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Time-domain reflectometry probing systems for the monitoring of hydrological processes in the unsaturated zone

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Abstract Precise measurements of the downward movement of precipitation through the unsaturated zone, as well as return flow of moisture to the atmosphere via evaporation, have always been challenging in regard to in-situ monitoring techniques. This study investigates the profile of volumetric water-content fluctuations within the unsaturated zone through a combination of field techniques, including in-situ measurements of the volumetric porewater content at different depths using specially designed time-domain reflectometry (TDR) probes. The probes are installed through direct-push vibro-coring methods, at significant depths within the unsaturated zone, providing continuous readings of the soil-moisture content throughout the unsaturated column. The measured waveform is analyzed by using the inverse modeling approach resulting in an apparent relative dielectric permittivity profile of the surrounding medium along the TDR probe length. The approach sufficiently analyzes the mechanisms of water fluxes through significant depths within the unsaturated zone, which in turn can be used to quantify groundwater recharge at areas where the unsaturated zone hydrology plays a key role in the recharge of the underlying aquifers (such as arid and hydrologically sensitive areas). The approach was applied at an experimental field site in the Upper Rhine Valley, Germany.

Keywords Time-domain reflectometry (TDR) · Groundwater recharge · Unsaturated zone · Dielectric permittivity · Moisture content

Introduction

Monitoring of the unsaturated zone is a challenging procedure in groundwater engineering, especially in the case where significant depths have to be reached. Continuous measurements of soil moisture in the unsaturated zone are necessary to study and predict numerous hydrological processes that take place under natural or artificial field conditions. Accurate and systematic measurements of the downward movement of the waterfront during infiltration can be proved crucial for several purposes such as estimating groundwater recharge, monitoring of the effectiveness of an artificial recharge basin, leakage of waste disposal sites and many others.

To tackle the aforementioned challenges, the development of geophysical techniques has proved to effectively serve investigations that seek to quantify the soil-moisture profile of the unsaturated zone down to significant depths. Also, the development of multilevel soil sampling techniques has led to the successful retrieval of undisturbed soil samples throughout the unsaturated zone providing in-depth analysis of the hydrogeological properties of the investigated soil.

Widely applied electromagnetic (EM) methods—such as time-domain reflectometry (TDR), ground penetrating

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radar (GPR), capacitance, and active microwave remote sensing—that are used in the collection of water-content data, have provided in-depth analysis of the unsaturated zone and the related hydrological processes (Topp 2003). TDR is a complex electronic technology originally used primarily for testing high-speed communication cables (Topp et al. 2003). According to Stacheder et al. 2009 "TDR estimates the bulk dielectric permittivity, ε_b, of the soil mixture (soil matrix, soil water and air) by measuring the propagation time of an EM pulse, generated by a pulse generator and containing a broad range of different measurement frequencies".

In principal, two approaches can be followed to retrieve information from the unsaturated zone: (1) quantification of its current water content and analyses of the water chemistry, and (2) monitoring of the changes of soil-moisture content in the unsaturated zone over extended periods of time. The first approach requires the retrieval of undisturbed soil samples from the unsaturated zone, while the second approach requires the installation of appropriate monitoring equipment.

This paper presents the results of the synthesis and combination of field and laboratory techniques (Fig. 1) in order to realize the aforementioned objectives. The results of both approaches are applied at an experimental field site in the Upper Rhine Valley close to Darmstadt in Germany (August-Euler Airport).

## Time-domain reflectometry technology

Time-domain reflectometry has been developed and widely used in water studies as an indirect geophysical technique, which is based on the relation between the dielectric permittivity of the soil and its containing porewater, with Hoekstra and Delaney (1974) and Topp et al. (1980) being the pioneers in the field. Whalley (1993) also states that "the use of TDR for measuring soil-water content was originally proposed by Davis and Chudobiak (1975), Davis and Annan (1977) and Topp et al. (1980), though the potential of a balanced two-wire transmission line for probing the soil had been recognized by Kirkschether (1960)". The most usual shape of a TDR probe is that of two or three parallel metallic rods of

limited length; however single rod probes have also been recorded in literature such as the prototype of Oswald et al. (2004), who investigated a TDR probe that employs only one single metallic rod for water content measurements, based on the concept of a Sommerfeld wire and the work of Nussberger et al. (2005). The latter inserted a single rod into the ground that acts as a waveguide that transmits the electromagnetic pulse launched by the TDR instrument, through a coaxial cable which connects the TDR instrument with the probe. The TDR pulse travels until the end of the transmission line (end of the probe) and it is reflected back, received from the TDR, where the signal is analysed. The velocity at which the pulse is propagated is related to the dielectric permittivity of the surrounding soil. Robinson et al. 2003 state that "the relative permittivity of air is 1, while those for common minerals in soils and rocks lie in the range of 4.5–10 (Keller 1989; Robinson and Friedman 2003), while water has a permittivity of 78.5 at 25 °C".

According to Evett et al. (2005), TDR technology aims at the accurate acquisition of soil-water content in the unsaturated zone, in order to determine the various important field parameters such as crop water use, water use efficiency, irrigation efficiency, and the hydraulic characteristics of soils. Therefore, most of the case studies reported in literature with respect to the application of TDR for the estimation of water content, are limited to within the upper layer of the ground, in the vicinity of the rhizosphere, where bulk soil is present (Souza and Matsura 2003; Kim et al. 2000; Schmitz and Sourell 2000; Jones et al. 2005; Blonquist et al. 2005; Laurent et al. 2005; Plauborg et al. 2005; Coquet et al. 2005; Jabro et al. 2009). Topp (2003) states that "TDR is most often applied within the upper 1 m depth of soil, while numerous variations of probe design have been used to obtain a profile distribution or total root zone water".

However, there are still many challenges which need to be faced in order to improve the effectiveness and accuracy from the application of TDR technology such as the influence of the soil matrix's bulk density, hydraulic conductivity, porosity and distribution of soil pore spaces. Malicki et al. (1996), Perdok et al. (1996) and Ferre et al. (2002) analyzed several porous materials using TDR to determine the contribution of bulk density, hydraulic conductivity and porosity to the function that

Fig. 1 Schematic conceptualization of the research approach and activities. *TDR* time-domain reflectometry, *WC* water content
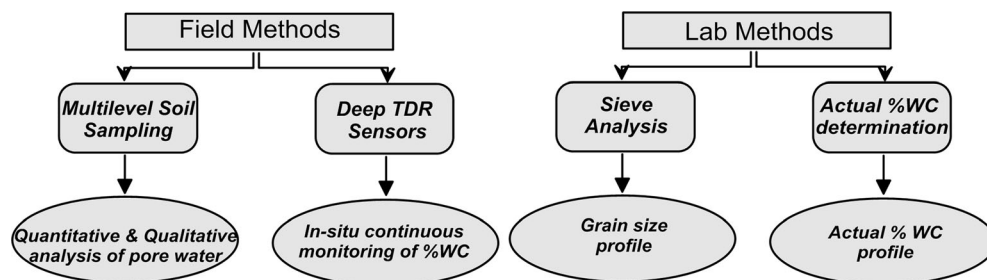
relates the dielectric constant to water content, as well as the electrical conductivity of the investigated soil. Wyseure et al. (1997) and Harlow et al. (2003), showed that for saline soils, the effects of conductivity and frequency on the travel time cannot be neglected and that, as a result, TDR systematically overestimates the water content in saline soils. Robinson (2004) in his findings reports that "the high surface area and charge of some clay minerals can bind polar molecules, fact which may lead to errors in determining the solid permittivity".

One of the main challenges regarding spatial TDR technology is the inverse modelling process to acquire accurate and reliable estimation of water content profiles through significant depths within the unsaturated zone (Oswald et al. 2003; Heimovaara et al. 2004; Schlaeger 2005; Greco 2006; Greco and Guida 2008; Scheuermann et al. 2009; Mboh et al. 2011; Laloy et al. 2014).

An expanded application of TDR technology for groundwater resources studies also involves the investigation of solute transport within surface soils, as investigated by Noborio et al. (2006), Al-Jabri et al. (2006) and Gaur et al. (2003); nevertheless, a holistic investigation of the water flux through the unsaturated zone, as well as the monitoring of the wetting front down to significant depths through the unsaturated zone, demands the installation of spatial TDR probes which penetrate significantly deep down through the unsaturated zone. Dahan et al. (2003) developed a new technique which uses a probe consisting of flexible TDR waveguides made of stainless-steel foil attached to the outer side of a sleeve made of flexible liner which is inserted into a small-diameter (15–20 cm) borehole, drilled at a 45° angle from the vertical, capable of penetrating significant depths through the unsaturated zone. Murdoch et al. (2000) developed a method for accessing the sidewall of a vertical or angled borehole at many discrete intervals along the entire length of the borehole. The method uses an access device that embeds sensors laterally through the borehole sidewall into the undisturbed formation to distances slightly less than the diameter of the borehole, while the system has been used under field conditions to place the TDR sensors at depths greater than 10 m. Schwartz et al. (2008), used a tube-shaped TDR unit to measure and record uncalibrated percent soil water by volume. West and Truss (2006) applied TDR probes against the wall of a borehole, where both portable and permanently installed inflatable packer devices with mounted flat-electrode TDR probes are used to monitor a 14-m-thick unsaturated zone. Stacheder et al. (2009) developed prototype dielectric sensors for measuring both the spatial, as well as vertical soil-moisture profiles using spatial TDR sensors, whereas Hopmans et al. (2001) alternatively used heat pulse probes (HPP) for the indirect estimation of soil thermal properties and water fluxes in the unsaturated zone.

Description of the unsaturated zone experiment

The unsaturated zone at the experimental field site (Upper Rhine Valley close to Darmstadt, Germany) has a thickness of approximately 15 m and consists of unconsolidated aeolian fine sands. Initial drilling activities were performed using a GEOTOOL© LMSR-Hk dynamic probing rig; later the retrieval of undisturbed soil cores and the installation of monitoring equipment were enabled by applying direct-push technology (Geoprobe© 7720DT). The technique is based on a hollow casing with an inner sampling liner that is driven into the subsurface by a percussion hammer. The liners (35 mm outer diameter, thin walled HDPE material, length 90 cm) have an integral core catcher at the end in order to maximize sample recovery and at the same time to minimize any entrance losses of sample material. When the required depth is reached, the casing with the sampling liner containing the undisturbed soil core is withdrawn and a new liner inserted into the hollow casing for sampling the next depth. No drilling fluids are necessary that would alter water content and water chemistry.

The synthesis of the aforementioned is expected to sufficiently analyze the mechanisms of water fluxes through significant depths within the unsaturated zone, which in turn can be used to quantify groundwater recharge at areas where the unsaturated zone hydrology plays a key role for the recharge of the underlying aquifers (such as arid and hydrologically sensitive areas).

Moisture content and grain-size analysis

For further analyses in the laboratory, each liner section was cut longitudinal. One part of the undisturbed soil sample was used for porewater extraction using azeotropic distillation (for further isotopic analysis, Kallioras et al. 2012), while the other part was used for thermogravimetric determination of water content and for sieve analysis. With this, information on the grain-size distribution of the sediments as well as on their water content could be retrieved from the three profiles in high resolution. The application of the direct-push vibro-coring technology was selected as an essential part of this research, partially in order to achieve sampling of undisturbed soil cores from unconsolidated formations. The technique uses vibration (either applied by weight or powered by hydraulic mechanism) to penetrate the subsurface with a hollow casing that contains an inner sampling liner.

Undisturbed soil cores were taken from three adjacent boreholes (GP1, GP2 and GP3), from surface down to a depth of approximately 10 m (distance between boreholes 1.0–1.5 m). The core liners (35-mm outer diameter, thin-walled HDPE material) have an integral core catcher at the end in order to maximize sample recovery and at the same time

minimize any entrance losses of sample material. Each soil core liner was partitioned into 30-cm sections sealed with tailored liner caps and isolated using an aluminum tape in order to eliminate any porewater losses due to evaporation. The soil samples were stored in place after the sampling campaign, in a vertical position. Then each liner section was cut longitudinally, and one part of the undisturbed soil sample was used for porewater extraction after azeotropic distillation (for further isotopic analysis), while the other part was used for thermogravimetric determination of water content and sieve analysis.

The partitioning of the liners in sections of 25 and 30 cm was aimed at the establishment of high-resolution qualitative and quantitative analysis of the porewater (GP1, GP2, GP3). This resulted in a median grain-size profile, from which it can be observed that fine sand particles are present throughout the entire unsaturated column, with smaller particle sizes being accumulated between a depth of 5 and 6 m from the ground surface (Fig. 2). This fine-sand accumulation obstructed the porewater moisture sensors, thus disenabling the system to penetrate deeper down (below depth of 5 m), due to higher friction between the sensor side-walls and the surrounding soil material. The grain-size distributions of the samples reflect the well-sorted aeolian sediments that frequently occur in the Upper Rhine Valley. The median grain-size typically ranged between 0.1 and 0.2 mm with only minor variations; however, in all three profiles, a distinct finer-grained sediment layer was found at depths between 5 and 6 m below ground surface (Fig. 2).

Figures 3, 4, and 5 show the influence of the median grain-size pattern on the containing porewater content down to 10 m within the unsaturated zone. With respect to Fig. 3, it can be realized that larger grain-size sands are associated with the lower gravimetric water content observation, which is more distinct at the depth of 4 m from the ground surface. This observation is even more prominent at depths 3–4 and 2.5–3.5 m at boreholes GP2 and GP3 respectively (Figs. 4 and 5).

Estimation of the soil-water content profile by inverse modeling

Todoroff and Lan Sun Luk (2001) present a numerical one-dimensional (1D) model to compute the water content profile along the TDR sensor, using TDR signal traces. It was also called an inverse model since the first stage of the model (direct), which computes simulated signal traces from water content distribution of the propagation medium, is applied in reverse order to compute the water content profile from measured signal traces from TDR measurement. The aforementioned inverse modeling approach (Todoroff and Lan Sun Luk 2001) considers the same non-uniform transmission line concept for the combined soil-sensor system and characterizes with respect to discrete electronic circuit blocks consisting of
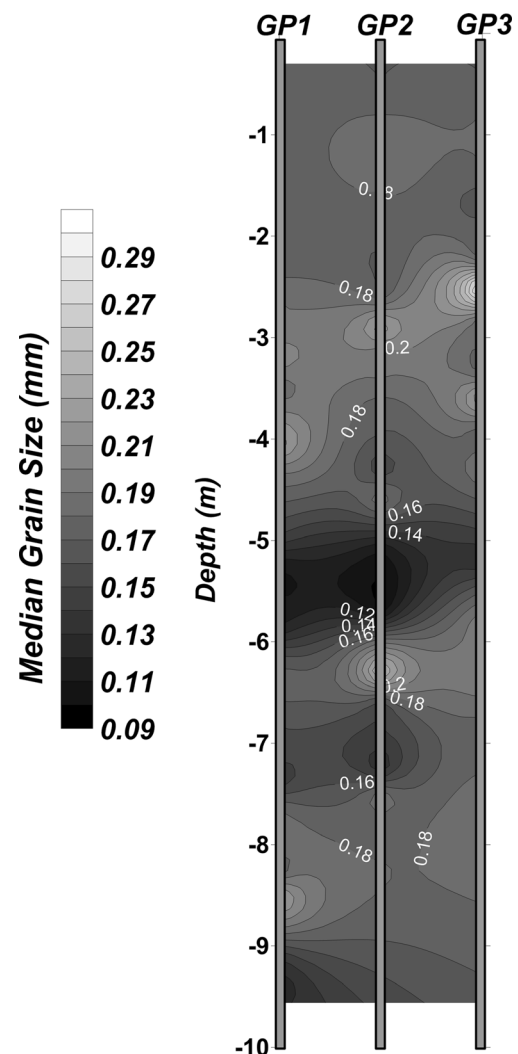

Fig. 2 Distribution of median grain size (mm) across axis *GP1-GP2-GP3* (the horizontal distance between each borehole is 50 cm)

series resistance, inductance, shunt capacitance and conductance as presented by Schlaeger (2005), and hence applies the same principle of a telegraph equation to represent voltage propagation along the transmission line. The lossless medium assumption is also valid for the Todoroff and Lan Sun Luk (2001) model which considers no electrical resistance of the conductors and no conduction between them. The solution provided for this model, which applies to the transmission line discretized into infinitesimally small segments, shows that each elementary segment of the transmission line (which are of identical transit time but of different length) is travelled by two voltage waves propagating in the positive direction (U_+). These voltage waves are known as the transmitted or up-going wave (U_+) in the + direction and as the reflected or down-going wave (U_-) in the reverse direction. Therefore, the wave propagation in a soil medium is represented as a series of elementary propagation processes, each generating an up-going as well as a down-going wave at each junction between

Fig. 3 Variation of median grain size (*MGS*) with gravimetric water content and with depth at borehole *GP1*
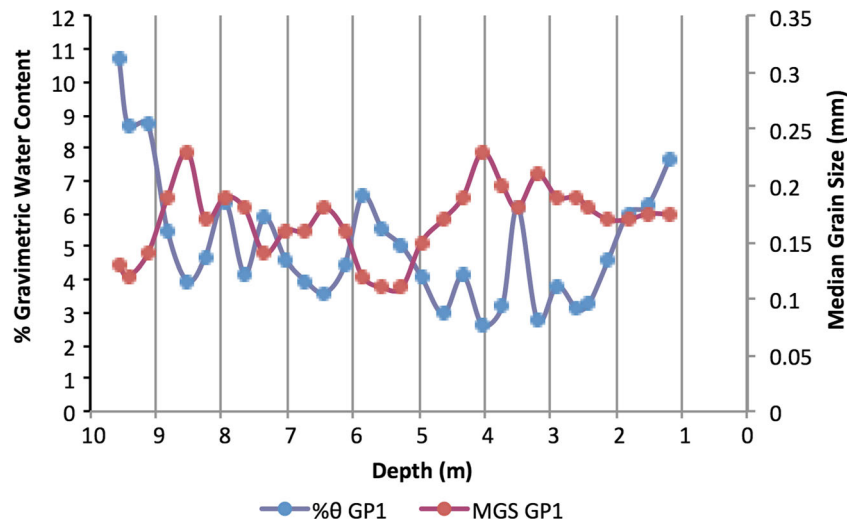
these elementary segments. Each junction between these segments is characterized by a reflection coefficient ρ for the up-going wave (U_+) and $-\rho$ for the down-going wave (U_-) and a transmission coefficient $(1+\rho)$ for the up-going wave U_+ and $(1-\rho)$ for the down-going wave U_-. The reflection coefficient ρ is defined as the ratio of the down-going and up-going wave and is determined by the impedance difference between the segments on both sides of the junction. Equations (1) and (2) are applied to calculate the up-going and down-going wave echoes generated at each junction; therefore, a unit pulse launched at the beginning of the transmission line, after several transmission and reflection processes at each junction between the transmission line segments, finally generates a series of echoes at the beginning of the transmission line system which enables one to build up the impulse response of the system at the beginning.

$$U_+(i,j) = (1+\rho_i)U_+(i-1, \, j-1) - \rho_i U_-(i+1, \, j-1) \qquad (1)$$

$$U_-(i,j) = \rho_i U_+(i-1, \, j-1) + (1-\rho_i)U_-(i+1, \, j-1) \qquad (2)$$

where $U_+(i-1, \, j-1)$ and $U_+(i,j)$ are up-going wave echoes and $U_-(i+1, \, j-1)$ and $U_-(i,j)$ are down-going wave echoes, whereas ρ_i and $-\rho_i$ are reflection coefficients and $(1+\rho_i)$ and $(1-\rho_i)$ are transmission coefficients at the junction (i,j) between segment $(i-1)$ and i (Todoroff and Lan Sun Luk 2001).

The followed modeling steps, based on the Todoroff and Lan Sun Luk (2001) inverse modeling approach are as follows:

1. The measured TDR waveform is a collection of reflection traces at the beginning of the transmission line which are required to normalize by setting the beginning of the trace to zero and by adjusting the plateau of the step pulse to one (i.e. the part of the waveform following the rise of the pulse and corresponding to signal propagation in the feeding cable).

Fig. 4 Variation of median grain size with gravimetric water content and with depth at borehole *GP2*
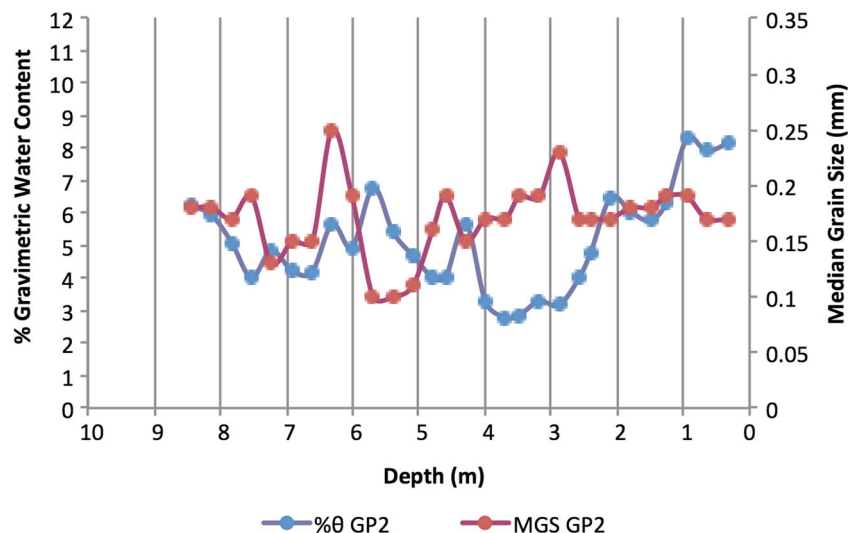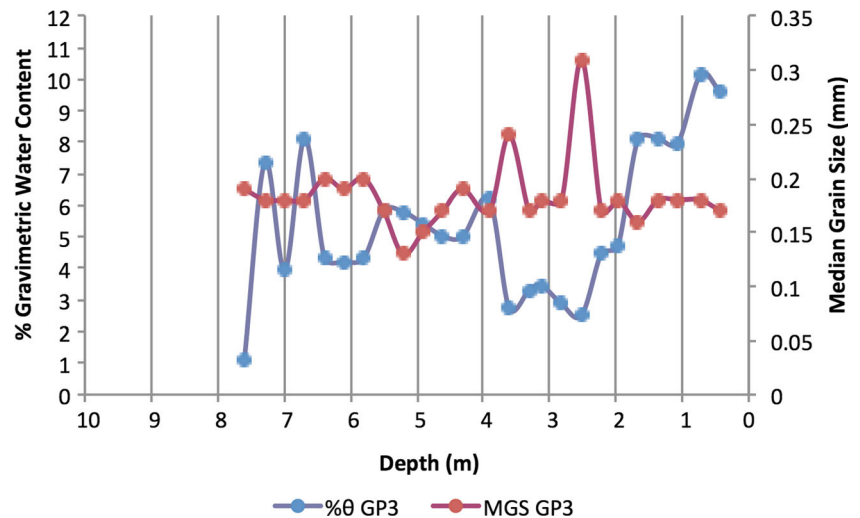
Fig. 5 Variation of median grain size with gravimetric water content and with depth at borehole *GP3*

2. The reflected signals are obtained by subtracting the incident pulse from the reflection traces in the waveform since the sampling receiver records both the incident and the reflected signals at the same time.
3. The impulse response is derived by derivation of reflected signals with respect to time steps.
4. A matrix is developed which consists of time steps (time steps from TDR measurement, each consisting of equal transit time) and corresponding transit time on the y-axis and a sequence of segments along the transmission line of identical transit time (but different length) on the x-axis.
5. Since the impulse response is the collection of final reflected wave echoes at different time steps at the beginning of the transmission line, the impulse response is copied into the first column of the matrix corresponding to the time steps.
6. Then up-going and down-going wave echoes at each junction between the segments are calculated following Eqs. (1) and (2). The ratio of resulted amplitude of down-going and up-going wave echoes is taken as the reflection coefficient at each corresponding junction. This computation process produces a reflection coefficient profile of segment junctions along the transmission line.
7. An impedance profile is calculated from the reflection coefficient profile using Eq. (3). The impedance at the beginning of the transmission line is considered the characteristic impedance of the coaxial cable.

$$Z_i = Z_{i-1} \frac{1 + \rho_i}{1 - \rho_i} \tag{3}$$

where Z_i and Z_{i-1} represent the impedance of each segment i and $(i-1)$ and ρ_i is the reflection coefficient of the junction between these two segments (Todoroff and Lan Sun Luk 2001).

8. At this stage it is necessary to identify the part of the transmission line which corresponds to the TDR sensor for calculation of apparent relative dielectric permittivity of the surrounding medium and the real distance of the sensor. The tangent line method is applied to select the start and end of the sensor.
9. An apparent relative dielectric permittivity for each segment is constructed using Eq. (4). Therefore, an apparent relative dielectric profile of the surrounding medium of the TDR sensor is achieved as a result of this inverse modeling approach, which is required to convert the data into a water-content profile applying a suitable calibration function.

$$\epsilon_{ai} = \left(\frac{Z_c}{Z_i} \right)^2 \tag{4}$$

where ϵ_{ai} is the apparent relative dielectric permittivity of each segment i, Z_i is the impedance of each segment i and Z_c is the characteristic impedance of the transmission line in the air (Todoroff and Lan Sun Luk 2001).

10. The water content profile can be achieved by employing a suitable calibration function.
11. The real length of each segment of the TDR sensor transmission line is calculated using Eq. (5).

$$L = \frac{\Delta t \times c}{2\sqrt{K_a}} \tag{5}$$

where K_a is the apparent complex dielectric permittivity of the soil mixture relative to the free space (measured by TDR), c is the velocity of electromagnetic signal in the free space (e.g. 3×10^8 m/s), Δt is the travel time (ns), L is the waveguide length (m) and 2 is used to represent the both-ways travel distance by the signal (incident and reflected) along the waveguide.

Determination of the deep moisture profile within the unsaturated zone using a new spatial TDR technique

The technique involves the attachment of three parallel flat copper wires (6.3×1.0 mm) on the outer side of a standard HDPE tube (Fig. 6) at a distance of 1 cm between them. The flat copper wires will act as waveguides, transmitting the electromagnetic pulse throughout the entire unsaturated zone column. The constructed probes (i.e. HDPE tubes with attached flat copper wires) are then inserted into a pre-drilled bore using the direct-push vibro-penetration method, whereas the diameter of the bore is such that best possible contact between the soil and the probe is achieved. The time domain reflectometer (TDR 100, Campbell Scientific) at first generates a short rise-time electromagnetic pulse which is applied through a coaxial cable to the TDR probe for soil-water measurements and then samples and digitizes the resulting reflection waveform for analysis or storage. The TDR device is in serial connection with a datalogger (CR800, Campbell Scientific) and a multiplexer (SDMX50SP, Campbell Scientific) for the continuous readings of the electromagnetic pulse of up to eight different channels (i.e. eight different TDR probes at different locations). The system can also be connected with an appropriate GPRS/GSM wireless modem device to achieve continuous online monitoring of the soil-moisture profile fluctuations throughout the entire unsaturated column. The initial drilling activities were achieved by using GEOTOOL LMSR-Hk dynamic probing rig equipment, to install the spatial TDR probes at significant depths within the unsaturated zone, whereas later on, the vibro-coring techniques were completed by using Geoprobe 7720DT series direct-push machinery. The investigations involved the drilling of boreholes of certain dimensions (Table 1), for the insertion of the spatial TDR probes within the unsaturated zone. The installed spatial TDR probes were installed at different depths, as shown in Fig. 7.

The experiments were initially carried out by applying artificial rainfall to observe the response of the TDR sensors in different changes of moisture content through the unsaturated zone at depths of 5 m below ground surface.

TDR waveform is an output of TDR measurement which is a magnitude versus time curve of reflected voltage. Figure 8, presenting TDR waveform measured at the sensor P4, is made up of recorded amplitude (ratio of reflected over incident voltage and termed as reflection coefficient) of successive reflections of incident pulse (voltage) from the TDR sensor and their corresponding recording time (ns).

The measured waveform is analyzed by using the inverse modeling approach as developed by Todoroff and Lan Sun Luk (2001), resulting in an apparent relative dielectric permittivity profile of the surrounding medium along the TDR sensor length. It is characterized as an
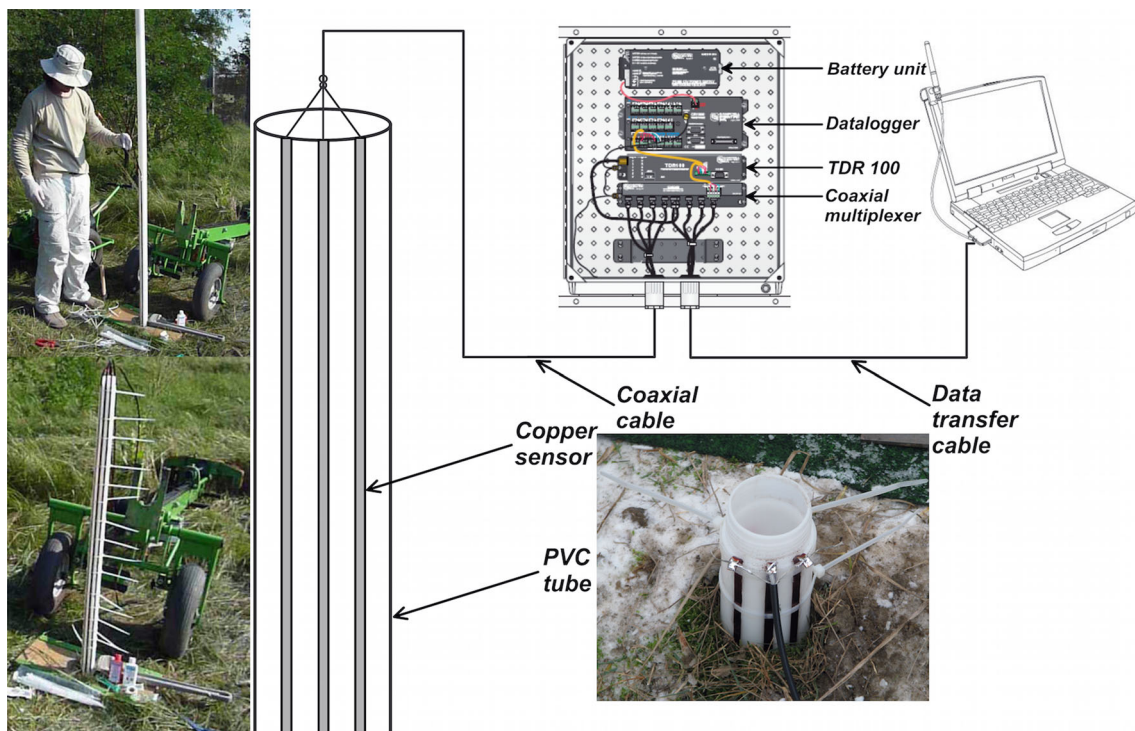

Fig. 6 Configuration of the developed soil-moisture sensing system

Table 1 Characteristics of experimental boreholes at the Technical University of Darmstadt experimental field site

Pushing rod diameter	Depth of borehole	Length of sensor pipe	Sensor material	Details
2,125 in (54 mm)	10 m	5 m	Flat Cu-wire	Direct-push vibro-coring and soil sampling with liners of 1.2-m length

inverse model because the first stage of the theory (direct)—that computes simulated signal traces of the propagation medium—is applied in reverse order to compute the water-content profile from measured signal traces from TDR measurement. It considers the same non-uniform transmission line concept for the combined soil-waveguide. It provides an analogue to discrete electronic circuit blocks consisting of a series of resistance, inductance, shunt capacitance and conductance and hence applies the same principle of a telegraph equation to represent voltage propagation along the transmission line.

The derived dielectric profile is then converted into a volumetric soil-water content profile along the sensor, applying the Topp et al. (1980) universal empirical equation (Eq. 6) which describes volumetric water content as a function of dielectric permittivity.

$$\theta = -5.3 \times 10^{-2} + 2.92 \times 10^{-2} \times K_a - 5.5 \times 10^{-4} K_a^2$$
$$+ 4.3 \times 10^{-6} K_a^3 \qquad (6)$$

where θ is the volumetric water content (m^3 m^{-3}) and K_a is the apparent permittivity measured by TDR.
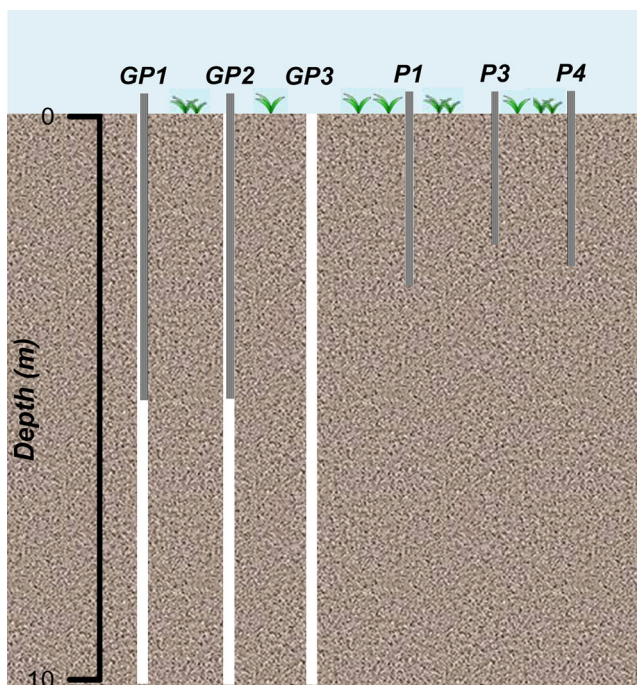

Fig. 7 Boring with direct-push methods for undisturbed soil sampling (*white columns*) and installation of moisture-content monitoring equipment (*grey-striped columns*)

Figure 9 presents a comparison of the water content in the profile of P4 estimated by TDR, and the water content measured gravimetrically in GPR2, about 0.5 m away from P4. Both profiles show a similar trend in water contents, but water contents estimated by the TDR measurements and Topp's equation seem to be underestimated. This observation suggests that Topp's general equation (Topp et al. 1980) considers some non-dispersive clay and organic matter content which are not present at the field site, leading to this underestimation.

Also, during the construction of the TDR probes, small parts of aluminum tape (with dimensions of 1 cm × 1 cm) were attached on the waveguides, in order to be used as "length markers" for the signal interpretation process. The effects of the aluminum tape on the entire signal are visible at certain depths (immediately after 1 m of waveguide); therefore, the comparison between estimated and actual water content profile was made using the interpolated dotted lines of Fig. 9.

It was concluded, that the TDR system is able to correctly display changes in water content, but not the absolute water content; therefore, in the following graphs the relative changes of the water content are relevant, but care has to be taken to conclude the absolute changes. For the x-axis, therefore, the maximum signal was set to a normalized value of 1.

Changes of water content at considerably significant depth and thereby movement of waterfront is clearly detected from water content profiles estimated from waveforms measured during the July–August 2010 period. Figure 10 presents profiles from selected TDR measurement of sensor P4 in July and
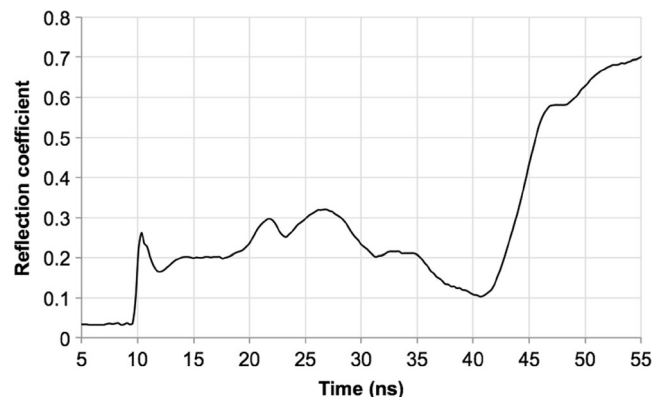

Fig. 8 Measured waveform from sensor P4 taken on 9 February 2010 at the experimental field site of Darmstadt airfield

Fig. 9 Comparison of estimated water content profile using Topp's equation with actual water content profile measured from borehole GP2. The water content profile is estimated from a waveform (Fig. 8) measured in February 2010 at P4 sensor; *dotted lines* represent the match between shapes of the measured and estimated water content profile
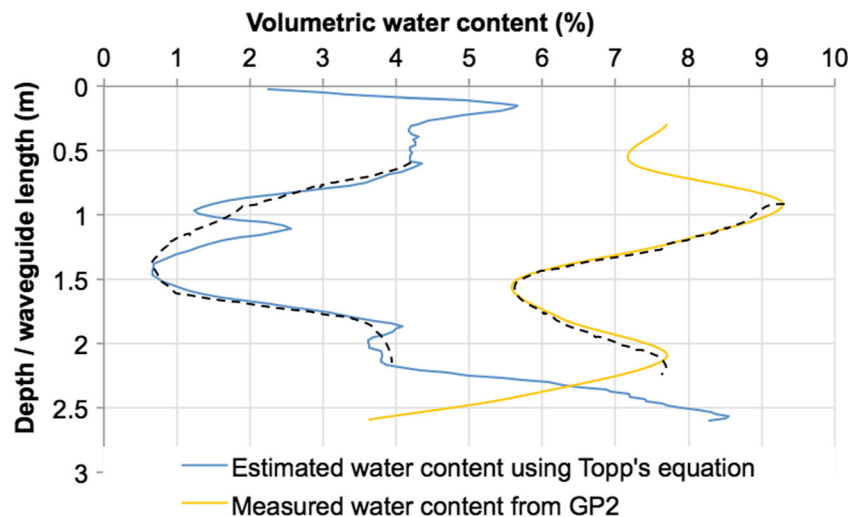
August. The water content profile estimated from a TDR measurement on the 30th of July demonstrates changes of soil-water content (dotted lines in Fig. 10 represent soil-water-content changes) down to a depth of 2.3 m within the unsaturated zone, indicating that water moves downwards at this depth due to infiltration caused by heavy and continuous rainfall events during the period of the 21st and 30th of July. Changes in soil-water content below 2.3 m depth cannot be easily identified since the length of the P4 sensor reaches that exact depth. The water content profile estimated from a measurement on the 13th of August shows a distinct tendency of increasing water content at approximately 1.0, 1.5 and 2.3-m depth, indicating deep percolation of previously infiltrated rainwater. There is a decrease in soil-water content in the shallow unsaturated zone (adjacent to the ground surface) which is due to the prolonged dry period between the 30th of July and the 13th of August. Because of this long dry period, water losses within the shallow unsaturated zone are partly due to evapotranspiration effects and partly due to the
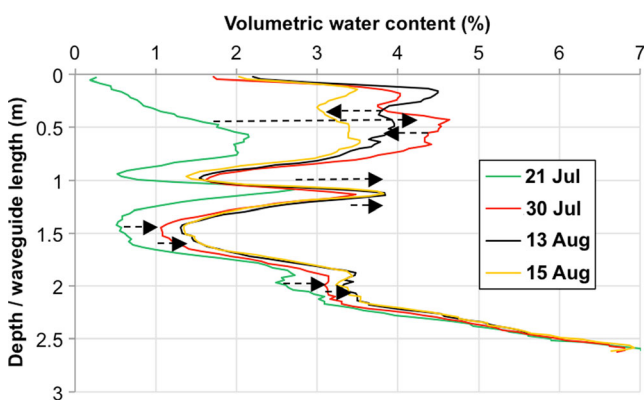
downward movement of porewater into deeper parts within the unsaturated zone. Estimated soil-water content from a measurement on the 15th of August (last day of the long dry period) shows a decreased porewater content in the shallow unsaturated zone, whereas the deeper unsaturated zone soil-water content remains unchanged, a fact which indicates that the deeper part has already reached field capacity, while the shallow part is still subjected to porewater losses due to evapotranspiration effects.

An artificial infiltration field experiment which helps to visualize responses of the upper part of measured waveforms to infiltration event, was carried out by gradually pouring a certain amount of water on top of the sensor P1, starting with 0.3 L, and subsequently continued with an increasing amount of 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5 and 4.0 L at certain time intervals. Continuous monitoring of the reflection coefficient through TDR measurements took place immediately and continued after each pouring event. For the purpose of simplification as well as to realize the artificial infiltration as a natural rainfall event, the amount of water added was calculated in mm against an approximate surface area around the sensor borehole. The time of TDR measurement regards the application of artificial irrigation at a relatively steady rate of ≈54 mm/min for a period of 25 min.

The entire artificial infiltration test and corresponding TDR measurement continued for approximately 1 h, which is an extremely short time to expect the infiltrated water to move deeper (deeper than 1 m) in the unsaturated zone; however, parts of the water content profile curves show changes of soil-water content even down to 3-m depth, which was later identified as a problem of regular shifting of profile curves. Profile curves representing the deeper (up to 3-m depth) unsaturated zone are shifted in case of excessive soil-water content changes in the shallower (shallower than 0.5-m depth) unsaturated zone (Fig. 11). This curve-shifting problem is still under investigation; however, it has been observed that an adjustment

Fig. 10 Soil-water content profiles (July–August 2010) estimated from waveforms measured with P4 sensor. The dates of measurement are shown in the legend; *dotted lines* represent the changes of soil-water content with the direction of the *arrows* representing increasing or decreasing content

Fig. 11 Soil-water content profiles estimated from waveforms measured during the artificial infiltration test: before adjustment (times of the TDR measurements are presented in the *legend*)
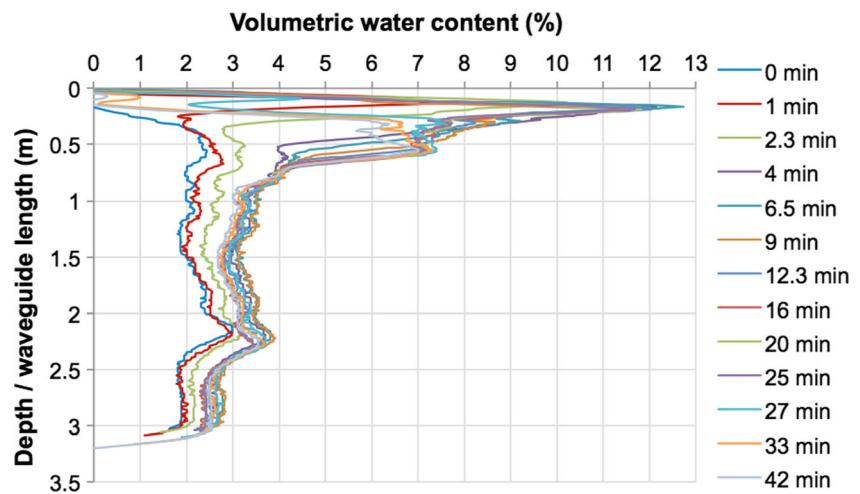
by a total reduction of 1 % of volumetric water content throughout the entire length of the porewater profile curve, produces reasonable results (Fig. 12). Figure 12 shows water-content profile curves estimated from TDR waveforms measured during the artificial infiltration test, which are more or less consistent after adjustment.

The artificial infiltration test also proves the immediate response of the upper part of the unsaturated zone as the soil-water content in this zone increases quite rapidly with increasing amount of infiltrating water (Fig. 13a). On the hand, a similar sharp decline in the porewater content is observed immediately after cessation of the artificial infiltration test. This observation gives rise to the argument that preferential flow occurs within the very shallow unsaturated zone either due to drilling (therefore artificial compaction of the soil), the existence of the TDR sensor itself (installed sensor tube provides a vertical pathway for the downward movement of porewater) or plant roots, providing a flow pathway which continues within the relatively deeper zone (shallower than 1 m depth). Another critical parameter for this specific method is the possible enhancement of preferential flow due to the

vertical drilling during the installation of the sensors. Possible compaction of the surrounding soil as well as possible compaction of the surface material might give rise to preferential flow phenomena.

Figure 13a,b clearly presents the vertical movement of infiltrated waterfront, which is indicated by dotted arrows in the vertical direction. The depth of the moving waterfront at each time step is identified with black circles (Fig. 13a). The velocity of vertical movement of the waterfront varies with depth since the waterfront is moving at relatively higher velocity between ground surface and 0.45 m depth, whereas the vertical velocity of the downward waterfront movement appears reduced in the part of the unsaturated zone between 0.45 and 0.65 m depth (Fig. 13a). Hence, using the information presented in Fig. 13a,b, an average velocity of vertical movement of the waterfront is estimated between 0.15 and 0.7 m depth. Waterfront movement in the first few centimeters of the very shallow unsaturated zone is not considered in the estimation of the velocity of the moving waterfront due to need to avoid the effect of preferential flow. The blue dotted lines in Fig. 13a,b indicate the exact depths of moving waterfront at 1- and 25-

Fig. 12 Soil-water content profiles estimated from waveforms measured during the artificial infiltration test: after adjustment (times of the TDR measurements are presented in the *legend*)
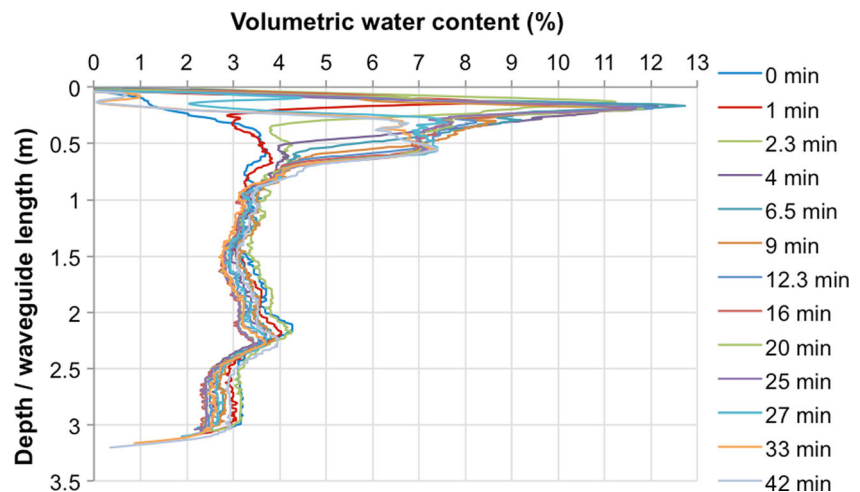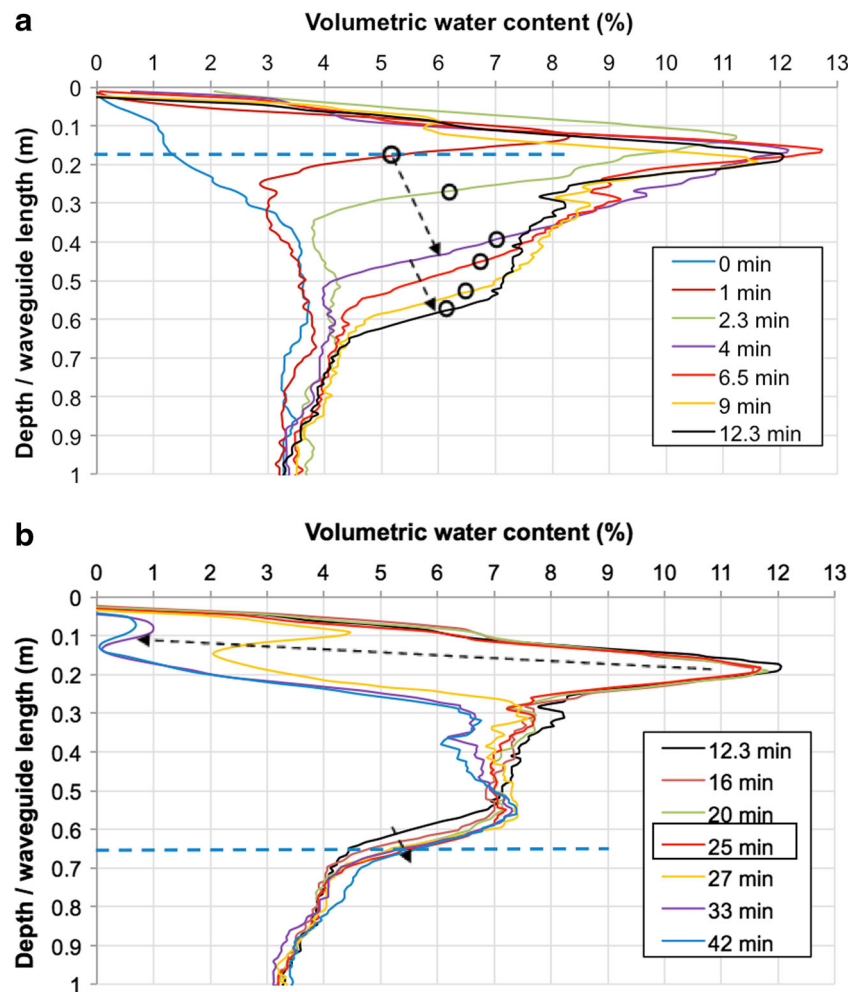
Fig. 13 Soil-water content profiles estimated from waveforms measured during the artificial infiltration test, zoomed to 1 m depth: **a** 0–12.3 min, **b** 12.3–42 min. *25 min* in the legend is *encircled* because the last amount of water is poured at this time step. *Black circles* in **a** represent the waterfronts on each water-content profile

min time steps, which are approximately 0.18 and 0.65 m respectively; therefore, the travelled depth in 24 min is about 0.47 m, which results in an estimated average vertical velocity of 3.26×10^{-4} m/s of moving waterfront. However, since this estimated vertical velocity of moving waterfront is based on an extreme infiltration event which is artificially made, this velocity must be checked and compared with an estimated velocity using the TDR technique under natural conditions before determining a vertical velocity measurement using TDR in the unsaturated zone.

Conclusions

Unsaturated zone processes play a key role in groundwater recharge as the thickness of the unsaturated zone in any region may reach several tens of meters. In principle, the water trapped in the unsaturated zone represents a historic record of infiltration events potentially enabling a quantification of present and past groundwater recharge. Therefore, different experimental techniques were applied, targeted to retrieve the information contained in the unsaturated zone,

complementary to the soil column experiments that were developed by Pfletschinger et al. (2012).

This paper refers to the investigation of the soil-moisture content profile within the unsaturated zone through field as well as laboratory techniques. The field techniques include in-situ measurements of the volumetric soil-water content at different depths using time domain reflectometry (TDR). The artificial infiltration test proved the immediate response of the upper part of the unsaturated zone, as the soil-water content in this zone increases quite rapidly with increasing amount of infiltrating water. A similarly sharp decline in the porewater content was observed, on the other hand, immediately after cessation of the artificial infiltration test. This observation gives rise to the argument that preferential flow occurs within the very shallow unsaturated zone either due to drilling (therefore artificial compaction of the soil), the existence of the TDR sensor itself (installed HDPE tube provides a vertical pathway for the downward movement of porewater) or plant roots, providing a flow pathway which continues within the relatively deeper zone (shallower than 1 m depth).

The study showed that by applying advanced direct-push sounding methods, specially designed TDR sensors can be

installed at significant depths within the unsaturated zone, providing continuous readings of the soil-moisture content. The investigation of the unsaturated zone can also be complemented with the determination of the temperature profile for the unsaturated column.

The unsaturated zone experiments of this study were carried out at a selected field site of the Technical University of Darmstadt (Germany), where the local conditions (unsaturated zone composed of aeolian sands with a thickness of approximately 20 m) were found ideal for unsaturated zone experiments. It is expected that the results will lead to a sufficient quantification of present and historic groundwater recharge in regions where the unsaturated zone plays a key role in hydrological processes.

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