Hydrology and Earth System Sciences Discussions

Polymer tensiometers with ceramic cones: performance in drying soils and comparison with water-filled tensiometers and time domain reflectometry

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Abstract

Measuring soil water potentials is crucial to characterize vadose zone processes. Water-filled tensiometers only measure until approximately −0.085 MPa, and indirect methods may suffer from the non-uniqueness in the relationship between matric potential and measured properties. Recently developed polymer tensiometers (POTs) are able to directly measure soil matric potentials until the theoretical wilting point (−1.6 MPa). By minimizing the volume of polymer solution inside the POT while maximizing the ceramic area in contact with that polymer solution, response times drop to acceptable ranges for laboratory and field conditions. Contact with the soil is drastically improved with the use of a cone-shaped solid ceramics instead of flat ceramics. The comparison between measured potentials by polymer tensiometers and indirectly obtained potentials with time domain reflectometry highlights the risk of using the latter method at low water contents. By combining POT and time domain reflectometry readings in situ moisture retention curves can be measured over the range permitted by time domain reflectometry.

1 Introduction

Measurement of the soil water matric potential (ψ_m) is important to characterize and monitor processes in vadose zone hydrology, such as plant growth, crop production, aquifer recharge, and leaching below buried waste disposal sites (Young and Sisson, 2002). Tensiometers are widely used instruments to monitor ψ_m, and have been used for almost 100 years (Or, 2001; Young and Sisson, 2002). All tensiometers consist of three elements: a ceramic that is in contact with the soil, a water reservoir in equilibrium with the soil water, and a pressure measurement device that measures this equilibrium accordingly. Unfortunately, water-filled tensiometers are only able to measure ψ_m above approximately −0.09 MPa, and soil physical experimental research is hampered by this very limited measurement range (We will consistently deploy the

pressure equivalent of the matric potential).

Reece (1996) stated that field psychrometers have a measurement range between −0.5 and −5 MPa when used with sensitive instrumentation, and without temperature gradients, but did not give additional quantitative data. Agus and Schanz (2005) on the other hand, note that thermocouple psychrometers have a slow response and are subject to significant measurement errors above −1.0 MPa. Measurements of ψ_m between −0.09 and −0.5 MPa can be done by filter paper, electrical resistance, inference from soil moisture content and soil moisture retention curve, and heat dissipation methods (e.g. Noborio et al., 1999; Andraski and Scanlon, 2002; Agus and Schanz, 2005). These methods are not derived from thermodynamic principles, but rely on calibrating sensor properties against known ψ_m (Campbell and Gee, 1986). Difficulties arise from the non-uniqueness in the relationship between ψ_m and measured properties, as the measured properties also depend on other variables (for example temperature) (Campbell, 1988).

Attempts have been made to circumvent cavitation of tensiometers and to extend their measurement range. Tamari et al. (1993) used microtensiometers that could measure until approximately −0.14 MPa for short time periods only. Nucleation particles were removed by purging the tensiometers extensively with demineralized water, and this created the possibility of having a metastable state of the liquid. Miller and Salehzadeh (1993) used a stripper to remove dissolved air from the tensiometer's water reservoir, and could thus reach −0.18 MPa. For geotechnical applications Ridley and Burland (1993) constructed a tensiometer that measured ψ_m down to −1.5 MPa, unfortunately the instrument worked for a few hours or less. This tensiometer, later studied by Tarantino and Mongiovì (2001), required a 24 h pre-hydration phase in a high pressure chamber, at 4.0 MPa, to dissolve air bubbles, and stopped working as soon as cavitation occurred. The tensiometer can only be used in the laboratory due to the elaborate preparation prior to use.

Peck and Rabbidge (1966, 1969) were the first to use a polymer solution instead of water. The osmotic potential (π) of a hydrophilic polymer causes a build-up of pressure

when the polymer is exposed to free water through a membrane permeable to water but not to the polymer. Using the subsequent drop in π as a measure for the actual ψ_m in the soil, Peck and Rabbidge (1969) were able to measure down to -1.5 MPa. Their instrument, later studied by Bocking and Fredlund (1979), suffered from gradual loss of pressure, unkown zero drift, temperature effects and slow equilibration times. Progress on polymer filled tensiometers was not made until a ceramic was used that greatly reduced polymer leakage (Biesheuvel et al., 1999). Bakker et al. (2007) presented a polymer filled tensiometer that worked properly beyond wilting point, and found an empirical relation to predict the remaining loss in pressure caused by to diffusion of some smaller-sized polymers through the membrane (Caulfield et al., 2003). It was also shown that by reducing the volume of the polymer solution, the polymer tensiometer's (POT) response time decreased. Bakker et al. (2007) used flat ceramics, which provided a challenge to ensure good contact between the soil and a POT.

In this paper we describe POTs that used ceramic cones instead of flat ceramics. The cones had an air entry value below -1.75 MPa, and thus they remained equally conductive until the theoretical wilting point of -1.6 MPa. The function of the cones is to transfer the ψ_m from the soil water to the polymer solution with minimum water displacement. We evaluated their performance in soil by comparing the recorded ψ_m by those derived from time domain reflectometry (TDR). The soil moisture content (θ_{TDR}) readings were converted to ψ_m using the soil moisture retention curve ($\theta_{GRAV}(\psi_m)$). TDR has gained widespread acceptance as a standard method to measure θ (e.g. Ferré and Topp, 2002), and has served as a method to develop sensors that infer ψ_m instantly (e.g. Or and Wraith, 1999).

The objective of this paper is to present POT designs that minimize the volume of the polymer solution while maximizing the ceramic area in contact with the polymer solution, and that solve contact problems between the ceramic and the soil. We thoroughly tested the designs in two soil types, and compared the observations with TDR and water-filled tensiometer measurements. Furthermore, we investigated the possibility of combining POT and TDR data to derive in situ moisture retention curves ($\theta_{TDR}(\psi_m)$).

2 Materials and methods

2.1 Design and operational procedures

We used a design (Table 1) that incorporated a solid cylindrical ceramic instead of a flat ceramic (Fig. 1) (Peck and Rabbidge, 1966, 1969; Biesheuvel et al., 1999; Bakker et al., 2007), to ensure good contact with the soil. A $2\,\mu m$ γ-Al_2O_3 ceramic membrane purposed to prevent large polymer leakage (Alami-Younssi et al., 1995; Bakker et al., 2007; De Vos and Verweij, 1998) was applied to the base of the cones. The construction details were described by Bakker et al. (2007), with the exception that their 0.2 mm synthetic ring was replaced by a rubber O-ring at the side of the pressure transducer. This modification eliminated undesired forces to the top of the transducer, which might lead to deformation and malfunctioning of the transducer.

We used four variants of the design, in which the surface area of the ceramic in contact with the soil and the surface area in contact with the polymer chamber were varied, i.e. by adjusting the length and diameter of the ceramic. This resulted in different polymer chamber heights (Table 1). The various POT designs (identified by a number in Table 1) had repercussions for the level of skill required to manufacture the POT, and also affected its behavior. The polymer chamber height (Table 1) ranged from 2.5 to 1.1 mm, which was 2 to 4 times smaller than described by Bakker et al. (2007). We used seven POTs filled with Praestol 2500 and one with Dextran 500 (see Table 2 for specific properties). The POTs were then placed in a temperature controlled water bath filled with demineralized water for at least 28 days at 25°C±0.01°C to allow the polymer to saturate. Long-term behavior and pressure-temperature relationships as described by Bakker et al. (2007) were determined before using the POTs in soil. From the measurements to determine the pressure-temperature relationships we could also determine temperature response times of the various POT designs (Bakker et al., 2007). Pressure change caused by external pressure variations were instantaneous regardless of POT design, and are therefore not further discussed.

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2.2 Evaporation experiments

To determine the ψ_m with POTs, the π of each individual POT in the water bath is required as a reference. By using the subsequent drop in pressure the positive π inside the POT can be related to the negative ψ_m in the soil. For the evaporation experiment this reference pressure was determined by averaging pressure measurements over 24 h before the instruments were taken out of the water bath, and installed in soil. We ignored the hydrostatic pressure component, since the immersion depth (<0.2 m) produced a pressure three orders of magnitude smaller than π inside the POT.

We filled two evaporation boxes (EB) of 0.40×0.30×0.40 m L×W×H (Fig. 2), one with sand (97.6% sand, 1.6% silt, 0.8% clay; EB1), and the other with loam (42.8% sand, 38.8% silt, 18.4% clay; EB2). Both materials were sieved at 2 mm, and uniformly pre-wetted. We added soil in 5 cm layers, tamped them, and raked the upper 2 cm before adding a new layer. The containers were equipped with a perforated bottom that was covered by a steel grid and a cloth, and with wall-to-wall perforated PVC tubes (outer diameter of 20 mm), also covered with cloth. The perforations facilitated fast and uniform drying of the soil. To enhance evaporation, the air humidity in the laboratory was kept low by using an air dryer.

Each EB was equipped with 4 POTs (see Table 1 for specific properties), 4 TDR-probes (Minitrase, Soilmoisture Equipment) and 4 conventional, water-filled tensiometers (CTs, Rhizo Instruments) that were installed while filling the boxes (Fig. 2). We used 3-rod TDRs with 8 cm long, 0.32 cm diameter rods spaced at 1.4 cm, which gives an approximate measurement volume of 250 cm^3 (Ferré et al., 1998; Huisman et al., 2001). The POTs and TDRs were placed opposite to each other; the CTs were placed in between. The CTs contained a gas stripper that was connected to a vacuum pump (Miller and Salehzadeh, 1993) to prevent formation of air bubbles inside the instrument. During the evaporation experiment, the POTs, TDRs and CTs had a measurement interval of 10 min. EB1 (sand) was gradually saturated from the bottom by placing the box in a larger, water tight encasing, and adding non-chlorinated tap water at 1 cm h^{-1}

(with a maximum of $8\,cm\,d^{-1}$) for seven days, then leaving the set-up water-logged for two days before opening an outlet in the outer casing to drain the sand. EB2 (loam) was similarly saturated at a rate of $2\,cm\,h^{-1}$ (with a maximum of $12\,cm\,d^{-1}$) for four days, and drained six days later. The influence of salts of the tap water and in the original soil solution on the osmotic potential inside the POTs was assumed negligible.

After some time the drying process slowed down in EB1. We therefore placed a small ventilator in front of the box facing the outlets of the PVC tubes 42 days after drying commenced. A similar ventilator was used for EB2 during the entire experiment. Soil samples of $20\,cm^3$ were taken during the experiment to establish a soil specific relation between the volumetric moisture content (θ) and measured dielectric permittivity of the TDRs. At the end of the experiment EB1 was moistened from below again for 7 days to verify the response of the POTs, then gradually saturated in 3 days. EB2 was not rewetted to prevent density changes due to soil swelling. Instead in EB2 the POTs were taken out of the soil, and placed back into the temperature controlled water bath. POT responses were recorded before, during and after the transfer from the soil to the water bath. After the evaporation experiments, pressure-temperature relations were again determined for all POTs, to monitor possible changes in the chemical properties of the polymer solutions.

We obtained $100\,cm^3$ soil cores ($N{=}27$) from both boxes to determine the $\theta_{GRAV}(\psi_m)$-curve and the bulk density. For ψ_m between -2×10^{-4} and $-1\times10^{-2}\,MPa$, we placed the soil cores in a hanging water column set-up (Romano et al., 2002), and related θ_{GRAV} to ψ_m in the center of the sample (sample height 5 cm). For $\psi_m < -1\times10^{-2}$ we used the pressure plate method with 0.5 cm high samples (Campbell, 1988; Dane and Hopmans, 2002).

To determine in situ retention curves, each POT was paired with an opposite TDR (Fig. 2). Data were paired according to measurement time. Differences between the internal clocks of the POTs and TDRs were negligible. We assumed that instrument location in the tank and the different measurement volumes of both instruments did not affect the shape of the retention curve. To fit the gravimetric measurements from soil

cores, and the in situ measured retention data we used the frequently used equation of van Genuchten (1980):

$$S_e = \left[1 + (-\alpha h_m)^n\right]^{-m} \tag{1}$$

Where S_e is the normalized volumetric moisture content, α (L^{-1}) is a parameter to scale the matric head h_m (L), and both n and m are independent, dimensionless parameters.

Because we initially saturated the soil, the resulting moisture retention curve is the main drainage curve (Dane and Hopmans, 2002). We fitted a retention curve to the soil core data. This retention curve was subsequently used to convert θ_{TDR} observations to ψ_m to compare the POT readings independently.

3 Results

3.1 Temperature response times

Temperature response times for the various POT designs are given in Table 3. The temperature response times include the time it took the water bath to heat up (in case of a temperature rise) and cool down (in case of a temperature drop). For 5°C increments, and depending on the temperature in the laboratory, a temperature drop could take up to 0.408 h and a temperature rise up to 0.166 h. For 2.5°C increments we could decrease cooling time to 0.166 h, and heating time to 0.084 h.

Smaller polymer chamber heights resulted in shorter response times. An exception is POT1B that had, despite its polymer chamber height of 2.5×10^{-3} m, a comparable response time with POT3B with a polymer chamber height of 1.1×10^{-3} m. In POT1B the response time for the 2.5°C drop was shorter than for the 2.5°C rise, whereas all other POTs showed the opposite. This deviating behavior can probably be attributed to the Dextran used in this POT.

POT design 3 and 4 (Table 1) show that a larger ceramic area in contact with the polymer solution shortened the temperature response time. Finally, the amount of

polymer inside the polymer chamber had an effect on the temperature response times. This effect could be observed in POT2, which has a larger polymer chamber height than POT3A and POT3B, but contained less polymer, and consequently had shorter response times. Similarly POT 4A had shorter response times than POT4B, even though the chamber depth and the ceramic area in contact with the polymer solution were equal.

3.2 The soil drying process

The initial θ_{TDR} in EB2 was higher compared to EB1; this is probably an effect of soil repacking (dry bulk density of EB1 1504 kg m^{-3} (N=16); of EB2 1366 kg m^{-3} (N=18)). Average reduction in θ_{TDR} per day was 0.0067 for EB1 and 0.012 for EB2; the latter was probably higher due to the use of the ventilator throughout the experiment. Average soil temperatures were also slightly higher in EB2 (25.9°C) than in EB1 (24.7°C).

Figure 3 shows the development of the ψ_m and the θ_{TDR} in time of EB1 and EB2. POT3B in EB1 showed a sudden drop in pressure after 21 October 2004, where the same POT3B showed a much more gradual drop in EB2. These pressure responses are consistent with the typical retention curves of sand (EB1) and loam (EB2). The TDR measurements showed a fast decrease of θ_{TDR} by drainage of the saturated soil, and a gradual decrease of θ_{TDR} as a result of evaporation. In EB1 the placement of the small ventilator at 1 October 2004 can be seen in the slope of θ_{TDR} around that date. We do not know the reason of the slightly erratic behavior around 8 September 2004.

3.3 Comparison of POTs, TDRs, and CTs

Moisture content measurements (θ_{TDR}) were converted to ψ_m by means of the independently determined moisture retention curve $\theta_{GRAV}(\psi_m)$ (gravimetric measurements on soil cores). Figure 4 shows the comparison for EB1 of POT measured potentials with converted θ_{TDR} measurements from the TDR opposite of each POT, and with potential measurements from the CTs in close vicinity of the POTs (see Fig. 2). Differences

between sensors were small until 7 October 2004. Then, the converted potentials from TDR1 and 2 started to deviate from the POT and CT measured potentials, while TDR3 and 4 still followed the trend of the other instruments. CT1 cavitated on 19 October 2004 at −0.025 Mpa and CT3 on 21 October 2004 at −0.082 Mpa. All POTs continued to function beyond the theoretical wilting point of −1.6 Mpa. The horizontal stretch immediately after cavitation represents atmospheric pressure within the polymer chamber (zero relative pressure). The negative ψ_m recorded just before cavitation reflects subatmospheric pressures. The γ-Al_2O_3 membrane will remain saturated until 112 Mpa, thus blocking air from entering the polymer chamber. Water can still leave the polymer chamber though, and as a result the volume of the polymer solution can become less than the chamber volume, producing negative pressure readings.

At 1 November 2004 when the evaporation container was moistened from below, all POTs regained their original pressure within 0.7 days, except POT4B that needed almost 4 days (Table 3). At 15 November 2004, small peaks in the measurements reflect replacement of the POTs of EB1 in a water bath with demineralized water. From 22–24 November 2004 we determined the temperature response of the POTs to compare to the temperature response before the evaporation experiment. No significant changes were found.

In EB1, the TDRs all started to show very noisy converted ψ_m after 20 October 2004, when the soil had dried considerably. This was due to the very low θ_{TDR} (Fig. 5). Even limited noise in θ_{TDR}-values is magnified in the derived ψ_m-values in the steep dry end of the moisture retention relationship.

For EB2, the comparison between POT, TDR and CT (Fig. 6) shows the same trends as in EB1; in the beginning all measurements were close, converted potentials of the TDRs started to deviate around 7 February 2004, and CT and POT data were in good agreement until the CTs cavitated; CT1 on 13 February 2005 at −0.083 Mpa, and CT4 on 15 February 2005 at −0.050 Mpa. All POTs functioned beyond wilting point. After the experiment, when we placed the POTs in the temperature controlled water bath, all POTs regained pressure within 0.7 d (Table 3). Comparison of the rewetting times of

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POT3B in the soil and the water bath indicate a faster pressure recovery in the water bath. The slower recovery in the soil probably stems from the wetting front that traveled upwards through the soil, and the available water flux at the interface between soil and ceramic. Temperature response of the POTs in EB2 was not significantly different before and after the evaporation experiment.

For both EB experiments, the POTs showed a bump that occurred at -1.3 to -1.7 Mpa (the starting point of the bump is determined by $d\pi/dt=0$, with t time). This would seem to reflect stagnation in the decreasing ψ_m, but did not happen at equal π for all POTs, thus suggesting a reason intrinsic to individual POTs. A possible explanation could be the air entry values of the ceramics. If the specified ceramic's air entry value is the result of averaging or random testing, the actual air entry value of an individual ceramic will deviate to some degree from the specified value. As soon as ψ_m reaches the air entry pressure of the ceramic, the soil is wetted by a small amount of water flowing out of the ceramic, thereby temporarily reducing the gradient between the soil and the polymer chamber. From the moment the soil is wetted by water in the ceramic, the POT essentially measures the potential of the partially saturated ceramic, which deviates a little from ψ_m because of the gradient that needs to be sustained to maintain the small water flux from the ceramic induced by the drying soil.

The TDR converted ψ_m showed some noise, but this did not explain the observed difference between the TDR and POT measurements, that was more pronounced in EB2 compared to EB1. These differences will be explained by comparing the moisture retention curves from in situ observation, soil core data, and the van Genuchten fits.

3.4 Comparison of moisture retention curves

We plotted retention curves of θ_{TDR} and the POT-measured ψ_m together with soil core data and fitted retention curves (Figs. 7 and 8). We were mostly interested in the dry end of the moisture retention curve, and therefore plotted on a linear scale instead of the more conventional log scale. For the in situ curve, data were selected with a θ interval of 0.05, and a ψ_m interval of 0.5 MPa. Additionally for EB1, a number of

strategic points were selected to better describe the sharp bend in the transition from the wet to the dry end of the retention curve. For EB2 the moisture retention curve was smooth and such additional points were unnecessary. During fitting, the residual moisture content was fixed at 0 in most cases to prevent the occurrence of negative volumetric moisture contents in the dry end of the curve. Fitted parameter values and R^2 for each data set are given in Table 4. For most in situ data, the retention curve showed a good fit, with R^2 above 0.75. For combination EB1 POT2 TDR3 the fit had a R^2 of about 0.3; this was due to the slightly deviating pressure values (<0.01 MPa) of POT2 between a θ_{TDR} of 0.3 to 0.4.

Values for n in Table 4 are very high, reflecting the flatness of the curve in the wet regions (where θ drastically drops and ψ_m decreases only marginally), and the sharp bend in the curve from the wet to the dry region (where ψ_m decreases). This apparently extreme behavior may well be caused by the limited vertical extent of the measurement region over which ψ_m is averaged. In standard laboratory set-ups, the samples are typically approximately 5 cm high, causing significant differences in the water content near the top and the bottom of the sample in the region where θ is very sensitive to ψ_m. This causes a smoothing of the apparent moisture retention curve, as Liu and Dane (1995) demonstrated, leading to lower values of n in the van Genuchten (1980) parameterization. As the measurement volume of the POT is essentially the surface of the ceramic, vertical averaging is much less significant. This explains the sometimes extreme values for n in Table 4.

From Figs. 7 and 8 it can be seen that in situ and soil core data deviate slightly from each other, probably as a result of different measurement techniques. Madsen et al. (1986) and Peck and Rabbidge (1969) also observed discrepancies between pressure plate and other methods, although these authors mostly observed moisture contents that were higher in case of the pressure plate method, while we sometimes observed lower moisture contents as well. Nevertheless, despite the differences in measurement volumes and instrument location of POTs and TDRs, the in situ retention curves are comparable with the retention curves determined on soil core data.

With the observed and fitted retention data we can explain the observed differences between TDR converted potentials and the POT measured potentials (Figs. 4 and 6).

In Fig. 7a and b, the soil core data and the fit on soil core data show slightly lower pressure values than the in situ observations when θ is between 0 and 0.05, while in Fig. 7c and d, the soil core data and fit show slightly higher values than the in situ observations in the same range. This explains the deviations of the TDR converted potentials from POT measured potentials in Fig. 4, where TDR3 and 4 seem to have slightly less negative potentials from 7 October 2004, while TDR1 and 2 show the opposite. In Fig. 7 it can also be seen that for pressure values higher than 0.01 MPa, fitted values are always positioned left from observed values, indicating that the fitted values will result in less negative pressure values at equal moisture contents. Due to the limited accuracy in dry soils, this cannot be seen in Fig. 4.

For EB2, the deviations between in situ observations, soil core data and fits are more pronounced, and occur over the entire range of measured potentials (see Fig. 8). In Fig. 8b, the soil core data and fitted values indicate higher absolute pressures than the in situ observations at a moisture content of around 0.25, while the fitted soil core observation at 1.6 MPa coincides with the in situ observations. This is resembled in Fig. 6b, where the TDR converted potentials are lower than the POT and CT observations from 7 to 27 February 2005, while later on the POT and TDR converted potentials lie much closer. In Fig. 8a and c, the fitted soil core observation at 1.6 MPa deviates as well, and similarly the TDR converted potentials show larger deviations in Fig. 6a and c. In Fig. 8d, the fitted soil core observation at a moisture content of about 0.25 does coincide with the in situ observations, but at 1.6 MPa the deviation from the in situ observations is even more pronounced than in Fig. 8a–c, and this can also be observed in the TDR converted potentials in Fig. 6d.

In the dry range, the fitted in situ data for both EBs always predicted lower ψ_m than was observed at any given moisture content. The underprediction indicates that retention curve fits have to be interpreted carefully in the dry range of the moisture retention curve, and in combination with the limited accuracy of TDR in dry soils highlight the

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risk of using TDR converted potentials in that range.

4 Conclusions

The temperature response times of the various designs indicate an effect of polymer chamber size, and ceramic area in contact with the polymer solution. Designs that
₅ minimized polymer chamber height, while maximizing the ceramic area in contact with polymer solution had the shortest response times. For all POT designs response times to regain pressure by rewetting were remarkably shorter than reported by Bakker et al. (2007). It should be noted that the reported response times are an extreme scenario; from completely dry polymer to fully saturated. In practice, pressure recovery
₁₀ will generally be much faster.

POTs with ceramic cones have enhanced soil contact compared to POTs with flat ceramics; we never observed poor soil contact. We compared four designs by testing them in soil, and the results showed similar responses. A preferred design therefore mostly depends on the maximization of the ceramic membrane's surface in contact
₁₅ with the polymer solution, and the polymer chamber's depth (Bakker et al., 2007).

In situ moisture retention curves were comparable to retention curves from soil cores, and could be fitted with the van Genuchten curve. Although in situ moisture retention curves will never exceed the upper measurement limit of POTs, pairing POT and TDR data will give a unique opportunity to study the dynamics of moisture retention curves
₂₀ in field soils. Furthermore, POTs can be applied for determination of unsaturated soil hydraulic properties over a larger continuous range, like the estimation of the unsaturated hydraulic conductivity in either conventional (Arya, 2002) or novel (Schneider et al., 2006) experimental setups.

A detailed analysis of POT-measured matric potentials, TDR-measured moisture
₂₅ contents, and the fitted retention curve revealed the risks associated with converting soil moisture readings in dry soils to matric potentials.

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Table 1. Properties of polymer tensiometers (POTs) used in the evaporation boxes (EB).

POT design	EB	Placement in EB[*]	Chamber depth (10^{-3} m)	Polymer type	Polymer amount (g)	Ceramic area in contact with polymer solution (10^{-3} m^2)	Ceramic surface in contact with soil (10^{-3} m^2)
1A	1	BR	2.5	Praestol 2500	0.275	0.167	1.45
1B	2	BL	2.5	Dextran 500	0.229	0.167	1.45
2	1	BL	1.2	Praestol 2500	0.087	0.224	1.76
3A	1	TR	1.1	Praestol 2500	0.124	0.224	1.76
3B	1,2	TL	1.1	Praestol 2500	0.100	0.224	1.76
4A	2	TR	1.1	Praestol 2500	0.067	0.260	1.74
4B	2	BR	1.1	Praestol 2500	0.090	0.260	1.74

[*] Top left (TL), Top right (TR), Bottom left (BL), Bottom right (BR).

Table 2. Properties of the polymers used in the polymer tensiometers.

Polymer (trade name)	Polymer type	Average molar mass (kg mol^{-1})	Percentage of anionic groups	Phase separation when dissolved in water at
Praestol 2500	Polyacrylamide	2500	1[†]	$<-35°C$[‡]
Dextran 500	Polysaccharide	500	0	$<0°C, >50°C$

[†] Davidson (1980, p. 16-2),
[‡] Molyneux (1983, p. 11, Fig. 1).

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Table 3. Temperature and rewetting response times for the various POT designs.

POT design	Temperature response time in hours averaged across the number of experiments (N) per temperature change[†]				Rewetting response times in days[‡]	
	5°C drop	2.5°C drop	5°C rise	2.5°C rise	In evaporation box 1	In a water bath
1A	2.76 (6)	–	2.54 (6)	–	3.98	–
1B	–	0.576 (2)	–	1.13 (2)	–	0.668
2	0.576 (6)	–	0.336 (6)	–	0.503	–
3A	0.816 (6)	–	0.672 (6)	–	0.615	–
3B	0.816 (6)	0.792 (2)	0.480 (6)	0.480 (2)	0.600	0.140
4A	–	0.240 (2)	–	0.168 (2)	–	0.203
4B	–	0.336 (2)	–	0.288 (2)	–	0.564

[†] See Bakker et al. (2007) for details,
[‡] Response time defined as the period between the onset of rewetting and the time at which the observed pressure change equaled the measurement noise.

Table 4. Parameter values for moisture retention curves fitted by Eq. (1).

EB	Provided data	θ_s	θ_r	α (cm^{-1})	m	n	R^2
1	Data from soil cores	0.44021	0.00	0.05735	0.27124	3.4232	0.9298
	POT1A TDR4	0.25111	0.00[†]	0.00542	0.34072	66.40	0.7410
	POT2 TDR3	0.16292	0.00[†]	0.00538	0.05245	12.16	0.3003
	POT3A TDR2	0.25306	0.00	0.01617	0.12297	211.385	0.7919
	POT3B TDR1	0.39595	0.00	0.02188	0.76923	3.4720	0.9034
2	Data from soil cores	0.42628	0.00	0.00192	0.48602	1.005	0.99278
	POT1B TDR3	0.4759	0.00[†]	0.01515	0.01777	17.5954	0.9241
	POT3B TDR1	0.4491	0.00[†]	0.00952	0.04364	8.1052	0.9660
	POT4A TDR2	0.4492	0.00[†]	0.00412	0.03578	12.056	0.9192
	POT4B TDR4	0.44919	0.00[†]	0.00412	0.03578	12.056	0.9192

[†] prefixed value.

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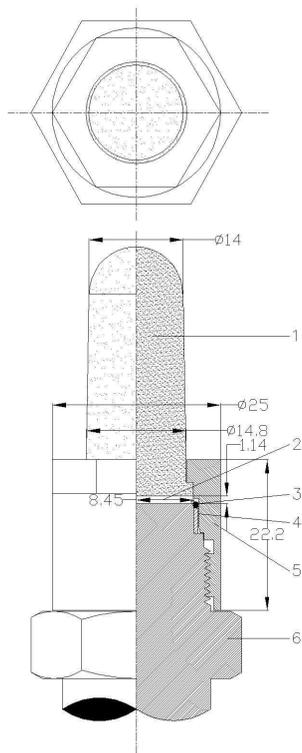
Fig. 1. Polymer tensiometer (POT) design with cone-shaped ceramic containing (1) an α-Al_2O_3 support layer with a γ-Al_2O_3 membrane at the base of the cone, (2) polymer chamber, (3) rubber O-ring, (4) stainless steel ring, (5) stainless steel mounting ring, and (6) a pressure transducer. Various arrows indicate lengths in mm of components of POT ($\emptyset$ is diameter).
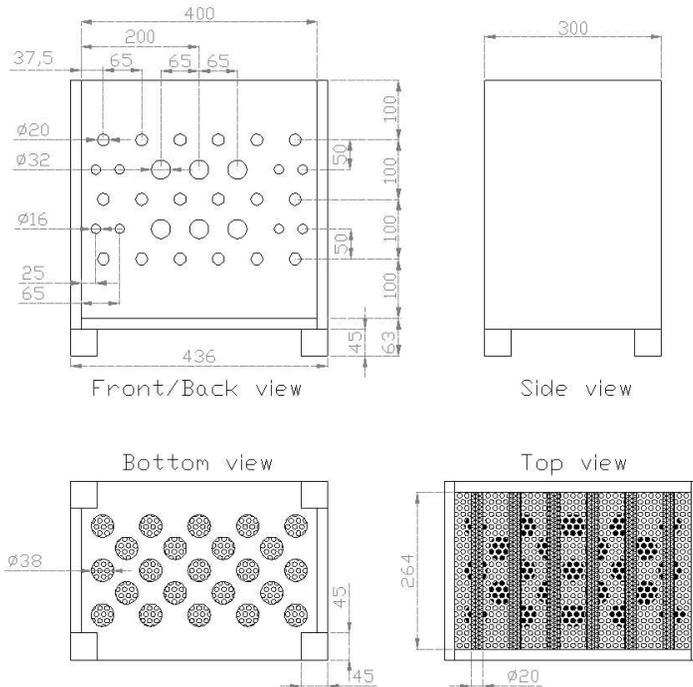
Fig. 2. Design of the box used for the evaporation experiment. Ports of 20 mm held wall to wall perforated tubes that were covered with cloth. Polymer tensiometers (POTs) were placed through the 32 mm front ports, top-left, top-right, bottom left, bottom right. Time domain reflectometry wave guides (TDR probes) were placed at the back ports, one opposite of each POT. Conventional tensiometers (CTs) were placed at the front and back top middle and bottom middle 32 mm ports. Ports of 16 mm facilitated soil sampling to verify the bulk electrical permittivity-volumetric soil moisture relationship during the experiment. All measures in mm.

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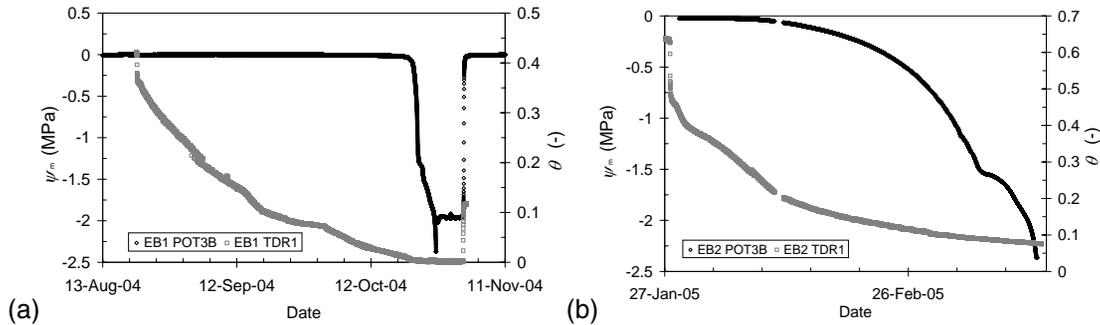
Fig. 3. Development of the matric potential ψ_m of polymer tensiometer 3B (POT3B) and moisture content θ (TDR1) in time for evaporation box EB1 **(a)** and EB2 **(b)**.

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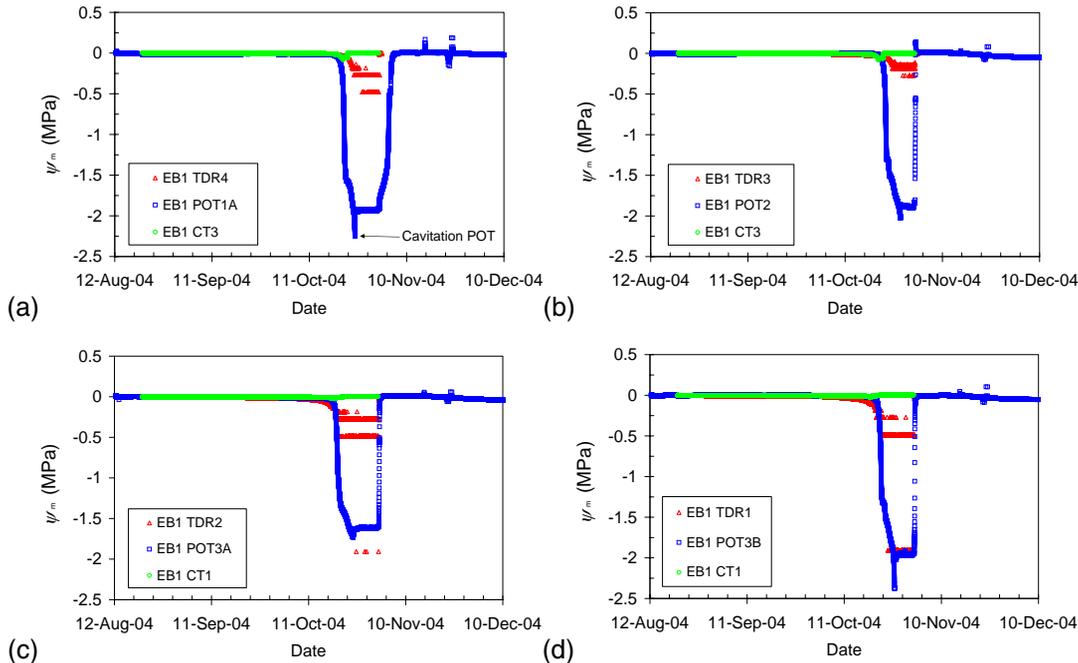
Fig. 4. Development of the matric potential ψ_m in time measured by polymer tensiometers (POT), time domain reflectometry probes (TDR) and water-filled tensiometers (CT) in evaporation container 1 (EB1) that was filled with sand. Each sub-figure shows a POT-TDR pair installed opposite to one another, and the nearest CT.
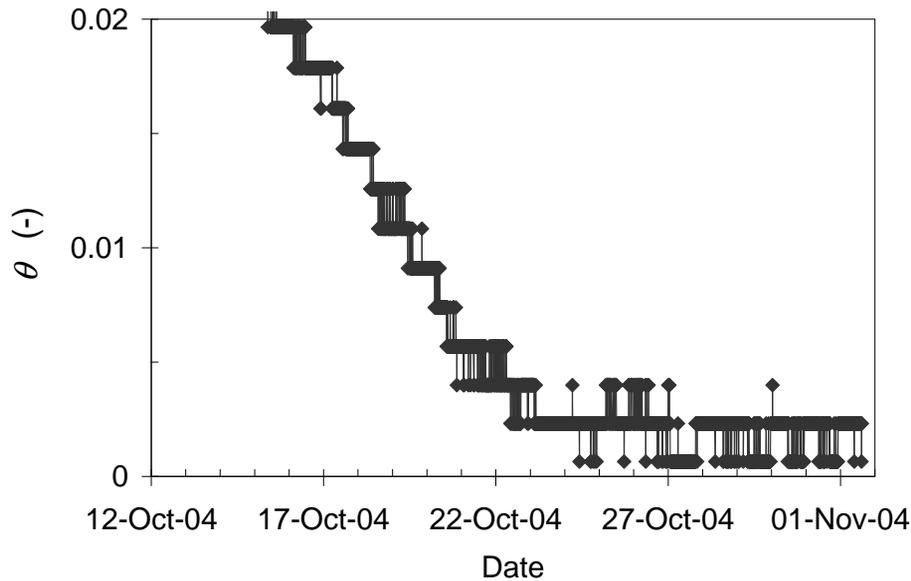
Fig. 5. Volumetric moisture content θ measurements in dry soil by one of the time domain reflectometers (TDR1) installed in evaporation container 1 (EB1).
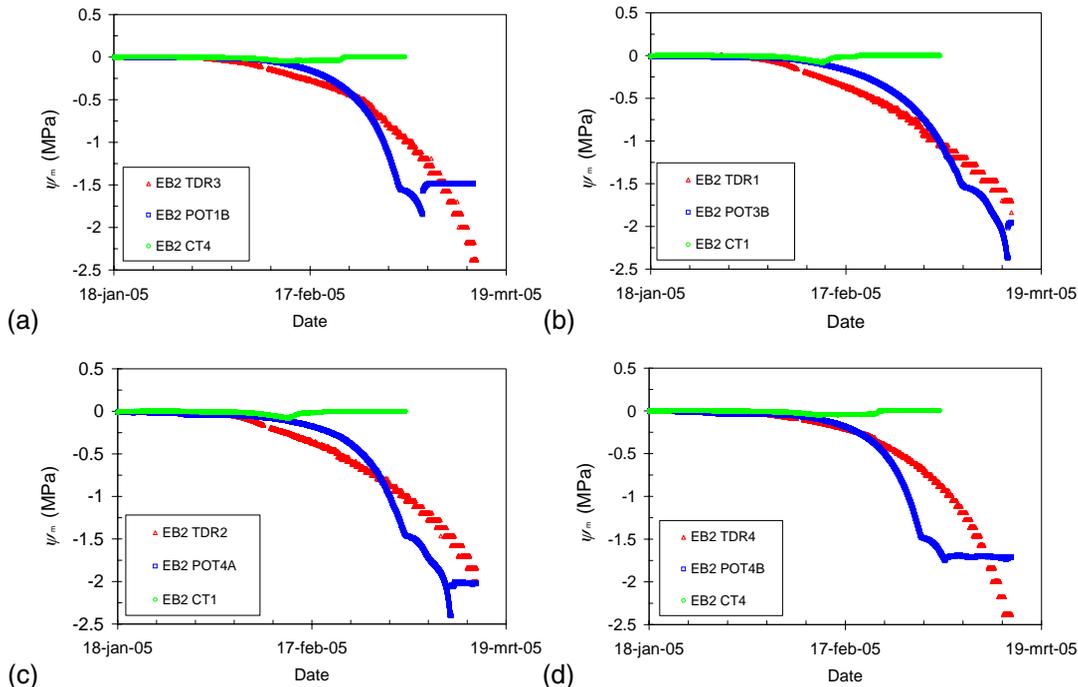
Fig. 6. Development of the matric potential ψ_m in time measured by polymer tensiometers (POT), time domain reflectometry probes (TDR) and water-filled tensiometers (CT) in evaporation container 2 (EB2) that was filled with loam. Each sub-figure shows a POT-TDR pair installed opposite to one another, and the nearest CT.
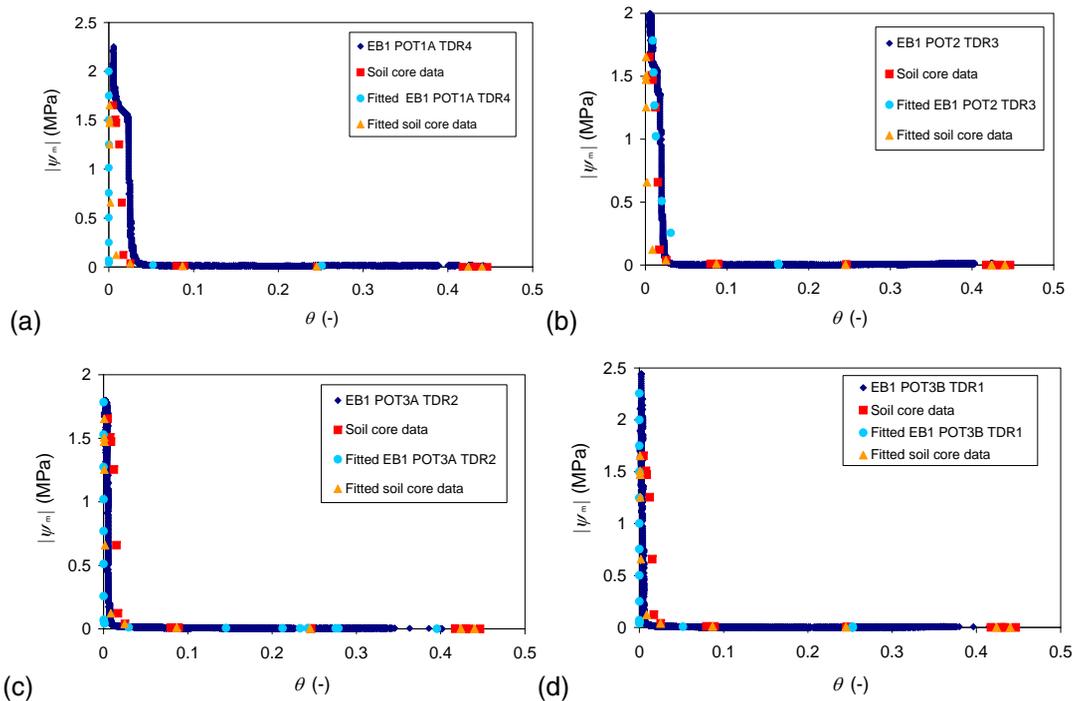
Fig. 7. Moisture retention curves of EB1 for the paired polymer tensiometers (POTs) and time domain reflectometers (TDR) together with gravimetric data from soil cores, and Van Genuchten fitted retention curves (Eq. 1). The minus sign of the matric pressure values (ψ_m (MPa)) has been omitted.
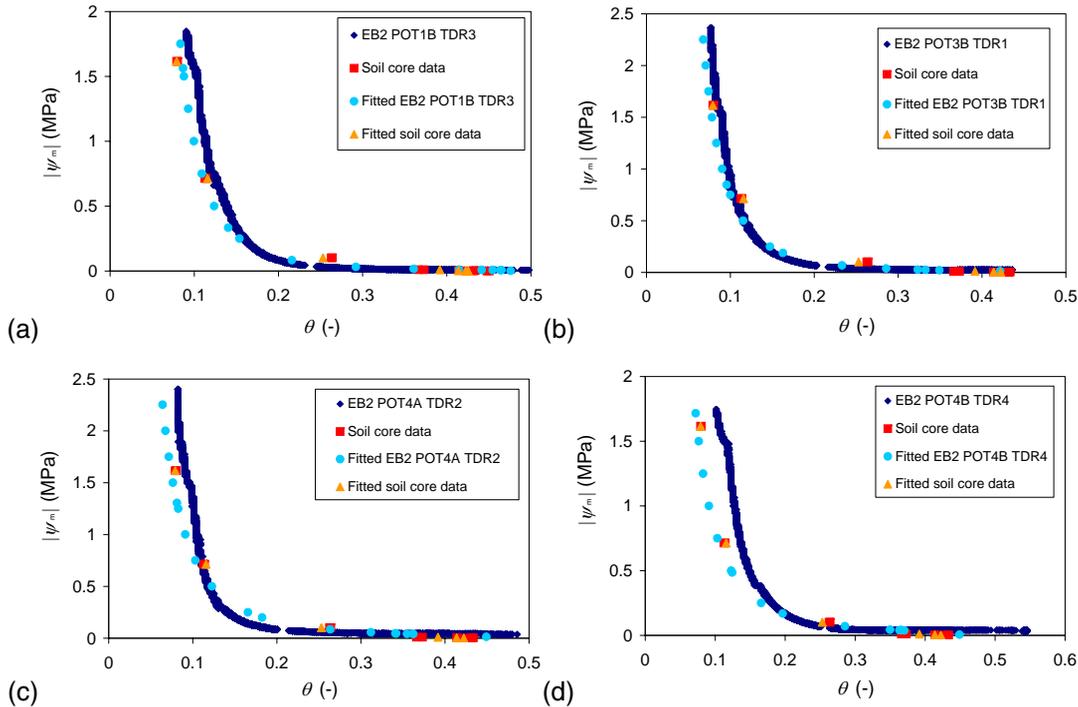
Fig. 8. Moisture retention curves of EB2 for the paired polymer tensiometers (POTs) and time domain reflectometers (TDR) together with gravimetric data from soil cores, and Van Genuchten fitted retention curves (Eq. 1). The minus sign of the matric pressure values (ψ_m (MPa)) has been omitted.