

A Novel Method for Quantifying Soil Hydraulic Properties

Uwe Schindler

Abstract A knowledge of soil hydraulic properties—the water retention curve and unsaturated hydraulic conductivity—is required for soil water modelling and for various studies of soil hydrology. Taking measurements using traditional techniques is time consuming, the equipment is costly and the results can be uncertain. The evaporation method is frequently used for the simultaneous determination of hydraulic functions of unsaturated soil samples, i.e. the water retention curve and hydraulic conductivity function. Due to the limited range of common tensiometers, all the methodological variations of the evaporation method suffer from the limitation that the hydraulic functions can only be determined to a maximum of 70 kPa. The extended evaporation method (EEM) overcomes this restriction. Using new cavitation tensiometers and setting the air-entry pressure of the tensiometer's porous ceramic cup as a final tension value allow both hydraulic functions to be quantified close to the wilting point. Additionally, soil shrinkage dynamics as well as soil water hysteresis can be quantified. Here, the HYPROP system was selected, a commercial device with vertically aligned tensiometers optimised to perform evaporation measurements. The HYPROP software was developed for recording, calculating, evaluating, fitting and exporting hydrological data. A good match between the results of soil hydraulic functions was shown when those obtained from traditional methods and the extended evaporation method were compared. Systematic deviations were not found.

Keywords Soil · Hydraulic properties · Measurement · Extended evaporation method (EEM)

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1 Introduction

Classical determination of soil hydraulic properties—the water retention curve and unsaturated hydraulic conductivity characteristics—has been carried out using various methods and procedures. Depending on the desired measuring range, different methods and devices are available to determine the soil water retention curve. In the low tension range, between 0 and 10 kPa, the sand box (Cresswell et al. 2008) is the common method for quantifying the water retention data points. The sand/kaolin box is mainly used in the tension range between 10 and 50 kPa. For higher tensions (100–1,500 kPa), the pressure plate extractor is applied (Dane and Hopmans 2002).

In addition, various methods are available to estimate the unsaturated soil hydraulic conductivity function of soil samples. The steady state pressure membrane procedure (Henseler and Renger 1969; Boels et al. 1978; Schindler et al. 2010a) and the tension disc infiltrometer method (Reynolds and Elrick 1991) allow the measurement of hydraulic conductivity values only in the low tension range. Hot-air methods (Arya 2002; Tyner et al. 2006) and centrifugation techniques (Nimmo et al. 2002) enable soil water diffusivity and unsaturated hydraulic conductivity to be measured rapidly. The measurement conditions, however, differ markedly from the natural conditions for all these methods. The one-step (Kool et al. 1985) and especially the multistep outflow method (Hopmans et al. 2002; Fujimaki and Mitsuhiro 2003; Durner and Iden 2011) produce reliable hydraulic conductivity data and are widely in use.

Evaluation of traditional methods:

- Expensive;
- Time consuming (several months to quantify both functions);
- High level of uncertainty;
- Artificial process;
- Inflexible—transporting the equipment requires a lorry and instrumentation takes several weeks or months.

The evaporation method (Wind 1966) allows the simultaneous determination of both the water retention curve and the hydraulic conductivity function. Some modifications have been developed as described by Becher (1970), Schindler (1980), Klute and Dirksen (1986), Plagge (1991), Halbertsma (1996), Wendroth et al. (1993) Bertuzzi et al. (1999), Šimunek et al. (1999) and Schindler and Müller (2006). Measurement time and cost of the equipment are much less than when using the traditional methods. However, all variations of the evaporation method suffer from one limitation, namely the measurement limit of about 70 kPa of the tensiometers. Unfortunately, most hydrological studies require exact soil hydraulic properties at higher tensions.

The extended evaporation method (EEM) described by Schindler et al. (2010a, b) overcomes this limitation. Using new cavitation tensiometers and setting the air entry value of the tensiometer's ceramic cup allows the range to be extended to close to wilting point.

Following the EEM method, the measurement device HYPROP (**HY**draulic **PRO**Property Analyser) and procedures are described, and measurements are presented. The results of a comparison between traditional and evaporation measurements are also shown.

2 Evaporation Method

2.1 Description, Based on Versions of Schindler (1980) and Schindler et al. (2010a, b)

Two tensiometers are installed at depths of 1.25 and 3.75 cm in a soil sample (250 cm³, height 5 cm) (Fig. 1). The sample is saturated with water from the bottom, sealed at the bottom and placed on a balance. Its surface remains open to free evaporation. Tensions (Ψ) and sample mass (m) are recorded at consecutive times. Single points of the water retention curve are calculated on the basis of the water loss per volume of the sample at time t and the geometric mean tension of the sample at that time. The hydraulic conductivity (K) is calculated according to modified Darcy-Buckingham's Law (Eq. 1) where the evaporated water volume per time interval relates to half the sample height versus hydraulic gradient as determined by the tensiometers (Schindler 1980). The flux (v) is derived from the soil water volume difference ΔV (1 cm³ of water = 1 g) per surface area (A) and time unit (Δt). The mean hydraulic gradient (i_m) is calculated on the basis of the mean tensions in time intervals

$$K(\bar{\Psi}) = \frac{\Delta V}{2A\Delta t i_m} \quad (1)$$

where $\bar{\Psi}$ is the mean tension geometric averaged over the upper and the lower tensiometer and the time interval, ΔV is the evaporated soil water volume [= mass difference (Δm)] during the interval, A is the cross-sectional area of the sample, Δt is time interval and i_m is the mean hydraulic gradient in the interval.

At the end of the measurement, the residual amount of storage water is derived from water loss through drying in the oven (105 °C). The initial water content is determined by total water loss (evaporation part plus residual amount) related to core volume. Dry bulk density is derived from dry soil mass divided by core volume. For this reason, the volume of the tensiometer holes (1 cm³) is subtracted from the core.

Assumptions for the validity of Eq. 1 are: (1) that water flow out of the core can be treated as a "succession of steady states" where the flux and hydraulic gradient are effectively constant within each time interval and (2) linear decreasing water content difference across the sample height in the measuring interval. Accordingly, the flux through the measuring layer is half of the total flux and can be calculated from the total evaporative soil water volume (mass) difference in the time interval.

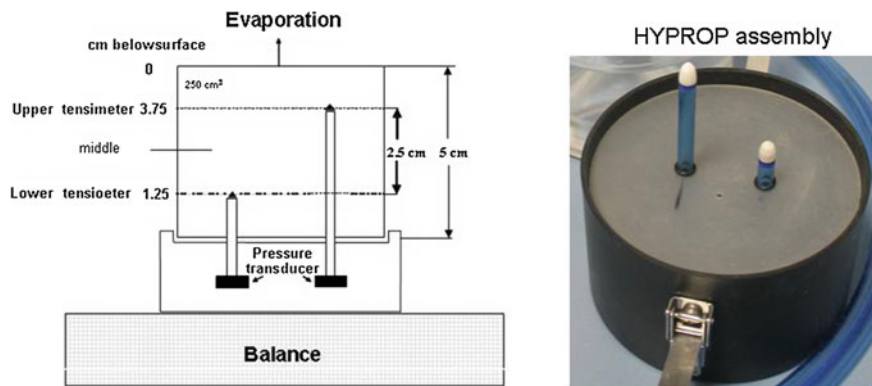


Fig. 1 Schematic illustration of the evaporation experiment and photo of the HYPROP device

The assumptions were found to be valid for sand, silt, loam and peat soils in the original measurement range between 0 and 60 kPa (Schindler and Müller 2006). Schindler et al. (2010b) reported that linearisation in space led to only minor errors, even in the late stage of evaporation where strongly nonlinear tension profiles emerge.

2.2 Procedure

Intact soil cores are placed in stainless steel cylinders (8 cm diameter, 5 cm height) with a sharpened leading edge to minimise soil disturbance during insertion. Cores are slowly saturated in the laboratory by placing them in a pan of water (tensiometer holes at the top) (Fig. 2). To minimise air entrapment, the water table should be increased slowly and in steps from an initial height of about 0.5 cm above the bottom of the sample to a final height of about 0.2 mm below the sample surface. Holes are vertically excavated for the tensiometers at the bottom of the core using a special auger and a template.

After saturation, tensiometers are prepared, and inserted in the core. The core is still in the pan at that time. The configuration is connected to the core (Fig. 3), it is removed from the pan (Fig. 4), inverted (Fig. 5) and the core ring is clamped to the tensiometer. This procedure prevents water drainage and evaporation out of the base of the core. All excess water is removed from the device, and the sample surface is sealed with a lid. The equipment is connected to the computer, and tensions are read. Hydraulic equilibrium is assumed when the tension difference between the upper and the lower tensiometer is 0.25 kPa. The whole device is placed on a balance, connected to the computer, the soil surface is exposed for evaporation and the measurement starts (Fig. 6).

Fig. 2 Saturation of samples and tensiometer holes



Fig. 3 Connection of the HYPROP device to the core



Tension (Ψ) and sample mass (m) are recorded consecutively using tensio-VIEW software (<http://www.ums-muc.de> 2012). The HYPROP-Fit software was developed for calculating, evaluating, fitting and exporting the hydraulic functions (<http://www.ums-muc.de> 2012). In the remainder of this paper, the difference between atmospheric pressure and water pressure inside a tensiometer is referred to as tension (Ψ) and is expressed as a positive quantity in hPa or kPa.

Fig. 4 Removing the device and the core from the pan



Fig. 5 Inverted device



Fig. 6 Sample is clamped, placed on a balance and connected to a computer



3 Extending the Range of Measurement

3.1 Tensiometric Measurements in a Drying Soil

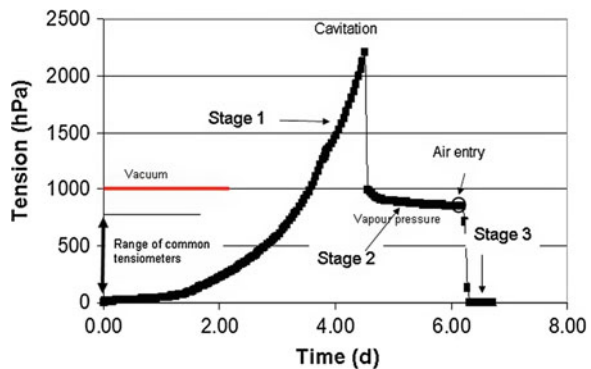
A top-of-the-range tensiometer with highly reproducible measuring characteristics is a prerequisite for extending the range of measurement (Schindler et al. 2010a). These tensiometers consist of three basic interconnected elements: (1) a semi-permeable porous cup (2) a water reservoir, and (3) a measurement gauge or pressure transducer. Pressure equilibrium between the water in the tensiometer and the surrounding soil is achieved through water movement across the porous tensiometer cup. If the tension of the soil water exceeds the air-entry pressure, the cup drains and becomes air-permeable. Air enters the tensiometer and its internal tension recedes. The tensiometer’s ceramic cup is therefore configured to ensure that its air-entry pressure is greater than the highest soil water tension (>100 kPa) that has to be measured.

The dynamics of a tensiometric measurement in a drying soil can be divided into three distinct stages (Fig. 7).

In the first stage, the measured tension reflects the matric potential of the surrounding soil. For most tensiometers, the upper limit of the tensiometer method is approximately 80 kPa (Young and Sisson 2002). For optimal performance, the water inside the tensiometers is free of dissolved gas. If dissolved gas is present, a small gas bubble will form that expands continually during the drying process and yields a slightly corrupted tensiometric measurement (Durner and Or 2005). This can be avoided by checking that the tensiometer is functioning properly before installation, as described in Schindler et al. (2010a).

The second stage is the vapour pressure stage. If the absolute soil water pressure is decreased to below the liquid’s vapour pressure, the water inside the tensiometer will start to boil. The pressure inside the tensiometer will equilibrate to the vapour pressure, which is close to vacuum. Water in contact with the porous cup will flow through it into the surrounding soil, whilst the vapour bubble inside the cup will expand continually. As a consequence, the soil in the immediate vicinity of the cup

Fig. 7 Tension stages



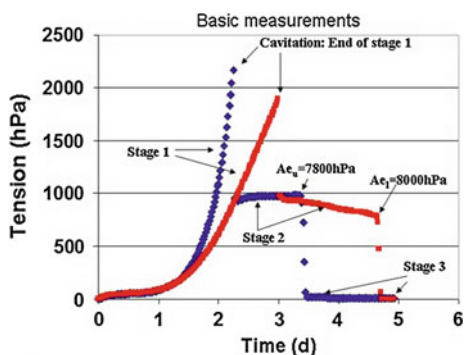
will be less dry (i.e. have a lower tension) than it would be without the presence of the tensiometer. The tensiometer readings in this stage are no longer representative of the soil water's matric potential. The initiation of stage 2, however, can be delayed if boiling retardation occurs. With a suitable tensiometer design, reliable tension values >400 kPa can be measured before cavitation occurs and the pressure inside the tensiometer collapses to the liquid's vapour pressure (Schindler et al. 2010a). The third and final stage can be called the "air-entry stage". It occurs when the tension in the surrounding soil exceeds the air-entry pressure of the ceramic material. The largest continuous pore of the ceramic cup drains and air enters from the soil into the tensiometer. At this moment, the measured tension collapses towards zero, which is easily visible in the tensiometer reading.

3.2 Principle of the Extension of the Measurements

The basic concept for extending the measurement range is to use the ceramic cup's air-entry pressure at the exact moment of the collapse in tension, i.e. at the initiation of stage three, as an additional measurement of the soil's matric potential. If this assumption is valid (which will be discussed later), an interpolation of the tension from the last reliable values of stage 1 to the initiation point of stage 3 can be performed. Figure 8 shows the basic values and in Fig. 9 the interpolation is demonstrated. Any smooth function with higher-order continuity, such as polynomial functions or Hermitian spline interpolation, can be used for interpolation with relatively little uncertainty. Applying this procedure to both tensiometers extends the data evaluation into the dry range (Schindler et al. 2010b).

As well as the general pre-condition that the matric potential of the tensiometer cup is in equilibrium with the soil with which it is in contact, the validity of the proposed method depends on the following points: (1) the air-entry pressure is well defined and reproducible, and (2) the water loss from the tensiometer to the surrounding soil during stage 2 does not affect the soil's tension at the beginning of stage 3. It is helpful, however, but not absolutely necessary, to achieve the

Fig. 8 Principle of tension interpolation—basic measurements



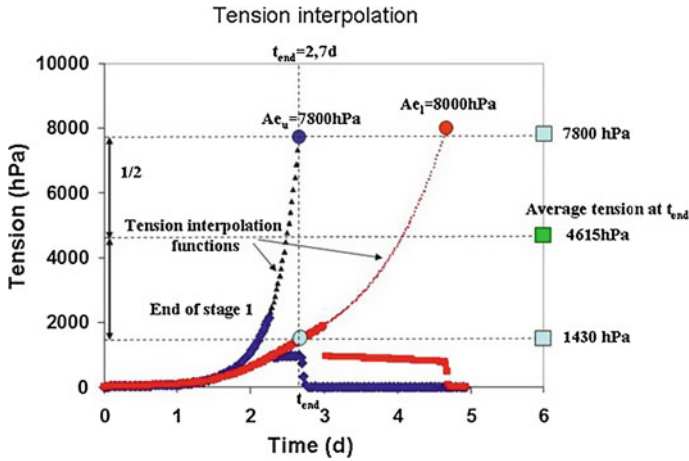


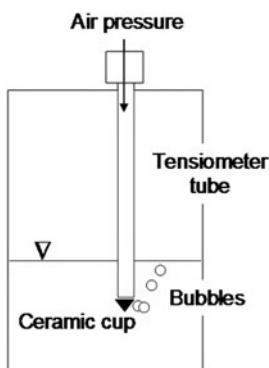
Fig. 9 Principle of tension interpolation

cavitation range for extending the range using the tensiometer’s air entry value. The first assumption can be tested empirically by repeatedly determining the air-entry pressure of the tensiometer cup material, as demonstrated in Schindler et al. (2010a). The second assumption depends on a variety of factors. Most important amongst them are (1) the speed of drying the soil, (2) the unsaturated hydraulic conductivity of the surrounding soil material, (3) the size of the contact area between tensiometer cup and the soil and, most importantly, (4) the amount of water loss from inside the tensiometer into the surrounding soil. The latter is directly related to the void space inside the tensiometer, but also to the alignment of the instrument. To investigate the bias in the tension measurements due to water loss from the tensiometer, HYDRUS-2D software was used to numerically simulate the drying process of the soil with an embedded tensiometer (Šimůnek et al. 1999). The HYPROP® (UMS Munich) system was used in the experiment. This is a commercial piece of apparatus with vertical aligned tensiometers that is optimised to perform evaporation measurements. Additionally, the effect of horizontally embedded tensiometers was simulated as this is typical in traditional laboratory design. It was found that the wetting effect is of negligible importance for the accuracy of hydraulic functions when the tensiometers used are designed and vertically embedded as in the HYPROP equipment (Schindler et al. 2010b).

3.3 Determining the Air-Entry Value of the Tensiometer’s Ceramic Material

To determine the air-entry pressure of the tensiometer cups, a procedure was developed (Fig. 10) that produces reliable and reproducible results (Schindler et al.

Fig. 10 Determination of the tensiometer's air-entry value



2010b). It is recommended that measurements are taken after those for evaporation. The protocol is as follows:

- (1) The procedure starts with the saturation of the ceramics, which follows the standard tensiometer preparation protocol before use. Saturate the ceramic cup carefully with de-ionised water under vacuum. This step takes approximately 1 h.
- (2) Empty the tensiometer and place it in a glass filled with de-ionised water.
- (3) Apply a positive pressure within the tensiometer tube by connecting it to a compressor or compressed air bottle. Increase the pressure up to the expected air-entry pressure p_1 (material characteristic—provided by the ceramic's manufacturer) and wait approximately 30 min (base check for tightness). If no visible bubbles form at the ceramic cup, increase the pressure slowly in 20 kPa steps and pause at each step for about 2 min. It is advisable to use a loupe for the observation.
- (4) Stop the experiment when bubbles leave the ceramic cup and take the pressure reading (p_2). To verify this air-entry pressure, repeat the procedure as described in the next step.
- (5) Saturate the ceramic cup again and start the experiment with pressure $p_3 = (p_1 + p_2)/2$. Wait approximately 30 min.
- (6) If no bubbles leave the ceramic cup, increase the pressure from p_3 in 10 kPa steps and wait at each step for approximately 30 min. The experiment is complete (specified air-entry pressure) when bubbles leave the ceramic cup.
- (7) If bubbles form already in the repetition cycle at p_1 , start the procedure at pressure p_1 minus 100 kPa, and repeat the procedure as described.

3.4 Extended Hydraulic Functions

Figures 11 and 12 show exemplary results for extended hydraulic functions for a sandy soil sample. The interpolation between representative measurements (stage

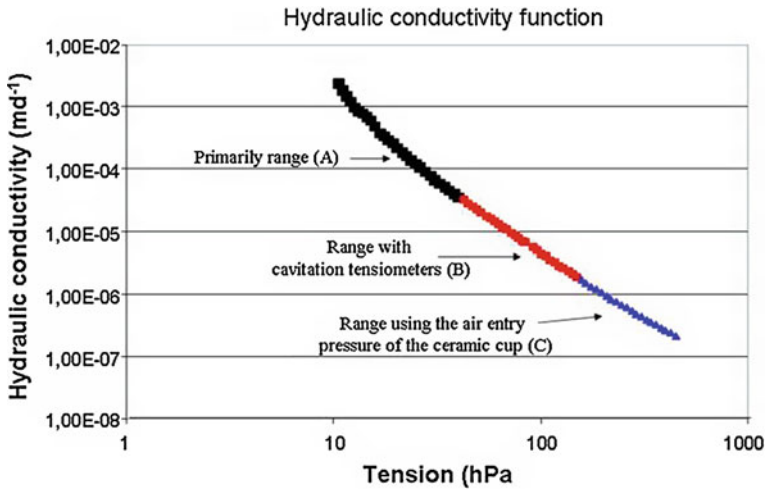


Fig. 11 Extended hydraulic conductivity function measured using the HYPROP system, sand, Al horizon, Muencheberg site

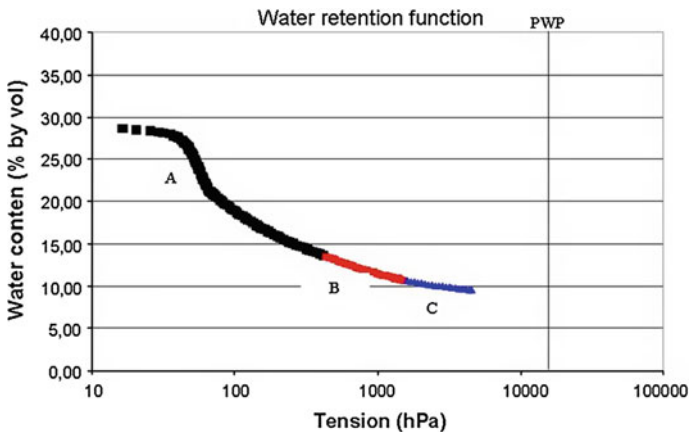


Fig. 12 Extended water retention function measured using the HYPROP system, sand, Al horizon, Muencheberg site

1) and air-entry pressure extends the range of the hydraulic functions almost by one order of magnitude, close to the permanent wilting point.

The actual range for the extension depends on (1) the air-entry pressure of the ceramic material and (ii) the tension difference between the tensiometers at the end of measurement. The HYPROP tensiometer’s ceramic material is very uniform. Generally, air enters the tensiometer interior between 8 and 9 bar. The procedure described above (Schindler et al. 2010b) enables this to be determined accurately. The tension difference at the end of measurements depends on the soil and the

evaporation rate. Generally, sand and clay soils have high tension differences, whereas the differences between peat and silt soil are rather small. Thus the extension ranges between 4.5 and 7.5 bar.

The measurement time depends on the soil and the evaporation rate. Under laboratory conditions with evaporation rates between 2 and 5 mm d^{-1} generally the total measurement varied between 3 and 10 days.

4 Conclusions

1. The evaporation method allows the water retention curve and the hydraulic conductivity function to be measured simultaneously.
2. Measurement time ranges between 2 and 10 days. The measurement of multiple samples can be achieved at the same time.
3. Applying evaporation functions reduces costs whilst retaining the accuracy of the measurement (Schindler et al. 2006).
4. Using specially designed tensiometers and setting the air entry pressure of the ceramic cup allows the extension of the measurement range to close to wilting point.
5. The HYPROP software tensioVIEW was developed for data recording, and HYPROP-Fit for calculating, evaluating, fitting and exporting hydraulic functions (UMS GmbH Munich (2012), <http://www.ums-muc.de> 2012).
6. Water retention measurements using traditional methods (CLM) corroborated EEM results. Systematic deviations between the methods were not found.

Acknowledgments Author thanks the HYPROP developer group of the UMS GmbH Munich (Dipl. Ing. Georg von Unold, Dipl. Ing. Thomas Pertasek, Dipl. Ing. Andreas Steins), Prof. Dr. Wolfgang Durner (TU Braunschweig), and Dr. Andre Peters (TU Berlin) for their cooperation.

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