TDR 2006

Purdue University

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Ref.: Dahan, Ofer, Rimon, Yaara, Tatarsky, Boaz and Talby, Ruti, “Deep Vadose Zone Monitoring System", Proc. TDR 2006, Purdue University, West Lafayette, USA, Sept. 2006, Paper ID 46, 15 p., https://engineering.purdue.edu/TDR/Papers

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Abstract

Water infiltration and pollutant transport through the deep vadose zone is a complex process involving physical, chemical and microbial processes. Recognizing that the vadose zone connects sources of pollution on land surface with the groundwater below has led to a greater scientific effort to understand water flow and contaminant transport within this zone, as manifested by the diverse literature published on the topic. However, it seems that the knowledge of theoretical models and simulations far exceeds our ability to provide real-time field data on the infiltration process in deep horizons of the vadose zone. Nevertheless, such data is essential for the validation of the theoretical and computer models. The need for real-time continuous information on the hydraulic conditions and chemical properties of the percolating water led us to develop a new deep vadose zone monitoring system.

The new monitoring system is a development of the method previously presented by Dahan et al. (2003). It is comprised of flexible TDR (FTDR) probes which are designed for continuous measurement of water content, assembled with vadose-zone sampling ports (VSP). The VSP function either as deep vadose zone tensiometers or pore-water sampling devices. The system is adapted for installation in small-diameter boreholes, allowing multiple measurements of the soil hydraulic conditions all along the vadose cross-section, from land surface to groundwater. The installation technique enables monitoring of the vadose cross-section under relatively undisturbed soil conditions.

The monitoring system has been implemented in several studies on water infiltration and groundwater recharge in different climatic and lithological setups, revealing interesting information on the complexity of the infiltration process through the deep vadose zone.

Keywords: vadose zone, infiltration, groundwater recharge, TDR, tensiometer

Introduction

The mechanisms controlling water flow and contaminant transport from land surface through the vadose zone have been extensively investigated for several decades. It has been recognized that the vadose zone plays a major role in controlling groundwater quality and recharge quantity. The scientific efforts to study flow and transport processes through the vadose zone are well documented in a large array of published studies, from small-scale laboratory experiments (Van Geel and Sykes, 1994; Glass et al., 1995; Walser et al., 1999; Heilig et al., 2003) to superfunded sites with large experimental field operations (Dahan et al., 1999; Wolfsberg et al., 1999; Doughty et al., 2000; Tsenga et al., 2003). Although the basic information that allows adequate characterization of the flow process in a well-defined medium is relatively well known, the processes occurring in a natural heterogeneous environment are still far from being clearly described or properly predicted. While theoretical models and computation tools have significantly improved in recent years (Philip, 1957; Kool et al., 1987; Verburg et al., 1996; Simunek et al., 1998; Flint et al., 2002), the ability to provide reliable field observations to support the simulated process is still being developed.

The scientific efforts to provide better monitoring tools for the study of flow and transport through the vadose zone have led to remarkable developments, from the construction of huge experimental monitoring test sites, e.g. in Nevada, Ohio, Denmark and Israel (Sidle et al., 1998; Nativ et al., 1999; Wolfsberg et al 1999; Liu et al., 2004), to the implementation of new technologies, such as airborne penetrating radar (Kowalsky et al., 2004). However, the most important monitoring tools traditionally used for the study of water flow and solute transport in unsaturated conditions are water-content sensors, such as TDR probes, tensiometers for water-tension measurements, and suction cups for pore-water sampling (Looney and Falta, 2000). These tools were originally designed to be implemented in shallow soils for agricultural purposes, and their implementation in deep sections of the vadose zone is usually not straightforward. Traditional TDR probes are made of two or three parallel metal rods (2-6 mm diameter and 10-30 cm long). The maximum depth for implementation of the traditional probes is usually limited by the ability to "push" the probe into the sediments.

The need for accurate, real-time measurements of water content in the deep vadose zone has spawned several technical developments. Yokuda and Smith (1993) developed TDR sensors embedded in a rigid rod that can be pushed into the ground using a vibratory drill to depths of up to 4.5 m. Although this increased the depth of installation, its use in consolidated sediment/rock or gravelly formations is still very limited. Measurements of water-content profiles in deep sections of the vadose zone may also be obtained through a permanently installed access borehole using neutron thermalization (Hillel, 1980, Flint and Flint, 2000), or the TRIME TDR system (www.mesasystemsco.com/trime_index.asp).

Application of tensiometers and suction cups in deep horizons of the vadose zone faces similar technical problems. The porous tip, which is usually made of brittle ceramic material, needs to be pushed into the ground or installed in a small-diameter hole specially drilled for that purpose. To overcome the limited installation depth of both TDR probes and tensiometers, Zilberbrand and Gvirtzman (1996) installed soil sensors through the walls of a wide-diameter vertical shaft. This concept was further developed by Murdoch et al. (2000), who developed an instrumentation technique that allows installation of soil sensors as TDR probes through borehole side walls. Haimerl (2004) used TDR probes and tensiometers in deep vertical boreholes (up to 20 m) drilled in a coarse alluvial formation. In his setup, the sensors were placed in the deepest part of a borehole that was filled with fine sand and then sealed to the surface. The measurements were conducted in a relatively large volume of sand embedded to the desired depth, assuming that the hydraulic conditions in sand reflect those in the surrounding formation.

The limited application depth for standard soil sensors and the need for a reliable monitoring system that can provide continuous real-time measurements under relatively undisturbed sediment conditions necessitated the development of an alternative monitoring setup. The alternative setup allows installation of multiple TDR probes, tensiometers and pore-water sampling ports at any depth from land surface to the groundwater. Although our current experience in a full-scale field experiment is to a depth of 21 m in the vadose zone, there is no technical limitation, and the same system could be applied to even greater depths. This manuscript presents the monitoring setup and preliminary results from several experiments that have been conducted with the vadose-zone monitoring system. The results are presented here in order to demonstrate the system's performance, rather than to provide a thorough discussion of the infiltration process that was observed in each experiment. Accordingly, only a "sample" of the data from each experiment is presented.

Methods

Methodological concept

The vadose-zone monitoring system allows attachment of customized probes to the upper side of an uncased small-diameter slanted borehole (Fig. 1). A flexible sleeve made of thin PVC or rubber liner, hosting several probes along its length in the desired distribution, is lowered into an uncased borehole (Fig. 2). The probes are attached to the sleeve's outer side (Fig. 3). In the borehole, the probes are aligned along its upper side wall facing the undisturbed sediment column extending from the probe to the surface (Figs. 1 and 2). Immediately after insertion of

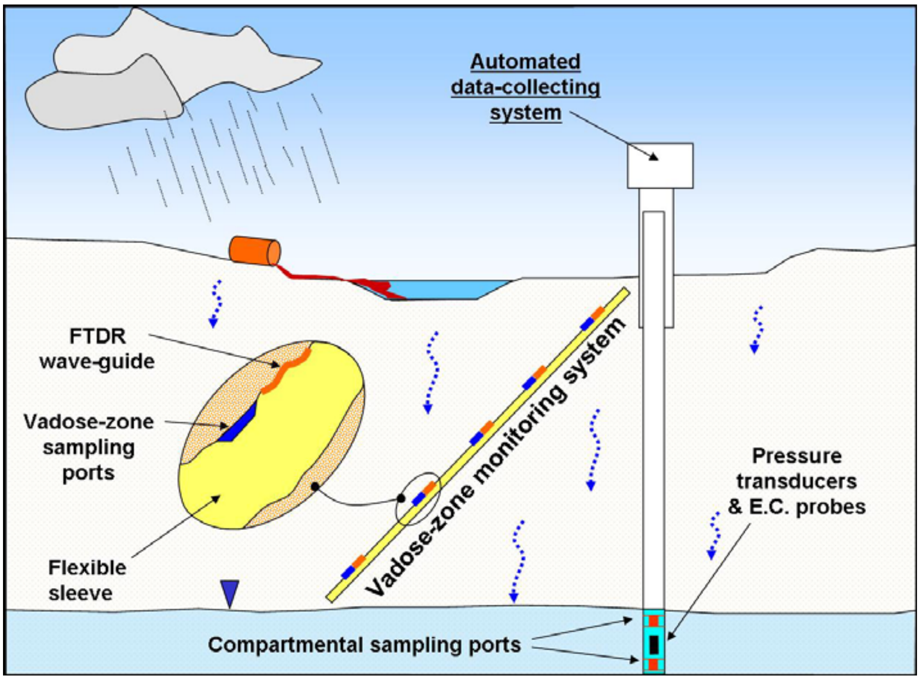


Figure 1: Schematic illustration of the monitoring setup, demonstrating the simultaneous monitoring of the three hydrological domains: surface water, vadose zone and groundwater

the sleeve into the borehole, the sleeve is filled with liquid filling material that solidifies in the mold (such as two-component urethane or concrete). The hydrostatic pressure generated by the filling material within the sleeve causes its expansion. As a result, the probes are pushed against the borehole's upper side wall with sufficient force to achieve good contact between the probe and the sediments on the upper side wall of the borehole. After curing of the filling material in the sleeve the probes are secured in position.

The combination of a flexible sleeve with high-density filling liquid (1.6 g/cm^3) assures that the borehole is sealed all along its length as the sleeve expands to fill the entire void, including small cavities or diameter irregularities (Fig. 4). Accordingly, the borehole itself becomes inert and potential preferential flow along its length is reduced. In addition, the high-density liquid used in the sleeve could potentially restore the tension-release cracks that might have been generated during drilling.

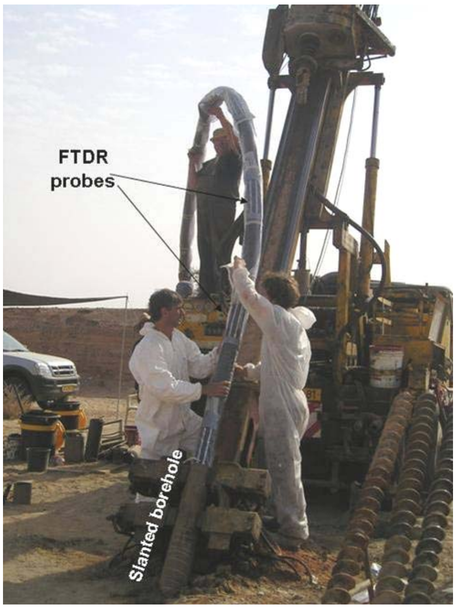


Figure 2: Insertion of FTDR probes on a PVC sleeve into a slanted borehole

Figure 3: VSP and FTDR probes on flexible sleeves

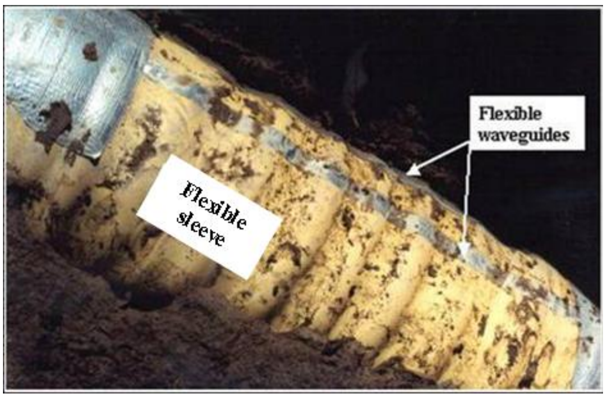


Figure 4: Flexible sleeve and FTDR probe exposed after the installation. The picture shows the attachment of the sleeve and probe to the borehole walls

Although the method can be implemented at any drilling angle, including vertical boreholes, a slanted drilling method is preferred to assure monitoring of an undisturbed soil column. Assuming that the general flow direction in the vadose zone is vertical, every point on the upper side of a slanted borehole faces an undisturbed sediment column. Though the sediments on the borehole side wall could potentially be disturbed by the drilling activity, it is obvious that from the borehole walls to land surface the sediment column is undisturbed. Accordingly, it is assumed that the flow regime from land surface to any given point on the slanted borehole takes place in an undisturbed soil column. This assumption is not valid for vertical boreholes where the probes are distributed along the drilling axis, which is also the general flow direction. Throughout our experience with slanted-borehole drilling, the drilling action has been shown to have very little disturbance effect on the upper part of the borehole side wall, since the heavy drilling shafts lie on the lower side of the borehole.

The drilling method depends on the site's geological characteristics and, of course, the available drilling facility. Nevertheless, we have drilled and successfully installed the monitoring system in a wide range of sedimentological setups, from fine sand dunes to coarse gravel alluvium, with a variety of drilling methods, such as simple flight-auger, odex and rock-bids.

To date, several probe types have been specially developed for this monitoring system and tested in the laboratory as well as in full-scale field experiments. These include flexible TDR or capacitance (FTDR) probes, which were previously presented by Dahan at al. (2003), and vadose-zone sampling ports (VSP), which allow either sampling of the vadose-zone pore water or measurement of the water potential. In addition, Eh sensors are in the process of being developed to allow redox-potential measurement with the monitoring system.

Flexible TDR probes—FTDR

One of the most important hydrological parameters required for the investigation of water flow and pollutant transport in the vadose zone is the water-content variation with time and depth. A variety of methods and commercial tools exist for this purpose. Among them, the most common method for water-content measurement is based on time-domain reflectometry (TDR). In general, the method measures the bulk dielectric properties of the moist sediments and infers the volumetric water content from the ratio between the high dielectric constant of the water (~80) and the very low dielectric constant of most geological material (~2-7). The TDR method was first developed for measurement of soil moisture in the early 1980s (Topp et al., 1984). Since then it has been refined, and studies on its performance, potential applications and limitations have been carried out by several researchers (Ledieu et al., 1986; Herkelrath et al., 1991; Dalton, 1992; Ferré et al., 1998). A thorough review on TDR was recently published by Robinson et al. (2003).

Dahan at al. (2003) presented flexible TDR (FTDR) probes which allow water-content measurement in the deep vadose zone. The method uses thin and flexible metal strips as waveguides (Fig. 3). The flexible waveguides are attached to the flexible sleeve (Fig. 2). As the sleeve is filled with resin, the waveguides are forced against the borehole walls and follow its roughness, undulation and diameter irregularities (Fig. 4). Accordingly, good contact of the probe with the borehole walls is achieved. The FTDR is usually operated with classic TDR operation systems (such as Tektronix or TDR 100). However, those systems are usually limited to a cable length of ~40 m, and beyond that length the measurement accuracy is reduced. To avoid cable-length problems and allow proper measurements at greater depths, water-content reflectometers (such as CS505, Campbell Sci.) may be connected directly to the flexible waveguides (Dahan et al., 2003).

Vadose-zone sampling ports—VSP

The VSP is designed to allow continuous monitoring of the water potential and frequent sampling of the sediment pore water all along the vadose zone. The VSP system was designed to be implemented together with the FTDR probes on a flexible sleeve system. Accordingly, the entire system provides a complete monitoring scheme that includes measurements of water content, water potential and the ability to sample the sediment pore water.

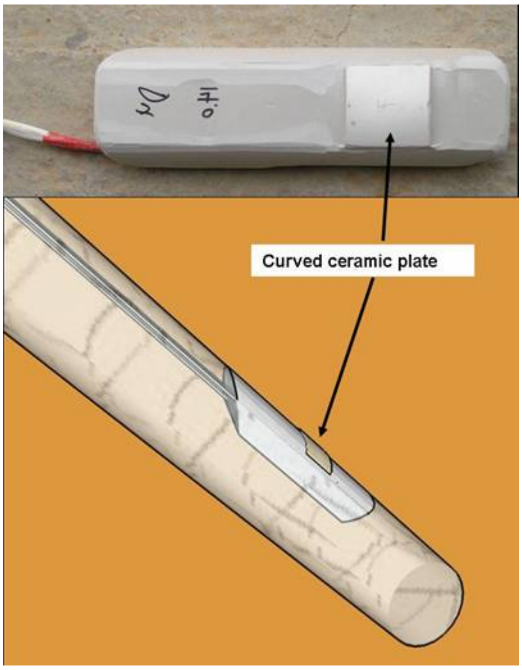
The VSP is based on a structural modification of standard tensiometers and suction cups. The probes were designed to allow their attachment to the sediments on the upper side wall of an uncased slanted borehole, similar to the FTDR probe. The sampling ports are mounted on the outer side of a flexible sleeve in the desired distribution, according to the lithological profile. After lowering the sleeve into the borehole, it is filled with two-component urethane. The hydrostatic pressure that is generated within the sleeve pushes the VSP against the borehole walls to achieve intimate contact between the probe and the sediments.

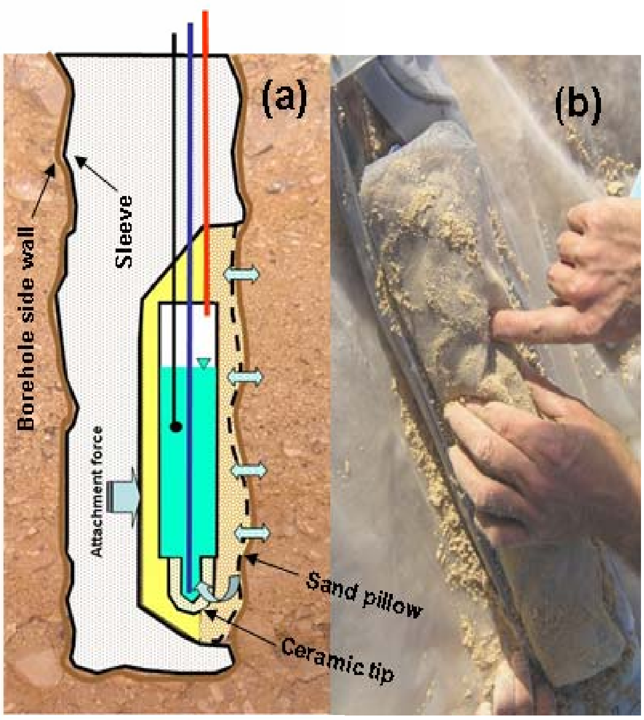
The general structure of the VSP is very similar to standard tensiometers or suction cups. It is constructed from a closed chamber with a porous section that needs to be in contact with the sediments and allows water continuity between the sediment pore water and the water within the chamber. Once hydraulic continuity between the sediment pore water and the closed chamber is achieved, the soil water pressure may be interpreted from the water pressure within the chamber. Alternatively, if sampling of the pore water is desired, then application of low pressure (vacuum) within the chamber will draw the sediment pore water into the chamber for later sampling.

Each cell has a set of small-diameter access pipes that extend from the cell to land surface. The access pipes allow water sampling and maintenance of the cell water solution. A set of valves and micro-pressure transducers in each cell allows measurement of the cell water pressure. A water-level mechanism monitors the water level in the cell.

Direct Contact VSP (DCVSP)

The VSP has two main models, designed for two environments. The first is called Direct Contact VSP (DCVSP). This model is designed for “soft” geological formations where the borehole drilling results in clean and smooth borehole walls (typical of sandy formations). For such boreholes, the VSP has a customized curved ceramic plate that is shaped to the exact borehole radial curvature (Fig. 5). The curved ceramic plate is attached to the cell chamber to form the DCVSP body. Accordingly the DCVSP body is designed to allow full contact of the curved ceramic plate with the borehole side walls. Once the sleeve with the DCVSP is inserted into the borehole and filled with urethane, the hydrostatic pressure in the sleeve pushes the DCVSP towards the borehole's upper side wall, allowing contact of the curved ceramic plate with the sediments. In this model, the curved ceramic plate is in direct contact with the soil. Accordingly, this model is less suitable for coarse gravelly sediments such as alluvial formations, since drilling in such material usually results in rough and undulating borehole walls, which may ultimately result in poor contact of the curved ceramic plate with the sediment.





(Left) Figure 5: Photograph and schematic illustration of DCVSP. Above: curved ceramic plate and cell body. Below: schematic demonstration of the DCVSP in a slanted borehole

(Right) Figure 6: (a) Schematic illustration of the PVSP installed in a borehole drilled in a coarse alluvial formation. The illustration shows the sand agent creating the contact between the coarse sediments and the ceramic tip. (b) A photo demonstrating the sand pillow's flexibility and ability to follow the borehole wall undulations

Pillow VSP (PVSP)

The second model is specially designed for coarse material where drilling produces rough borehole walls with irregular diameter. In such boreholes, contact between the solid ceramic plate and the coarse sediment may not be achieved. In this case, the hydraulic continuity between the ceramic cup and the borehole side wall is achieved through an unconsolidated agent that bridges between the coarse material and the cell (Fig. 6). The connecting agent is customized from a soft sand “pillow” that helps create hydraulic continuity between the cell's porous tip and coarse sediments on the borehole walls. The pillow is made of a flexible fiber mesh that covers the cell with very find sand. The installation technique is identical to that described for the FTDR probes and DCVSP. While pressed against the rough wall, the sand from the pillow is pushed out of the mesh into the sediment cavities to generate fine pore continuity between the cell and the coarse sediments.

Results

To date, the method has been successfully installed in numerous studies on water infiltration and groundwater recharge in several countries, including Israel, Namibia, South Africa, Spain and the US (Arizona). The studies have included investigation of floodwater infiltration from ephemeral stream channels into alluvial aquifers as well as the impact of land use on groundwater recharge in a coastal aquifer with a thick vadose zone of ~20 m.

The results presented here are data samples from three different field experiments. The experiments were conducted under different climatic, geological and hydrological conditions. The data samples demonstrate the system's performance and the ability to monitor hydrological aspects of the infiltration process.

Monitoring of floodwater infiltration using FTDR

A study on floodwater infiltration and groundwater recharge was conducted in several ephemeral rivers in hyper-arid deserts around the world. The study sites were located along wadi Arava (Israel), Kuiseb River (Namibia), Buffels River (South Africa), and Rio Andarax (Spain). Each site was instrumented to monitor the hydraulic conditions of all three hydrological domains participating in and controlling the infiltration process: (a) the flood on the surface, (b) the vadose zone as the linking domain between the surface water source and the groundwater below, and (c) the groundwater. The floodwater and groundwater were continuously monitored for water levels and electrical-conductivity variation with time, and in the vadose zone, water-content variations were continuously monitored by the FTDR system. At each site, several independent FTDR systems were installed in different boreholes drilled in different directions to allow an evaluation of the potential impact of sediment heterogeneity on the infiltration process.

The data presented here demonstrates the infiltration process from the relation between the floodwater stage to the wetting-front propagation, through the vadose zone and finally the groundwater level response to the recharge event.

The data is taken from a monitoring station that is located in the Kuiseb River by the Gobabeb Research Center, Namibia. Figure 7a gives the river water stage during a flood event that was recorded in January 2006. The river stream bed is composed of fine sand with small amounts of gravel and the water table is located ~5 m below land surface. Figure 7b gives the water-content variation with depth as measured by one of the FTDR systems that was placed in the stream bed. Each curve on the figure presents the water-content variation at a different depth and clearly shows the infiltration process along the entire vadose zone, from land surface to the groundwater. This data allows calculation of wetting-front propagation with depth as well as the rate of change in water content. Accordingly, flow velocity and flux rate may be calculated directly from multiplication of the velocity by the change in water content. The floodwater infiltration through the vadose zone and groundwater recharge may be confirmed from the rise in the water table (Fig. 7c).

Although the data presented here is only a sample from a single monitoring station during a single flood event, very similar results were observed from all monitoring stations. Though the wetting pattern is similar, the measured magnitude of each parameter varies from site to site according to the specific hydrological, geological, and geomorphological settings that characterize them.

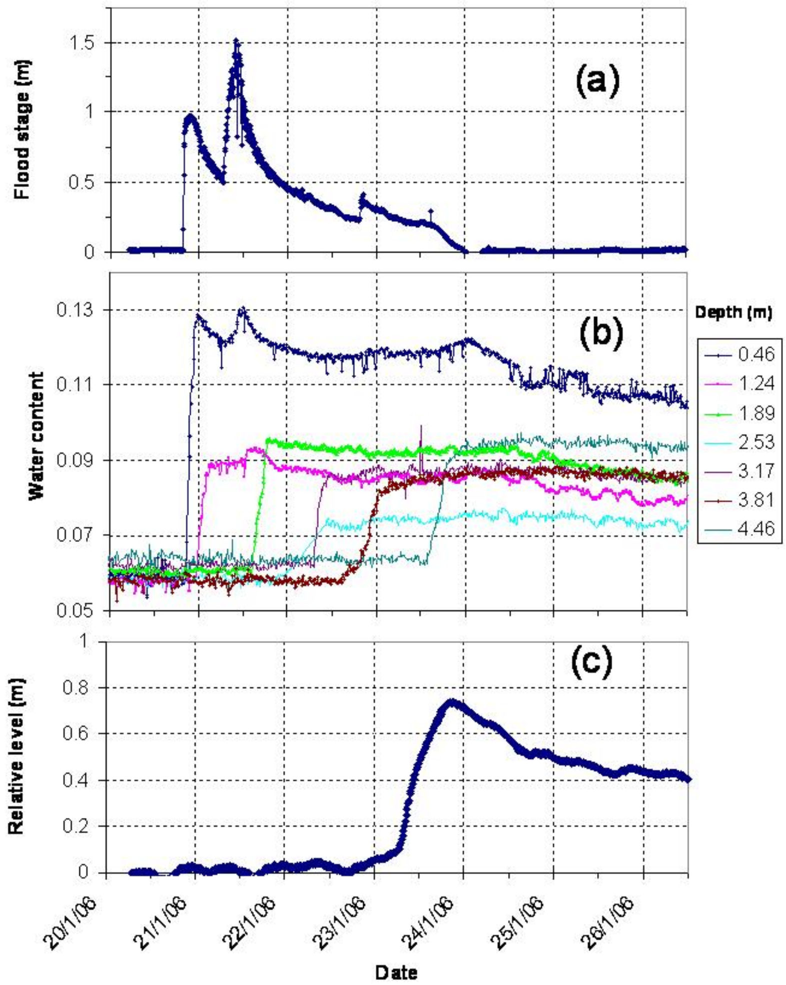


Figure 7: Monitoring of floodwater infiltration and groundwater recharge from a stream bed of an ephemeral river in a hyper-arid environment. (a) Floodwater stage. (b) Water-content variation in the vadose zone underneath the stream bed during the flood. (c) Water-table response to the flood event

Monitoring of deep vadose zone water potential—DCVSP

Land-use impact on groundwater recharge of the coastal aquifer is currently being studied using the deep vadose zone monitoring system. The study is being conducted in urban, agricultural, and open sand dune spaces around the coastal city of Ashdod, Israel. The sand-dune study site is instrumented with several independent monitoring FTDR systems and two additional DCVSP systems. Though the two DCVSP systems are identical, one system is dedicated to pore-water sampling and the other to water-pressure measurements. The systems were installed away from each other (6 to 15 m) to prevent any influence of the pore-water sampling on the water-pressure measurements. The vadose zone in this site is composed of an ~20-m thick unconsolidated sand dune and sandstone with a single, ~1.5-m thick clay layer ~7 m below surface level. The climate is characterized by rainy winters (~500 mm from October to April) followed by dry summers. Since the study site is located on bare sand dunes with no vegetation, the recharge process is controlled primarily by direct percolation of intense rain events.

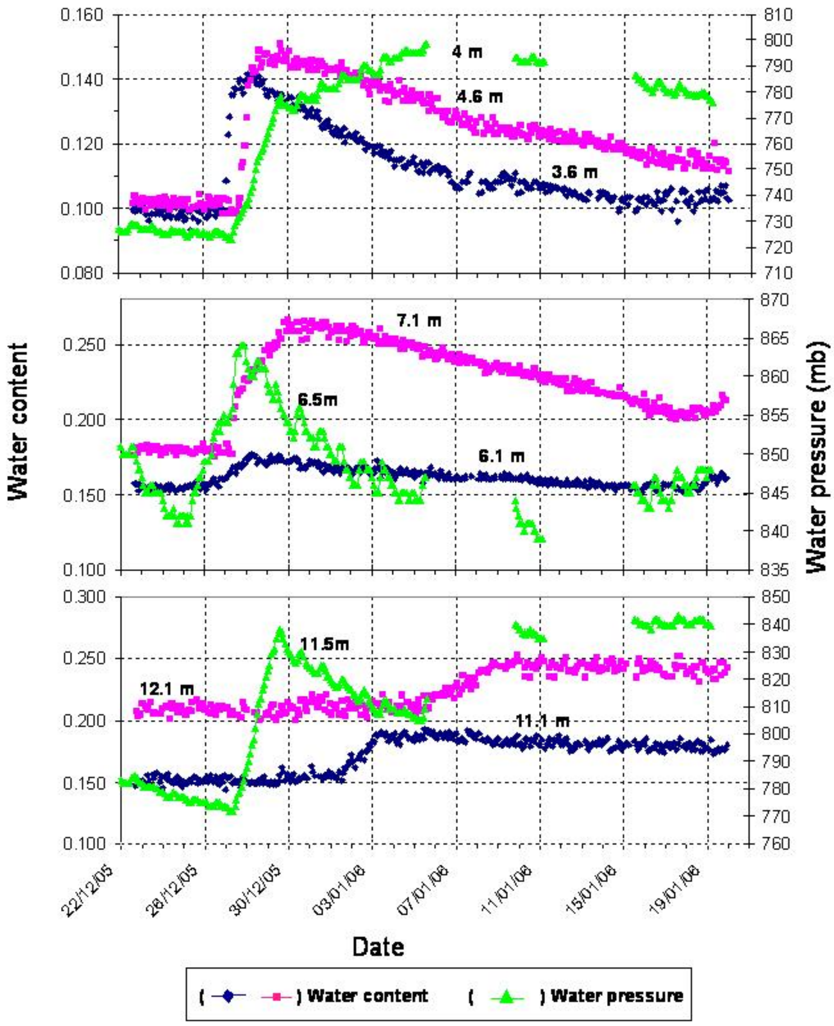


Figure 8: Water-content and water-pressure variations at three different depths as measured by the vadose-zone monitoring system following a rain event

Preliminary results from this site demonstrate a pore-water pressure response to an infiltration process generated by a rain event (Fig. 8). The water pressure is measured by the DCVSP as absolute pressure (1000 mb represents atmospheric pressure) at three different depths of 4, 6.5 and 11.5 m below surface level. The water-content variation above and below each DCVSP is monitored with FTDR probes. The figure shows that each monitored wetting process is followed by a water-pressure increase. Alternatively, reduction in water content is followed by a water-pressure decrease. Deviation from this pattern can be seen on the set of probes that was installed at 11.5 m. Prior to the increase in water pressure that follows the water-content increase, a pressure rise is observed with no change in water content. Since the pressure transducers measure absolute pressure, it is possible that the pressure rise occurred due to a pressure increase in the vadose-zone gas phase and not directly as a result of a change in the water tension. The pressure increase may be generated by the infiltration event that, while propagating down the vadose zone, entraps and pressurizes air in the lower layers.The other DCVSP system that was installed at this site allowed frequent water sampling at various depths from land surface to the groundwater throughout the season. The water samples are still undergoing analysis and results from that part of the study are not available at this stage. This set of DCVSP was the first prototype to be installed in the field and a new, more efficient and accurate monitoring set will be installed in the near future.

Pore-water sampling using PVSP

Water flow and contaminant transport from land surface to the groundwater was investigated in an alluvial formation in wadi Arava, Israel. To investigate the solute-transport pattern, a multi-tracer test was conducted on a section of the stream channel which was instrumented with a vadose-zone monitoring system. The system included five PVSP to sample the percolating water and five FTDR probes to monitor the vadose-zone wetting process. The sampling ports were equally distributed on a 5-m long flexible sleeve that was installed in a slanted borehole (Fig. 6b). Figure 9 shows a schematic illustration of the experimental setup. The experiment was conducted in a pond that was constructed above the sampling system. Large ring infiltrometers were installed above each sampling cell to allow flux measurements in several sections of the stream channel and allow infiltration of different tracer solutions above the sampling cells.

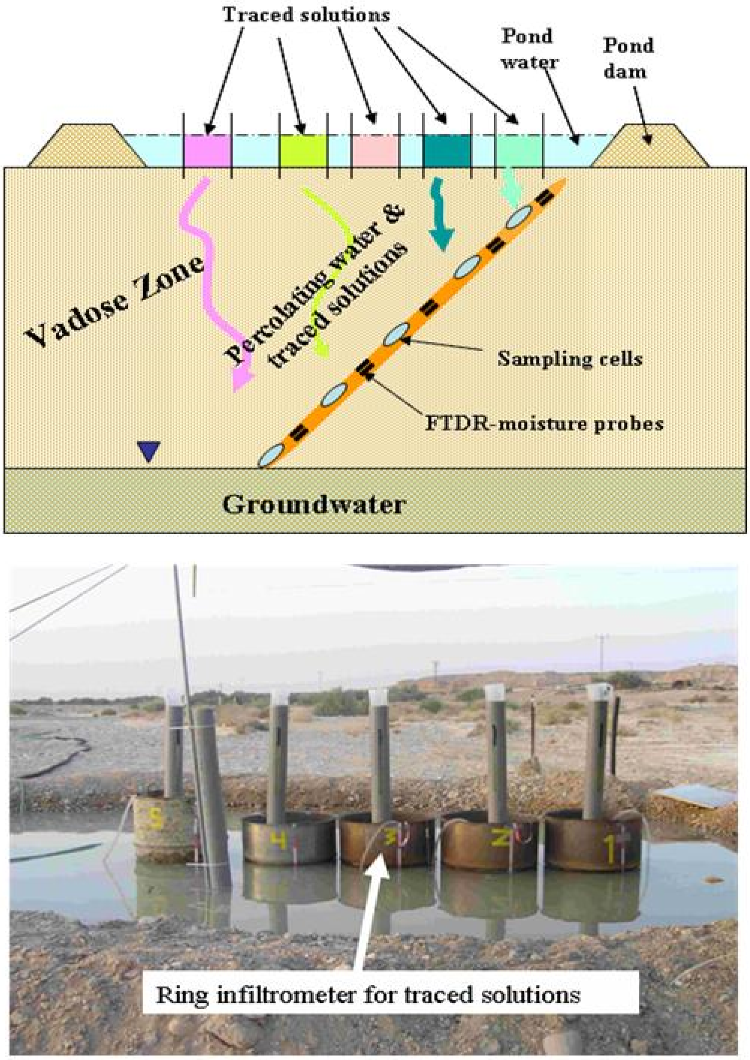


Figure 9: Schematic illustration of the tracer test experimental setup and sampling port system (above), and a photo of the infiltration pond with the ring infiltrometers for the traced solution (below)

The pond was flooded with water to achieve a constant water head. Equal water head between the ring's inner side and the pond was maintained throughout the experiment. The water-content profile in the vadose zone was continuously monitored by the FTDR system, and the sampling cells were frequently sampled. Two tracer tests were conducted in two different sessions, using 10 different tracers [five isomers of fluorobenzoic acid (FBA), Br, Li, eosin, Na naph and uranine]. During each tracer test, a certain mass of traced solution at a constant concentration was allowed to percolate through each ring.

Monitoring of the wetting/draining process by the FTDR system allowed tracing of the wetting-front propagation. In addition, analyzing the water samples that were obtained by the sampling cells allowed establishment of the breakthrough curves for all tracers in all samples.

Figure 10 presents the breakthrough curves of the FBA tracers that were injected into the different infiltration rings on the surface during the first tracer test, in the sampling cell located 2.3 m below land surface. The tracer breakthrough curves emphasize the complexity of the infiltration process through layered soil. The graph clearly shows the flow lines' mixing pattern, and demonstrates that the flow pattern is far from being vertical. Moreover, some of the tracers appear in the cells with a breakthrough curve characterized by two distinct concentration peaks. A multi-peak breakthrough curve is a typical indication of dominancy of a preferential flow mechanism with a dual-porosity system. Analysis of the results from all sampling cells in the two tracer tests revealed similar flow behavior.

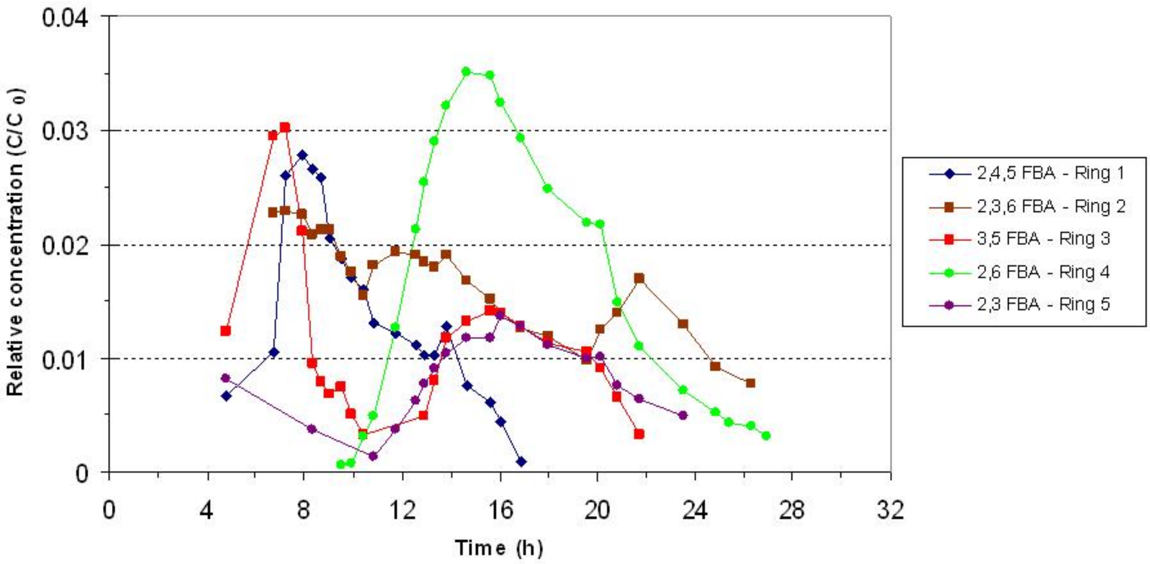


Figure 10: Breakthrough curves of the five FBA tracers that were injected through the ring infiltrometers on the surface as they appear in the sampling cell that is located 2.3 m below surface

Summary

A vadose-zone monitoring system that provides real-time information on the infiltration process through the deep vadose zone was developed and tested in several laboratory and field experiments. The system is composed of FTDR probes, which are designed to monitor the wetting/draining process, and VSP sampling cells, which are designed to allow measurements of the deep vadose zone's water potential and allow sampling of the sediment pore water. Preliminary results from several studies demonstrate the ability to trace the wetting-front propagation velocities and thus allow direct calculation of the water fluxes. Continuous monitoring of water content and water pressure combined with the ability to sample the sediments' pore water in deep undisturbed sections of the vadose zone allows better evaluation of vadose-zone flow and transport models.

Acknowledgements

We thank Michael Kugel and Michael Fulton for their technical assistance and creative ideas. Funding for the studies was provided by the Israel Science Foundation (Grant #276/03) and the 6^{th} framework program of the European Commission (WADE). We would like to express our appreciation to the Gobabeb Research Center and the Desert Research Foundation of Namibia.

*** Note:** A patent is pending on the system described in this manuscript.

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