TECHNICAL NOTE

Innovative method for installing soil moisture probes in a large-scale undisturbed gravel lysimeter

Margaret E. Stevenson[1,2] | **Monika Kumpan**[3] | **Franz Feichtinger**[3] |
Andreas Scheidl[3] | **Alexander Eder**[3] | **Wolfgang Durner**[4] | **Alfred Paul Blaschke**[2,5] |
Peter Strauss[3]

[1] Centre for Water Resource Systems, Vienna Univ. of Technology, Karlsplatz 13, A-1040, Vienna, Austria

[2] Interuniversity Cooperation Centre Water and Health (ICC), Vienna, Austria

[3] Institute for Land and Water Management Research, Federal Agency of Water Management, Pollnbergstrasse 1, A-3252, Petzenkirchen, Austria

[4] Institute of Geoecology, Soil Science and Soil Physics Division, Technische Univ. Braunschweig, Langer Kamp 19c, Braunschweig 38106, Germany

[5] Institute of Hydraulic Engineering and Water Resources Management, Vienna Univ. of Technology, Karlsplatz 13, A-1040, Vienna, Austria

Correspondence
M.E. Stevenson, Centre for Water Resource Systems, Vienna Univ. of Technology, Karlsplatz 13, A-1040 Vienna, Austria
Email: stevenson@waterresources.at

Assigned to Associate Editor Qinhong Hu.

Abstract

Aquifers of coarse gravel are an important source for drinking water; however, coarse sediments are also particularly susceptible to the rapid and long-range transport of pollutants through the vadose zone. Therefore, understanding the flow and solute transport in unsaturated gravel material is of utmost importance for the protection of drinking water resources. Experimental investigations of flow and transport processes are dependent on suitable sensor technology, but it is a considerable challenge to install soil moisture sensors in gravelly material. In this note, we developed a novel method to install soil moisture sensors with minimal disturbance in a large lysimeter with undisturbed gravelly sedimentary material, based on drilling access cavities in frozen material. We investigated whether it is possible to obtain reliable soil moisture measurements and found that the probes measured the flow dynamics pattern well but could not quantify realistic absolute water content values.

1 | INTRODUCTION

Water in gravel aquifers is an important drinking water resource, used around the world for human consumption. These aquifers often lie close to the ground surface, are heterogeneous with preferential flow paths, and have fast travel times in the subsurface, causing them to be vulnerable to contamination (Pang, Close, Goltz, Noonan, & Sinton, 2005).

Shallow unconfined aquifers are especially susceptible to microbial and chemical contamination, particularly in intensively used agricultural regions where fertilization (organic and mineral) and pesticide application may be used to increase crop yield. In order to protect this valuable resource from surface contamination, water movement in the vadose zone needs to be understood. Lysimeters offer a unique opportunity to measure flow characteristics in detail under close to natural conditions. More realistic flow parameters can be determined for heterogeneous material on a larger scale using a

---

Abbreviations: TDR, time-domain reflectometry.

lysimeter and undisturbed material conditions (Maciejewski, Maloszewski, Stumpp, & Klotz, 2006).

Modeling flow and transport in large columns and lysimeters containing gravel material is challenging due to the heterogeneity of the porous media and the inherent issues with respect to characterizing hydraulic properties of stony soils (Naseri, Iden, Richter, & Durner, 2019). Furthermore, the instrumentation of the lysimeter while not disturbing the material is very difficult. This makes it almost prohibitive to define unsaturated zone properties in undisturbed gravel material with standard techniques (Mali, Urbanc, & Leis, 2007). Local water content measurements based on dielectric permittivity usually require the installation of sensors that use metal rods as electromagnetic waveguides. Besides disturbing the material, a common problem with the installation of such sensors is the creation of artificial voids along the water content probes and the deformation of the probe's metal prongs, as they are pushed into the gravelly material. However, it is not clear if there is an effect from the stones in the soil causing the prongs to converge or diverge towards the ends, and this needs to be examined in more detail (Graeff et al., 2010). Another problem is the altered pore structure along the rods, which is no longer representative of the undisturbed soil and leads to biased sensor readings as compared with undisturbed in situ conditions.

The aim of this study was the development of an installation technique for soil moisture probes in a large, undisturbed lysimeter dominated by gravel material. We describe our novel technique to install time-domain reflectometry (TDR) soil moisture probes in gravelly material, include a discussion of the disadvantages of this method, and show preliminary results of the measurements. The results will lead to further detailed modeling and data interpretation. The study is part of a larger research project that aims at understanding the recharge and transport processes in gravel material, by measuring the seepage through the vadose zone using a well-instrumented lysimeter and detailed measurements. Compared with fine soils, there are very few studies that investigate in detail the vertical flow of water through several meters of gravel material; thus, there is a demand for reliable data that would allow providing hydraulic property values, specifically unsaturated hydraulic parameters (Thoma, Barrash, Cardiff, Bradford, & Mead, 2014).

2 | MATERIALS AND METHODS

2.1 | Lysimeter excavation and installation

The large-scale lysimeter consists of a 4-m -high and 0.78-m-diam. gravel column (cross-sectional area of 0.5 m^2) encased by a fiberglass wall of 16-mm thickness. The column was constructed from two 2-m-long undisturbed sections, and the

---

Core Ideas

- A novel method was developed to install soil moisture sensors in gravelly sediments.
- Sensors were installed with minimal disturbance by drilling in frozen material.
- An aluminum sleeve on TDR rods still leads to reliable measurements.

---

material in the columns is dominated by gravel (up to 85%) but contains some fine material including loamy sand and sand (Table 1). The columns were taken from a gravel pit near Neuhofen an der Ybbs, Austria (14°51′56″ N, 48°04′17″ E), by driving the 2-m-long pipes, with a sharpened metal ring attached, into the ground with a front end loader, 2 m apart. This was done such that the top of the second pipe was taken at the same elevation as the bottom of the first, so that the original stratification of the material in the columns remains intact.

For transportation and subsequent instrumentation, solid caps were firmly mounted at both ends of each of the two lysimeter sections. The lysimeters were then transported in their original alignment (vertically) to the laboratory.

2.2 | Material characterization

To characterize the material, additional cores were taken every 25 cm until 4-m depth, from the gravel pit. They were analyzed for grain size distribution, organic matter content, pH value, carbonate content, and particle density (Table 1). Based on material characteristics, the lysimeter was divided into two sections. The upper 75 cm is considered Material A and consists of loamy sand and gravel. From 75-to-400-cm depth (Material B), the column contains sand and gravel and has a high carbonate content. Grain size distribution curves were generated from the sieving data (Figure 1), and the largest gravel grain size diameter identified was 120 mm. The organic matter content was below the limit of detection for both materials.

2.3 | Lysimeter instrumentation

In total, 19 three-pronged 20-cm-long TRASE Buriable Waveguide (6050 × 3K1B Minitrase Kit) soil moisture (TDR) sensors (Soil Moisture Equipment Corporation) were installed along the entire length of the column at depth intervals of 10–30 cm, and measurements were analyzed using the manufacturer's software (Figure 2, installation details are

TABLE 1 Characterization of the gravel material

Sample	Sample depth	D_{50}[a]	D_{60}/D_{10}[b]	Clay (<0.002 mm)	Silt (0.002–0.063 mm)	Sand (0.063–2.0 mm)	Gravel (>2.0 mm)	CaCO$_3$	Particle density	pH
	cm	mm				—————%—————			g cm^{-3}	
Material A	0–25	7	356	4.6	8.1	13.1	74.2	70.2		7.82
	25–50	9.5	50	2.8	4.9	12.7	79.6	77.5	2.82	7.78
	50–75	9	48	3.2	4.0	18.5	74.4	85.0		7.94
Material B	75–100	7.6	10	0.6	1.5	12.6	85.2	93.6		7.91
	100–125	9	33	0.7	2.5	17.2	79.5	94.2	2.82	7.92
	125–150	6.8	2	0.4	2.2	22.7	74.7			
	150–175	8.2	12	0.3	0.8	16.7	82.2	97.4		7.93
	175–200	8.1	13	0.3	1.0	17.8	80.8			
	170–195	7.6	12	0.7	1.2	15.5	82.6			
	195–220	13	35	0.3	2.1	17.1	80.5	97.3	2.81	7.89
	220–245	8	16	1.0	1.9	17.5	79.6			
	245–270	7	11	0.1	1.1	18.5	80.3	97.6		7.95
	270–295	5	23	0.2	1.9	28.4	69.6			
	295–320	6.1	15	0.2	1.4	21.4	77.0	98.9	2.81	8.06
	320–345	7	17	0.6	1.1	18.8	79.4			
	345–370	7	14	0.4	1.0	19.5	79.1	99.2		7.70

[a]D_{50} refers to the grain size at which 50% of the material (mass/total mass) is smaller.

[b]D_{60} refers to the grain size at which 60% of the material (mass/total mass) is smaller. D_{10} refers to the grain size at which 10% of the material (mass/total mass) is smaller.
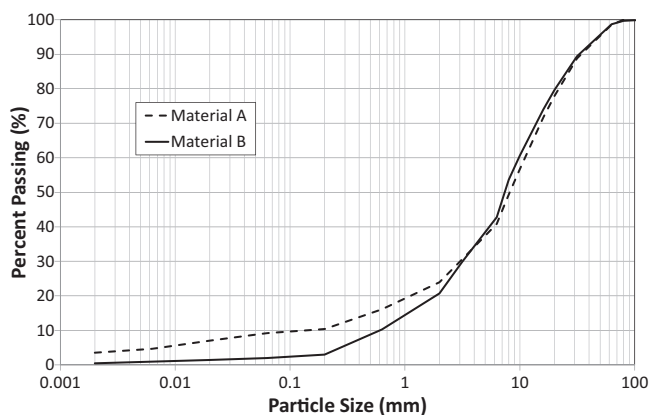

FIGURE 1 Grain size distribution curves of Material A (0-to-75-cm depth) and Material B (75-to-400-cm depth)

given in Section 2.4). In addition, 21 tensiometers and 11 temperature sensors were installed, which are not covered in this note. After installation of the sensors, all access openings in the fiberglass cylinder wall were sealed watertight, and the two 2-m-long sections were stacked on top of each other and mounted on a bottom cone that was packed with material from the site. The bottom cone has an outflow pipe with a diameter of 35 mm and was placed on a scale with three point contacts (Shear Beam Load Cell Model 3510, Tedea-Huntleigh). Additionally, there are two scales (resolution = 1 g) weighing the inflow and outflow water. The outlet at the bottom of

the column is controlled by a tap, so that the water can drain freely by gravity but can also be injected from the bottom.

An irrigation system was installed at the top of the column, which dripped directly onto the material surface, with no vegetation present. The irrigation system consisted of a multichannel peristaltic pump (Watson-Marlow) with tubes being pumped simultaneously on seven channels, all connected to a plastic plate onto which the outlets of the seven tubes were evenly distributed. Mass and TDR data were transmitted to a datalogger every 15 min.

2.4 | TDR recalibration and installation

The two 2-m-long columns, laid horizontally, were frozen to −8 °C in the laboratory in insulated containers with an electrical freezing device, in order for the material to remain undisturbed for the TDR installation. At each point of TDR installation, 10-cm-diam. access holes were bored in the fiberglass cylinder wall. Through these openings, water was added to the frozen material, which froze within a short time. This process was repeated twice to locally fill the pores with ice to an extent sufficient to ensure a compact and firm connection of all embedded gravel and soil particles. With the help of a template, three holes were then drilled into the frozen material at each installation point, lined up with the TDR probes (Figure 3, center and right) in order to prepare for the
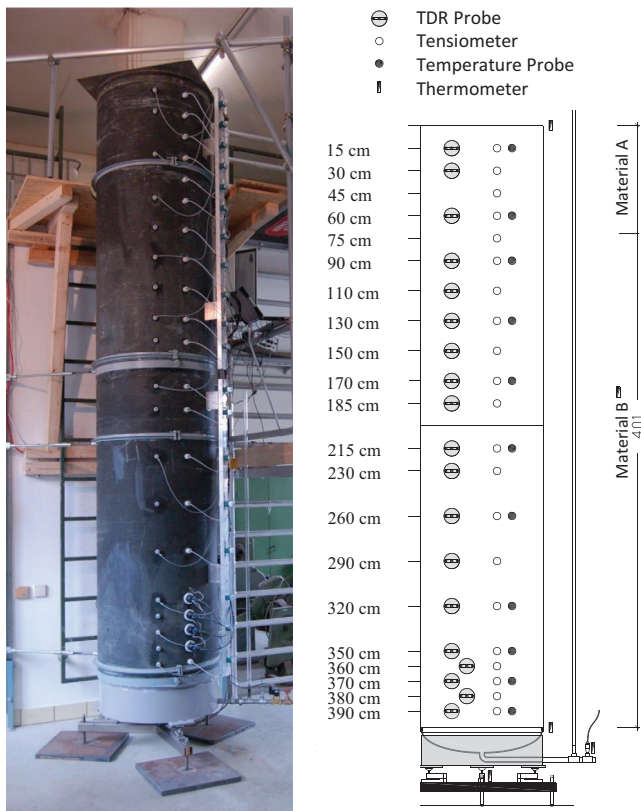
FIGURE 2 Column setup in the laboratory of the Institute for Land and Water Management Research in Petzenkirchen, Austria. TDR, time-domain reflectometry

FIGURE 3 Left: Time-domain reflectometry (TDR) probes in original (top) and modified form (bottom). Centre: Drilling 8-mm access holes using a template. Right: Open 8-mm access holes for modified TDR rods

installation of the modified TDR probes, each of which has three 20-cm-long metal prongs (Figure 3, left). The rotary hammer drill that was used had a drill bit for stone that was 8 mm in diameter, and drilling and hammering were done simultaneously. It took between 2 and 5 min to drill each hole, and if big stones were encountered, it took longer; thus, the installation for one TDR probe (three boreholes) took ∼10 min. Melting of the gravel material, due to heat production of the drill and hammering, was not visible and the material remained in position. Melted water froze again immediately when rotation stopped due to the low temperatures (−8 ˚C) of the surrounding material. An 8-mm drill bit was necessary for successful drilling,

and therefore, the 3-mm-diam. prongs of the TDR probes were enlarged to 8 mm using aluminum sleeves (Figure 3, photo left).

Time-domain reflectometry probes measure the dielectric permittivity (resistance to form an electric field) of a medium, which can be related to water content with an accuracy of 1–2% volumetric water content (Jones, Wraith, & Or, 2002), for fine soils under ideal conditions. We investigated the reliability of the TDR readings and the potentially altered calibration of the modified sensors in a side experiment prior to installation of the TDR probes. For the calibration, air-dry quartz sand was poured into a bucket. Three modified TDR probes were then vertically inserted at different positions, and one measurement was taken for each. The mean of these measurements was related to the mean of three inserted original (unmodified) probes, which were regarded as unbiased. Water was then added to the sand and mixed, and the probes were again inserted and measurements were taken. This process was repeated until the sand was completely saturated.

2.5 | Flow-through experiments

After completion of the sensor installation and column assembly, the lysimeter was gradually saturated with water up to the top by flooding it via the bottom tap. After that, the water was allowed to drain, and irrigation from the top was applied at different intensities. Four successive water applications with increasing flow rates were applied, always with free discharge. In this technical note, we will show results for the intermediate flow rate of 30.7 mm d^{-1} for illustrative purposes. This test took place from 8:00 a.m. on 27 June 2011 to 10:00 a.m. on 7 July 2011 and involved continuous irrigation from 8:00 a.m. on 27 June 2011 for 48 h, followed by free drainage.

3 | RESULTS AND DISCUSSION

3.1 | TDR calibration

The modified TDR probes were tested against the unmodified probes in sand at different water contents, as described in Section 2. Figure 4 (left) illustrates that the modified TDR probes slightly overestimate the water content by ∼2%. The alteration of the probe's design has ramifications, which are not clear. The new probe design with thicker prongs may not affect the travel time, but rather the geometry factor of the TDR probe, with unknown significance to the shape of the TDR waveform and possibly the measurement volume. Therefore, the modified TDR probes were recalibrated according to the bucket experiment, and the small but systematic deviation that was found; the deviation depends linearly on the water content (Figure 4, right). We thus corrected the readings of
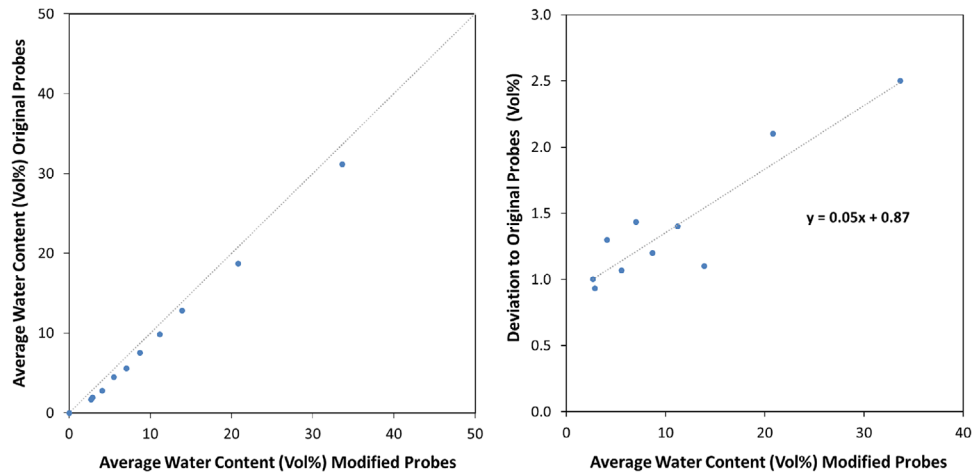
FIGURE 4 Left: Calibration of modified time-domain reflectometry (TDR) probes (*x* axis) vs. original TDR probes (*y* axis). Right: Water content-dependent deviation of readings of modified vs. original TDR probes

the modified TDRs by subtracting the bias $\Delta\theta = 0.05\theta + 0.87$, where θ is the raw reading of the modified TDR probe.

3.2 | Reliability of TDR measurements

The installation method of the TDR probes presented several challenges, as it was sometimes necessary to drill through large pieces of gravel. Resulting changes in the dielectric permittivity along the waveguide, such as stone (which has a low permittivity), could theoretically cause a misinterpretation of water content values and could have a strong effect on the results (Knight, Ferre, Rudolph, & Kachanoski, 1997; Topp, Davis, & Annan, 1982).

Figure 5 shows the results of the TDR measurements at five selected depths during the infiltration experiment. The upper graph shows the measured values of volumetric water content (%), whereas the lower graph presents these values normalized to an initial water content of 0% (i.e., to reflect the water content change). The measurements successfully caught the dynamics of infiltration and the drainage front over time. Specifically, they show the dissipating wave propagation of the irrigation front within the lysimeter, the dampening of the water pulse height with increasing depth, and the almost synchronous decrease of the water content during the drainage phase.

With respect to the absolute values of the water contents, we assume that there is some error in the data. This is indicated by the different levels of the water contents before the arrival of the infiltration front and similarly after the passage of it. These water content levels vary from 13 to 24% (Figure 5, top), with the variability being higher than expected from random heterogeneity. Bias in the absolute measurement is not uncommon in field studies, even in "normal" soils (Jackisch et al., 2020). Material texture, bulk density, clay, and organic matter can all affect the accuracy and precision of
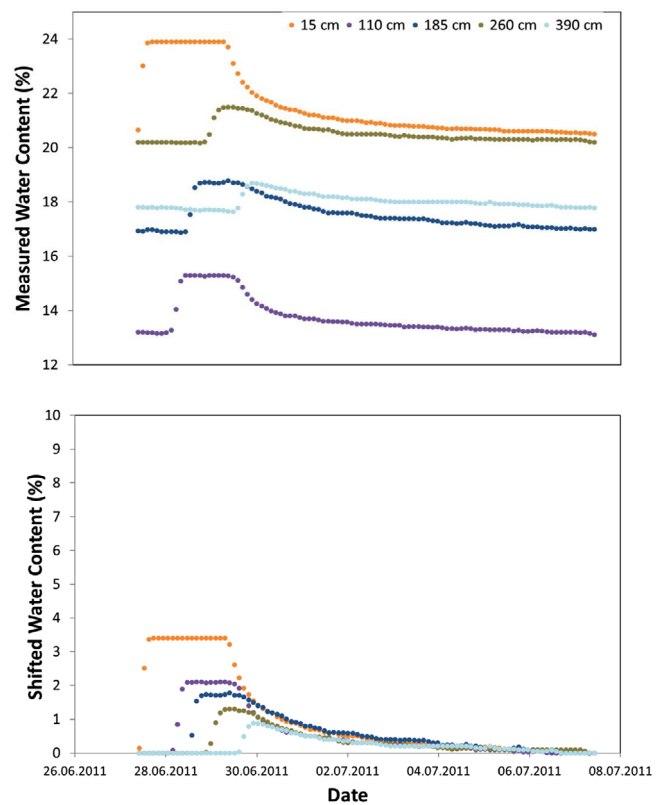

FIGURE 5 Measured water content curves (upper graph) and water content curves shifted to zero (lower graph) to illustrate flow dynamics

the measurements (Persson, 2001; Ponizovsky, Chudinova, & Pachepsky, 1999). In our case, relatively low water contents were especially noticeable at sampling points 110, 185, and 390 cm, which all lie in the portion of the column with coarser gravel and higher gravel content. With respect to variability, we may speculate that in this portion of the lysimeter, the sensor's measuring volume does not reach the representative elementary volume (REV) that is required to give a

representative measurement in a porous medium, due to reduced volume because of the thicker prongs.

Further sources of error might be that the Topp equation (Topp, Davis, & Annan, 1980) used in this study, which is commonly used for mineral soils to convert the measured permittivity from the TDR probes to water content, is not equally applicable in gravelly material. Topp et al. experimented with porous media ranging from sandy loam to clay, and particle size distributions of their soils were all below a grain size of 2.0 mm, which is the approximate D_{20} for our material, meaning 20% of the material mass has this grain size or smaller (see Figure 1). Other equations have been suggested as more appropriate for stony materials (Coppola et al., 2013; Pakparvar, Cornelis, Gabriels, Mansouri, & Kowsar, 2016). Since all these potential sources of error are relatively insignificant due to the dominant effect being the heterogeneity of the material, we have not tried to test alternative calibration equations in this phase of our project. We assume, however, that the individual offset errors are most probably not due to the aluminum sleeve on the TDR probes because, as mentioned above, the calibration showed that the modified probes lead to only a slight overestimation of the water content values. Furthermore, this newly developed method does not cause material compaction around the sensor prongs, which would show an error involving an increase in water content values, especially in material with coarse pore space (Iwata, Miyamoto, Kameyama, & Nishiya, 2017).

Over the course of the infiltration experiment, the measurements of water contents by TDR can be integrated for the column and compared with the total mass change. This allows us to assess the accuracy of the TDR measurements with respect to water content changes. For that purpose, the water content at all 19 sampling points was multiplied by the corresponding volume, according to cross-sectional area along the length of the column, and integrated for every 15 min (frequency of recorded measurements). This integrated cumulative mass was then compared with the cumulative mass of the column over the duration of the experiments (i.e., from 27 June 2011 to 7 July 2011).

Figure 6 shows the net change in column mass and the calculated water mass change from the water content measurements. The qualitative agreement is very good and indicates the general high reliability of the TDR measurements; however, the integrated mass change from the TDR measurements overestimates the mass change obtained from the column mass measurements systematically, by ~8%. It is likely that this discrepancy is due to the difference in scale (i.e., the relatively small sample volume of the TDR sensors compared with the volume of the entire column). Since we can assume that the column mass measurements are unbiased and accurate (Fank & Unold, 2007; Schrader et al., 2013), we can scale the TDR data in order to come to an optimal match. The result was obtained with a scale factor of 0.92 (equivalent to a slope correction of the TDR readings of 8%) and is shown in
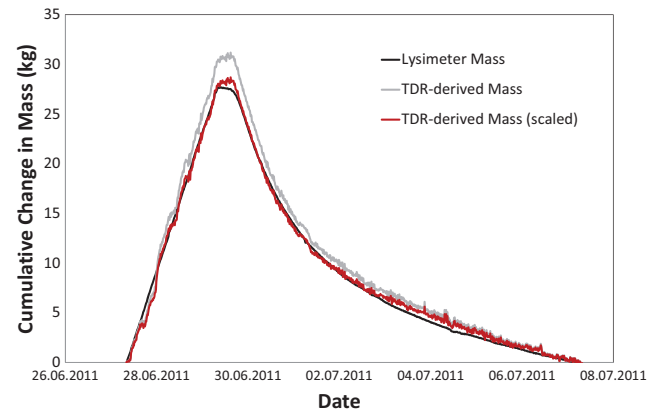

FIGURE 6 Cumulative change in mass. Lysimeter mass change is obtained from mass measurements and outflow, time-domain reflectometry (TDR)-derived mass is calculated by integrating the 19 TDR measurements with their respective depth intervals

Figure 6 as a red line. The excellent match shows that the TDR probes were successful in quantifying the change in water content over the course of the experiment and thus are suitable tools to measure the dynamic pattern of water content changes in the lysimeter.

4 | CONCLUSIONS

Our novel method of installing TDR probes in coarse gravel material was successful in recording the unsaturated flow dynamics in a large column. Although individual TDR probes could not consistently measure the absolute water content values, the water content changes were measured with high accuracy after a moderate correction of the slope of the TDR readings by 8%, as can be seen from the comparison of the results with the total mass of the column. Thus, the measurements of the TDR probes contributed to the understanding of the dynamics of the water content and can help to identify the flow properties in the vadose zone of this undisturbed gravel material. We intend to use the measurements of this and subsequent experiments to identify unsaturated hydraulic functions by inverse modeling and to produce effective water retention curves and unsaturated hydraulic conductivity curves. With this lysimeter and its instrumentation, we hope that it will be possible to better understand the unsaturated flow characteristics in gravelly material and, in future studies, the solute transport with a specific focus on potential removal of pathogenic microorganisms and micropollutants in the unsaturated and saturated zones of gravel aquifers. The implications of this work may thus be important for drinking water protection.

AUTHOR CONTRIBUTIONS

Margaret E. Stevenson: Conceptualization; Visualization; Writing-original draft. Monika Kumpan: Data curation; Writing-original draft. Franz Feichtinger: Conceptualization; Investigation; Methodology; Project administration; Supervision; Writing-review & editing. Andreas Scheidl: Conceptualization; Investigation; Methodology. Alexander Eder: Writing-review & editing. Wolfgang Durner: Validation; Visualization; Writing-review & editing. Alfred Paul Blaschke: Conceptualization; Supervision; Writing-original draft. Peter Strauss: Conceptualization; Project administration; Supervision; Writing-original draft.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

A short video of the lysimeter installation process is available: https://doi.org/10.5061/dryad.mw6m905vz.

ORCID

Margaret E. Stevenson https://orcid.org/0000-0002-4259-4033
Monika Kumpan https://orcid.org/0000-0001-8947-7195
Wolfgang Durner https://orcid.org/0000-0002-9543-1318
Alfred Paul Blaschke https://orcid.org/0000-0001-8617-5802
Peter Strauss https://orcid.org/0000-0002-8693-9304

REFERENCES

Coppola, A., Dragonetti, G., Comegna, A., Lamaddalena, N., Caushi, B., Haikal, M. A., & Basile, A. (2013). Measuring and modeling water content in stony soils. *Soil & Tillage Research*, *128*, 9–22. https://doi.org/10.1016/j.still.2012.10.006

Graeff, T., Zehe, E., Schlaeger, S., Morgner, M., Bauer, A., Becker, R., … Bronstert, A. (2010). A quality assessment of spatial TDR soil moisture measurements in homogenous and heterogeneous media with laboratory experiments. *Hydrology and Earth System Sciences*, *14*(6), 1007–1020. https://doi.org/10.5194/hess-14-1007-2010

Fank, J., & Unold, G. V. (2007). High-precision weighable field lysimeter: A tool to measure water and solute balance parameters. *International Water and Irrigation*, *27*, 28–32.

Iwata, Y., Miyamoto, T., Kameyama, K., & Nishiya, M. (2017). Effect of sensor installation on the accurate measurement of soil water content. *European Journal of Soil Science*, *68*, 817–828. https://doi.org/10.1111/ejss.12493

Jackisch, C., Germer, K., Graeff, T., Andrä, I., Schittenhelm, S., & Durner, W. (2020). Soil moisture and matric potential: An open field comparison of sensor systems, *Earth System Science Data*, *12*, 683–697. https://doi.org/10.5194/essd-12-683-2020

Jones, S. B., Wraith, J. M., & Or, D. (2002). Time domain reflectometry measurement principles and applications. *Hydrological Processes*, *16*, 141–153. https://doi.org/10.1002/hyp.513

Knight, J. H., Ferre, P. A., Rudolph, D. L., & Kachanoski, R. G. (1997). A numerical analysis of the effects of coatings and gaps upon relative dielectric permittivity measurement with time domain reflectometry. *Water Resources Research*, *33*, 1455–1460. https://doi.org/10.1029/97wr00435

Maciejewski, S., Maloszewski, P., Stumpp, C., & Klotz, D. (2006). Modelling of water flow through typical Bavarian soils: 1. Estimation of hydraulic characteristics of the unsaturated zone. *Hydrological Sciences Journal*, *51*, 285–297. https://doi.org/10.1623/hysj.51.2.285

Mali, N., Urbanc, J., & Leis, A. (2007). Tracing of water movement through the unsaturated zone of a coarse gravel aquifer by means of dye and deuterated water. *Environmental Geology*, *51*, 1401–1412. https://doi.org/10.1007/s00254-006-0437-4

Naseri, M., Iden, S. C., Richter, N., & Durner, W. (2019). Influence of stone content on soil hydraulic properties: Experimental investigation and test of existing model concepts, *Vadose Zone Journal*, *18*. https://doi.org/10.2136/vzj2018.08.0163

Pakparvar, M., Cornelis, W., Gabriels, D., Mansouri, Z., & Kowsar, S. A. (2016). Enhancing modelled water content by dielectric permittivity in stony soils. *Soil Research*, *54*, 360–370. https://doi.org/10.1071/Sr15154

Pang, L. P., Close, M., Goltz, M., Noonan, M., & Sinton, L. (2005). Filtration and transport of *Bacillus subtilis* spores and the F-RNA phage MS2 in a coarse alluvial gravel aquifer: Implications in the estimation of setback distances. *Journal of Contaminant Hydrology*, *77*, 165–194. https://doi.org/10.1016/j.jconhyd.2004.12.006

Persson, M. (2001). Solute transport measurements in different soil types using time domain reflectometry. *Nordic Hydrology*, *32*, 99–114.

Ponizovsky, A. A., Chudinova, S. M., & Pachepsky, Y. A. (1999). Performance of TDR calibration models as affected by soil texture. *Journal of Hydrology*, *218*, 35–43. https://doi.org/10.1016/S0022-1694(99)00017-7

Schrader, F., Durner, W., Fank, J., Gebler, S., Pütz, T., Hannes, M., & Wollschläger, U. (2013). Estimating precipitation and actual evapotranspiration from precision lysimeter measurements. *Procedia Environmental Sciences*, *19*, 543–552.

Thoma, M. J., Barrash, W., Cardiff, M., Bradford, J., & Mead, J. (2014). Estimating unsaturated hydraulic functions for coarse sediment from a field-scale infiltration experiment. *Vadose Zone Journal*, *13*(3). https://doi.org/10.2136/vzj2013.05.0096

Topp, G. C., Davis, J. L., & Annan, A. P. (1980). Electromagnetic determination of soil-water content: Measurements in coaxial transmission-lines. *Water Resources Research*, *16*, 574–582. https://doi.org/10.1029/WR016i003p00574

Topp, G. C., Davis, J. L., & Annan, A. P. (1982). Electromagnetic determination of soil-water content using TDR .1. Applications to wetting fronts and steep gradients. *Soil Science Society of America Journal*, *46*, 672–678.