# Modern Soil Moisture Monitoring Methods

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## Introduction

Potatoes (*Solanum tuberosum* L.) are susceptible to soil moisture stress due to their shallow root system and high water consumption (Powelson and Rowe, 1993). As a result, knowing the soil moisture status of the potato crop is crucial for maximizing marketable yield. For the past several decades, irrigators have used the "hand-feel," and hand-push probe method to monitor soil moisture status and schedule irrigation (Morris, 2006). However, these methods are time intensive, lack accuracy, and continuous monitoring. In the past three decades, new soil moisture monitoring methods have been changing how irrigators monitor soil moisture status and have potentially improved water use efficiency. According to the USDA, approximately 40% of irrigators in Washington State schedule irrigation by monitoring soil moisture status using the "hand-feel" method, and only about 10% monitor soil moisture status using soil moisture sensing devices (NASS, 2013).

It is estimated that by 2050, the world's population will reach 9 billion, which means more food will need to be produced ("FAO's Director-General on How to Feed the World in 2050," 2009). In addition, water is a limited resource and its use may rise in conjunction with the exponential population growth. Because of these major concerns, irrigation-dependent agricultural producers will need to maximize production and water use efficiency. To improve water use efficiency, irrigators must have methods to track soil moisture for irrigation scheduling.

Today, irrigators have many options for monitoring soil water status and a choice of whether to monitor soil water status quantitatively and or qualitatively. This paper will describe two approaches used to describe soil water status, and four non-destructive soil moisture monitoring methods that have been in development for as long as 70 years and are now readily available.

## Neutron Scattering Method

The next three methods will describe how soil water status is determined using a quantitative approach, which describes water content as the volume of water within a volume of soil ($V_w/V_s$), usually reported as a fraction in $m^3/m^3$. This fraction is referred to as volumetric water content (VWC, Cooper, 2016). In the United States, when water is applied to cropland by irrigation or rainfall, the quantity is usually reported as depth in "inches of water." Similarly, the soil water content is reported in "inches of water per foot of soil" by multiplying the VWC by 12 (Gardner, 1965; Cooper, 2016; Datta et al., 2017).

Determining the optimal VWC range in the soil to maximize potato yields requires a soil texture analysis to establish the upper and lower range. The upper limit is called field capacity (FC) and is defined as the fraction of water held in soil after excess water has drained after a rain or irrigation event (Hillel, 1998). The lower limit is called management allowable depletion (MAD) which is the percent soil moisture from the FC allowed to deplete without causing yield reductions. In the case of potatoes, MAD is 35 percent. For example, soil with an FC of 3 inches will have a lower limit/MAD of 1.95 inches.

The neutron scattering method is implemented by a device called a neutron probe, first used in the 1940s to measure soil water content in the lab (Brummer and Mardock, 1945). Neutron probes determine soil water content indirectly by measuring the thermalized ion cloud density formed around the probe, which is created by the collision of hydrogen nuclei with fast neutrons emitted by a decaying radioactive source. Since water is the primary source of hydrogen in most soils, the thermalized ion density is proportional to the volumetric water content present in the soil (Fityus et al., 2011; Couchat, 1967).

In order to use a neutron probe (Fig.1), it must first be calibrated to account for the different soil textures at each of the depths, following the instructions provided by the manufacturer. Secondly, access tubes must be installed following the recommendations of Ward and Wittmans (2009) to avoid air gaps. Lastly, measurements are made by placing the neutron probe over the access tube and lowering the probe to the desired depth (InstroTek Inc., 2019; Ward and Wittmans, 2009).

The main advantages of this method include ease of use, a large sphere of influence (15 cm in wet soils) that is not influenced by salinity, temperature, and soil cracking. On the other hand, this method does require special licensing to implement, equipment is heavy, continuous field measurements are not allowed, and near-surface measurements are challenging to make (Washington, 2019; Cooper, 2016).

There are two leading suppliers of neutron probes in the US, InstroTek (Research Trial Park, NC), which offers the CPN503 Hydroprobe (Fig. 2), and Troxler labs (Research Triangle Park, NC) which, offers the Model 4300 soil moisture gauge (Fig. 3). However, the process of acquiring one is relatively complicated due to the regulations on the radioactive material used in neutron probes (WSDH, 2019). The alternative is to hire a neutron probe services if one is available in your area. However, this type of service is disappearing rapidly due to new, less regulated technology.

***Figure 1*** *Image depicting the CPN503 Hydroprobe neutron probe from InstroTek implemented in the field. Courtesy of InstroTek Inc., TRC, USA*

***Figure 2*** *Image of CPN503 Hydroprobe Elite. Courtesy of InstroTek Inc., TRC, USA*


***Figure 3*** *Model 4300 Soil Moisture Gauge. Courtesy of Troxler Inc., TRC, USA*

**Time Domain Reflectometry**

Time domain reflectometry (TDR) was first used for measuring soil water content by Topp et al. (1980), their work paved the way for what we know today as TDR (Cooper, 2016). TDR relies on the dielectric constant of soil and water to determine soil water content, which is described merely by the capacity of soil [the capacitor] to hold on to a larger charge by adding additional water [the dielectric] to the soil (Cooper, 2016). Soil water content is indirectly determined by measuring the time it takes for a generated electromagnetic pulse (EMP) to travel the length of parallel rods inserted in soil. Since plain water is a great conductor, additional water

in the soil increases the speed of the pulse. Thus, the travel time of the electromagnetic pulse is a function on the dielectric constant of the soil and proportional to the squared travel time of the pulse (Dalton and Van Genuchten, 1986; Jones et al., 2002)

In the field, TDR system installation is relatively simple (Fig 4). Probes consisting of two or more metal prongs are inserted in the soil and connected to a pulse generator and a data logger (Patterson and Smith, 1981). Measurements can be scheduled manually or via a telemetry option, including cellular and GPS (Campbell Sci., 2019).

The TDR method has many advantages, amongst the best include excellent accuracy and precision, and the ability to choose how much of the soil depth to measure. For example, a 30 cm probe installed on a 30-degree angle will measure a depth of 15 cm; the same probe installed vertically will measure a depth of 30 cm (Campbell Sci., 2019; Jones et al., 2002). Disadvantages include high initial capital cost, errors caused by improper installation, and the instruments may be difficult to configure (Campbell, 2014). However, TDR-probe variations are being made available by companies like Campbell Sci., which simplify configuration and installation, as well as reduce cost.

The leading supplier of TDR systems in the US is Campbell Scientific Inc., located in Logan, Utah. They offer a number of TDR system variations, “true” TDR systems, reflectometer TDR systems, and multi-depth systems (Fig. 7). Reflectometer and multi-depth probes are equipped with all the necessary electronics to excite an EMP and measure the travel time of the pulse within.

***Figure 4*** *Image depicting a TDR system implemented in the field. Courtesy of Campbell Sci. Inc., Utah, USA; and, Acclima, Meridian, USA, respectively.*

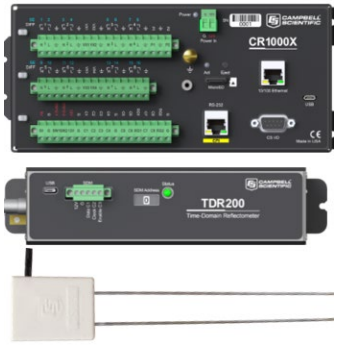


***Figure 5*** *Image of a TDR system is characterized as a "true” TDR system, and is comprised of a CR1000X data logger, a TDR200 pulse generator, and a CS605 probe. Courtesy of Campbell Sci. Inc., Logan, USA.*


***Figure 6*** *Image of a TDR system comprised of a CR310 data logger, and a CS625 probe. Courtesy of Campbell Sci. Inc. Logan, USA.*


***Figure 7*** *Image of a TDR system comprised of a CR1000X data logger, and a SoilVUE10 multi-depth probe. Courtesy of Campbell Sci. Inc., Logan, USA.*

**Capacitance**

This method is also referred to as frequency domain reflectometry (Cooper, 2016). The idea to measure soil water content using capacitance was conceived in the 1950s and 1960s. However, the technology was not available for practical use until the late 1970s when high-frequency electronics became available (Grant et al., 1957; Summerhill, 1967; Cooper, 2016). The principle of capacitance probes is relatively modest, it relies on the same principle as TDR, which states that with an increase of water in the soil, there is also an increase in the charge-capacity of the soil (Dalton and Van Genuchten, 1986; Jones et al., 2002). In this case, the soil water content is determined indirectly by measuring the capacitance of the soil [which acts as the capacitor] after being polarized by an electromagnetic field created by two plates. The capacitance measured in the soil is a function of the water content in the soil and is thus proportional to the soil water content (Bell et al., 1987).

Implementing a capacitance system to monitor soil moisture in the field is relatively easy. Capacitance systems with multi-depth probes may require access tubes (Fig. 8). If this is the case, users should install them using the manufacturer's instructions. Single-depth probes can be installed in any direction. However, precaution must be taken to avoid preferential flow by packing the soil that was removed to its original bulk density. This method allows for continuous monitoring, which means that the user can choose how often measurements are made. Moreover, this method allows for the use of telemetry, which gives users the capability of managing their system from anywhere.

The main advantages of this method are lower cost per unit, simple readout devices, easy to install/use, low power consumption, multi-depth devices available, and the best resolution of any method. However, it also has several disadvantages which include sensitivity to soil texture and temperature, fluctuations at different frequencies, and sensitivity to air gaps (Baumhardt et al., 2000; Campbell, 2014).

Capacitance probes are extremely popular, and as a result, there are many companies that retail these devices. There are three main suppliers of capacitance probes, Meter Group Inc., located in Pullman, WA, USA, Delta-T Devices, located in Cambridge, UK, and Sentek, located in Stepney, AUS. Some of the most popular setups offered by these three companies are as follows: Meter Group offers the ZL6 data logger equipped with the TEROS 12 probe (Fig. 9), or the portable ProCheck equipped with the TEROS 12 probe (Fig. 10); Delta-T Devices offers the GP2 data logger equipped with the Theta Probe (Fig. 11) or the portable HH2 reader equipped with the PR2 Profile probe (Fig. 12); and, Sentek offers the portable Diviner 2000 equipped with a multi-depth probe (Fig. 13) or the drill n' drop multi-depth probe connected to a CR310 Campbell Sci. data logger (Fig. 14).

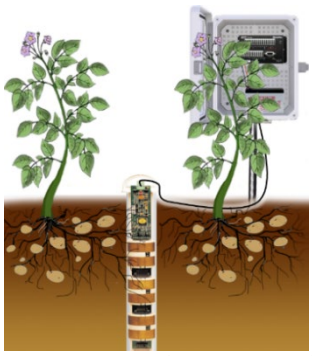

***Figure 8*** *Image of capacitance soil moisture monitoring system implemented in the field, using a data logger, and a multi-depth probe. Courtesy of Campbell Sci. Inc., Logan, USA; and, Sentek, Stepney, AUS, respectively.*

***Figure 9*** *Image of capacitance soil moisture monitoring system comprised of a data logger and probe. Courtesy of METER Group Inc., Pullman, USA.*


***Figure 10*** *Image of the handheld ProCheck reader equipped with a TEROS 12 probe. Courtesy of METER Group Inc., Pullman, USA.*


***Figure 11*** *Image of the handheld HH2 reader equipped with the PR2 Profile Probe. Courtesy of Delta-T Dev., Cambridge, UK.*

***Figure 12*** *Image of the handheld HH2 reader equipped with the PR2 Profile Probe. Courtesy of Delta-T Dev., Cambridge, UK.*


***Figure 13*** *Image of the handheld Diviner 2000 reader equipped with depth probe. Courtesy of Sentek, Stepney, AUS.*


***Figure 14*** *Image of capacitance soil monitoring system comprised of a data logger from Campbell Sci., and a multi-depth probe. Courtesy of Campbell Sci. Inc., Pullman, USA; and, Sentek, Stepney, AUS, respectively.*

**Capacitance with Calibrated Medium**

The methods previously discussed determine soil water status quantitatively. In contrast, this method measures soil water status qualitatively in terms of soil water potential (SWP) in kPa, which is a measurement of the work required to overcome the forces that adhere water molecules to the soil particle. Moreover, soil water potential is an excellent indicator of plant stress (Hillel, 2004).

It is the consensus that most plants cannot extract water from the soil when the soil water potential is above -1500 kPa, a reference point referred to as wilting point (Andraski and Scalon,

2002). In the case of potatoes, it is recommended to maintain SWP below -60 kPa to optimize production (Kang et al., 2004), regardless of soil type. Additional information on managing soil water potential for potatoes can be found in Shock and Wang (2011).

Capacitance probes with calibrated media determine SWP using the same dielectric constant principle that is used by TDR and capacitance probes. However, this method has two additional components, a porous medium [usually ceramic], and a soil water characteristic curve (SWCC, Fig. 15), which describes the relationship between soil water content and potential (Whalley et al, 2001; Or et al, 1999).

A SWP device is merely a capacitance probe modified so that the electrodes and porous medium (Fig. 16) are amalgamated to each other (Whalley et al, 2001). To determine SWP, capacitance probes determine the percent water content of the porous medium [which is in equilibrium with the soil] and converts it into an SWP value, using the SWCC (Hilhorst and De Jong, 1988; Whalley et al, 2001).

Since this system uses the same data loggers as their capacitance probe counterparts, the same procedures are followed (Fig.17). Also, the same telemetry options are available for this system, since this system uses the same data loggers as capacitance systems.

The main benefits of measuring soil water potential using this method include, easy to use/install, low maintenance, long-lasting, low power consumption, relatively accurate, excellent resolution, excellent range, and provide temperature readings (Delta-T Dev., 2019; METER, 2019). This methodology, however, can be more complex to comprehend than other systems.

The two main suppliers of capacitance probes with calibrated medium are METER Group located in Pullman, WA, and Delta-T Devices located in Cambridge, UK. Meter group developed and retails the TEROS 21soil water potentiometer, which is connected to their ZL6 data logger (Fig. 18). Delta-T Devices manufactures and retails the EQ3 Equitensiometer soil water tensiometer, which is connected to their GP2 data logger. (Fig. 19).

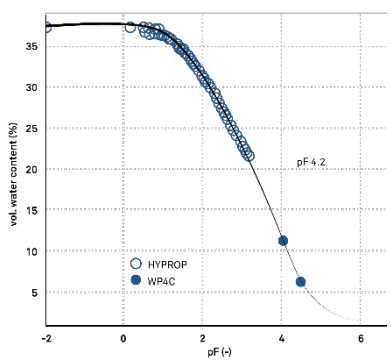


***Figure 15*** *Image of a soil water characteristic curve, (METER Group B, 2019)*

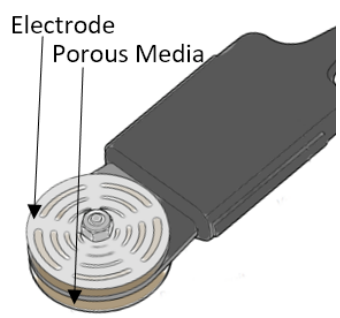


***Figure 16*** *Diagram of capacitance probe with calibrated media, TEROS 21, (METER Group, 2019)*

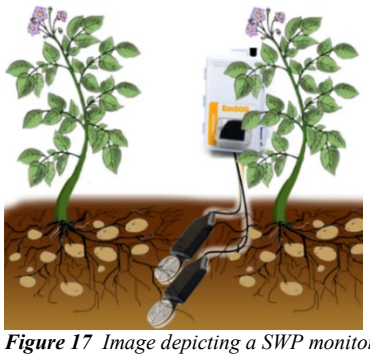

***Figure 17*** *Image depicting a SWP monitoring system, using capacitance probes with calibrated. Courtesy of Meter Group Inc., Pullman, USA.*


***Figure 18*** *Image of SWP monitoring system is comprised of a data logger, and a capacitance probe w/ calibrated. Courtesy of METER Group Inc., Pullman, USA.*


***Figure 19*** *Image of SWP monitoring system comprised of a GP2 data logger, and an EQ3 Equitensiometer capacitance probe with calibrated media. Courtesy of Delta-T Dev., Cambridge, UK.*

**Discussion**

The WSU Potato Research Group has had the opportunity to work with all of the aforementioned methods. In their opinion, the capacitance method for determining VWC is the most effective method today, because capacitance systems are more affordable than others, more readily available, easiest to implement, and are offered in the most configurations.

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