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New Approaches to Quantify Groundwater Recharge in Arid Areas

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Abstract: Semi-arid and arid regions represent 30% of global terrestrial surface area and are expanding. For groundwater resources management in arid environments, the rate of aquifer replenishment due to groundwater recharge is one of the most important factors and unfortunately also one of the most difficult to derive with sufficient accuracy. In general, the potential evaporation by far exceeds the precipitation limiting groundwater recharge. Unsaturated zone processes play a key role in groundwater recharge as the thickness of the unsaturated zone in arid areas may reach several tenths of meters. In principal, the water trapped in the unsaturated zone represents a historic record of infiltration events potentially enabling a quantification of present and past groundwater recharge. An approach is presented for the investigation of the unsaturated zone through a combination of laboratory and field techniques. They include direct push techniques to get undisturbed soil samples, extraction of pore water for isotope analyses and application of Time Domain Reflectometry (TDR) to determine soil moisture content. It is expected, that the combination of these techniques will result in a better quantification of present and historic groundwater recharge in arid environments.

Key words: Arid hydrogeology · Groundwater recharge · Moisture content · TDR · Pore water extraction

INTRODUCTION

Semi arid and arid regions represent 30% of global terrestrial surface area and are expanding [1]. For groundwater resources management in arid environments the rate of aquifer replenishment due to groundwater recharge is one of the most important factors and unfortunately also one of the most difficult to derive with sufficient accuracy. In general, the potential evaporation by far exceeds the precipitation limiting groundwater recharge [2].

To estimate groundwater recharge, a variety of techniques can be used. Scanlon *et al.* [3] summarize these techniques and relate them to the investigated hydrological zone. In principal, surface water, unsaturated zone or saturated zone measurements can be used to quantify recharge. Approaches include physical, chemical or isotope techniques as well as numerical modeling. However, especially in arid environments a lack of tailored techniques to generate high quality data hampers the precise determination of the generally low water fluxes.

Unsaturated zone processes play a key role in groundwater recharge as the thickness of the unsaturated zone in arid areas may reach several tenths of meters. In principal, 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, we apply a combination of different experimental techniques that are targeted to retrieve the information contained in the unsaturated zone.

In a first step, experiments are carried out at the August-Euler airfield of the Technical University of Darmstadt, an experimental field site with a tailored scientific infrastructure. Here, the unsaturated zone has a thickness of about 15 m and consists of unconsolidated fine sands of eolian origin. The site offers the advantage to test and optimize the techniques under well controlled conditions. In a second step, the same techniques will be applied at several pre-selected field sites in the Kingdom of Saudi Arabia that represent typical settings for groundwater recharge in arid environments.

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In this publication we present our experimental approach and show first results of the unsaturated zone investigations at the August-Euler airfield.

Experimental Approach: The unsaturated zone represents an archive of present and past infiltration events and therefore of potential groundwater recharge. In principal, two approaches can be followed to retrieve information from the unsaturated zone: (i) quantification of its current water content and analyses of the water chemistry and (ii) 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 monitoring equipment.

Both requirements can be satisfied by applying a direct push technology that was developed to take undisturbed soil cores from unconsolidated formations. The technique uses vibration to penetrate the subsurface with a hollow casing that contains an inner sampling liner. When the required depth is reached, the casing with the sampling liner is withdrawn and the liner can be capped for further analysis. No drilling fluids are necessary that would alter water content and water chemistry. In a second step, the open borehole can be used for the installation of monitoring equipment again using direct push methods.

On the airfield of the Technical University of Darmstadt we used a Geoprobe 7730 series direct push machine to retrieve undisturbed soil samples to a depth of 10 m below surface. In addition, monitoring equipment was installed to a depth of 5 m.

Evaluation of Undisturbed Soil Samples: The water contained in the unsaturated zone can be used to determine the time scale of groundwater recharge. For this, the water has to be analyzed for appropriate tracers. These are isotopes such as $\delta^{18}O$, $\delta^{2}Ç$, ^{3}H and ^{36}Cl, that are frequently used for groundwater dating, as well as chlorine for mass balance calculations. For example, Tritium is used to verify the occurrence of waters younger than about 50 years and $\delta^{18}O$ and/or δD values of pore waters have yielded long-term trends of past climatic changes [4].

However, the pore water has to be extracted efficiently for further analyses. Possible extraction techniques include centrifugation, mechanical squeezing, vacuum heating, cryogenic micro distillation and azeotropic distillation with an immiscible organic solvent. Each of these techniques has limitations and the potential for causing isotopic fractionation. However, azeotropic distillation was suggested as the appropriate technique as it is most conservative with respect to the isotopic composition of the water [5]. The principle of the method is based on the observation that water and toluene being immiscible at ambient temperature form an azeotropic mixture that boils at 84.1°C. In a special distillation apparatus, the boiling liquid mixture can be separated quantitatively. Traces of toluene are removed using activated carbon and the sample can be analyzed.

Undisturbed soil cores were retrieved from the boring at the Darmstadt airfield down to a depth of 10 m, subdivided into 20-50 cm sections and split in half. To test the efficiency of the azeotropic distillation, one half of the samples were oven dried at 105°C to get volumetric water content. Then the water content of the other half of the samples was determined using azeotropic distillation. Figure 1 shows the comparison of the two methods in terms of the determined water content. It can be seen that both methods yield very similar results with the azeotropic distillation giving slightly lower but consistent water contents (ranging from 2% to 8%). Several peaks showing high water contents were observed that are attributed to infiltrated water after rainfall events. Eventually, this water will reach the groundwater table causing groundwater recharge.

From the experiments it is concluded, that azeotropic distillation is an appropriate method for the extraction of small water volumes from soil samples. It is further concluded, that water volumes as low as 1 ml per 100 g of soil can be extracted quantitatively. For lower water contents the amount of soil sample can be increased, however, a loss in vertical resolution has to be accepted.

The extracted water samples are currently analyzed for their isotopic composition and results will be presented at the conference. To proof whether the method is conservative with respect to the isotopic composition, soil samples mixed with water of known isotopic composition are extracted and analyzed as references.

Monitoring of Changes in Soil Moisture Content: The in-situ measurement of changes in soil moisture content is a difficult task and is in general achieved using Time Domain Reflectometry (TDR). TDR is an indirect geophysical technique which is based on the relation

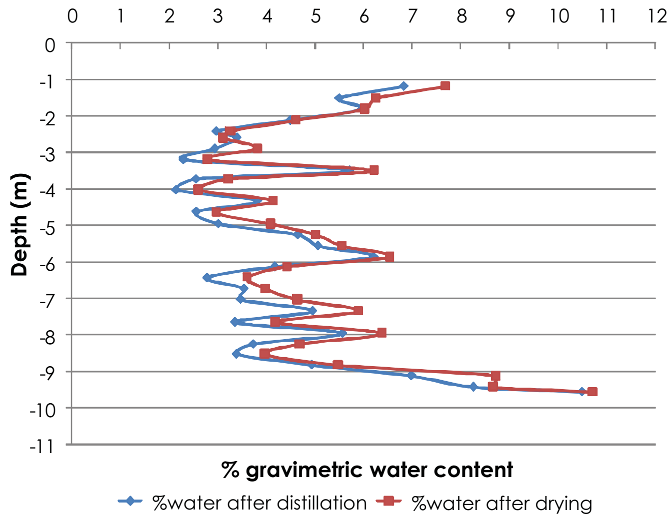

Fig. 1: Change of gravimetric water content (%) with depths (m) obtained from undisturbed samples from the August-Euler airfield in Darmstadt after azeotropic distillation (blue) and oven drying (red)

Fig. 2: Installation of the continuous TDR equipment into a predrilled boring at the August-Euler airfield

between the permittivity of soil and its volumetric water content. The bulk dielectric permittivity, ε_b, of the soil mixture (soil matrix, soil water and air) is determined by measuring the propagation time of an EM pulse, generated by a pulse generator and containing a broad range of different measurement frequencies [6]. The pulse propagates along a coaxial cable and enters the TDR probe, which is traditionally a pair of parallel metallic rods inserted into the soil.

However, only point measurements are possible with standard equipment, therefore soil moisture profiles lack high vertical resolution. The majority of the reported case studies focus on the installation of such equipment within a depth of 60-80 cm from the ground surface [7].

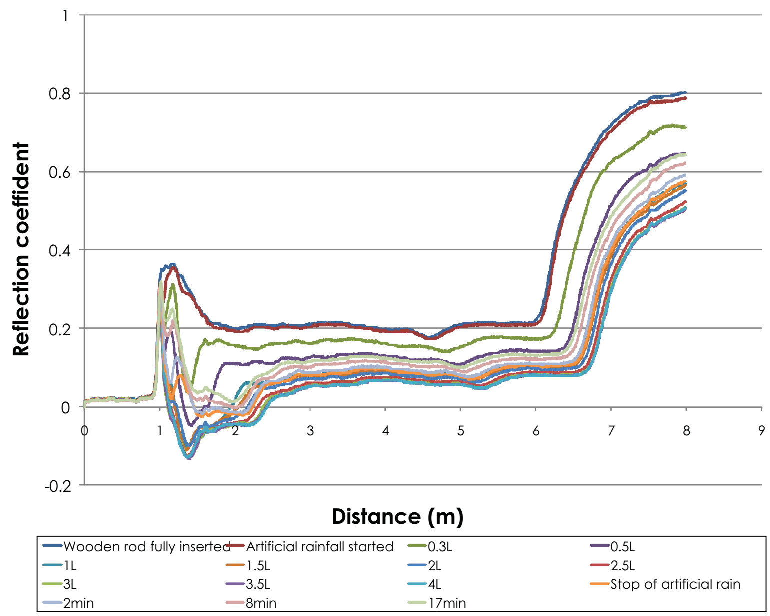

Fig. 3: TDR responses after the application of different artificial rainfall events

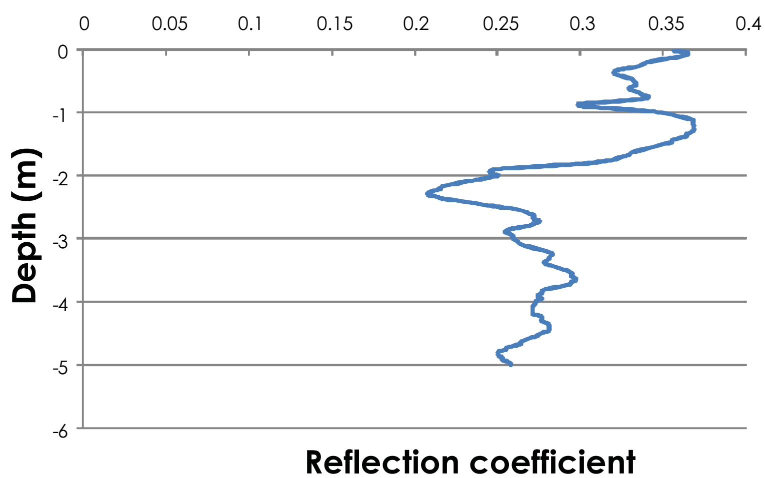

Fig. 4: Normalization of the TDR signal over the penetrated vertical depth

Recently, Stacheder *et al.* [6] presented a new TDR design that allows the continuous recording of the vertical soil moisture profile over several meters. For this, specially designed copper sensors which are installed vertically into the unsaturated zone are used.

We used this technique at the August-Euler airfield by gluing three flat copper cables in a distance of 2 cm on standard PVC well pipes (Figure 2). The pipes were then installed into a predrilled boring using the direct push method. A length of 5 m was installed at the airfield, however, in principal the installation depth is only limited by the depth that can be reached by the Geoprobe machine.

To test the function of the system, rainfall was simulated by infiltrating stepwise a total of 4 liters of water around the boring. Figure 3 shows the TDR response of the installed system after each infiltration event and at three time intervals after infiltration was stopped. It can be seen that the TDR sensor records the propagation of the water front.

By normalizing the electromagnetic pulse to the depths (Figure 4) the soil moisture content can then be derived after calibration with a standard profile.

The first experiments with the continuous TDR showed that it is possible to record continuously soil moisture profiles with high vertical resolution over several meters. In addition, several TDR devices can be connected in series with a data logger (i.e. 8 different TDR sensors at different locations). The system can also be connected to an appropriate GPRS/GSM wireless modem that qualifies it for remote operations.

CONCLUSIONS

Field experiments to qualify appropriate techniques for the quantification of groundwater recharge were carried out on the August-Euler airfield in Darmstadt. The experiments showed, that techniques are available for the efficient extraction of low quantities of soil water and for the continuous in-situ monitoring of soil water profiles in high vertical resolution.

As next step similar experiments are planned on selected sites in the Kingdom of Saudi Arabia that are typical for groundwater recharge scenarios in arid areas. This will include undisturbed soil sampling for the determination of the soil water age in the unsaturated zone. In addition, high resolution TDR probes will be installed in the unsaturated zone over several meters to record changes in the soil moisture content over extended time periods (years). It is expected, that the combination of these techniques will result in a better quantification of present and historic groundwater recharge in arid environments.

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