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Rapid Percolation of Water through Soil Macropores Affects Reading and Calibration of Large Encapsulated TDR Sensors

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Abstract

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The electromagnetic soil water content sensors are invaluable tools because of their selective sensitivity to water, versatility, ease of automation and large resolution. A common drawback of most their types is their preferential sensitivity to water near to their surfaces. The ways in which the drawback manifests itself were explored for the case of large Time-Domain Reflectometry (TDR) sensors Aqua-Tel-TDR (Automata, Inc., now McCrometer CONNECT). Their field performance was investigated and compared with the results of field and laboratory calibration. The field soil was loamy Chernozem on a carbonate-rich loess substrate, while the laboratory calibration was done in fine quartz sand. In the field, the sensors were installed horizontally into pre-bored holes after being wrapped in slurry of native soil or fine earth. Large sensor-to-sensor variability of readings was observed. It was partially removed by field calibration. The occurrence of percolation events could be easily recognised, because they made the TDR readings suddenly rising and sometimes considerably exceeding the saturated water content. After the events, the TDR readings fell, usually equally suddenly, remaining afterwards at the levels somewhat higher than those before the event. These phenomena can be explained by the preferential flow of water in natural and artificial soil macropores around the sensors. It is hypothesised that the percolating water which enters the gaps and other voids around the sensors accumulates there for short time, being hindered by the sensors themselves. This water also has a enlarged opportunity to get absorbed by the adjacent soil matrix. The variance of TDR readings obtained during the field calibration does not differ significantly from the variance of the corresponding gravimetric sampling data. This suggests that the slope of the field calibration equation is close to unity, in contrast to the laboratory calibration in quartz sand. This difference in slopes can be explained by the presence or absence, respectively, of gaps around the sensors. A typical percolation event and dry period records are presented and analysed. Sensors of this type can be used for qualitative detection of preferential flow and perhaps also for its quantification. The readings outside the percolation events indicate that the sensor environment imitates the native soil reasonably well and that the field-calibrated sensors can provide us with quantitative information about the actual soil water content.

Keywords: gap; preferential flow; rain; sensor installation; time-domain reflectometry

Gravitational water is the main vehicle of percolation through the unsaturated zone and thereby of aquifer recharge. This percolation takes place rapidly without necessarily saturating the vadose zone. In Chernozem loamy soils like the one described below, the rapid percolation is mainly generated by preferential flow in macropores (such as fissures, cleavage planes, inter-aggregate voids and tubular biopores). Fingering was never observed. It is rarely possible to measure the preferential flux density directly and continuously under field conditions (Allaire *et al.* 2009). One possible option is to derive it from the spatial and temporal variability of water content or suction sensors' readings. What matters are the number, size, shape and orientation of the sensors with respect to the size, shape and orientation of

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individual rivulets of preferential flow. Allaire *et al.* (2009) state that it may be more advantageous to place the sensors horizontally and to measure at high temporal frequency. The electromagnetic soil water content measurements requires that the undisturbed soil with its natural structure and exposed to natural external influences surrounds the sensor as intimately as possible, because the latter is extremely sensitive to gaps or disturbed zones between the sensor and the natural soil (Paltineanu & Muñoz 2010; Vaz *et al.* 2013). The sensors used in this paper are of the TDR type, namely Aqua-Tel-TDR, supplied by Automata, Inc. (now McCrometer CONNECT). The manufacturer (J&S Instruments, Inc. 2010) recommends to install the sensor into the soil in a vertical position. However, horizontal installation is also mentioned. The problem of the gap between the sensor and the surrounding soil is conceded. For vertical installation, it is recommended either to fill the hole with slurry made from the native soil and then to insert the sensor into the hole, or to bring the soil into an intimate contact with the soil by driving rods into the ground in parallel with the sensor about 0.08 m away from it. For horizontal installations, it is recommended to put the sensor in a trench, then backfilled and packed with soil. A newer video (McCrometer CONNECT 2014) recommends to drill a wider vertical hole in the soil, insert the sensor into the hole with a PVC pipe pulled onto it, then slide the PVC pipe up along the sensor's cable and backfill the gap around the sensor with original soil while compacting the backfill with the PVC pipe still pulled on the sensor and its cable.

Literature references to Aqua-Tel-TDR sensors are rare. Adamsen and Hunsaker (2000) stated that the Aqua-Tel-TDR sensor, in the same way as the other sensors tested, did not provide sufficiently accurate data when the soil was close to saturation. Zhao *et al.* (2006) reported a similar effect. Both quartz sand and a simulated dump site material (composed of paper, plastics, textile, and soil) showed, according to Zhao *et al.* (2006), an approximately linear calibration relation between the actual volumetric water content of the soil and the volumetric water content indicated by the sensor. Deboodt (2008) used the Aqua-Tel-TDR sensors without calibration and regarded their data as providing a picture of relative values. Vaz *et al.* (2013) did not mention Aqua-Tel-TDR in their list of commercially available electromagnetic sensors.

Doležal *et al.* (2010) found by laboratory experimentation that the Aqua-Tel-TDR sensor, when surrounded by air, only starts to respond to water at distances less than 10 mm from its surface. However, when the sensor is surrounded by water, its zone of sensitivity to a low-permittivity environment (e.g., air) extends to about 50 mm from its surface. Hence, the radius of sensor's sensitivity in a real moist soil should lie between these two limits.

Doležal *et al.* (2012a, b) used the Aqua-Tel-TDR sensors in a loamy Chernozem soil, installing them horizontally into pre-made holes on carbonate-rich loess substrate. The sensors were wrapped in slurry made of local soil and water before installation, but some gaps between the soil and the sensors remained. The authors described peculiar behaviour of the sensors during intensive percolation events and proposed to use this effect for detection of preferential flow in the natural soil macropores near to the sensors. The present paper complements the two previously published (Doležal *et al.* 2012a, b) in the sense that it pays equal attention to the percolation events and the periods outside these events. It explores the effects of preferential flow in both types of situations, relying on actual field measurements and both laboratory and field calibration. The two types of calibration are compared and contrasted graphically. While the basic corpus of data is the same and the preferential flow, including the problem of its sensing, is permanently in the centre of attention, the three papers look at the matter from somewhat different perspectives, namely, from the point of view of sensors' installation (Doležal *et al.* 2012a), calibration (Doležal *et al.* 2012b) and field performance (present paper).

MATERIAL AND METHODS

Sensors. The sensors used in this paper are Aqua-Tel-TDR, supplied by Automata, Inc. (now McCrometer CONNECT). They are designed for practical operation in irrigated agriculture and are relatively large and robust. Their basic technical parameters were described by the manufacturer (the description is presently available, e.g., from J&S Instruments, Inc. 2010). The sensors are cylindrical, about 700 mm long with a diameter of about 20 mm. The sensing TDR elements (457 mm long) and the primary electronics are encapsulated within the sensor (Figure 1). The outer diameter of the sensor is not constant; there are several places where it is larger than 20 mm, up to about 25 mm. The sensors were connected to a telemetric unit Multi-Mini (Automata, Inc., now

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McCrometer CONNECT), in which their current output was converted into the volumetric soil water content. The data were read every hour. Manual measurements were made using the Aqua-Tel Meter unit. As the primary output of the sensors in mA was not directly available, we express all primary data in terms of the volumetric water content, i.e, in m^3/m^3. Out of seven Aqua-Tel-TDR soil moisture sensors available, six were installed in the field and one sensor was left for laboratory calibration.

Field measurements. The research was conducted at the Demonstration and Experimental Grounds of the Czech University of Life Sciences in Prague-Suchdol (50°8'N, 14°23'E, 286 m a.s.l.). Average annual precipitation and temperature over the last twenty years were 495 mm and 9.1°C, respectively. The soil is a loamy carbonate Chernozem on loess (22–33% sand, 40–54% silt and 22–28% clay). It has a moderate capacity to swell and shrink. The saturated hydraulic conductivity varies between 1×10^{-7} and 7×10^{-5} m/s. The dry bulk density ranges between 1.20 and 1.55 g/cm^3, being on average 1.43 g/cm^3. The average particle density is 2.63 g/cm^3 and does not vary significantly. The soil water content at field capacity varies between 0.30 and 0.35 m^3/m^3. The total organic carbon content is about 2.5% in the ploughed layer. Precipitation was measured on the site.

The crop production experiments carried out in parallel with our measurements on the same plots required that no parts of the sensors or any cables stuck out from the soil. This requirement, together with the intention to obtain higher vertical resolution, led us to the decision to place the sensors horizontally, and not vertically. The installations in trenches was regarded inappropriate, because the refill might preserve its disturbed structure for long time and could excessively facilitate downward percolation of water towards the sensors. The sensors were therefore inserted into pre-made holes bored horizontally into vertical walls of the installation pits. The soil above the sensors and elsewhere around them thus remained undisturbed. The diameter of the holes (25–27 mm) was made slightly larger than the diameter of the sensors (20–25 mm), otherwise the sensors could not be pushed in. The air gaps between the sensors and the soil were eliminated as far as possible by smearing the sensors before insertion with soft plastic slurry made of the disturbed soil or fine earth from the same depth. As the slurry could not fill the gaps completely and homogeneously, the readings of the sensors were biased with respect to each other. This bias had to be eliminated by field calibration (see below). Three sensors were installed under permanent grass (at 10, 20 and 30 cm) and the other three under silage maize (at 15, 30 and 50 cm).

In order to interpret the TDR readings taken during rainless periods and to compare them with the readings obtained during rapid percolation events, attempts were undertaken to relate the former readings to the soil water contents determined gravimetrically, i.e., to carry out field calibration. It consisted in collecting disturbed soil samples with a gouge auger at the depths of the sensors (three samples at each depth) at a horizontal distance 50 to 240 cm from the sensors, large enough for future readings of the same sensors not to be affected and small enough to expect, in the statistical sense, the water content of the samples equal to that of the natural soil around the sensors. The time interval between consecutive samplings varied from two weeks to three months. Different samplings were made at different positions in the plan view so that no place was sampled twice. The gravimetric water content was then converted into the volumetric one, using the dry bulk density of undisturbed 100 cm^3 cores. The cores, three from each pit and each depth, were taken only once, in parallel with the installation of the sensors, from the sides of the installation pits, at horizontal distances about 1 m from the sensors.

Laboratory measurements. For comparison with the field data, a detailed laboratory calibration of the single remaining Aqua-Tel-TDR sensor was carried out in a box with fine quartz sand (Figure 1), in which case there were no gaps between the sensor and the soil. We used a plastic box (approximately

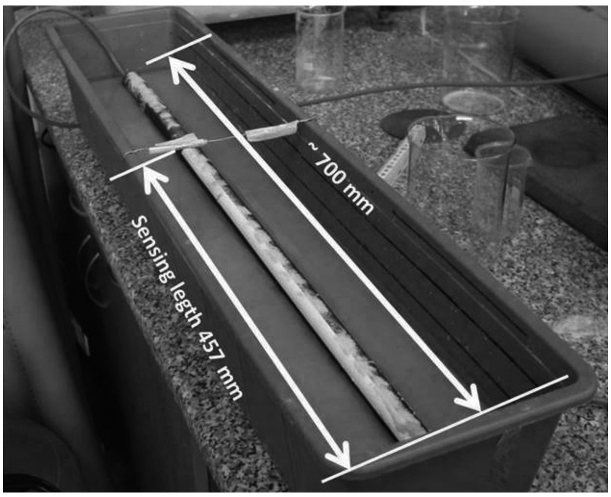

Figure 1. Overall appearance of the Aqua-Tel-TDR sensor during laboratory calibration

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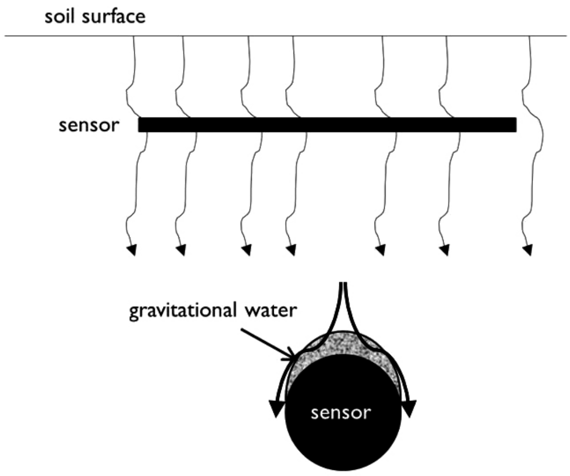

Figure 2. Schematic diagram of probable mechanisms of the preferential flow sensing by the Aqua-Tel-TDR sensor

80 × 12 × 13 cm) filled with re-packed fine quartz sand (with the size of grains about 0.1 mm) at various water contents, into which the sensor was inserted during the packing. The dry bulk density of the sand was 1.44 to 1.50 g/cm^3 for all water contents except for the totally dry and totally saturated sand, for which it was about 1.66 and 1.61 g/cm^3, respectively. The relatively low dry bulk density at intermediate soil water contents was caused by capillarity that held the fine sand grains together at positions not allowing a denser packing. No bulk density correction was made.

RESULTS AND DISCUSSION

General. We hypothesise that the incomplete filling of the space around the sensor with the slurry, as well as the subsequent shrinking of the slurry, made a system of artificial macropores arise all around the sensor. This system was connected with the systems of macropores in the surrounding natural soil. The presence and connectedness of these systems of macropores were qualitatively confirmed by a later visual inspection during the sensors' uninstallation (see photos in Doležal *et al.* 2012a, b). Under such circumstances, the water percolating through natural soil macropores can easily penetrate into the artificial macropores around the sensor and come into intimate contact with the sensor surface. As the sensor is long, it safely intersects several (prevailingly vertical) rivulets of preferential flow in planar and interaggregate pores. The sensor itself, an impermeable cylinder placed horizontally, presents an obstacle to the percolating water, reduces the hydraulic gradient and delays the downward progress of the water. A layer of water arises above the upper surface of the sensor for at least a few hours (sometimes up to several days) before having been drained away around the sides of the sensor (Figure 2). The water that accumulates on top is detected by the sensor. In the meantime, the water also has an enlarged opportunity to get absorbed by the adjacent soil matrix, which may keep the sensor-reported water content elevated over a longer time after the drainage.

Calibration. The data obtained by the field calibration procedure reveal a considerable dispersion (see the points in Figures 3 and 4). The outlier on the right-hand side of the group of points for 10 cm under grass (Figure 3) is a result of the continuing rapid percolation a day after rain. It was therefore not included in further calculations. Except for this single outlier, all other points in Figures 3 and 4 were obtained during rainless and snowless periods. It should be emphasized that, on the days of sampling, some locations in the

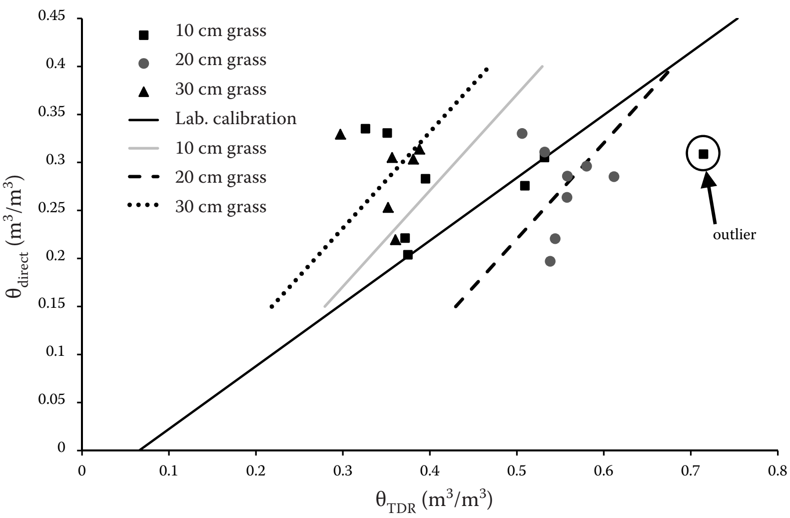

Figure 3. Field calibration of three Aqua-Tel-TDR sensors under grass between 8 March and 22 October 2010; the groups of points for individual sensors are approximated by Eq. (2); the laboratory calibration curve (Eq. (1) and Figure 5) is plotted for comparison; the outlier for 10 cm depth is affected by a previous percolation event

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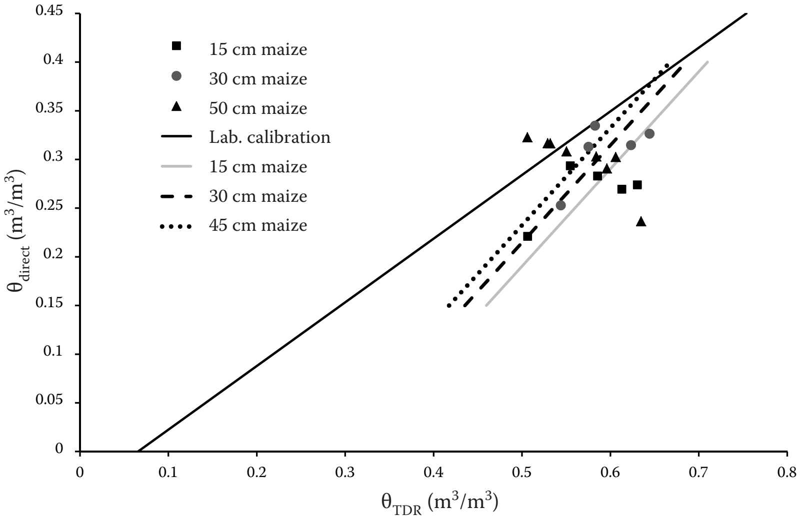

Figure 4. Field calibration of three Aqua-Tel-TDR sensors under maize between 8 March and 22 October 2010; the groups of points for individual sensors are approximated by Eq. (2); the laboratory calibration curve (Eq. (1) and Figure 5) is plotted for comparison

soil may still have been wetter than others because of previous passage of gravitational water through them. The large dispersion of points in Figures 3 and 4 may be associated with the presence of moist places left in the soil matrix after the preferential flow streams. While the large TDR sensors may sense the two categories of soil water (matrix and preferential) roughly in the same manner and provide an average water content over a large volume, the small soil samples collected by the gouge auger consist almost exclusively from the plain soil matrix that may either have been hit by a preferential stream (which would result in overestimation of the water content so determined) or not (which would result in its underestimation).

The mean water contents obtained by direct sampling over the entire period of observation were significantly different from the corresponding mean water contents obtained by TDR at the same depth and under the same crop (see Doležal *et al.* 2012b for details). As expected, the differences were different for different sensors. The highly dispersed scatter graphs relating the gravimetric and the TDR-measured soil water contents (Figures 3 and 4) cannot be used for meaningful estimation of true soil water contents from the TDR readings without additional assumptions.

The laboratory calibration of another Aqua-Tel-TDR sensor in quartz sand, with no gaps between the sensor and the repacked soil, resulted in a virtually linear calibration equation (Figure 5):

$$\theta_{direct} = 0.654 \times \theta_{TDR} - 0.043 \quad (1)$$

where:

θ_{direct} – regressed volumetric water content (m^3/m^3), equivalent to that obtained by sampling in the laboratory

θ_{TDR} – non-calibrated TDR output (m^3/m^3)

A linear relation was also found by Zhao *et al.* (2006). We therefore adopted an assumption of virtually linear relations between the TDR-measured field data and the actual water content of the soil. However, the scatter graphs in Figures 3 and 4 did not provide enough information for estimating the slopes of these relations. When looking for the most adequate slopes of the field calibration lines, we noted that the standard deviation of soil water contents obtained in the field by gouge auger sampling for a particular depth and a particular crop (that is, near to a particular sensors) was not significantly different from the standard deviation of the corresponding non-calibrated TDR readings of the same sensor in terms of the volumetric water content units, provided that rapid percolation events and their immediate aftermaths had been excluded. The insignificance was tested using a standard *F*-test (Doležal *et al.*

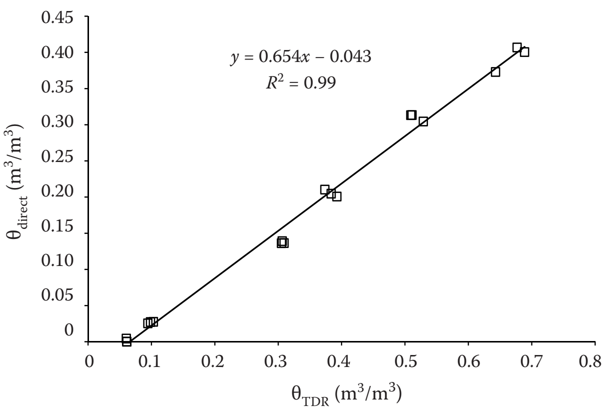

Figure 5. Laboratory calibration curve obtained in a box with quartz sand and its linear regression line (1)

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2012b). Realizing that the sensitivity of the TDR probes installed in the natural soil (with a thin layer of artificial soil and/or a thin gap in between) can be lower than that of the sensor placed without a gap in the quartz sand, we concluded that the slope of a field regression line analogous to Eq. (1) should be larger than that of Eq. (1). For comparison, the laboratory calibration line (Eq. (1)) is also drawn in Figures 3 and 4. Moreover, in view of the absence of significant differences in variability (as quantified by the standard deviations) between the water contents from direct field samplings and those from the corresponding non-calibrated field TDR measurements, we considered it adequate to relate the two sets of variables with a unity-slope straight line, rather than with Eq.(1). Hence, the field calibration data were approximated with the equations of the type:

$$\theta_{direct} = 1.000 \times \theta_{TDR} + \text{offset } (1.000) \quad (2)$$

where:

θ_{direct} – value expected from the field sampling (if this were made at the instant of the TDR measurement)

θ_{TDR} – non-calibrated output of a particular TDR sensor (m^3/m^3)

offset (1.000) – difference (m^3/m^3) between the mean volumetric water content obtained by field sampling at a particular depth under a particular crop and the mean non-calibrated volumetric water content obtained from the corresponding TDR sensor

The values of the offsets were of course different for different sensors, depths and crops (Table 1). The resulting six field calibration lines for particular sensors (that is, for particular crops and depths) are also depicted in Figures 3 (for grass) and 4 (for maize). The calibration equations (2) were then used to rectify all field-measured data, both during the percolation events and outside these events.

Indication of rapid percolation events. Figure 6 displays the volumetric water contents, θ_v, obtained by TDR and corrected for the offsets using Eq. (2), as functions of time during a typical percolation event caused by an early autumn rainstorm. The accumulation of water on top of and around the sensors is indicated by a sudden increase in the volumetric water content (as measured by TDR), frequently up to 0.50 m^3/m^3 or above this value, while the average porosity of the natural soil was 0.457 m^3/m^3. The very high values of the TDR-measured soil water contents, lying significantly above the soil's porosity, were in this case displayed by a single sensor only, namely, the one under grass at 10 cm. However, the record of a similar summer event presented by Doležal *et al.* (2012a) in their Figure 2 confirms that such high TDR values can be indicated by the other sensors, too (three sensors in that particular case). A probable explanation of this phenomenon is that water fills, at least partially and for a short time, the artificial macropores immediately at the surface of a particular TDR sensor, to which the sensor is enormously sensitive. At this point it should be stressed that the occurrence of TDR-values above the nominal porosity of the natural soil is not a necessary condition for qualifying a water content peak as an indicator of preferential percolation. Any sudden increase and a following decrease of the TDR-values, even if the peak value is below the nominal porosity, indicate rapid percolation of gravitational water. Figure 6 shows a three-day percolation event, caused by three partial rainfall events occurring shortly one after another. The rain total over this period, measured by a tipping bucket rain gauge, was 58.4 mm, which can be obtained by integration of the rain intensity in Figure 6.

The before-event soil water content was close to field capacity, varying at different depths under grass and maize from 0.28 to 0.36 m^3/m^3. All three partial rainfall events probably caused accumulation of gravitational water above and around the sensor at the depth of 10 cm under grass, as can be seen from three high water content peaks. The maximum observed during the first peak was over 0.80 m^3/m^3. The top of the first peak is almost flat, which indicates that the pores around the sensor were close to saturation. The undulation of the flat top of the peak suggests that some air bubbles were first temporarily entrapped in and then released from the artificial macropores around the sensor. Some other sensors

Table 1. The field calibration derived offsets to be added to the non-calibrated TDR-measured data

Sensor	Crop	Depth (cm)	Offset (1.000) (m^3/m^3)
1		10	–0.129
2	grass	20	–0.280
3		30	–0.068
4		15	–0.310
5	maize	30	–0.285
6		50	–0.267

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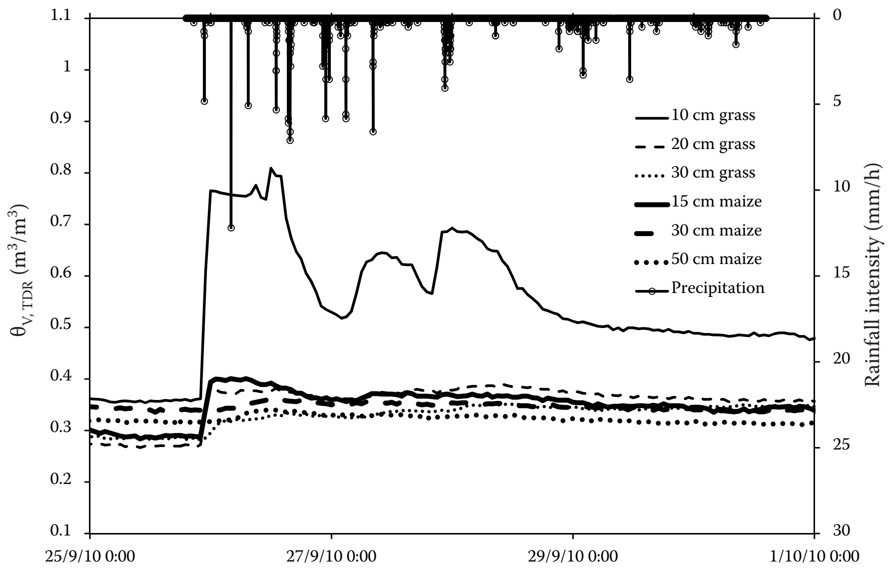

Figure 6. Volumetric soil water contents, θ_v, measured by TDR at different depths and corrected for offsets using Eq. (2), and hourly precipitation rates for the percolation event 25–30/9/2010

(grass 20 and 30 cm and maize 15 cm) experienced a rapid and distinct, but not so large increase of soil water content by about 0.06 to 0.10 m^3/m^3, caused as well, at least partially, by the rapid percolation of gravitational water, as we can conclude from the rapidity of their response to the onset of rain and a similarly rapid response to the end of the rainfall events. However, the soil water content variations indicated by these sensors need not necessarily be associated with a significant water accumulation over the sensors. The increase in the TDR-measured soil water content at 30 and 50 cm under maize was also distinct, but not so rapid, and may have been produced by the flow through soil matrix. The differences in patterns of percolation under grass and maize may be significant but there are no replications that could support this statement by a statistical test. A possible explanation is that the soil under maize, which has been ploughed and cultivated every year, contained less macropores; hence, the preferential percolation in it was slower, providing thus more opportunity for water to get imbibed by the soil matrix.

By the end of the period depicted in Figure 6, the TDR-measured offset-corrected soil water content remained elevated at 10 cm under grass (0.48 m^3/m^3, which is by 0.12 m^3/m^3 higher than the pre-event level), at 20 cm under grass (0.36 m^3/m^3, by 0.09 m^3/m^3 higher), at 30 cm under grass (0.34 m^3/m^3, by 0.06 m^3/m^3

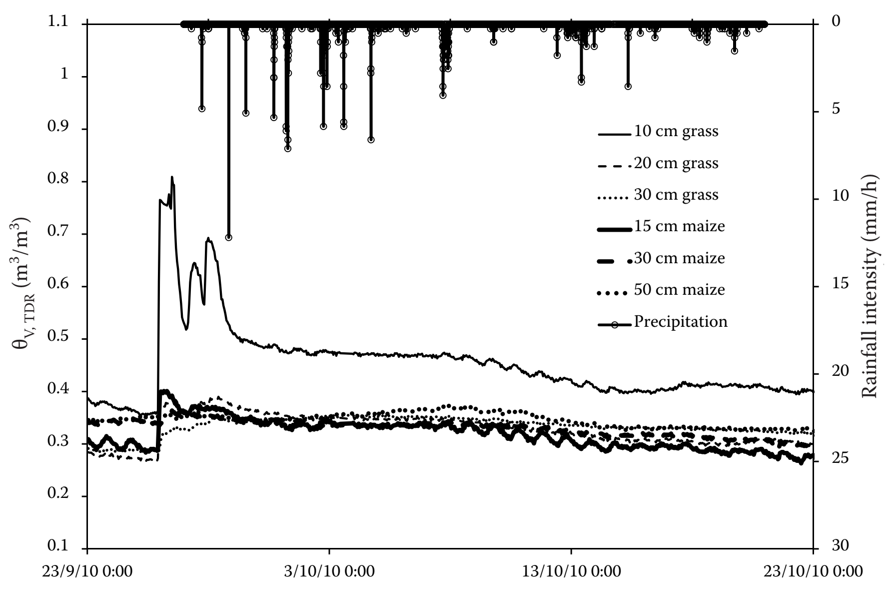

Figure 7. Volumetric soil water contents, θ_v, measured by TDR at different depths and corrected for offsets using Eq. (2), and hourly precipitation intensities for the monthly period 23/9–22/10/2010

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higher) and at 15 cm under maize (0.34 m^3/m^3, by 0.05 m^3/m^3 higher), while the post-event soil water contents at 30 and 50 cm under maize virtually returned to the values before the event. The elevated post-event values can be partly attributed to the real increase in the soil water content, which would occur even if the sensors were absent, and partly to the preferential wetting of soil matrix in the vicinity of the sensors, due to water delayed by the sensors. A quantitative distinction between these two effects would require further measurement and analysis. Many more similar events have been observed (Doležal *et al.* 2012a, b), among them also some snowmelt-generated events (e.g. Doležal *et al*. 2012b, their Figure 3).

Performance outside percolation events. Figure 7 shows the percolation event depicted in Figure 6 within the context of a longer period, which includes few days before the event and three weeks after the event. First of all, this graph demonstrates that the water contents at different depths and under different crops are quite similar, except for the percolation event itself and for the remarkably elevated post-percolation water content at 10 cm under grass. Second, an almost consistent decrease in soil water content during the dry period after the percolation event is indicated by all sensors, with a notable exception of 50 cm under maize that may have experienced passage of a matrix flow wave. Third, the decrease of soil water content was perceivably faster between about 9th and 14th November, when weather was radiation-dominated and the evaporation rates were therefore higher (weather details are not shown). All these observations support an approximate validity of the calibration equations (2) and, thereby, reasonably good performance of the Aqua-Tel-TDR sensors outside percolation events. Fourth, as the Aqua-Tel-TDR sensors are not temperature-compensated, we see a distinct diurnal variation of their readings, especially at the shallowest depths. These variations may be partly removed based on parallel soil temperature measurements. Similar observation would pertain to the other rainless periods measured.

CONCLUSIONS

We installed the Aqua-Tel-TDR sensors horizontally in pre-drilled holed, using slurry for partial filling of the gaps around the sensors. The performance of such sensors was reasonable over the periods when there were no rapid percolation events. It appears that the sensor environment, even though modified due to the slurry-filled gap, imitates the native soil reasonably well. With the calibration equations of the type (2), i.e. with the unit slope, these sensors are suitable for a quantitative measurement of the actual soil water content, at least in the soils similar to our loamy Chernozem on loess.

However, we observed a pronounced reaction of the sensors, especially those at shallow depths under grass, to intensive percolation events caused by rainstorms or snowmelts. Under these circumstances, the readings of the sensors rose more than it would correspond to the rise of actual soil water contents in the natural soil. We explain this reaction by the high probability of intersection between horizontal sensors and vertical preferential flow paths, by temporary accumulation of water on top of the sensors of non-negligible diameter, by the sensor's virtual impossibility of being installed tightly into a pre-made constant-diameter hole and by the gaps between the sensors and the holes. Similar problems can be expected even with vertical or inclined installations. Sensors of smaller size may be less affected but, on the other hand, they are less capable of averaging the soil water content over large volumes.

The reaction of the sensors to the rapid percolation events is surely a disadvantage from the point of view of standard measurement, but these very artefacts can be exploited to indicate preferential percolation. We assume that the use of Aqua-Tel-TDR or similar sensors for this purpose will not remain on the qualitative level and can be quantified with the help of a suitable mathematical model, e.g. a dual porosity model (Kogelbauer *et al*. 2015). While the information provided by the sensors that are separated from the native soil by a gap and a layer of slurry may be a little blurred, there is additional information available due to simultaneous measurements at several different depths (three depths in our case), so that identification of main parameters of the model may be feasible. The model then may help us quantify or at least semi-quantify the complex interactions involved, in particular the interaction between the preferential flux and the intensity of matrix-macropore water exchange.

The installation of Aqua-Tel-TDR and similar large encapsulated sensors in a horizontal position, using slurry, is viable and works well, except for rapid percolation events. The newly proposed method of installation (McCrometer CONNECT 2014) with compaction of the soil around the sensor using a pipe pulled on the sensor is principally applicable to horizontal installations, too. It might be desirable to find out if the compacting procedure does not isolate the sensor excessively from the natural soil macropores. Some other techniques, such as using expandable foam (Tokumoto *et al.* 2011) may also be useful. On the other hand, any technique trying to eliminate the effect

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of gaps and artificial macropores around the sensors will also eliminate the potentially attractive opportunity to use the sensors for indication of preferential flow.

The readings outside the percolation events can be used for field calibration of the sensors. The field calibration is meaningful and its results (the offsets) should also be applied to the periods of percolation events, in order to make the data of these periods formally consistent with the data of dry periods. However, even the calibration does not (and, as it appears, cannot) bring the data of percolation events to correspondence with the actual soil water contents in the natural soil. To fulfil the latter task, the sensor would have to be installed in a different way (if this is possible) or another type of sensors would have to be used.

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