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Measuring very negative water potentials with polymer tensiometers: principles, performance and applications

Gerrit H. DE ROOIJ[1], Martine J. VAN DER PLOEG[1], Hermanus P.A. GOOREN[1], Gerben BAKKER[2], Cornelis W. HOOGENDAM[3], Cindy HUISKES[4], Henk KRUIDHOF[4] & Luuk K. KOOPAL[3]

[1] *Environmental Sciences, Soil Physics, Ecohydrology and Groundwater Management Group, Wageningen University, P.O. Box 47, 6700 AA Wageningen, the Netherlands; e-mail: ger.derooij@wur.nl*
[2] *Wageningen Univ. and Research Centre, P.O. Box 47, 6700 AA Wageningen, the Netherlands*
[3] *Laboratory for Physical Chemistry and Colloid Science, Wageningen University, P.O. Box 8038, 6700 EK Wageningen, the Netherlands*
[4] *Faculty of Science and Technology, Twente University, P.O. Box 217, 7500 AE Enschede, the Netherlands*

Abstract: In recent years, a polymer tensiometer (POT) was developed and tested to directly measure matric potentials in dry soils. By extending the measurement range to wilting point (a 20-fold increase compared to conventional, water-filled tensiometers), a myriad of previously unapproachable research questions are now open to experimental exploration. Furthermore, the instrument may well allow the development of more water-efficient irrigation strategies by recording water potential rather than soil water content. The principle of the sensor is to fill it with a polymer solution instead of water, thereby building up osmotic pressure inside the sensor. A high-quality ceramic allows the exchange of water with the soil while retaining the polymer. The ceramic has pores sufficiently small to remain saturated even under very negative matric potentials. Installing the sensor in an unsaturated soil causes the high pressure of the polymer solution to drop as the water potentials in the soil and in the POT equilibrate. As long as the pressure inside the polymer chamber remains sufficiently large to prevent cavitation, the sensor will function properly. If the osmotic potential in the polymer chamber can produce a pressure of approximately 2.0 MPa when the sensor is placed in water, proper readings down to wilting point are secured. Various tests in disturbed soil, including an experiment with root water uptake, demonstrate the operation and performance of the new polymer tensiometer and illustrate how processes such as root water uptake can be studied in more detail than before. The paper discusses the available data and explores the long term perspectives offered by the instrument.

Key words: aridity; irrigation; root water uptake; soil physics; soil water; tensiometer; water stress

Introduction

In well vegetated areas (natural or agricultural), transpiration is generally much larger than evaporation, i.e., most of the water transferred from the soil to the atmosphere passes through the vegetation. During dry periods, the vegetation may not be able to maintain transpiration at its potential level, because plant roots cannot extract the required amount of water from the soil. This leads to agricultural yield reduction and is often remedied by irrigation. Worldwide, 2.77×10^6 km^2 of land is irrigated, and irrigation accounts for 2300 km^3 yr^{-1} of global freshwater withdrawal from surface water and aquifers (UNESCO-WWAP 2006, p. 250), which amounts to approximately 70% of the total global fresh water withdrawal (UNESCO-WWAP 2003, p. 193). With fresh water becoming an increasingly scarce resource in many areas of the world, its use needs to be optimized. Considering that of the 2300 km^3 yr^{-1} used for irrigation only about 900 km^3 yr^{-1} are consumed by the crops, a vast improvement is possible in agricultural fresh water use efficiency. In recognition of the scarcity of fresh water, the focus in irrigated agriculture is shifting from land productivity (harvest per hectare) to water productivity (harvest per cubic meter of water; UNESCO-WWAP 2006, p. 156).

The ability of plant roots to extract water from the soil is governed by the forces that bind the water to the soil, and, in the course of a growing season, by the ability of the soil to transfer water from wet regions to the rhizosphere. Water flow is driven by the gradient in total water potential ψ_{tot} (Pa = N m^{-2}). (Equivalent expressions with different units can be found in soil physics text books, e.g., Warrick 2002.)

The total water potential in unsaturated soil can be partitioned in several potentials:

$$\psi_{\mathrm{tot}} = \psi_{\mathrm{m}} + \psi_{\mathrm{g}} + \psi_{\mathrm{o}}$$

The matric potential ψ_{m} (in soils often the largest component of ψ_{tot}) describes the forces of capillarity in plant and soil, in addition to molecule imbibition forces

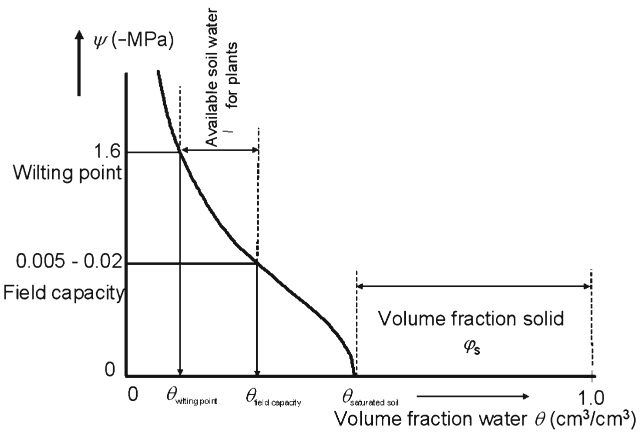

Fig. 1. Soil water release characteristic.

associated with cell walls in plants, and colloidal surfaces that bind some of the water in the soil. The gravitational potential ψ_g reflects the position in the gravity field, and the osmotic potential ψ_o denotes the influence of dissolved solutes. While the matric potential (further denoted as ψ) can be conveniently expressed as a pressure-equivalent, it represents forces attracting the water, and can therefore take on negative values. By convention its value is zero for free water at atmospheric pressure (i.e., at the groundwater level). One can view ψ to represent the energy per volume needed to remove an infinitesimal amount of water from a particular location in the soil (see Jury at al. 1991, p. 51 for a complete definition). At the groundwater level, no effort is required, consistent with the zero value of ψ; in saturated capillaries above the groundwater, water pressure is subatmospheric (ψ slightly negative), and some effort is required to extract water, and in dry soil, where water is concentrated in films around the grains and in pendular rings (Bear & Bachmat 1991, p. 336–338) water is bound strongly to the solid surface (ψ large and negative). Clearly, the drier a soil becomes, the more difficult it will become to remove water from it. Therefore, the soil water characteristic (Fig. 1), relating the volumetric water content θ to ψ, figures prominently in unsaturated flow theory. The theory of unsaturated flow in soils is given by Jury et al. 1991 (p. 34–158) and Hillel 1998 (p. 127–241), among others.

The above establishes the pivotal role of ψ in determining the ease with which roots can extract water from a soil and the soil's ability to replenish the extracted water through flow from regions with higher ψ-values. It is therefore unfortunate that for many decades, ψ could be measured directly over a very limited range only by conventional tensiometers. These typically consisted of a hollow tube with a ceramic cup on one end and a pressure sensor on the other. The instrument was filled with water, the ceramic cup saturated with water, and the instrument installed in the soil. The water in the cup could equilibrate with the soil water since water could flow freely through the ceramic. By measuring the water pressure in the water reservoir, ψ could be inferred. Unfortunately, when the pressure inside the cup drops too far below the atmospheric pressure, vapor bubbles will appear spontaneously inside the cup, which corrupts the readings. Furthermore, if ψ would become so large and negative that, according to the $\theta(\psi)$ relationship of the ceramic, the cup would desaturate, air could enter the cup and the tensiometer would empty. Consequently, ψ could only be observed to about -85 kPa, while agricultural crops typically can take up water for $\psi \geq -1.6$ MPa (termed the wilting point), thereby leaving 95% of the range of interest unobservable. Details of tensiometry are given by Young & Sisson (2002).

To extend the tensiometer's measurement range, Peck & Rabbidge (1966, 1969) proposed to replace the water by a polymer solution. They reported promising results, but their sensor suffered from drawbacks that apparently could not be resolved at the time, and it never left the prototype phase.

Improvements in polymer production and ceramic manufacturing led to renewed interest in what we shall term the polymer tensiometer (POT). Bakker et al. (2007) and van der Ploeg et al. (2008) built improved versions of the POT. Their instruments have a proven ability to measure reliably down to wilting point for prolonged periods of time. For details of the construction and calibration we refer to the above papers. Our objectives here are to describe the new POT in general terms, discuss a selection of the data produced with them, and provide an outlook for future research opportunities and potential applications of the POT.

Materials and methods

The polymer tensiometer

The principle of POTs (Fig. 2) is based on the osmotic pressure of a hydrophilic polymer solution. The soluble polymer molecules are retained inside the POT by a porous ceramic membrane impermeable to the polymers. The ceramic remains saturated for $\psi > -1.8$ MPa. When the POT is placed in water ($\psi > 0$), osmosis creates a pressure inside the instrument. When placed in soil ($\psi < 0$) the water inside the POT equilibrates with the soil water, causing a reduction in its potential that can be measured as a pressure drop. The high initial pressure delays cavitation of the polymer solution. Thus, a much wider range of ψ can be measured than with a water-filled instrument.

Filling polymer tensiometers

A POT can be filled with dry polymer. The assembled POT is then placed in water. The ceramic saturates, the polymer dissolves, and builds up an osmotic pressure large enough to remove all air from the polymer chamber (Bakker et al. 2007, and van der Ploeg et al. 2008).

Operation

After calibration, the POTs can be installed in the soil. Current prototypes have a pressure sensing unit connected by cable to the data logger. The pressure sensors are buried while the data loggers remain at the soil surface. The expected battery life of a POT is about seven years, and the data storage capacity is large enough to store data of an entire growing season or longer, depending on the measurement frequency.

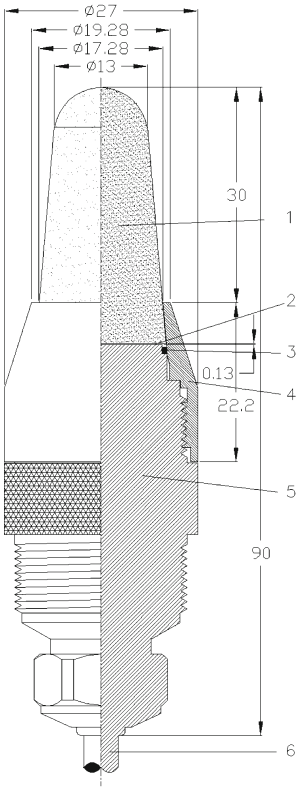

Fig. 2. Polymer tensiometer containing (1) ceramic with a radius at the base of the cone of 9.1 mm, (2) polymer chamber, (3) rubber O-ring, (4) stainless steel socket, and (5) a pressure transducer, (6) cable to data logger and power supply. Arrows indicate lengths in mm (ø denotes diameter).

In very dry soil, even the POT ceramic can dry out. The hydrophilic nature of the polymer ensures that during a subsequent wetter period, the POT spontaneously rewets and resumes acquiring valid data. This property is another major advantage over conventional tensiometers, which need manual refilling or excavation when dried out. Together with the long battery life and large data storage capacity this makes the POT an instrument capable of functioning in stand-alone mode for prolonged periods of time.

Evaporation container experiments

We installed POTs, Time Domain Reflectometry (TDR) water content sensors (Ferré & Topp 2002), and conventional, water-filled tensiometers in a 40 × 30 × 40 cm (H × L × W) container with a perforated bottom and wall-to-wall perforated vapor outlet tubes (Fig. 3). The container was filled with sieved sandy loam (14% clay, 31% silt, 55% sand). The soil was thoroughly wetted and then left to dry while the sensors monitored the decreasing θ and ψ. Volumetric soil samples were taken regularly and their water content determined by oven drying (Topp & Ferré 2002) to calibrate the TDR sensors and determine the $\theta(\psi)$ relationship (Dane & Hopmans 2002a,b). Bakker et al. (2007) provide details of the experimental set-up.

In a similar, prewetted container (2% clay, 7% silt, 91% sand) we sowed 18 maize seeds (*Zea mays* L.). The container was wetted from below at constant ψ from DAS 39 until DAS 60 (DAS: days after sowing). Then, the soil was left to dry until $\psi = -0.8$ MPa, and rewetted from below from DAS 81 to 85. Finally, the soil was left to dry until the POTs cavitated and stopped working.

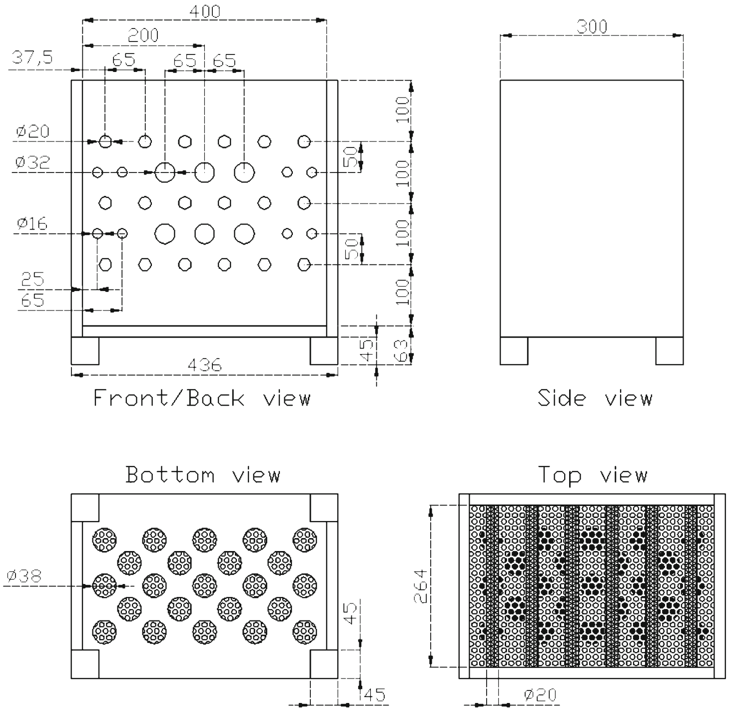

Fig. 3. The box used for the evaporation experiment (measures are in mm). 20 mm ports accomodated perforated tubes that were covered with cloth. Polymer tensiometers (POTs) were placed through the outer 32 mm front ports. Time domain reflectometry wave guides (TDR probes) were placed at back ports of 32 mm, one opposite of each POT. Conventional tensiometers (CTs) were placed at the front and back central 32 mm ports. Ports of 16 mm facilitated soil sampling to calibrate the TDR probes.

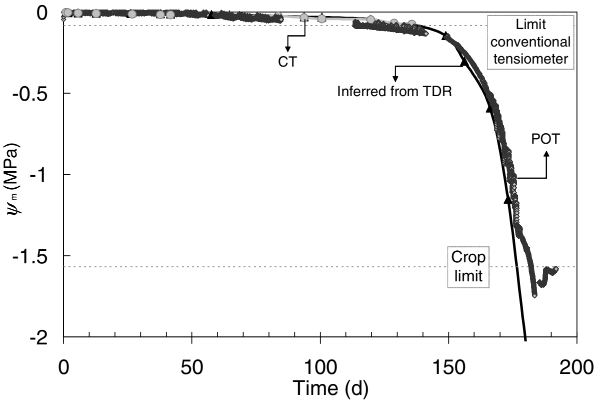

Fig. 4. The performance of conventional (water-filled) tensiometers (CT) and the polymer tensiometer (POT) in a drying soil container. The container was equipped with vapor outlets in the soil to allow relatively uniform drying (from Bakker et al. 2007).

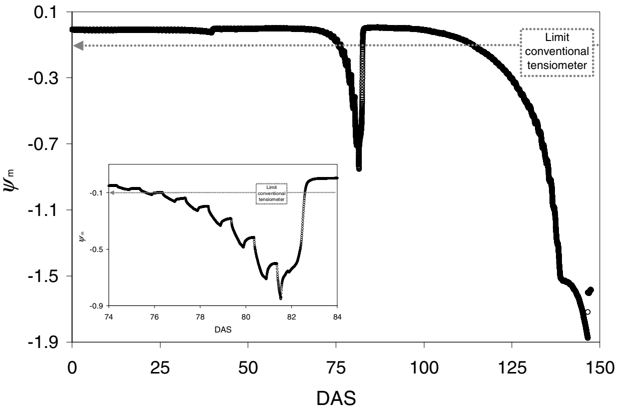

Fig. 5. Development of the matric potential (ψ_m) in days after sowing (DAS) as measured by a polymer tensiometer in an evaporation container cropped with maize (*Zea Mays, L.*), subject to intermittent drying and wetting. Inset shows a detail of 10 days when the influence of root water uptake on ψ_m was clearly visible.

Results and discussion

Evaporation container experiments

We report data from only one POT in each container. Figure 4 (from Bakker et al. 2007) clearly shows the POT's capability to provide valid data for a prolonged period of time and over the range of interest. During the experiment, changing weather gave a sudden increase in temperature, which explains the accelerated drying. The conventional tensiometers cavitated rapidly, but the POT remained very close to the ψ-values estimated from the water content readings using the $\theta(\psi)$-relationship, even well beyond the wilting point. In the cropped container, the POT allowed us, for the first time, to observe directly and quantitatively root water uptake under water stress (Fig. 5).

The striking day-night rhythm of the matric potential corresponds to the switch-on and -off times of the growing light (Fig. 5, inset). Water extraction by the roots when the light was switched on reduced ψ. When the light was switched off, the driest soil was partially replenished by flow from wetter regions outside the sphere of influence of the roots, creating the saw-tooth shape.

Future applications

The POTs developed by Bakker et al. (2007) and van der Ploeg et al. (2008) allow observing the potential energy of water in the rhizosphere rather than its water content, and thus can provide a measure of the degree of water stress experienced by a crop. This in turn can facilitate a more sophisticated irrigation strategy, for instance by targeting different levels of water stress depending on the varying sensitivity to water stress of different stages in a crop's development (see Bernstein 1974). Depending on the lay-out of the irrigation system, the number of available POTs, and data processing capability, irrigation timing and volume can even be fine tuned to conditions in small section of a field, providing an additional opportunity for precision agriculture. In this way, combining plant physiology, soil physics, and monitoring of the crop and the soil water status can improve the water productivity while at the same time enhancing the sustainability of irrigated agriculture.

For fundamental soil physics, the POT extends experimental methods to determine $\theta(\psi)$, and allows experimental exploration of water behavior in dry soils, in which, for instance, vapor flow can contribute significantly to the water movement. The stand-alone capability and the limited maintenance requirement of the instrument facilitates long monitoring campaigns in the field, or even the establishment of large, semi-permanent monitoring networks extending into remote areas. Here, opportunities exist to link up with space-borne Earth Observation programs that can at this time mainly monitor shallow soil moisture but cannot assess the energy status of the soil water.

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