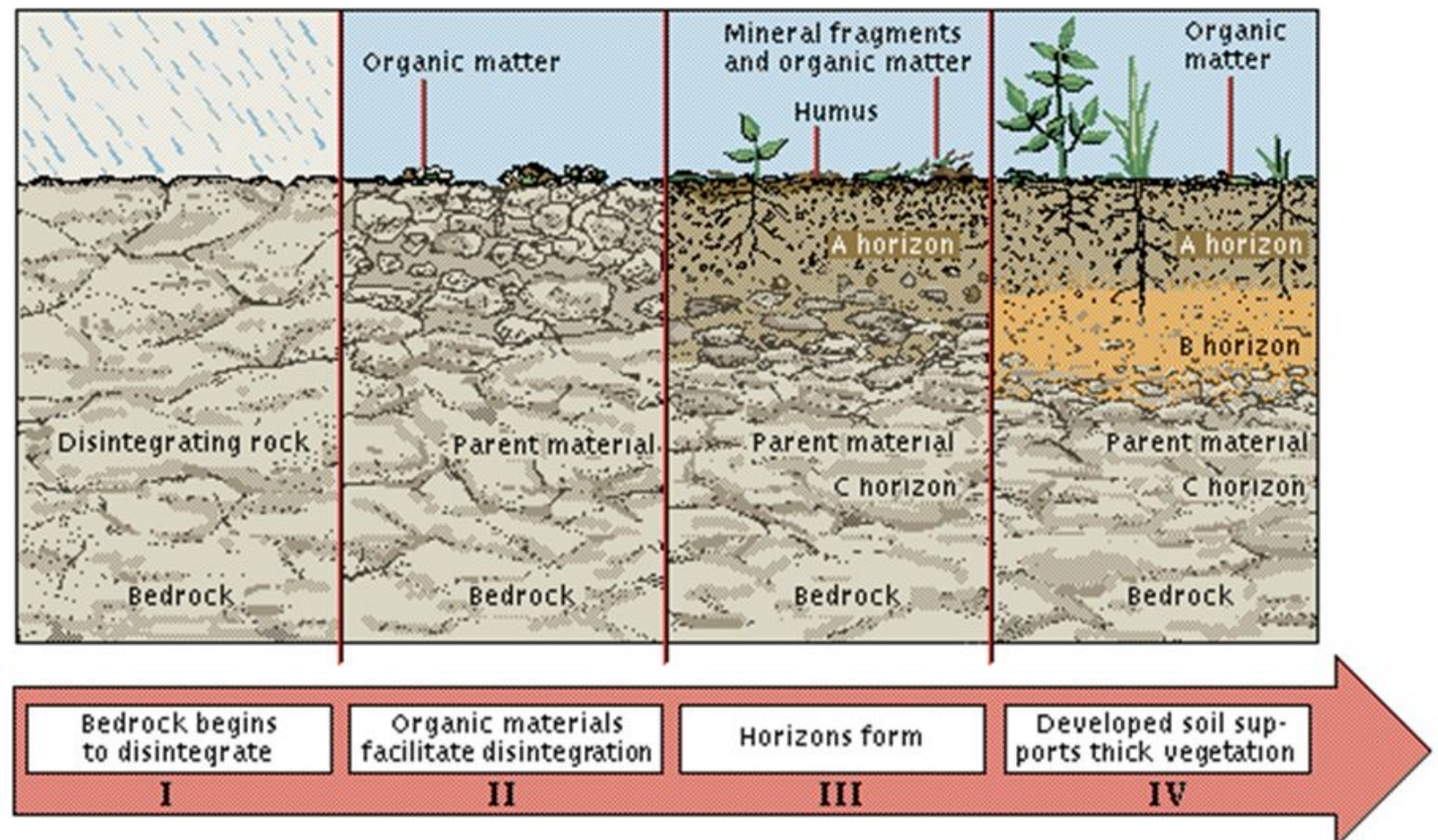




# SOIL GEOMORPHOLOGY

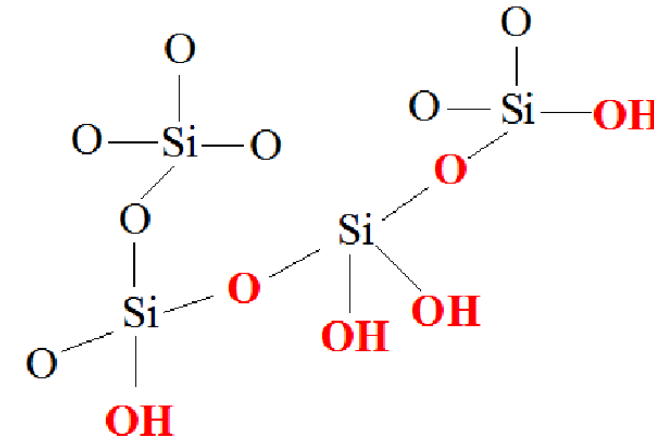
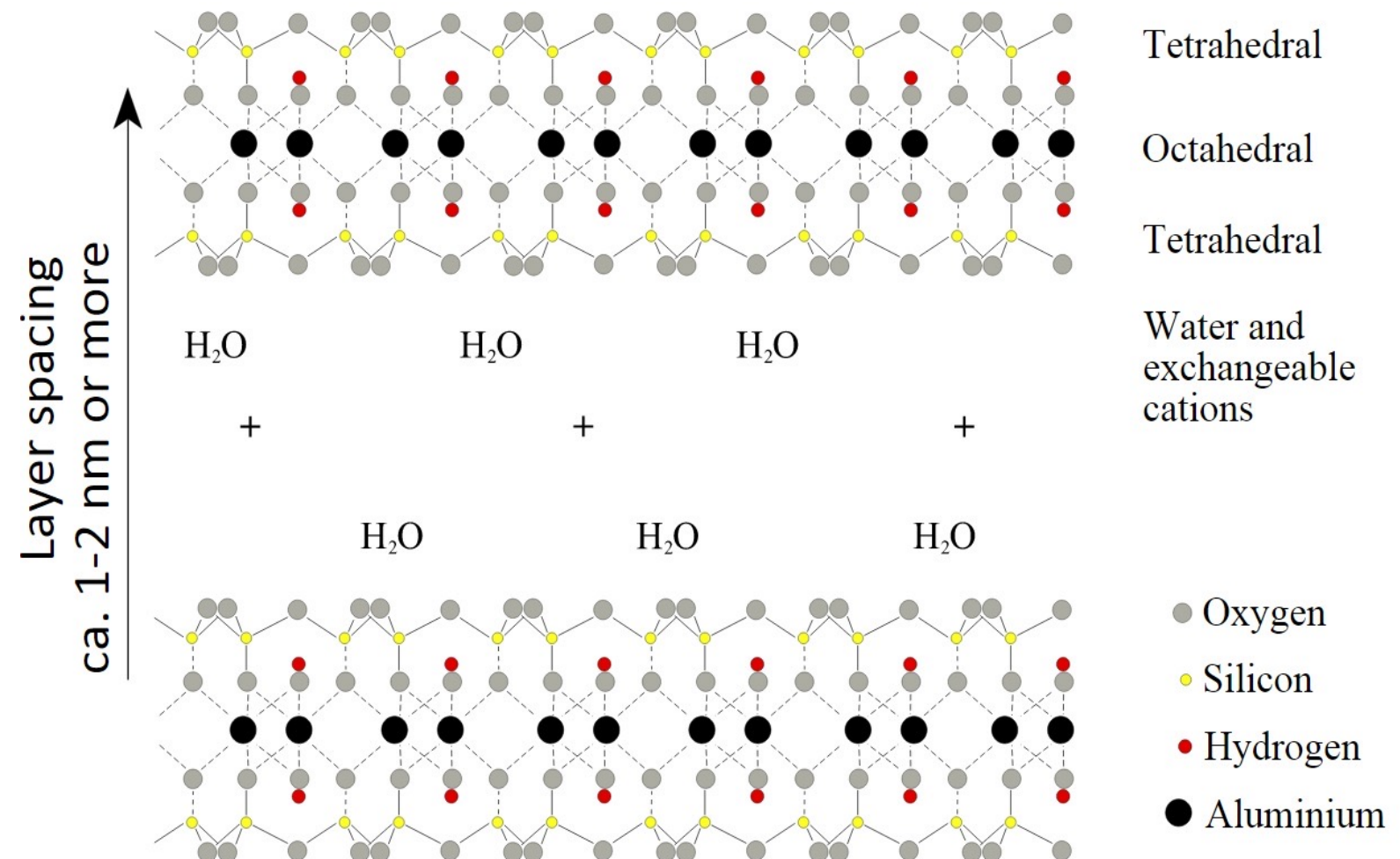
- Soil is Complex chemically, physically, hydrologically and biologically.
- Soil forms from the weathering of rock. As rock ages, it breaks down into sand. Sand continues to break down into smaller components and oxidizes to transform into silt. Silt continues to break down, rearrange into a planar configuration which leads to the formation of clay.

## Soil Development Over Time



# SOIL GEOMORPHOLOGY

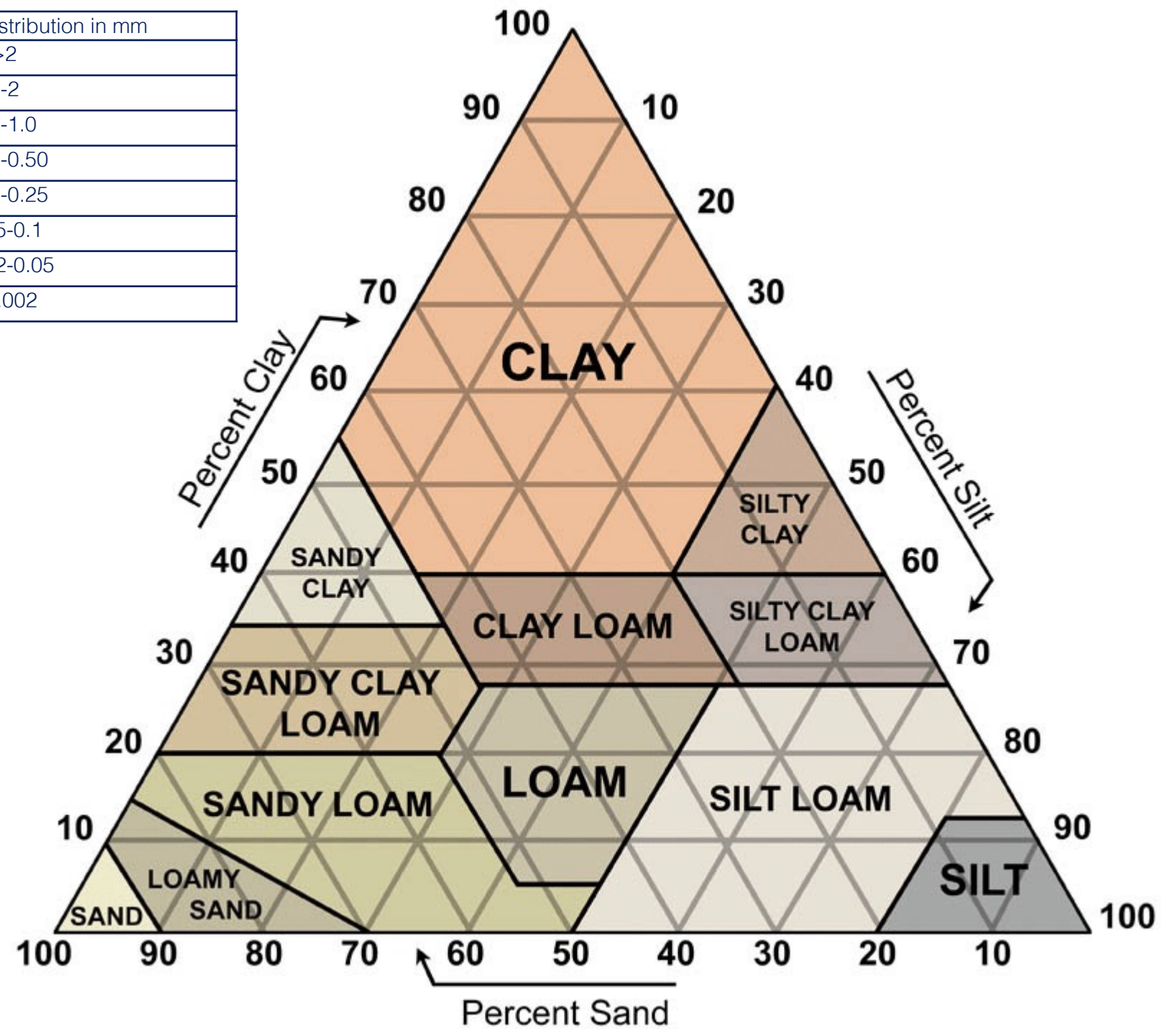
- The elemental chemical composition of soil Si, Al, Fe(III), Fe(II), O, and H.
- Particle Size: Sand>Silt>Clay
- Particles of silt and sand are spherical where clay is planer. [capillary forces is greatest in clay]
- Clay will have more negative charge distribution and is more oxidized. [nutrient holding capacity]





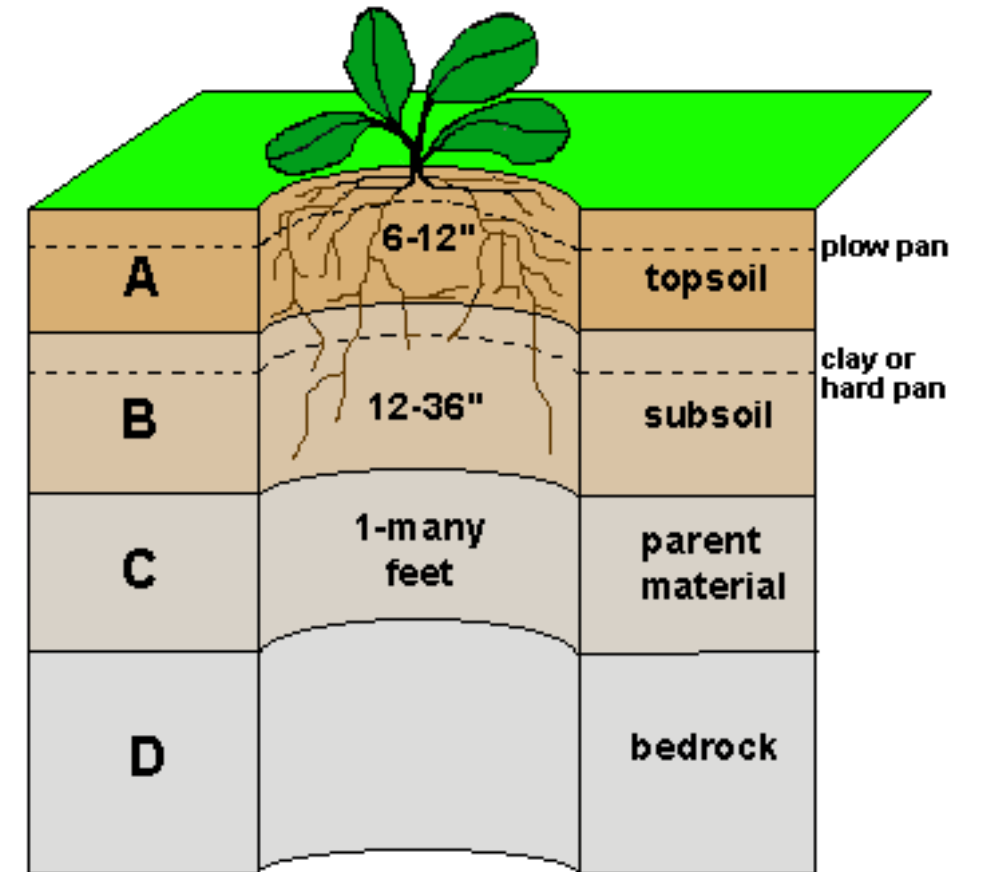
# SOIL TEXTURAL CLASS

| Mineral Type     | Particle size distribution in mm |
|------------------|----------------------------------|
| Gravel           | >2                               |
| Very course sand | 1-2                              |
| Coarse sand      | 0.5-1.0                          |
| Medium sand      | 0.25-0.50                        |
| Fine sand        | 0.10-0.25                        |
| Very fine sand   | 0.05-0.1                         |
| Silt             | 0.002-0.05                       |
| Clay             | <0.002                           |



# SOIL HORIZONS

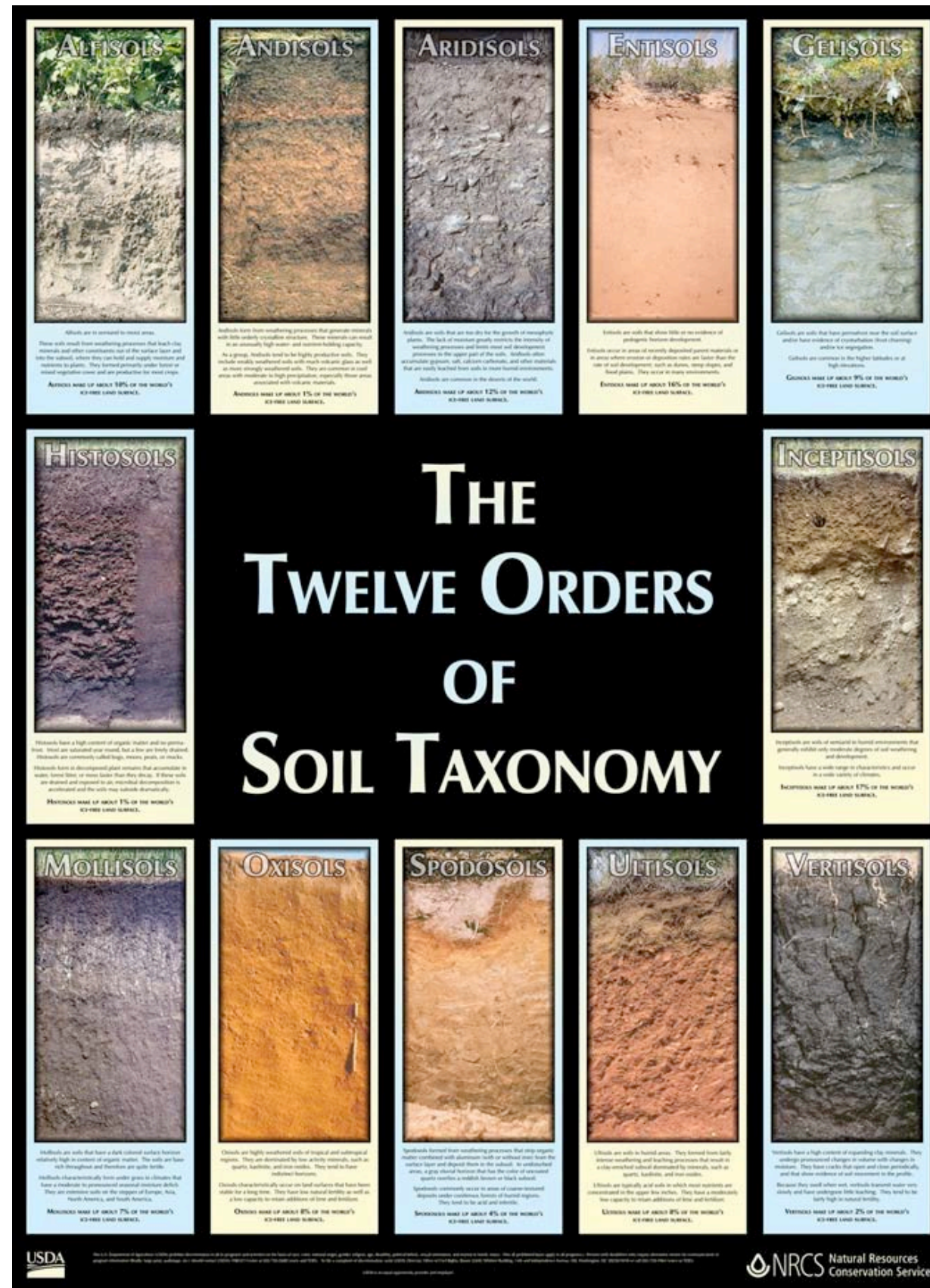
| Soil Horizon | Typical Depth                                                                                                                                                                               | Features                                                                                                                                                                                                                             |
|--------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| O            | On top of soil, Soil Surface                                                                                                                                                                | Composed of mainly Organic material such as dead plants, sticks, leaves and inorganic dust. Also contain live roots.                                                                                                                 |
| Oa           | On top of soil, Soil Surface                                                                                                                                                                | A well decomposed O Horizon with a fiber content less than 17% by volume                                                                                                                                                             |
| A            | Under O Horizon and can be 0 to 30 cm in depth                                                                                                                                              | The A horizon is the top soil which is a mixture of highly organic material and inorganic soil.                                                                                                                                      |
| Ap           | Under O Horizon and can be 0 to 30 cm in depth                                                                                                                                              | An A horizon that has been plowed and farmed and has less organic content than an undisturbed A horizon.                                                                                                                             |
| B            | Under an A Horizon, 5cm to over 100 cm typical. The depth of the B horizons is highly variable and depends on soil and the region. In some areas the B horizon can be many meters in depth. | B Horizons are the subsoil which is characterized by having a minimal amount of organic matter and little evidence of the soil's parent material. It is the developed layers of the soil showing the development of silts and clays. |
| Bh           | Under an A Horizon, 5cm to over 100 cm typical                                                                                                                                              | A Bh horizon is an illuvial horizon that was formed from deposition of silt.                                                                                                                                                         |
| Bk           | Under an A Horizon, 5cm to over 100 cm typical                                                                                                                                              | B horizon that is slightly alkaline and has an accumulation of calcium carbonate                                                                                                                                                     |
| Bt           | Under an A Horizon, 5cm to over 100 cm typical                                                                                                                                              | A Bt horizon is a well developed B horizon with high concentrations of clay. Older soils (paleosols) many contain many Bt horizons.                                                                                                  |
| Bw           | Under an A Horizon, 5cm to over 100 cm typical                                                                                                                                              | A Bw horizon is a younger B horizon and will have a reddish color.                                                                                                                                                                   |
| Bx           | Under an A Horizon, 5cm to over 100 cm typical                                                                                                                                              | A Bx horizon is a fragipan which a a dense layer of silt that sometime slows water movement and forms from windblown silt called loess.                                                                                              |
| K            | Under an A Horizon, 5cm to over 100 cm typical                                                                                                                                              | Cemented horizon high in Calcium carbonate.                                                                                                                                                                                          |
| C            | Under a B horizon or A horizon or on surface. Variable depths.                                                                                                                              | Unconsolidated geologic material, sands and gravels. Possibly a parent material.                                                                                                                                                     |
| E            | Under an A horizon or within a B Horizon. From 5 to 100 cm in depth typical                                                                                                                 | Highly oxidized silty sands that are very light in color that form from organic acids from needle leaf trees.                                                                                                                        |





# SOIL ORDERS OF TAXONOMY

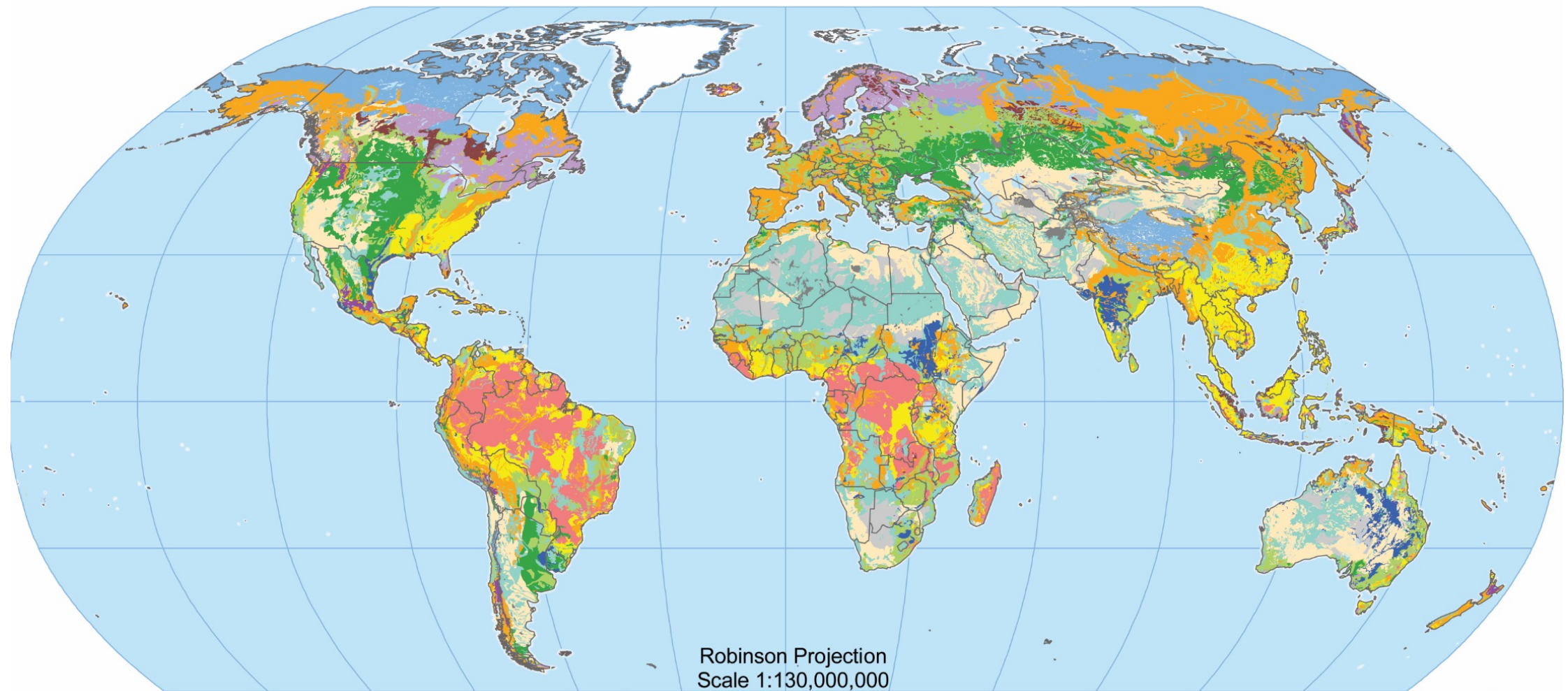
Knowledge of soil classification provides insight into the soil's hydrology (sensor installation and data insights)





# SOIL ORDERS OF TAXONOMY

## Global Soil Regions



### Soil Orders

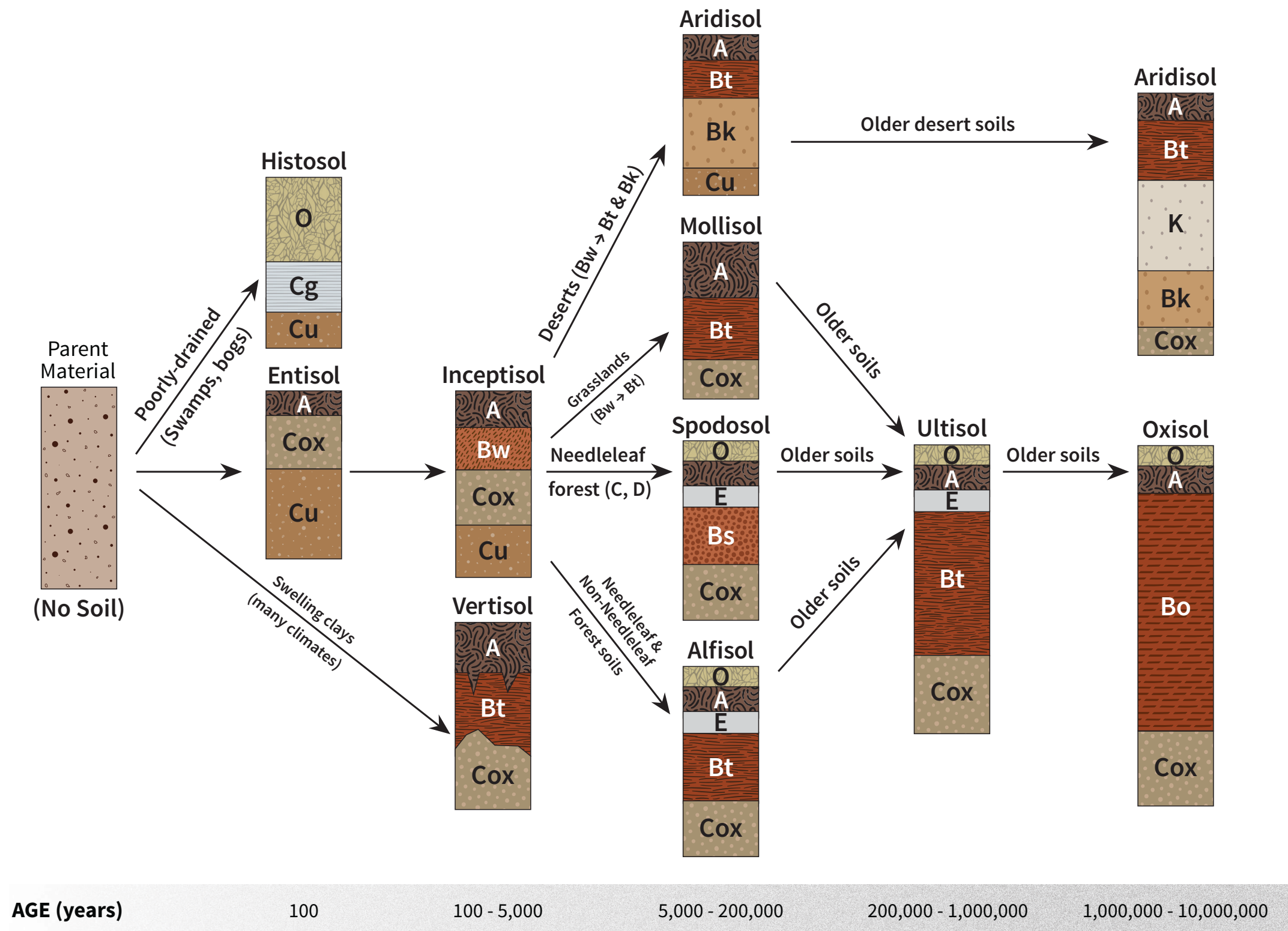
|                                                                                               |                                                                                               |                                                                                                   |                                                                                                 |                                                                                                     |
|-----------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------|
|  Alfisols  |  Entisols  |  Inceptisols |  Spodosols |  Rocky Land    |
|  Andisols  |  Gelisols  |  Mollisols   |  Ultisols  |  Shifting Sand |
|  Aridisols |  Histosols |  Oxisols     |  Vertisols |  Ice/Glacier   |

# SOIL EPIPEDONS

(SET OF HORIZONS THAT GIVE A SOIL PROFILE ITS CHARACTERISTICS)

| Epipedon  | Basic Defining Criteria                                        |
|-----------|----------------------------------------------------------------|
| Mollic    | Highly alkaline with a thick A horizon.                        |
| Umbric    | Similar to a mollic epipedon but less alkaline.                |
| Histic    | Highly organic, poorly drained, anoxic.                        |
| Albic     | Has B horizon that are lighter in color                        |
| Argillic  | Well-developed B horizon with moderate to high levels of clay. |
| Spodic    | Soil that contains E horizons above or within a B horizon.     |
| Salic     | Saline soil                                                    |
| Cambic    | Soil with a Bw horizon and very low in carbonate.              |
| Duripan   | Silica Cementation, occurs in arid regions                     |
| Fragipan  | Dense silt B horizons formed from loesses or other processes   |
| Anthropic | Impacted by humans, agriculture or other activity              |

# Soil Development Chart





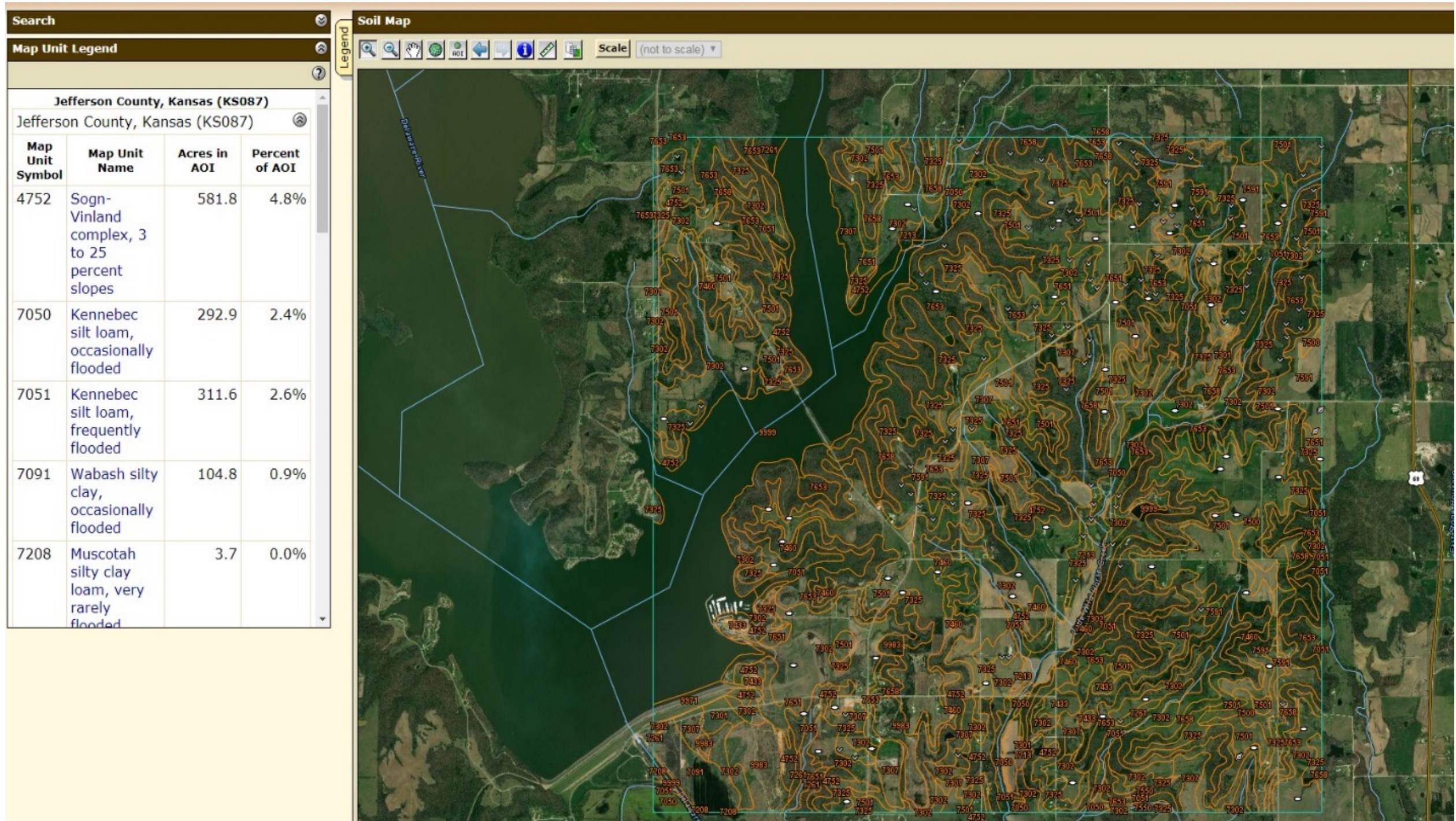


[Soil Survey Division Staff [1993]]





# SOIL MAPS





# FEATURED SOIL SENSOR HYDRAPROBE SOIL SENSOR





# DEVELOPMENT OF HYDRAPROBE

- Public Private Partnership
- Developed by the Physics Department at Dartmouth College in the late 1980s.
- The Patent and the intellectual property was purchased by Stevens in 2000.
- Calibrated by the US Department of Agriculture in 2005



# HYDRAPROBE

- Moisture, salinity and temperature
- First and only soil sensor to fully characterize the dielectric permittivity to provide a more stable calibration and lower inter-sensor variability
- Most scientifically-researched soil sensor available
- 5-year warranty
- The HydraProbe is one of the most robust, accurate and quantitative soil sensors available





# RATIOMETRIC COAXIAL IMPEDANCE

- First soil sensor to fully characterize the dielectric permittivity to provide a more stable calibration and lower inter-sensor variability [Campbell 1990] [Seyfried 2004] [Logsdon 2005]
- The Stevens HydraProbe is one of the most robust, accurate and quantitative soil sensors available; covering a dielectric range from 1 to 80.
- Measures soil moisture, temperature, and electrical conductivity (NO calibration required in most soils) [Seyfried 2005]
- 5 year warranty



STEVENS



# BENEFITS OVER TDR AND CAPACITIVE -BASED PROBES

The importance of separating out the real from the imaginary dielectric permittivity:

- Less influenced by temperature [\[Seyfried 2007\]](#)
- Less influenced by salinity [\[Leao 2009\]](#)
- Less error due to soil mineralogy [\[Logsdon 2008\]](#) [\[Ojo 2015\]](#)
- Better inter-sensor variability, better calibration for soil water content [\[Seyfried 2003\]](#)





# LONG-TERM PREDICTABLE ACCURACY IN HARSH ENVIRONMENTS AND RESEARCH APPLICATIONS

## 90% of Top Mesonet and Climate Reference Networks (USA)

Environment Canada's  
Saskatchewan Mesonet

Kansas Mesonet

Kentucky Mesonet

New York Mesonet

NOAA Climate Reference Network

NOAA Crest

South Dakota Mesonet

USDA Agriculture Research Service  
(ARS)

USDA SNOTEL Network

USDA Soil Climate Analyses Network  
(SCAN)

US Army Corp of Engineers

US Environmental Protection Agency

## Proven in Soil Research Community

Alabama A&M University

Arizona State University

Clemson University

Colorado State

Dessert Research Institute

Guelph University

King Abdullah University of Sci & Tech

Louisiana State

McMaster University

New Mexico State University

Oregon State University

Penn State

Syracuse

Texas A&M University

University of Alaska

University of Calgary

University of California

University of Florida

University of Illinois

University of Saskatchewan

University of Wyoming

Utah State University

Villanova University

## Respected in Agriculture and Turf

AgFood Canada

John Deere

Li-Cor

Rain Bird

100+ Golf Courses

NASA

Boeing

Acknowledged for durability,  
accuracy, consistency and  
simplicity

**Deployments – Tens of  
Thousands**

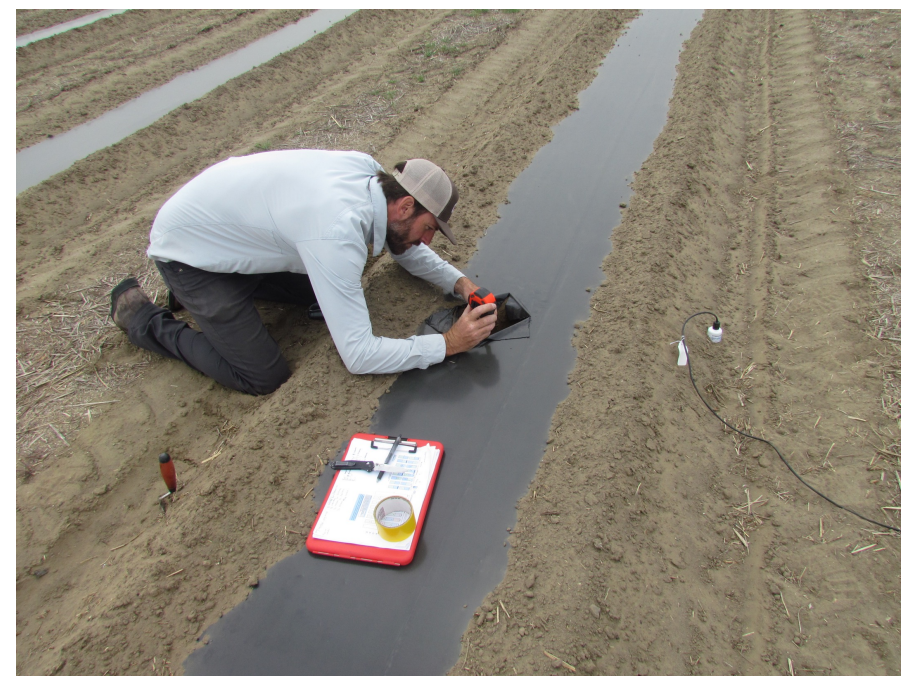


# SOIL SENSOR APPLICATIONS



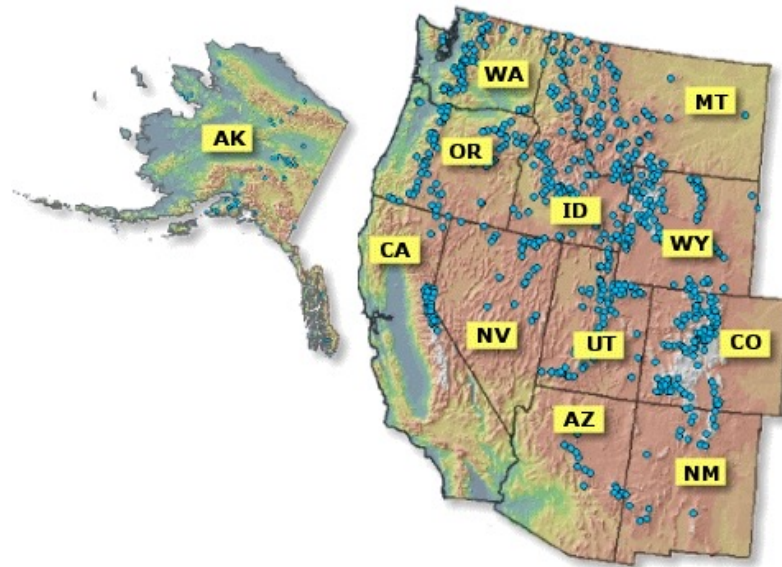


# SOIL MONITORING APPLICATIONS



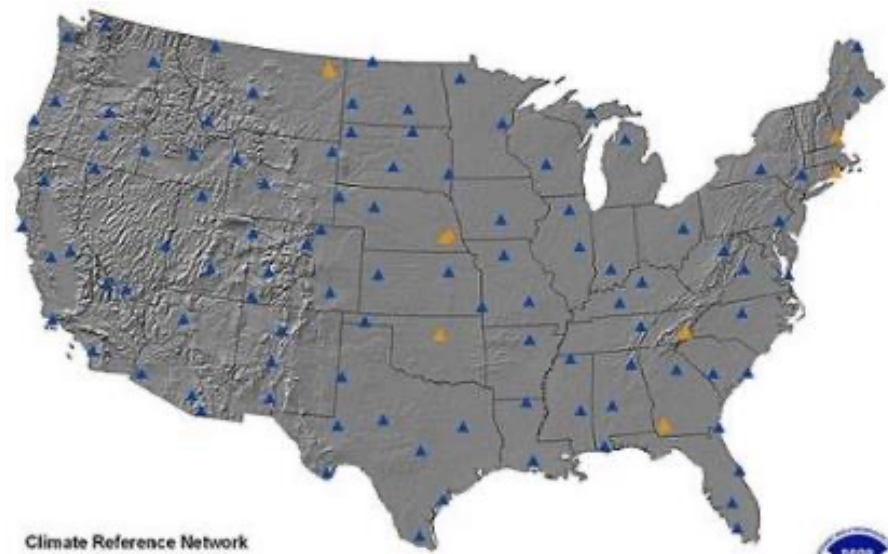


# SOIL MONITORING NETWORKS



[www.wcc.nrcs.usda.gov/scan](http://www.wcc.nrcs.usda.gov/scan)

Water Supply Forecasting

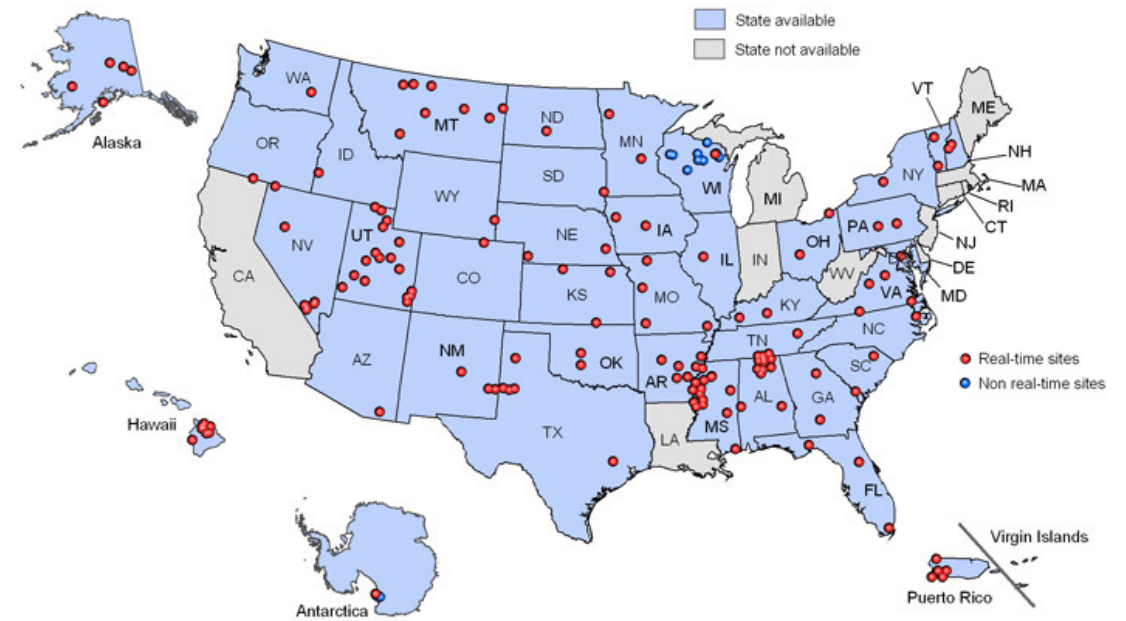


Climate Reference Network  
▲ Paired Stations  
▲ Gauge Stations



[www.ncdc.noaa.gov/crn](http://www.ncdc.noaa.gov/crn)

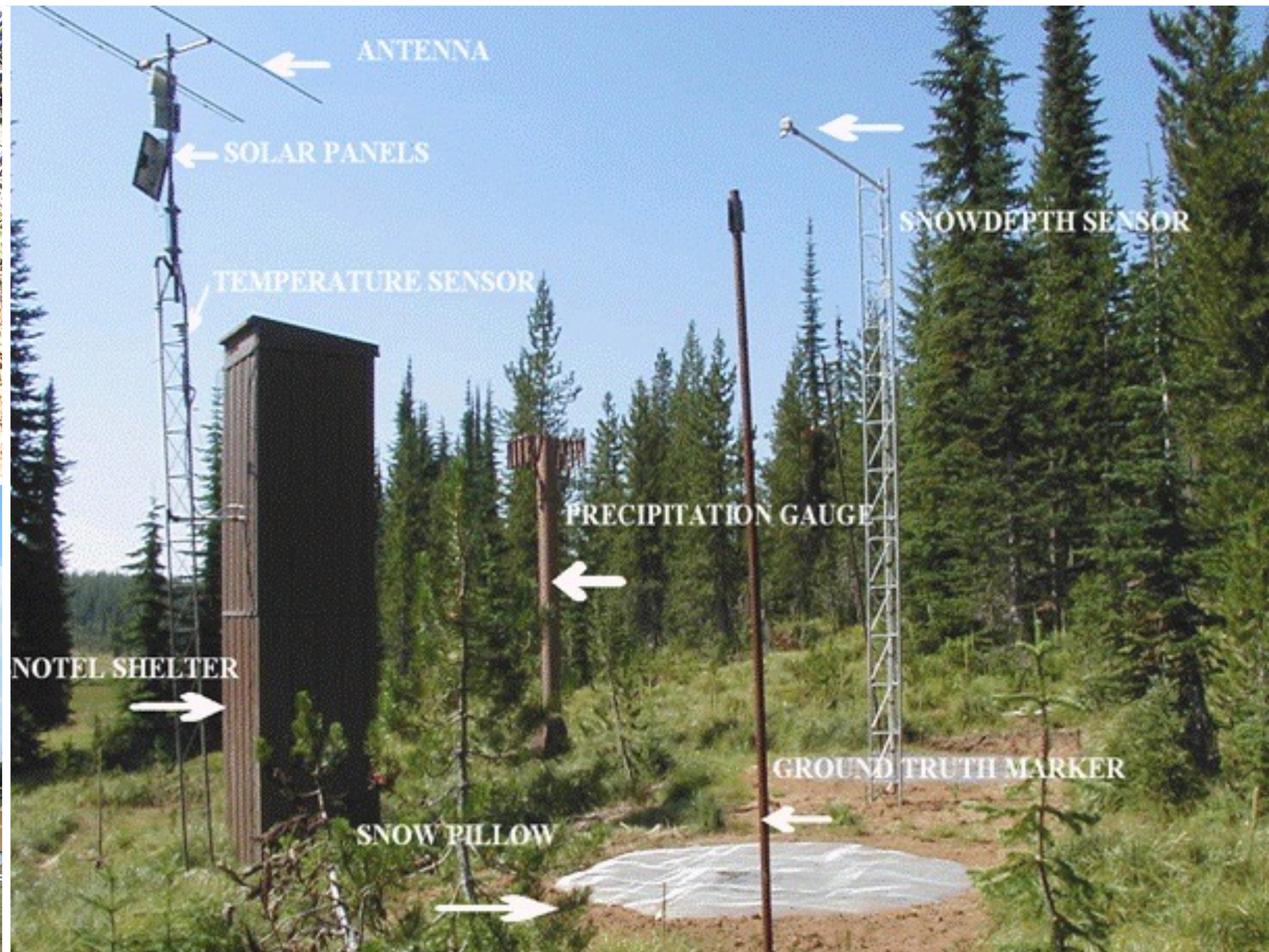
Drought Forecasting



[www.wcc.nrcs.usda.gov/snow](http://www.wcc.nrcs.usda.gov/snow)

Satellite Ground Truthing







# SOIL MOISTURE MONITORING NETWORKS IN THE US

(ALL USE THE STEVENS HYDRAPROBE)



**\*1,750  
Sensors**

[USDA's Soil Climate Analysis Network \(SCAN\) \(350 Stations, 5 Sensors/ Station\)](#)



**4,500  
Sensors**

[NOAA's Climate Reference Network \(300 Stations, 15 Sensors/ Station\)](#)



**4,500  
Sensors**

[USDA's SNOTEL Network \( 900 Stations, 5 Sensors/ Station\)](#)

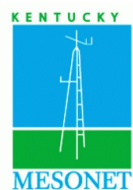


**60  
Sensors**

[US Bureau of Reclamation's AgriMET \(12 Stations, 5 Sensors/ Station\)](#)



[RIMSA Network \(40 Stations, 2-10 Sensors/ Station\)](#)



**700  
Sensors**

[Kentucky Mesonet \(140 Stations, 5 Sensors/ Station\)](#)



**750  
Sensors**

[New York Mesonet \(150 Stations, 5 Sensors/ Station\)](#)





# APPLICATIONS OF THE HYDRAPROBE

- Irrigation Management and Optimization
- Networks
- **Phytoremediation**
- Low Tillage and Carbon Sequestration
- GPR Attenuation
- **Satellite Ground Truthing**
- **Drought Forecasting/Water supply forecasting**
- Dust Control
- Land Slide Studies
- Green Roofs
- Biofuels and Ag Research
- Forest fire potential
- Infiltration rates
- **Flood Warning**
- Restoration
- **Climate Change**

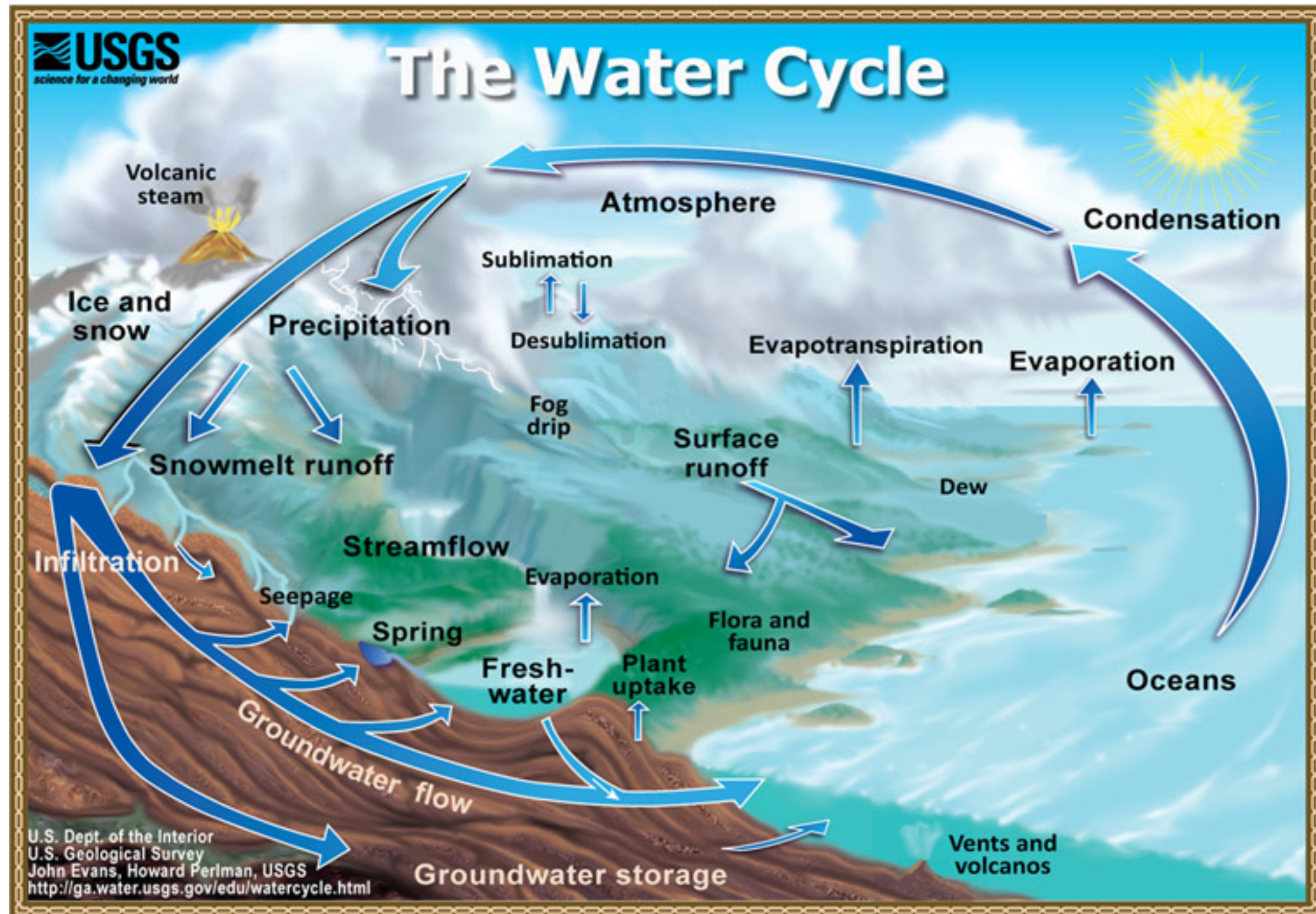


# SOIL WATER MOVEMENT





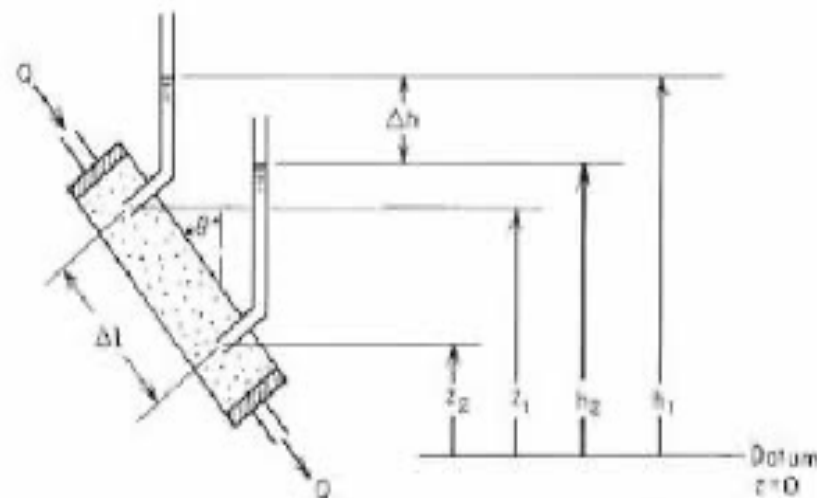
# SOIL IS AN IMPORTANT PART OF THE GLOBAL HYDROLOGICAL CYCLE



# DARCY'S LAW AND SATURATED FLOW

Saturated flow is almost all driven by gravity

$$v = -K_{sat} \frac{\Delta h}{\Delta l} \qquad Q = -K_{sat} \frac{dh}{dl} A$$
$$v = -K_{sat} \frac{dh}{dl}$$





# VADOSE MOVEMENT OF WATER

Vadose zone water cycle moves in one demission.

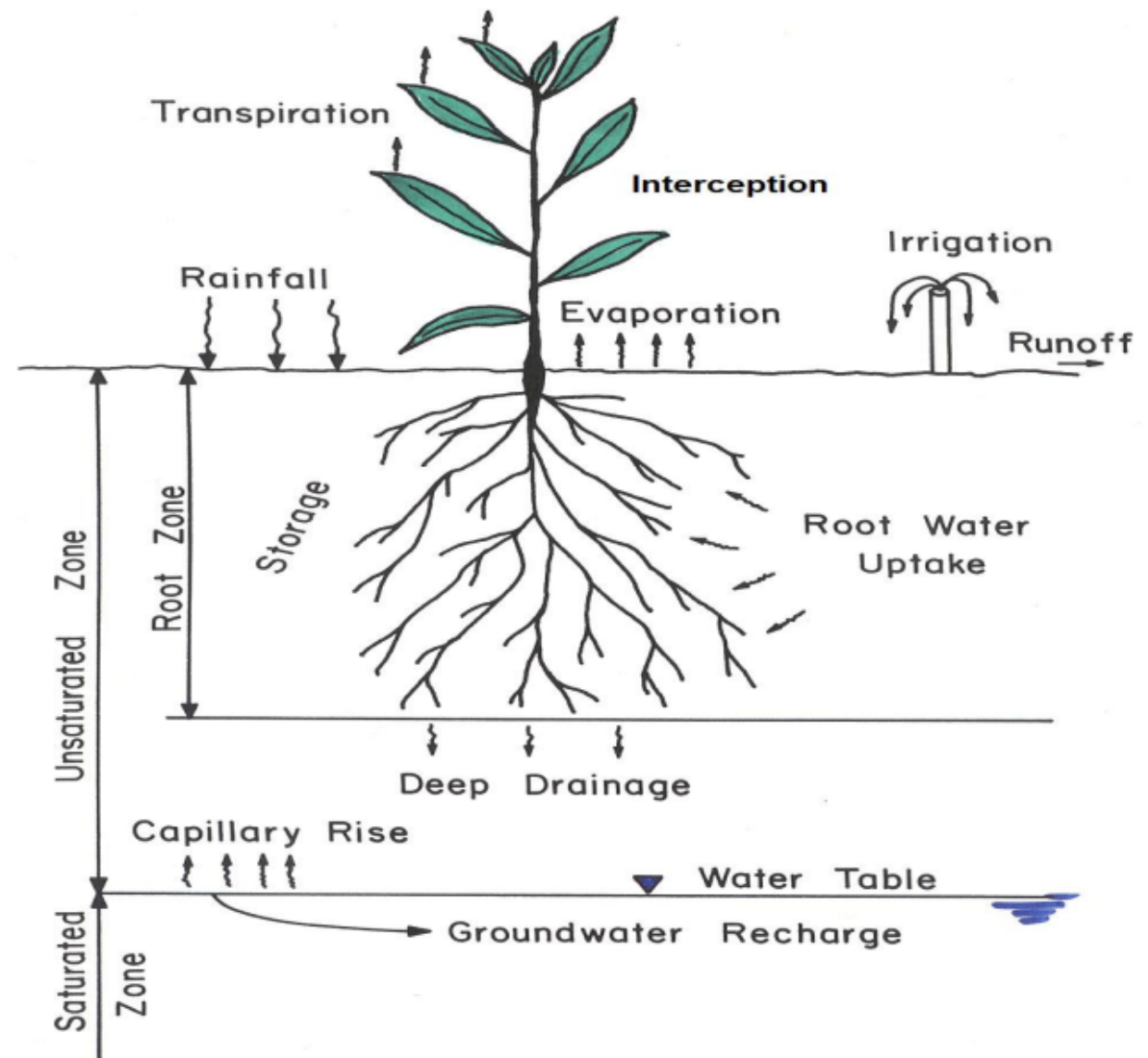
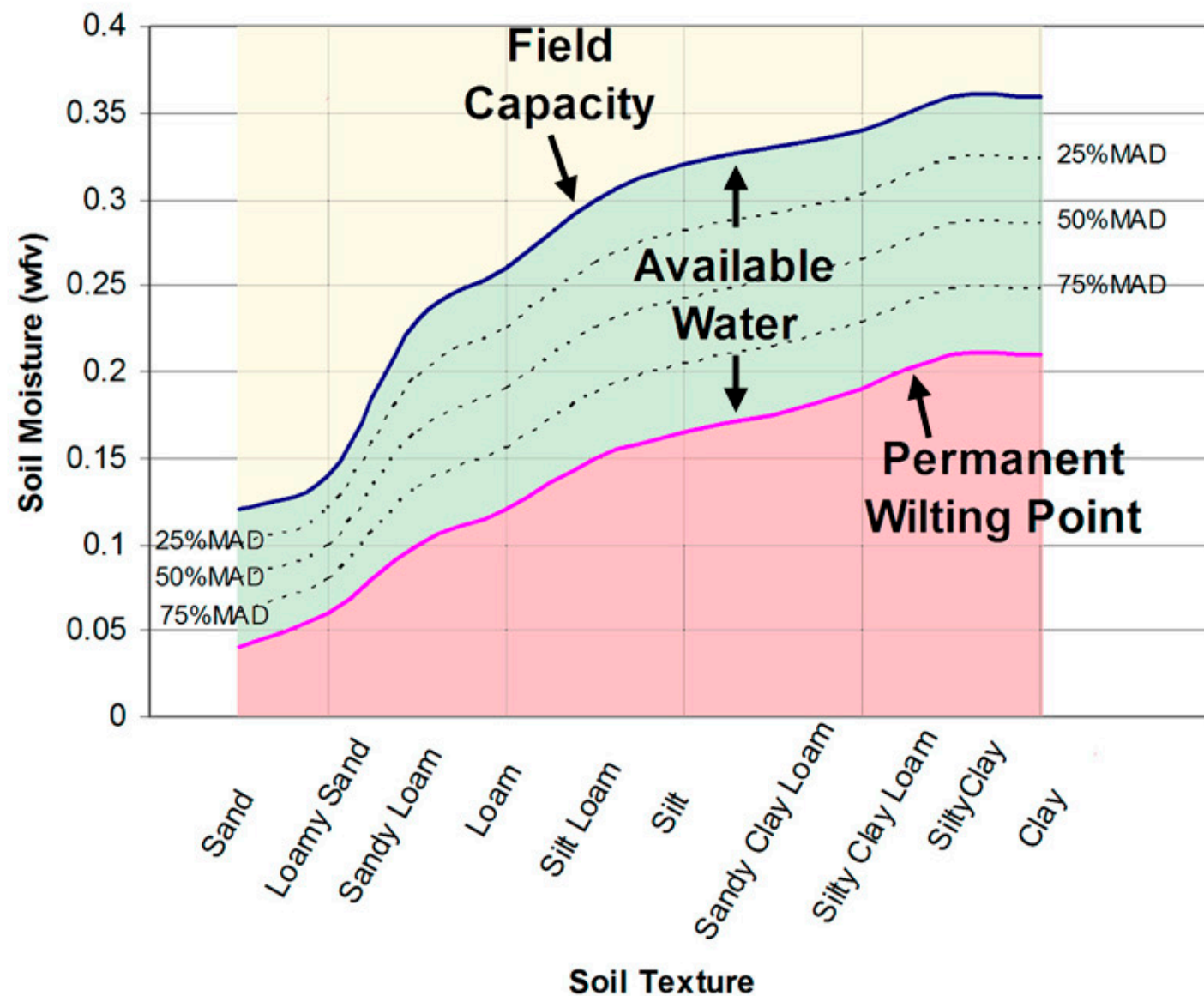
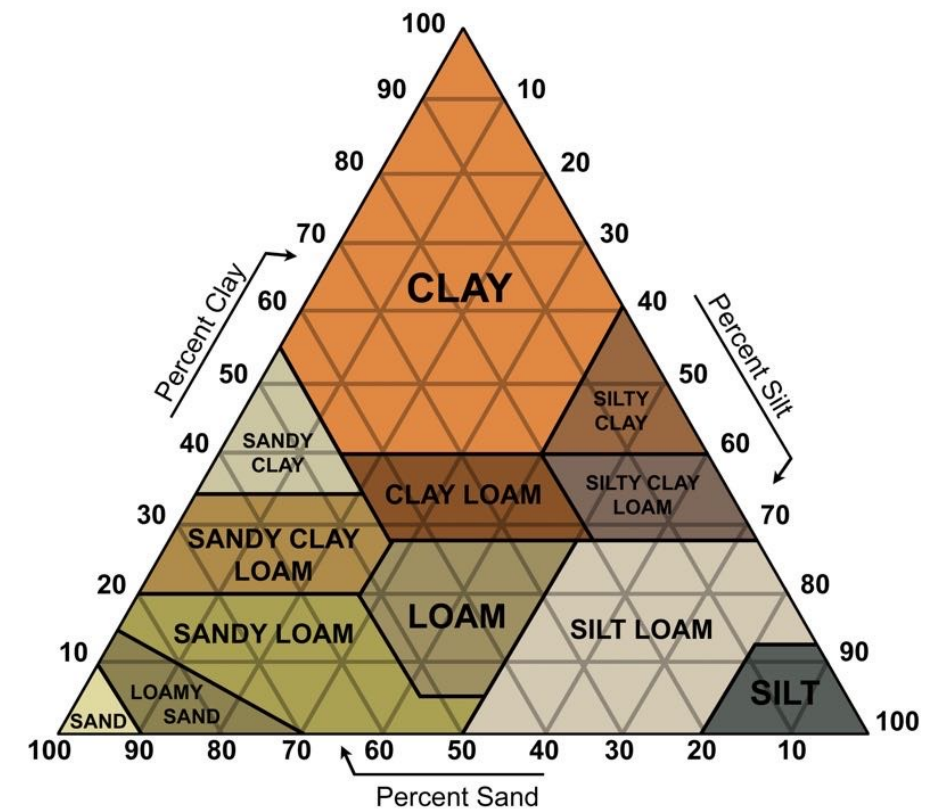


Figure 5.1 Transient water flow processes in soil (Šimůnek and van Genuchten, 2007).



# SOIL WATER DYNAMICS

## Soil Moisture Target

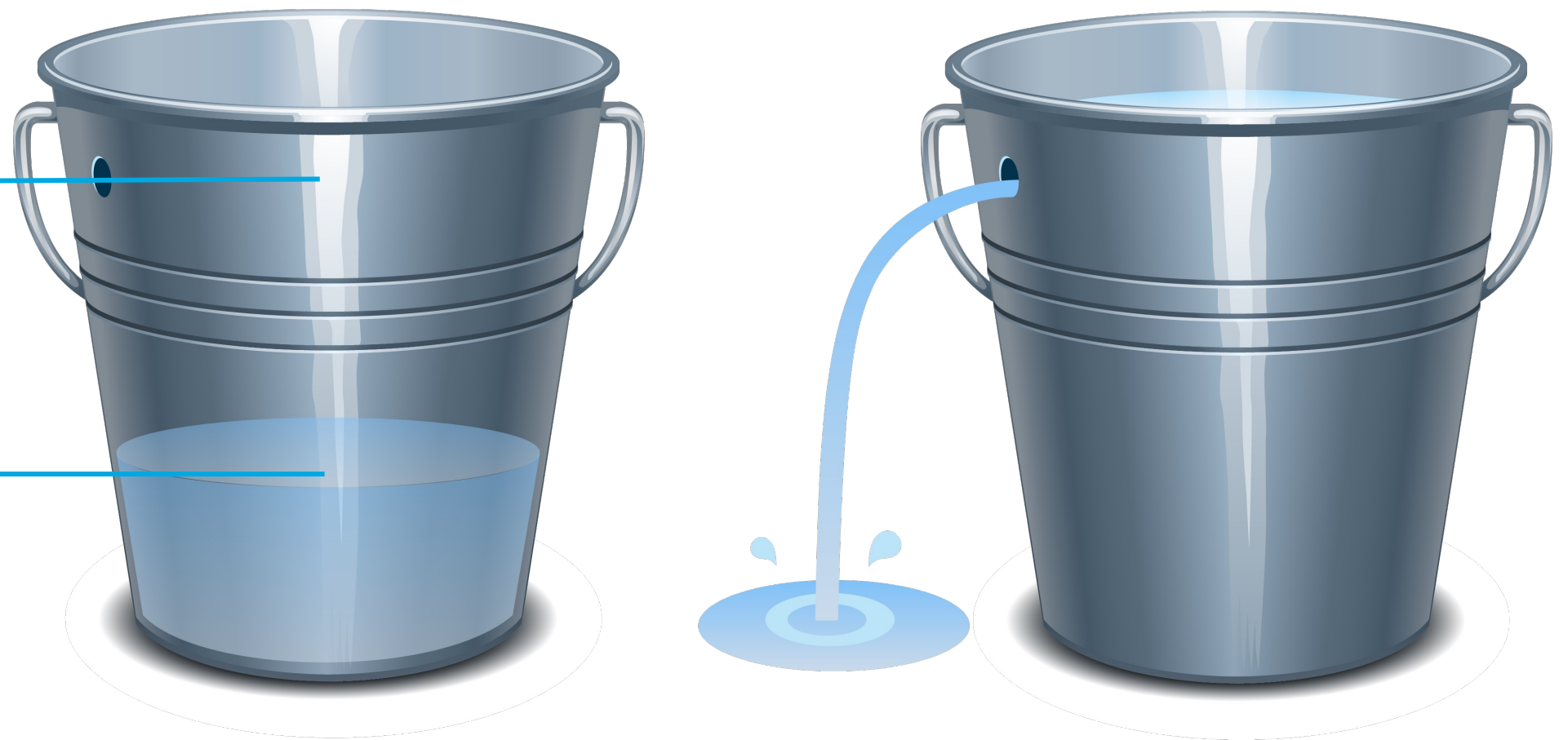




# SOIL MOISTURE DEFICIT INDEX

$$\theta_{di} = \bar{\theta} - \theta_{fc}$$

How much  
more water  
can be added?



Measured Soil Moisture – Field Capacity = how much more water you can add to the soil  
(Insight into amount of irrigation water to apply)

# SOIL WATER POTENTIAL $\psi$

The difference between the energy state between pure water and soil water.

$$\psi_{tot} = \psi_p + \psi_m + \psi_o$$

$\psi_m$  is the matric potential  
It represents the amount of pressure it takes to  
pull water out of soil due to capillary forces.

Matric potential is 0 at saturation and gets  
higher the drier the soil gets.





# SOIL WATER POTENTIAL $\psi$

$\psi_m$  is the matric potential in units of negative pressure such as Pa.

$$\psi_m = -\rho_w g H$$

$\psi_m$  is the matric potential which is a product of the density of water, gravity and the matric head.

Units for H are in meters.

$$pF = \text{Log } \psi_m$$



# MATRIX POTENTIAL FOR SOIL TEXTURE (INORGANIC MINERAL SOIL)

|                         | Matric Potential |      |       |        |        |        | Soil Moisture % |      |      |
|-------------------------|------------------|------|-------|--------|--------|--------|-----------------|------|------|
|                         | Bar              | kPa  | hPa   | PSI    | ATM    | pF     | Sand            | Silt | Clay |
| Saturation              | 0                | 0    | 0     | 0      | 0      |        | 42%             | 40%  | 55%  |
|                         | 0.2              | 20   | 200   | 2.9007 | 0.1973 | 2.30   |                 |      |      |
| Field Capacity          | 0.33             | 33   | 330   | 4.7862 | 0.3256 | 2.515  | 10%             | 30%  | 40%  |
|                         | 1                | 100  | 1000  | 14.503 | 0.9869 | 3      |                 |      |      |
| Permanent Wilting point | 15               | 1500 | 15000 | 217.55 | 14.803 | 4.1760 | 4               | 15%  | 21%  |





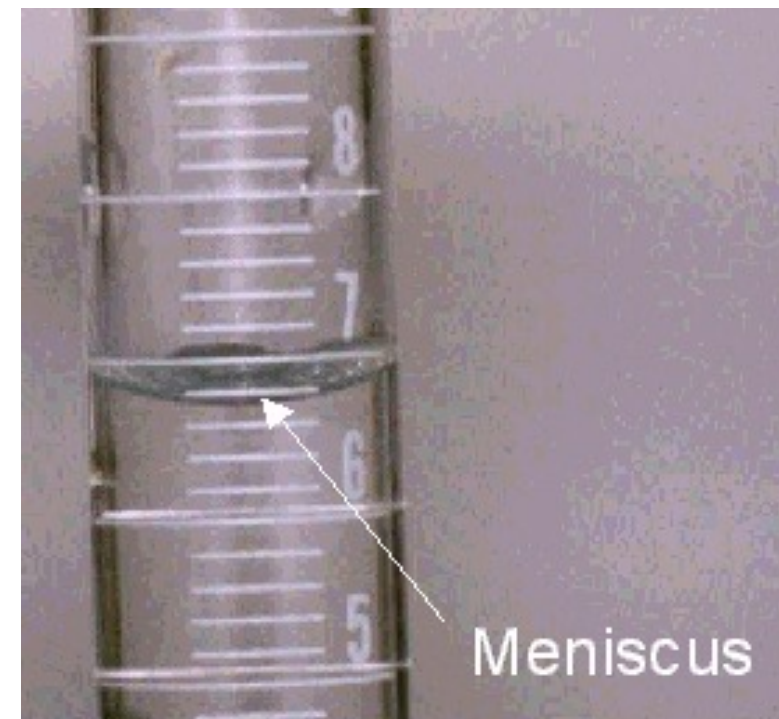
# SOIL CAPILLARY FORCES

Capillary Force is a force that results from the surface tension of a liquid.

The water at the surface will have a tension, meaning that the water molecules are bunched up and want to move apart. We see this if you put water in a small area. The water tension will make the water climb the walls and form a meniscus.

Surface tension between air and water is caused by the mismatch in charge (electrons around the molecules).

Water is unrelaxed in contact with air.

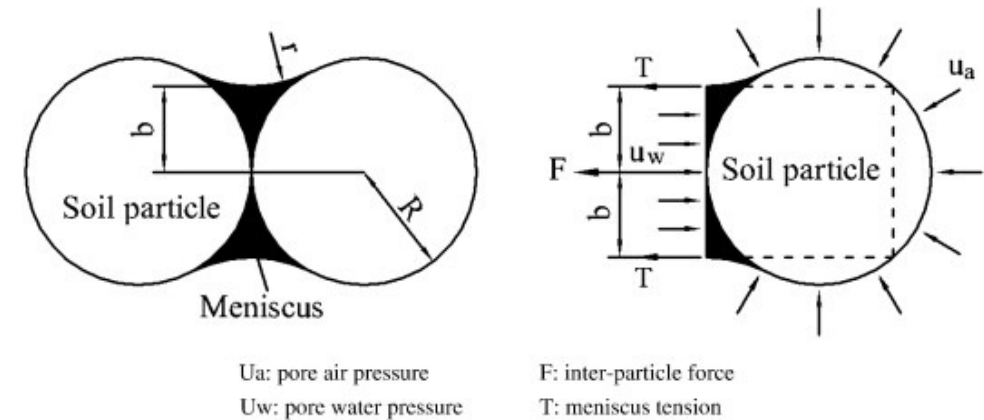


Matric potential is caused by Capillary Force

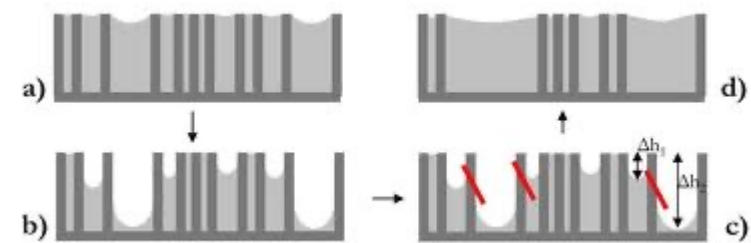


# CAPILLARY FORCE

Soil can be thought of as a bunch of little tiny tubes of different sizes. The water in the tubes will have a little tiny meniscus.

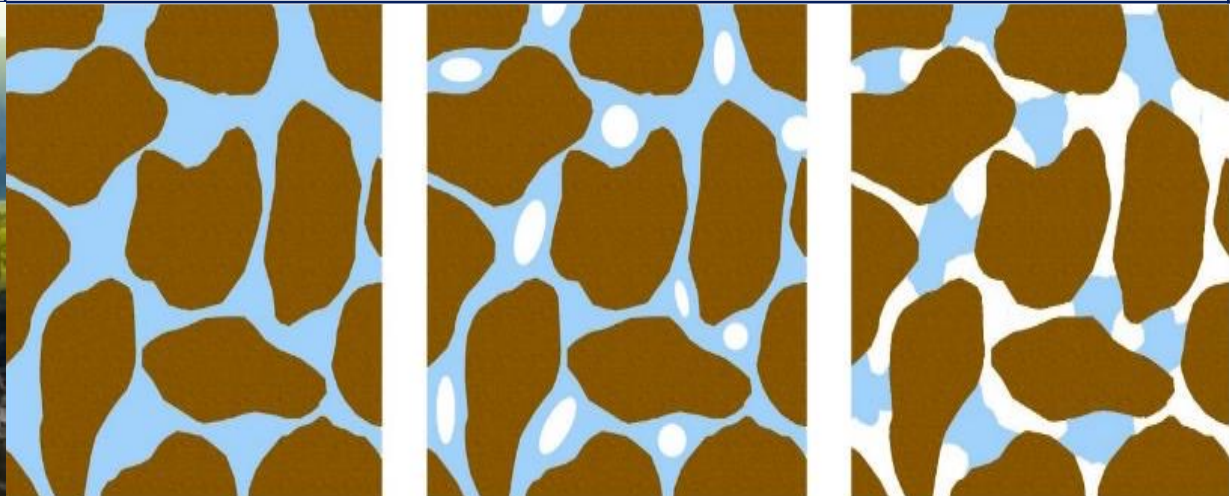


If the soil moisture is under field capacity, capillary forces are the primary driver for the movement and retention of water.





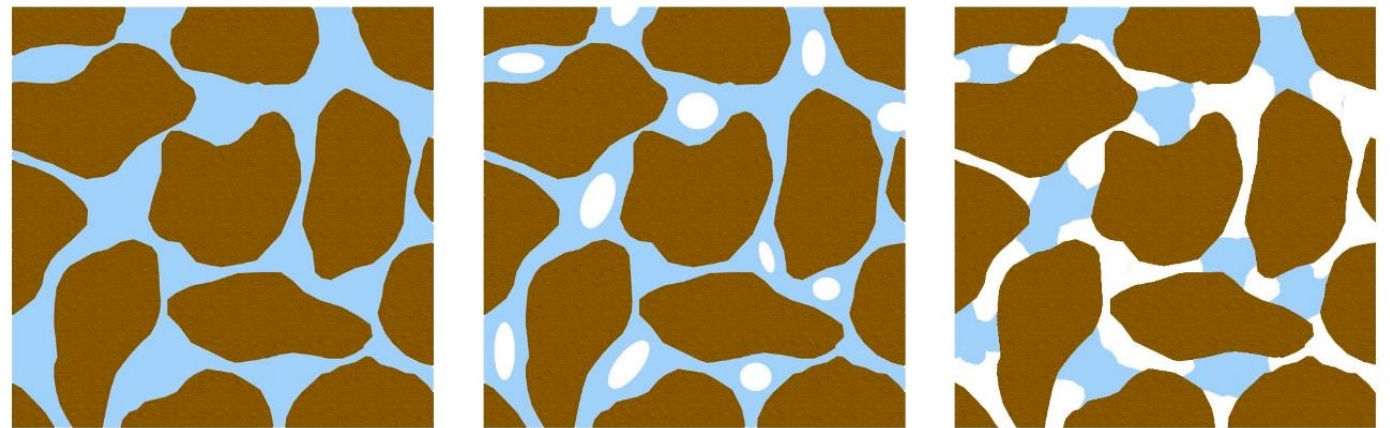
# GRAVITATIONAL FORCE COMPARED TO CAPILLARY FORCE

| Gravitational Force                                                                  | Capillary Force                                                                       |
|--------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|
| Gravity holds water in the river                                                     | Capillary forces hold and suspend water in soil                                       |
| Gravitation forces pulls water down hill toward the sea                              | Capillary forces pull pore water down gradient from wet to dry                        |
| As the water flows down hill it can hit obstacles like dams and get bunched up       | As water moves through soil it can be slowed by the sorptivity of the soil.           |
|  |  |



# FIELD CAPACITY/CAPILLARY FORCES

- As the soil fills up with water, it will reach a point where the gravitational force will be greater than the capillary force and water will drain downward. This threshold is called field capacity.

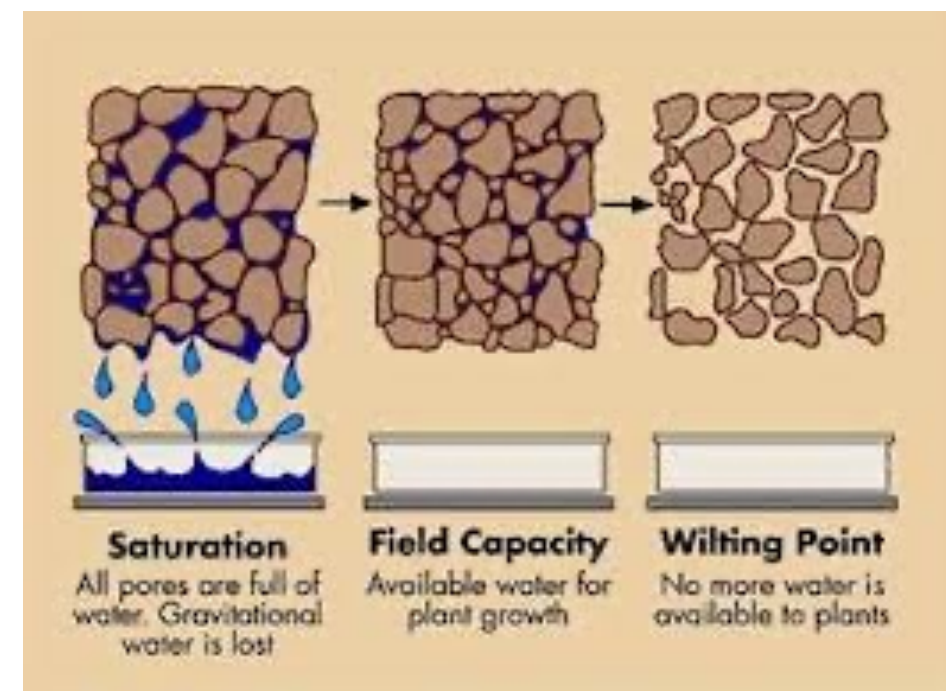


Saturation

Field Capacity

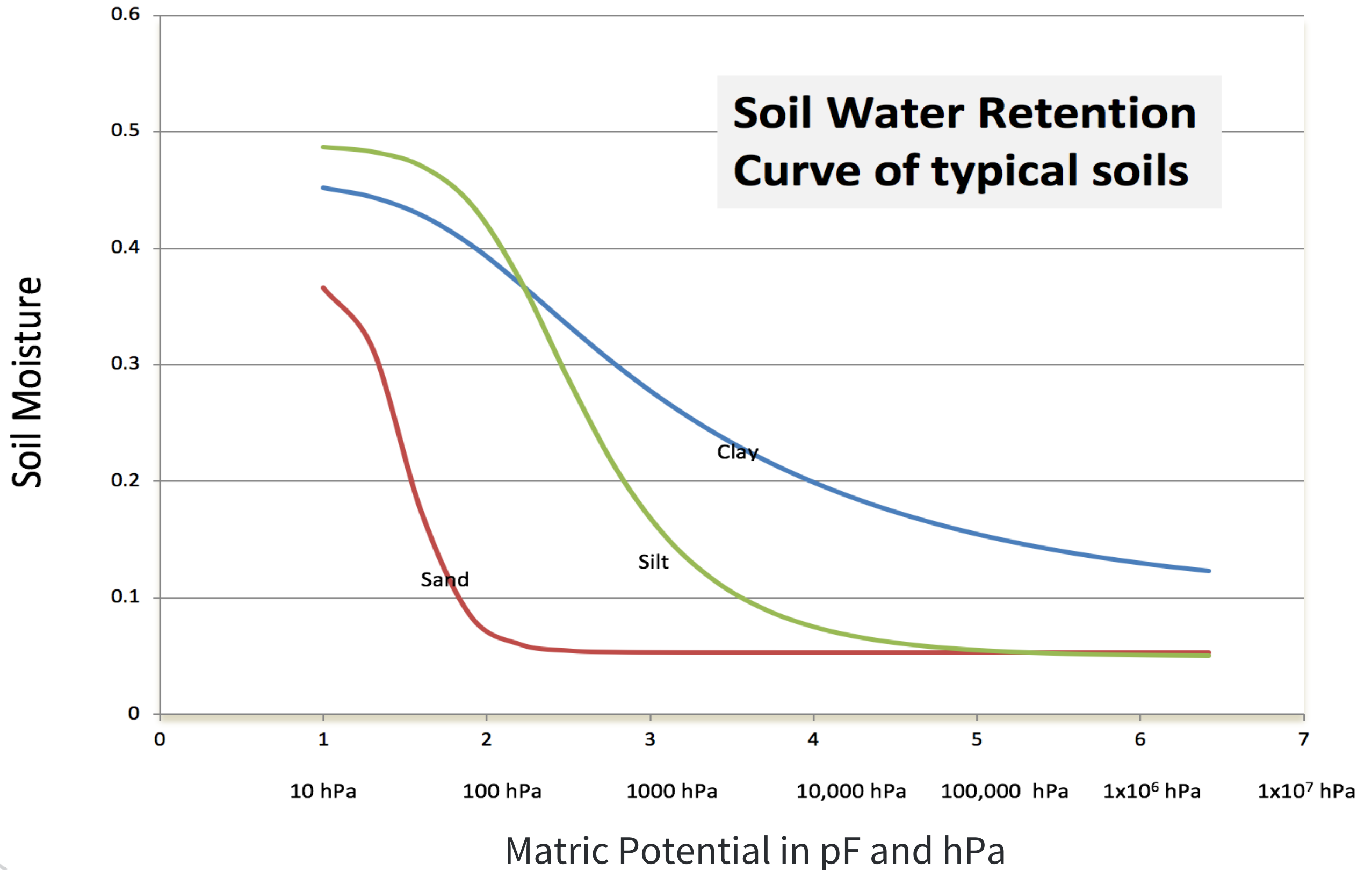
Less than field capacity

- At field capacity, the  $pF$  will be near 0. The water will drain out of the soil without any external pressure.





# MATRIC POTENTIAL AND MODELING TOOLS



# VAN GENUCHTEN EQUATION

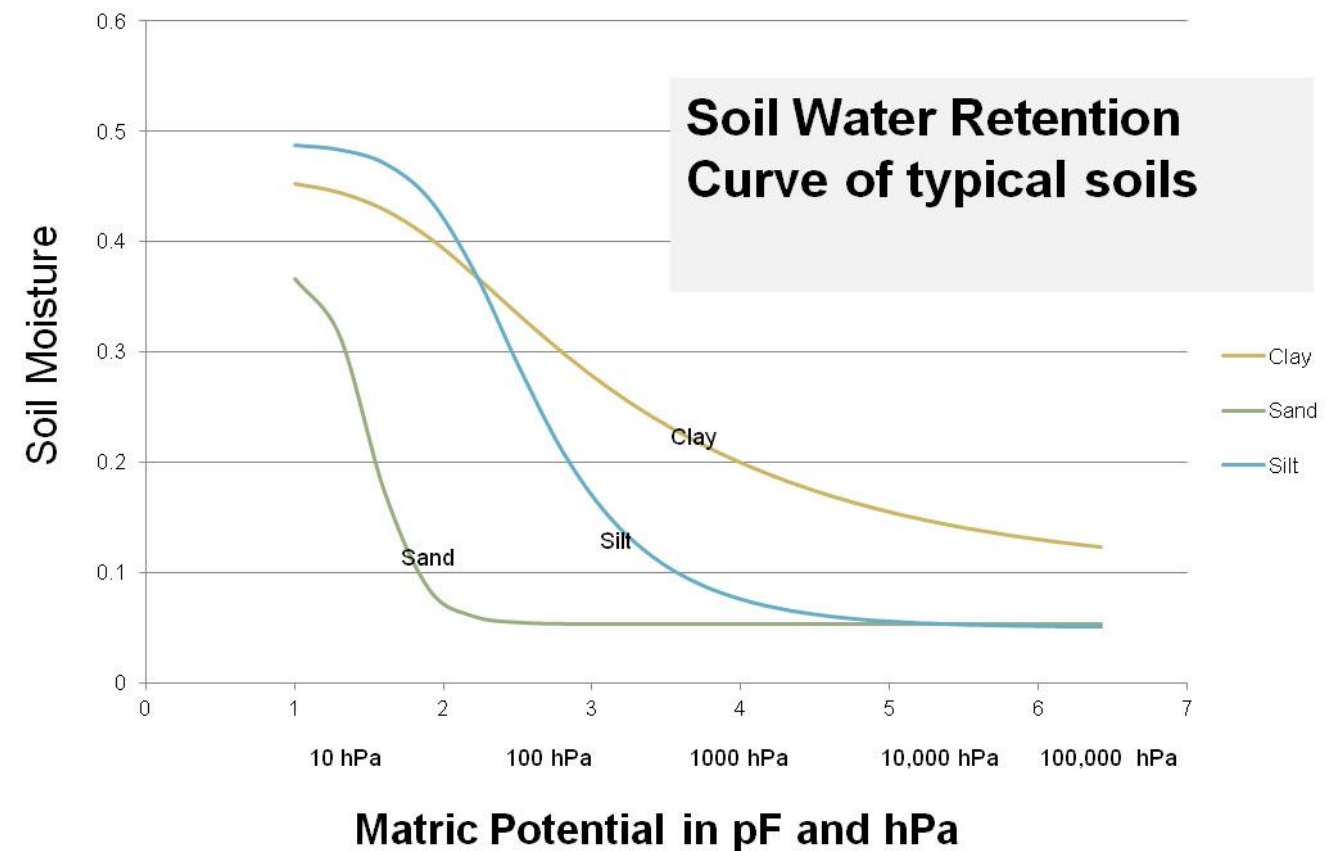
Water Content Modeling and Prediction

$$\theta(h) = \frac{\theta_s - \theta_r}{[1 + |\alpha h|^n]^m}$$

$$S_e(h) = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r}$$

$$K(h) = K_s S_e^\ell \left[ 1 - (1 - S_e^{1/m})^m \right]^2$$

$K(h)$  = The Unsaturated Hydraulic Conductivity  
[a parameter that indicates how well water moves through soil]



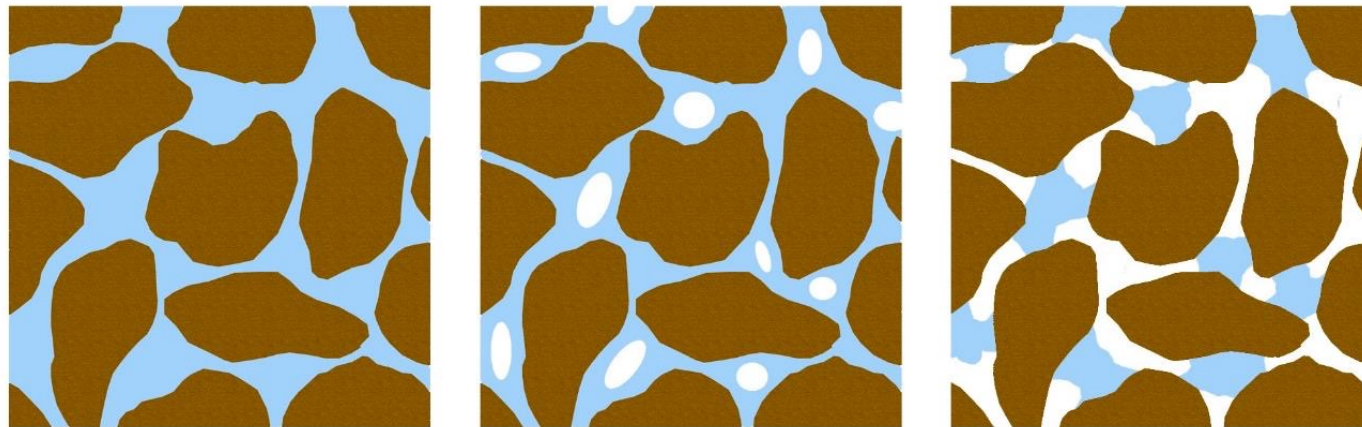
| Soil Texture               | Homogeneous Clay | Structured Clay | Loam      | Fine Sand | Sand | Gravel |
|----------------------------|------------------|-----------------|-----------|-----------|------|--------|
| $K(SAT) \text{ cm s}^{-1}$ | $10^{-8}$        | $10^{-6}$       | $10^{-4}$ | $10^{-2}$ | 1    | 10     |



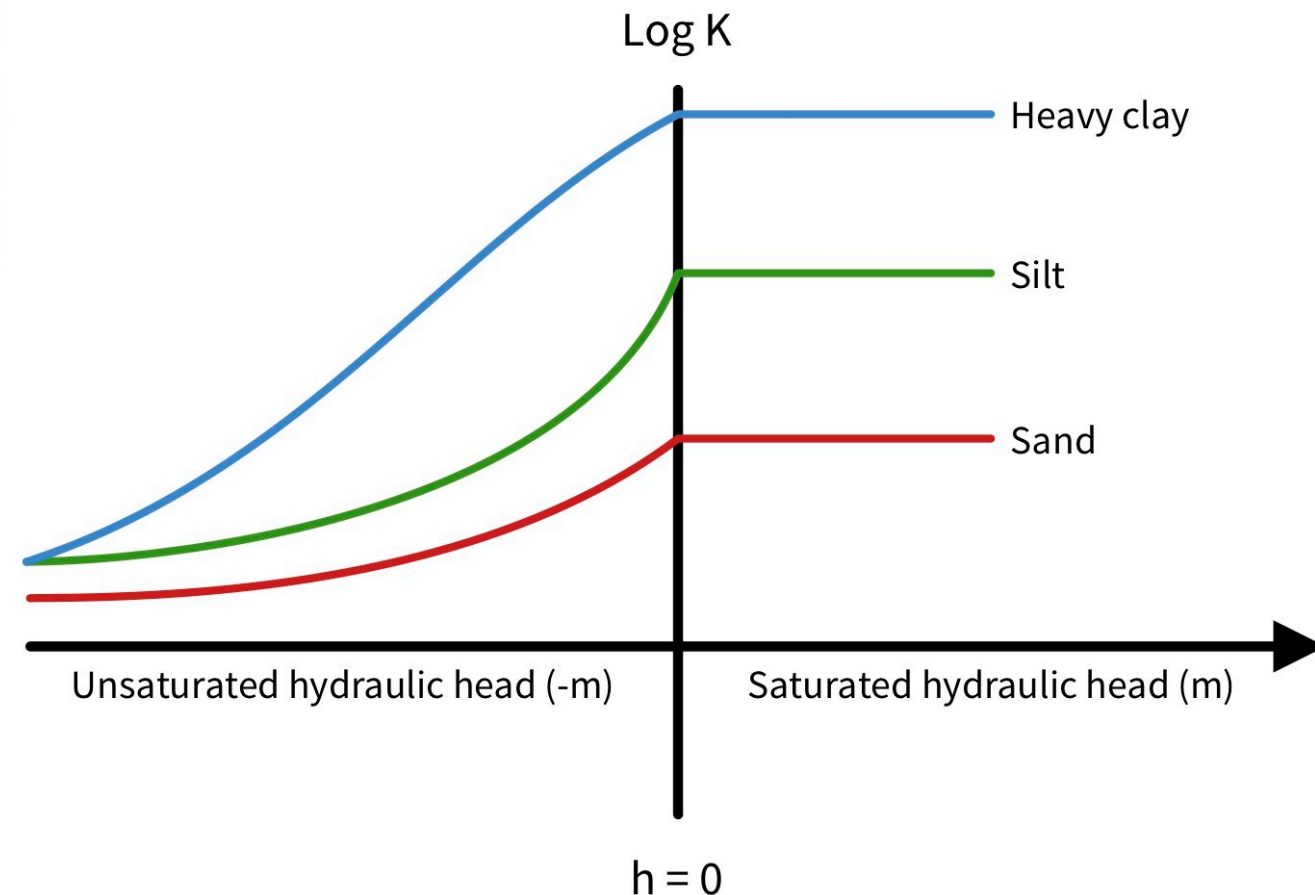


# UNSATURATED HYDRAULIC CONDUCTIVITY

- Theta  $r$  is the residual water content where the films of water are no longer connected.  $K_{\text{unsat}}$  is 0. As the soil dries, the water flows along the films in a much more tortuous path than if it was saturated.  $K_{\text{unsat}}$  decreases from  $K_{\text{sat}}$  because 1) the flow paths become longer, 2) less cross sectional area through which water can flow, 3) the paths are thinner.



## Hydraulic Conductivity as a Function of Head



# ONE DIMENSIONAL RICHARDS EQUATION

## Modeling and Prediction Mathematical Relationship

The Richards equation helps predict soil moisture at depth and time

$$\frac{\partial \theta(h)}{\partial t} = \frac{\partial}{\partial z} \left( K(h) \frac{\partial h}{\partial z} \right) + \frac{\partial K(h)}{\partial z} - S(h)$$

An initial  $h$  and moisture are selected. HYDRUS 1D then iterates and solves the Richards Equation from weather data as an input.  $S(h)$  is ET.





# FICK'S 2<sup>ND</sup> LAW

$$\frac{\partial C}{\partial t} = D \left( \frac{\partial^2 C}{\partial x^2} \right) - \alpha$$

Gas Diffusion where  $\alpha$  is the desorption term.

Fick's Second law can also describe water movement in a vapor phase and transport of solutes

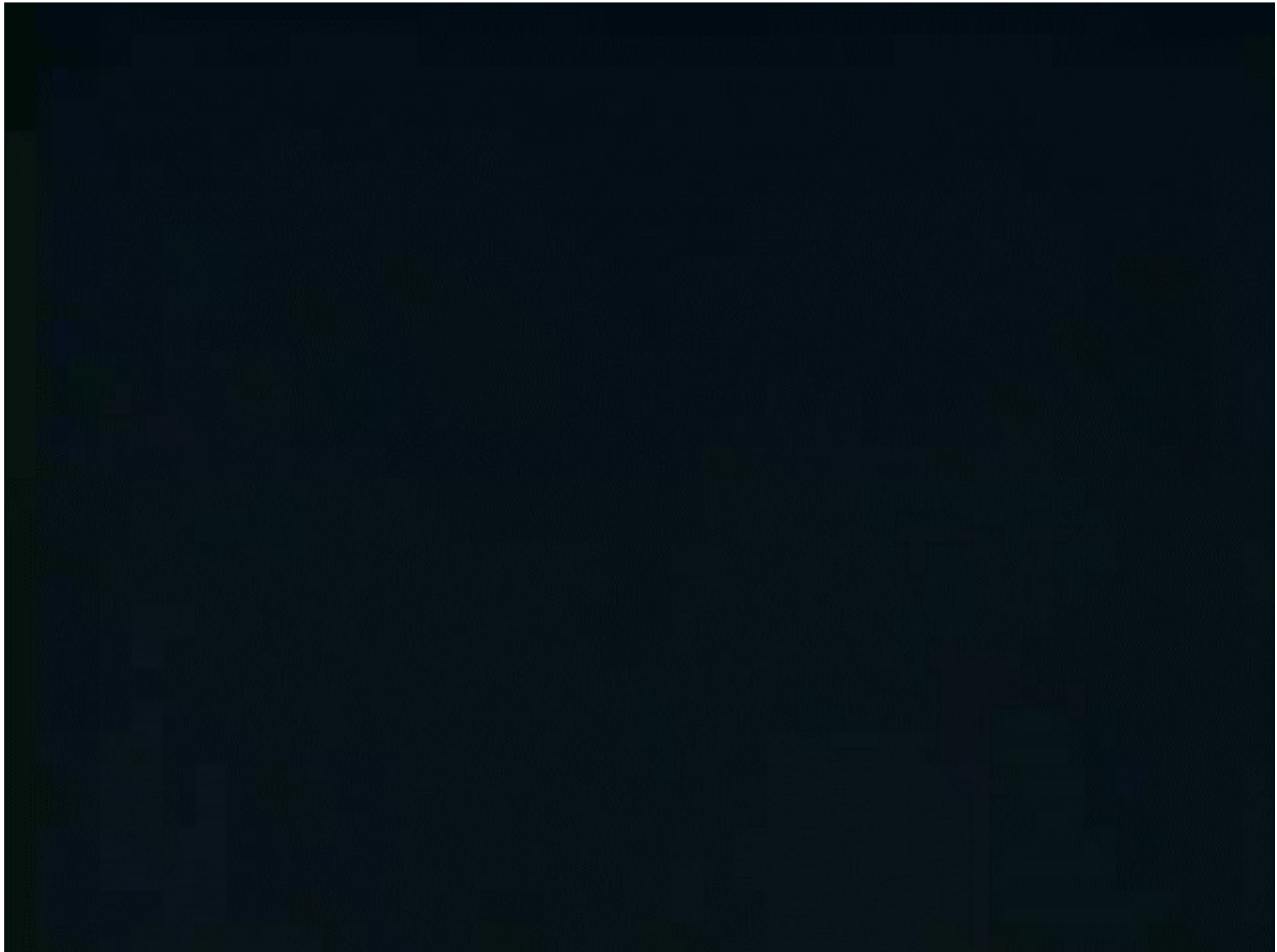


# CAPILLARY FRINGE

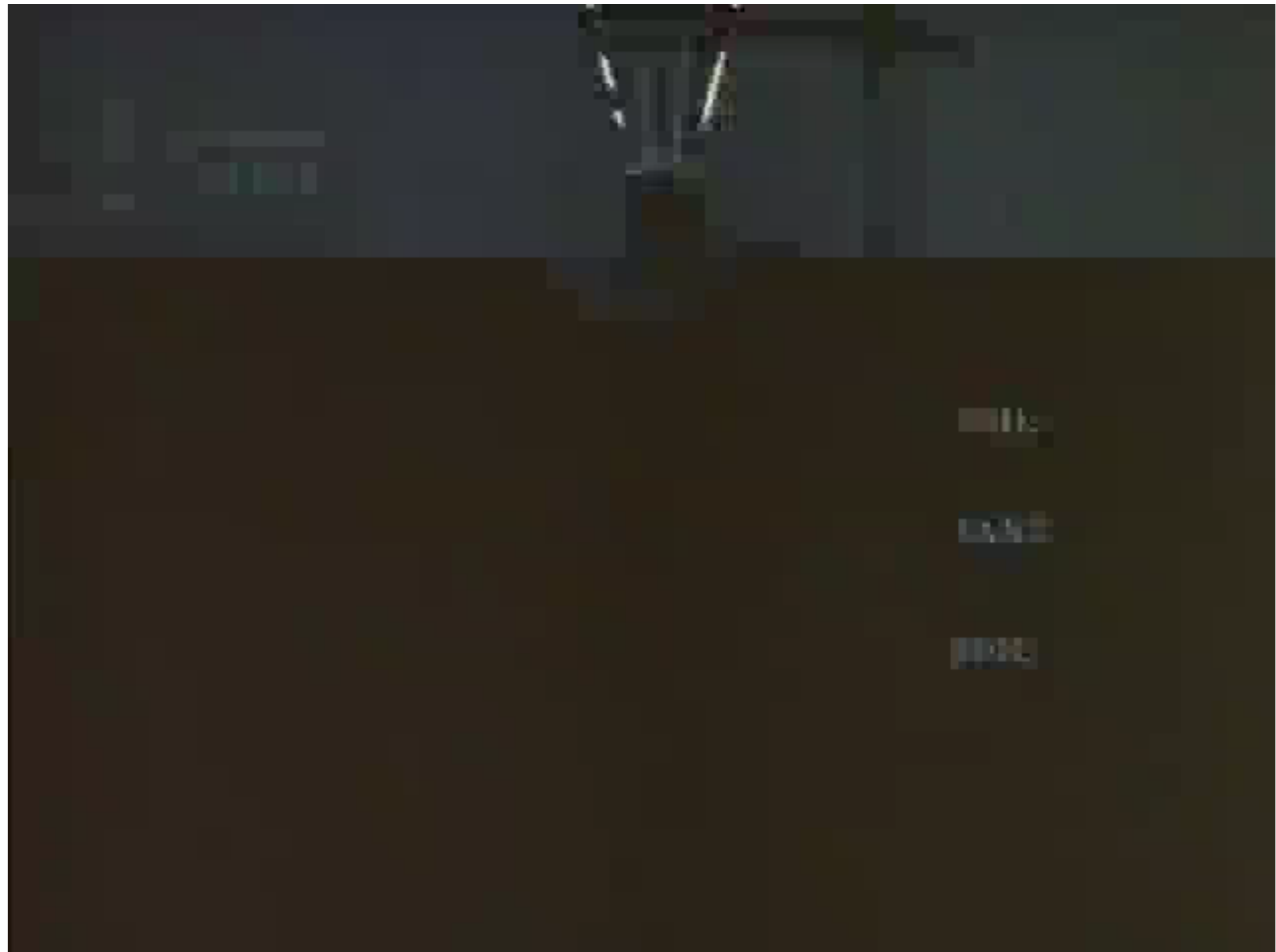




# SAND LAYER IN A SILT LOAM



# CLAY LAYER IN A SILT LOAM



# SATURATED FLOW





# MOIST VS. DRY SOIL



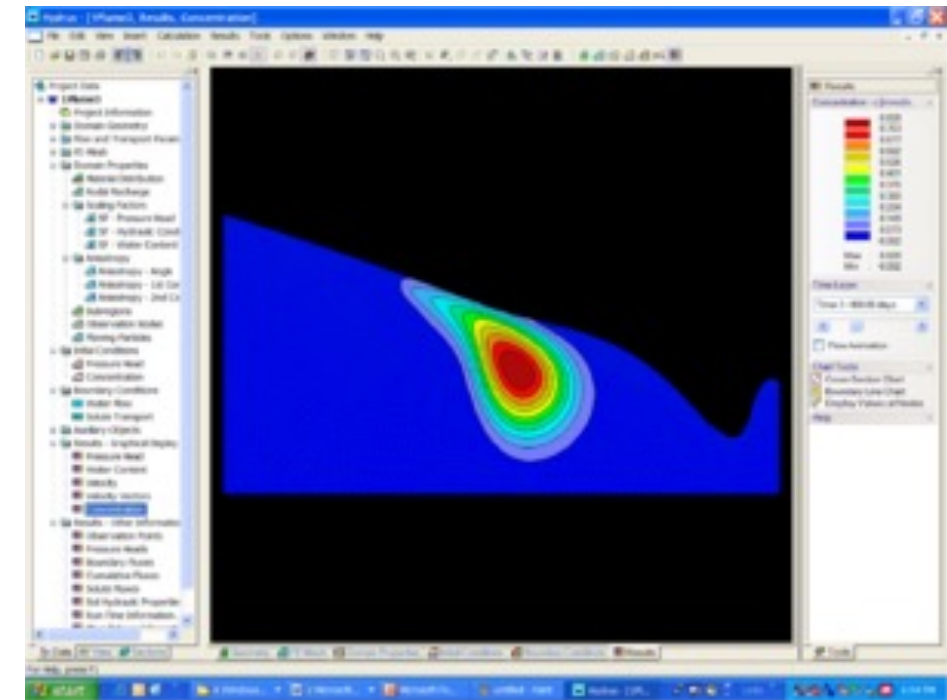
# SOIL TEXTURE AND VELOCITY



# FREE TOOLS

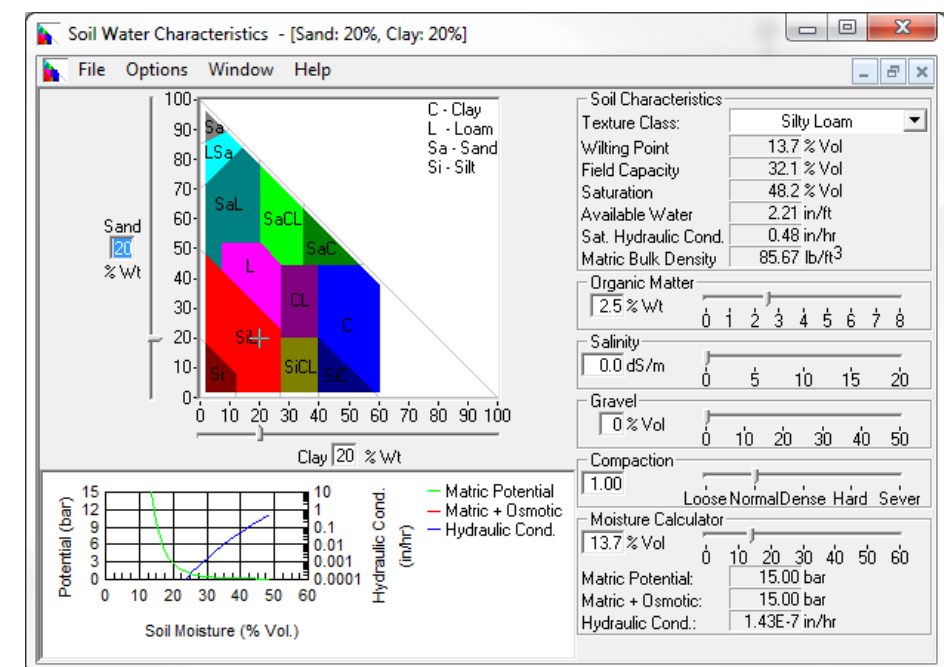
- Hydra 1D, Modeling tool for soil moisture

<https://www.ars.usda.gov/pacific-west-area/riverside-ca/us-salinity-laboratory/docs/hydrus-1d-model/>



- SWC, Soil Properties  
<https://hrsl.ba.ars.usda.gov/soilwater/Index.htm>

- SHAW, Modeling thermal fluxes  
<https://www.ars.usda.gov/pacific-west-area/boise-id/watershed-management-research/docs/shaw-model/>





# HOW MUCH DO YOU IRRIGATE?

- 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.



# HOW MUCH DO YOU IRRIGATE?

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.

$\theta_{PWP} = 16\%$  and the field capacity,  $\theta_{FC}$  is 32%.

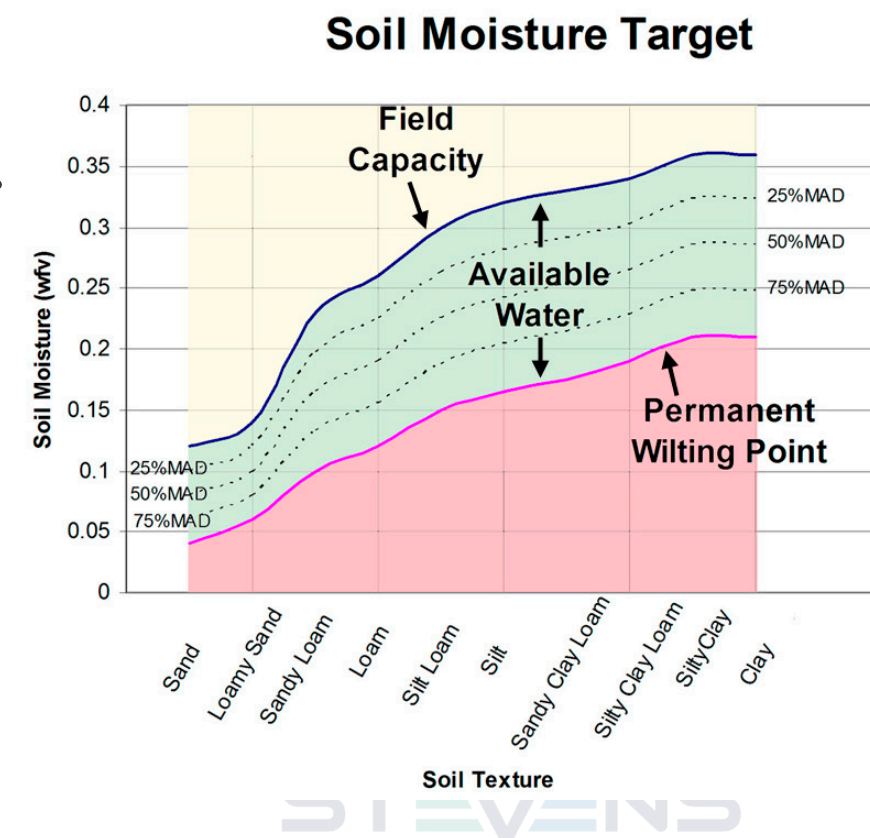
-Optimal soil moisture range =  $[(32\% - 16\%) \times 50\%] + 16\% = 24\%$  to 32%

-Increase moisture by  $32\% - 20\% = 12\%$

-24 cm X 12% = 2.88 cm of water

2.88 cm / 75% = 3.84 cm of water to be applied.

Being mindful of infiltration rate,  
deep drainage, and ET.



# DIELECTRIC PERMITTIVITY





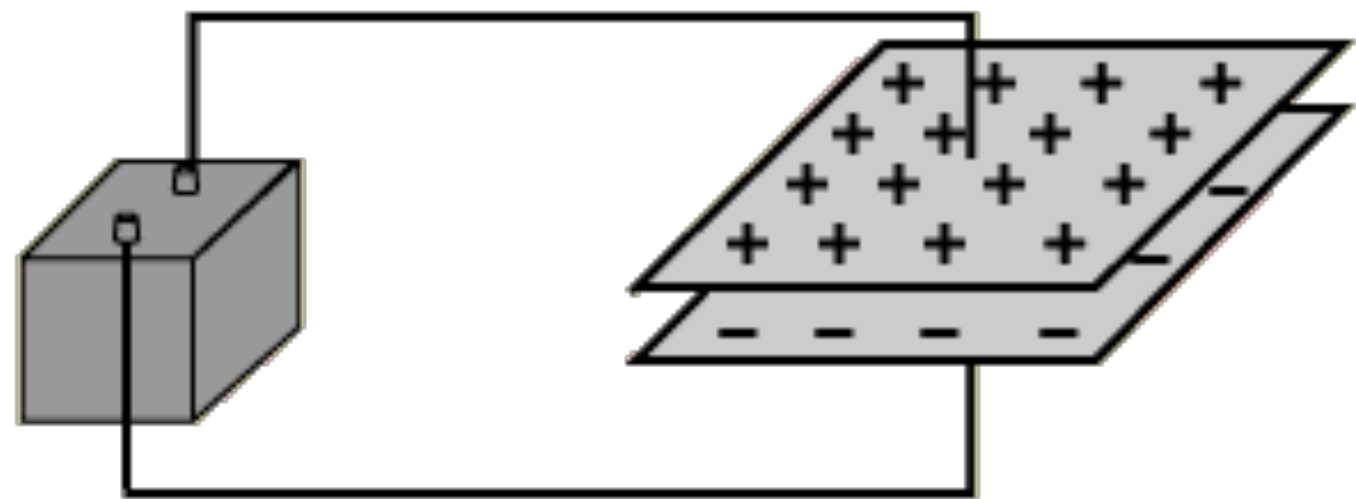
# DIELECTRIC PERMITTIVITY

Permittivity is a physical quantity that describes how an electric field affects, and is affected by a dielectric medium, and is determined by the ability of a material to polarize in response to the field, and thereby reduce the total electric field inside the material. Thus, permittivity relates to a material's ability to transmit (or "permit") an electric field.

# EXAMPLE OF THE RELATIONSHIP BETWEEN CAPACITANCE AND DIELECTRIC PERMITTIVITY

$$C = \epsilon \epsilon_v \frac{A}{d}$$

C is capacitance  
 $\epsilon$  is the dielectric constant,  $\epsilon_v$  is the dielectric of a vacuum, A is the area of the plates, d is the distance apart of the plates

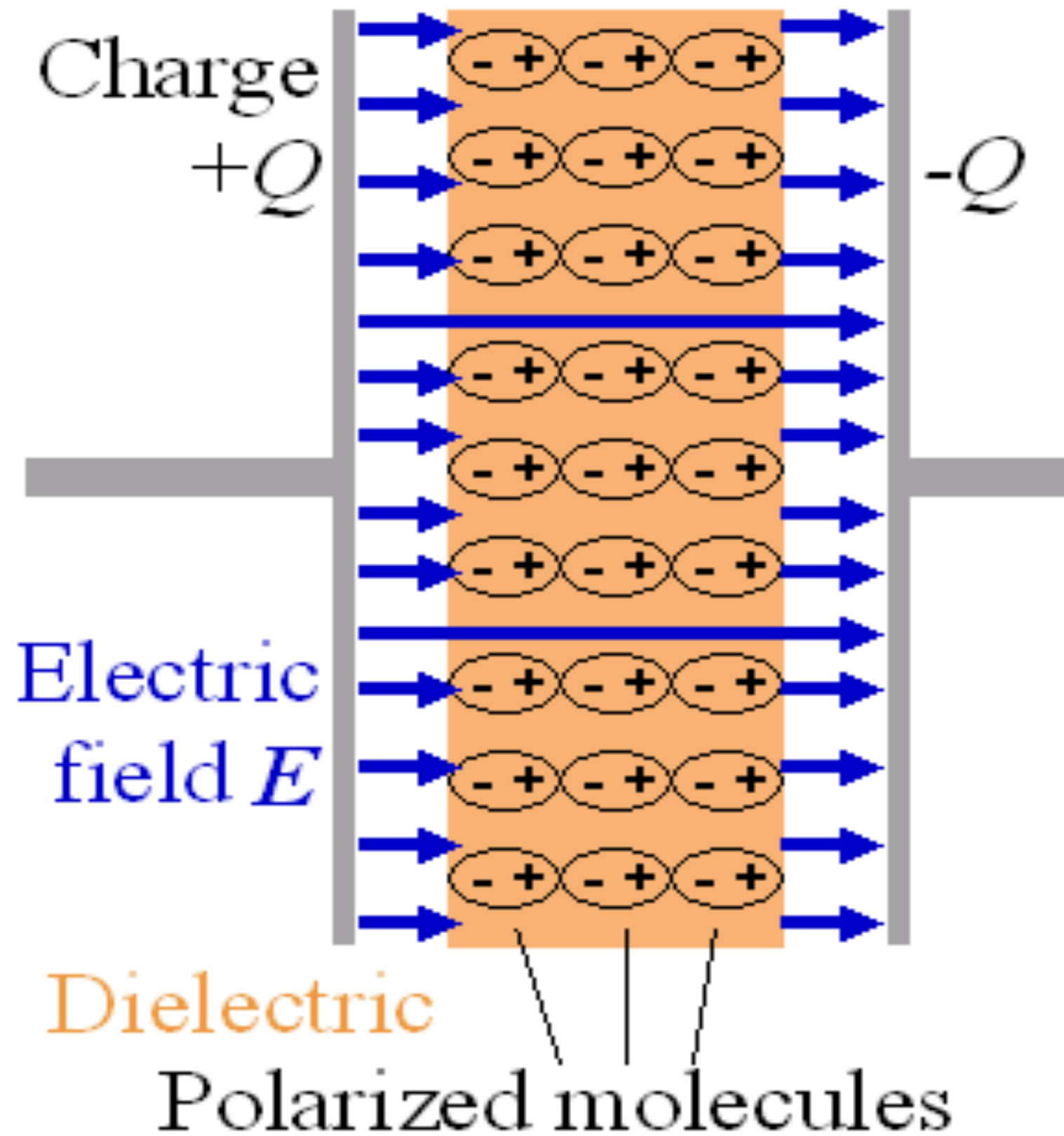


Capacitor

A battery will transport charge from one plate to the other until the voltage produced by the charge buildup is equal to the battery voltage.

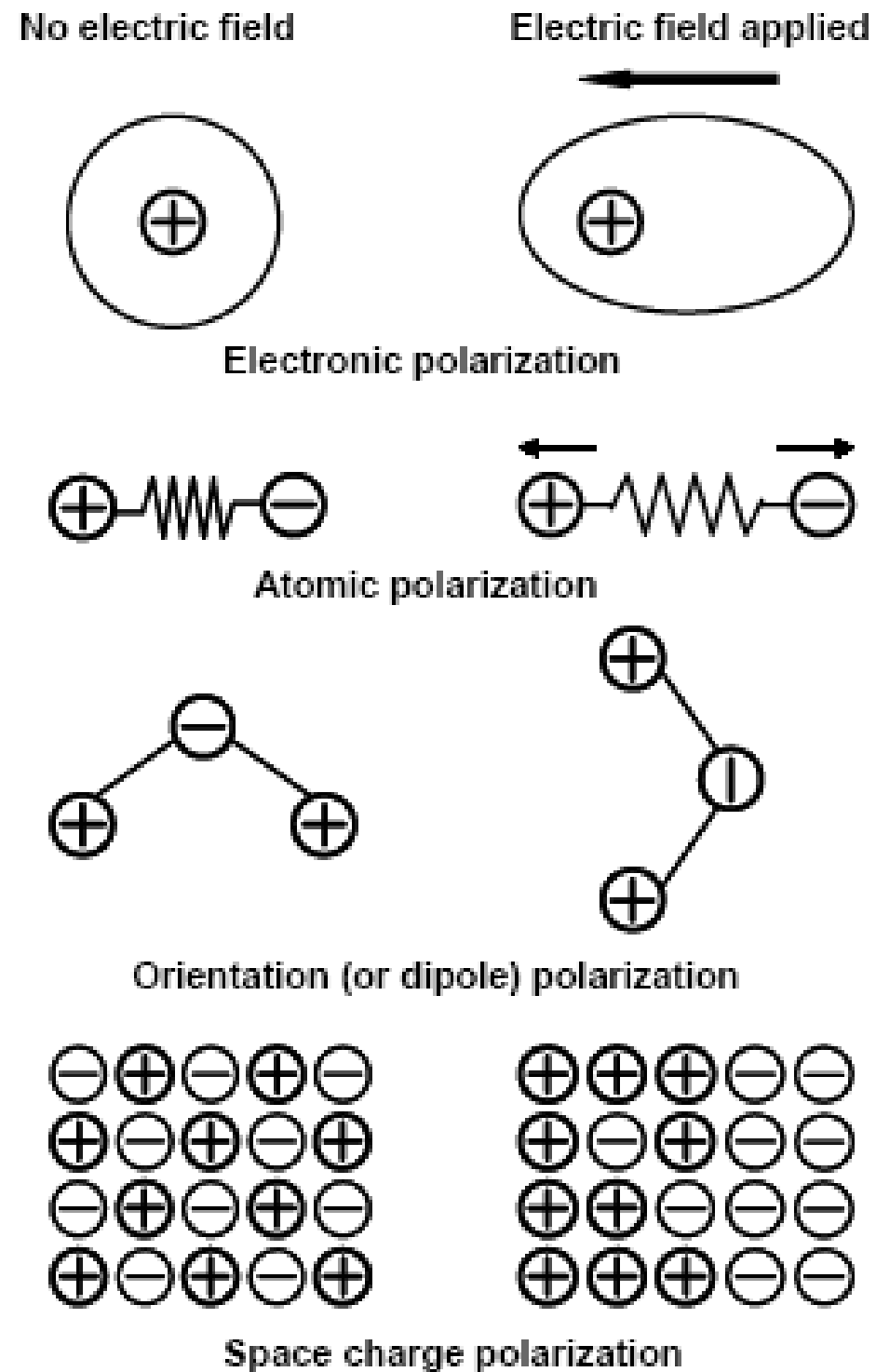


# POLARIZATION OF A DIELECTRIC

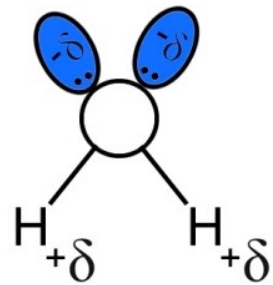
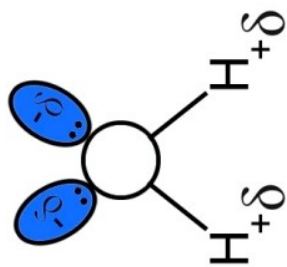
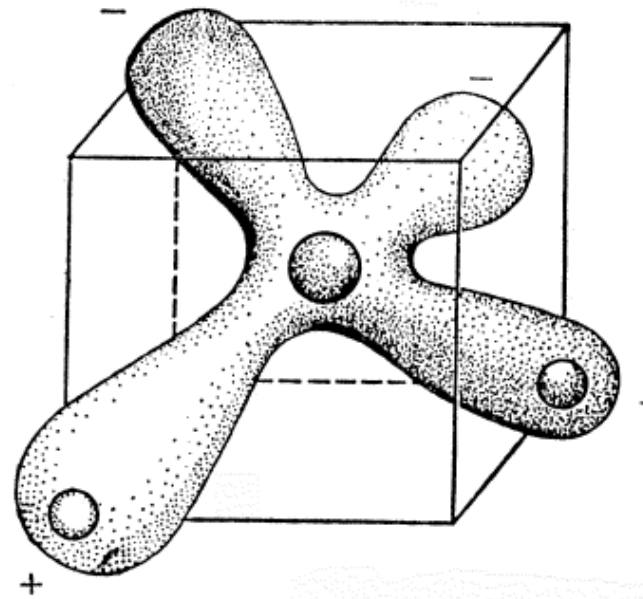




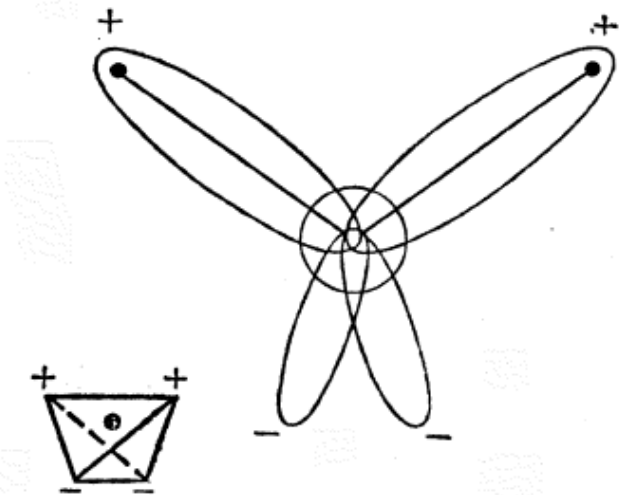
# POLARIZATION OF A DIELECTRIC CONT.



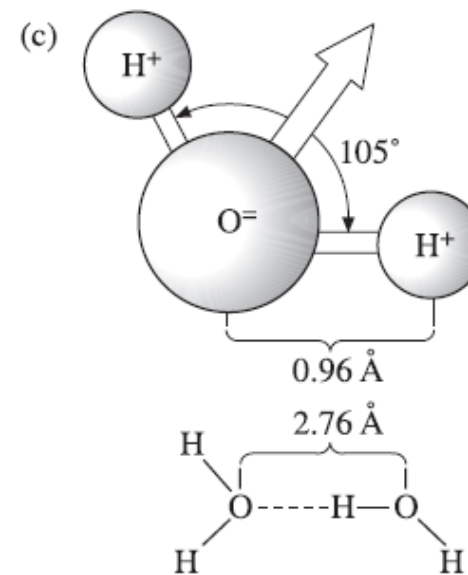
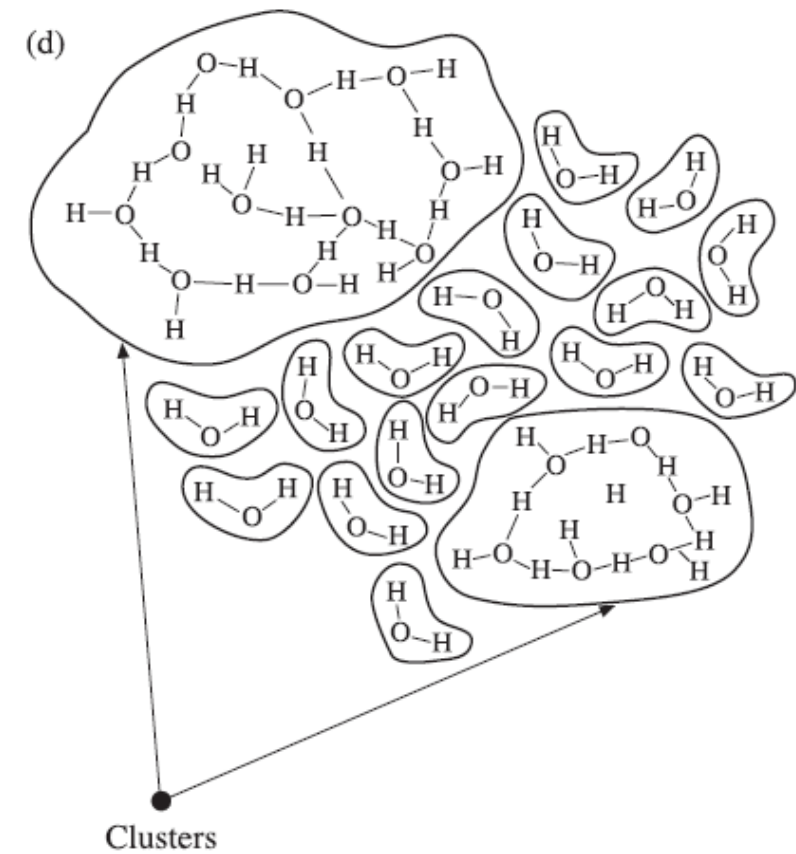
# ELECTRICAL PROPERTIES OF WATER



(a)



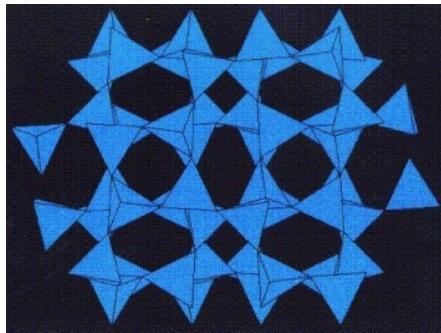
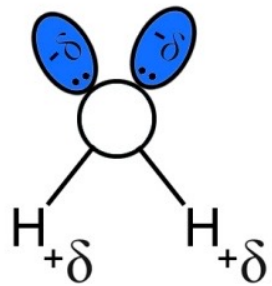
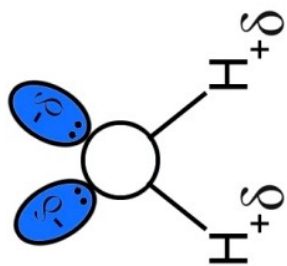
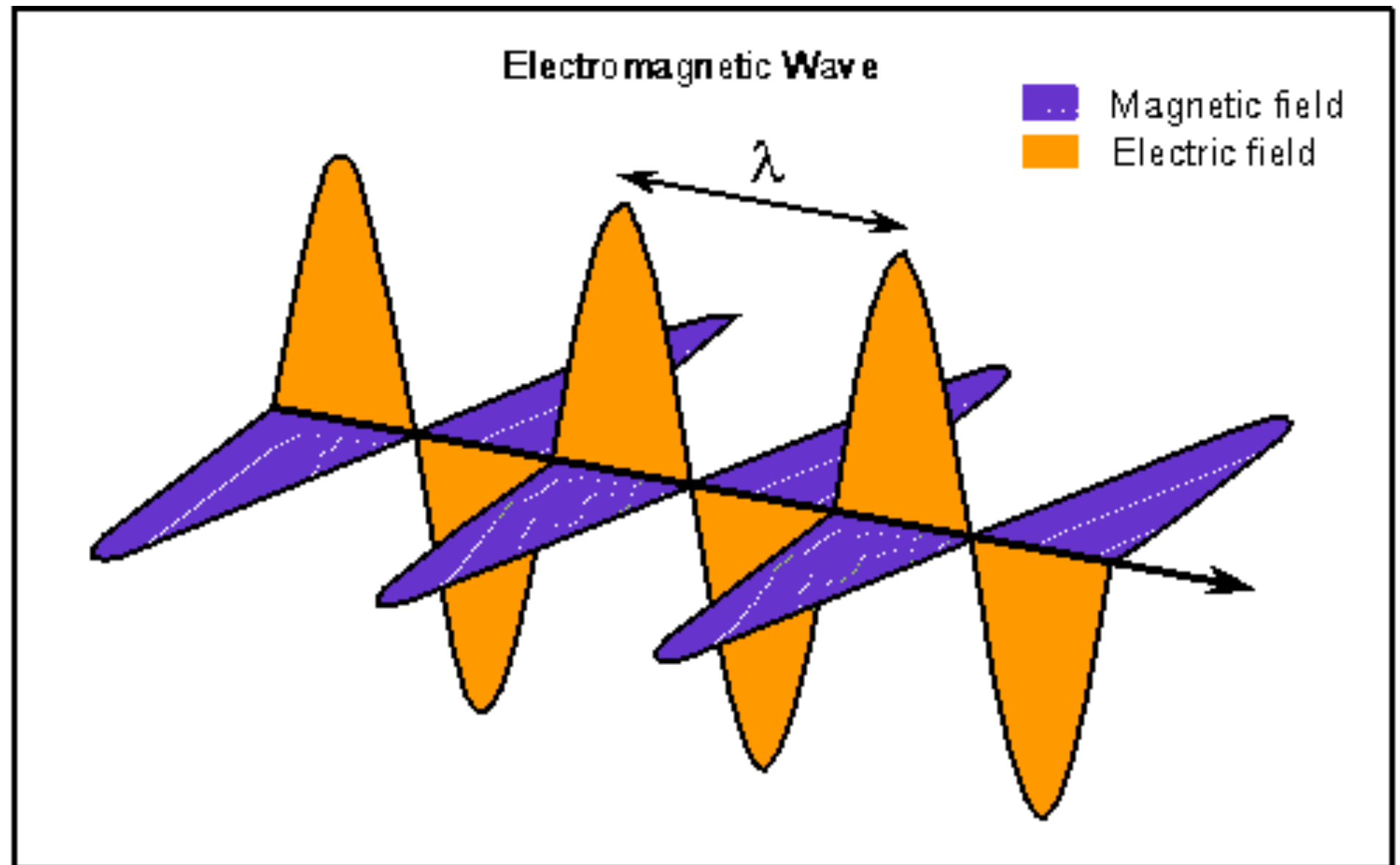
(b)



Clusters



# ELECTROMAGNETIC WAVES





# COMPLEX DIELECTRIC PERMITTIVITY

$$\mathbf{K}^* = \epsilon_r - j\epsilon_i$$

$$j = \sqrt{-1}$$

- $\epsilon_i$  Imaginary Dielectric Permittivity (energy loss)
- $\epsilon_r$  Real Dielectric Permittivity (energy storage)
- $\mathbf{K}^*$  Complex Dielectric Permittivity



# COMPLEX DIELECTRIC PERMITTIVITY CONT.

$$\mathbf{K}^* = \varepsilon_r - j\varepsilon_i \quad j = \sqrt{-1}$$

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

- The imaginary permittivity is a function of molecular relaxations, electrical conductivity and frequency
- Molecular relaxations represents the energy loss which is not going into promotion of the dipole moment. It is a measure of the lag time of the dipole moment which increases with frequency.
- Electrical conductivity represents the soil's salinity



# THE APPARENT PERMITTIVITY REPRESENTED AS AN ANALOG SIGNAL

Analog Signal from sensor  $\sim \epsilon_a$

$$\epsilon_a \longleftrightarrow V_{\text{raw}}$$

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

- $\epsilon_a$  Apparent Dielectric Permittivity
- $\epsilon_i$  Imaginary Dielectric Permittivity
- $\epsilon_r$  Real Dielectric Permittivity
- $K^*$  Complex Dielectric Permittivity  $r$





# SOIL SENSING TECHNOLOGY AND THE APPARENT PERMITTIVITY

Real and Imaginary mixed together

- TDR/TDT
- FDR
- Capacitive (Time of charge)
- Simplified impedance

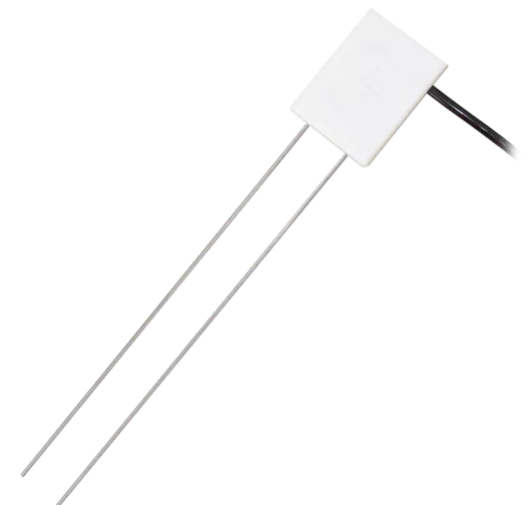


# TDR AND TDT

- Time Domain Reflectometry  
Time Domain Transmission
- The travel time of an electromagnetic wave is a function of the apparent dielectric permittivity. The wetter the soil the slower the wave will travel.

- $T$  = time
- $L$  = length
- $c$  = Speed of light
- $\epsilon_a$  = Apparent dielectric permittivity

$$T = \frac{2L\sqrt{\epsilon_a}}{c}$$



# FREQUENCY DOMAIN REFLECTOMETRY

$$F = \frac{1}{2\pi\sqrt{LC}}$$

Sensor response Voltage that is related to the capacitance which in turn is related to the apparent permittivity

- F = Resonant frequency (frequency that is reflected)
- L = inductance (H)
- C is Capacitance
- $\epsilon_a$  = is the apparent permittivity the soil
- $\theta$  = Soil Moisture (wfv)

$$\theta = a + bv + cv^2 + dv^3$$



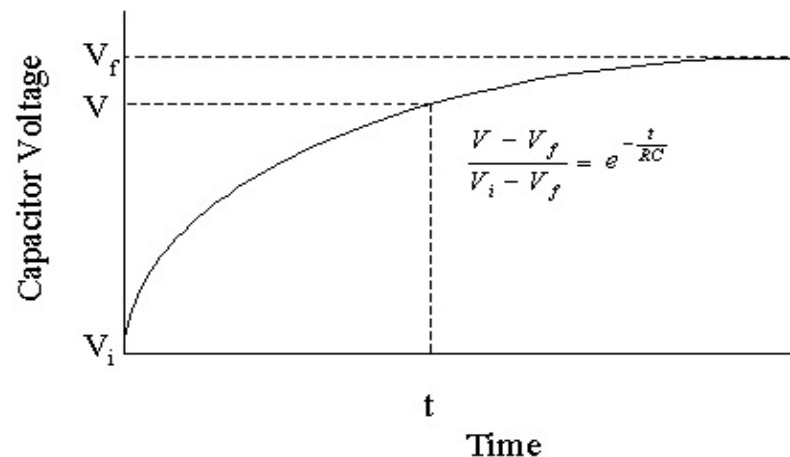


# CHARGE TIME OF A CAPACITOR

$$t = -RC' \ln \left( \frac{V - V_f}{V_i - V_f} \right)$$

$$C' \approx \epsilon^* = \epsilon_r + j\epsilon_i$$

$$\theta = a + b\epsilon_a + c\epsilon_a^2 + d\epsilon_a^3$$



- $t$  = Charge Time
- $R$  = Resistance (ohms)
- $V$  = charged voltage
- $V_i$  = Starting Voltage
- $V_f$  = Applied Voltage
- $C'$  = Capacitance of Soil



# SIMPLIFIED IMPEDANCE

$$V_j - V_0 = 2a \left( \frac{Z_p - Z_{soil}}{Z_p + Z_{soil}} \right)$$

$$Z_{soil} = \frac{60}{\sqrt{\epsilon_a}} \ln \left( \frac{r_1}{r_2} \right)$$

$$\epsilon_a \leftrightarrow V_{raw}$$

$$\theta = a + bv + cv^2 + dv^3$$

- $V_j$ =amplitude of reflected wave
- $V_0$ =amplitude of incident wave
- $Z_p$ = Impedance of the probe
- $Z_{soil}$ = Impedance of the soil



# HYDRAPROBE

$$\frac{Z_p}{Z_c} = \frac{1 + \Gamma}{1 - \Gamma}$$

$$K^* = \epsilon_r - j\epsilon_i$$
$$j = \sqrt{-1}$$

$$Z_p = \frac{Z_0}{\sqrt{\epsilon^*}} \cotanh\left(\frac{\omega\sqrt{\epsilon^*}L}{c} j\right)$$

Z = impedance

$$\Gamma = V_r/V$$

$\omega$  = Frequency

L Geometric factor

The impedance is calculated from the ratio of reflected to the incident signals eliminating the difference from sensor to sensor.





# THE IMPORTANCE OF SEPARATING OUT THE REAL FROM THE IMAGINARY DIELECTRIC PERMITTIVITY (HYDRAPROBE)

- Less influenced by temperature
- Less influenced by salinity
- Less error due to soil mineralogy
- Better inter-sensor variability, better calibration for soil water content



# 4/22 HYDRAPROBE BENEFITS TO REMEMBER

- Durable, Accurate and Reliable
- Separation of real and imaginary dielectric permittivity
- Inter-sensor variability

# CALIBRATION OF SOIL SENSORS





# CALIBRATION

- Water has a Real Dielectric Constant of 80
- Dry Soil has a Real Dielectric Constant of 2
- Changes in the real dielectric permittivity or the apparent dielectric permittivity correspond to changes in soil moisture and can be described empirically.
- $\theta$  = Soil Moisture, Water fraction by volume ( $\text{m}^3 \text{m}^{-3}$ )
- Lots of Time domain and other electronic sensors use the Topp Equation



# FACTORY CALIBRATION

$$\theta = A \varepsilon_r^{1/2} + B$$

- $\theta$  Soil Moisture (wfv)  $\text{m}^3 \text{m}^{-3}$
- $A$  = Slope (0.109)
- $\varepsilon_r$  = Real Dielectric Permittivity
- $B$  = Intercept (-0.179)

Seyfried, M. S., L. E. Grant, E. Du-, and K. Humes. 2005.

Dielectric Loss and Calibration of the Hydra Probe Soil Water Sensor.  
Vadose Zone Journal 4:1070-1079 (2005)



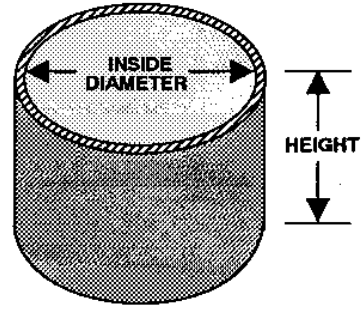
# VALIDATE BEFORE YOU TRY TO RECALIBRATE



$$\theta_{Sensor} \longleftrightarrow \theta_{lab} = w_{loss}/V \qquad \theta = \theta_g \frac{\rho_b}{\rho_w}$$

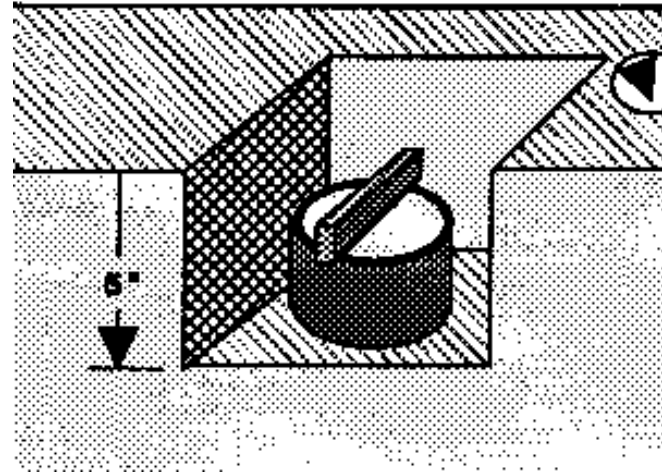
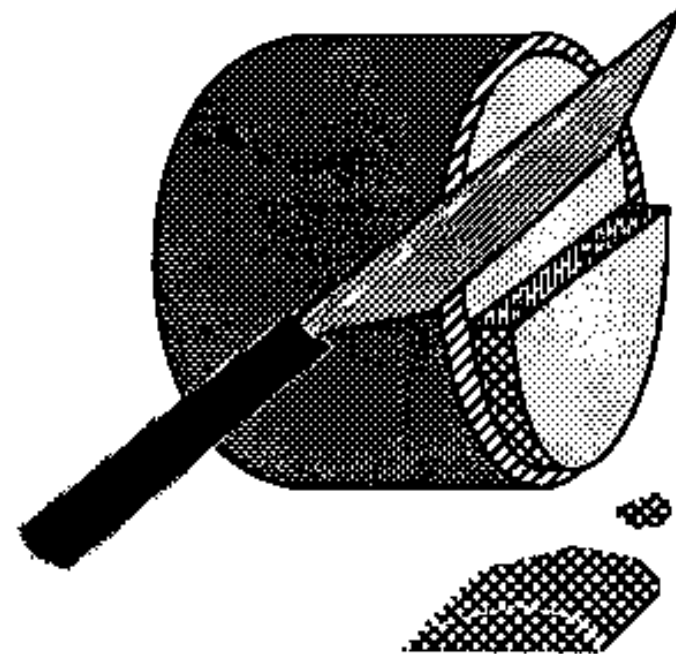
You always want to collect the temperature and dielectric permittivities in case you want to try a new calibration in the future.





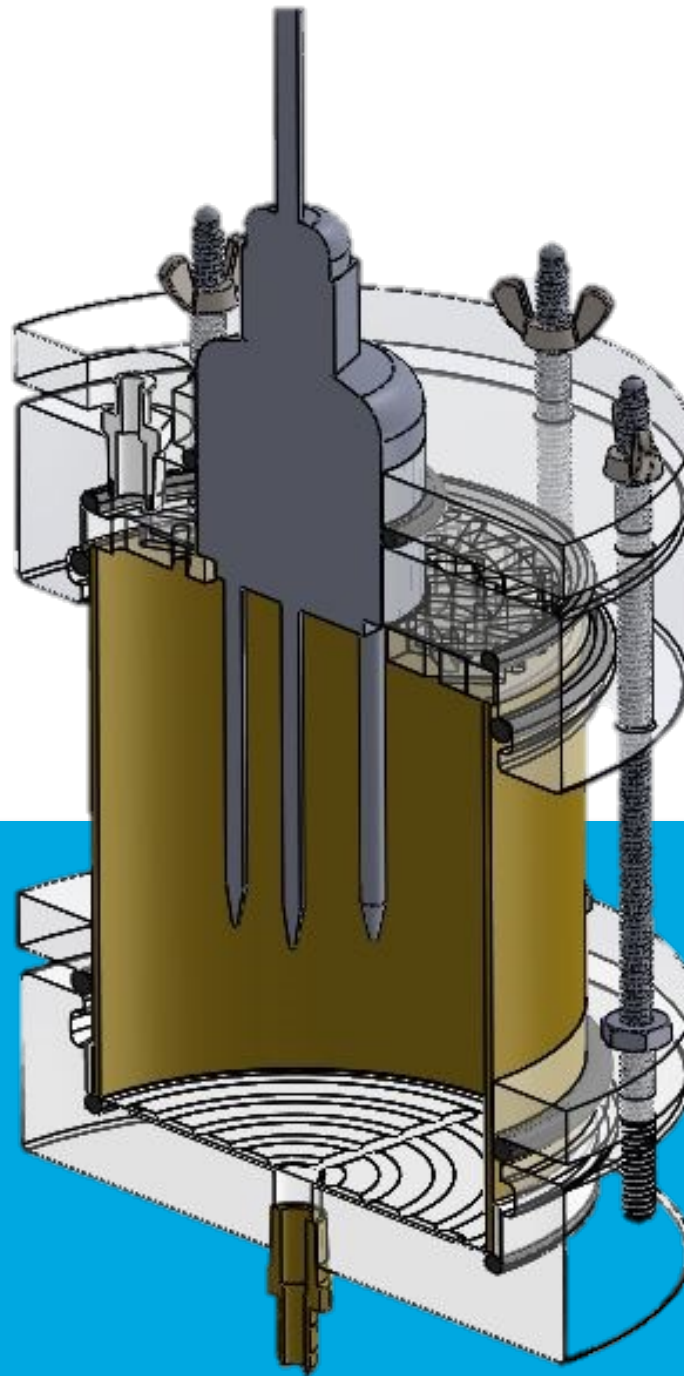
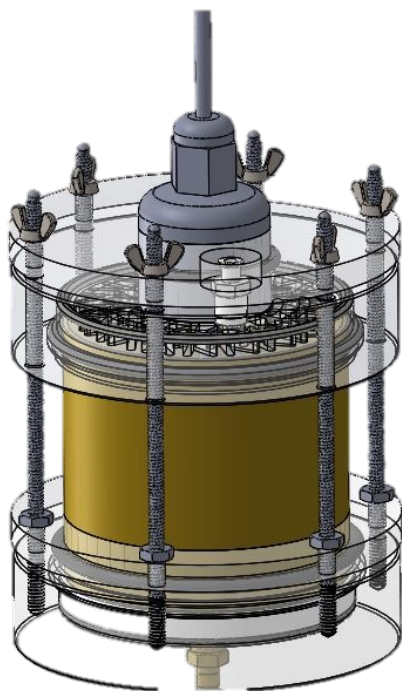
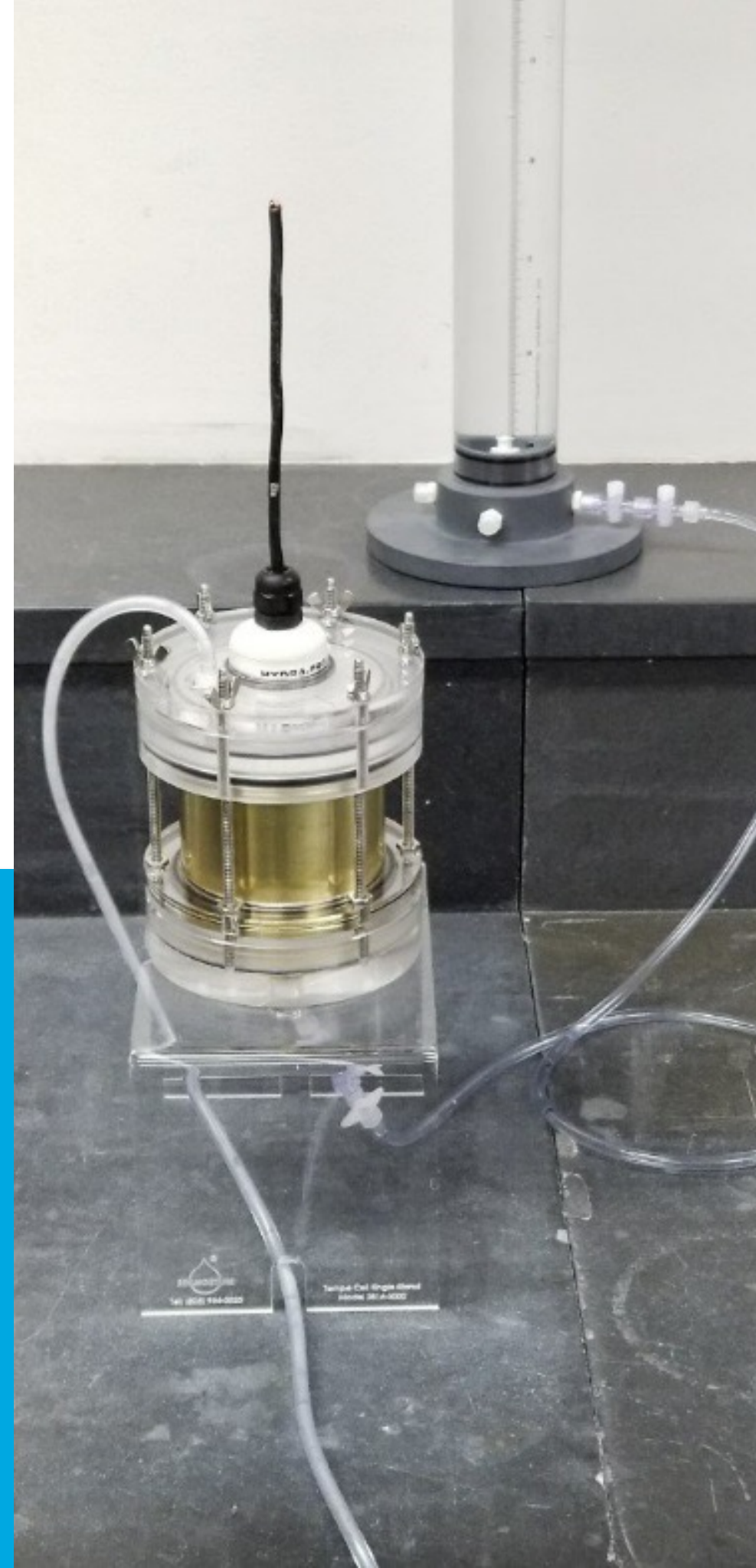
$$\text{VOLUME (CORE)} = \frac{3.14 \times \text{INSIDE DIAMETER}^{\text{(SQUARED)}} \times \text{HEIGHT}}{4}$$

$$V = \frac{3.14 D^2 H}{4}$$





# TEMPE CELL



TECHNICAL  
Tel: 0511 144-0000  
Tempe Cell Single Head  
Model: SH-A-0000



# IF YOU NEED TO RECALIBRATE CURVE FIT

| Real Dielectric Permittivity | Water Content Volumetric determined by dry down weigh down |
|------------------------------|------------------------------------------------------------|
| $\epsilon_1$                 | $\theta_{g1}$                                              |
| $\epsilon_2$                 | $\theta_{g2}$                                              |
| $\epsilon_3$                 | $\theta_{g3}$                                              |
| $\epsilon_x$                 | $\theta_{gx}$                                              |

$$\theta = \theta_g \frac{\rho_b}{\rho_w}$$



# OTHER CALIBRATION EXPRESSIONS

$$\theta = A\varepsilon_r^{1/2} + B$$

$$\theta = A\varepsilon_r + B$$

$$\theta = a + b\varepsilon + c\varepsilon^2 + d\varepsilon^3$$

$$\theta = \phi \frac{\sqrt{\varepsilon} - \sqrt{\varepsilon_{dry}}}{\sqrt{\varepsilon_{sat}} - \sqrt{\varepsilon_{dry}}}$$





# STATISTICAL PARAMETERS USED

$$RMSE = \left[ \frac{\sum_{i=1}^n [C_i - M_i]^2}{n} \right]^{0.5}$$

Absolute Error or Magnitude of the error.

$$ME = \frac{1}{n} \sum_{i=1}^n (C_i - M_i)$$

Mean Error, The Bias. Is the model over or under predicting.

$$E_f = \left( \sum_{i=1}^n (M_i - \bar{M})^2 - \sum_{i=1}^n (C_i - M_i)^2 \right) / \sum_{i=1}^n (M_i - \bar{M})^2$$

Model Efficiency

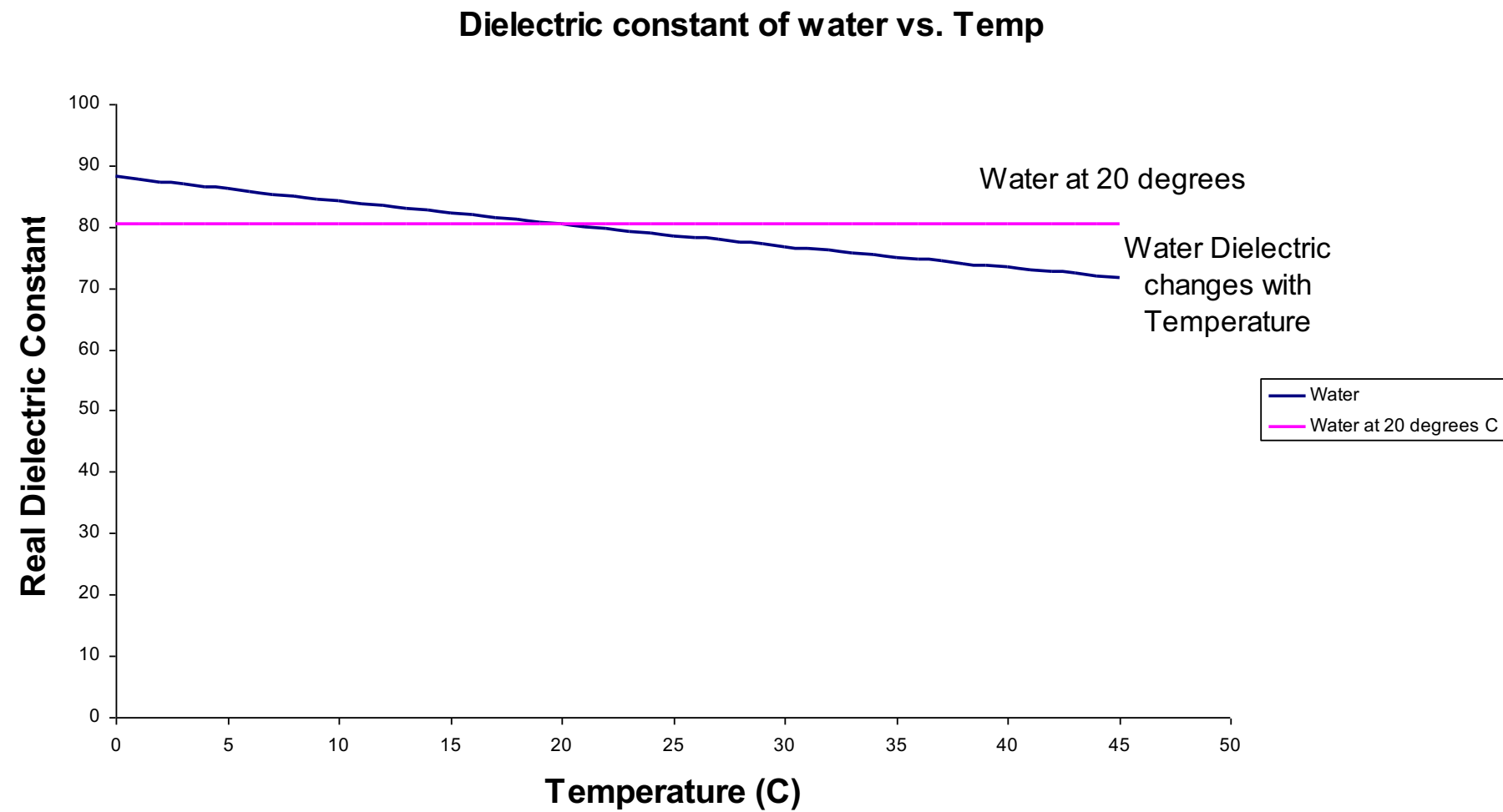


# TEMPERATURE CORRECTION

- The Hydra Probe is less sensitive to changes in temperature than other capacitance based soil sensors.
- The dielectric permittivity of water decreases with temperature due to molecular vibrations
- There can be strong dielectric temperature dependencies in some soils caused by “Bound Water” in some clays.

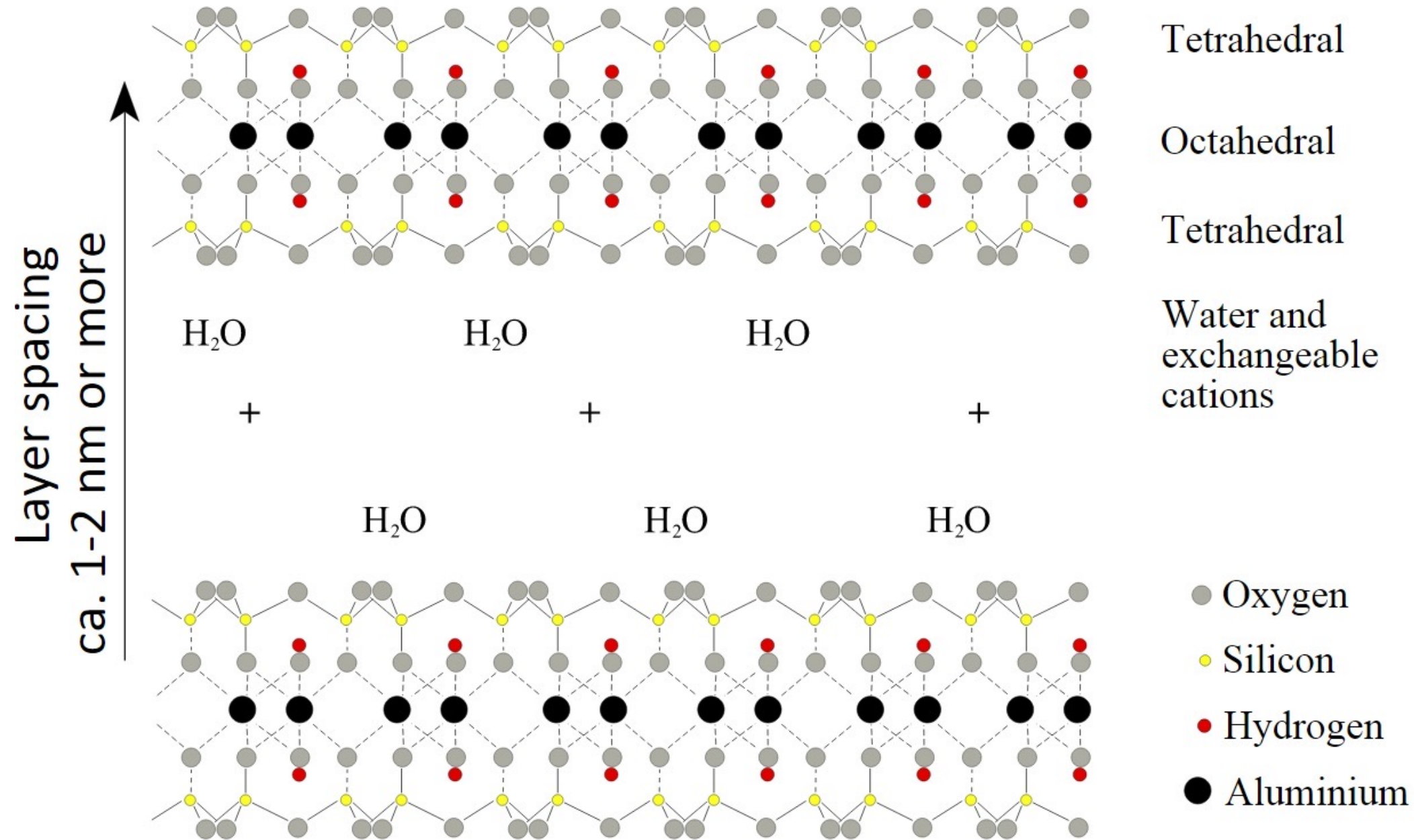


# WATER BY ITSELF



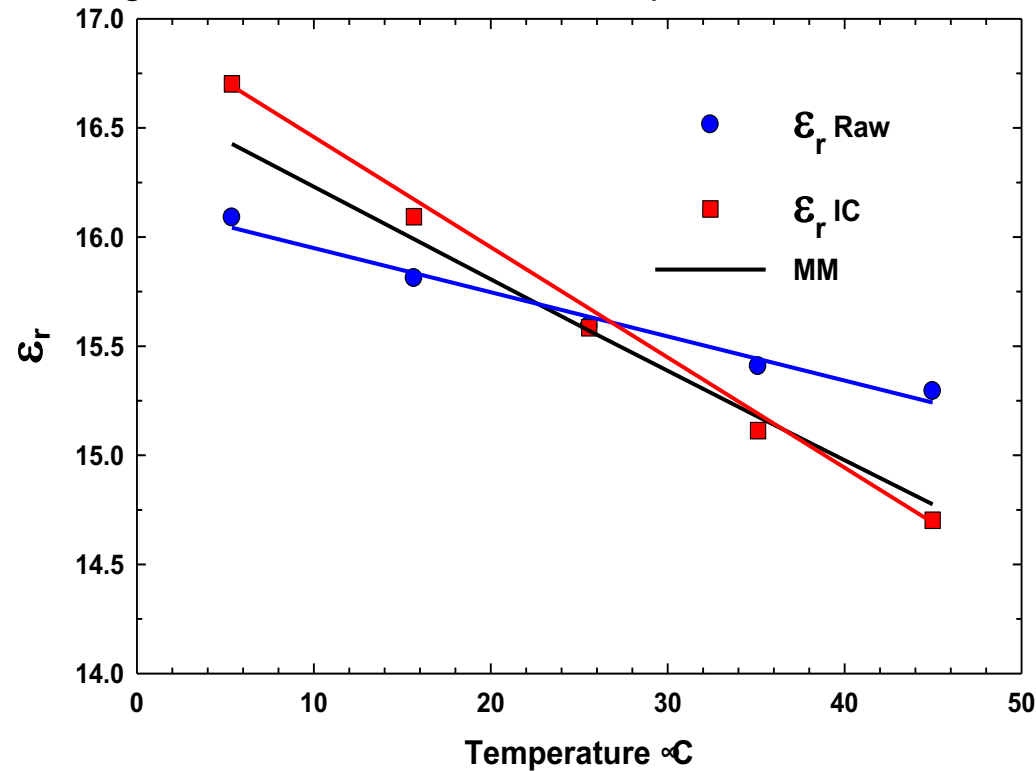


# CLAY LATTICE



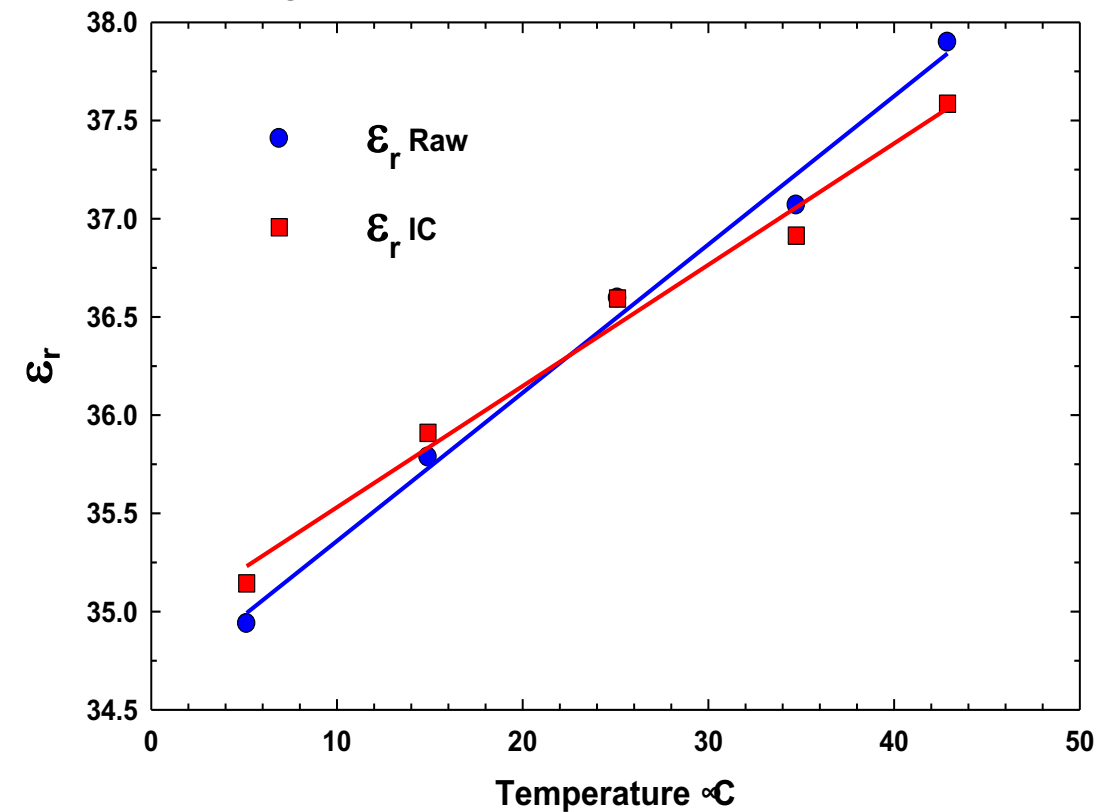
# TEMPERATURE AFFECTS OF PERMITTIVITY IN SOIL

The negative T effect for Tifton soil is predicted from water  $\epsilon_r(T)$ .



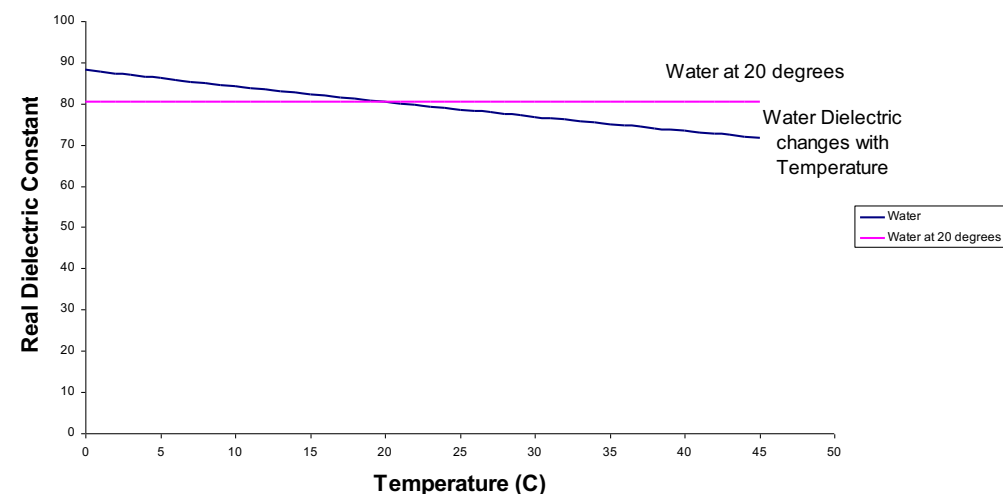
Change in  $\epsilon_r$  with T (Raw), instrument correction (IC) and dielectric mixing model (MM) calculation.

Strong positive T effect for the Ames soil.



Change in  $\epsilon_r$  with T with (Raw) and without instrument correction (IC).

Dielectric constant of water vs. Temp



# BULK EC, SALINITY AND OTHER IONS





# SOIL SALINITY

- If ET is greater than Precipitation, you will have a net upward movement of salt
- Poor irrigation Water
- Poor Drainage





# APPLICATIONS FOR MEASURING EC IN SOIL

- Crop Health
- Salt water intrusion studies
- Crop Pathogens
- Soil reclamation and cations exchange
- Soil Hydrology



# SOIL ELECTRICAL CONDUCTIVITY IN SOIL

- A material that inhibits the propagation of an electromagnetic wave is energy loss.
- Electrical conductivity is the movement of electric charge.
- Electrical conductivity is the indirect measurement of sodium chloride (NaCl).
- EC in soil is qualitative most of the time



# IONS IN SOLUTION IN THE SOIL

| Anion (-)                     | Cation (+)       |
|-------------------------------|------------------|
| OH-                           | H+               |
| Cl-                           | Na+              |
| NO <sub>3</sub> -             | K+               |
| SO <sub>4</sub> <sup>2-</sup> | Ca <sup>2+</sup> |
| CH <sub>3</sub> COO-          | Fe <sup>3+</sup> |

# IMAGINARY DIELECTRIC PERMITTIVITY

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

$$\sigma_{dc} = 2\pi f \epsilon_v \epsilon_i$$

$\epsilon_i$  Imaginary Dielectric Permittivity

$f$  Frequency (50 MHz)

$\epsilon_v$  Permittivity of a Vacuum

$\epsilon_{rel}$  Molecular Relaxation

$\sigma_{dc}$  DC electrical conductivity





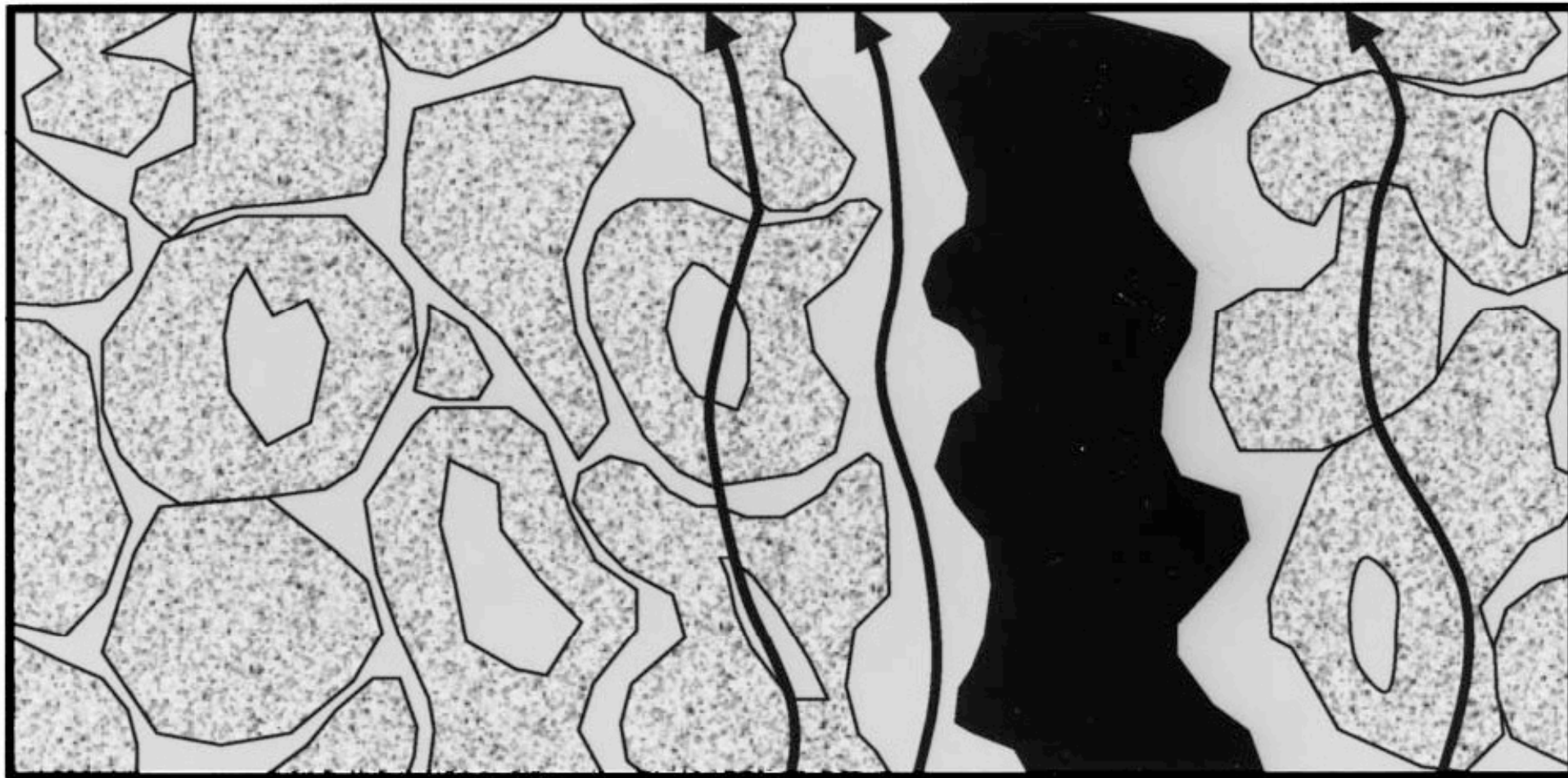
# PORE WATER EC AND BULK EC

- Bulk EC is the EC of the soil matrix as a whole. It is what the soil sensors measure.
- Pore Water EC is the EC of the water in the soil.
- If there is no water, there is no pore water EC because the ions need to be in solution to conduct electricity.



# ELECTRICAL CONDUCTIVITY PATHWAYS IN SOIL

**Soil Cross Section**

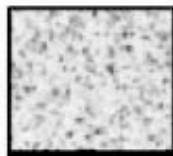


1

2

3

**Solid**



**Liquid**



**Air**

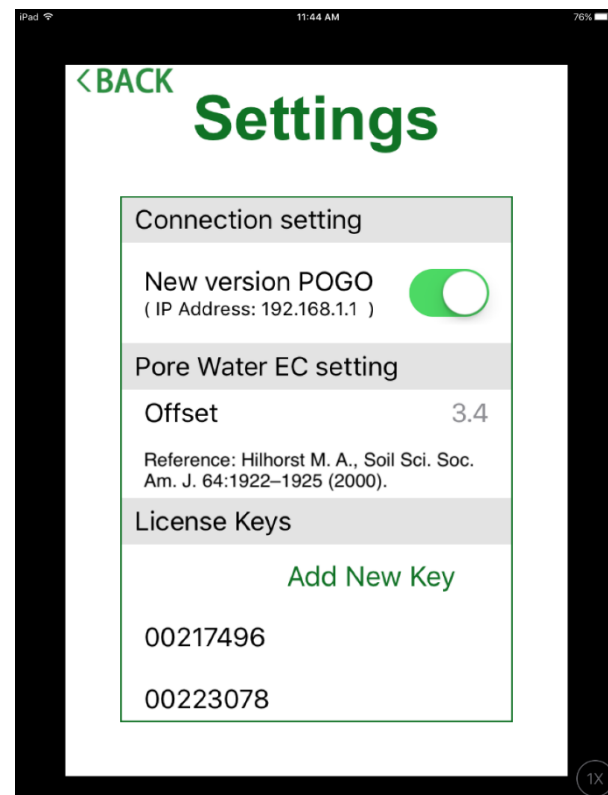
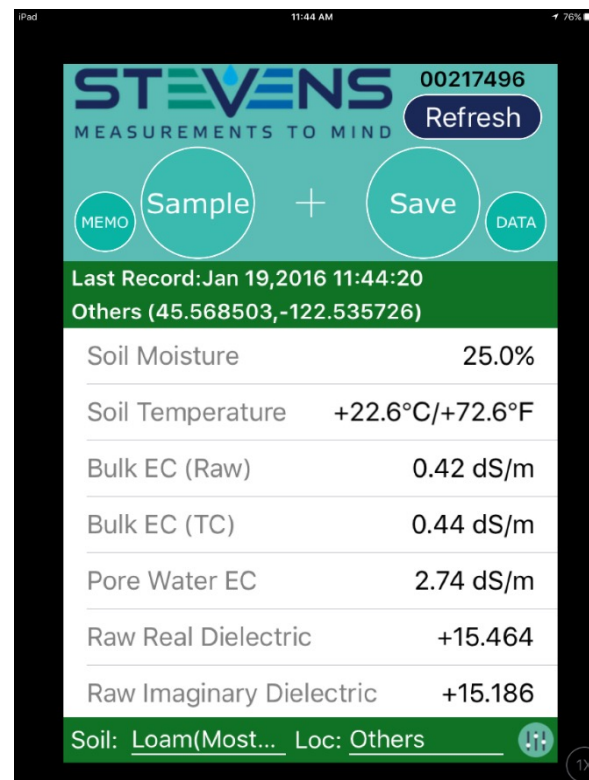
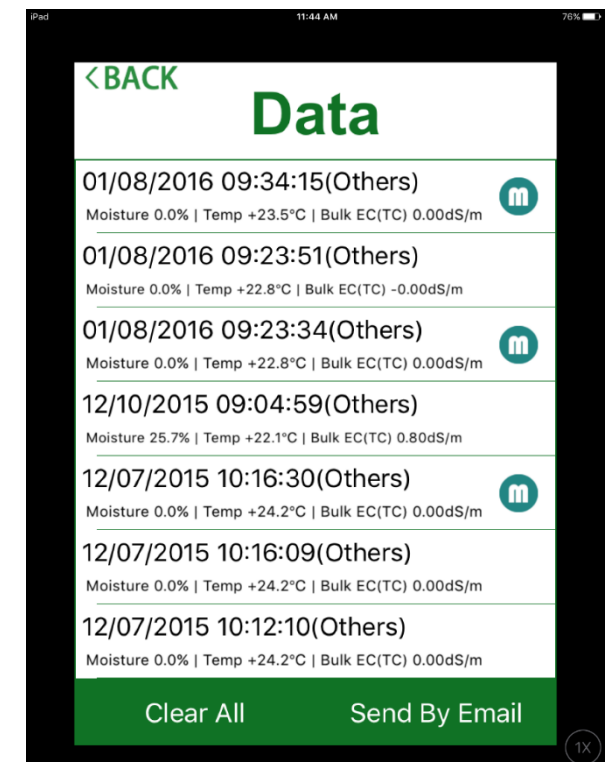


Plot 2 EC and WFV



# THE HILHORST MODEL TO DETERMINE PORE WATER EC FROM BULK EC

$$\sigma_p = \frac{\epsilon_{r,pw} \sigma_b}{\epsilon_r - \epsilon_{\sigma b=0}}$$





# OTHER BULK EC TO PORE WATER EC RELATIONSHIPS

$$\sigma_b = [c\theta - d]\sigma_w + [a\theta - b]$$

a, b and c are empirical coefficients



# SOIL ACIDITY

-The pH is related to the acidity or basicity

Bacteria will breakdown organic material producing  $\text{CO}_2$  which dissolves and helps produce  $\text{H}^+$



$$\text{pH} = -\text{Log}[\text{H}^+]$$



# PH AND FERTILIZERS

The pH can also drive the availability of fertilizers. If nitrate is applied to the soil, the nitrate can get all consumed shifting the pH lower which in turn shifts the nitrate back to ammonium ion.



Adding lime or a calcium carbonate to the soil will help adsorb the excess  $[H^+]$  increasing the availability of the  $[NO_3^-]$



# INSTALLATION





# TROUBLESHOOTING AND INSTALLATION

## Before you go into the field:

- Make sure every SDI-12 sensor has a unique address
- Before going into the field, test the probe in water. Parameter K should be about 78 and the EC should be 0.
- Make sure the cable is labeled at both ends.
- Write down the Serial Numbers and assign the address to it. [Stevens can't honor the warranty without the SN#]



# FIELD INSTALLATION OF SOIL MONITORING STATIONS

## CHECK LIST

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



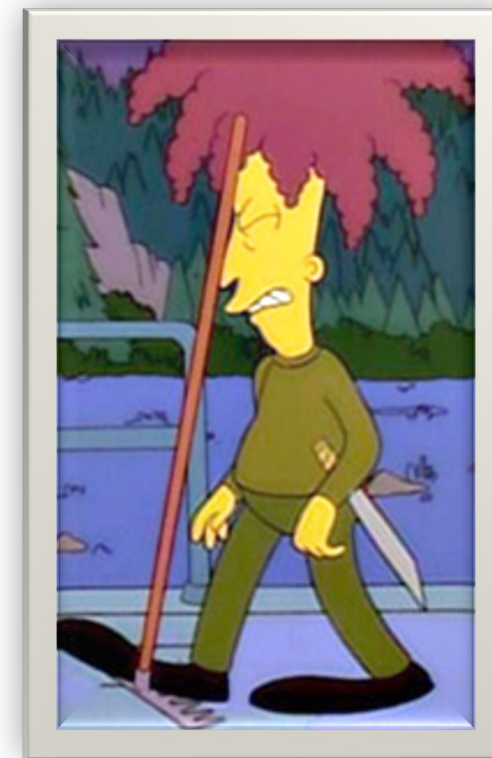
# SITE SELECTION

- Make sure the soil column is not in a plow zone.
- You can use existing soil maps to see where soil is different regionally.  
<https://websoilsurvey.sc.egov.usda.gov/>
- It should be representative to the soil hydraulic properties and the ET regime.
- Take slope and wetlands into consideration
- Make sure you have enough probe cable to get to back to the logger.



# PRECAUTIONS

- Don't fall in the hole.
- Watch out for cables and other trip hazards.
- Do not leave shovels and rakes laying on the ground.
- Protect yourself from sun, rain and the elements.
- Wild animal considerations.
- Careful with augers.





# PREPARE THE HOLE

- Prepare the Hole, save the dirt that came out of the hole on a tarp on a flattened out cardboard box. You will want to back fill the hole with the dirt that came out of it.
- Calibration of the probe is not normally required.

## **Digging the hole:**

- Spade
- Post-Hole Digger
- Motorized Auger
- Backhoe

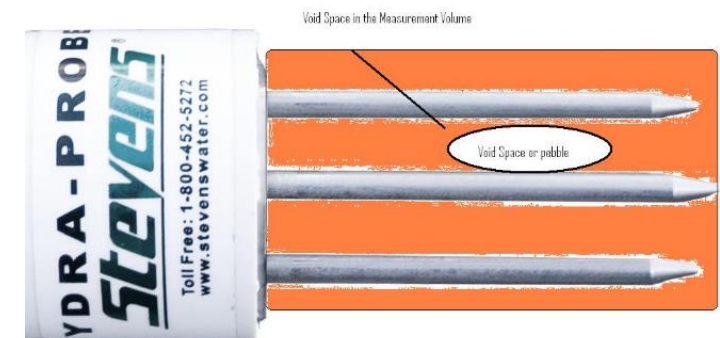


# INSTALLATION OF THE HYDRAPROBE IN THE HOLE

- 1) Use a trowel, knife or small shovel to smooth the wall of the hole so that the probe's base plate or ground-plane is flush with the wall of the hole
- 2) It is important that the tine assembly is all the way in and has full contact with the undisturbed soil.
- 3) Any air gaps between the tines will be averaged into the measurements causing errors.
- 4) Don't forget to document the depth, the address and the serial number.



Downward looking view into the hole



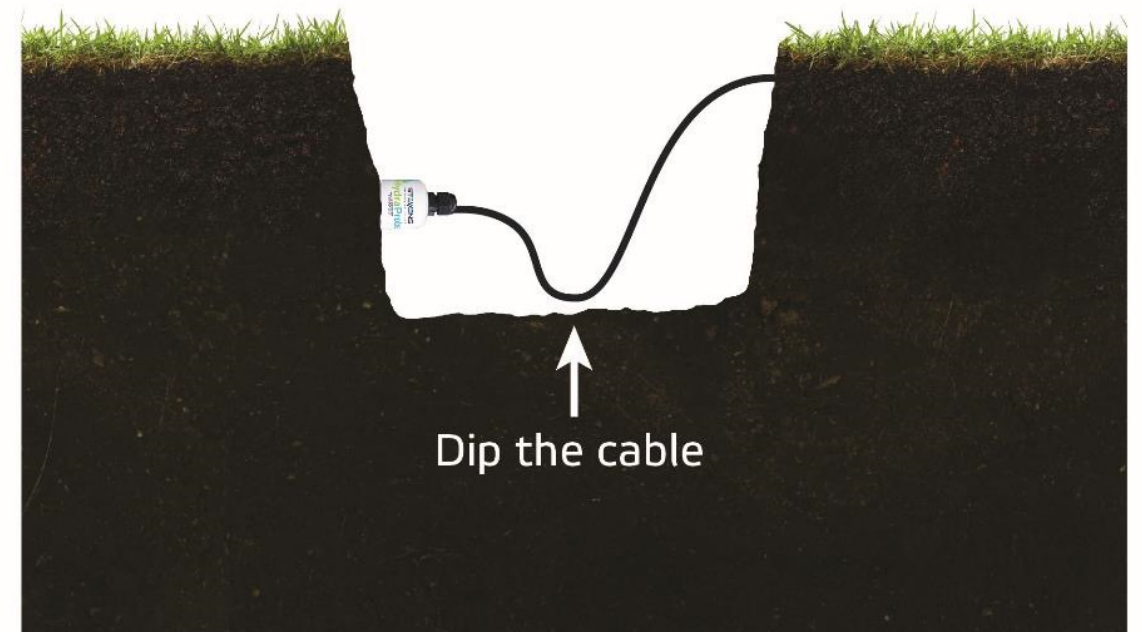
Avoid rocks and air gaps between the tines



# HORIZONTAL VS. VERTICAL



**INCORRECT**

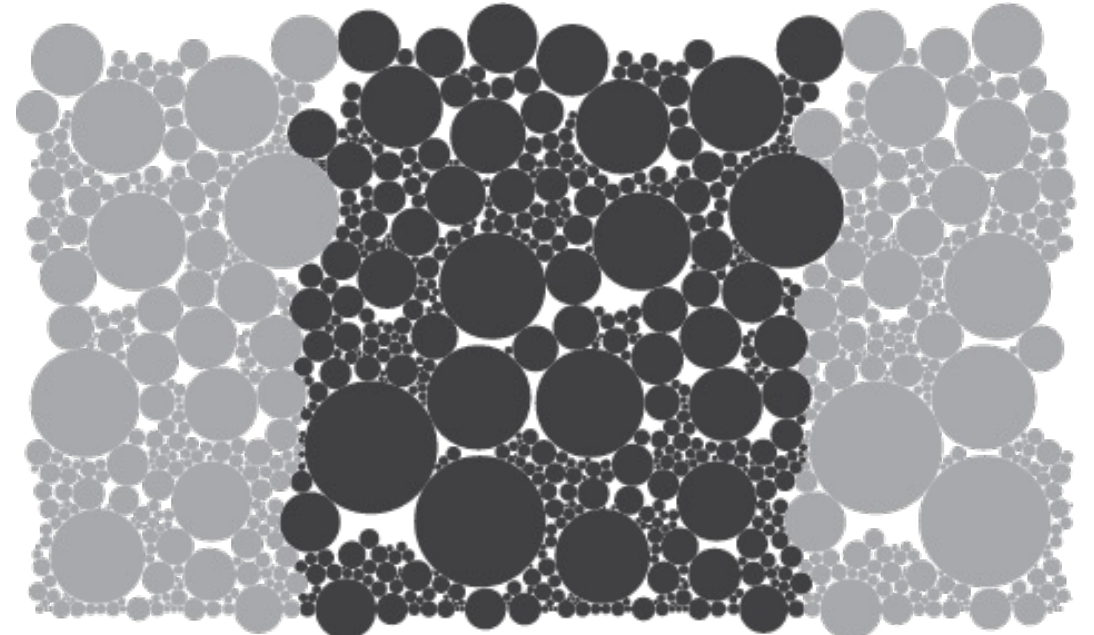


**CORRECT**



# DISTURBED VS. UNDISTURBED SOIL

- Changes the porosity
- Changes the tortuosity
- Changes the capillaries and the water potential properties
- Changes the ped structure
- Changes  $K$  the hydraulic conductivity
- Changes the saturation and field capacity





# INSTALLATION TIPS (BEFORE BACKFILLING THE HOLE)

- Check the bus with a voltmeter. Should be 12 V.
- Before you fill in the hole, wire the probes to the logger. In the logger's SDI-12 Transparent mode, send an aM! Followed by the D command to take a reading.
- Dip the cable, make sure the cable isn't a conduit for water.
- As an option, the probe cable could be ran through a pipe or electrical conduit.

| The SDI-12 "aM!" Command followed by aD0!,      |               |                      |
|-------------------------------------------------|---------------|----------------------|
| Parameter 1                                     | Parameter 2   | Parameter 3          |
| Soil Moisture (m <sup>3</sup> m <sup>-3</sup> ) | Bulk EC (S/m) | Soil Temperature (C) |



# BACK FILLING THE HOLE

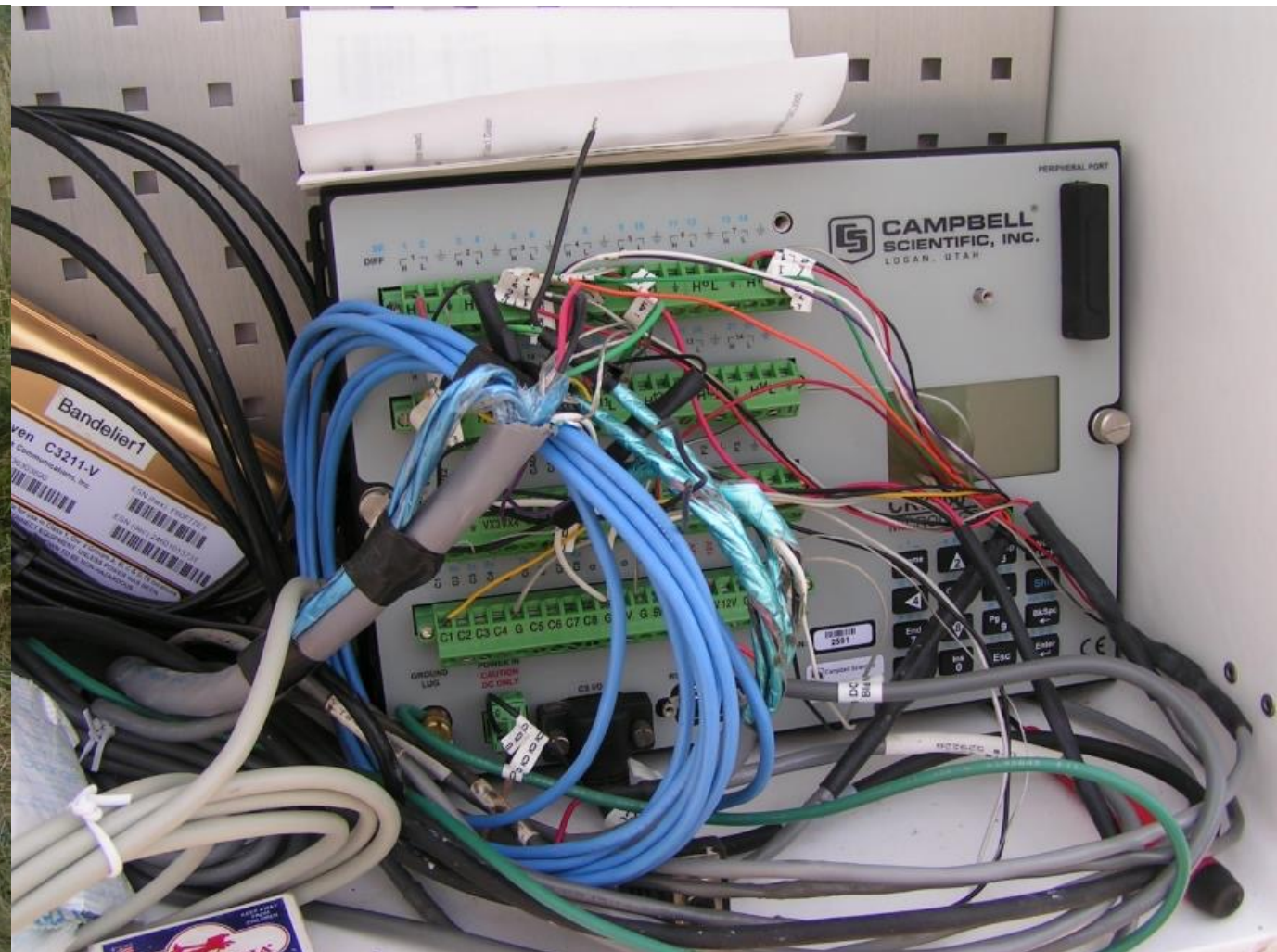
- Refill the hole with the dirt that came out of it.
- About every 30cm/12”, pack the soil down with a piece of wood. Be careful not to knock the cable or the probe because it will dislodge the probe from its spot.





# LOGGER STATION

Coil unused cable with zip ties.



# OTHER CONSIDERATIONS AND TROUBLESHOOTING

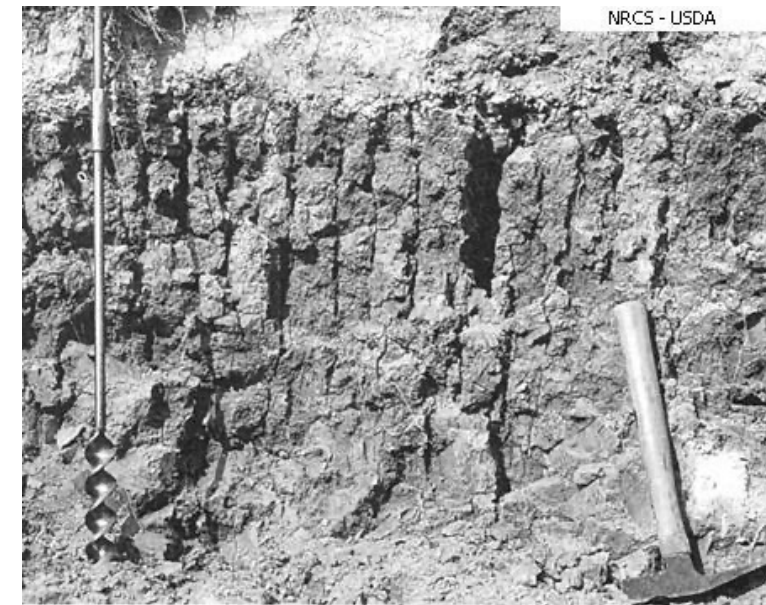
- Peds
- Hardpans, aquitards and perched water
- Bioturbation
- Capillary rise



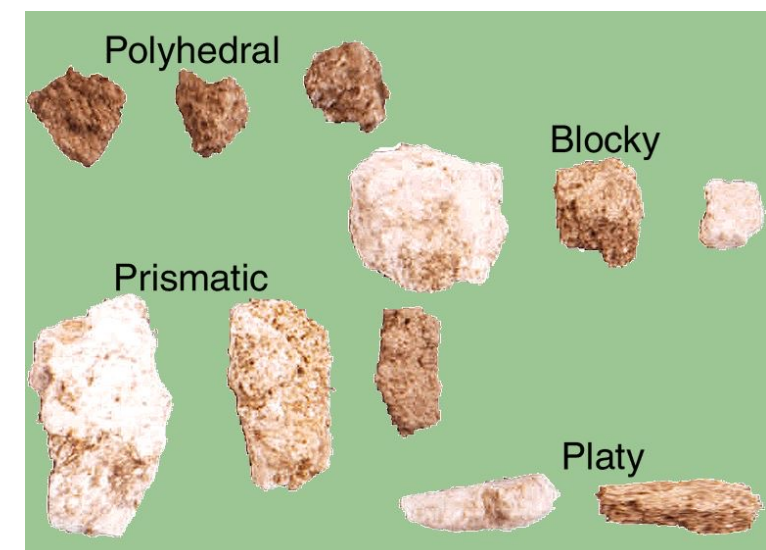


# PEDS AND PEDOLOGY

- A ped is a unit structure of soil that forms from wetting and drying events.
- A ped defines the water flow path.
- Ped wetting: the soil wets up around the ped and the tines may be going through 2 peds.



Prismatic Structure - prisms are 35 to 45 mm across.



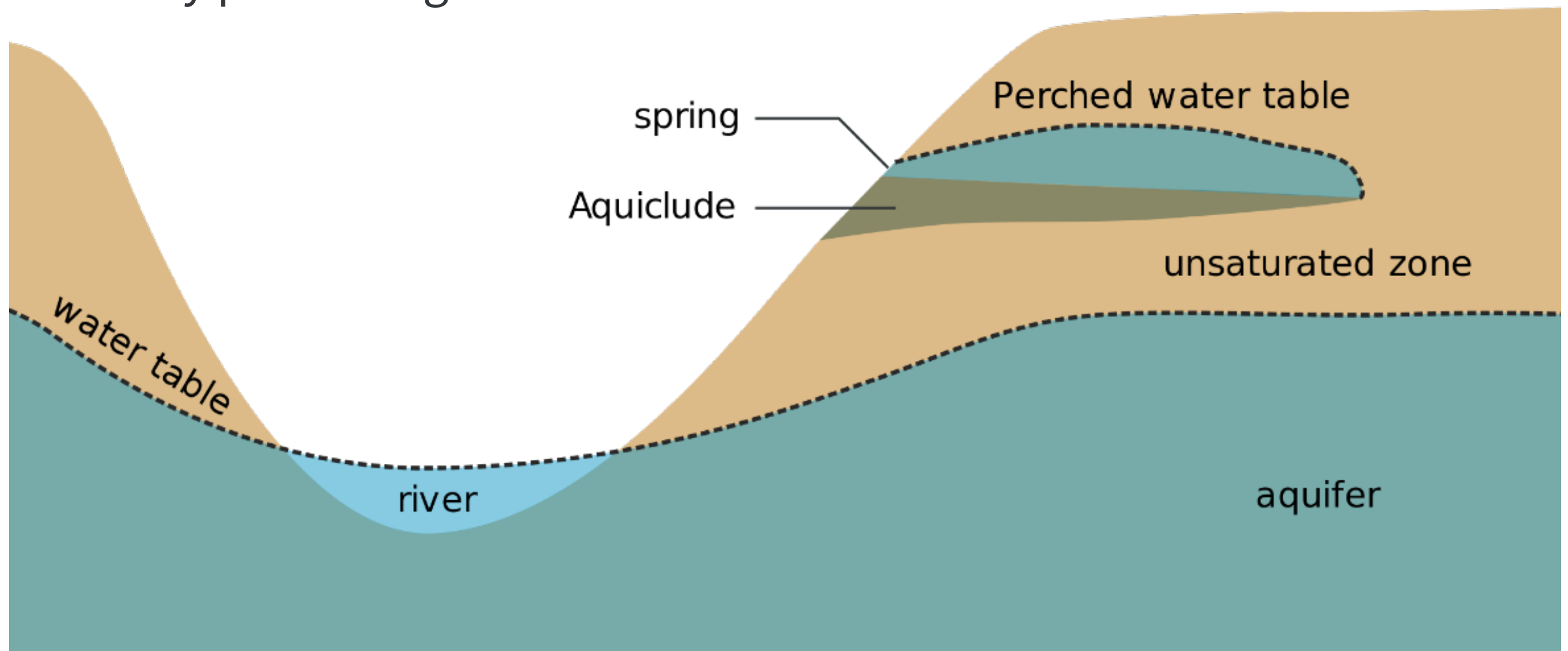
# VERTISOLS AND SMECTITES AND SHRINK-SWELL CLAYS

- You could be seeing a preferential pathway of water.
- You could be seeing a wetting front
- Make sure the tine assembly is in the ped.



# HARDPANS, AQUITARDSS AND PERCHED WATER

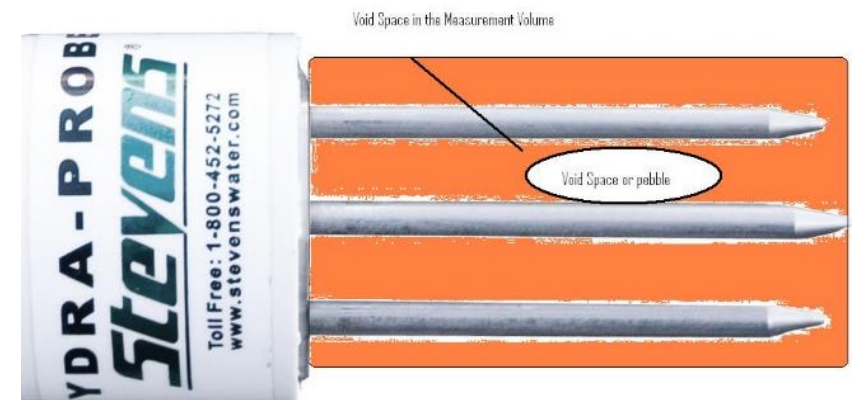
- There could be perched water in the soil column.
- Hard pans will stop water flow.
- The surface can be compacted locally preventing infiltration.
- A fragipan be very dense not allowing much water to infiltrate.
- Bulk density affect water holding capacities





# BIOTURBATION

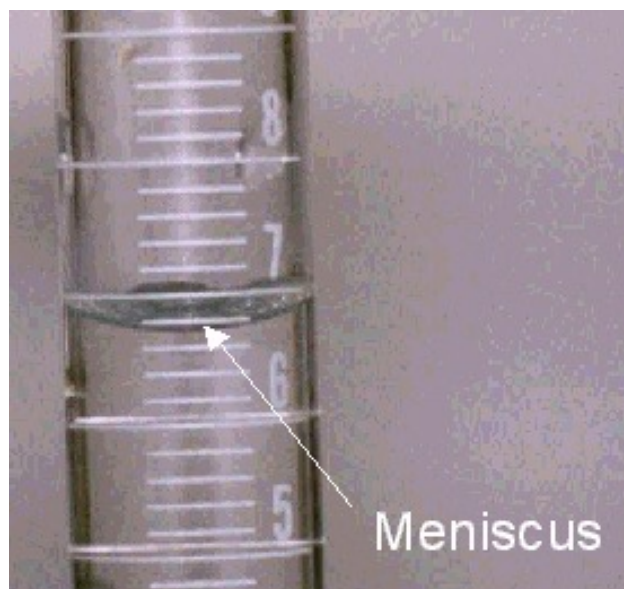
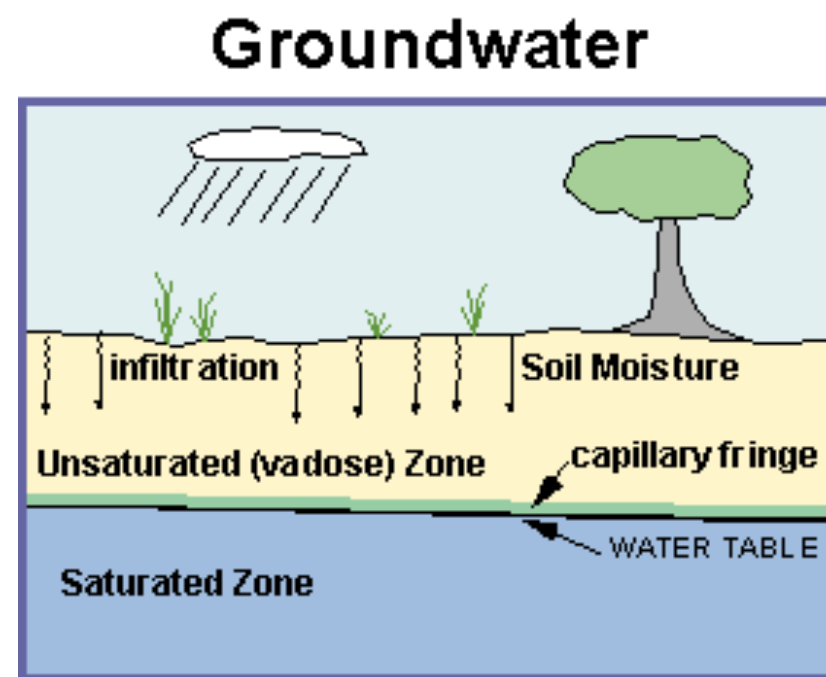
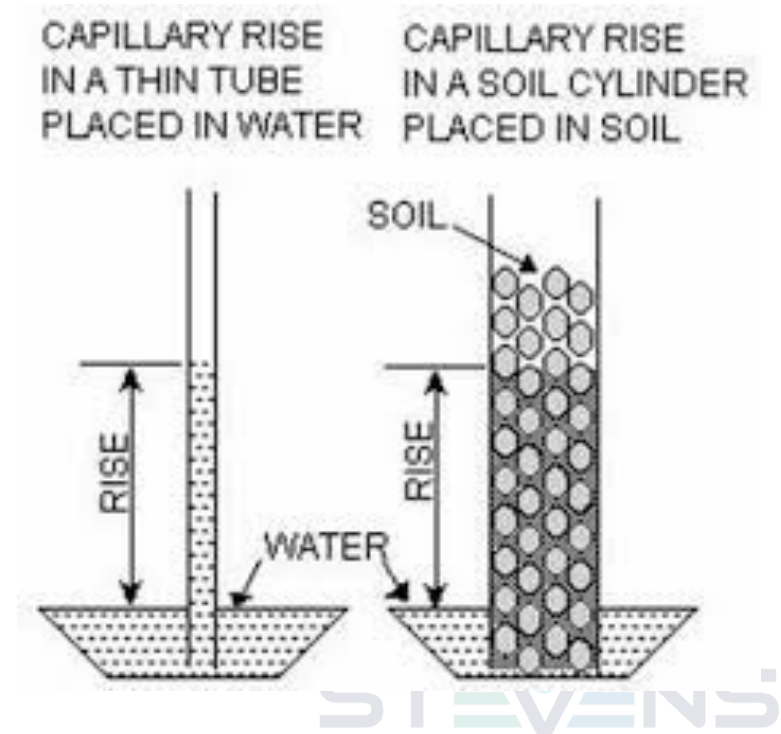
- Tree roots and burrowing animals.
- You may need to dig the probe up and relocate it.
- Frozen conditions.





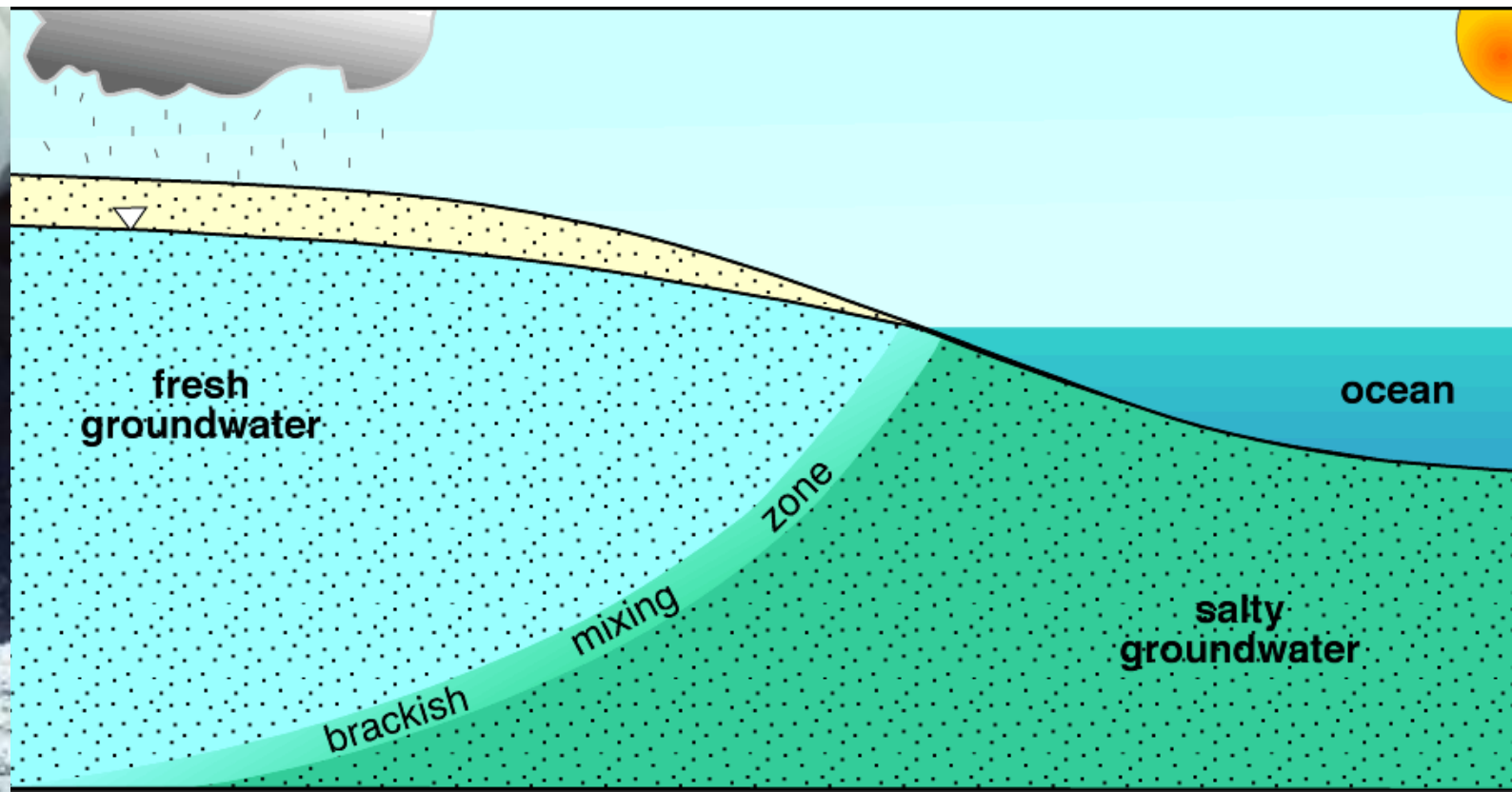
# CAPILLARY RISE AND CAPILLARY FORCES AND MATRIC POTENTIAL

- Capillary forces will draw ground water up above the water table.
- The matric potential is how much pressure it takes to pull water out of soil.
- Capillary forces are the forces that hold water in the soil and distribute water throughout soil.



# SALINITY

- High Salinity may generate errors.
  - Poor quality irrigation water
  - Poor drainage
  - Seawater intrusion



# WHAT IF THE PROBE IS NON-RESPONSIVE?

- Check the wiring
- Check the address and the SDI-12 bus
- Check the power on the bus
- Put a volt meter in milliamp mode in series with the SDI-12 bus. SDI-12 sensors in general will draw 1mA idle.
- Try to communicate with the sensor by itself on the bus in an SDI-12 transparent mode.
- Verify SDI-12 communication with a second SDI-12 host.

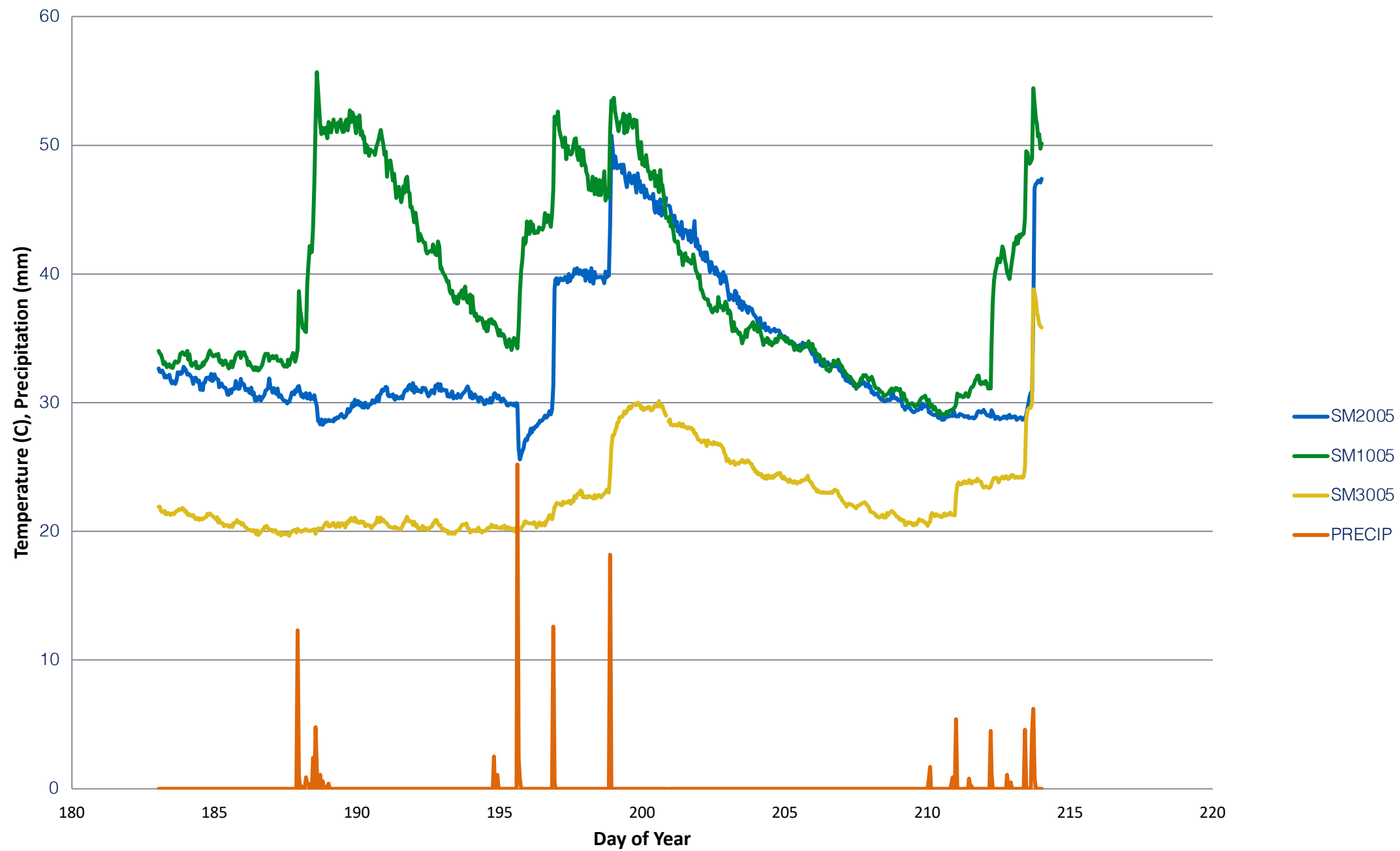


# HOW TO INTERPRET SOIL MOISTURE DATA

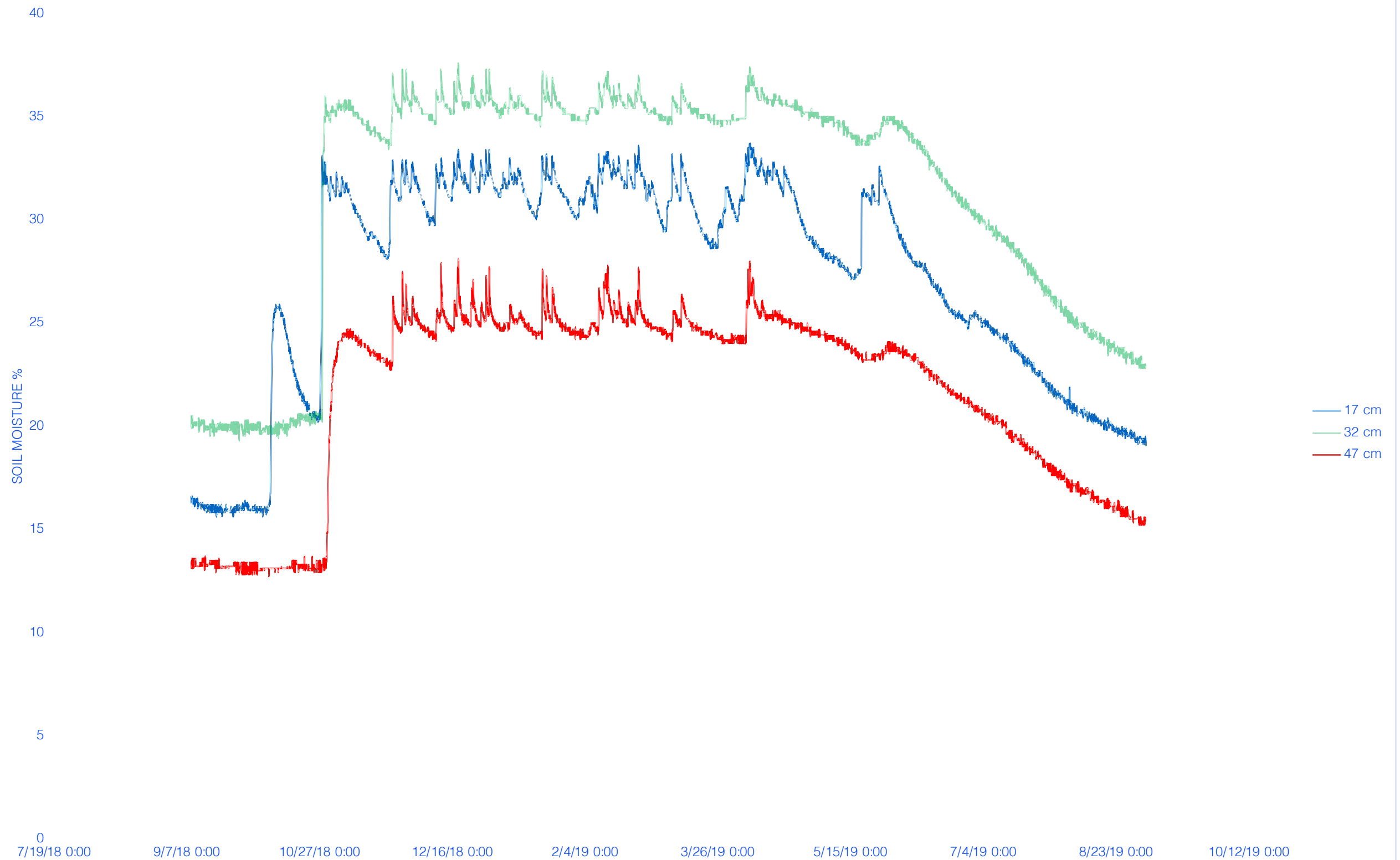




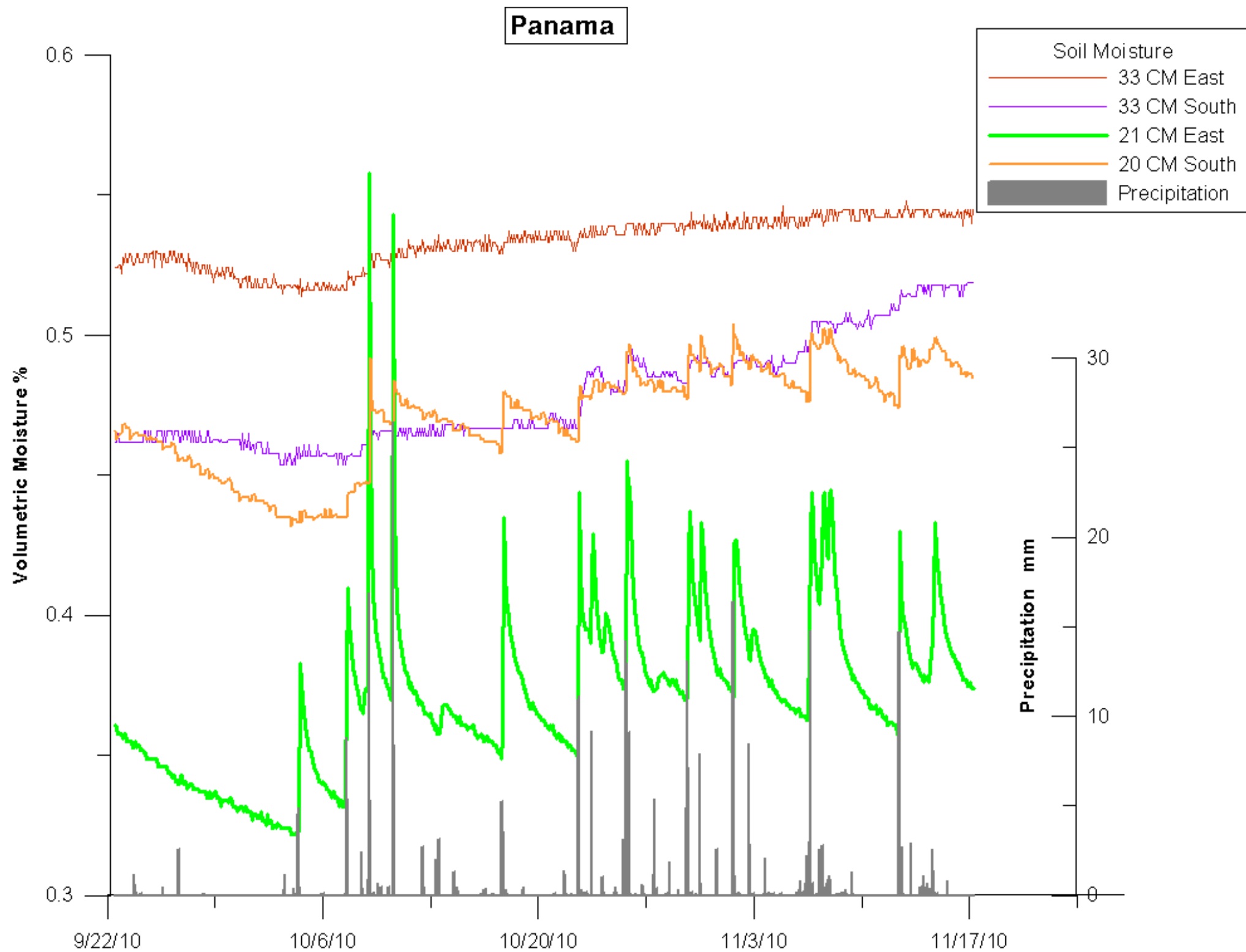
## Precipitation and Moisture



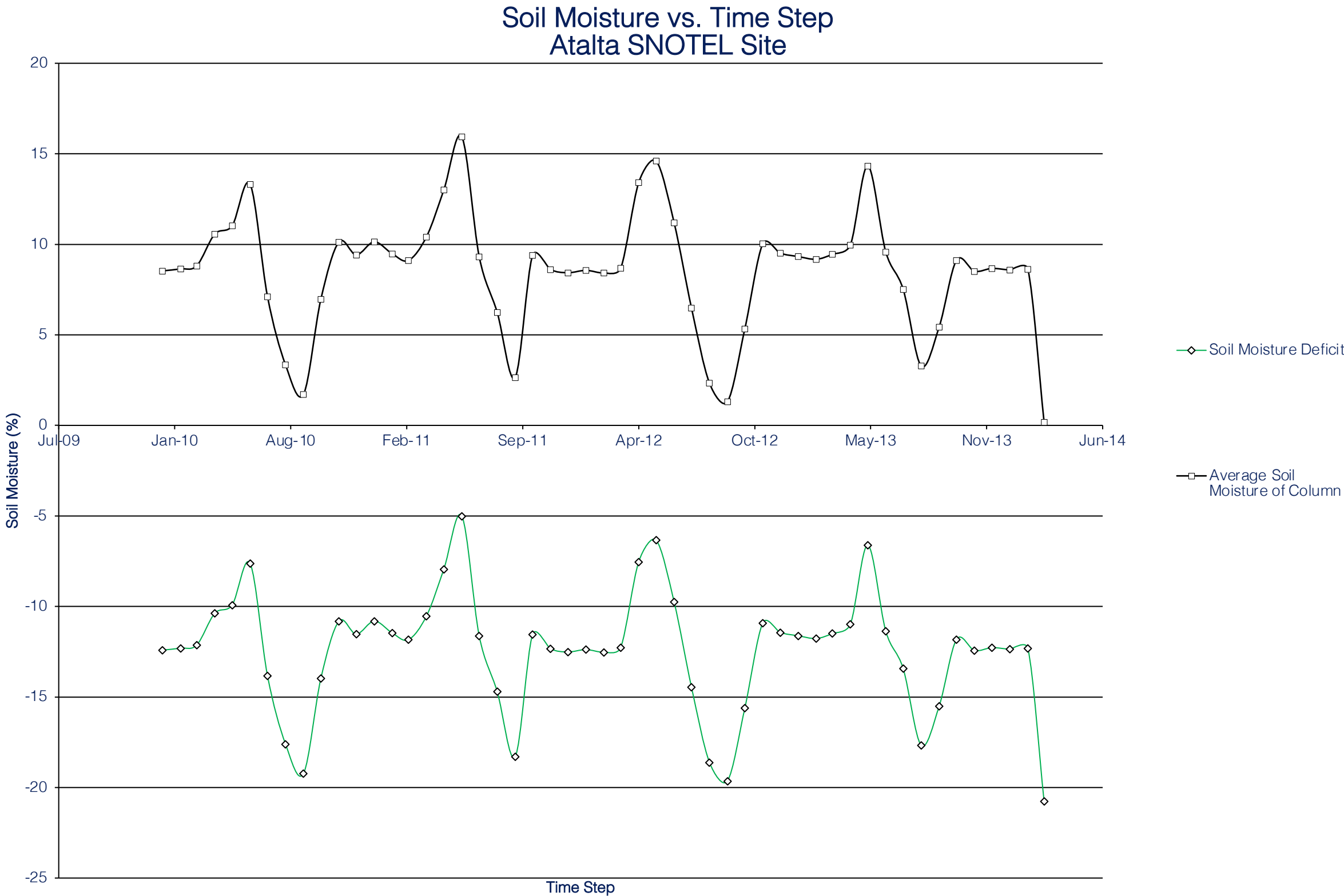
## Steven Test Site 11



# DIFFERENCE BETWEEN A CLAY AND SAND

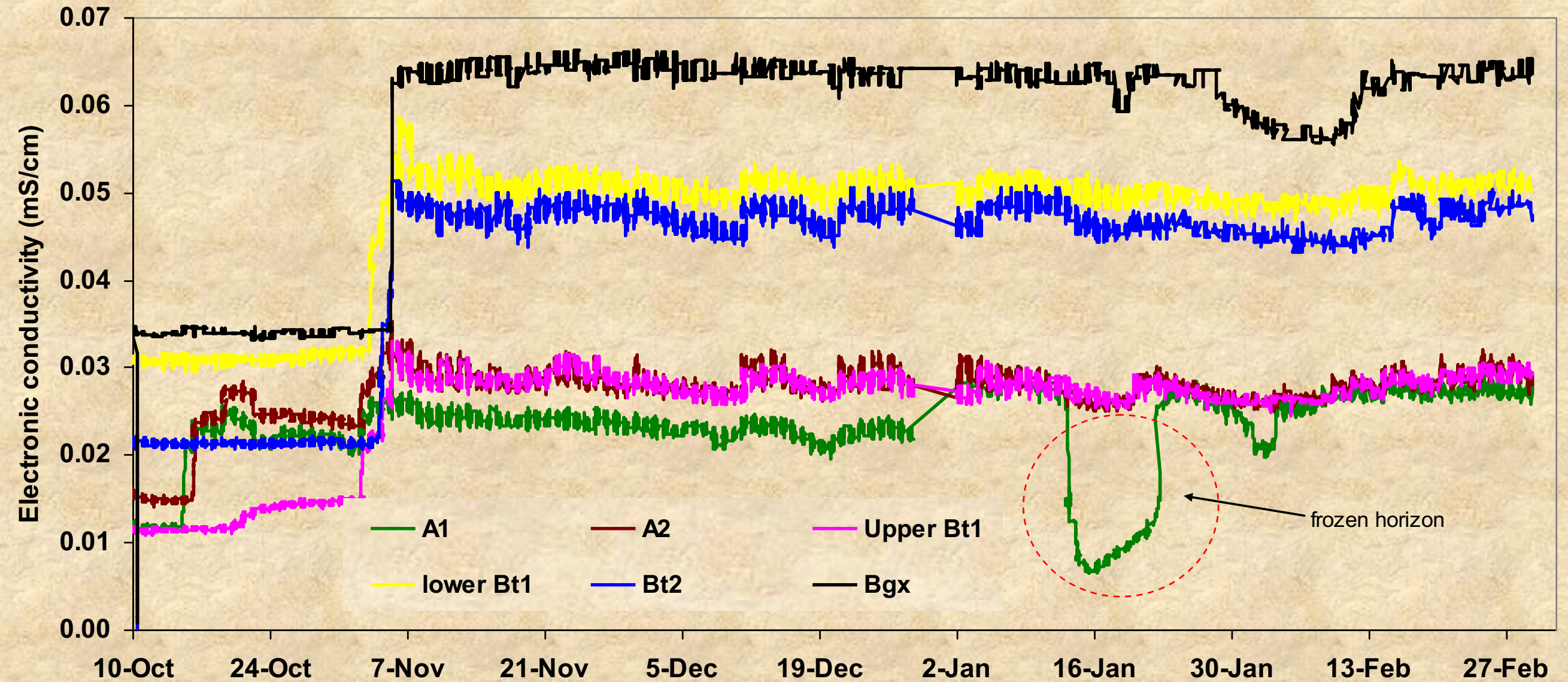


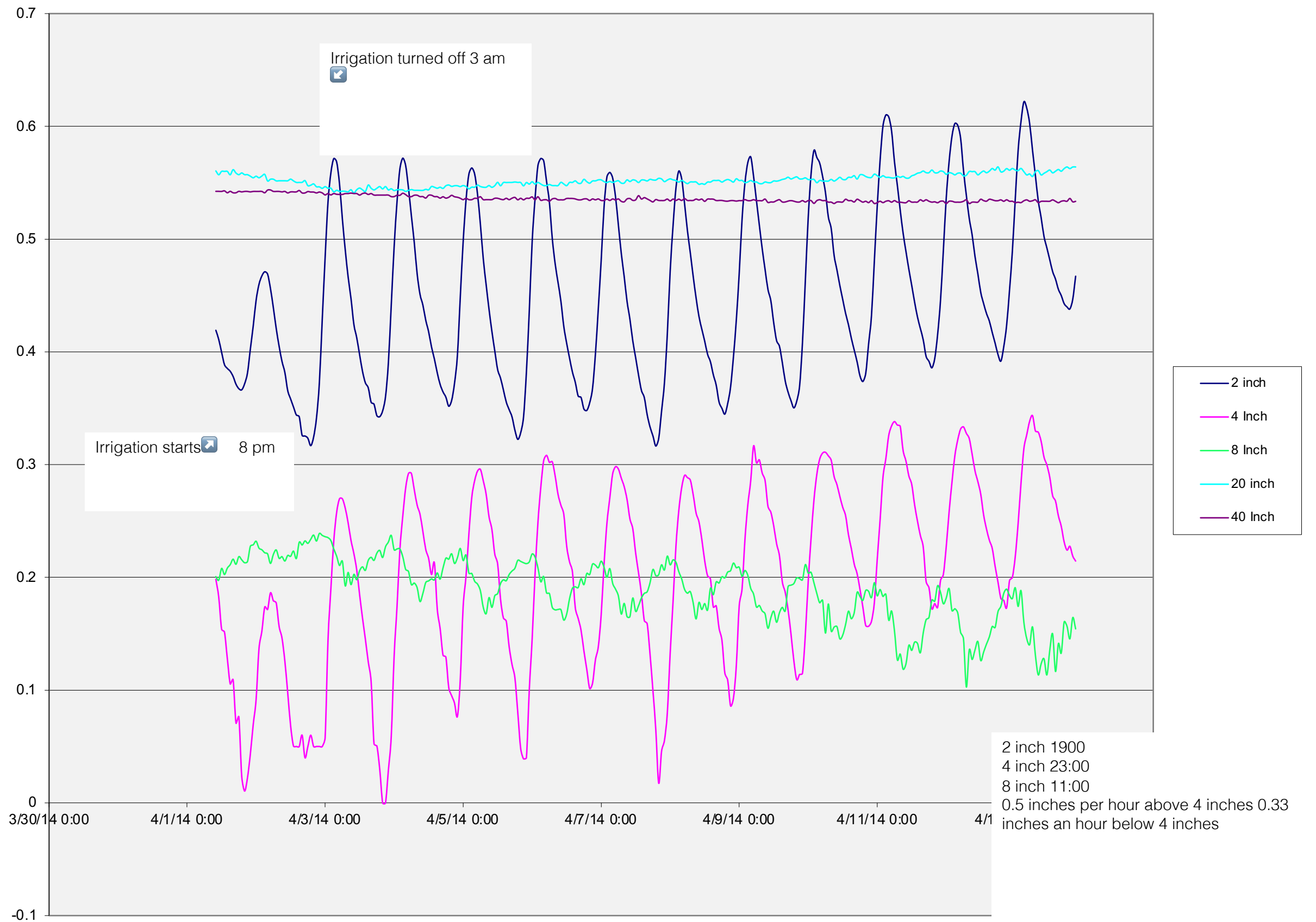
# UNDER HEAVY SNOW PACK



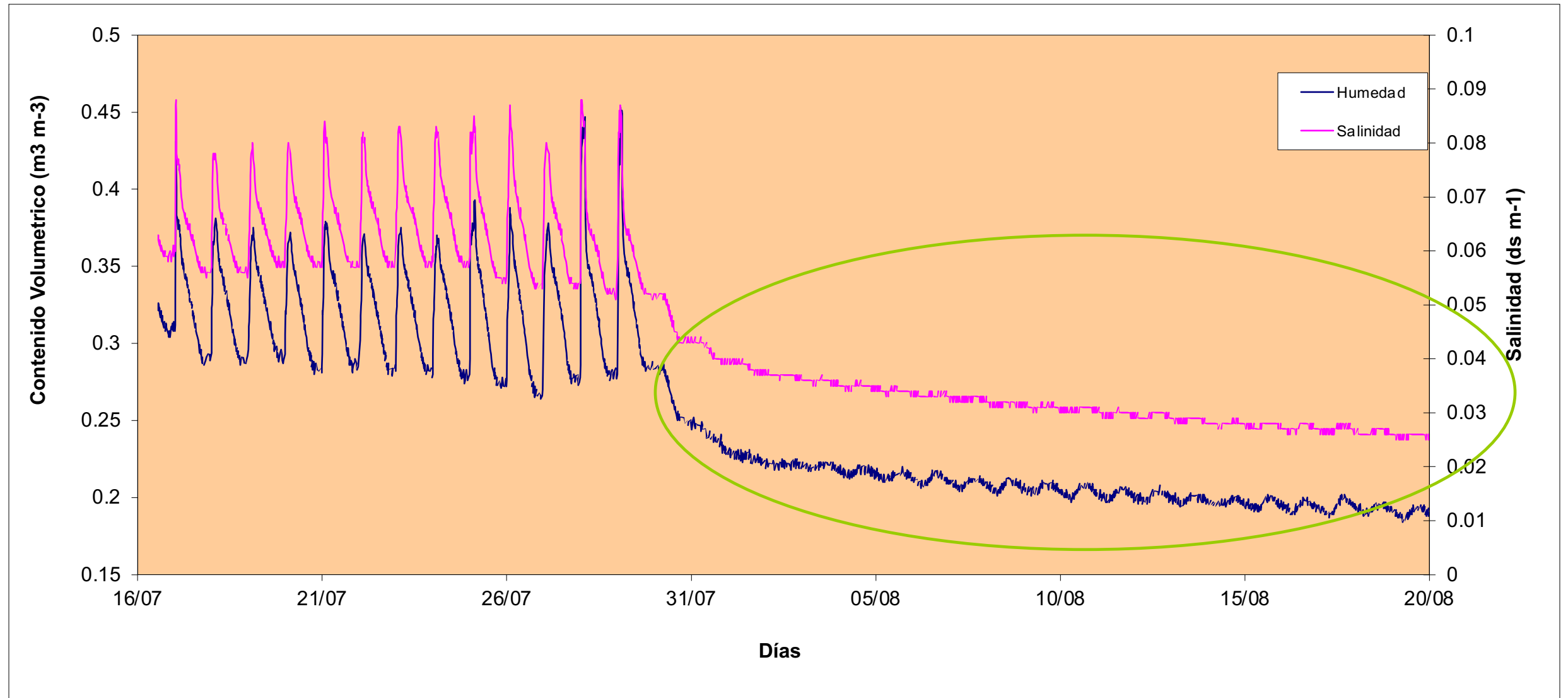


## Calvary Cemetery Soil Conductivity Variation





# SALINITY AND SOIL MOISTURE



# LIGHTNING PROTECTION





# LIGHTNING PROTECTION

- Lightning is the leading cause of issues with electronics in the field
- If you have soil sensors, it is important to surge-protect the station above ground and below ground.



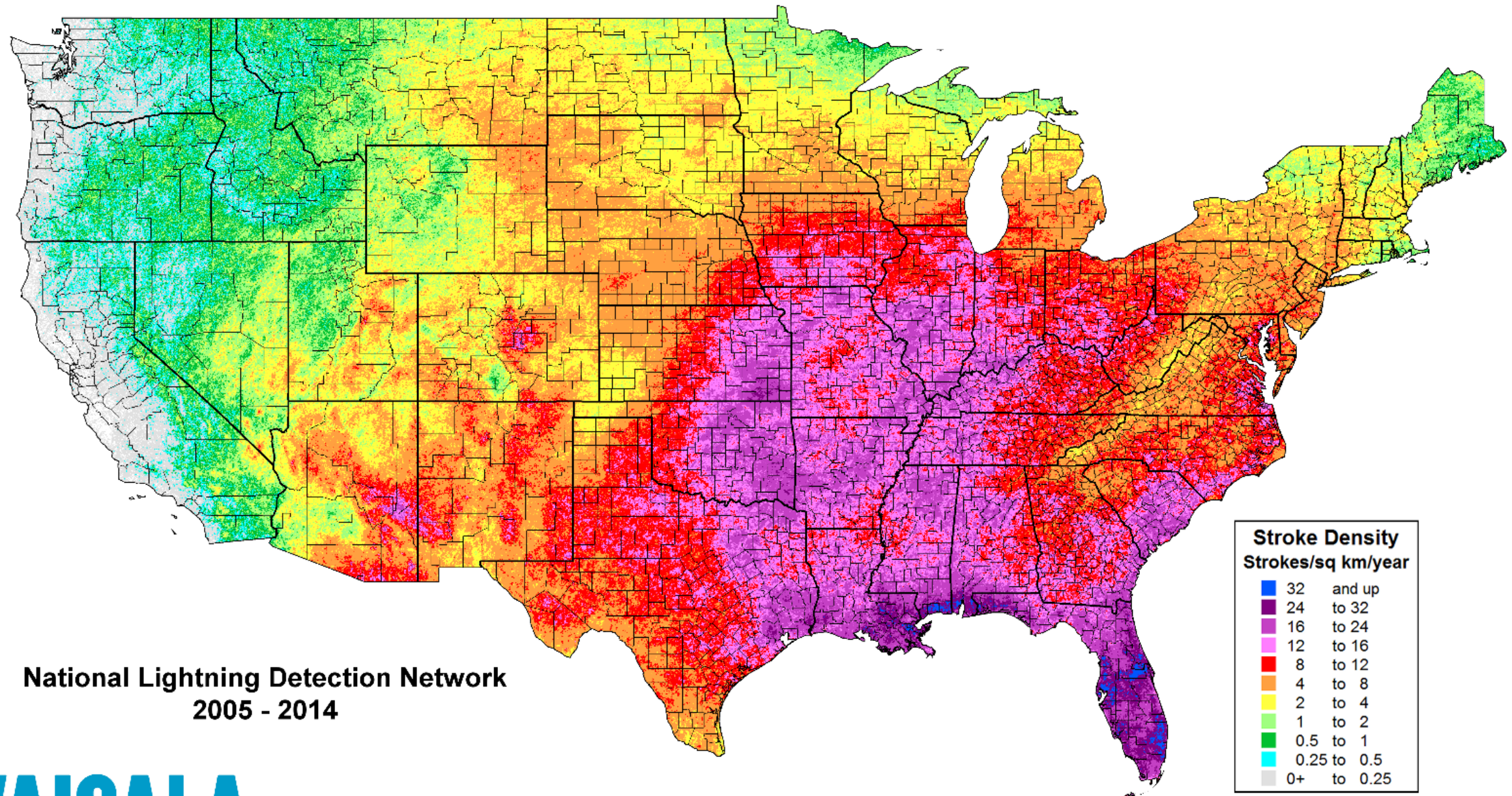
# LIGHTNING FACTS

- The average bolt of lightning in the air is 3 km in length.
- It last on average 30  $\mu\text{s}$ .
- $10^{13}$  watts.
- Average temperature is 25,000 degrees C
- A transient voltage surge or earth current transient can travel up to 75 km in soil.





# LIGHTNING OCCURRENCE IS REGIONAL



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**STEVENS**



# LIGHTNING PROTECTION

| Substance            | Resistance Ohm-Meter |
|----------------------|----------------------|
| Sea Water            | 1 to 2               |
| Clay                 | 3 to 160             |
| Loam                 | 10 to 1350           |
| Shale                | 100 to 500           |
| Sand                 | 90 to 800            |
| Non Crystalline Rock | 500 to 10,000        |

The more conductive the soil the higher the risk of damage from a surge.

Clay is generally more conductive than sand because clay can hold charge conducting ions. Probes in clay are at greater risk of damage than other soil types. In many soil morphologies, the clay content increases with depth. Soil sensors that are deeper in the ground are more susceptible to damage because the soil can be wetter, more saline, and a higher clay content.





# LIGHTNING PROTECTION

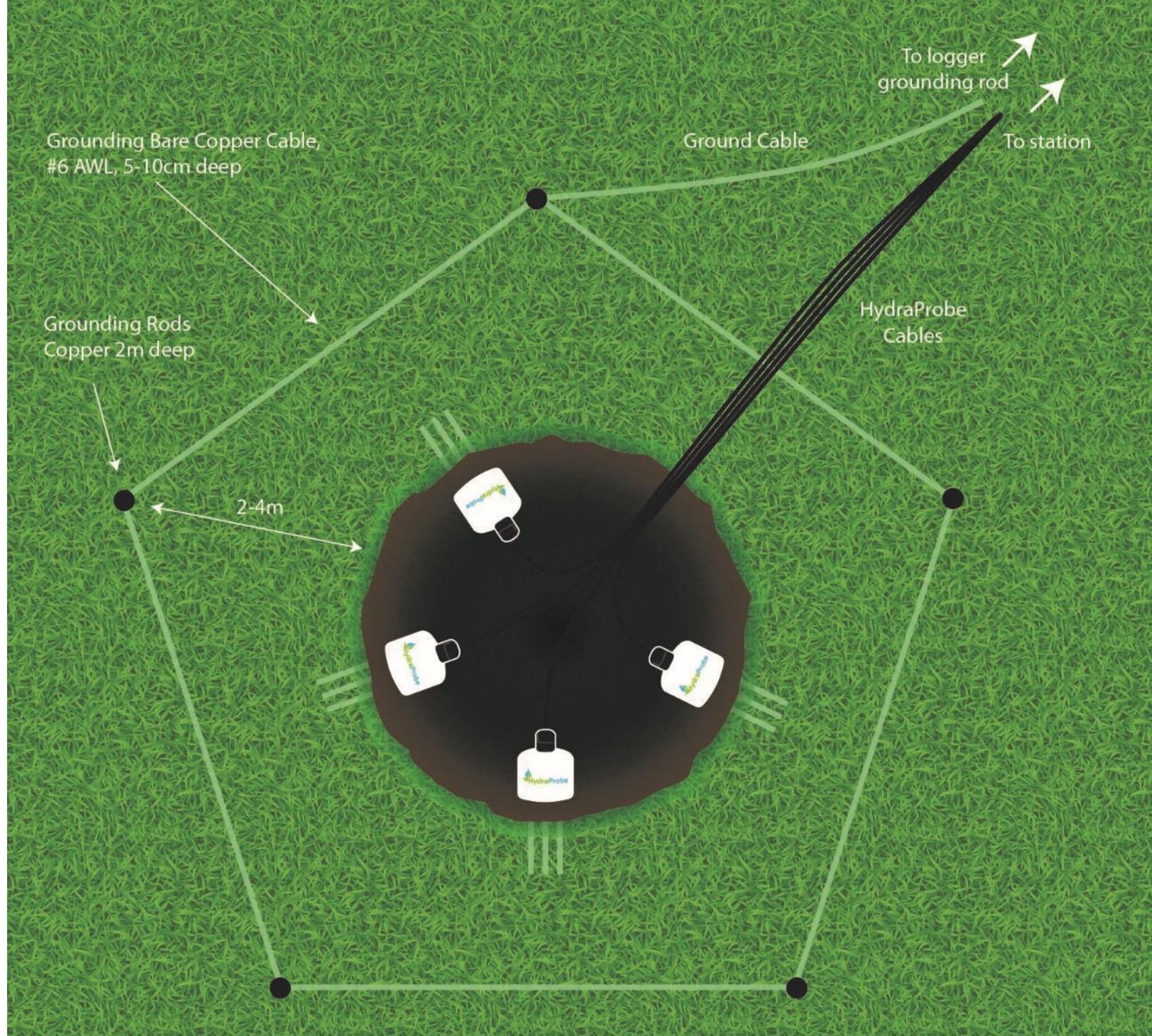
- While protecting the logger station above ground is important, you also need to protect below ground.
- Most soil probes that sustain damages, are damaged through the tines underground.
- The deepest probes are the ones that are most at risk.
- Surges will always take the path of least resistance. The path of least resistance is the sensor's metal tine assembly.
- The lightning that damages most soil sensors is not local but happened far away. It is the propagation of the surge through the ground that enters the tine assembly where it then damages the circuit board of the soil sensor.
- The Hydra Probe is surge protected up to 4000 volts.



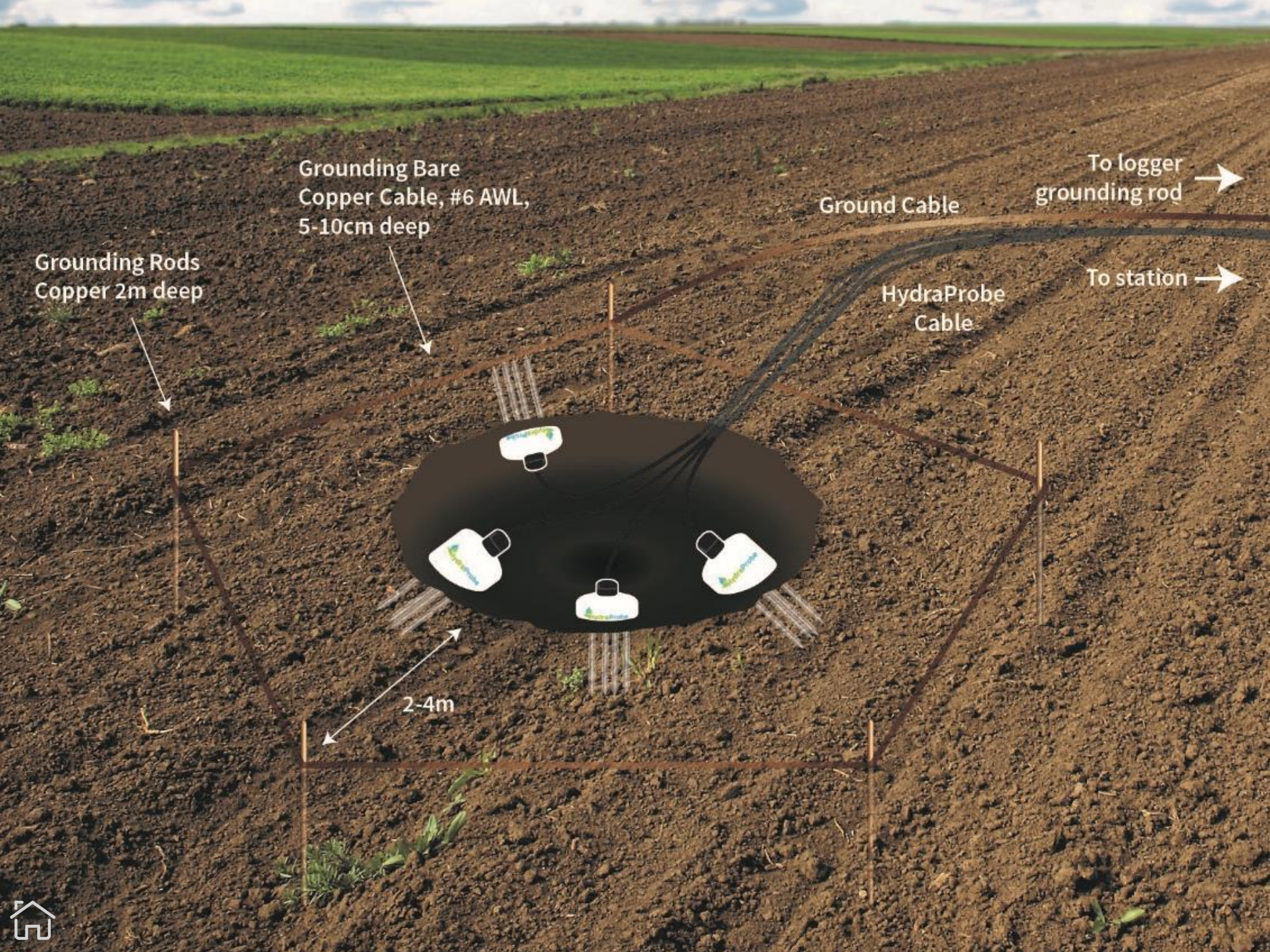


- Dual Dissipator (Stevens Part number 92673) can be clamped to the top of a mass and grounded to the main grounding rod.
- Use automotive hose clamps to make a good electrical connection between the copper cables and ground rods. For best results, use multiple clamps to secure connection.









Grounding Bare  
Copper Cable, #6 AWL,  
5-10cm deep

Grounding Rods  
Copper 2m deep

Ground Cable

To logger  
grounding rod

HydraProbe  
Cable

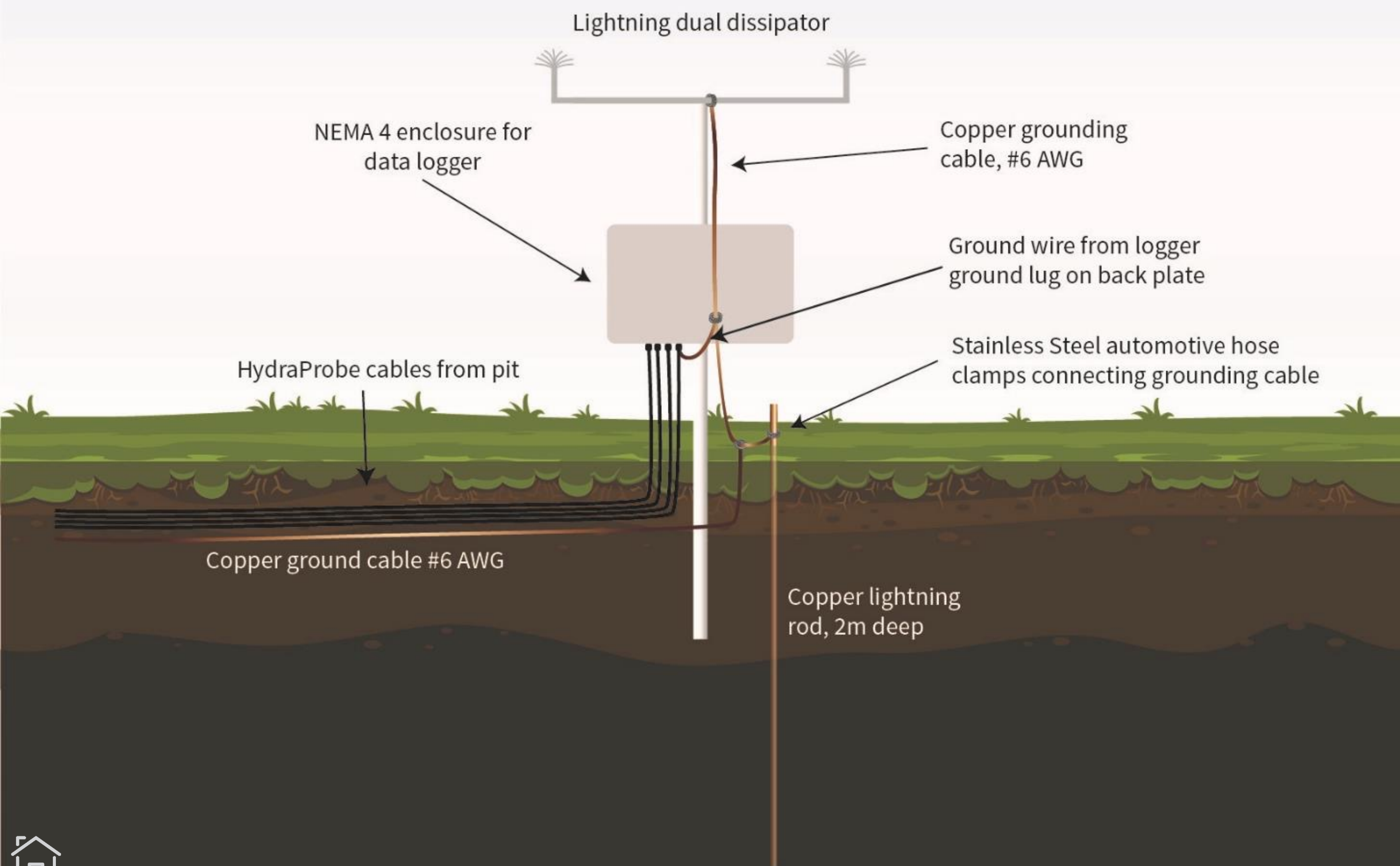
To station

2-4m





# LOGGER STATION GROUNDING



# GROUNDING THE LOGGER STATION

- Electrically connect the grounding lug on the logger to the metal back plate inside the enclosure then run a ground wire out of the box and connect it to the grounding rod.
- Use two automotive hose clamps to secure the grounding cable to the rods.
- Use dual dissipators and ground them to the rod.
- The grounding rod should be pounded 2 meters deep.





**Fluke 1625**

**FLUKE**



**Earth Ground Tester**





IN CONCLUSION



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Thank You

