METER

SOIL ELECTRICAL CONDUCTIVITY: A BEGINNER'S GUIDE TO MEASUREMENTS

WHY MEASURE EC?

Irrigated land accounts for 40% of our food supply, and salts impact yields on approximately one fifth of those acres. All irrigation water contains at least some salt. If salts are allowed to build up around the root zone of a crop, they injure plants, reduce yields, and even change soil structure causing long term damage to the land itself. In order to preserve the productivity of irrigated land, it is important to understand how to manage salts.

The steps to managing salts are:

- Measure how much salt is currently in the soil
- Determine how much salt is added through irrigation
- Monitor continuously during irrigation to manage salts

Electrical Conductivity (EC) is the key to making these measurements. Pure water does not conduct electricity, but most water, even tap water, has enough dissolved salts to be conductive. Because the concentration of salts in water directly affects its conductivity, the measurement of electrical conductivity is a very effective way of measuring salt concentrations in soil water.

SALT AND PLANTS: WHAT'S THE PROBLEM?

Most people have had the experience of fertilizing too heavily, perhaps by accident, and killing grass or other plants. It is often said that the fertilizer has "burned" the plants, but generally it isn't the nutrients themselves that cause the damage. It's often their effect on water. Plants take up water, but they don't take up salts in any appreciable quantity. When salt is added to the soil through fertilization and irrigation, it becomes concentrated there.

CROP SALT SENSITIVITY	MODERATELY TOLERANT	HIGHLY TOLERANT
RED CLOVER	WHEAT	DATE PALM
PEA	TOMATO	BARLEY
BEAN	OAT	SUGAR BEET
PEAR	ALFALFA	COTTON
ORANGE	POTATO	SPINACH

Table taken from Campbell, Gaylon. 2013. Virtual Seminar: Making Soil EC measurements more meaningful.

Salt may cause a variety of problems for plants. For instance, Na^+ may reach concentrations that are toxic to plants. Salt also attracts water and makes it more difficult for plants to take up water from the soil. Some plants are more sensitive than others to salt in the soil. Bean yield will be affected if soil saturation extract EC exceeds 2 dS/m, for example, while barley can be grown without yield reduction in soil saturation extract up to 16 dS/m. Ultimately, however, high salt content will affect all plants.

COMMON UNITS FOR EC

The SI unit for electrical conductance is the Siemen, so electrical conductivity has units of S/m. Units used in older literature are mho/cm (mho is the reciprocal of ohm). Soil EC was commonly reported in mmho/cm. 1 mmho/cm

METER Group, Inc. USA
2365 NE Hopkins Court, Pullman, WA 99163
T 509.332.2756 **F** 509.332.5158
E info@metergroup.com **W** metergroup.com

equals 1 mS/cm, but because SI discourages the use of submultiples in the denominator, this unit is changed to deciSiemen per meter (dS/m), which is numerically equivalent to mmho/cm or mS/cm

- Electrical resistance – ohm
- Conductance = 1/ohm
- mho – now siemens
- Old units – mmho/cm
- Modern units – ms/cm or dS/m

SALINITY CLASSES FOR SOILS

USDA CLASS	SATURATION EXTRACT	SALT IN SOIL (g SALT/100g SOIL)	OSMOTIC POTENTIAL (kPa)	CROP TOLERANCE	EXAMPLE CROPS
A	0-2	0-0.13	0 to -70	SENSITIVE	BEAN
B	2-4	0.13-0.26	-70 to -140	MODERATELY SENSITIVE	CORN
C	4-8	0.26-0.51	-140 to -280	MODERATELY SENSITIVE	WHEAT
D	8-16	0.51-1.02	-280 to -560	TOLERANT	BARLEY

Richards, L.A. (Ed). 1954. Diagnosis and Improvement of Saline and Improvement of Saline and Alkali Soils, USDA AG Handbook 60, Washington DC.

MORE THAN ONE WAY TO MEASURE EC

There are three ways to measure EC in soils: measuring pore water EC, bulk EC, or saturation extract EC. All three are related, but there are tools to convert one into the other. In order to understand measurement data, it is important to know what type of EC is being measured.

PORE WATER EC: WHAT MANY RESEARCHERS ASSUME THEY'RE MEASURING

Pore water EC or soil water EC (σ_w) is the electrical conductivity of the water in the soil pores. Researchers often mistake the value coming out of a soil EC sensor for pore water EC. It would be ideal to simply measure the electrical conductivity of pore water in situ. Try to imagine how this would work, however. Tiny sensors would have to be inserted into microscopic water-filled pores. Obviously, it's not possible to measure the EC of water on that scale. In fact, the only way to measure pore water EC is by extracting a soil water sample and measuring the EC of that sample.

BULK EC

Bulk EC (σ_b) is the electrical conductivity of the bulk soil (soil, water, and air). Sensors installed into the soil all measure bulk EC. Empirical or theoretical equations can be used to determine pore water EC and saturation extract EC (σ_e) from measured bulk EC values. Bulk EC is the only EC measure that can be continuously monitored in situ.

SATURATION EXTRACT EC: THE TRADITIONAL METHOD

Saturation extract EC (σ_e) tells exactly how much salt is in the soil and can be converted to soil salinity. This is the traditional way to measure EC. It is measured by taking a soil sample, making a saturated paste of soil and deionized water, extracting the water, and then measuring the EC of the extracted solution. Published EC values reported in the literature are almost always saturation extract EC.

CONVERTING BULK EC TO PORE WATER EC

As stated previously, in situ sensors measure the electrical conductivity of the bulk soil surrounding the sensors (σ_b). A considerable amount of research has been conducted to determine the relationship between σ_b and the conductivity of the pore water (σ_w). Recent work by Hilhorst (2000) has taken advantage of the linear relationship between the soil bulk dielectric permittivity (ε_b) and σ_P to allow conversion from σ_b to σ_w if ε_b is known. The GS3, TEROS 12 and 5TE sensors measure ε_b and σ_b nearly simultaneously in the same soil volume. They are well-suited to this method. The pore water conductivity can be determined from (see Hilhorst, 2000 for derivation)

$$\sigma_\omega = \frac{\varepsilon_\omega \sigma_b}{\varepsilon_b - \varepsilon_{\sigma_{b=0}}}$$ **Equation 1**

where σ_w is the pore water electrical conductivity (dS/m); σ_w is the real portion of the dielectric permittivity of the soil pore water (unitless); σ_b is the bulk electrical conductivity, (dS/m), which is measured directly by the sensor; ε_b is the real portion of the dielectric permittivity of the bulk soil (unitless); $\varepsilon_{wb=0}$ is the real portion of the dielectric permittivity when σ_b = 0 (unitless). ε_w (2) has a value of around 80. A more accurate value can be calculated from soil temperature using

$$\varepsilon_\omega = 80.3 - 0.37 \times (T_{soil} - 20)$$ **Equation 2**

where T_{soil} is the soil temperature (°C) measured by a temperature sensor co-located with the bulk EC measurement, as is common with METER soil EC sensors.

ε_b is also measured by most research-grade volumetric water content sensors.

Finally, $\epsilon_{\sigma_{b=0}}$ is an offset term loosely representing the dielectric permittivity of the soil when the EC=0. Hilhorst (2000) recommended that $\epsilon_{\sigma_{b=0}}$ = 4.1 be used as a generic offset. Hilhorst (2000) offers a simple and easy method for determining $\epsilon_{\sigma_{b=0}}$ for individual soil types, which will improve the accuracy of the calculation of σ_w in most cases.

Our testing indicates that the above method for calculating σ_w results in good accuracy (± 20%) in soils and other growth media at high water content. As water content decreases, the denominator of equation 1 becomes small, leading to large potential errors in the calculation. For best results, we recommend using the Hilhorst equation when water content is high to obtain saturation extract EC (σ_e) and then computing the pore water EC at lower water content assuming that the salt stays in the soil while the water is being removed (shown in equation 3). Using this assumption

$$\sigma_w = \sigma_e \left(\frac{\theta_s}{\theta} \right)$$ **Equation 3**

where θ is the volumetric water content of the soil and θ_s is the water content at saturation, which can be computed from the bulk density of the soil

$$\theta_s = 1 - \left(\frac{\rho_b}{\rho_s} \right)$$ **Equation 4**

b is the bulk density of the soil (Mg/m^3) and s is the density of solids (2.65 Mg/m^3 for mineral soil).

CONVERSION OF PORE WATER EC TO SATURATION EXTRACT EC

EC of the saturation extract (often shown as EC_e or σ_e) is the electrical conductivity of pore water removed from a saturated paste of the soil. The soil is wetted with distilled water until the soil saturates, then the soil is placed on filter paper in a vacuum funnel and suction is applied. An electrical conductivity measurement on the water removed from the sample will give EC_e. The EC_e of a soil is the value used for almost all salinity recommendations (see, for example, Richards, 1954) and is therefore an important value to obtain. It can be computed from the pore water EC using the following equation

$$\sigma_e = \sigma_w \left(\frac{\theta}{\theta_s} \right)$$ **Equation 5**

Combining equations 1 and 4 give

$$\sigma_e = \frac{80 \theta \sigma_b}{\theta_s (\varepsilon_b - 4.1)}$$ **Equation 6**

Equation 6 is likely to be the most useful equation for assessing salinity in the field. Again, use it when water contents are highest to maximize accuracy.

As an example, assume the bulk density of our soil is 1.33 mg/m^3. From equation 4 this would give a saturation water content of 1 – 1.33/2.65 = 0.5. Assume we have measured a bulk EC of 0.3 dS/m when the water content is 0.345 m^3/ m^3, and ε_b = 20. The EC_e would be

$$\sigma_e = \frac{80 * 0.345 * 0.3}{0.5(20 - 4.1)} = 1.04 dS/m \qquad \textbf{Equation 7}$$

CALCULATING PORE WATER EC FROM BULK EC

Calculating pore water EC from bulk EC is not the same as converting from one set of units to another—it's actually a model. Or rather, it's many different types of models. Some are empirical, some are theoretical, but all have their own strengths and weaknesses. We've presented the Hillhorst model, but there are other popular models, including the Rhodes model and the Mualem and Friedman model.

	SATURATION EXTRACT EC	SOIL BULK EC	PORE WATER EC
DEFINITION	THE ELECTRICAL CONDUCTIVITY OF A SOLUTION OF WATER EXTRACTED FROM A SATURATED SOIL SAMPLE.	THE COMBINED ELECTRICAL CONDUCTIVITY OF THE SOIL, AIR AND WATER IN POROUS SOIL SUBSTRATE.	THE ELECTRICAL CONDUCTIVITY OF THE SOLUTION CONTAINED IN THE SOIL PORES.
APPLICATIONS	FIELD AGRICULTURE APPLICATIONS FOR SALT MANAGEMENT.	ANY TIME CONTINUOS MEASURMENTS ARE NEEDED, USED FOR CALCULATING PORE WATER AND SATURATION EXTRACT EC.	GREENHOUSE AND NURSERY APPLICATIONS, LEACHING FRACTION CALCULATIONS.
BENEFITS	QUANTITATIVE MEASURE OF THE AMOUNT OF SALTS IN THE SOIL (SOIL SALINITY) BEST MEASURE FOR DETERMINING CROP SUITABILITY FOR A PARTICULAR SOIL.	CAN BE MEASURED CONTINUOUSLY WITH AN IN SITU PROBE. VALUE CAN BE USED IN CONJUNCTION WITH COLUMETRIC WATER CONTENT TO MODEL SATURATION EXTRACT EC OR PORE WATER EC.	MEASURES WHAT THE PLANT IS ACTUALLY EXPERIENCING. QUANTIFIES HOW MUCH SALT IS BEING TRANSPORTED BY DRAINAGE WATER.
HOW PARAMETER IS MEASURED *ALL METHODS ASSUME TEMPERA-TURE CORRECTED EC VALUES	A SOIL SAMPLE TAKEN FROM THE FIELD AND MIXED WITH DEIONIZED WATER UNTIL SATURATED. THEN WATER IS EXTRACTED OUT THROUGH A FILTER, AND THE EC AND TEMPERATURE OF THE WATER ARE MEASURED WITH AN EC METER. THE VALUE IS CALCULATED FROM BULK EC AND VWC MEASUREMENTS.	TWO-PROBE OR FOUR-PROBE ELECTRICAL CONDUCTIVITY SENSOR IS PLACED IN THE SOIL AT THE DESIRED DEPTH.	SOIL PORE WATER SAMPLER IS USED TO EXTRACT PORE WATER FROM THE SOIL AT A SPECIFIC DEPTH. AN EC METER IS USED TO MEASURE THE EC OF THE WATER. VALUE IS CALCULATED FROM BULK EC AND VWC MEASUREMENTS.

APPLICATION 1: MINIMIZING SALT BUILDUP

One of the most common reasons for measuring EC in soils is to minimize salt in the root zones of actively-growing plants. If the EC in the root zone becomes too high, a grower can add additional irrigation water to leach salts below the root zone.

The illustration below demonstrates how, on a relative basis, saturation extract values might compare to one another with a lighter color indicating lower saturation extract EC and a darker color indicating higher saturation extract EC.

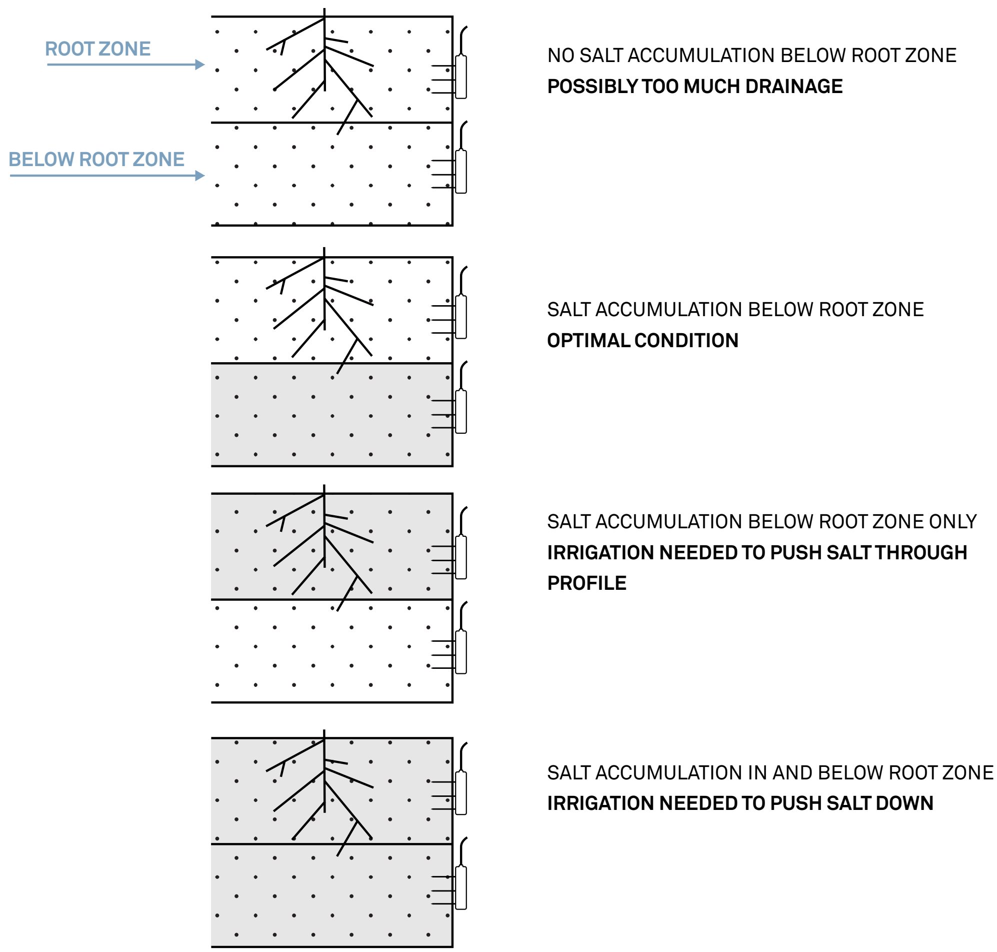


Image taken from Stirzaker, Richard. 2010.

APPLICATION 2: CALCULATING LEACHING FRACTION

Leaching fraction is defined as the depth of water draining out of the bottom of the root zone divided by the depth of water applied (through irrigation and precipitation) to the soil profile.

Use leaching fraction to compute how much water needs to run through the profile to maintain a particular electrical conductivity in the root zone.

$$LF = \frac{EC_{applied}}{EC_{drain}} = \frac{D_{drain}}{D_{applied}}$$

For example, if the EC of liquid irrigation water were 0.3 dS/m, and the water draining past the root zone should have an EC of no more than 3 dS/m, irrigators should run a tenth of the applied water through the profile.

All this assumes, however, that drainage (how much water is draining out the bottom of the root zone) is accurately measured. In practice, this is a very difficult thing to measure. An innovative approach is to turn the leaching fraction equations around and use the EC of the drainage water to calculate deep drainage. The EC of drainage water can be measured by installing probes below the root zone.

Rearranging the equations, depth of drainage water is equal to the depth of water applied, multiplied by the EC of the applied water (precipitation and irrigation), divided by the EC of the drainage water.

$$D_{drain} = D_{appl} * \frac{EC_{appl}}{EC_{drain}}$$

In most areas, rain–which doesn't contain salts–will play a significant role in overall salt balance. A good way to adjust the EC of the applied water for the contribution of rain is to multiply the EC of the applied water times the depth of irrigation and divide by the depth of the rain plus the irrigation

$$'C_a = \frac{D_{rain}EC_{rain} + D_{irrig}EC_{irrig}}{D_{rain} + D_{irrig}} \approx EC_{irrig}\frac{D_{irrig}}{D_{rain} + D_{irrig}}$$

EXAMPLE CALCULATIONS FOR LEACHING FRACTION USING EC MEASUREMENTS

$EC_{irrig} = 0.5$ dS/m, $EC_{drain} =$ dS/m

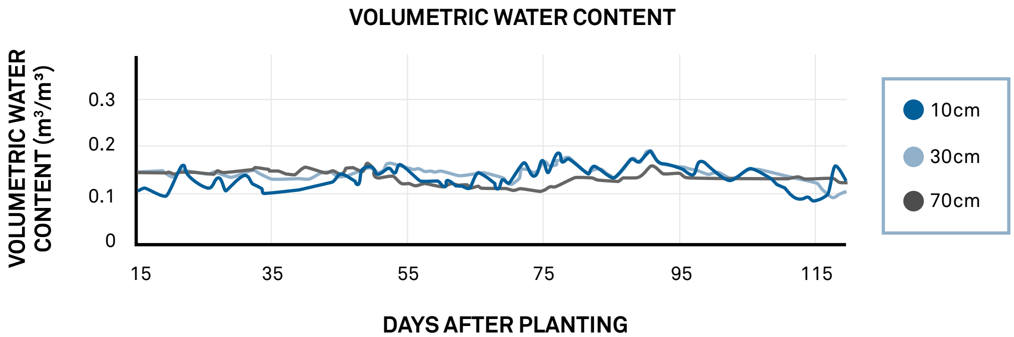
$D_{irrig} = 20$ cm, $D_{drain} = 5$ cm

$$EC_{apple} = EC_{irrig} * \frac{D_{irrig}}{D_{rain} + D_{irrig}} = 0.5 * \frac{20}{5+20} = 0.4 \text{ dS/m}$$

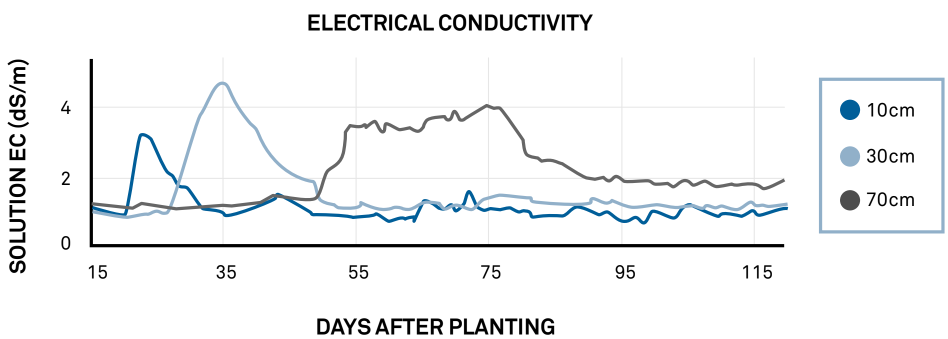
$$D_{rain} = D_{apple} * \frac{EC_{apple}}{EC_{drain}} = 25 * \frac{0.4}{4} = 2.5 \text{ cm}$$

Leaching fraction is 0.4/4 which is 10%
The total water lost from draingage is 2.5 cm

APPLICATION 3: TRACKING NUTRIENTS IN THE ROOT ZONE



The figure above shows soil water content values at three depths over time, immediately following fertilization. But where's the fertilizer? Soil moisture values give no indication of nutrient leaching or drainage.



In this graph, measurements of bulk EC and volumetric water content from a GS3 were used to calculate solution EC at the same three depths. Note how the fertilizer stays in the root zone temporarily but is leached out with water draining from the root zone.

Ref: Both charts taken from: Stirzaker, Richard. 2010.

COLLECTING DATA FOR EC

The following sensors will allow you to gather data for specific EC models and applications.

5TE, GS3, TEROS 12

can be used to determine

- EC of soil drainage water (EC_w) - soil moisture/temperature/EC sensors installed below the root zone.
- bulk EC of soil or soilless substrate (EC_b) – soil moisture/temp/EC sensors installed in the root zone.
- soil moisture – volumetric water content or dielectric permittivity values.
- soil temperature – temperature values need to be collocated with soil EC measurements.

G3 DRAIN GAUGE

can be used to determine

- EC of soil drainage water (EC_w) – when installed below root zone.

ES-2 TEMPERATURE SENSOR

can be used to determine

- EC of irrigation water ($EC_{applied}$) – when installed inline in the irrigation line.

ATMOS 31 RAIN GAUGE

can be used to determine

- depth of rain (D_{rain})

BADGER FLOW METER

can be used to determine

- depth of irrigation (D_{irrig})

REFERENCES

Hilhorst, M.A. 2000. A pore water conductivity sensor. *Soil Science Society of America Journal* 64:6 1922-1925.

Richards, L. A. 1954. Diagnosis and Improvement of Saline and Alkali Soils. USDA Handbook 60, United States Dept. of Agriculture.