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Monitoring water content changes in a soil profile with TDR-probes at just three depths - How well does it work?

Monitoramento das mudanças no conteúdo de água em um perfil do solo com sondas TDR em três profundidades - Como funciona?

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ABSTRACT

TDR-probes are widely used to monitor water content changes in a soil profile (ΔW). Frequently, probes are placed at just three depths. This raises the question how well such a setup can trace the true ΔW. To answer it we used a 2 m deep high precision weighing lysimeter in which TDR-probes are installed horizontally at 20, 60 and 120 cm depth (one per depth). ΔW-data collected by weighing the lysimeter vessel were taken as the true values to which ΔW-data determined with the TDR-probes were compared. We obtained the following results: There is a time delay in the response of the TDR-probes to precipitation, evaporation, transpiration or drainage, because a wetting or drying front must first reach them. Also, the TDR-data are more or less point measurements which are then extrapolated to a larger soil volume. This frequently leads to errors. For these reasons TDR-probes at just three depths cannot provide reliable data on short term (e.g. daily) changes in soil water content due to the above processes. For longer periods (e.g. a week) the data are better, but still not accurate enough for serious scientific studies.

Keywords: TDR; Soil water content; Measurement accuracy; Water balance.

RESUMO

As sondas TDR são usadas para monitorar alterações no conteúdo de água no perfil do solo (DW). Freqüentemente, as sondas são colocadas em três profundidades. Isso levanta a questão de como essa configuração pode mostrar os verdadeiros DW´s. Para respondê-lo, usamos um lisímetro de pesagem de alta precisão de 2 m, no qual as sondas TDR são instaladas horizontalmente a 20, 60 e 120 cm de profundidade (uma por profundidade). Os dados DW coletados pela pesagem do lisímetro foram comparados com os valores reais dos dados DW determinados com as sondas TDR. Obtivemos os seguintes resultados: Há um atraso na resposta das sondas TDR à precipitação, evaporação, transpiração ou drenagem, porque uma frente de umedecimento ou secagem deve primeiro alcançá-las. Além disso, os dados do TDR são medições pontuais que são extrapoladas para um volume de solo maior. Isso freqüentemente leva a erros. Por esses motivos, as sondas TDR em apenas três profundidades não podem fornecer dados confiáveis sobre alterações de curto prazo (por exemplo, diárias) no conteúdo de água do solo devido aos processos apresentados aqui. Por períodos mais longos (por exemplo, uma semana), os dados são melhores, mas ainda não são precisos o suficiente para estudos científicos confiáveis.

Palavras-chave: TDR; Teor de água no solo; Precisão na medição; Balanço hídrico.

INTRODUCTION

Soil water content is an important state variable of the hydrologic cycle. For water balance studies as well as for many practical purposes (e.g. irrigation scheduling) data on water content changes in the soil are required. The efficient use of water resources also depends on the accuracy of the measured soil water content (Lozoya et al., 2016; Silva et al., 2018).

There are several methods for the measurement of soil water content (Lal & Shukla, 2005; Romano, 2014; Vereecken et al., 2014). The oldest one is to collect soil samples, weigh them, then dry them in an oven and weigh them again (gravimetric sampling; Klute et al., 1986). This method is still employed, in fact it is the standard against which all other methods are usually calibrated. However, because soil is permanently removed by gravimetric sampling, it cannot be repeated too often without affecting the study site. In addition, it cannot be automated and is therefore labour intensive. For these reasons this method is not suited to gather data at short intervals over a long study period, e.g. daily for a growing season.

A big step forward was the advent of the neutron probe which is inserted into a soil profile via an access tube and can be placed at any position along this tube. It sends out fast neutrons and then records the number of slow neutrons bouncing back to the probe from water molecules (more precisely from the hydrogen ions in these molecules; Hillel, 1998). Being non-destructive, apart from installing the access tube at the beginning of a study, water contents can be measured as often as required and at any depth along the tube. However, this method cannot be automated either and is therefore labour intensive, too. Anyhow, it has virtually disappeared in recent years due to radiation safety concerns.

Arguably the most widely used method today is time domain reflectometry (TDR; Dalton, 1992; Noborio, 2001). Here an electric pulse is sent down a pair or triplet of metal rods, depending on the design of the probe (Zegelin et al., 1989), and reflected at their end. The time the pulse needs to travel along the rods and back is determined by the dielectric constant of the soil around the probe, which in turn is largely a function of the water content of the soil (Topp et al., 1980). This method is non-destructive, too, except for the installation of the probes in the soil profile at the beginning of a study. Water contents can be measured as often as required and at any depth a probe is placed in. A big advantage of this method compared to the aforementioned ones is that the probes can be hooked up to a data logger so that the measurements can be automated and carried out at any desired time interval (e.g. every few minutes, every hour or every day). The labour input to collect the data automatically is small and stays the same, regardless of the number of measurements to be taken.

Zotarelli et al. (2011) show that the sensor position affects the accuracy of the soil water content measurement. Also, the number of TDR-probes used and the depths they are placed in differ widely between studies. Frequently only three depths are sampled with one probe per depth. Oliveira et al. (2010) and Feltrin et al. (2017) used this approach in an investigation of the soil water balance in southern Brazil. In Germany this is done in the ongoing TERENO (Zacharias et al., 2011; Pütz et al., 2016) and NaLaMa-nT projects (Paul et al., 2014). The aim of our study is to analyse how well such a setup can trace the true water content changes (ΔW).

To do this one needs to compare ΔW-values obtained with probes at three depths with the true values. Currently the most accurate tool to measure ΔW is a high precision weighing lysimeter (Meissner & Seyfahrt, 2004; Hannes et al., 2015). State of the art models can register mass changes as low as $\pm$ 100 g, under favourable conditions even as low as $\pm$ 20 g (Xiao et al., 2009). For a 2 m deep soil column with a surface area of 1 m^2, which are common dimensions for such lysimeters, this translates into a ΔW of 0.1 and 0.02 mm, respectively.

At Falkenberg in Germany there are several weighing lysimeters with the aforementioned precision. Some of them also contain TDR-probes at three depths. This made them ideally suited for this study. We selected one of them and took the ΔW-data collected by weighing the lysimeter vessel as the true values to which to compare the ΔW-data determined with the three TDR-probes.

MATERIAL AND METHODS

The Helmholtz Centre for Environmental Research - UFZ maintains a lysimeter station at Falkenberg which is located in northern Germany about halfway between Berlin and Hamburg. The mean annual temperature at the site is 8.5°C, the mean annual precipitation 541 mm, and the mean annual grass reference evapotranspiration 535 mm. Precipitation in summer is higher than in winter. The wettest month is June (64 mm), the driest February (29 mm).

The station contains 13 weighable lysimeters of various designs. The selected lysimeter has a depth of 2 m and a circular surface area of 1 m^2. Further details of its design are given by Meissner et al. (2007). It can register mass changes of $\pm$ 100 g, under favourable conditions (low wind, small temperature fluctuations) even as low as $\pm$ 20 g (Xiao et al., 2009). The soil in the lysimeter vessel has a loamy texture, the vegetation on the lysimeter is grass.

Note that weighing registers the sum of the mass of the vessel, the soil and the water in it. Thus, it gives a composite value and not the actual water content. The mass of the vessel and the soil stay constant, so any change in mass is due to a change in water content. Since the initial mass of each component is usually unknown, weighing can only determine water content changes. In addition, weighing cannot differentiate between various depths and therefore can only yield the change in water content in the soil profile as a whole. However, this is done with a very high precision (see above).

Three TDR-probes (TRIME-PICO 32, IMKO GmbH, Ettlingen, Germany) are horizontally installed in the soil in the lysimeter vessel, one each at a depth of 20, 60 and 120 cm. The probes consist of two 110 mm long parallel rods 3.5 mm in diameter and spaced 25 mm apart. At one end the rods enter into a 155 mm long cylindrical body which contains the electronics. The probes sample a soil volume of about 0.25 L each and determine the actual water content at the positions where they are placed. They can measure the water content repeatedly to a precision of $\pm$ 0.2%-vol.

With respect to the 2 m^3 (2000 L) of soil in the lysimeter vessel the TDR-probes take point measurements, because each of them only samples 0.0125% thereof, i.e. 0.25 L. It is then assumed that a measurement represents the water content in a soil volume assigned to the probe, i.e. the point values are extrapolated to a larger volume. This volume is usually chosen such that the probe is located at its centre. Following this approach we assigned the soil volume between 0 and 40 cm depth to the probe at 20 cm depth, the volume between 40 and 80 cm depth to the probe at 60 cm depth, and the volume between 80 and 160 cm depth to the probe at 120 cm depth. For a surface area of 1 m² this is equivalent to 400 L, 400 L, and 800 L of soil, respectively. (The lowest 40 cm of soil are not considered here.) Hence, the volume of water in the profile (W in units of L) based on TDR-readings is calculated as:

$$W = \theta_{20} \cdot 400\ L + \theta_{60} \cdot 400\ L + \theta_{120} \cdot 800\ L \quad (1)$$

where θ_{xx} = volumetric soil water content (usually given as cm³ of water / cm³ of soil, which is numerically the same as L of water / L of soil) at 20, 60 and 120 cm depth, respectively.

TDR-readings and the lysimeter mass are logged every hour. Changes in the volume of water in the soil profile from one point in time (t) to a previous one (t-1) are calculated as:

$$\Delta W = W_t - W_{t-1} \quad (2)$$

To assess the correctness of ΔW for the soil profile derived from the point measurements with the TDR-probes (ΔW_{TDR}) they are compared to ΔW_{true} obtained by weighing the lysimeter vessel. One can assume that the lysimeter weights give a true ΔW, because the weighing precision is very high (up to ± 20 g or 0.02 mm of water, but at least ± 100 g or 0.1 mm) and weighing covers the entire 2 m³ of soil in the vessel. In contrast, the TDR-probes have a measurement precision of ± 0.2%-vol. and only produce point values which are then extrapolated to a larger soil volume. Due to this extrapolation ± 0.2%-vol. at the probe translates to ± 0.8 mm in the volume assigned to the first and second probe (0.4 m³ each), and to ± 1.6 mm in the volume assigned to the third one (± 0.8 m³). If applied to the soil profile in the lysimeter (minus the lowest 40 cm), this (im)precision amounts to ± 3.2 mm. However, it is unlikely that at a given time of measurement all three probes show the maximum error and in the same direction. Hence, the actual imprecision is less, but still much higher than that of weighing.

Note that here we can only look at the soil profile as a whole, because weighing cannot differentiate between different parts of it. Also, for the remainder of this paper all water contents shall be given in mm of water in the soil profile.

Several years of data were available for a comparison. The period from January 1st to October 24th, 2010 was chosen, because the record is fairly complete, except for a gap from August 23rd to September 7th, and September 20th to 24th. At first daily values of ΔW_{TDR} and ΔW_{true} were compared, then longer intervals were looked at (3, 5, 7, 10 and 30 days).

RESULTS

Figure 1 compares the total amount of water in the lysimeter vessel at the end of each day in the study period determined with the TDR-probes to the true value. The values on January 1st, 2010 were arbitrarily set to zero.

The shape of both curves is similar, but the absolute values deviate substantially most of the time. In January and February the agreement is quite good, apart from a short period in late January when W_{TDR} briefly drops well below W_{true}. Towards the end of February W_{TDR} rises above W_{true} and remains there for the rest of the observation period. At first glance it seems that the two curves approach each other for a few days in August and late September, but they don't. It only appears that way, because the horizontal scale is too coarse.

Figure 2 depicts the time course of the true daily changes in water content in the soil profile (ΔW_{true}) and the daily changes determined with the TDR-probes (ΔW_{TDR}). The individual values are plotted against each other in Figure 3. Sometimes both values agree reasonably well, at other times the deviation is very large, on most days there is an appreciable difference. This is quantified in Table 1, column 2. On 41 days (15% of the time) ΔW_{TDR} deviates by ≥ 5 mm from ΔW_{true}, on 108 days (39%) the deviation is ≥ 2 mm, and on 188 days (68%) ≥ 1 mm. Only on 90 days (32%) is the deviation < 1.0 mm, and on 43 days (15%) < 0.5 mm.

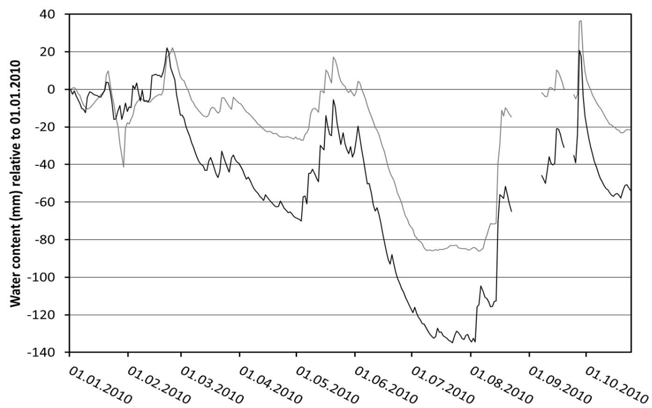

Figure 1. Time course of the water content in the soil profile at the end of each day in the study period. Black line = true values (ΔW_{true}), grey line = values determined with TDR-probes at three depths (ΔW_{TDR}).

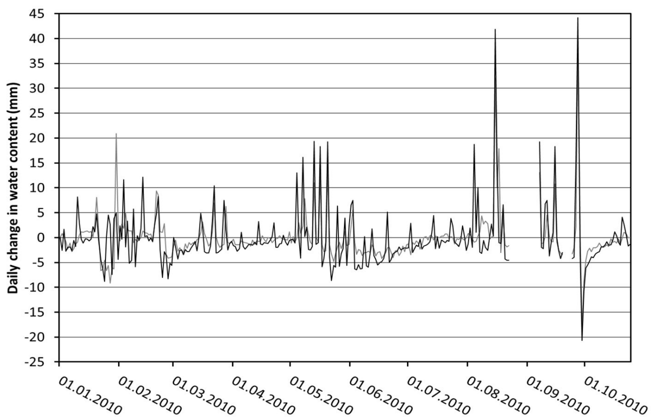

Figure 2. Time course of the change in water content in the soil profile for daily intervals over the study period. Black line = true values (ΔW_{true}), grey line = values determined with TDR-probes at three depths (ΔW_{TDR}).

Table 1. Number of data points where the change in water content in the soil profile determined with TDR-probes at three depths (ΔW_{TDR}) deviates by a certain amount (column 1) from the true value (ΔW_{true}). Column 2: Data from Figure 3 for 1-day intervals. Column 3: Data from Figure 5 for 7-day intervals. Column 4: Data from Figure 5 divided by 7 to convert the 7-day deviations to mean daily deviations.

$\|\Delta W_{TDR} - \Delta W_{true}\|$ (mm)	1-day interval	7-day interval	7-day interval, deviations divided by 7
< 0.5	43	14	94
0.5 to < 1.0	47	13	69
1.0 to < 1.5	40	13	48
1.5 to < 2.0	40	16	18
2.0 to < 3.0	31	24	20
3.0 to < 5.0	36	48	11
5.0 to < 10	31	82	-
10 to < 20	10	38	-
≥ 20	-	12	-

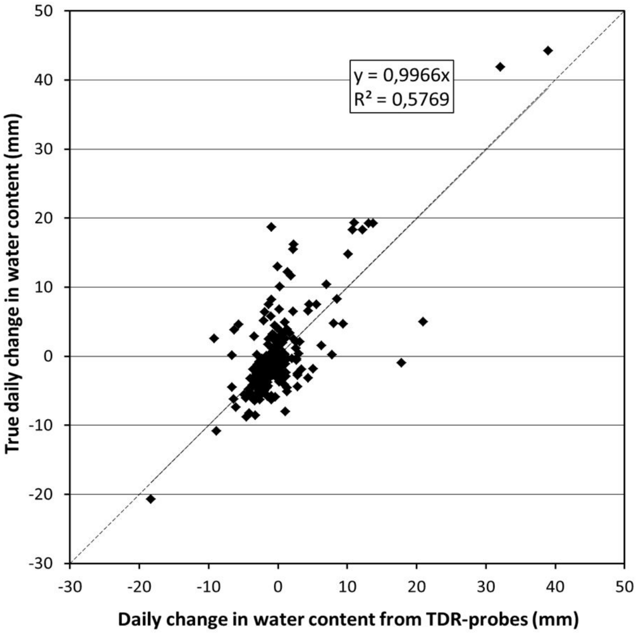

Figure 3. Relationship between the change in water content in the soil profile determined with TDR-probes at three depths (ΔW_{TDR}) and the true change (ΔW_{true}) for daily intervals. Besides the regression line, the 1:1-line is shown as well.

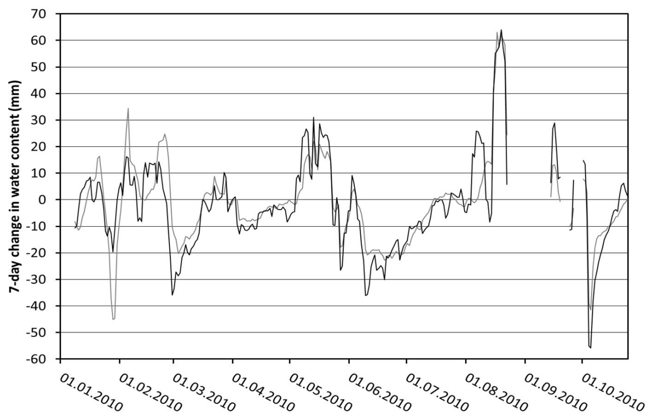

Figure 4. Time course of the change in water content in the soil profile for 7-day intervals over the study period. Black line = true values (ΔW_{true}), grey line = values determined with TDR-probes at three depths (ΔW_{TDR}).

In winter daily evapotranspiration (ET) at the study site is ≤ 1 mm, in summer it can reach 4 to 5 mm. On days with rain the amount is usually between 1 and 5 mm. Typical net changes in daily water content (ΔW_{typ}) therefore lie between ± 1 and ± 5 mm. Comparing these values to the data in column 2 in Table 1 shows that 53% of the time the TDR-probes yield water content changes which deviate from the true value by as much as ΔW_{typ}, and 15% of the time by more than that. This makes it clear that water content changes in a soil profile from one day to the next cannot be determined reliably with TDR-data from just three depths.

Figure 4 is equivalent to Figure 2, but for 7-day intervals, i.e. the difference in soil water content from day 1 to day 7, from day 2 to day 8, and so on. As for the daily interval the shape of both curves is similar. Even though there are several short periods with substantial deviations, they agree quite well over the entire time span. Figure 5 correlates the data obtained from the TDR-probes with the true values. The correlation is better than for daily data, as evidenced by the higher R^2 (0.73 compared to 0.58).

Column 3 in Table 1 shows how often the difference between ΔW_{TDR} and ΔW_{true} for 7-day intervals exceeds the range stated in column 1. The deviations are larger than for daily values (column 2). This is not surprising, because they accumulated over seven days. If these deviations are divided by 7, one gets an average daily deviation (column 4). On that basis ΔW_{TDR} agrees much better with ΔW_{true} for 7-day intervals (column 4) than for daily intervals (column 2). Now 63% of the average daily deviations are < 1 mm and 36% are < 0.5 mm. This leads to the higher R^2 for the correlation observed for 7-day intervals (Figure 5). However, even at 7-day intervals the accuracy of the water content changes determined with the three TDR-probes is not really satisfactory. About half the time the deviation per 7-day interval (column 3) is ≥ 5 mm, i.e. it exceeds one to several days worth of ET or precipitation.

We did the same analysis for other intervals (3, 5, 10 and 30 days). The results are not presented here in detail, but Table 2 lists the R^2-values for the regressions between ΔW_{TDR} and ΔW_{true}. We fitted a regression equation of the form y = a·x, because for all time

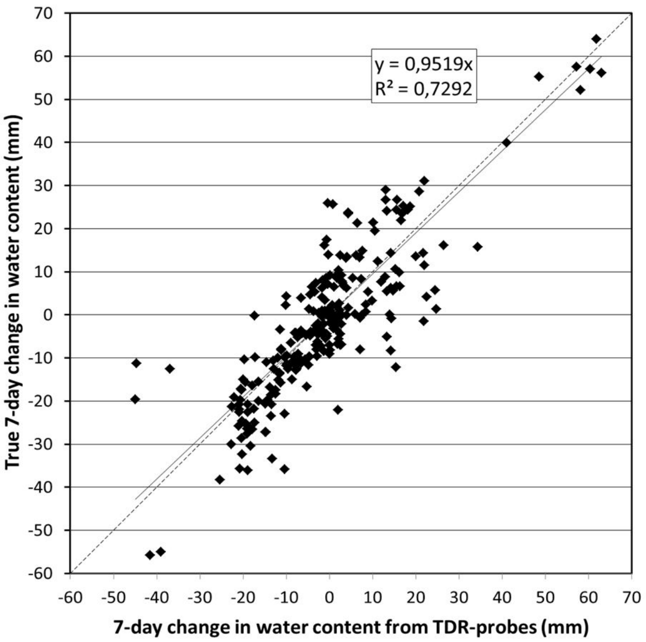

Figure 5. Relationship between the change in water content in the soil profile determined with TDR-probes at three depths (ΔW_{TDR}) and the true change (ΔW_{true}) for 7-day intervals. Besides the regression line, the 1:1-line is shown as well.

Table 2. Coefficient of determination (R^2) for the relationship between the change in water content in the soil profile determined by TDR-probes at three depths (ΔW_{TDR}) and the true change (ΔW_{true}) for different time intervals.

Time interval	R^2
1 day	0.577
3 days	0.664
5 days	0.675
7 days	0.729
10 days	0.770
30 days	0.861

intervals the data scattered fairly evenly around the 1:1-line. The scatter became less and, hence, R^2 better as the time interval increased. The slope was close to 1 in all regressions.

DISCUSSION

The water content changes we derived from TDR-data sometimes agree reasonably well with the true water content changes, but most of the time they do not. This can be observed in the data of Young et al. (1996), too, which were obtained with TDR-probes placed horizontally at 50 cm depth intervals in a 4 m deep weighing lysimeter.

Since the early work of Topp et al. (1980) TDR has been widely used to determine soil water content. There is now a lot of literature about this technique (e.g. Roth et al., 1990; Dalton, 1992; Zegelin et al., 1992; Noborio, 2001) with the consensus that it is a pretty accurate method to determine the water content in the vicinity of the rods. So, if the method is sound, why does our ΔW_{TDR} often differ so much from ΔW_{true}? The reason is this: While the measured data are correct for the soil surrounding the rods, the vertical spacing of horizontally installed probes leads to a time delay in their response to precipitation, evaporation, transpiration or drainage, and this in turn leads to errors when the TDR-readings are extrapolated to an assigned soil volume. This is explained in more detail below.

The uppermost TDR-probe in the soil profile is located some distance below the surface, in our case 20 cm, and only samples the soil volume a few centimetres around the probe. Hence, precipitation must first reach this depth before it can be registered. This takes time, how much depends on the precipitation rate and the antecedent soil moisture content. At high rates and high moisture contents it happens faster than at low rates and low moisture contents. In some cases precipitation may not even reach the probe, because is retained in the soil above it or removed by ET before it gets there. Of course, the time it takes a TDR-probe to respond to rain also depends on the depth of the probe in the profile. This is nicely illustrated by data of Zegelin et al. (1989) where probes installed horizontally 4, 9, 15 and 20 cm below the soil surface react with increasing delay.

Evaporation first reduces the water content at the top of the soil profile and then in increasing depths (Hillel, 1998). However, in humid environments, e.g. Germany or southern Brazil, it rarely affects the soil below a depth of 20 cm and often not even below 10 or 15 cm, because frequent rains reset this process to the surface. Consequently, a TDR-probe placed at some depth below the soil surface registers water content changes due to evaporation only with some delay and not to the full extent. If a probe is located below the zone influenced by evaporation, it will not register it at all.

Water extraction by plants (transpiration) also starts at the top of a profile and then moves downwards (e.g. van Bavel et al., 1968; Acevedo Hinojosa, 1975). TDR-probes will register it with delay, namely only once the extraction has reached a probe. Also, if the water withdrawn by plants is replenished by rain, water uptake, like evaporation, is reset to the top of the profile. Hence, in situations where light rains alternate with moderate evapotranspiration TDR-probes may not trace any of these dynamic changes in soil water content, or only some of it and with delay.

Our TDR-data are more or less point measurements which are then extrapolated to an assigned volume. This frequently leads to errors. For example, if a wetting front has penetrated the volume assigned to a probe, but not reached the probe itself, extrapolation of the point measurement results in an underestimation of the water content in the volume. On the other hand, if a drying event has penetrated this volume, but not reached the probe, extrapolation leads to an overestimation.

It follows that TDR-probes in the spacing used here need a rather large addition of water to or removal from the soil profile before they respond. Larger additions or removals mean a deeper penetration of the wetting or drying front and, thus, a greater likelihood that the front reaches the probes. The longer the sampling interval is, the greater the chance that a sufficiently large addition or removal has occurred. For example, on one summer day in Germany ET may remove 4 to 5 mm of water from the soil, while on seven days it may remove 28 to 35 mm. This illustrates why data from the TDR-probes tend to agree better with the true values the longer the observation period is (Table 2).

In summary, TDR-probes exhibit a delayed response to precipitation, evaporation, transpiration and drainage at best, and no response at worst. TDR-probes deeper in the profile respond later and remain untouched by these processes more often.

Some of this is exemplified in Figure 6 where precipitation, ΔW_{true} and ΔW_{TDR} are displayed as hourly values for 13 consecutive days. There was no drainage out of the soil profile during this period. The probe at 20 cm depth showed by far the greatest response to the events on these days, the probe at 60 cm depth reacted a little bit, and the probe at 120 cm depth remained virtually unaffected. Recall that we only have ΔW_{true}-data for the profile as a whole. Hence, ΔW_{TDR} is only displayed for the profile as a whole, too, and the data for the individual depths are not presented in this paper.

In the evening of May 2nd a significant rainfall began. With some short interruptions it lasted until 10 p.m. the next day and delivered 13.3 mm. This led to a rise in the water content in the soil profile which continued as the amount of precipitation received by the profile increased. The probes only began to notice the rain some 14 hours later (around noon on May 3rd), because it took time for the wetting front to get to the first probe. In addition, the registered increase in water content is much less (4.2 mm) than the amount of rain which actually fell (13.3 mm), and the increase lasts much longer (until midday on May 5th) than the actual rainfall event. This means only some of the rain eventually reached the probe, and only rather slowly.

In the morning of May 4th there were another 2.1 mm of rain which further increased the soil water content. Later in the day there was a decrease in the water content due to ET. The TDR-probes do not show this rainfall or the ET afterwards, both are swallowed up in the still ongoing rise in water content from the previous strong rainfall.

In the night of May 4th to May 5th there was a bit of rain (0.5 mm) which was followed by a lot of ET (4.6 mm) during the day until 6 p.m. Then another small rainfall set in (0.4 mm) which ended at 6 a.m. the next day. By noon it was followed by some

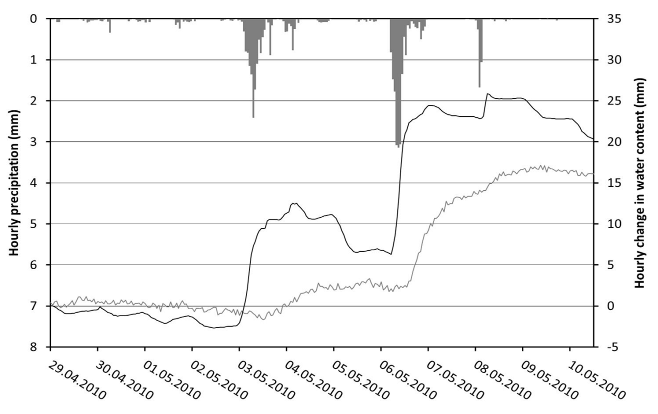

Figure 6. Time course of the hourly change in water content in the soil profile from April 28th to May 10th, 2010. Black line = true values (ΔW_{true}), grey line = values determined with TDR-probes at three depths (ΔW_{TDR}). Also shown is the hourly rainfall during this period (grey columns).

1 mm of ET. The TDR-probes did not log the two small rainfall events or the ET on May 5th. Instead they recorded a slow and decreasing rise in water content over this period still caused by the rain on May 2nd and 3rd.

At noon on May 6th another strong rainfall started (18.1 mm) and lasted until 6 a.m. the next day. Because the amount of rain was rather large and the antecedent moisture higher than prior to the event on May 2nd and 3rd, the infiltration front moved faster so that now the first TDR-probe responded with a delay of just 4 hours. Also, more water moved into the zone measured by the probe. Still, the amount of rain registered by the probe was once more less than the amount which actually fell. By the time this rainfall stopped the probe had recorded just 7.5 mm, followed by another 4 mm before the next rainfall set in at 9 a.m. on May 8th.

The rain in the morning of May 8th lasted until 1 p.m. and was recorded by the probes fairly quickly (< 1 hour delay), because the soil was pretty wet so that water movement in the profile was fast. However, the recorded rise in water content is not as steep as the true rise. This time the probes eventually registered the full 3 mm of rain, but it took 32 hours.

From 1 p.m. on May 8th to the end of May 10th there was no rain, only 5.5 mm of ET. The typical daily time course of the water content is clearly visible in the ΔW_{true} data: ET during the day (falling lines), no ET at night (flat lines). The TDR-probes on the other hand merely show a slow decrease in water content of about 1 mm during this time. Apparently the "ET-front" which starts at the top of the profile and then moves down had not fully reached the first probe.

For completeness we point out that between April 28th and May 2nd there were several light rains (< 1 mm) followed by ET. They were hardly noticed by the TDR-probes.

If more probes in a closer spacing were employed, e.g. starting at a depth of 5 cm and then another probe every 10 cm, better results should ensue, because the time delay in the response to precipitation, evaporation, transpiration or drainage is much less and the sensitivity to these processes much higher since it takes less addition of water to or removal from the soil profile for the probes to show a response. In addition, each probe then only represents 100 L of soil instead of 400 or 800 L as in our setup, which reduces errors due to extrapolation. Zegelin et al. (1992) equipped a soil profile with TDR-probes in a similarly close arrangement as just mentioned and found that water content changes measured with the TDR-probes were within 10% of the changes registered by a weighable lysimeter some 40 m away. This is a much better agreement than we got with our TDR-arrangement. Nevertheless, even with such a close spacing there is still some delay in the response, as the data of Zegelin et al. (1989) show, and some precipitation, evaporation, transpiration or drainage may be missed by the probes. Some extrapolation error remains, too. Hence, with a closer spacing the aforementioned problems are smaller, but not totally gone. Even with a 5 cm spacing Zegelin et al. (1989) still observed deviations of up to 10% between the amount of water actually applied to a soil profile and the amount recorded by the TDR-probes.

A way to avoid the problems arising from the vertical spacing of horizontally installed probes is to install them vertically. This approach was successfully used by Baker & Spaans (1994) and Plauborg (1995) to determine evaporation from the upper 20 to 50 cm of a soil profile. The values obtained with the vertical TDR-probes agreed well with the values determined by weighing microlysimeters. Young et al. (1997) vertically installed TDR-probes up to 80 cm in length in a 4 m deep weighable lysimeter with a turfgrass cover and also found that water content changes determined with the probes were in close agreement with those determined by weighing, as long as there were no water content changes below the distance sampled by the probes. This qualification also applies to the studies of Baker & Spaans (1994) and Plauborg (1995).

However, vertically installed probes have problems of their own. For example, if there is a steep change in soil properties or water content along the length of the probe, it becomes difficult to interpret the TDR-signal and, hence, to determine the correct water content. In line with this Topp & Davis (1985) found that soil water contents around a probe are determined more precisely with horizontally than with vertically installed probes. Further problems with vertically installed probes are addressed by Zegelin et al. (1992).

CONCLUSIONS

TDR-probes at just three depths are insufficient to trace short term changes in soil water content due to precipitation, evaporation, transpiration or drainage, especially if the amounts of water involved are small and the soil water contents low. For longer periods, e.g. a week, they can give a rough idea of water content changes. Depending on the intended use of the data, this may suffice, but for studies requiring good accuracy a three TDR-probe arrangement is insufficient. More TDR-probes in a closer spacing will yield more accurate data. How many probes at which spacing are required for good results needs to be investigated.

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Authors' contribution

Heinz Borg: Is Professor at the University in Halle, where the study was implemented, and leader of the German part of the project. He had the idea to compare the two measurement techniques (weighing lysimeter and TDR) and selected the data.

Jens Hagenau: Performed the data analysis and was chiefly responsible for writing the article as well as preparing the figures and tables.

Vander Kaufmann: Project-partner in Brazil, where he is involved in soil water measurement activities which use TDR and lysimeters. His experience with these measurement techniques helped in the interpretation of the data.