Sep 20, 2024

USDA LTAR Common Experiment measurement: Soil water potential and matric potential

DOI
dx.doi.org/10.17504/protocols.io.8epv5rzb4g1b/v1

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OPEN ACCESS

DOI: dx.doi.org/10.17504/protocols.io.8epv5rzb4g1b/v1

External link: https://ltar.ars.usda.gov

Protocol Citation: Andrew M O'Reilly, Claire Baffaut 2024. USDA LTAR Common Experiment measurement: Soil water potential and matric potential. **protocols.io** https://dx.doi.org/10.17504/protocols.io.8epv5rzb4g1b/v1

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Protocol status: Working
We use this protocol and it's working

Created: April 16, 2024

Last Modified: September 20, 2024

Protocol Integer ID: 98805

Keywords: Long-Term Agroecosystem Research, LTAR, USDA LTAR, Common Experiment, potential energy, kinetic energy, temperature, solutes, atmospheric pressure, subsurface flow, unsaturated conditions, vadose zone, soil water potential, soil water, osmotic pressure, vapor pressure, water table

Funders Acknowledgement:
United States Department of Agriculture
Grant ID: -

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This research is a contribution from the Long-Term Agroecosystem Research (LTAR) network. LTAR is supported by the United States Department of Agriculture. The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the United States Department of Agriculture or the Agricultural Research Service of any product or service to the exclusion of others that may be suitable. USDA is an equal opportunity provider and employer.

Abstract

The *potential* of subsurface water measures the energy associated with position or internal conditions, thus representing the *potential energy* of a parcel of water (Hillel, 1998). Given the typically small flow velocity of subsurface water, its kinetic energy commonly can be assumed negligible; thus, the *total potential* represents the *total energy* status of the water parcel. Potential energy due to position depends on the location of the water parcel within the Earth's gravitational field, and potential energy due to internal conditions depends on the temperature and solute concentration of the water parcel. Because all systems equilibrate by moving from higher to lower energy states, a difference in potential energy from one point to another drives water moving between those points. The absolute value of the potential energy of a water parcel at any given point is irrelevant to its movement. Therefore, the potential of a water parcel is defined by the *specific potential energy* and may be expressed in three common forms:

1. Energy per unit mass (Φ), [L^2T^{-2}];
2. Energy per unit volume, [$ML^{-1}T^{-2}$], or pressure (P); and
3. Energy per unit weight, [L], or head (H);

where M, L, and T represent mass, length, and time dimensions, respectively, in a chosen unit system.

The different expressions for potential relate with each other through the gravitational acceleration constant (g) and density of water (ρ_w):

$$\phi = \frac{P}{\rho_w}$$

$$H = \frac{P}{\rho_w g} = \frac{\phi}{g}$$

Because the change in energy drives water movement, a reference state is necessary. Thus, potential is the work per unit quantity (mass, volume, or weight) required to transport an infinitesimal parcel of water reversibly and isothermally to a point of interest from a point representing a reference state for a pool of water defined by the following criteria: (1) pure water, (2) free water (not bound, i.e., adsorbed to solid phase), (3) air phase at atmospheric pressure, and (4) located at an established vertical datum (arbitrary reference elevation) (Hillel, 1998). Total potential is used to define the subsurface flow of water under saturated and unsaturated conditions.

In the vadose zone, total potential is commonly called **soil water potential** and obtained by summing the gravitational pressure (Φ_g), pressure (Φ_p) and osmotic potentials (Φ_o) generated by the respective force fields acting on water. Pressure potential (Φ_p)results from forces acting at the air–water and water–solid interfaces and is equal to the sum of pneumatic (Φ_a) and matric potentials (Φ_m) respectively. Osmotic potential results from solutes in the soil water solution, which lower the potential energy of the soil water by reducing its vapor pressure, and, in the presence of a semipermeable membrane, produce an osmotic pressure gradient. Osmotic potential typically can be neglected for dilute soil solutions. Where the air phase pressure is equal to its reference pressure (atmospheric pressure), as often is the case for a well-aerated subsurface, the pneumatic potential is zero. Therefore, for a dilute soil solution in a well-aerated porous medium,

soil water potential (total potential) is equal to the sum of gravitational and matric potentials, making Φ_m measurements a prerequisite for predicting water movement in the subsurface.

Matric potential represents the specific potential energy attributable to capillary and adsorptive forces, i.e., the total effect resulting from the affinity of water to the whole soil matrix (pores and particle surfaces). The values of Φ_p and Φ_m (where Φ_a= 0) are negative above a free water surface and thus are negative at elevations above the water table. Sometimes, the terms suction or tension are used to treat these potentials as positive values above the water table.

Data collection

1 **Equipment**

Gravitational potential is measured simply as the vertical distance of the measurement point of interest above an established datum. Matric potential can be measured in the field and (or) laboratory using the following instruments:

1.1 Tensiometer, e.g., SMS https://www.soilmeasurement.com/products/tensiometers. Young et al. (2008) provide detailed guidelines on the theory and use of tensiometers, including field and laboratory applications.

1.2 Dielectric permittivity, e.g., METER Group TEROS 21 https://tms-lab.com/product/soil-water-potential-sensor-meter-teros-21/#. The TEROS 21 sensor measures the water content of porous ceramic discs and converts the measured water content to water potential using the moisture characteristic curve of the ceramic. Scanlon et al. (2008) describe the theory and use of this type of sensor.

1.3 Dew point potentiometer, e.g., METER Group WP4C (lab only) https://tms-lab.com/product/soilwater-potential-lab-instrumentation-meter-wp4c/. This method measures osmotic potential as well as matric potential, giving $\Phi_m + \Phi_o$. Scanlon et al. (2008) provide detailed guidelines on the theory and use of a dew point potentiometer.

Note

Andraski and Scanlon (2008) and Scanlon et al. (2008) provide additional methods and instrumentation for measuring matric potential.

For recommendations on equipment placement, follow the general recommendations outlined for LTAR water quantity variables. Please refer to the "Placement and site maintenance" section in the *USDA LTAR Common Experiment measurement: Best practices for collection, handling, and analyses of water quantity measurements* protocol (Baffaut et al., 2024).

2 **Measurement**

2.1 A tensiometer measures matric potential using a “hanging” water column; thus, the practical upper limit of suction is 0.8 atm (0.8 bar, 80 kPa, 800 cm H_2O).

2.2 A dielectric permittivity sensor has lower and upper limits related to the properties of the ceramic disc. For example, the TEROS 21 sensor has a manufacturer-stated range of suctions from 9 to 100 kPa at an accuracy of ±10% of reading +2 kPa; sensor-specific calibrations can extend the range up to suctions of 1,500 kPa.

2.3 A dew point potentiometer has relatively poor accuracy in the wet range but is well suited for high suction conditions. For example, the WP4C instrument has a manufacturer-stated accuracy and suction range of ±0.05 MPa from 0 to 5 MPa, respectively, and 1% from 5 to 300 MPa, respectively. Given the effects on osmotic potential, soil water quality must be considered when using a dew point potentiometer to estimate matric potential from the value ($\Phi_m + \Phi_o$) measured by the instrument.

3 **Site Maintenance**

The tensiometer must be protected or removed during freezing temperatures.

Data processing and quality control

4 For recommendations on data processing and quality control, follow the general recommendations for water quantity variables. Please refer to the "Quality control" section in the *USDA LTAR Common Experiment measurement: Best practices for collection, handling, and analyses of water quantity measurements* protocol (Baffaut et al., 2024).

5 For tensiometers, verify electronically recorded data by making measurements of the water pressure within the tensiometer using an analog or digital gauge, e.g., SMS Tensimeter https://www.soilmeasurement.com/products/tensimeter. Electronic sensors, such as pressure transducers, may be used to record tensiometer pressures; these sensors require calibration.

Data file formats and metadata

6 For recommendations on data storage and metadata, follow the general recommendations for water quantity variables. Please refer to the data storage and accessibility section, as well as the "Metadata" section, in the *USDA LTAR Common Experiment measurement: Best practices for collection, handling, and analyses of water quantity measurements* protocol (Baffaut et al., 2024).

7 Data are best stored as text files or in standardized relational databases for maximum portability among computer systems. Metadata must adhere to the principles of FAIR (findability, accessibility, interoperability, and reusability) and include details on equipment, measurement procedures, and study sites and/or objectives.

Collecting and archiving raw data from the sensor is preferable. Whether data adjustments occur in the data logger program or elsewhere, a record of adjustments is necessary, including the type of adjustment, why it is necessary, over what period, who did it, and when.

Recommendations for data collection

8 Table 1. Summary of recommendations for measuring soil water and matric potential.

A	B	C	D
Attribute	**Preferred**	**Minimum**	**Comments**
Spatial scale	Plot	Not applicable	Metric is effectively a point measurement
Frequency	Sub-hourly	Not applicable	Frequency should be sufficient to provide representative statistics (e.g., mean) by integrating over desired temporal resolution
Covariate metrics	Soil water content, water table, rainfall, evapotranspiration	Soil water content	

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